Volume 11 | Issue 1 Winter 2015

Acoustics Today

A publication of the Acoustical Society of America

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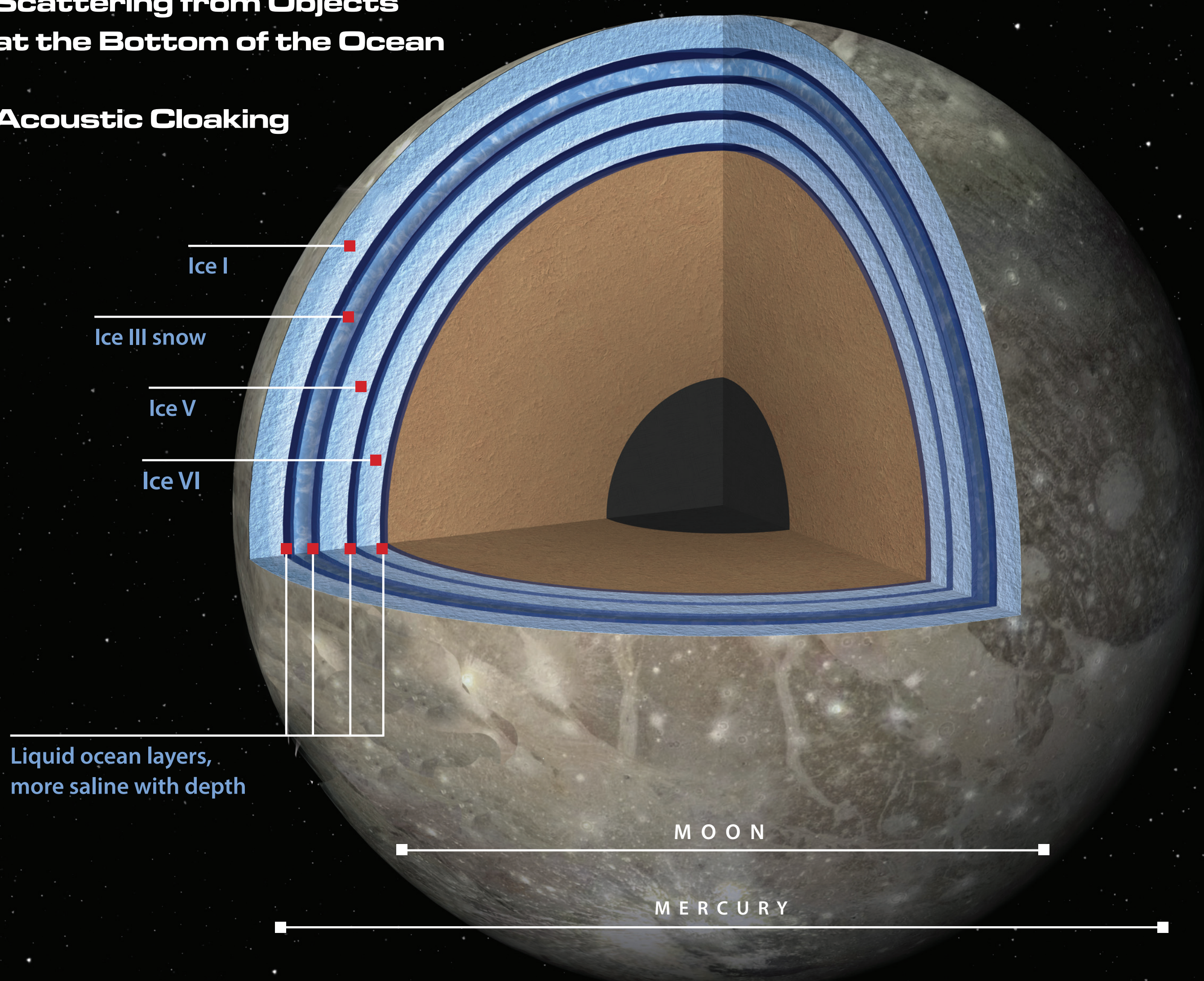

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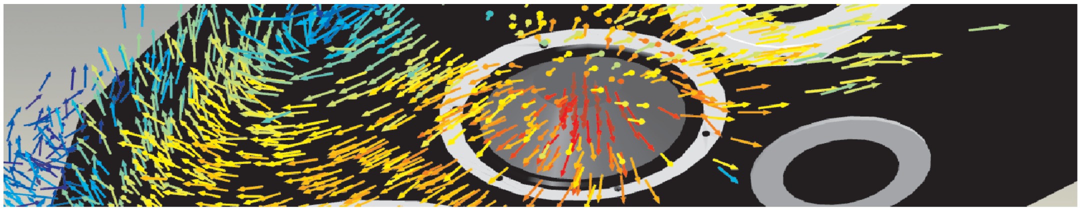

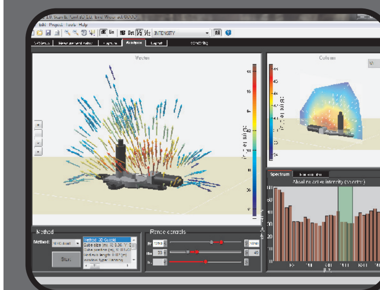

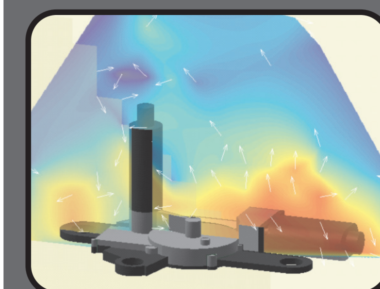

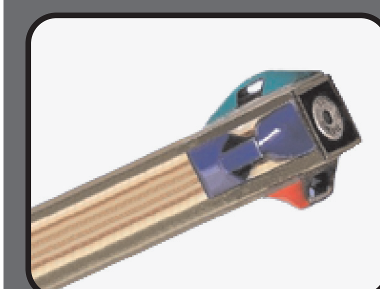

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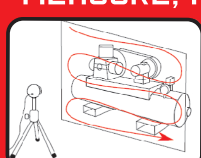

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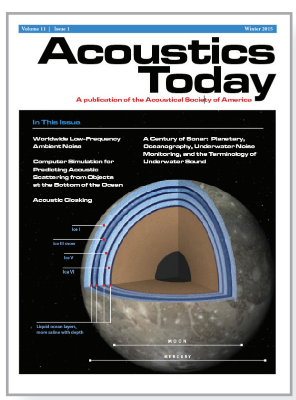

The cover image is from the article, "A Century of Sonar: Planetary Oceanography, Underwater Noise Monitoring, and the Terminology of Underwater Sound," by Michael A. Ainslie. Ganymede, Jupiter's largest satellite, is one of several moons in the Solar System thought to contain liquid water. (Source: NASA [NASA, 2014], Image credit: NASA/JPL-Caltech)

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PO Box 274, 1170 Main Street
West Barnstable, MA 02668
508-362-1211

Acoustical Society of America

The Acoustical Society of America was founded in 1929 "to increase and diffuse the knowledge of acoustics and to promote its practical applications." Information about the Society can be found on the Internet site: **www.acousticalsociety.org.**

The Society has approximately 7,000 members, distributed worldwide, with over 30% living outside the United States.

Membership includes a variety of benefits, a list of which can be found at the website:
www.acousticalsociety.org/membership/membership_and_benefits.

All members receive online access to the entire contents of the *Journal of Acoustical Society of America* from 1929 to the present. New members are welcome, and several grades of membership, including low rates for students and for persons living in developing countries, are possible. Instructions for applying can be found at the Internet site above.

ACOUSTICS TODAY *(ISSN 1557-0215, coden ATCODK) Winter 2015, volume 11, issue 1, is published quarterly by the Acoustical Society of America,* ***Suite 300,1305 Walt Whitman Rd., Melville, NY 11747-4300****. Periodicals Postage rates are paid at Huntington Station, NY, and additional mailing offices. POSTMASTER: Send address changes to Acoustics Today, Acoustical Society of America,* ***Suite 300, 1305 Walt Whitman Rd., Melville, NY 11747-4300****.*

From the Editor | Arthur N. Popper

We very much appreciate feedback from ASA members about *Acoustics Today* and www.AcousticsToday.org. We particularly welcome and value new ideas about things we can do to make the magazine and the web site even more interesting and useful.

"History" Papers for AT

I do want to share one of the suggestions I received recently from my friend (and former ASA president) Bill Yost. I'd asked Bill to consider doing an article for AT on psychoacoustics. Bill's response was that he would like to do this, but he wanted to take an historical perspective and write about the history of the field. This led to discussions from which arose the idea that AT have a series of articles on the history of disciplines. The rationale is that many of us would benefit from not only knowing about a subject, but also developing an understanding of where modern ideas arose.

My personal observations (and that of numerous friends) are that many younger colleagues would benefit from knowing the early history of their fields since many of the earlier ideas and papers (e.g., before 1970) are exceptionally useful and provide insights that are not found in current work.

Indeed, about 15 years ago years I realized that my own doctoral students and postdocs had no idea of the early literature in our field (marine, and particularly fish, bioacoustics). So, we spent a year reading the older literature, starting as far back as Aristotle and Pliny the Elder. One of my postdocs started to call these "paleopapers" and the name stuck. What was interesting is that my students found that reading paleopapers was very enjoyable and invaluable, particularly when they discovered that many of the issues they were tackling now had been first discussed, with great insight, by investigators in the 1920's to 1960's.

So, I want to first thank Bill Yost for raising this idea and then to invite colleagues in ASA to consider writing a "history" of their discipline. This could be a broad field, such as marine bioacoustics, or something somewhat narrower like the article Bill will do for the summer 2015 issue of *Acoustics Today*. Furthermore, working with Bill, I have developed some general guidelines for how to do this kind of paper. For example, history articles should focus on the major ideas and milestones in a field, they should primarily deal with material prior to around 1960 (though discussion of very formative articles up to about 1999 would be acceptable), they should consider the contributions of major historical contributors to the field, and, where possible, highlight the work of ASA members. More details about these papers can be found in our instructions to authors found at http://acousticstoday.org/authors/#.VGDkEDTF8ko.

If anyone is interested in doing this kind of article, please drop me a note and we can discuss your ideas.

AT Interns

Our first AT Intern, Laura Kloepper, has been focusing on social media. Laura keeps an active AT Twitter account going with really interesting material, and she took the lead in doing social media for the Indianapolis meeting. This included a very exciting session on Reddit where ASA members from Laura's own field, animal bioacoustics, spent several hours answering dozens of questions from the public, and the session was observed by several thousand individuals. This was, as we can all appreciate, good for our field and for ASA. I want to thank Laura for taking the lead in social media for AT (and making significant contributions to ASA as well). We understand that several other Technical Committees are already thinking of doing Reddit sessions at future ASA meetings, and we are very pleased that AT could help initiate this start of a strong ASA foray into social media.

I want to again put in a "plug" for additional AT interns. If you speak with Laura you will discover that she has really gotten a lot out of her experience as our first intern. She has had the opportunity to learn a good deal about publishing and her ASA network of acquaintances has grown substantially. And, very importantly, Laura continues to make invaluable contributions to AT and to ASA.

I would hope that Laura's experience will prompt other people to consider becoming interns. The position is not very time consuming, and we work with the interns to ensure that they get to do "jobs" that appeal to them and for which they can learn a good deal and also contribute in meaningful ways to ASA. In return, interns get a small stipend at the

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Preparing a President's column is a good time to look back at ASA's past and envision its future. With 75 former ASA Presidents, http://goo.gl/cakgED, there are several decades of President's reports and columns available to review, many of which are contained within *JASA's* rich archives. Reading these reports opens a window on ASA's history and traditions, as evidenced by what has been sustained over the decades – the creative and collegial environment at ASA meetings, organization of technical programs, presentation of awards and prizes to distinguished acousticians, awarding of fellowships and scholarships to promising students and early career acousticians, high-quality journals and standards programs, and the extraordinary contributions of dedicated ASA staff and member volunteers.

What has changed is size, in numbers of members, meeting abstracts and attendance, and journal pages. Of course, technical advances and new innovations continue to transform the science of acoustics and its practical applications, and the use of technology has changed the way the Society does business – one previous President's report mentioned the importance of daily use of fax machines and the introduction of "PINET" to distribute electronic abstracts.

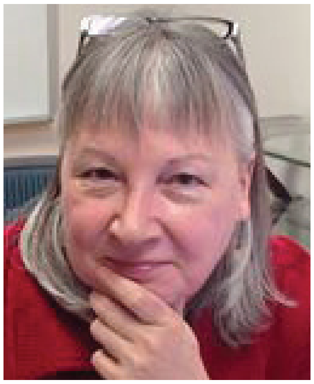
An extraordinary example of envisioning the future in a President's report is contained within President Robert E. Apfel's "Presidential address: Acoustical Society of America – 2016," which was given at a previous ASA meeting in Indianapolis in 1996 (see *Journal of Acoustical Society of America* 100, 1947-1948, 1996 or http://wp.me/p4zu0b-Np to view Apfel's Presidential address). President Apfel presented his vision of ASA 20 years into the future in light of the "information-internet revolution." As we approach nearly 20 years since that address, I encourage you to read this remarkable report, and admire the accuracy of his predictions. Just one example: "…in the year 2016, you can go to your computer and call up any article you want. It will contain not only text and graphics, but color images, video, sound, of course, and data, in the form of spreadsheets and computer programs. It will permit automatic links to other articles, and you will probably be able to send a message to the author directly from the midst of his or her article. Quite a vision!" Yes, that was indeed quite a vision by President Apfel.

Today, ASA continues to change and evolve within the ongoing information-internet revolution – many activities and discussions on this topic took place at Executive and Technical Council and other meetings at the most-recent ASA meeting in Indianapolis. A Reddit "Ask Me Anything" live discussion on animal bioacoustics, organized by *Acoustics Today* Intern and postdoctoral fellow Laura Kloepper, featured six prominent scientists answering questions from some of the 5,000 followers listening in – answers included links to articles in *JASA* and *Acoustics Today*. Twitter transmitted information about the 168th ASA meeting (@ASA168). Live webcasts were conducted featuring meeting presenters discussing New Discoveries in Acoustics and The Science of Spooky Sounds (a Halloween-themed session). Around committee meeting tables, lively discussions focused on best practices for the Society using social media and social science networks. New procedures are being tested for online organization of meeting technical programs. In addition, early discussions are underway for offering webcasting of portions of ASA meetings, in order to provide access to scientific content for a larger and more diverse audience.

Looking further into the future, it is critical that ASA members, staff, and leaders work together to keep the Society strong so it can continue to provide the environment for exchanging scientific information, assuring high quality in publications and standards, and educating future acousticians and the public. Toward this goal, more than 60 ASA members and others, representing all of the Society's diverse communities, gathered in Austin in January for the first ASA Strategic Leadership for the Future Summit (see Executive Director's column). At this Summit, plans for the challenges and changing needs of the future were considered and discussed, keeping in mind the high value we hold for ASA's mission and how best to continue to honor our strong traditions. Perhaps a future President's report in 2029 that cites ASA's 100th anniversary will look back at the Summit as an important milestone in ASA history.

Judy R. Dubno
President, Acoustical Society of America

From the Executive Director | Susan E. Fox



As you may recall from my piece in the Spring 2014 issue of *Acoustics Today*, please visit http://goo.gl/Yqj4FS, ASA is undergoing a process of strategic planning in order to achieve four goals, namely to:

- be prepared to meet future challenges in publishing and beyond;
- expand our value to members and the field of acoustics;
- focus on the highest impact priorities for practical action; and
- ensure that the organizational structures and processes needed for a vital future are in place.

Our most recent set of activities involved consulting with a broad range of constituencies in order to gather information, perspectives, and opinions about where ASA is today and where we need to focus our attention in the future. To accomplish this, the President, Past President, and President-Elect identified ASA's key constituencies including: Leader/Executive Council members; Leader/Technical Council members; Leader/Other (Past Presidents; Past Chairs, Medal, and Awards Winners, etc.); Leaders from Publishing (Publisher, Editors); Donors/Sponsors; Staff, Related Organizations; Students/Early Career; and international members.

Marybeth Fidler and Cate Bower, founding partners of Cygnet Strategy, LLC, conducted hour-long one-on-one interviews with 29 people from the constituencies identified above. They explored perceptions about ASA's external environment and the challenges acousticians face in carrying out their work. What, they asked, are the expectations for ASA in helping to manage these challenges? Are there opportunities to be seized or new roles the Society should play?

What competencies need to be in place in order for ASA to succeed in serving members and the profession well?

At the 2014 fall meeting in Indianapolis, Marybeth Fidler presented to the Executive and Technical Councils some headlines, as described below, from these conversations.

Perceptions

- Many members view ASA as the premier acoustical society in the world.
- The incredible diversity of fields in the acoustical science community is one of our greatest strengths and one of our greatest challenges.
- The *Journal of the Acoustical Society of America* and the meeting proceedings are high quality and highly respected.

Challenges to the Field of Acoustics

- Diminished research funding.
- Rapidly changing interest areas in the field of acoustics.
- The threat of a scientific workforce that exceeds the number of available jobs in the field.

Challenges to ASA

- Managing the breadth of scientific diversity amongst ASA members.
- Keeping ASA relevant, with scientists interested and renewing membership, especially young scientists.
- Improving and modernizing *The Journal of the Acoustical Society of America.*

Potential Roles ASA can assume to Address Challenges

- Create a database of what members want and need from ASA.
- Raise the profile of new and exciting things happening in acoustics for ASA members and the general public.
- Focus on young scholars and applied scientists.

ASA Governance Advantages

- Executive Council is small and pretty nimble.
- Not too many layers to negotiate before one's voice is heard.
- Grassroots approach makes governance accessible.

ASA Governance Disadvantages

- Rapid turnover of leadership makes it hard to have individual impact.
- Few non US members in leadership positions.
- Leadership service is exclusive because of the cost to travel to two meetings a year.

Continued on next page

We are grateful to all who contributed so generously of their time and thoughtful attention. One thing that stood out most from these conversations is the unusual degree of warmth, respect, and affection ASA members have for the Society. This is perhaps our greatest strength of all, and an important leverage point as we consider our collective future.

Next Steps

At the start of 2015, we convened an in-person meeting of about 60 individuals, again representing a broad cross-section of the Society, to the "Strategic Leadership for the Future Summit" held January 12-14, 2015. This meeting, based on the "Future Search" methodology was facilitated by Cate Bower and Marybeth Fidler.

Day 1 - We focussed on setting the stage. We reviewed our past, where we have been, and what this means to us as we move forward. We focussed on the present, what our world looks like now, and trends for the future.

Day 2 - We discussed what we are doing to address the trends identified on Day 1 and to envision what kind of future we want to create.

Day 3 - We confirmed our common ground and developed an agreement on what will be needed to achieve our future vision.

Our next step will be for the Executive Council to meet in Melville for two days, scheduled 30-31 March 2015, to take the results of the Summit and create the first draft of the Strategic Plan. In late April or early May this draft will be put out to members and all interested parties for comment. Those comments will help inform drafting of the final plan that will ultimately help us focus our invaluable time, attention, budget, and efforts toward these clearly articulated goals. To learn more about the ASA Summit visit:
http://wp.me/P4zu0b-LT

The process is designed to be as inclusive as possible. I am always interested in hearing from you and especially hearing your thoughts about ASA and the future of the profession and the Society. Please feel free to contact me at any time. You can reach me at sfox@acousticalsociety.org or via my direct line 516-576-2215.

Susan E. Fox
Executive Director, Acoustical Society of America

From the Editor

Continued from page 6

end of their year, and they get free registration at meetings they attend while they are in the position. AT Interns also have their name on our masthead and are invited to attend, and participate in, AT Advisory Committee meetings. Interns are advanced graduate students or early career people within three years of their terminal degrees, but we are most willing to be a bit flexible in requirements if the opportunity would benefit ASA and the person. If you are interested in exploring being an intern drop me a note and we can discuss ideas. And, you can find out more about being an AT intern, and see the application, at http://wp.me/P4zu0b-lH.

This Issue

I hope that everyone will enjoy the articles in this issue of AT. Without specific planning, three of the articles deal with underwater sound in various ways. These include a very interesting piece on underwater noise standards by Michael Ainslie, and Michael also considers how one might do a sonar study of a distant moon. Underwater ambient noise, a topic of particular interest to me, is discussed by David L. Bradley (former ASA president) and Stephen M. Nichols. Their article provides insight into measuring low frequency ambient noise in the oceans, a project that grew out of approaches to detecting nuclear tests. David Burnett does the third underwater paper with a discussion of how one can use acoustic scattering to find objects at the bottom of the ocean. Coincidently, this issue's Technical Committee report is on acoustical oceanography.

The fourth paper in this issue is on acoustic cloaking by Andrew Norris. When I first read the article I was not sure what was meant by acoustic cloaking, but then I realized that cloaking is what the Romulans used to hide their space ships in Star Trek, and so I started to see the fascinating implications of the work discussed in this article.

Finally, I was very pleased that Leo Beranek, the honoree of our fall issue (on his 100th birthday) agreed to write a short article for this issue. It was an honor for me to meet Dr. Beranek at the Indianapolis meeting, and I was delighted to hear him speak about his work and to learn more about his amazing career.

Arthur N. Popper

A Tribute to the Acoustical Society of America

Leo L. Beranek
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beranekleo@ieee.org

At a special reception, members of the ASA presented Dr. Beranek with a cake to celebrate his centennial birthday.

First, I wish to express my deep appreciation for the fall 2014 issue of *Acoustics Today* which is dedicated to me and covers my activities throughout my career as an acoustician. I am particularly indebted to Carl Rosenberg and William Cavanaugh who solicited and edited the articles in the issue and to President Judy Dubno and Editor Arthur Popper who approved and put the publication together. In the paragraphs that follow I make some remarks that relate to my activities as a scientist and teacher to the Acoustical Society of America.

My career as an acoustician has spanned a period of 77 years. I first attended a meeting of the Acoustical Society of America in Iowa City in November 1939. There were only 27 papers at that meeting which meant no parallel sessions and thus the opportunity for one to meet every leading acoustician several times. I received my doctorate in 1940. I submitted two papers, based on my thesis, to *JASA* that they acknowledged having received June 1, 1940. They were published in the July 1940 issue. This rapid publication was most fortunate for me as Professor Philip Morse at MIT expressed great interest in my work and this led to an unusual happening in my career that very October. The newly established U.S. National Defense Research Committee had received a request from the US Air Corps to develop a new light-weight acoustical material for use in reducing noise levels in the cockpits of combat airplanes. Morse recommended me as director of the project which was named the Electro-Acoustic Laboratory at Harvard University. We also made major improvements in voice communication in high-altitude, unpressurized, combat aircraft and in ground vehicles. These wartime efforts led to the publication, after the war, of my first book, *Acoustic Measurements.*

I have taken particular interest in the Acoustical Society. As President, in 1954, I saw that the Society needed to change its governance and to better bond its members. The ultimate result was the creation of 13 technical committees, the chairs of which now serve as members of the Technical Council, which is under the general chair of the Vice President of the Society. The technical committees help put together the technical programs of the Society's biannual meetings and they bring, via the Technical Council, recommendations for actions by the Executive Council.

I have enjoyed teaching. I was on the physics faculty at Harvard University before and after WW-II. There, I taught electronics and supervised laboratory experiments. At MIT, as Associate Professor, I taught electrical engineering courses and initiated an acoustics course that led to my 1954 book *ACOUSTICS.* This book largely changed the way acoustics had been taught. The text has been translated into many languages and is still available today. The teachings of that text led to smaller loudspeakers, hastened the adoption of FM broadcasting, and gave the basis for noise control.

I believe that the Acoustical Society should do everything possible to see that acoustics is taught in a significant number of universities. Society members should be encouraged to make contributions to the Acoustical Society Foundation so that students are given travel money to go to meetings and receive supplementary scholarship aid. Government and industry should be urged to support basic research in the various branches of acoustics. Manufacturers are learning that quieter products sell better. At very little increased cost dwellings can be made quieter. As a further example, airplane engines are enormously quieter today as a result of substantial government and industry support.

Noise control has been an important part of my acoustics activities. I have published six books either alone or with co-authors on the subject of noise and vibration control. Two of my largest and most important projects were the quieting of an enormously noisy NASA supersonic-jet engine during tests, which resulted in my designing the world's largest muffler which was built at the facility.

The other project was working with the owner and operator of the airports around New York City, namely the Port of New York Authority. They asked my company, Bolt Beranek and Newman, to determine the maximum noise levels that jet-propelled passenger aircraft should be permitted to radiate when passing over neighborhoods surrounding their airports. I supervised this project and the result was that the first jet passenger airplanes were required to put mufflers on their engines and later planes had to be equipped with high-by-pass engines.

My efforts in recent years have been devoted to concert hall acoustics. In my 1962 book *Music, Acoustics, and Architecture* I published photographs and architectural drawings of 54 concert halls in 16 countries. Measurements of the acoustical properties of these halls were assembled from the files of my company and from leading acoustical consultants. That book was followed by a second book in 1996, *Concert and Opera Halls, How They Sound*, that covered 76 halls and which was published by the Acoustical Society of America. The most recent book, in 2004, is titled, *Concert Halls and Opera Houses: Music, Acoustics, and Architecture*. It covers 100 halls and houses. Through the years I have interviewed over 30 conductors and 20 music critics and from their statements I have rank-ordered 58 halls according to those person's perception of acoustical quality. No one has openly criticized these rankings. Since then, I have published papers, largely in *JASA*, on concert hall acoustics as new findings have evolved.

In conclusion, I am grateful to the Acoustical Society of America for their publications which have enabled me to exchange my findings with the research of others in the field. I enjoy the Society's biannual meetings where one becomes acquainted with colleagues and learns about their recent activities. I especially look forward to attending the ASA meeting in Boston, Massachusetts, in 2017.

Photographs courtesy of the Acoustical Society of America

Top left. *Dr. Leo Beranek addresses the audience at the Plenary Session on October 30, 2014 at the 168th Meeting of the ASA in Indianapolis, Indiana.*

Top right. *Fall Acoustics Today guest editors Carl Rosenberg (left) and William Cavanaugh (right) pose with Dr. Beranek at the reception.*

Center left. *Acoustics Today Editor Arthur Popper presents Dr. Beranek with a framed cover of the fall issue dedicated to Dr. Beranek and his lifetime achievements, contributions to the ASA, and in celebration of his 100th birthday.*

Center right. *Dr. Leo and Gabriella Beranek.*

Bottom. *Michael Taroudakis, President of the European Acoustics Association, and ASA President Judy Dubno present Dr. Beranek with certificates from the EAA and ASA honoring him on his 100th birthday.*

A Century of Sonar: Planetary Oceanography, Underwater Noise Monitoring, and the Terminology of Underwater Sound

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No self-respecting science – or scientist – would tolerate a factor of four uncertainty in the interpretation of a reported measurement or model prediction, arising from poorly defined terminology alone, so why do we?

Introduction

The current terminology of underwater sound, as documented, for example, by (Urick, 1983), was developed during and after the Second World War (ASA, 1951; Urick, 1967), and has evolved little since then (Jensen et al., 2011). When examined against a modern requirement, with particular attention to the needs of planetary oceanography and underwater noise, this 60-year old terminology is found wanting.

The Sonar Equations and "Noise Level"

The development of passive and active sonar during the first half of the 20th century, motivated by the loss of RMS *Titanic* in April 1912 and by two world wars (Wood, 1965; Hackmann, 1984), was directed almost exclusively towards the detection and localization of objects in seawater. In order to understand the performance of underwater detection systems, a theoretical framework (known today as the 'sonar equations' (Urick, 1983)) was developed for quantifying that performance in terms of the signal-to-noise ratio (Horton, 1959).

The traditional meaning of the term "noise level," in the sonar equations, is the level of the masking background against which a signal is to be detected. In the 21st century, underwater sound is increasingly seen as a potential pollutant, for which "noise level" is then taken to mean the amount of that pollutant. For the bulk of this article, I focus on the sonar equation, and return in the final section to the possible impact of noise on aquatic life.

The sonar equations are in widespread use on Earth (Urick, 1983), and are starting to find application in space (Arvelo and Lorenz, 2013). Whether in search of signs of extra-terrestrial life in subsurface water oceans (Hussmann et al., 2006) or of vast hydrocarbon resources on distant moons (Stofan et al., 2007), these new uses encounter harsh conditions that are very different to those on Earth. These extreme conditions serve to expose a fundamental ambiguity in the way the individual terms in the sonar equations are expressed as levels. Although the ambiguity is minor for the range of conditions usually encountered in water on Earth, it becomes important in some situations, and is seen on closer inspection to be a symptom of a deeper malaise, namely a dearth of widely accepted definitions for even the most basic terminology used in undersea acoustics. My main purpose is to demonstrate the need to adopt a more rigorous terminology if we wish our science to be taken seriously as it enters its second century of existence.

By convention, the sonar equations are written in a logarithmic form by converting ratios of acoustic intensities to differences between the corresponding levels in decibels. The "intensity" is usually not the true intensity of the sound in question, but its equivalent plane wave intensity (EPWI), defined as the magnitude of the time-averaged intensity of a propagating plane wave with the same root-mean-square (RMS) sound pressure as that sound (Urick, 1983). Denoting the time-mean-square sound pressure (MSP) by $\overline{p^2}$, and characteristic impedance (Morfey, 2000) by Z, intensity ratios are therefore formed by dividing the noise EPWI, $N_{\mathrm{EPWI}}(\boldsymbol{x})=\overline{p_N^2(\boldsymbol{x})}/Z(\boldsymbol{x})$, where p_N is the noise sound pressure, by a reference intensity I_0. In equation form, the noise level according to these conventions, using $\boldsymbol{x}$ to denote the receiver position, is

$$L_N(\boldsymbol{x}) = 10\log_{10}\left[\frac{N_{\mathrm{EPWI}}(\boldsymbol{x})}{I_0}\right]\mathrm{dB}. \tag{1}$$

A similar equation can be written for the signal level, and the difference between these two levels is a logarithmic measure of signal-to-noise ratio.

While the value of I_0 in **Equation (1)** is not needed for the signal-to-noise ratio (because it cancels), when either of signal or noise level is reported separately, the correct reporting and interpretation of that level requires a shared understanding of the value of I_0. By a convention that dates to the Second World War (Horton, 1959), the reference intensity in underwater acoustics is understood to be the magnitude of the time-averaged intensity of a propagating plane wave in seawater whose RMS sound pressure is equal to an agreed reference pressure (p_0) (Urick 1967, 1983). For example, with p_0 = 1 μPa, the level would be reported in units of "dB re 1 μPa" (or, equivalently, "dB // 1 μPa"), a shorthand used to mean that the level expressed in decibels is that of the EPWI, relative to the magnitude of the time-averaged intensity of a plane wave whose RMS sound pressure is 1 μPa (Urick 1967). The reference intensity according to this convention is $I_0 = p_0^2/Z_0$, where Z_0 is the characteristic impedance of seawater. If the local impedance is $Z(\boldsymbol{x})$ it follows that

$$\frac{N_{\mathrm{EPWI}}(\boldsymbol{x})}{I_0} = \frac{\overline{p_N^2(\boldsymbol{x})}}{p_0^2}\frac{Z_0}{Z(\boldsymbol{x})}, \tag{2}$$

and the pertinent question, given the need to define I_0 unambiguously, becomes "what are p_0 and Z_0?" During the period 1951-1960 one could have answered this question with some confidence. The then current US acoustical terminology standard ASA Z24.1-1951 (ASA, 1951), published by the American Standards Association (ASA) – now the American National Standards Institute (ANSI), permitted both p_0 = 20 μPa and $p_0 = 10^5$ μPa. Further, Z24.1-1951 specified a standard reference sound speed of c_0 = 1500 m/s, with the reference density ($\rho_0 \approx$ 1023.38 kg/m^3) inferred from specified conditions of temperature and pressure. The corresponding reference impedance is $Z_0 = \rho_0\, c_0 \approx$ 1.53507 MPa s/m (see **Figure 1**), from which the reference intensity can be calculated as either $I_0 \approx$ 260.57 aW/m^2 (using p_0 = 20 μPa) or 6.5144x10^9 aW/m^2 ($p_0 = 10^5$ μPa), where 1 aW (one attowatt) = 10^{-18} W.

9.040 Standard Sea Water Conditions. Standard sea water conditions are those of sea water at a static pressure of 1 atmosphere, a temperature of 15 C, and a salinity such that the velocity of propagation is exactly 1500 meters per second.

NOTE: Under these conditions, the following other properties are derived from experimental data:

Salinity[1] S = 31.60 parts per thousand
Density[2] ρ = 1.02338 grams per cubic centimeter
Characteristic acoustic impedance, $\rho c = 1.53507 \times 10^5$ cgs units

Figure 1. Extract from withdrawn American Standard Acoustical Terminology Z24.1-1951, entry 9.040 Standard Sea Water Conditions (ASA, 1951). The value inferred for the impedance of seawater under these standard conditions was 1.53507 MPa s/m. The CGS unit of impedance is 1 dyn s/cm^3 = 10 Pa s/m.

In 1960, ASA Z24.1-1951 was superseded by ANSI S1.1-1960 (ANSI, 1960), which made no mention of a standard reference impedance for use in water, and introduced in its place the standard reference *intensity* of 1 pW/m^2, where 1 pW (one picowatt) = 10^{-12} W. In 1969 the modern reference value of sound pressure p_0 = 1 μPa was adopted by ANSI S1.8-1969 (ANSI, 1969) for sound in liquids. Today these standard values for sound pressure and sound intensity in liquids are recognized by both the International Electrotechnical Commission (IEC) (IEC, 1994) and the International Organization for Standardization (ISO) (ISO, 2013). The situation is summarized in **Table 1.**

Table 1: Evolution of American national and international standard reference values of acoustical quantities in liquids since 1951. The SI prefixes μ, n, and p represent the numbers 10^{-6} (micro-), 10^{-9} (nano-) and 10^{-12} (pico-), respectively. For example the modern reference value for sound particle velocity is 1 nm/s (one nanometer per second) = 10^{-9} m/s.

		Reference value (q_0)					
Quantity (q)	**Field (F) or Power (P)**	**ASA Z24.1-1951**	**ANSI S1.1-1960**	**ANSI S1.8-1969**	**ANSI S1.8-1989**	**IEC 60050-801:1994**	**ISO/DIS 1683:2013**
sound pressure	F	20 μPa or 10^5 μPa	20 μPa or 10^5 μPa	1 μPa	1 μPa	1 μPa	1 μPa
sound exposure	P						1 μPa² s
sound power	P			1 pW	1 pW	1 pW	1 pW
sound intensity	P		1 pW/m²	1 pW/m²	1 pW/m²	1 pW/m²	1 pW/m²
sound energy	P			1 pJ			1 pJ
sound energy density	P			1 pJ/m³			
sound particle displacement	F						1 pm
sound particle velocity	F			10 nm/s		1 nm/s	1 nm/s
sound particle acceleration	F			10 μm/s²			1 μm/s²
frequency					1 Hz		
distance							1 m

None of the applicable modern standards (ANSI 1989, 2013; IEC, 1994; ISO, 2013) specifies or mentions a standard value of impedance for use in **Equation (2)**. Despite the resulting ambiguity in the value of I_0, the convention to report levels in "dB re 1 μPa" is still in widespread use today. For the range of representative conditions listed in S1.1-1960, all at atmospheric pressure, the corresponding reference intensity would be between 0.64 aW/m² and 0.71 aW/m², and in the examples that follow I adopt 0.65 aW/m² precisely, which to two significant figures is equal to the value that would be implied by the standard impedance value from Z24.1-1951.

Planetary Oceanography

With the surfaces of many planets thoroughly mapped using radar, planetary scientists are becoming curious about what lies beneath those surfaces. In order to satisfy this curiosity, they turn to sound for much the same reasons as oceanographers and seismologists do on Earth. Several of Jupiter's moons are thought to contain liquid water (Hussmann et al., 2006; NASA, 2014) (see also **Figure 2**), and the methane-rich atmosphere of Saturn's moon Titan gives rise to a unique hydrocarbon precipitation and evaporation cycle (Lunine and Atreya, 2008). Both Europa (Kovach and Chyba, 2001; Lee et al., 2003; Leighton et al., 2008) and Titan (Leighton et al., 2004; Arvelo and Lorenz, 2013) have been the subject of acoustical oceanography, so far of a theoretical nature only, but the issues apply as much to model predictions as to measurements.

The sonar equations were developed for conditions involving a source and receiver in seawater at Earth's atmospheric pressure. What happens when we take our receiver out of these benign conditions on Earth and put it instead on Titan, Europa, or Ganymede? This seemingly hypothetical question is increasingly becoming a reality as sound is proposed to probe bodies other than Earth in our solar system (Lee et al., 2003; Leighton et al., 2004; Arvelo and Lorenz, 2013).

The presence of hydrocarbon seas on its surface makes Titan a particularly suitable example to examine the consequences of different choices of Z and Z_0 in **Equation 2**. (Arvelo and Lorenz, 2013) examined the potential for sonar to map the depths of *Ligeia Mare*, a hydrocarbon-rich sea on Titan comprising a mixture of ethane and methane in their liquid forms. The principle they investigated is the same as used in conventional echo sounders fitted to ships on Earth, whereby a pulse transmitted downwards from a surface vessel is reflected by the seabed and received at the same surface vessel. For a known sound speed, the depth of the liquid (usually seawater) is then inferred from the two-way travel time. Thus, for the hypothetical *Ligeia* echo sounder, both source and receiver were immersed in liquid methane, liquid ethane, or some mixture of the two. Associated sonar performance calculations require concepts of signal level and noise level in *Ligeia*, and I focus here on the noise level at the receiver position. This noise level was expressed by (Arvelo and Lorenz, 2013) as a spectral density level, presumably of the EPWI (the convention when not stated otherwise), de-

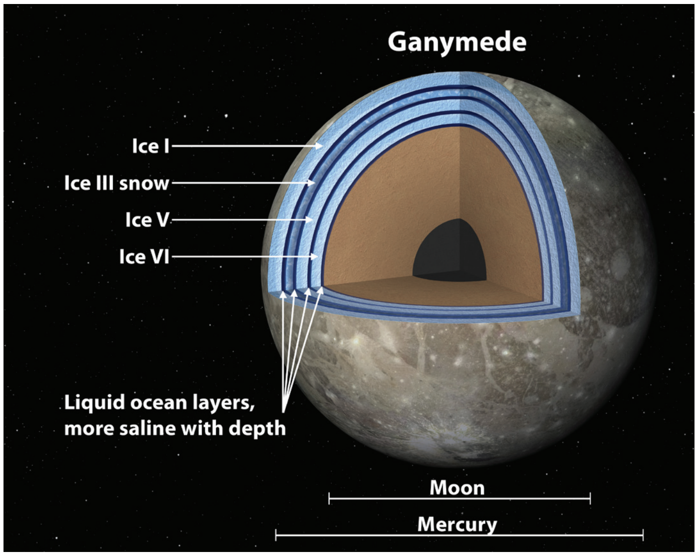

Figure 2*. Ganymede, Jupiter's largest satellite, is one of several moons in the Solar System thought to contain liquid water. Source: NASA [NASA, 2014], Image credit: NASA/JPL-Caltech*

noted in the following by $N_{\mathrm{EPWI},f}$, with corresponding level $L_{N,f} = 10 \log_{10}[N_{\mathrm{EPWI},f}/(I_0/f_0)]$ dB, where f_0 is a suitable reference frequency. Although the quantity $L_{N,f}$, defined in this way, has a reference value of I_0 / f_0 (i.e., 0.65 aW/(m² Hz) on Earth, with f_0 = 1 Hz), its value is widely reported in units of "dB re 1 μPa²/Hz", consistent with the reference values of sound pressure and frequency from **Table 1**, but raising questions about the appropriate choice of Z, Z_0 in **Equation 2**. The definition of $L_{N,f}$ leads to several different interpretations of the stated noise value ($L_{N,f}$ = 40 dB re 1 μPa²/Hz), depending on this choice. For a receiver in *Ligeia, Z* must be the impedance of the local medium (e.g., Z ≈ 1.2 MPa s/m for a measurement in liquid ethane, or Z ≈ 0.67 MPa s/m for liquid methane), but what is Z_0? On Titan there is no established convention, but one possible interpretation is that the reference intensity is a universal constant, i.e., that the value for seawater (I_0 = 0.65 aW/m²) is used as a universal standard reference intensity. In this interpretation, the 40 dB corresponds to EPWI = 6500 aW/(m²Hz), leading to an MSP spectral density of precisely 7800 μPa²/Hz for a receiver in ethane or 4355 μPa²/Hz in methane. Four further values are obtained if the reference intensity is based instead on the impedance of either liquid ethane (I_0 = 0.83 aW/m²) or liquid methane (I_0 = 1.49 aW/m²), making six combinations in all. These six possibilities are summarized in **Table 2**, illustrating a maximum difference in MSP exceeding a factor of four.

It is not the hydrocarbon nature of *Ligeia Mare* that results in the ambiguity illustrated by **Table 2**, but the contrast between the impedance of *Ligeia's* (liquid) hydrocarbons and that of seawater under standard conditions on Earth. Pointed out originally by (Horton, 1959) (Horton's proposed solution at the time was the adoption of a standard reference intensity of 1 W/cm²), it is also not a new problem, but Horton's warning has gone unheeded for more than half a century.

The ambiguity exists in any medium whose impedance differs from Z_0 ≈ 1.5 MPa s/m, including water subject to high pressure. The impedance of liquid water increases with increasing pressure, up to about 1.7 MPa s/m in a deep ocean trench on Earth (Leroy et al., 2008). Even higher pressures are to be found at the bottom of the oceans thought to exist in the Jovian moons Europa and Ganymede and other ocean planets (Hussmann et al., 2006), with sound speeds in liquid water of up to 1750 m/s estimated for Europa (Leighton et al., 2008) and 2500 m/s measured for conditions similar to those expected on Ganymede (Vance and Brown, 2010), compared to 1500 m/s in seawater at atmospheric temperature and pressure. Taking into account expected variations in density with pressure (Vance, 2007), the estimated impedance values corresponding to these sound speeds are Z ≈ 1.7 MPa s/m (ocean trench), 1.9 MPa s/m (Europa) and 2.9 MPa s/m (Ganymede). The resulting uncertainty in any reported noise level, estimated as $10 \log_{10}(Z/Z_0)$ dB, is between 0.5 dB (ocean trench) and 2.8 dB (Ganymede).

Table 2: Possible values of the spectral density of EPWI and MSP, all consistent with the noise level in *Ligeia Mare* of 40 dB re 1 μPa²/Hz, depending only on the choice of Z and Z_0.

	EPWI spectral density / aW m⁻² Hz⁻¹	**MSP**	**Spectral Density / μPa² Hz⁻¹**
case	$Z^{-1}\mathrm{d}\overline{p^2}/\mathrm{d}f$	receiver in liquid ethane (Z = 1.2 MPa s/m) $\mathrm{d}\overline{p^2}/\mathrm{d}f$	receiver in liquid methane (Z = 0.67 MPa s/m) $\mathrm{d}\overline{p^2}/\mathrm{d}f$
universal standard (seawater: I_0 = 0.65 aW/ m²)	6500	7800.00	4355.00
local *Ligeia* standard (liquid ethane: I_0 = 0.83 aW/ m²)	8300	9960.00	5561.00
alternative local *Ligeia* standard (liquid methane: I_0 = 1.49 aW/ m²)	14900	17880.00	9983.00

Even without considering extremes of high pressure, circumstances occasionally arise on Earth that lead to the deployment of a hydrophone or modeling of sound propagation in a medium of abnormally high or low impedance (Lamarre and Melville, 1994; Beaudoin et al., 2011). Transmission of sound across a boundary with a large impedance contrast then gives rise to a further ambiguity depending on whether the associated transfer function (transmission loss or propagation loss) is corrected for the impedance ratio (Ainslie and Morfey, 2005; Ainslie, 2008).

What Exactly is a Level?

Given that the ambiguity illustrated by **Table 2** stems from the reporting of a level in decibels, the only way to resolve it, short of discarding the decibel altogether (Horton 1952, 1954, 1959; Chapman and Ellis, 1998; Clay, 1999; Hickling, 1999; Chapman, 2000), is to be more precise in our use of the decibel as a unit of level. To achieve this we first need to understand what a level is. According to ISO 80000-1:2009 'Quantities and Units Part 1: General' (ISO, 2009), and ANSI S1.1-2013 'Acoustical Terminology' (ANSI, 2013), a level, L, is the logarithm of the ratio of a quantity q to a reference value of that quantity q_0. In equation form, $L = \log_r q/q_0$, from which it is clear that the value of q (the nature of which must also be specified) can only be recovered unambiguously from that of L if the base of the logarithm (r) and the reference value (q_0) are both known precisely.

The convention to use $[1\ \mu\mathrm{Pa}]^2/\rho_0 c_0$ as a reference intensity … is neither an American national standard nor an international standard, nor has it ever been.

Q1 What is the base of the logarithm?

ISO 80000-3:2006 (ISO, 2006) distinguishes between the *level of a field quantity* on the one hand and *level of a power quantity* on the other. In **Table 1**, field quantities (e.g., sound pressure) and power quantities (e.g., sound power) are identified by an 'F' or 'P', respectively, in the second column. The level of a field quantity F, with reference value F_0, is $L_F = \log_e F/F_0$, implying that, for the level of a field quantity, the base $r = e$. Similarly, the level of a power quantity P (reference value P_0) is $L_p = (1/2)\log_e P/P_0$, from which it follows that $L_p = \log_{e^2}(P/P_0)$ and therefore, for the level of a power quantity, $r = e^2$.

For every real, positive power quantity P there exists a field quantity $F = P^{1/2}$, in which case that field quantity may be referred to as a root-power quantity (ISO, 2009), and for which (assuming also that $F_0 = P_0^{1/2}$) the level L_F as defined above is equal to the level L_P. Further, the term "field quantity" is deprecated by ISO 80000-1:2009. For these reasons, attention is restricted in the following to real, positive power quantities and to their corresponding root-power quantities.

Q2 What is the reference value?

International standard reference values for selected power quantities, indicated by a 'P' in column 2 of **Table 1**, are given in column 7(q_0) of that Table, and the reference value of each corresponding root-power quantity is $q_0^{1/2}$. For example, the reference value of sound exposure, E, is $q_0 = 1\ \mu\mathrm{Pa}^2\ \mathrm{s}$; the corresponding root-power quantity is $E^{1/2}$, whose reference value is therefore $q_0^{1/2} = 1\ \mu\mathrm{Pa\ s}^{1/2}$.

International standard reference values for selected root-power quantities, indicated by an 'F' in column 2 of **Table 1**, are given in column 7(q_0) (remember that root-power quantities are also field quantities), and the reference value of each corresponding power quantity is q_0^2. For example, the reference value of RMS sound pressure, p_{RMS}, is $q_0 = 1\ \mu\mathrm{Pa}$; the corresponding power quantity is $\overline{p^2} = p_{\mathrm{RMS}}^2$, whose reference value is $q_0^2 = 1\ \mu\mathrm{Pa}^2$.

Corollary: how large is a decibel?

Although correct (by definition), the equation $L_P = (1/2)\log_e P/P_0$ is rarely used in that form. Instead the decibel (dB) is introduced, defined in such a way that $L_P = 10 \log_{10} P/P_0$ dB. It follows by equating these two expressions for L_P that the decibel is a dimensionless constant, equal to $(1/20)\log_e 10 \approx 0.115\ 129$.

International Harmonization

Don't write so that you can be understood, write so that you can't be misunderstood. – William Howard Taft (1857-1930)

The effective communication of precise information and ideas requires a precise language. Our ability to communicate effectively is compromised by the ambiguity inherent in conventional reporting of levels in decibels.

The convention to use $(1\ \mu\mathrm{Pa})^2/Z_0$ as a reference intensity is widely used, primarily due to its adoption and promulgation by (Urick 1967, 1983), but it is neither an American national standard nor an international standard, nor has it ever been, and the absence of a standard value of Z_0 leads to widespread ambiguity. Under normal conditions on Earth, the effects

Table 3: Who polices the police? ANSI and ISO define "sound pressure" to mean $p(t)$, the difference between instantaneous pressure and static pressure, whereas IEC defines the same term to mean p_{RMS}, the RMS value of $p(t)$. Similar differences arise for the definition of "sound pressure level."

Organization	Sound Pressure	Sound Pressure Level (SPL)	Reference
American National Standards Institute (ANSI)	$p(t)$	$10 \log_{10}[p_{\mathrm{RMS}}{}^2/p_0{}^2]$ dB	(ANSI, 2013)
International Organization for Standardization (ISO)	$p(t)$	$10 \log_{10}[p(t)^2/p_0{}^2]$ dB	(ISO, 2007)
International Electrotechnical Commission (IEC)	p_{RMS}	$20 \log_{10} [p_{\mathrm{RMS}} / p_0]$ dB	(IEC, 1994)

of this ambiguity are small, and we don't notice them. For some applications, however (e.g., calibration of transducers in fresh water (Horton, 1959), even small ambiguities lead to significant errors, while for others we depart sufficiently from the standard seawater conditions that the effects are no longer small. Even if we never put a hydrophone in Ganymede's oceans, the question "what is the reference intensity?" will still arise for model predictions reported in decibels.

The "obvious" way to remove the ambiguity is to follow a national or (better) international standard instead of the convention. After all, the whole purpose of standardized terminology is to facilitate unambiguous communication, and if there existed a single unambiguous standard terminology, the adoption of that standard would indeed be the solution. Unfortunately, while there is international agreement on reference values for sound pressure (1 μPa) and sound intensity (1 pW/m^2), different national and international standards bodies have chosen different definitions even for basic terminology such as "sound pressure" and "sound pressure level," pointed out below and summarized by **Table 3**, so there remains some harmonization work to be done.

Why it Matters, Here on Earth

The examples considered so far involve exotic conditions on distant moons, but there is no need to look so far for examples of the need for national and international harmonization. Sound (or "noise") in water is increasingly seen as a potential pollutant, and offshore contractors are required by regulators to assess or mitigate the risk of exposing marine animals to noise (Lucke et al., 2014). For example, the National Marine Fisheries Service (NMFS) in the US (NMFS, 2013), and the *Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit* (BMU) in Germany (BMU, 2013) specify thresholds of levels (e.g., of sound pressure or of sound exposure) that are either not to be exceeded at all or only by permit. While it is up to each national authority to define the terms used in its national regulations or guidelines, underwater sound, like salmon and dolphins, shows scant regard for national boundaries, creating regulatory confusion if the nationally adopted terminologies differ from one another, and highlighting the need for international harmonization. In Europe, the Marine Strategy Framework Directive (EC, 2008) requires EU Member States to co-operate at a regional level to achieve good environmental status. Specifically, EU Member States are required to monitor trends in underwater noise levels (EC, 2010), and associated monitoring programs can only yield comparable results if the Member States are measuring the same quantity (Dekeling et al., 2014).

Recent advances in scientific knowledge about risks of underwater sound have been reviewed by (Southall et al., 2007) (for marine mammals) and (Popper et al., 2014) (for fishes and sea turtles). These expert reviews provide stakeholders with sorely needed risk criteria, and insights into the latest scientific findings. In the absence of widely accepted international standard terminology, the onus is on the authors of such reviews related to underwater sound to provide a complete list of acoustical terms used, and their definitions. To the extent that neither review defines all the terms used, the onus is then placed on the reader (who is unlikely to have the same in-depth expertise as the authors) to refer to the original research literature to find the missing definitions, increasing both the reader's effort and risk of misunderstanding.

The International System of Quantities

We are witnessing the birth of a new science, planetary oceanography, and a new societal concern, underwater noise pollution. Before reaching maturity, both will need a more precise terminology than is presently available.

Help is on its way in the form of a long-standing collaboration between ISO and IEC that has borne as fruit the 14-

part standard ISO/IEC 80000 'Quantities and Units' (Jensen and Thor, 1995; IEC, 2012). This joint ISO/IEC Standard describes the International System of Units (SI), other standardized units intended for use alongside the SI such as the decibel and the neper, and the corresponding system of quantities, known as the International System of Quantities (ISQ) (BIPM, 2006).

In 2011, an ISO technical sub-committee (ISO/TC 43/SC 3) dedicated exclusively to underwater acoustics was established (ISO, 2012). The need for an unambiguous underwater acoustics terminology was identified in June 2012, at the inaugural meeting of that sub-committee. The new standard ISO 18405 Underwater Acoustics - Terminology, under development by ISO Working Group ISO/TC 43/SC 3/WG 2, is based on Parts 3 and 8 of ISO/IEC 80000, and is scheduled for publication as an International Standard in 2016. This new standard will include definitions, reached by international consensus, not only of basic terminology already mentioned ("sound pressure," "sound pressure level," "sound exposure"), but also of more advanced terminology such as "source level" (a measure of source power,) "temporary hearing threshold shift" (a measure of change in hearing sensitivity,) and "detection threshold" (a measure of the minimum signal-to-noise ratio required for a sonar to correctly identify a signal in the presence of noise.)

A Parting Plea

Underwater acousticians, myself included, have a responsibility to provide a clear, concise, and unambiguous language with which to communicate results and ideas about our science. The sooner we provide that language, the sooner industry, governments, and scientists will start to benefit from its use. We must not let them wait a minute longer than is necessary.

Acknowledgments

I thank Timothy Leighton and Arthur Popper for detailed reviews, Steve Vance for tips on planetary acoustics, and Michele Halvorsen, Amy Scholik-Schlomer, and René Dekeling for helpful comments.

Biosketch

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Worldwide Low-Frequency Ambient Noise

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Hydrophone stations deployed for ensuring compliance to the Nuclear-Test-Ban Treaty offer a tremendous tool for monitoring and understanding the underwater acoustic environment.

Introduction

The United Nations Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) has a broad spectrum of sensors to monitor the earth for nuclear explosions. Included in that sensor suite are underwater hydrophone systems that have collected and stored acoustic underwater ambient noise. This article discusses that data, its value to the research community, and some potential uses.

Discussion of low frequency ambient noise in the ocean inevitably results in a long list of "sub-topics," which is NOT the intent of this article. The focus is on three subjects: the change of ambient noise with time, the use of it to monitor meteorological conditions in remote locations; and the introduction of a technique to better define the source properties of ambient noise.

At very low frequencies (e.g., less than 100 Hz), the physical conditions in the ocean allow for very efficient sound propagation. Briefly, sufficient energy from the source must make its way to the depth of the minimum sound speed, referred to as the sound channel axis, which, as illustrated in **Figure 1** has some variation in each major ocean basin and also varies with latitude in all basins, ranging from the nominal depth values indicated in **Table 1**, to at, or near, the ocean surface at polar latitudes.

Figure 2 illustrates the fact that acoustic signals, if they reach the sound channel axis at angles of the order 0-15 degrees with respect to the horizontal, will travel without encountering the ocean boundaries, and at low frequencies with low energy losses, have the potential to travel long distances and still retain enough signal strength to be detected by hydrophones in the sound channel. This characteristic provides the potential to monitor the world's oceans with a few sensors strategically located geographically, and placed at the sound channel axis. This is exactly what the UN's CTBTO (Auer and Prior, 2014) has done to assure international compliance with the Comprehensive Nuclear-Test Ban Treaty. Three of the hydroacoustic systems of the International Monitoring System (IMS), and the data collected by those sites are the subject of this discussion.

Table 1. Locations and depths of the three hydrophone arrays used in this discussion

ID	Location	Latitude	Longitude	Depth (m)
HA08	Diego Garcia	7° S	72° E	1300
HA10	Ascension Island	8° S	14° W	850
HA11	Wake Island	19° N	166° E	740

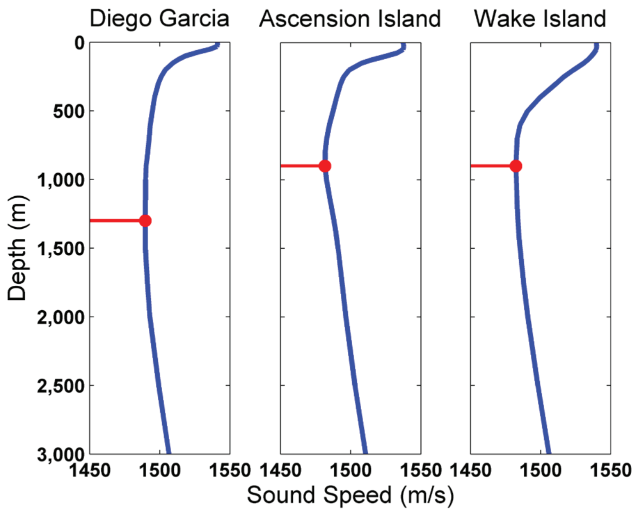


Figure 1. Sound speed profiles for the three hydrophone stations, retrieved from the World Ocean Atlas (NOAA, 2001). The depth of the sound channel, located at the sound speed minimum, is marked in red.

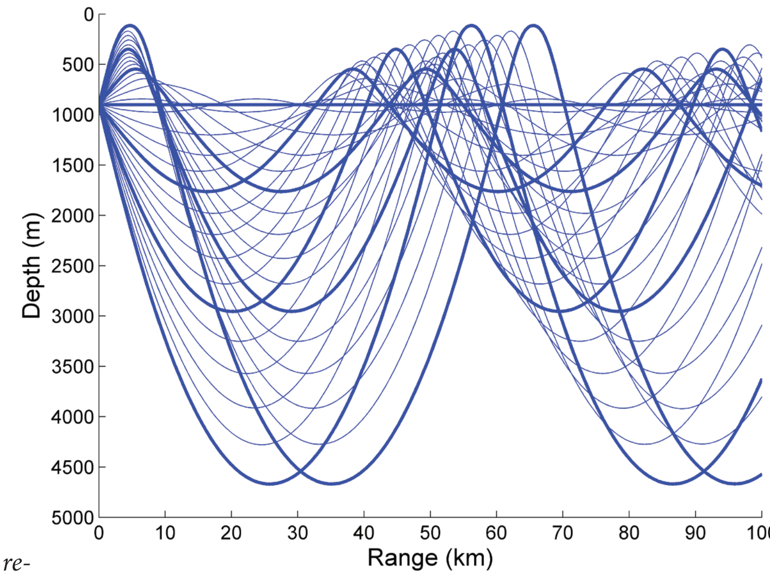


Figure 2. Propagation paths of sound from a source at the sound channel depth, in the sound speed profile reported near Wake Island. Ray launch angles range from -15 (Below the horizontal) to +15 degrees (Above), with an interval of 1 degree. Every fifth ray is drawn with a bold line for ease of viewing.

The ambient noise data discussed were obtained from the hydroacoustic stations located at Diego Garcia (Chagos Archipelago), Ascension Island, and Wake Island, shown in **Figure 3** and described more precisely in **Table 1** (Lawrence, 2004). Each of these stations consists of a pair of triangular hydrophone arrays (three hydrophones) at the sound channel axis, situated on opposite sides of a host island. This arrangement helps to limit the area of detection due to the acoustic shadow zone produced by the host island and also provides some degree of directionality of the sound field. Each hydrophone is equipped with a preamplifier/filter and a 250-Hz digitizer. Buried fiber optic cables carry the digitized ambient noise signals from the moored hydrophones to a station on the surface of the host island, where they are transmitted via satellite to the CTBTO headquarters in Vienna for monitoring (Auer and Prior, 2014). The data is also available from the host country (of the site) via contact with the appropriate government agency. While these stations were built with the primary purpose of monitoring the world's oceans for unsanctioned nuclear weapons testing, the nearly continuous recordings produced by this network, spanning over 10 years in duration at some locations (data logs received from CTBTO), constitute one of the best collections of low-frequency ambient noise data currently available.

Figure 3. Map of the three hydrophone arrays providing the data for this discussion. The three island stations are: Diego Garcia in the Indian Ocean, Ascension Island in the Atlantic Ocean, and Wake Island in the Pacific Ocean.

The Data: Details and Some Characteristics and Comparisons with Other Ambient Noise Data

The requirements of the CTBTO monitoring system limit the acoustic bandwidth of the data recorded to range from approximately 1 to 100 Hz. This region is where the dominant sources of acoustic signals are non-linear sea surface wave interaction; seismic activity; some biologic; and finally, commercial shipping. More about each of these sources later. The underwater acoustics community, since 1962, have used what are casually called "The Wenz Curves" as the "standard" for ocean ambient noise, so the normal procedure is for experimentalists at sea to collect and plot the data under consideration on those curves to provide a "sanity check." Since the Wenz Curves are accepted by researchers to be typical of ambient noise for various environments encountered at sea, the comparison gives confidence that the current data collected is good data. In keeping with that process, first consider some long term average levels from the Indian, Pacific, and Atlantic Oceans in the context of the Wenz curves (Wenz, 1962) (**Figure 4**):

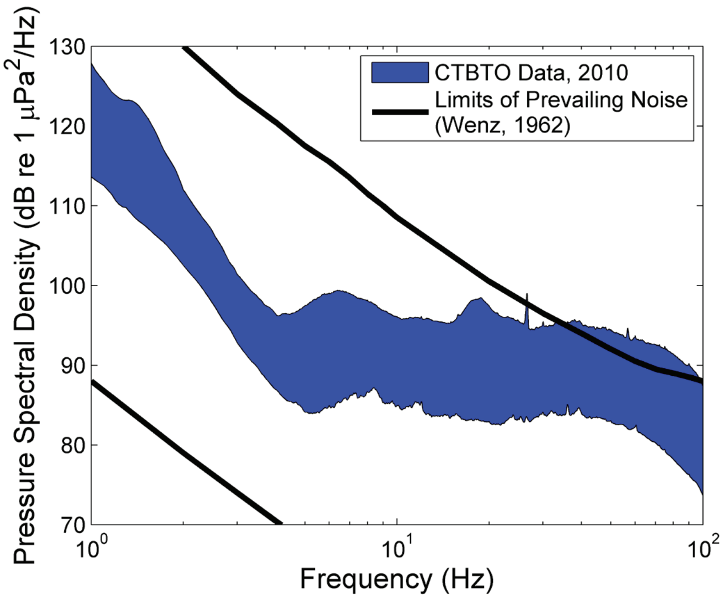


Figure 4. Ambient noise levels measured at the CTBTO hydroacoustic monitoring stations for 2010. The reported levels are superimposed on the "Limits of Prevailing Noise" curves published by Wenz (1962).

Figure 4 shows a full year (2010) of data from CTBTO sites in the Atlantic, Pacific, and Indian Oceans, superimposed on the limits of prevailing noise, as published by Wenz in 1962. The large blue band shows the range of year-averaged spectral levels seen across the three sites. At frequencies below 5 Hz, the very steep spectral slopes appear reasonably well centered as averages, as expected. Above 5 Hz, the flatter spectrum is a combination of biologic, anthropogenic (usually shipping, but can be other human-caused sources), and geophysical sound sources. As one approaches the upper frequency limit of the CTBTO System around 100 Hz, the more recent averages move to above average and even exceed the upper limit seen by Wenz more than 50 years ago. Since the acoustic sources, as 100 Hz is approached, are considered to be dominated by shipping, those anthropogenic contributions were predicted to increase (Ross, 1987, 1993) and recent measurements have borne out that hypothesis over the intervening five decades. This behavior was expected and clearly illustrated in the figure.

A more graphical way to emphasize this increase is seen in **Figure 5**, which displays both the Wenz values from the 1950's and 1960's and more recent data from the Pacific Ocean, west of California, collected in the late 1990's and early 2000's (Andrew et al., 2002), together with the averaged values of the present data for the frequency region 10 to 60 Hz.

Much of the recent attention given to underwater noise is concerned with the effect of human activity on the ambient noise levels in the ocean (Hawkins and Popper, 2014; Ketten, 2014). Since many marine mammals rely on sound as their primary means of communication, increasing levels of noise may hinder their ability to survive in an environment that is changing faster than their ability to adapt, and over geographic regions large enough to impact their established travel patterns (Southall et al., 2007; Hawkins and Popper, 2012). Several studies have reported that noise levels in the frequency range of shipping activity have increased since the 1960s. The data from Andrew et al. (2002), between 10 and 60 Hz, shows that noise levels measured at a receiver located in the Eastern Pacific Ocean were more than 10 dB louder in the late 1990s than in the mid-1960s. Several measurement sites, including the three of interest here, are clearly louder than they were in the 1960s, but the rate of increase appears to be leveling off, or even decreasing (Andrew et al., 2011).

Acoustic (and Meteorological) Weather

A major contributor to noise from 1-5 Hz is sea surface motion caused by storm (high wind) events. Because there is also another wind generated contribution at frequencies above the 100 Hz upper limit of the CTBTO data, some explanation is necessary. The phenomena generating this very low frequency noise is a non-linear effect (Longuet-Higgins,

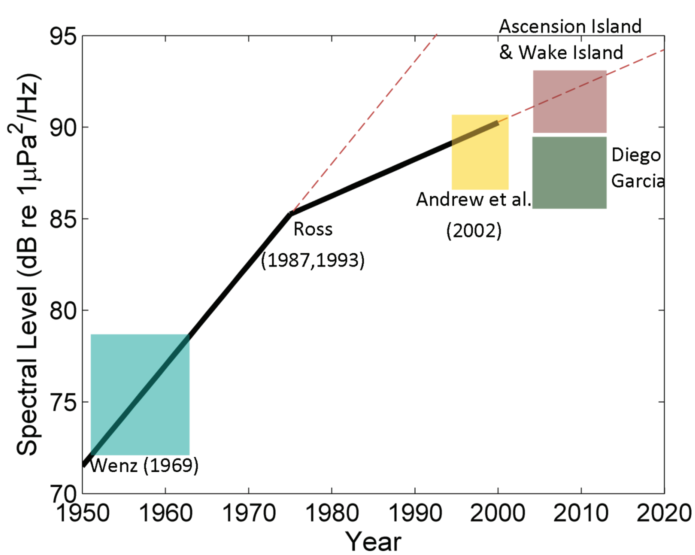


Figure 5. Comparison of ambient noise levels over time, based on measurements reported by Wenz (1962) and Andrew et al. (2002), with data from the CTBTO stations for 2010. The black lines, and extrapolated dashed lines, show two differing ambient noise trends noted by Ross, with a prediction that the noise levels would only increase 5 dB in the last quarter of the twentieth century (Ross, 1987 and 1993).

1950) resulting from two ocean surface waves that are traveling toward one another and their consequent interaction, creating a standing wave which results in a pressure change sensed by the hydrophone(s). Below 5 Hz, it has been noted that the amplitude of the pressure variations produced by the Longuet-Higgins mechanism correlate well with surface wind speeds (McCreery et al., 1993).

As winds blow along the surface of the sea, surface waves start to develop, which increase in amplitude as wind speeds increase. Logically, surface wave heights can only increase up to a certain point before they start to break, limiting the height of a wave. Since longer wavelength waves can support higher amplitude than shorter wavelength waves before the onset of breaking, the height limit of a surface wave is dependent on its frequency. For oceanic surface waves of frequencies between about 0.1 and 10 Hz, this limiting height spectrum, often referred to as a "saturation spectrum", is proportional to frequency^{-5} (Pierson and Moskowitz, 1964).

The effect of the surface wave saturation spectrum is demonstrated in **Figure 6**, with measurements made near Diego Garcia over the year 2010. In this plot, the ambient acoustic spectrum is grouped by the surface wind speed at the time of measurement. As surface winds increase, noise levels below 5 Hz increase up to a similar saturation spectrum, but not that of the acoustic ambient noise. As derived by Hughes (1976) and Lloyd (1981), the saturation spectrum of the noise generated by the Longuet-Higgins mechanism is proportional to frequency^{-7} below about 5 Hz.

To illustrate the contribution of a passing storm to the ambient sea noise background, a typical storm passing Wake Island was "tracked" acoustically and displayed in **Figure 7**, which displays a nine day period near Wake Island, during which wind speeds quickly rise, and then gradually decay. As the wind speeds increase, so do the sound levels at 1 Hz, with some delay time to allow wave heights to build up.

The acoustic energy in the 1 -5 Hz band, illustrated in **Figures 6** and 7, is "local" in the sense that the wave interaction phenomena and its resultant acoustic signal are present in the water column. The signal can, and does, propagate. In fact, its initial discovery was observed by land based seismometers, often many kilometers from the location of the signal generation. The contribution of ambient noise from a passing weather system that enters the sound channel noted in the introduction is still a research issue. With the assumption that a reasonable estimate (prediction), or a measurement can be made to quantify that contribution, the use of

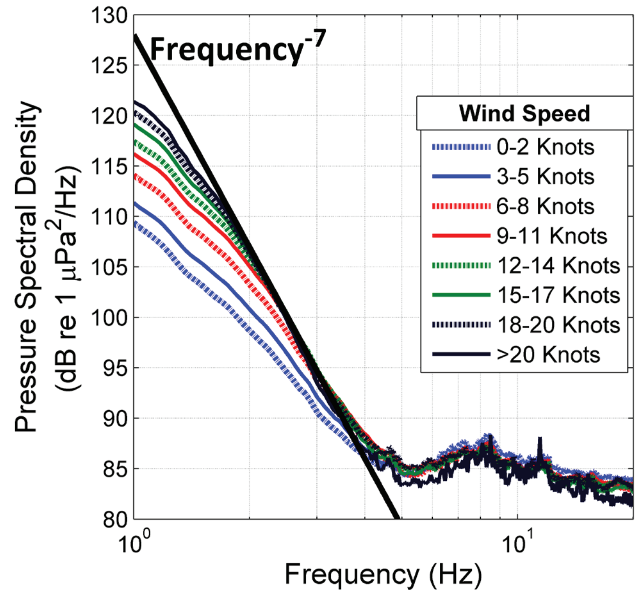


Figure 6. Ambient noise spectra measured near Diego Garcia during the year 2010, divided into groups based on the surface wind speed at the time of measurement.

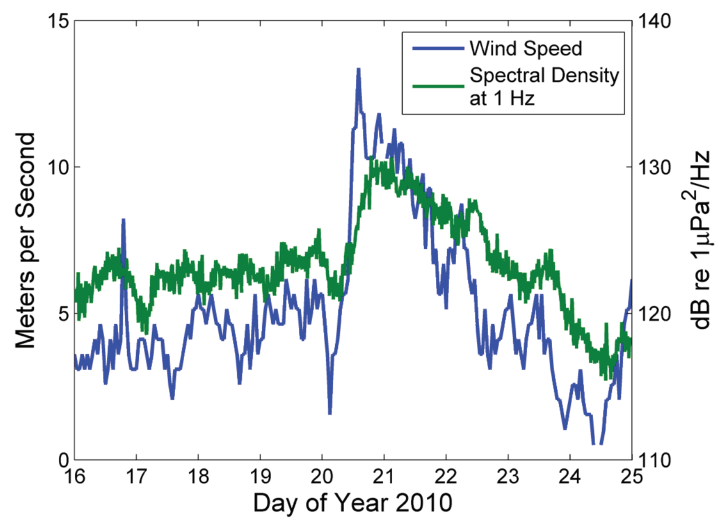


Figure 7. Wind speeds and 1 Hz noise levels measured from January 16th to 25th, 2010, near Wake Island.

the CTBTO hydroacoustic arrays as remote "weather" stations has a value in the global mapping of weather conditions and their change over time. It must be emphasized, however, that any given hydroacoustic site would be integrating the effect of a number of simultaneous storms over a potentially very large oceanic surface area, depending on storm intensity and size, so the value is one of averaging (smoothing) the impact of (likely) a number of storms. The use of hydroacoustic sites to provide, via an "acoustic weather" metric, a view of averaged atmospheric weather, has an interesting potential.

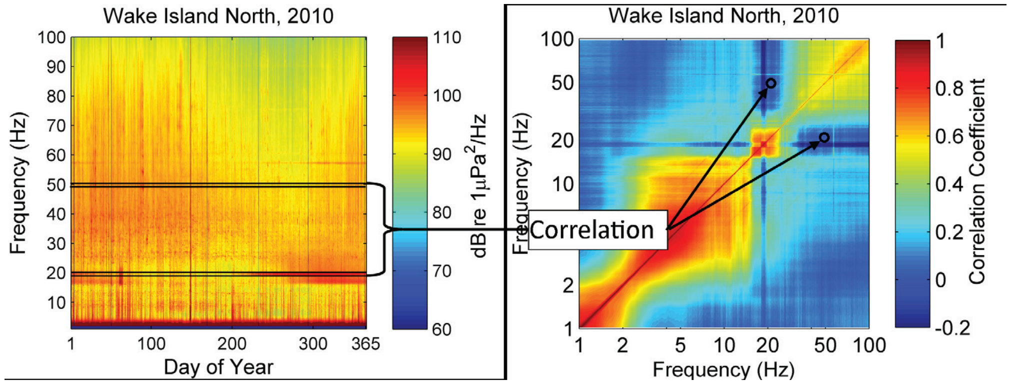


Figure 8. Illustration of the correlation process in which spectral levels pairs of frequencies are correlated, populating a matrix of correlation coefficients which is symmetric around the main diagonal.

What do you mean, "Biologics"?

The answer expected is "A North Atlantic Right Whale mother signaling its calf to 'stay close.'" A conundrum faced in underwater acoustics and one of its consequences is the use of words like "seismic events," "distant shipping," or "biologics" to describe sources of sounds that clearly should have much more precise definitions. A value of the CTBTO data sets is the opportunity to examine hundreds, if not thousands, of "events," and to consequently isolate those events that have a common source. To be sure, enormous advances have been made in the marine biology world, as each form of life has a taxa, hence a specific source can be (and is) identified and associated with a received and catalogued acoustic signal. (Stafford et al., 2004; Neukirk et al., 2012).

Searching for methods to isolate specific source functions leads to the application of a correlation technique that has been used (Nichols and Sayer, 1977; Curtis et al., 1999; Nichols and Bradley, 2013, 2014), where the frequency content of a specific signal is displayed in a manner that emphasizes the correlation (or similarity) between (or lack thereof) a particular frequency value and other frequencies, also contained in the same signal. The technique appears to provide unique and repeatable "structures" for a number of those sources that are typically labeled by a generic title such as "seismic event." The technique, illustrated in **Figure 8**, displays the correlation coefficient between spectral levels at two frequencies for a period of time (in the figure, it is one year, but the time "window" selected would be driven by the time associated with a particular phenomenon, or an estimate, if an actual measurement is not available).

Figure 9 (a)-Ascension Island (North), (b) Diego Garcia (North), and (c) Wake Island (North), displays a full year (2010) of averaged behavior using this correlation method and provides strong evidence that the detailed contributions to the ambient noise at each site has distinct differences. All have a contribution due to storms at the below 5 Hz; this contribution is seen as a region of high correlation in the low frequency (bottom left) corner of each figure. Looking to higher frequencies, each of the locations behaves differently. At Ascension Island in the Atlantic Ocean, the dominant source of noise (at least, in 2010) is geophysical exploration, which creates the high correlation region between 4 and 100 Hz in **Figure 9(a)**. Noise from these surveys was detected nearly every day of the year near Ascension Island. Within the 4 to 100 Hz high correlation region produced by the survey noise, a pair of plus-sign shaped features at about 18 and 26 Hz denotes the presence of a source which is relatively uncorrelated with the seismic survey noise. These features within the correlation matrix denote narrow-band whale vocalizations which are present for a large portion of the year (Nichols and Bradley, 2013).

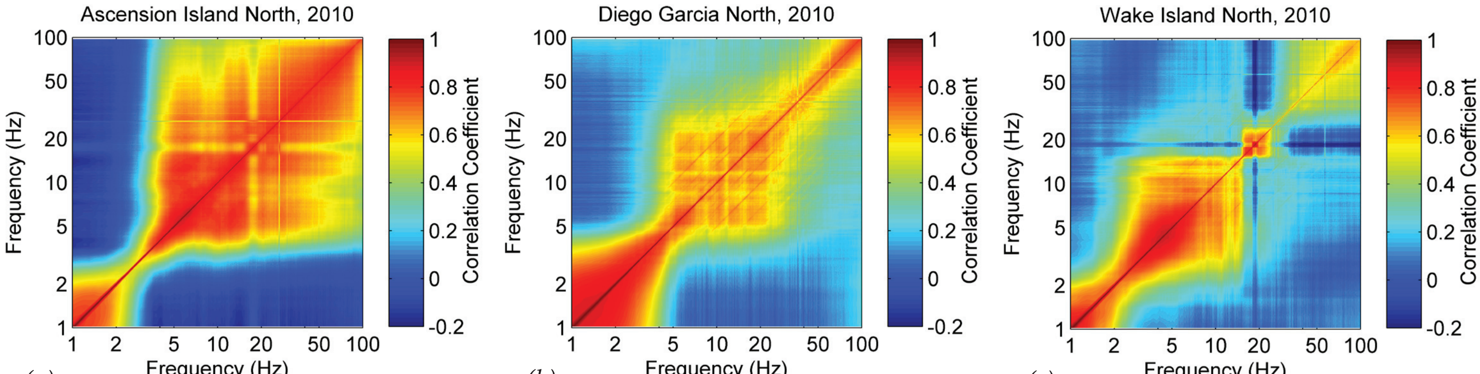
Near Diego Garcia in the Indian Ocean, seismic activity (solid earth movement) is responsible for a great deal of acoustic energy over the course of the year, as is evidenced by the region of correlation between 5 and 30 Hz in **Figure 9(b)**. Within this frequency band, parallel diagonal lines occur where the ratio between the two frequencies is an integer ratio. These integer ratio diagonal lines correspond to the harmonic nature of ship noise.

Figure 9(c) illustrates the acoustic activity near Wake Island in the Pacific Ocean. Similar to **Figure 9(b)**, the region of higher correlation from 3 to 18 Hz indicates the predominant region of seismic activity noise. The high end of this region is followed by a band of correlation ranging from about 18 to 22 Hz. This region consists of a larger band of correlation, spanning from 18 to 22 Hz, and a narrower band, from 19 to 20 Hz. The dual-band feature shows the presence of two different types of whale vocalizations.

The richness of variability in these correlation displays, both in location and time (not discussed here), will contribute to the acoustic ambient noise source function descriptions.

Summary

The CTBTO data sets provide an enormous storehouse of information that can be (and is being) mined for information on the details of oceanic acoustic ambient noise. Comparison with similar data collected decades ago clearly displays



(a) *(b)* *(c)*

Figure 9*. Correlation matrix of the acoustic field measured near (a) Ascension Island, (b) Diego Garcia, and (c) Wake Island during the year 2010.*

an increase in the levels of ambient noise in those frequency bands that are dominated by anthropogenic sources. The potential of using the CTBTO system to provide an acoustic "weather" counterpart to meteorological weather, which is a temporal and spatial average, more amenable to tracking long term changes should be investigated. Finally, the use of a frequency correlation method to better define ambient noise source functions removes the indistinctness of terms like "shipping" or "seismic events."

Biosketches

David L. Bradley received a Ph.D. in Mechanical Engineering in 1970 from The Catholic University of America. His work career has been a combination of US Navy supported research, Laboratory Directorship at the NATO Undersea Research Centre, La Spezia, Italy and university research and academic activity at The Pennsylvania State University, the Applied Research Laboratory. Currently a Professor of Acoustics, he is funded by the Office of Naval Research. He has served as President and Associate Editor for the Acoustical Society of America. A Fellow of the Acoustical Society, he has served on the Executive Council and chaired Society committees.

Stephen M. Nichols is a graduate research assistant at the Applied Research Laboratory at The Pennsylvania State University. He earned his B.S. in Physics from the University of California, Los Angeles in 2011. He is currently working on his Ph.D. in Acoustics at Penn State. His graduate work is focused on the analysis of large sets of very low frequency underwater ambient noise, looking primarily at the source mechanisms responsible for creating the ambient noise field.

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Errata

The following corrections have been offered by authors of various articles:

SUMMER 2014

Vol. 10 (3), pp. 8-15."Bioacoustic Monitoring Contributes to an Understanding of Climate Change." P. 10, Column 2. "Thresholds of neural responses from auditory nuclei in the brain varied with housing temperature (Wysocki et al., 2009); at high temperatures, thresholds increased and hearing sensitivity decreased."

Correction: "Thresholds of neural responses from auditory nuclei in the brain varied with housing temperature (Wysocki et al., 2009); at high temperatures, thresholds decreased and hearing sensitivity increased."

Vol. 10 (3), pp. 46-56. "Sonars and Strandings: Are Beaked Whales the Aquatic Acoustic Canary?"

P. 46: d.ketten@curtin.edu.aa should be d.ketten@curtin.edu.au

P. 50, Column 1 "By-catch once accounted for as many as 100,000 cetaceans annually worldwide (Read, 2006, 2008), but in recent years, through gear improvements, the numbers have decreased to less than 2,000 annually, which is approximately equal to animals taken in commercial and scientific whaling fisheries."

Correction: "By-catch once accounted for as many as 300,000 cetaceans annually worldwide (Read, 2006, 2008), but in recent years, through gear improvements, numbers have decreased to less than 2,000 annually in critical areas, or approximately equal to animals taken in commercial and scientific whaling fisheries."

FALL 2014

Vol. 10 (4), pp. 9-11. "Guest Editors' Introduction." The parenthetical statement on page 10, right column, top paragraph 10th line incorrectly lists Ray Nickerson as first to use the @ sign in email addresses. The correct listing is Ray Tomlinson.

Fall 2014, Vol. 10 (4), p. 14. The photo was taken in November 2003 in relation to the conferring of the National Medal of Science by President George W. Bush on Dr. Beranek.

Computer Simulation for Predicting Acoustic Scattering from Objects at the Bottom of the Ocean

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Applying the modern discipline of computational mechanics to solving complex mathematical problems in acoustics.

Introduction

Since the early 20th century, SONAR (SOund Navigation And Ranging) has been used in military, commercial and scientific applications to help find objects submerged in the oceans, either by listening passively with underwater hydrophones to the sounds that noisy objects emit (passive sonar) or by actively projecting sound into the water and listening to the echoes reflected from quiet objects (active sonar, **Figure 1**). Sonar has been used successfully for detection (is there something out there?), localization (where is it?), some degree of classification (what type of object is it, e.g., man-made or marine organism?) and some degree of identification (what is the object?). In order to more precisely identify the nature of a detected object, an active sonar technique has recently emerged that produces additional information about the object, including not only its size and shape but also its internal composition. The resulting body of information is referred to as the "acoustic scattering signature" (Burnett, 2015), or just acoustic signature, of the object.

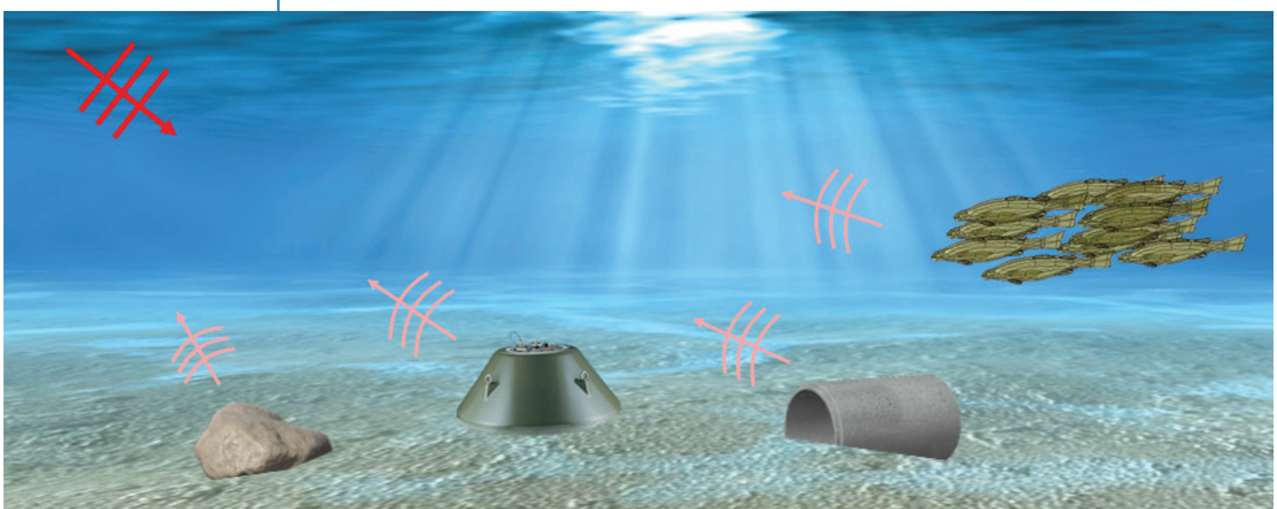

Figure 1 *An underwater scenario depicting a sonar wave (red arrow) insonifying various objects on or near the sedimentary ocean bottom – rock, mine, concrete pipe, fish school – and the resulting sound waves scattered back from the objects (pink arrows).*

The Physics Underlying an Acoustic Scattering Signature

Consider an arbitrary object in free space that is insonified by a monochromatic (single frequency) sound wave (**Figure 2**). Real objects are made of solid materials (metals, plastics, bones, flesh, etc.) which change shape or volume "elastically" when any stress is applied (albeit by microscopic amounts when small acoustic pressures are applied). The incident sound wave is an oscillatory pressure disturbance in the water. As it strikes the object, the oscillating pressure on the surface of the object induces elastic (solid) waves to propagate throughout all parts of the structure. The vibrating object will, in turn, exert an oscillating pressure on the surrounding water, which produces pressure waves in the water that propagate away from the object, so-called scattered waves (also called echoes). The scattered waves will propagate out in all directions, with different intensity in different directions. As the incident sound wave changes direction relative to the object (the angle θ in **Figure 2**) or changes frequency, the vibrations in the object will change, which, in turn, will change the scattered waves.

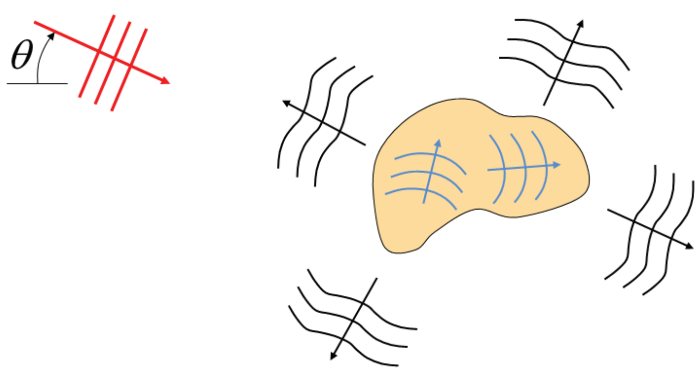

Figure 2. *An object submerged in a fluid is insonified by a plane wave (red arrow), causing the object to vibrate (interior elastic waves, represented by blue arrows), which re-radiates scattered waves (black arrows) back into the fluid in all directions.*

When an object (also called "target") is insonified by a plane wave (wave fronts are planar, rather than curved, as occurs when the sound source is far from the object), the intensity of the scattered pressure wave back in the same direction that the sound wave came from is expressed by the monostatic (source and observer in same direction) far-field target strength, TS:

$$(1)\qquad TS(f,\theta) = \underset{r\to\infty}{Lim}\ 20\,\mathrm{Log}_{10}\left(\frac{r\left|p(\boldsymbol{r})\right|}{r_0 p_0}\right)$$

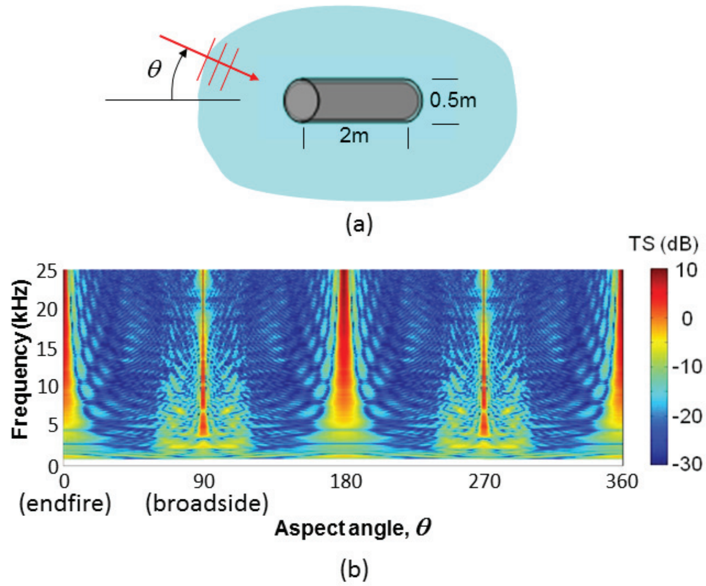

Figure 3. *(a) Insonifying a steel cylindrical closed shell. (b) The resulting acoustic scattering signature template.*

where f is frequency, θ is the aspect angle of the incident sound wave (defined for each different problem, but is usually the azimuthal angle, which is a horizontal angle about the vertical to the ocean bottom), $p(\boldsymbol{r})$ is the pressure of the scattered wave, | | indicates magnitude (since p is a complex-valued function), $\boldsymbol{r}$ is a position vector from the object to the "observer" (where the TS is being measured), r is its magnitude, and r_o and p_o are a reference distance and pressure that normalize and make dimensionless the argument of the logarithm. In 3-dimensional space, $p(\boldsymbol{r})\ \boldsymbol{\alpha}\ 1/r$ far away from the object, in the so-called far field; hence the numerator, $r|p(\boldsymbol{r})|$, converges to a limiting value as $r\to\infty$. The symbol $\underset{r\to\infty}{Lim}$ means evaluate the scattered pressure far enough away to obtain the limiting value. The units of TS are decibels (dB).

An acoustic scattering signature is the target strength of an object, **Equation (1)**, that has been insonified over a broad band of frequencies and, for each frequency, over a broad range of aspect angles. The resulting values of TS are plotted as a template (terminology from radar) of TS vs. f and θ, with TS displayed as a color. This is illustrated below for a steel cylindrical closed shell, with a color bar on the right to quantify the TS values (**Figure 3**).

One can see that there is a great deal of information about the object in such a template. For example, the geometry of object and incident sound wave in part (a) of **Figure 3** is clearly symmetric about the incident directions that are parallel to the axis of the cylinder (endfire, $\theta = 0^o$) and perpendicular to the axis (broadside, $\theta = 90^o$), and this is manifested in corresponding symmetries in the template in part (b).

The TS is also strongest (red color) in these two directions because there are parts of the surfaces of the shell that are oriented perpendicular to the incident wave and therefore reflect part of the energy directly backward; at other angles the surfaces are oblique, reflecting energy in other directions. Other intense areas of the template (yellow, green, light blue) are caused by resonances of various types of internal elastic waves.

Acoustic Signature vs. Imaging

The dimension*less* frequency band of acoustic signatures is the same for all objects, no matter how large or small: from about $ka = 1$ to about $ka = 30$, where ka is dimension*less* frequency, k is wavenumber ($2\pi/\lambda$), λ is the wavelength of the insonifying plane wave (recall **Figure 2**) and **a** is an approximate "radius" of the object, namely, an average "radius" of chunky objects or shorter "radius" of long objects. At the lower frequencies, wavelengths are comparable to the exterior dimensions of the object; at the higher frequencies wavelengths are comparable to smaller interior dimensions. Equivalently, this is the range of the lower natural modes of vibration of the object. To illustrate, the vertical frequency axis in **Figure 3**, using the speed of sound in water as 1500 m/s and $a = 0.25$m, ranges from $ka = 1$ to $ka = 26$.

Sonar classification has traditionally relied on much higher frequencies, where wavelengths are very small relative to the object and therefore can produce a rough image of the object, that is, its external shape, but it cannot reveal internal composition because the shorter wavelengths can't penetrate very deeply before they die out due to attenuation per wavelength. Consequently, acoustic signatures and imaging complement each other in modern sonar systems. A key difference between the two approaches is the amount of information needed to interpret sonar output: imaging produces a picture of the object so an engineer can identify the object simply by looking at the image, whereas a signature produces only a TS template, which requires a computer to detect meaningful patterns in the template.

The Need for Computer Simulation

One approach to the computer search for such patterns is to see if there are similarities with the templates of similar objects in a variety of realistic configurations, for example, rest ing on the bottom, partially buried, fully buried, tipped, etc., or in different types of sediment such as sand, clay, mud, etc., as well as objects with similar construction, for example, decoys or manufacturing variations. All of these variations can have a significant effect on the vibrational response of the object and hence its acoustic signature. That requires having a large library of reference acoustic signature templates.

To construct such a library, one could perform experiments on actual objects. But experiments are expensive and time consuming so only a few can be performed, and one cannot perform experiments on unavailable objects or environments. Computers, however, can model virtually any object/environment scenario of interest, including nonexistent scenarios. The cost of computer resources per model is negligible compared to that of a real underwater experiment and often faster by orders of magnitude, sometimes enabling hundreds or thousands of templates to be computed in the same time as performing one underwater experiment. There is clearly a need for a computer simulation system that is both high-fidelity and computationally fast.

Computer Simulation

The Naval Surface Warfare Center Panama City Division (NSWC PCD) has developed a high-fidelity, broadband (CW analyses), three-dimensional (3-D), finite-element (FE) computer simulation system called PC-ACOLOR (Panama City-Acoustic COLOR), which models the acoustic scattering signature (also called acoustic color) of single or multiple realistic targets at the bottom of the ocean.

The principle challenges to developing such a system were as follows:

- Multiscale spatially: From small details in the objects (cm) to large distances in the ocean (km).
- Broadband: A five-octave range, $ka \approx 1$ to 30.
- A need for extraordinarily high computational efficiency: One acoustic signature template requires sweeping typically over several hundred frequencies, and, for each frequency, several hundred aspect angles, requiring $O(10^5)$ 3-D models. Modeling techniques developed by the author since the 1980s have enabled the code to currently compute about one template per day, an adequate pace for applications so far. Nevertheless, the next level of applications will require computing several hundred templates per day in order to create statistically robust acoustic signature libraries. R&D to achieve such speeds is underway and should be operational when this article is published (see The Way Forward at the end of this article).

The next three subsections describe the approach used by NSWC PCD: the physics, the governing mathematics, and the computational modeling technique.

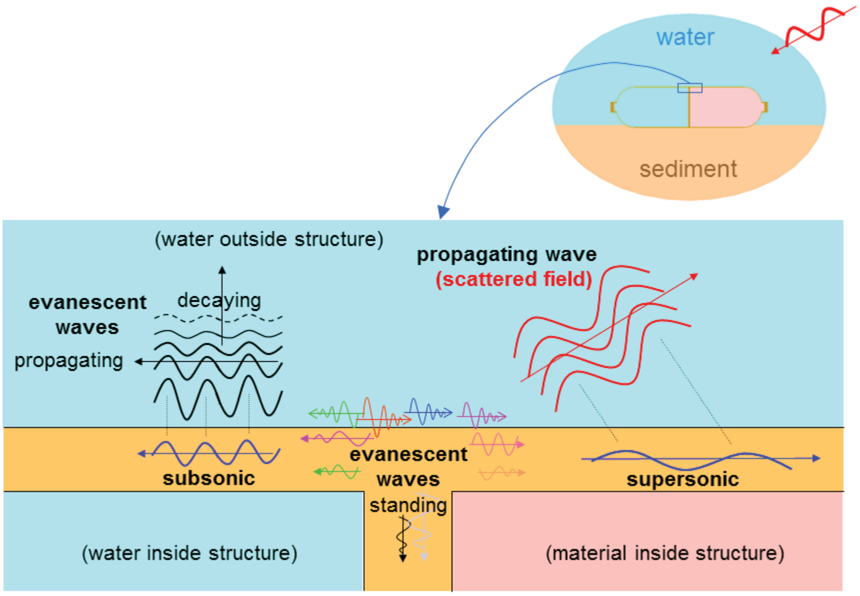

Figure 4. A concept sketch illustrating how both evanescent and propagating waves exist in the elastic structure and in the surrounding fluid.

It Begins With the Physics

High fidelity means high accuracy relative to reality, which means the inclusion of many structural details in the objects and, equally important, all the physics necessary for describing all possible types of wave motion in the objects and surrounding fluids. This includes not only the many types of propagating waves that are described in most textbooks (e.g., Lamb waves, Love waves, creeping waves, etc.) but also so-called evanescent waves, which are rarely mentioned in textbooks.

Evanescent waves exist at the interfaces between different materials and generally have shorter wavelengths than propagating waves (Mindlin, 1960; Zemanek, 1972). They are spatially decaying in one or more directions and are standing waves in the directions of decay. Their spatial decay is not due to material damping or geometric spreading. Nature needs such waves to satisfy continuity of physics at material discontinuities or near small-scale features where the wavelengths of propagating waves are too long to resolve those features. (The word "evanescent" is misleading, implying temporal decay (ephemeral, fleeting); however, the decay is spatial, not temporal.)

Evanescent waves are especially important at the fluid/solid interface ("wet surface") of targets since this is where scattered waves are launched into the fluid. **Figure 4** illustrates these concepts with a sketch of an underwater manmade structure, consisting of a thin-shell container with an internal partition. It zooms in on a typical small structural discontinuity – in this case, the intersection of the outer shell and the internal partition – showing both propagating and evanescent waves and especially those "trapped" on the outer wet surface of the target, which are evanescent normal to the surface while propagating parallel to the surface.

Figure 4 illustrates a very important aspect of the small-scale/large-scale interaction in structural acoustics that is often over-looked in the literature on computer modeling of such phenomena: small-scale local evanescent elastic waves inside the structure can have a significant effect on the propagating acoustic field (scattered field) far away, the latter usually being the goal of computer modeling of target scattering. Thus, the amplitudes and phases of the local elastic waves near a shell/partition intersection affect the amplitudes and phases of the propagating elastic waves along the length of the shell, and these, in turn, affect the amplitudes and phases of the propagating acoustic waves (the scattered waves) launched from the wet surface into the fluid. All these interactions will vary as a function of frequency and aspect angle of the incident wave.

In short, high fidelity modeling requires an approach that captures the full 3-D nature of the complicated wave fields near structural discontinuities as well as the wide range of wavelengths associated with evanescent and propagating waves, even for single-frequency (CW) models. To this end, PC-ACOLOR employs 3-D physics throughout all solids and fluids; no engineering approximations are made anywhere.

The Governing Mathematical Equations

The PC-ACOLOR system is frequency-domain (also called monochromatic, steady state or CW, the latter meaning continuous wave) rather than time-domain, for several reasons, foremost being (i) analyses are 3-D rather than 4-D, (ii) parallel computation using distributed processing is more easily facilitated, (iii) material properties (e.g., frequency-dependence and attenuation) are more readily available, and, of course, (iv) templates are in the frequency domain. When time-domain solutions are desired, such as for comparison with time-series responses from experiments, they are computed by inverse Fourier transforming the broadband frequency-domain solutions.

PC-ACOLOR separates the analysis into a local analysis in the "target region," which is analyzed using partial differential equations (PDEs), and a global analysis in the "exterior to target region," which is analyzed using an integral equation. The separation introduces no approximations to the 3-D physics.

Target Region:

The region for modeling local scattering from targets, the so-called "target region," comprises the targets and the fluids surrounding the targets out to an ellipsoidal boundary circumscribing the targets and separated from them by approximately half the characteristic wavelength of the fluids (**Figure 5a**). Inside the target region PC-ACOLOR finds a solution to two partial differential equations (PDEs) – one for fluids and the other for solids – that describe all phenomena within linear acoustics.

The PDE for describing monochromatic (single frequency) sound waves in fluids is the Helmholtz equation (also called the monochromatic wave equation),

$$-\nabla\cdot\left(\frac{1}{\omega^2\rho}\nabla p\right)-\frac{1}{B}p=0 \tag{2}$$

where p is the scattered pressure field, $\omega = 2\pi f$, f is frequency, and B and ρ are the bulk modulus and density, respectively, of the fluid.

The PDE for describing monochromatic elastic waves in solids is the elastodynamic equation,

$$-\nabla\cdot\left(\boldsymbol{c}\nabla\boldsymbol{u}\right)-\omega^2\rho_S\,\boldsymbol{u}=\boldsymbol{f}_S \tag{3}$$

where $\boldsymbol{u}$ is the (vector) displacement of a particle of the material as the wave passes by, $\boldsymbol{c}$ is a 4th-rank tensor of elastic moduli, ρ_S is the density of the solid material and $\boldsymbol{f}_S$ is an applied force (vector) per unit volume.

In addition, conditions for continuity of normal stress and normal displacement are applied on fluid/solid interfaces and radiation boundary conditions (rad BCs), which contain the physics for the large exterior region, are applied to the ellipsoidal boundary (Burnett, 2012).

Equations (2) and **(3)**, combined with the continuity conditions, radiation boundary conditions and applied excitations (e.g., incident acoustic field), constitute a well-posed mathematical problem for which there exists a solution valid anywhere inside the target region.

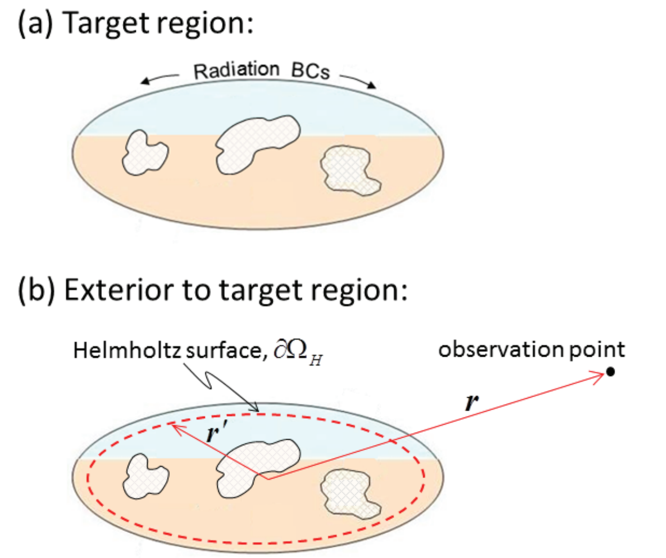

Figure 5. *Different governing equations are used for computing the scattered field inside the target region (Figure 5a) and exterior to the target region (Figure 5b).*

Exterior to Target Region:

The solution anywhere outside the target region is computed using the Helmholtz integral,

$$p(\boldsymbol{r})=\iint_{\partial\Omega_H}\left(\frac{\partial G(\boldsymbol{r},\boldsymbol{r}')}{\partial n}p(\boldsymbol{r}')-G(\boldsymbol{r},\boldsymbol{r}')\frac{\partial p(\boldsymbol{r}')}{\partial n}\right)d\Gamma \tag{4}$$

where the integration is over a mathematical surface, $\partial\Omega_H$, called the Helmholtz surface, that circumscribes the objects (**Figure 5b**). The quantities $p(\boldsymbol{r}')$ and $\partial p(\boldsymbol{r}')/\partial n$ are the scattered pressure and its derivative normal to the surface, respectively, which are the solution to **Equation (2)** inside the target region. $G(\boldsymbol{r}, \boldsymbol{r}')$ is the Green's function for the environment, which describes how sound waves propagate in the large ocean environment in the absence of the target. It can sometimes be expressed with simple formulas for simple idealized environments but can also be computed numerically in a separate computer simulation for more complicated realistic environments. The pressure $p(\boldsymbol{r})$ computed from **Equation (4)** is the pressure $p(\boldsymbol{r})$ in **Equation (1)**.

The Computational Modeling Technique

It is impossible to obtain an exact solution to **Equations (2) – (4)** for virtually any realistic objects using classical methods of applied mathematics unless one simplifies the equations a great deal, thereby eliminating much of the physics. Fortunately, that is not necessary, as the branch of modern mathematics known as finite-element (FE) analysis can produce an approximate solution that is as close as desired to the exact solution without simplifying any of the physics.

FE analysis is an extension of classical calculus (Burnett, 1987). It began in the mid-20th century and has grown rapidly, becoming such a powerful theoretical/numerical technique that it can find solutions to virtually any differential or integral equations that model (simulate) applications of almost any complexity. It has often been described as the most significant revolution in applied mathematics in the twentieth century, a perception that this author, who has worked with FE analysis for almost half a century, can heartily agree with. The merging of FE analysis with computer technology – two sciences that evolved concurrently and synergistically – has created the modern discipline known as computational mechanics (IACM, 2014). As computers continue to evolve, the power of FE analysis continues to grow apace. This article on predicting acoustic signatures is just one illustration of the power of modern computer simulation.

The essence of FE analysis is to subdivide the domain of a mathematical problem into a mesh of very small, simply shaped "elements" and then to approximately represent **Equation (2)** or **(3)** inside each and every element by transforming the differential equations into approximately equivalent algebraic equations. The algebraic equations in adjacent elements are interrelated, producing a continuity of physics across all the elements. Consequently, all of the element equations are coupled together into a very large system of simultaneous algebraic equations, typically hundreds of thousands or millions or even billions, which must then be solved on a computer. As elements in a mesh are made progressively smaller, or the mathematical representation inside each element is enriched, the FE approximate solution becomes progressively more accurate, converging eventually to the exact solution of the original mathematical problem.

The FE modeling process is illustrated below for the problem of acoustic scattering from a spherical steel shell resting on (almost touching) a fluid-like sandy ocean bottom. In this model, the very large ocean and sediment regions can be considered mathematically as "infinitely large" regions (**Figure 6 (a)**). To reduce the computational size of this problem, the large water and sediment regions can be replaced by a small surrounding ellipsoid (or spheroid or sphere) of water and sediment, with all the physics in the removed regions represented instead by mathematical relations, known as radiation boundary conditions, or rad BCs, applied to the outer boundary of the ellipsoid (**Figure 6 (b)**). This reduced model can be reduced further, to just one quadrant, by dividing it by any two perpendicular vertical planes intersecting the center of the spherical shell (**Figure 6 (c)**). One can then analyze just the one quadrant by decomposing all acoustic fields into components that are symmetric or antisymmetric with respect to those planes, in a way that preserves all the physics in the reduced model. The last step in the modeling process is to create a computationally efficient FE mesh for the quadrant model: larger elements away from the shell to represent long-wavelength propagating waves, smaller elements near to the shell to represent shorter-wavelength evanescent waves, and even smaller elements in the gap between the shell and the ocean bottom (**Figure 6(d)**).

In addition to the above computational efficiencies, the model is scaled with respect to frequency: as frequency increases, the ellipsoidal outer boundary moves closer to the targets in order to maintain a separation of about half a wavelength at all frequencies. This yields the additional advantage of maintaining approximately uniform modeling error across the frequency band.

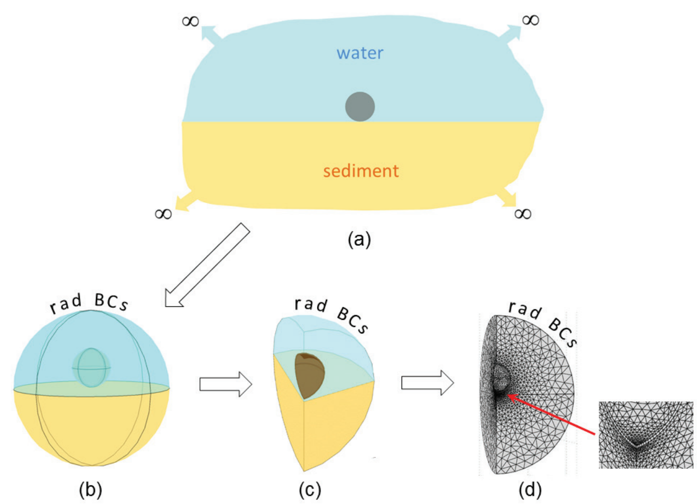

Figure 6. *(a) Full model: A spherical steel shell resting on the ocean bottom. The infinity symbols (∞) imply the water and sediment each occupy an infinite "halfspace". (b) Reduced model. (c) One quadrant of the reduced model. (d) The FE mesh for the quadrant model.*

In summary, the computer modeling process consists of using FE analysis to find numerical solutions to **Equations (2)** and **(3)** that describe the physics of wave propagation in fluids and solids, and then using **Equation (4)**, in conjunction with those solutions, to find the scattered acoustic pressure anywhere in the ocean. This process is repeated over and over for different frequencies and different aspect angles. Inserting those scattered pressures into **Equation (1)** yields the sought-after TS as a function of frequency and aspect angle, which is the acoustic signature of the object.

Verification & Validation

In the modern world of computational science, computer simulation has evolved to become the third essential research methodology, alongside theory and experiment (Oberkampf, 2002; Post, 2005). Since computer simulation is prone to human errors throughout the development and modeling process, it is important, in order to achieve reliable solutions, to continually subject models to a process of experimental validation (of the physics) and numerical verification (of the mathematics), also known as V&V (**Figure** 7). Ideally, this is a continuous, never-ending process.

Following are two examples, one of verification and one of validation. Both examples illustrate an essential feature of V&V: a comparison of two different approaches to a problem. Each approach has strengths and weaknesses and is prone to human error, so neither solution is certain. Thus, V&V is a two-way street, each approach providing increased confidence in the other. As more and more V&V testing is done, it might be said that one's confidence level can approach certainty asymptotically!

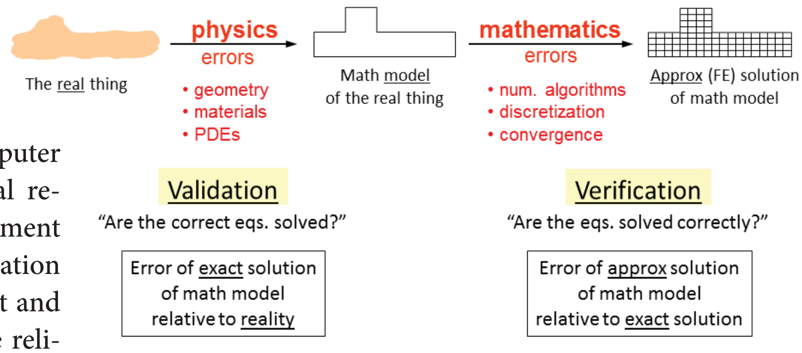

Figure 7. *Validation of physics and verification of mathematics.*

Verification

Verification is often accomplished by comparing two models using *independent* modeling techniques and looking for agreement over a broad range of the variables (not just at a few isolated spots). The rationale is this: two modeling techniques that use different methods are unlikely to produce the same errors over a broad, continuous span of data; ergo, if both solutions agree, then there are probably no errors, so both have probably found the correct solution.

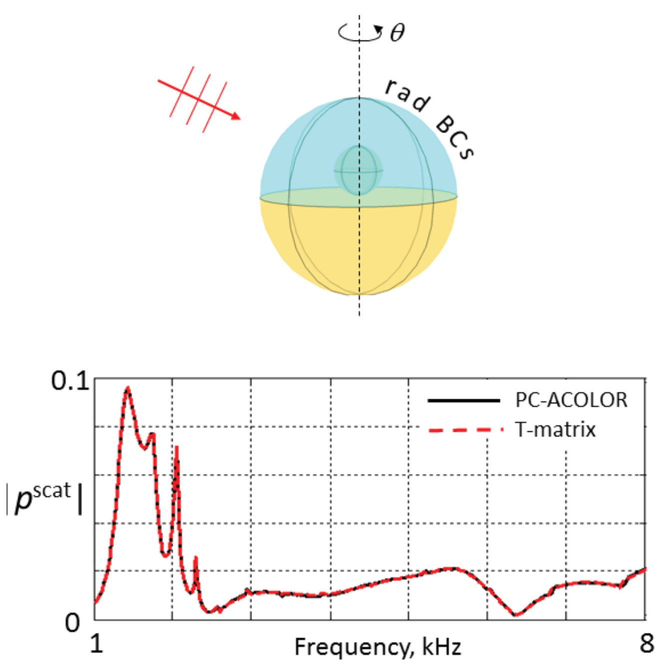

Figure 8. *Verification of computer simulation of scattering from spherical shell resting on sediment on ocean bottom, vis-à-vis an independent analytical technique (T-matrix method).*

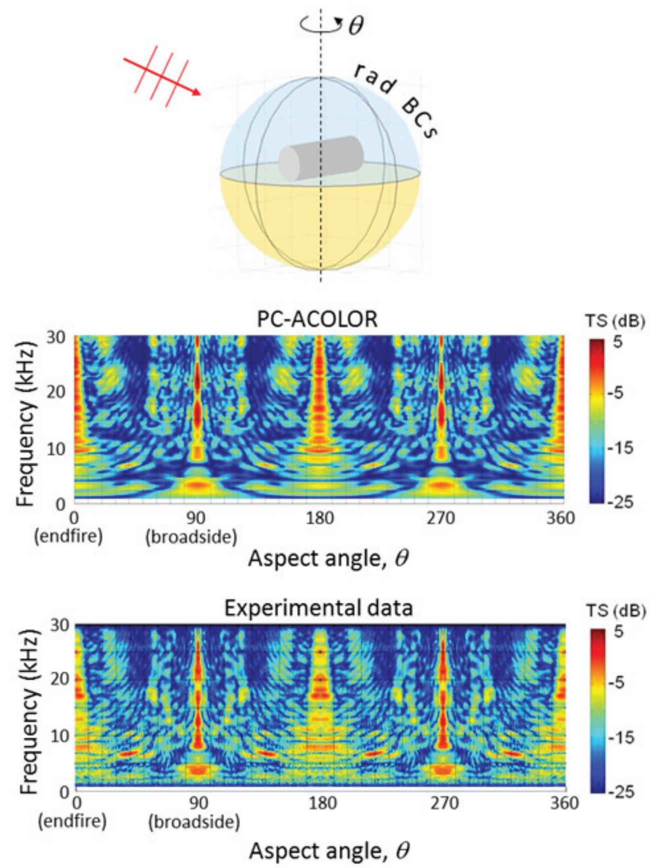

Figure 9. *Validation of computer simulation of scattering from a solid aluminum cylinder resting on sediment, vis-à-vis data from an in-water experiment. (Experimental data exhibit noise at the low frequencies due to a low signal-to-noise ratio for the equipment.)*

Figure 8 illustrates verification vis-à-vis a non-FE analytical method, for the problem of scattering of a plane wave from a spherical steel shell resting on the sediment (cf. **Figure 6**). The geometry of a sphere is very simple, so this problem is amenable to other, non-FE solution techniques, such as the T-matrix method, which is limited to very simple geometric shapes. The mathematical formalism and computer codes are completely different for FE and T-matrix analyses.

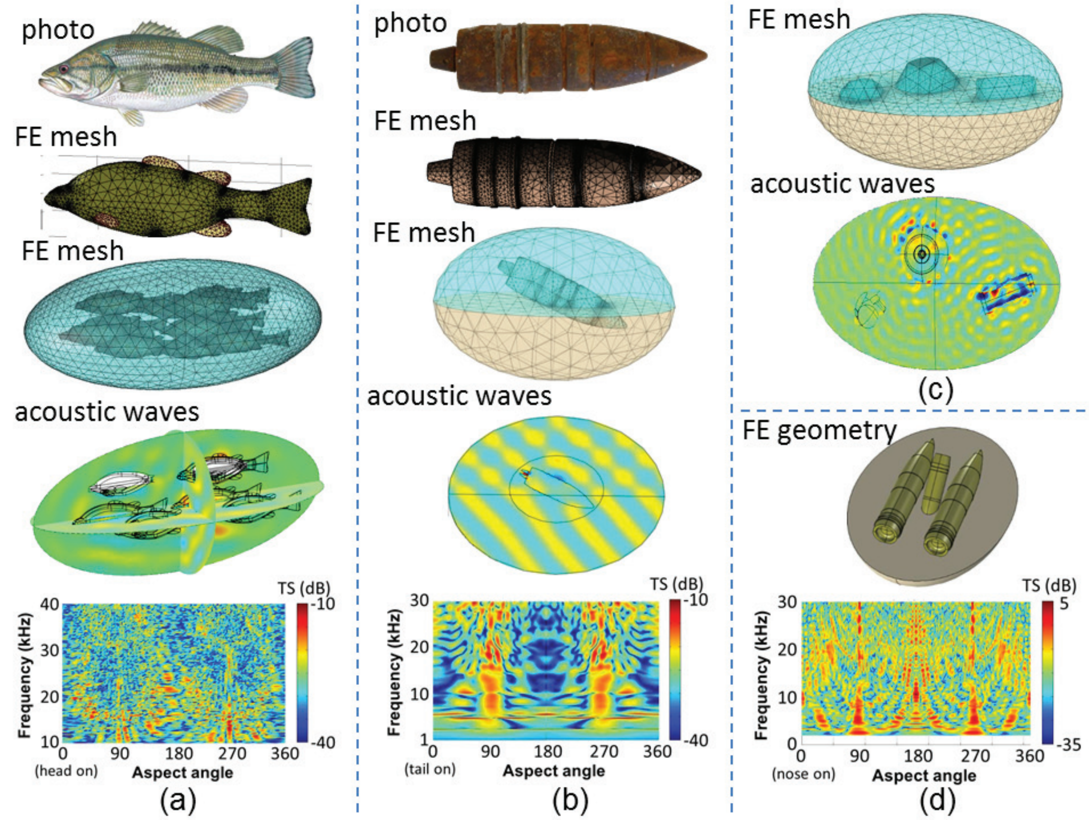

Figure 10. (a) Fish and school of fish (cf. Figure 1). (b) Unexploded artillery shell partially buried in sediment. (c) Rock, mine and concrete conduit pipe on sediment (cf. Figure 2). (d) Unexploded Howitzer shells on sediment and bullet partially buried.

Since the sphere and its environment are axisymmetric about the vertical (dashed line), the backscattered pressure is independent of the aspect angle, θ, so verification only needs to be done as a function of frequency. The two solutions in **Figure 8**, for the magnitude of the backscattered pressure vs. frequency, agree to about 3 significant figures over the entire three octaves of frequency, including the sharp spikes. Such strong agreements provide confidence in both mathematical techniques.

Validation

Validation is accomplished by comparing computer model predictions with data measured in experiments with real objects. This tests whether the correct physics is being used in the computer models (cf. **Figure 7**). For example, are **Equations (2)** and **(3)** adequate to capture all phenomena of interest or are additional equations necessary? Are there physical features in the real object that were intentionally omitted from the model to simplify the modeling, but perhaps shouldn't have been omitted? Has all the experimental equipment been calibrated properly? Validation tests the physics in the model against the real world, which involves ranges of uncertainty in physical properties, experimental imprecision, etc. Therefore, accuracies are generally much lower than those for verification; agreements to within a few dB are often considered very good.

Figure 9 illustrates validation vis-à-vis experimental data, for the problem of scattering of a plane wave from a solid aluminum cylinder resting on the sediment (Williams et al, 2010). There is very good agreement (to within about 3 dB) over almost the entire range of frequencies and aspect angles. This provides some confidence that the computer simulation is based on the correct physics.

Some Models of Realistic Objects

This article has used simple objects – spheres and cylinders – to explain and illustrate the physics, mathematics and FE concepts for the computer simulation of acoustic scattering from submerged objects. This concluding section shows a variety of images from models of more realistic objects, all of which used the above-described techniques. In addition to these, much more complicated underwater structures have also been modeled, which have included a considerable amount of interior structural detail.

The Way Forward

The current PC-ACOLOR computer simulation system takes one or two days to compute a typical high-fidelity acoustic signature template using a dedicated in-house rack computer with 25 quad-core processors. This pace has been adequate for several years, but the uniqueness of this type of simulation has spawned an interest in using this technology in a more aggressive way: doing massive parametric studies of large varieties of possible real-world target/environment scenarios, in order to create statistically robust acoustic signature libraries. Having such a large data base of signatures will help improve the reliability of sonar systems trying to identify an object, irrespective of small variations in construction or different types of surrounding environments. This will require tens of thousands or even hundreds of thousands of templates. To produce that many in a reasonable time will require computing at least several hundred templates per day, or a computational speed of only a few minutes per template.

R&D at NSWC PCD has just recently achieved such a speed, while preserving all the same 3-D high-fidelity physics in the simulation mathematics! In addition, the radically new system will be ported to a High Performance Computing (HPC) center with several thousand processors so that it is realistic to expect that these high-fidelity simulations will soon be performed at a speed of only a few seconds per template, or thousands of templates per day. The future of this work, and its value to the U. S. Navy mission, looks very exciting indeed.

Acknowledgments

The author extends his sincere appreciation to Drs. Kwang Lee and Gary Sammelmann at NSWC PCD: Kwang for building and executing PC-ACOLOR simulations and Gary for his systems and mathematics support. The Office of Naval Research has sponsored the development of the PC-ACOLOR simulation system since its inception.

Biosketch

Dave Burnett is the U.S. Navy's Senior Technologist for Computational Structural Acoustics. He holds 25 U.S. and international patents in the fields of computational acoustics and electromagnetism and is the author of two books on finite element analysis. Springer/ASA Press recently approved his writing a new book on computational structural acoustics. He is a Fellow of Bell Labs (formerly the R&D division of AT&T) and of the Acoustical Society, an associate editor for JASA, and an editor for the Journal of Computational Acoustics. He holds BS, MS, and PhD degrees from Cornell, Caltech and U. C. Berkeley, respectively.

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Acoustic Cloaking

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It might drive bats batty, but there is no fundamental physical limitation on developing acoustic cloaking devices.

Introduction

An *acoustic cloak* is a shell surrounding an object so that sound incident from any direction passes through and around the cloak, making the cloak and the object acoustically "invisible." We do not experience acoustic cloaking because the materials required are exotic and, as far as we know, not found in nature. Yet there is no fundamental physical restriction on acoustic cloaking. Implementation is a matter of developing *metamaterials* with very unusual properties. Acoustic cloaking is in fact more likely to be achieved before its electromagnetic (EM) counterpart. The reason is that the cloaking material must have structure on sub-wavelength scales. Specific examples will be explained below. Acoustic wavelengths are typically orders of magnitude larger than optical wavelengths, meters vs. microns, which makes the acoustic problem easier, in principle.

This review attempts to explain the physics behind acoustic cloaking. No complicated mathematics is necessary to understand the concept of *transformation acoustics*, which defines the type of metamaterial required. We will see that acoustic cloaking is not an analog of EM cloaking but has unique features. Other cloaking methods based on passive and active *wave cancellation* are discussed. Practical realizations are reviewed. This survey does not discuss some related topics, such as negative dynamic properties. However, comprehensive technical reviews are available: Chen and Chan (2010) provide an early overview; Kadic et al. (2013) review acoustic metamaterials; Fleury and Alù (2013) give a recent review of cloaking and invisibility. Detailed reviews specific to acoustics can be found in (Craster and Guenneau, 2013).

Cloaking is an admittedly fantastic concept, well represented in popular culture (The Invisible Man, Invisible Woman, Harry Potter, etc.) using ingenious "technologies." The Cloaking Field Generator in Star Wars is an example of an active de-

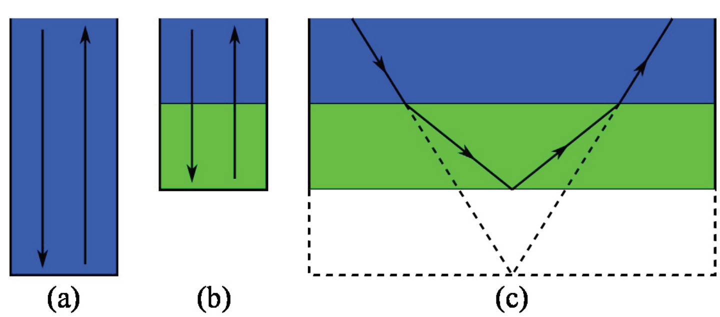


Figure 1. *Some space is made available in (b) by shrinking a region of (a) into the transformed green material. As explained in the text, the original and transformed ray paths in (c) imply that the transformed medium must display acoustic anisotropy. The wave speed in the horizontal direction is unchanged while the vertical speed is lower than the original.*

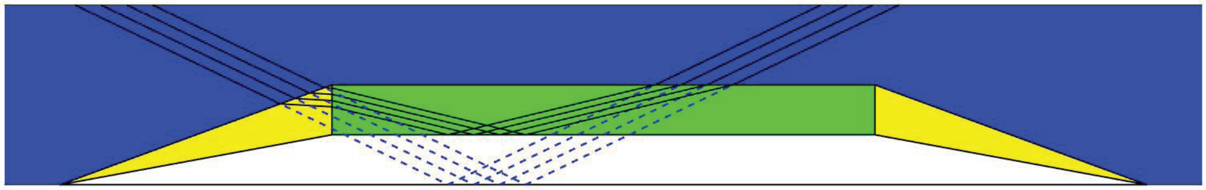


Figure 2. A carpet cloak. The white region is freed up by squashing the entire white+green+yellow region into the green and yellow segments. The green region is a one dimensional compression, as in Figure 1. The transformation in the yellow region depends on both the vertical and horizontal coordinates, resulting in a compression and an extension in orthogonal directions not aligned with the coordinates axes (Craster and Guenneau, 2013, Ch. 7).

vice requiring a power supply (*"They can't have disappeared. No ship that small has a cloaking device."* Lorth Needa). Dr. Who's famous Tardis, which is much larger inside than it appears from the outside, uses "transdimensional engineering" to make the interior and exterior exist in different dimensions (!). Yet, this is not too far removed from the actual basis for passive cloaking devices, described next.

Transformation Acoustics

The trick in passive acoustic cloaking is to somehow shrink the object and cloak from the observer's viewpoint, so that the object appears to be vanishingly small. This geometrical metamorphosis of a large virtual region into a smaller physical one is called *transformation acoustics* (TA). The technical details of TA convert the acoustic wave equation from one coordinate system to another, which can quickly obscure the concepts.

The simple example of acoustic wave reflection in **Figure 1** captures the essence of TA. The incident wave reflects from a fixed boundary at the bottom of the uniform fluid (**Figure 1(a)**). The same response is obtained from a non-uniform acoustic medium (**Figure 1(b)**), if (i) the time taken for the sound to travel back and forth is unchanged, and (ii) there is no reflection except at the bottom of the medium, assumed to be rigid. These conditions clearly constrain the acoustic speed and impedance in the green section. The no-reflection condition is then met if the green slab has the original acoustic impedance. Let f be the fractional ratio of the length of the green fluid to the original, the time constraint is then satisfied if the green index of refraction is $1/f$. The relative density and compressibility are therefore both $1/f > 1$. The lesson of this simple mirage (Norris, 2009) is that the transformed acoustic parameters depend upon the *geometrical* quantity f. One can already gain some appreciation for the difficulties in the full cloaking problem. In order to achieve a sizable effect the value of f must be significantly different from unity. A fluid of much greater density and compressibility is necessary to "squeeze" the original fluid into a much smaller space ($f \ll 1$), freeing up a relatively large amount of space. Extreme phenomena require extreme physical properties.

Acoustic anisotropy distinguishes cloaking from everyday acoustics. Consider the mirage in two dimensions, (**Figure 1(c)**). The index of refraction determined above implies a travel time for the transmitted ray (solid line) different from the original (dashed line). The only resolution is to allow for directional wave speed dependence, also known as anisotropy. For a wave incident near glancing the travel time condition requires that the green wave speed is the same as the original, hence the horizontal index of refraction is unity as compared to $1/f$ for normal incidence. A full analysis shows that the index of refraction (i.e. slowness) in any other direction describes an ellipse with major and minor axes corresponding to the normal and glancing incidence values.

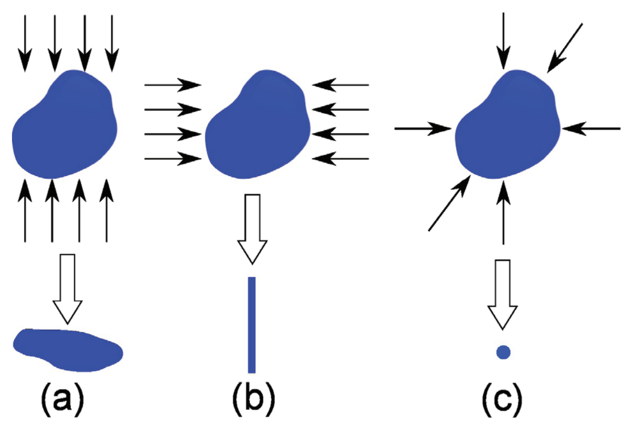


Figure 3. (a) The cloaked region is flattened by a one dimensional-like mapping. (b) The cloaked region has the scattering cross-section of a thin cylinder. (c) A fully 3D transformation; the cloaked region scatters like a point.

Transformation in more than one dimension (1D) follows the same principle of squeezing a virtual region into a smaller physical volume. The *carpet cloak* (aka ground-plane cloak) (**Figure 2**) frees up a finite volume. The anisotropy in the green part is like that of **Figure 1**, with faster vertical wave speed and unchanged horizontal speed. In the yellow section the principle axes for the wave speeds are rotated from the vertical and horizontal, one faster and the other slower than the background speed. The difference in properties is evident from the ray paths (**Figure 2**). Each ray is the transformation of the straight rays in the virtual region, the dotted lines in **Figure 2**. As long as the bottom surface of the carpet cloak is the same as the virtual region, the net effect of the carpet cloak is to make the cloaked region appear to be infinitely thin. The general carpet cloak transformation (**Figure 3 (a)**), is suitable for hiding in "plain sight" against a flat surface. But in the absence of a flat boundary to provide camouflage, TA must reduce the combined cloak and the cloaked region into an infinitesimally small scatterer with zero scattering cross-section.

Cloaking in free space requires a vanishing target strength; the virtual image of the cloaked region must shrink to a point (**Figures 3 (a), (c)**). As in the 1D case, the TA mapping is not unique. **Figure 4** shows an example where the outer surface of the cloak is an oblate spheroid, while the cloaked region is a prolate ellipsoid (egg shaped) (Norris, 2008). Some of the transformed region must be rotated in addition to stretching/compression as in the examples of **Figures 1 and 2**. The rays shown for horizontal wave incidence are the transformed versions of straight lines in the virtual domain. The rays around the central cloaked region, which is the image of a point in the virtual domain, must have infinite wave speed. Conversely, the wave speed perpendicular to the inner boundary is zero, which explains the sharp curvature of the rays near the "stagnation" point. Thes extreme effects, infinite speed, infinite slowness and ray bifurcation, are a consequence of the fact that the transformation is much more severe than in **Figures 1 and 2**. In **Figure 1** the virtual region $0 < x < 1$ transforms to the physical one $1-f < x' < 1$. Consider a simple linear mapping, $x' = 1-f + f\,x$. The analogous mapping in 2 or 3-dimensions is $r' = 1-f + f\,r$ where $0 < r < 1$ and $1-f < r' < 1$ define the virtual and physical radii. Volume elements transform as $dV' = \left(\frac{r'}{r}\right)^{d-1} f\, dV$ where $d = 2$ or 3 is the dimension (Norris, 2008). The singularity as $r \to 0$ reflects the fact that a finite area or volume is compressed to a point, leading to infinite values of speed and slowness. These are clearly unattainable implying that the perfect cloak is impossible in 2 and 3 dimensions, the best one can achieve is a "near cloak" in which the cloaked region is the image of a small but finite area/volume.

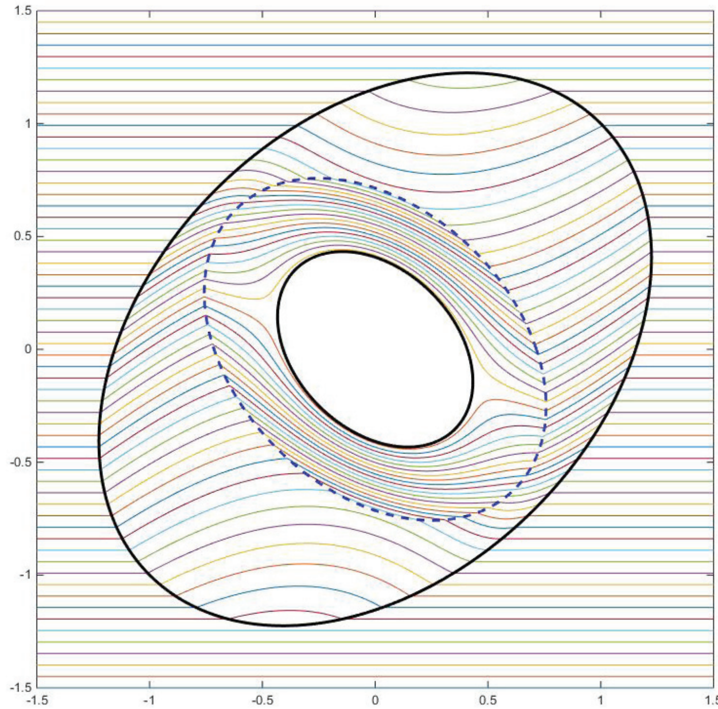


Figure 4. *Ray paths through a non-radially symmetric cloak. The solid curves are the inner and outer surface of the cloak.*

The original motivation for TA and acoustic cloaking came from the remarkable observation of Pendry et al. (2006) that singular transformations provide cloaking of EM waves. However, in a sense TA preceded cloaking, because the idea of mapping the acoustic wave equation has been used for decades in simplifying numerical problems. One application is the surface flattening transformation for rough surface scattering (Beilis and Tappert, 1979); by mapping the rough surface to a flat one the numerical geometry becomes simpler to mesh, at the expense of an inhomogeneous wave equation and more complicated boundary conditions.

Anisotropic Density or Stiffness?

How can acoustic anisotropy be achieved in practice? It is not observed in natural acoustic fluids where wave propagation depends on density ρ and compressibility C. At least one more parameter is required; this could be introduced by allowing density or compressibility to be tensors (i.e., matrices). Tensorial density means that the force per unit volume $\rho\mathbf{a}$ is not necessarily aligned with particle acceleration $\mathbf{a}$. This is not ruled out on fundamental grounds and in fact a physical mechanism for anisotropic inertia exists. Schoenberg and Sen (1983) showed that the inertia tensor in a layered fluid is transversely isotropic with elements $<\rho>$ normal to the layering, and $1/<\rho^{-1}>$ in the transverse direction, where $<\cdot>$ is the spatial average. Anisotropic effective density can arise from other sub-wavelength microstructures, such as arrays of rigid cylinders in water (Torrent and Sánchez-Dehesa, 2008b). The anisotropic wave speed follows from the force balance $\rho\dot{\mathbf{v}} = -\boldsymbol{\nabla} p$ and the pressure relation $C\dot{p} = -\boldsymbol{\nabla}.\mathbf{v}$ Eliminating particle velocity v yields the wave equation $\boldsymbol{\nabla}.(\rho^{-1}\boldsymbol{\nabla} p) - C\ddot{p} = 0$ which is anisotropic by virtue of the tensor ρ^{-1}.

The first papers on acoustic cloaking assumed anisotropic mass density. Cummer and Schurig (2007) noted the analogy between the EM wave equation with anisotropic permittivity and the acoustic equation with a density tensor to describe a 2D cylindrically symmetric cloak. Chen and Chan (2007) proposed a spherically symmetric cloak with anisotropic density. Most subsequent acoustic cloaking literature is based on anisotropic inertia, what we call *inertial cloaking (IC)*. Particular realization of ICs are in principle feasible using layers of isotropic fluid (Torrent and Sánchez-Dehesa, 2008a), a strategy which has proved very successful in realizing carpet cloaks, as discussed below. However, fully enveloping cloaks require extreme anisotropy near the inner boundary that can only be achieved by alternating layers of fluids with extremely small and large densities. At the same time, the compressibility must be such that the homogenized value is that of TA. The cylindrical or spherical layered cloak does not seem to be possible with existing fluids. Models such as (Torrent and Sánchez-Dehesa, 2008a) require hundreds of fluids with different properties, some with very large compressibility and density. One possible solution is to take advantage of the non-uniqueness of TA and find the best possible transformation for a given set of fluids (e.g. 2 or 3 (Norris and Nagy, 2010)) but this also requires that the constituents have widely disparate properties not found in available materials.

Another possibility exists: anisotropic wave speeds can be achieved with anisotropic bulk modulus rather than density. It turns out that TA is fundamentally different from its EM counterpart where the transformation uniquely defines the EM material and, for instance, the tensors of electric permittivity and magnetic permeability display the same level of anisotropy for a transformation of the vacuum. In acoustics, by contrast, there is a wide range in material properties that can yield a given transformation. The non-uniqueness comes from the freedom to introduce an arbitrary positive definite symmetric divergence free matrix *S* into TA (Norris, 2008; Norris and Shuvalov, 2011). The inertial cloak corresponds to *S*=*I*, the identity, which partly explains why this degree of freedom in TA had not been noticed earlier. Any other choice of *S* leads to anisotropic stiffness in the sense of elasticity, however it is a special type of elastic material known

Acoustic cloaking is more achievable than its optical counterpart because of the much larger wavelengths involved.

as a *pentamode material* (PM). An elastic solid is characterized by six modes of deformation, a PM is the limiting case where five of the six are "soft" modes (Milton and Cherkaev, 1995) with one stiff mode. PMs generalize the property of an acoustic fluid that it can shear without effort but resists hydrostatic compression with a stress $-pI$, where ρ is acoustic pressure. The PM stress is proportional to *S*.

Pentamode cloaks have, in principle, distinct advantages over ICs. For instance, cylindrical or spherical cloaks with isotropic density are possible, in which case the total cloak mass is simply the mass of the original, virtual region (Norris, 2009). In contrast, the mass of a perfect IC becomes unbounded (Norris, 2008). The PM in the cloak must still have continuously varying properties defined by TA. Scandrett et al. (2010) examined the effect of piecewise layering in a spherical cloak, and found that an optimized three layer PM cloak provides better target strength reduction than a 3-layer IC. The best performance was found by combining both properties in a PMIC cloak. Scandrett and Vieira (2013) showed that the dominant scattering from heavily fluid loaded thin shells in the mid- and high-frequency regimes can be essentially eliminated by PM cloaking.

The current limitation on PM cloaking is fabrication. Solid materials with five soft modes and one stiff mode with desired stress state *S* can be achieved with periodic foam-like networks in which the microstructure lattice members only support axial forces. In practice, this means thin members that are flexible in bending but stiff in compression. Fabrication of such microstructured lattices is possible using rapid prototyping and related technologies; for instance Bückmann et al. (2014) designed and fabricated a PM "unfeelability" cloak, essentially a static cloak for elastic fields. The difficulty as far as cloaking sound in water is concerned is to achieve just the right properties. In order to get density and stiffness values similar to those of water using thin lattice members of low volume fraction the structural material must be very dense and stiff relative to water. Metals provide the appropriate reservoir of density and stiffness. The first realization of a metal-based microstructure with 2D PM behavior close to water, called "metal water" (Norris and Nagy, 2011), was an Aluminum lattice with hexagonal unit cells. The metal lattice model has also been studied by Layman et al. (2013) who simulated a slab of PM designed to provide a 2D acoustic illusion of **Figure 1**.

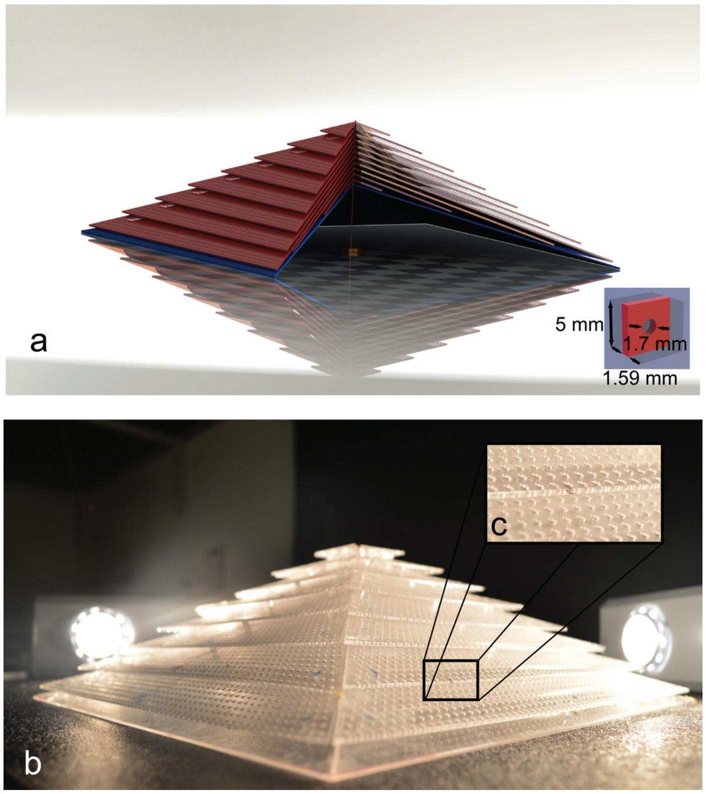


__Figure 5.__ The pyramidal acoustic carpet cloak of Zigoneanu et al. (2014). Reprinted with permission.

Design and Realization of TA Devices

We follow the progression of **Figure 3**, starting with carpet cloaking. Popa et al. (2011) demonstrated the first acoustic carpet cloak in air using a 2D inertial design. Anisotropic density was realized with thin, heavy (relative to air) plates perforated to allow the air to permeate the plates stacked with air gaps between them, giving a mass density ratio of about 5 to 1 in orthogonal directions. Scanned microphone measurements showed good cloaking for incident waves of center frequency 3 kHz with a 3 dB bandwidth of 1 kHz. The broadband nature of the device can be ascribed to the long wavelength, 10 cm at 3 kHz in air, compared with the lattice constant for the perforations (5 mm) and the plate spacing, yielding good effective medium properties.

Zigoneanu et al. (2014) fabricated a fully 3-dimensional omnidirectional carpet cloak based on the same design principles. A pyramidal structure (**Figure 5**) rendered a region of space three wavelengths in diameter invisible to sound. Experiments were performed using a Gaussian pulse of 600µs half-amplitude duration modulated with a 3 kHz sinusoid. The measured response is shown in **Figure 6.**

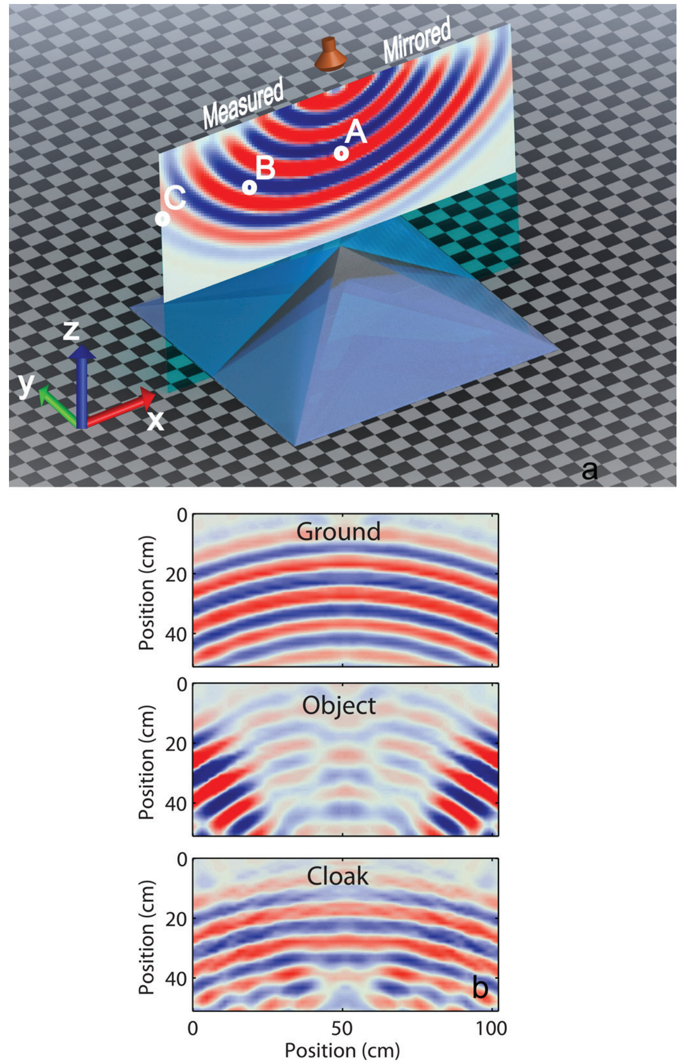


__Figure 6.__ (a) The setup for the 3D carpet cloak of Figure 5. (b) Measured reflected pressure fields for three cases: ground only, object, object+cloak. Reprinted from (Zigoneanu et al., 2014) with permission. (Movie version https://www.youtube.com/watch?v=k13L8u2tACY)

Kan et al. (2013) presented an experimental demonstration of an acoustic cloak designed to hide an object in a corner. The device used thin slabs in air separated to provide a mass anisotropy ratio greater than 6 at 1700 Hz operating frequency. This design could, in principle, be adapted to manipulate the acoustic field near boundaries of arbitrary curved geometry.

Zhang et al. (2011) gave the first demonstration of cylindrical cloaking in water at ultrasonic frequencies. The design is unique in that it uses a 2-dimensional network of 1D channels in the radial and circumferential directions, where each channel is an acoustic circuit of TA-defined lumped parameters.

Passive Cancellation and Directional Cloaking

More "traditional" techniques have been proposed using passive sound cancellation. The idea is to coat an object with a layer that eliminates the scattered sound. In the long wavelength, low frequency limit, this can be achieved by eliminating the monopole and dipole scattered terms, which amounts to making the cloak plus the target have effective density and compressibility of water (Zhou and Hu, 2007; Guild et al., 2011) so the scatterer behaves as a "neutral acoustic inclusion." Omnidirectional cancellation can be achieved at finite frequencies using optimization methods to determine the coating properties (Guild et al., 2011). Martin and Orris (2012) proposed a hybrid design combining TA with scattering cancellation and showed that it outperforms both a cancellation layer and a discretized TA design over a broad frequency range in cloaking an Aluminium cylinder in water.

Guild et al. (2014) used the fact that cancellation eliminates the scattering in the exterior fluid without removing the field inside the object, to consider non-scattering sensors. This would enable the sensor to detect sound without disrupting the acoustic field. Simulations of a scattering cancellation cloak made of two fluid layers surrounding a piezoelectric sensor showed a 20-to-50 dB scattering strength reduction compared to the uncloaked sensor over the typical frequency range of operation.

Directional cloaking (as opposed to omnidirectional) can be achieved for specific directions of incidence using simpler cancellation designs. Thus, García-Chocano et al. (2011) demonstrated a 2D narrow band cloak in air comprising 120 aluminum cylinders of 1.5 cm diameter surrounding the cloaked cylinder of diameter 22.5 cm. The 120 positions were determined by optimization at an operating frequency of 3061 Hz, yielding good cloaking over a bandwidth of 100 Hz. Sanchis et al. (2013) used the same design strategy to experimentally characterize a 3D acoustic cloak in air that significantly reduces scattering for a unique incidence direction. The cloak consists of 60 tori made by 3D printing, arranged concentrically around the 4 cm radius cloaked sphere. Measurements show an approximately ten-fold scattering reduction at operating frequency 8600 Hz with a bandwidth of 200 Hz.

Urzhumov et al. (2012) proposed a uni-directional cloak comprising a spherical shell of isotropic (i.e. normal) acoustic material. The cloak, designed to operate in transmission mode, uses a conformal mapping (the only case of TA that does not require anisotropy) to yield an *eikonal cloak*, a cloak which partially preserves the ray structure of TA in the desired direction but without the necessary impedance. Conversely, Hu et al. (2013) designed and tested a 2D unidirectional cloak that specifically reduces backscattering by surrounding an object with layers of perforated plates that make the target appear narrow in reflection. Measurements show at least 20 dB reduction in sound pressure level near the backscatter direction over a frequency range 1500 to 2200 Hz.

Cloaking of Elastic and Other Waves

Elastic waves present a greater challenge for cloaking because of the two wave types as compared with one in acoustics. Theoretical analyses (Brun et al., 2009; Norris and Shuvalov, 2011) show that even more exotic material properties are required for TA in the presence of waves with transverse and longitudinal polarization. The cloak material must display significant stress asymmetry, which is not found in natural solids and difficult to achieve with microstructure. Asymmetric stress is a feature of small-on-large elasticity, the type of linear elasticity found in hyperelastic solids after large static strain, offering one possible cloaking mechanism (Norris and Parnell, 2012).

One area of elastic waves has seen practical cloaking: flexural (or bending) waves in thin plates are polarized in a single direction (normal to the plate) and satisfy a Helmholtz-like equation similar to acoustics. Stenger et al. (2012) adapted the TA design proposed by Farhat et al. (2009) to make a flexural wave cloak comprising 20 concentric rings of PVC and PDMS machined into a 1 mm thin PVC plate. The cloak was demonstrated at acoustic frequencies (**Figure 7**). This device exhibits the largest measured relative bandwidth (more than one octave) of reported free-space acoustic cloaks.

Cloaking has been demonstrated for gravity waves in water (Farhat et al., 2008) which satisfy a wave equation amenable to TA. Modifications of acoustic cloak design to include convective effects for moving objects and cloaks was considered by Huang et al. (2014). Thermal effects have even been proposed for 2D acoustic cloaking in air. García-Chocano et al. (2012) simulated cylindrically layered anisotropic density by controlled heating or cooling of cylinders. Numerical results showed reduced acoustic backscatter in certain frequency bands using this exotic mechanism.

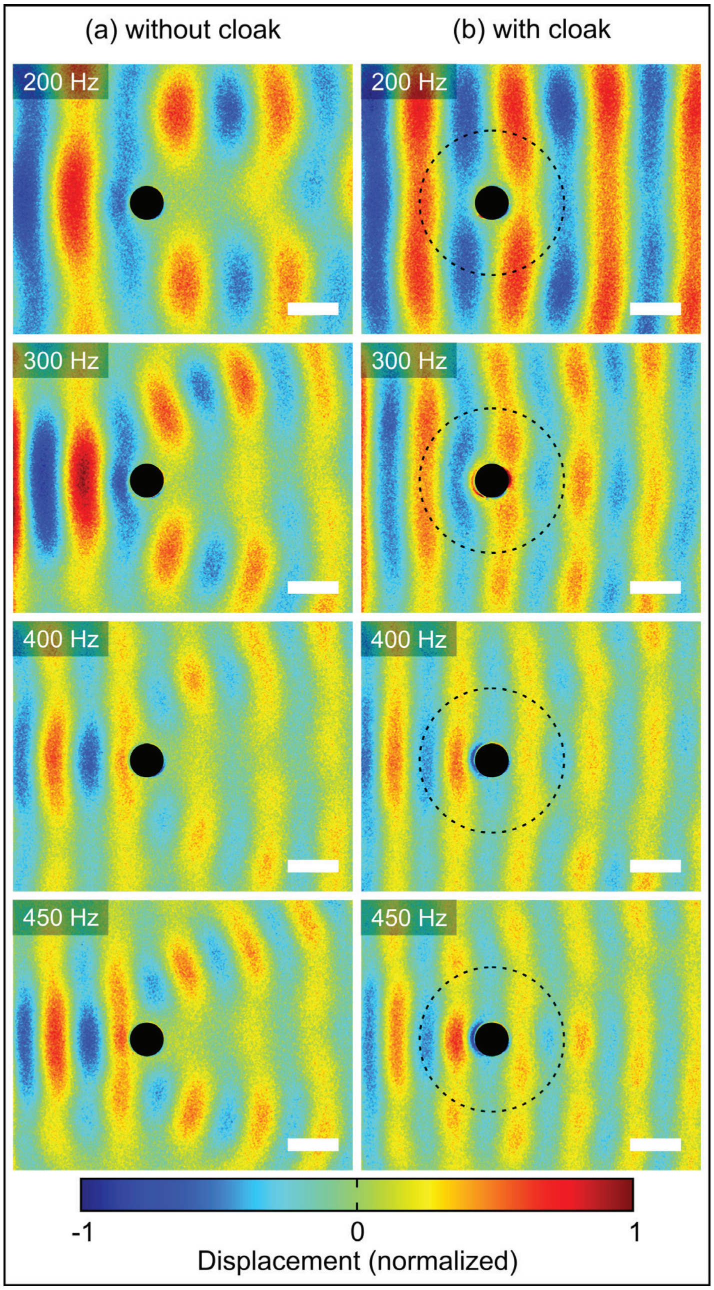


Figure 7. *Cloaking of flexural waves. The black cloaked region of di-ameter 3 cm is clamped, the dashed lines depict the outer bound-ary of the cloak. Reprinted from (Stenger et al., 2012) with permis-sion. This movie shows experimental results at 200 Hz.* (To view movie please visit *http://wp.me/p4zu0b-MY*)

Cloaking of seismic waves has obvious potential but is es-sentially a pipe dream, the wavelengths are so long that any structure providing significant cloaking effect would be huge. Nevertheless, several ideas have been floated for cloak-like effects. Kim and Das (2013) proposed attenuating seis-mic energy using large buried "meta-boxes" with resonance frequencies of the seismic waves. Simulations with boxes of volume ≈ 100 m^2 show significant attenuation at 10 Hz. Brûlé et al. (2014) proposed a phononic crystal design to reflect geophysical surface noise such as pile drivers. Large scale tests were made on a periodic 2D mesh of cylindrical empty boreholes of 0.32 m diameter drilled 5 m into the top soil layer, with a lattice constant of 1.73 m. The configuration was designed to have a bandgap at the operating frequency of 50 Hz. Measurements showed greater than 50% decrease in surface wave amplitude for transmitted waves.

Cloaking by Active Cancellation

The methods discussed so far are passive, reliant on material properties for cloaking. *Active cloaking*, on the other hand, uses sound sources to cancel the incident wave. It is closely related to active noise control and *anti-sound* which creates a zone of silence, although unlike cloaking, the sound is gen-erally not required to be non-radiating. Recent theoretical work on active acoustic cloaking provides insight into the older problem of active sound control.

Miller (2006) proposed cloaking a region by sensing sound on a closed surface while simultaneously exciting sources with amplitudes defined by the measurements. The method relies on the Kirchhoff-Helmholtz integral (Nelson and El-liott, 1992) whereby a continuous distribution of monopoles and dipoles completely suppresses sound. The difficulty with this approach is realizing acoustically transparent sen-sor and actuator surfaces, replacing the surfaces by a finite number of discrete sensors and sources is preferable. A solu-tion to this problem was provided by Guevara Vasquez et al. (2011) who showed, remarkably, that cloaking requires as few as three active sources in 2D and four in 3D. Norris et al. (2012) subsequently found explicit formulas for the source amplitudes. The catch with this approach is that the sources are multipoles, and full cloaking requires multipoles of all order. Point multipoles are not possible in practice, neither are monopoles or dipoles for that matter. Furthermore, the multipole expansion is divergent, a point noted earlier in an-ti-sound research (Nelson and Elliott, 1992, pp. 262-4). This motivates truncating the series, limiting accuracy, although numerical simulations indicate that only a small number of multipoles may be required. Despite these difficulties, Gue-vara Vasquez et al. (2011) provide a rigorous basis for sub-sequent approximation. Other approaches to active cloaking have been suggested; for instance, Bobrovnitskii (2010) pro-posed acoustic cloaking using a non-local impedance coat-ing extended reaction.

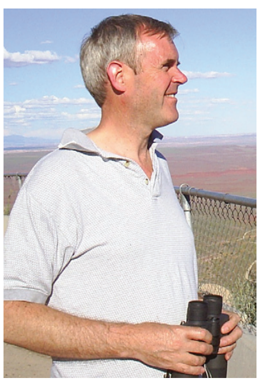
Conclusion

Cloaking of sound, first proposed only seven years ago, has been shown to be feasible with practical demonstrations appearing regularly and more frequently. How will this emerging acoustic technology impact society? We can expect applications in improved noise reduction, sound absorbtion, architectural acoustics, and envornmental acoustics, not to mention defense interest in underwater sound control.

Acknowledgment

Thanks to Adam Nagy and Xiaoshi Su for discussions and graphical assistance. This work was supported by ONR MURI Grant No. N000141310631.

Biosketch



Andrew Norris received the BSc and MSc in Mathematical Physics from University College Dublin, and the PhD from Northwestern University in 1981. Following a postdoc at Exxon Research and Engineering Corporate Laboratories he joined Rutgers University where he is now Professor of Mechanical and Aerospace Engineering. He has worked on geophysical, structural and ultrasonic NDE wave problems. His current interests are in metamaterials that exhibit extraordinary wave bearing properties. He is editor of Wave Motion, an Associate Editor of JASA and a Fellow of the ASA. In his off time he enjoys reading, running and the great outdoors.

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TECHNICAL COMMITTEE REPORT

Acoustical Oceanography

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The Technical Committee (TC) on Acoustical Oceanography (TCAO) was founded in 1991 and is made up of scientists and engineers interested the development and use of acoustical techniques to understand the physical, biological, geological, and chemical parameters and processes that occur in the ocean, broadly described here as "oceanography." This requires a fundamental knowledge of the physics of the generation, scattering, and propagation of sound in a spatially and temporally complex and dynamic ocean. Combining this fundamental understanding with knowledge of the underlying oceanography, allows relevant parameters to be remotely inferred at scales often unachievable by more traditional oceanographic sampling techniques.

There is strong overlap in the areas of interest to the TCAO and the TCs on Underwater Acoustics (TCUW) and Animal Bioacoustics (TCAB). This overlap is highlighted in a recent *Acoustics Today* article on the effects of climate change on acoustical oceanography, animal bioacoustics, and underwater sound (Kloepper and Simmons, 2014). There is also significant overlap with the TCs on Signal Processing, Physical Acoustics, Atmospheric Acoustics, and Biomedical Acoustics, as is evidenced by the number of co-sponsored special sessions at ASA meetings. As with many areas of acoustics, the majority of researchers in acoustical oceanography have not received formal training in acoustics, but instead, "ended up" in the field with backgrounds rooted in a broad array of disciplines. The highly interdisciplinary nature of the research is considered one of the primary strengths and distinguishing characteristics of the TCAO.

An area of research in the TCAO that has received sustained attention is the area of geoacoustic inversion, an area of research with particular synergy with the TCUW. The general approach is to estimate geoacoustic parameters by comparing modeled predictions with measurements, such as transmission loss. In general, the ability to predict transmission loss, particularly in shallow waters typical of continental shelves, is severely constrained by the lack of knowledge of the geoacoustic properties of the bottom, such as sediment layer thicknesses, sound-speed profiles, etc. Since the inception of the TCAO, significant progress has been made in the development of active and passive inversion methods for seabed characterization that complement and extend the capabilities of conventional techniques such as seismic reflection imaging and coring. In 2014 alone, at least ten papers involving different aspects of geoacoustic inversion have been published in the *Journal of the Acoustical Society of America* and *Express Letters*, including papers on the continued development of "passive" geoacoustic inversion methods that exploit ambient ocean noise (Yardim et al., 2014).

Though there is heavy overlap with other TCs in some areas, there are certain areas of research that are almost exclusively studied by members of the TCAO, such as seismic oceanography. The prestigious Munk Award, granted for significant original contributions to the understanding of physical processes related to sound in the sea, was awarded in 2013 to Steven Holbrook, who was honored as the father of seismic oceanography. In one of the seminal seismic oceanography papers, Holbrook et al. (2003) determined that a technique routinely used to image the solid earth beneath the ocean, seismic reflection profiling, could also provide details of thermohaline fine structure within the ocean, at horizontal scales of tens to hundreds of kilometers and at full ocean depth. This was exciting to physical oceanographers as acoustic imaging allowed the dynamics and evolution of thermohaline fine structure to be investigated at unprecedented resolution (Ruddick, 2003). Since then, seismic reflection profiling has been applied to investigate many physical oceanographic processes such as internal tides, internal waves, and fronts.

Ambient noise in the ocean is another archetypal research topic that continues to receive significant attention in the TCAO. Ocean ambient noise is comprised of both natural and anthropogenic sources, and its characteristics are influenced by the strongly frequency-dependent nature of absorption in the ocean, as well as the propagation physics of the natural ocean environment (Hildebrand, 2009). Natural sources of noise in the ocean include wind-driven surface waves, sea ice, rainfall, bubbles, biological sources (marine mammals, fish, snapping shrimp, etc.). For example, there is evidence that the disintegration of Antarctic icebergs results in seasonal increases in ocean noise levels in mid-to-equatorial latitudes (Matsumoto et al., 2014). Ambient noise in the ocean has also been used for often clever and diverse remote sensing and imaging purposes, coined "ambient noise oceanography." A recent example includes the use of seismic ambient noise to obtain high resolution tomographic maps of ocean surface waves (Sabra et al., 2005).

Much of the recent attention, however, has focused on anthropogenic sources of sound, including sonars, seismic exploration, shipping traffic, and construction, such as noise generated by wind farms and pile driving. Noise due to shipping traffic alone is thought to have increased almost 12 dB over the past few decades (Hildebrand, 2009). Some regions are particularly susceptible to increases in anthropogenic ambient noise, such as the Arctic. It is expected that the reduction in sea ice cover will lead to increases in oil exploration and shipping traffic, resulting in increases in anthropogenic ambient noise. An important motivation for understanding the steady (Ross 2011) and pervasive increase in anthropogenic ambient noise stems from the generally deleterious consequences to marine animals. Understanding the background "din" these animals experience is an active area of research. Describing the health of marine ecosystems in terms of their soundscape is a current hot topic, with significant overlap with research performed in the TCAB. Papers are emerging on "soundscape ecology" (Staaterman et al., 2014), with particular attention given to reef habitats as model systems, though there is still no convergence on a formal definition of the term with consensus amongst the various TCs.

Herman Medwin, past President of ASA, first chair of the AOTC, and founder of the ASA Medwin Prize in Acoustical Oceanography, has been recognized in large part for his work on bubbles in the ocean. His work includes some of the first backscattering, attenuation, and dispersion measurements of microbubbles in the laboratory and ocean, experimental attribution to the Knudsen sea noise spectrum to bubbles produced by breaking waves, understanding bubble noise produced by rainfall, and the development of methods for measuring the vertical distribution and sizes of bubbles close to the sea surface. One could argue that Medwin didn't leave a lot of stones unturned when it comes to understanding the role of bubbles in the ocean, and yet this continues to be an area of active research within the TCAO. Bubbles near the sea surface impact such critical issues such as air-sea gas exchange, affect ambient noise generated by breaking waves, modify acoustic scattering from the surface of the sea, and can have significant impact on the performance of acoustic communications systems (Deane et al., 2013).

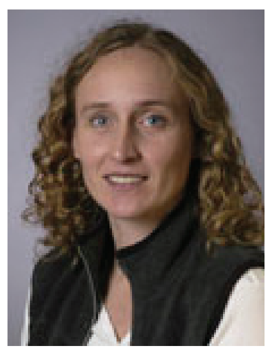
One important recent development in "bubble acoustical oceanography" is the possibility of quantifying the flux of methane from gas seeps on the seafloor to the atmosphere and dissolved into the ocean (Weber et al., 2014), thus potentially affecting ocean acidification and the global carbon cycle. In fact, acoustic techniques may play a potentially critical role in mapping natural methane seeps. For example, Skarke et al. (2014) have recently used multibeam mapping to identify extensive methane gas seeps along the US Atlantic margin, a region not generally considered for widespread seepage. To extend this work from imaging to quantification of gas bubble size distribution it will be necessary to understand the role of hydrate coating and significant deviations from spherical bubbles.

Other areas of research that fall into the TCAO purview include the use of active acoustic scattering and propagation techniques for the remote quantification of marine organisms (Medwin and Clay, 1998; Simmonds and MacLennan, 2005). Fisheries acoustics research is particularly active, with multiple special sessions dedicated to this topic over the last decade or so. One of the goals of fisheries acoustics is to assist in making wise fisheries management decisions for the sustainable exploitation of this natural resource. Traditional fisheries acoustics approaches for quantifying fish biomass and abundance involve the use of single frequency sonars typically at frequencies much higher than the resonance frequency associated to the swim bladder. Recent progress in developing sea-worthy broadband sonar techniques (Stanton et al., 2010) has opened to the door to improved quantification of fish by allowing the swim bladder resonance to be mapped. In fact, Holliday (1972) used broadband explosive acoustic sources in 1972 to very successfully map the spectral returns of various pelagic fish schools and compared the measured spectra to predictions based on rigorous acoustic approaches. However, there are significant modern headaches associated to obtaining permits for use of explosive sources! Fisheries acoustics worldwide has generally been very receptive to advances in acoustics techniques and in adopting such technologies into fisheries management decisions.

Other acoustical approaches to quantifying fish include resonance absorption spectroscopy and the use of ocean waveguide acoustics for synoptic imaging, which takes advantage of the waveguide generated by trapping sound between the air-sea and ocean-seabed boundaries (Makris et al., 2006). In fact, marine ecosystem acoustics, involving the use of acoustic techniques for quantifying and monitoring entire marine ecosystems at the spatio-temporal scales on which they occur (Godo et al., 2014), is currently a growing area of research. It is anticipated that ecosystem acoustics approaches will be one of the principal tools in operational Ecosystem Based Integrated Management. The success of this approach is yet to be determined, but depends on cooperation between fisheries acoustics, physics, engineering, biology, oceanography, and ecology. This is precisely the type of interdisciplinary science that the TCAO thrives on. An entire upcoming ICES symposium (May 2015), co-sponsored by ASA, will focus on marine ecosystem acoustics.

Although the TCAO is one of the smaller technical committees within ASA, its primary strength lies in the highly interdisciplinary nature and impressive scope of the research performed by its members. A glance at recent recipients of the Lindsay Award, A.B. Wood Medal, and the Medwin Prize, reveals that the TCAO is home to a talented, rigorous, and gritty cohort of young scientists sustaining multifaceted careers, despite a particularly challenging funding environment, and simultaneously advancing research in acoustical oceanography by building on a legacy of excellence in research developed by the founding members of the TCAO. As current chair of the TCAO, it has been my pleasure to see the level of involvement of these younger scientists in the affairs of the ASA, and their commitment to performing outstanding research in acoustical oceanography, the best possible approach to maintaining the TCAO healthy and vibrant.

Biosketch



Andone C. Lavery received the B.A. degree in mathematics from Cambridge University, U.K., in 1991 and a Ph.D. degree in physics from Cornell University in 1999. She was a Postdoctoral Scholar/Fellow from 1999 to 2002, and was hired onto the scientific staff in 2002, at the Woods Hole Oceanographic Institution. Her research interests include acoustic scattering and propagation in discrete and continuous random media, with a focus on marine organisms and small scale fluid processes. Dr. Lavery is a member of ASA, current chair of the Acoustical Oceanography Technical Committee, and associate editor for JASA-EL.

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Noisy Planet and ASA: Partnering to Help Youth Develop Healthy Hearing Habits

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The science of sound and the science of hearing go hand in hand (or is that ear in ear?). No matter which aspect of acoustics—musical, architectural, physical, underwater to name a few you are fascinated by—it is the ability to hear and enjoy sounds that enhances the human experience and our quality of life. That is why the National Institute on Deafness and Other Communication Disorders' *It's a Noisy Planet. Protect Their Hearing®* is proud to be collaborating with the Acoustical Society of America to encourage youth to develop healthy hearing habits and prevent noise-induced hearing loss.

For millions of people, the ability to appreciate the acoustics of an amphitheater or hear the voice of a loved one is made more difficult because they have hearing loss. Some of these people have noise-induced hearing loss, the only form of hearing loss that is completely preventable. Nearly 26 million American, ages 20 – 69, have high frequency hearing loss due to exposure to loud noises, either at work or during leisure activities.

In June 2008, the NIDCD launched the Noisy Planet campaign, a national education program to increase awareness among children, ages 8 to 12, about the causes and prevention of noise-induced hearing loss (NIHL). With this information, parents, health professionals, educators, and other adults help children (and themselves) protect their hearing by encouraging them to adopt healthy hearing habits. These healthy habits include three simple steps:

- Lower the volume. Set the volume on electronic devices to a level that allows you to still hear what's going on around you.
- Move away. Put some distance between you and the noise source to reduce the impact on your ears.
- Wear hearing protectors. Have earplugs or earmuffs on hand, and use them if you can't leave a noisy place.

Noisy Planet has been reaching the campaign's target audiences through several outreach efforts, most notably through partnerships with organizations like ASA.

As one of Noisy Planet's longest collaborators, ASA has been instrumental in helping expand the campaign's hearing loss prevention messages. Working with ASA is a natural fit, given the Society's involvement in the study of noise, its measurement, its effects, and ways to reduce noise to improve the human environment. In addition to linking to each other's website, Noisy Planet has presented to ASA's Education Committee and introduced them to Noisy Planet's science-based information on hearing loss prevention. Recently, Noisy Planet encouraged youth and their parents to visit ASA's Listen to Sounds and Explore Sounds websites to enjoy interesting animal noises while learning more about the science of acoustics. Through these activities, Noisy Planet hopes that youth will begin to engage with and understand the science of acoustics and noise, and start taking the steps necessary to protect their hearing.

Another key activity to reach preteens with healthy hearing messages is through outreach to schools. Noisy Planet staff have been providing 45-minute, interactive presentations to students in grades 3-8 in the greater Washington, D.C. area. Since June 2010, Noisy Planet staff have reached more than 12,500.

Noisy Planet is in the process of developing a training guide that will allow other interested adults, whether they are educators, health professionals, or acoustics experts, to give the presentation and expand the reach of this engaging activity to more youth across the country. Stay tuned for future announcements on how you can get involved in helping youth learn about the science of hearing and how to develop healthy hearing habits.

As an ASA member, Noisy Planet encourages you to visit the website at www.noisyplanet.nidcd.nih.gov. The website includes a range of materials from free fact sheets to shareable images and Web banners and interactive quizzes and games for preteens. Please feel free to link to our website, share our images and graphics, and sign up for the Noisy Planet E-bulletin, which provides regular updates on partner activities, new publications and materials, and other activities. If you have an opportunity to work with preteens and parents, Noisy Planet encourages you to contact us for free materials at NPInfo@nidcd.nih.gov or 800-241-1044. And we welcome any and all feedback on our materials and how we can work with ASA and its membership to amplify our healthy hearing habit messages!

Student Activities at the ASA Indianapolis Meeting

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The 168th meeting of the ASA featured many wonderful student activities. About 60 students came to the Student Orientation Session, half of whom were attending their first Society meeting. Monday's Meet and Greet attracted more than 130 students. Wednesday's Social was equally successful, and we would like to thank the NCAC for helping to make the event possible!

A special poster session on graduate programs in acoustics was held Wednesday morning and was very well attended. A total of 17 departments gave presentations and well over 100 undergraduates, graduate students, and other members stopped by to learn about the great acoustics research going on at these universities.

Student and Young Presenter Paper Awards will be given out to members of the AO, AB, AA, BA, EA, MU, NS, SP, SC, SA, and UW Technical Committees for their papers presented at the Indianapolis meeting. More information can be found at the ASA student website, http://asastudentcouncil.org. *Congratulations to the winners!*

At the Providence meeting, the Student Council began giving out stickers to attendees that are color coordinated to each TC, so if they see somebody with their same color, they know they can start a discussion about their TC. This has been a great icebreaker and was continued at the Indianapolis meeting. We plan to continue the tradition at future meetings, so look out for your TC's sticker color and feel free to stop by to see your student council representative to get a sticker!

The Student Council Mentoring Award will be presented at the Pittsburgh meeting. The Mentoring Award has been given out by the Student Council since 2004 to recognize a person who has demonstrated exceptional ability in guiding the academic and/or professional growth of her/his students and junior colleagues. More information can be found at http://asastudentcouncil.org.

Students mingle at the Meet and Greet on Monday, October 27, 2014 during the 168th Meeting of the ASA in Indianapolis.

As always, we would like to encourage all undergraduates, graduate students, and new post-docs to come to all of our student events, including the Orientation and Meet and Greet on Monday, the Wednesday social and ASA Jam, and the student outings. It's a great way to meet fellow students and learn about their research while having a great time! For all the latest information, follow the student council on Facebook, https://www.facebook.com/ASAStudents, and follow us on Twitter, https://twitter.com/ASAStudents. See you in Pittsburgh!

News from the Acoustical Society Foundation

Mission of the Acoustical Society Foundation Board: To support the mission of the ASA by developing financial resources for strategic initiatives and special purposes.

For quite some time, the Acoustical Society has subsidized travel expenses for students to attend the semi-annual ASA meetings. This brings new members to the meetings that they otherwise may not be able to attend, increases opportunities for students to present papers and network for future careers in acoustics, and enables the Society to grow and engage students in the future of the profession. The support for these subsidies comes from donations to the Acoustical Society Foundation. For each meeting, anywhere from two to four dozen students or groups of students apply for these subsidies. The total available funds for each meeting is around $15,000 (only about half of the total amount requested), and this amount is then pro-rated among the applicants to be as fair as possible to all. The Acoustical Society Foundation is appreciative of the support from donors to the Fund so we can provide these subsidies. We encourage you will continue this support so we can expand and maintain this program.

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