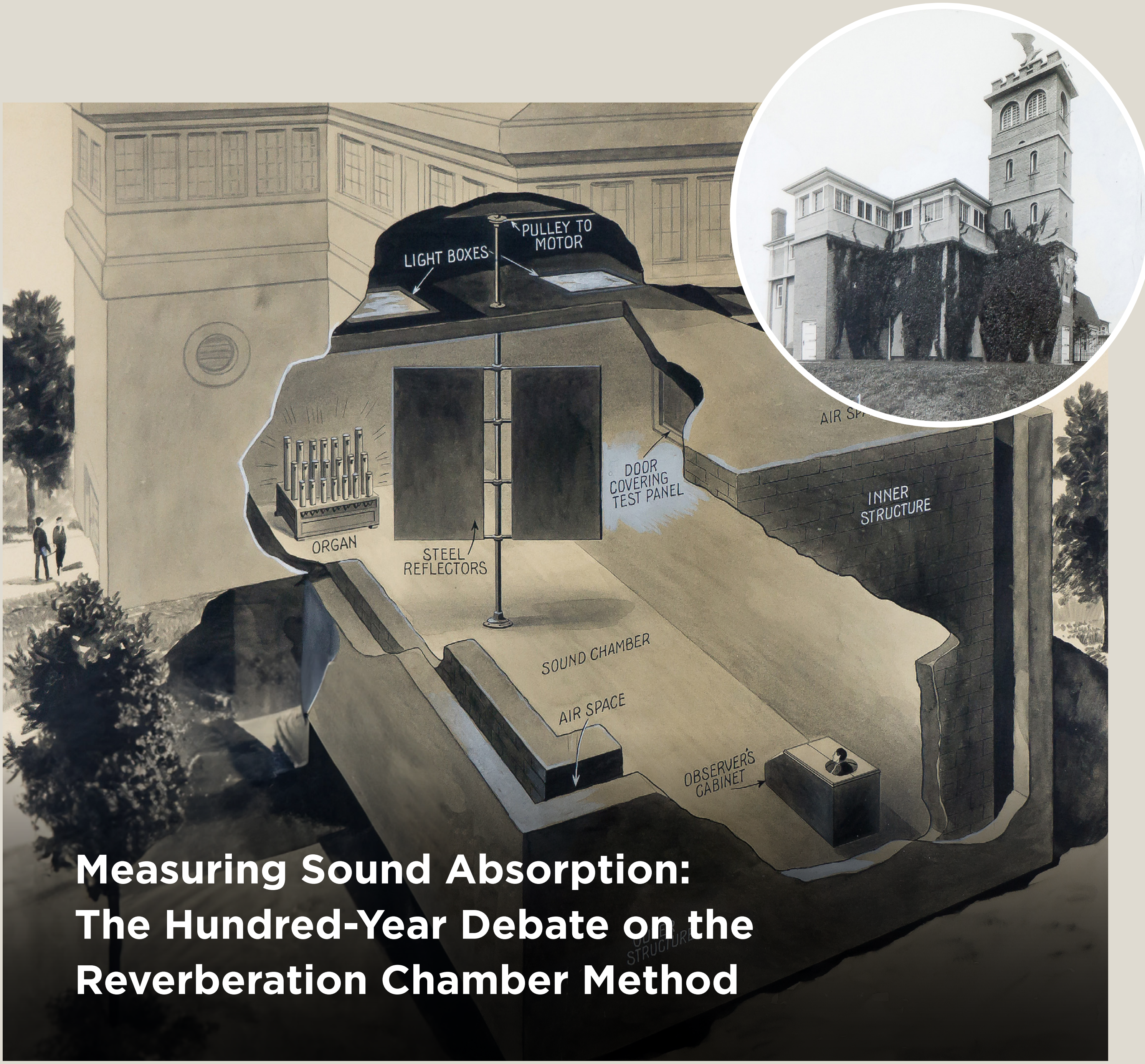
# Acoustics Today

ASA
ACOUSTICAL SOCIETY OF AMERICA

**Fall 2023** Volume 19, Issue 3

An Acoustical Society of America publication




## Measuring Sound Absorption: The Hundred-Year Debate on the Reverberation Chamber Method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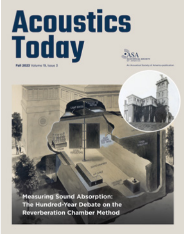


### About the Cover

Drawing of the Riverbank Laboratories with a detailed view of the reverberation chamber, from "Measuring Sound Absorption: The Hundred-Year Debate on the Reverberation Chamber Method" by Jamilla Balint, Marco Berzborn, Mélanie Nolan, and Michael Vorländer (page 13). First published in Lescarboura (1923). Courtesy of JSTOR and Eric Wolfram, Riverbank Acoustical Laboratories.


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Acoustics Today (ISSN 1557-0215, coden ATCODK) Fall 2023, volume 19, issue 3, is published quarterly by the Acoustical Society of America, 1305 Walt Whitman Rd., Suite 110, 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, 1305 Walt Whitman Rd., Suite 110, Melville, NY 11747-4300.

## From the Editor

Arthur N. Popper

The first article in this issue of *Acoustics Today* (*AT*) is by Jamilla Balint, Marco Berzborn, Mélanie Nolan, and Michael Vorländer. The authors write about sound absorption in different types of rooms and discuss the issues that make measuring sound absorption under different conditions a very substantial challenge. They also discuss the quite interesting history of measurements of sound absorption, starting when investigators had a person sitting in a room listening to the sound.

In our second article, Ewa Jacewicz, Joshua M. Alexander, and Robert A. Fox consider the range of frequencies needed for human speech. Although we tend to think of human speech as requiring sounds up to perhaps 5 kHz, the authors focus on higher frequencies and demonstrate that they add great value to speech comprehension.

Brain surgery is often difficult and dangerous for the patient. However, a wealth of new techniques are being developed, some of which are noninvasive. In our third article, Meaghan A. O'Reilly discusses one such noninvasive approach, the use of focused ultrasound to do incisionless treatment for certain types of surgery. Meaghan discusses the history of this approach as well as its strengths and weaknesses.

Our fourth article, by Raghu Raghavan and George Hrabovsky, provides another approach to the use of sound for medical treatment. In their article, they discuss using acoustic streaming to move materials in the human circulatory system. In particular, Raghu and George consider a relatively new approach that uses ultrasound to increase the concentration of drugs to a region of the body that might otherwise be hard to reach.

In our fifth article, Aaron N. Rice, Marissa L. Garcia, Laurel B. Symes, and Holger Klinck discuss a relatively new approach to conservation biology, the use of passive sound recordings to assess the environment and the animals. This approach, called Conservation Bioacoustics, allows long-distance and long-term monitoring of anything from insects to elephants. As a result, Conservation Bioacoustics provides new insights into a myriad of biological and conservation issues. The authors also discuss the history of the field and how it has evolved with the changing technology.

The sixth article by Samuel A. Verburg, Kenji Ishikawa, Efren Fernandez-Grande, and Yasuhiro Oikawa focuses on acousto-optics, which is the interactions between sound and light. In the article, the authors discuss the use of the measurement of acoustic phenomena using light. In essence, light is used to visualize acoustic phenomena that would otherwise be difficult to observe.

Our first "Sound Perspectives" essay is by Jennifer Cooper, who writes as part of our series "Conversation with a Colleague." Jennifer discusses her work that focuses on research, design, testing, and employment optimization of sonar systems used by the US Navy. Past essays are at bit.ly/ATC-CWC.

One thing we like to do at *AT* is to share information about ASA publications. Thus, I invited Megan S. Ballard, Kent L. Gee, and Helen Wall Murray to provide an update on the ASA journal *Proceedings of Meetings on Acoustics* (*POMA*). The goal is to bring members up-to-date on the journal and its many valuable uses for members and the Society. The authors also share the winners of the student paper competitions that the journal has organized.

Steven L. Garrett is well-known to many Acoustical Society of America (ASA) members. He is now retired from Penn State and living in California. One thing Steve wanted to do upon retirement was to continue to employ his physics expertise, but in new and fulfilling ways. To do this, Steve now volunteers as a substitute science teacher in high schools near his home, and he describes his experiences in his essay. Besides telling an interesting story, a goal for the essay is to serve as an inspiration and guide for other ASA members who are starting to think about postretirement activities.

Indeed, if other ASA members have retired and found new and fulfilling ways to use their scholarly expertise, please drop me a note (apopper@umd.edu). If what you have done might be applicable to other ASA retirees, perhaps we can share this in *AT*.

As most ASA members know, the Society is very engaged in outreach, a program that is led by L. Keeta Jones. One exciting outreach activity is the very interesting ASA website ExploreSound.org. As Keeta describes it, ExploreSound.org provides many tools to help teachers in K-12 (and college) teach acoustics. I encourage you to read Keeta's essay and then explore the site. It is a wealth of ideas and activities that might give you some creative ideas for your teaching or perhaps to share with other teachers.

In our final essay, Abbey L. Thomas and Peter F. Assmann discuss the International Science and Engineering Fair winners whose work focused on some aspect of acoustics. The essay features short descriptions of the work done by these very talented high-school students.

*Stan Dosso*

## Acoustical Society of America Conferences: Thoughts and Plans

Shortly after I became Acoustical Society of America (ASA) president at the end of the Chicago ASA meeting, *Acoustics Today* (*AT*) Editor Arthur Popper invited me to continue the presidential tradition of writing a "From the President" column for each issue of *AT* during my term as a way of communicating regularly with the ASA membership on topics of choice. I'm pleased to do so! For my first column, I'd like to consider one of the ASA's most important activities: our twice yearly conferences, including their value and benefits to members, challenges we face, and ongoing/future plans. But first, let me briefly introduce myself because I personally know only a fraction of the ASA membership, although I hope to get to know many more members during my term.

I was born and raised in beautiful Victoria, British Columbia, Canada, and attended the University of Victoria and University of British Columbia for undergraduate and graduate degrees in physics, applied mathematics, and geophysics. During my BSc degree, I spent a summer work term in underwater acoustics at the Defence Research Establishment Pacific (DREP) working with Ross Chapman, who went on to be a mentor to me throughout my career. Because of this experience, when I completed my PhD in geoelectromagnetic induction, I was offered a research position at DREP in Arctic Ocean acoustics, including yearly multiweek fieldwork based in tent camps on the polar ice pack, adventures that I loved. After five years at DREP, I moved to an Ocean Acoustics Research Chair in the School of Earth and Ocean Sciences, University of Victoria, where I've remained to the present, including a six-year term as director of the School. I teach geophysics-related courses at the undergraduate level and ocean acoustics and inverse theory at the graduate level and run an active research program in geophysical inversion, with primary applications in ocean acoustics, geoacoustics, and seismology.

I've been an ASA member for almost 30 years and a Fellow since 2001. I'm a member of the Acoustical Oceanography and Underwater Acoustics Technical Committees (TCs), with strong interests also in Signal Processing, Computational Acoustics, and Animal Bioacoustics. I've been a longtime associate editor (underwater sound) for *The Journal of the Acoustical Society of America*, served on/chaired several ASA committees, and been one of three co-organizers for the biennial ASA School (interacting with keen acoustics students there is a particular joy). I chaired the fall 2018 ASA Conference in Victoria and enjoyed welcoming the Society to my hometown. I served as ASA vice president (VP-elect, VP, past VP) from 2019 to 2022 and was then elected president, with my year in office starting in May 2023. I've also been a longtime member of the Canadian Acoustical Association (CAA), served as CAA president, and chaired three CAA conferences (two in Victoria, one in Banff).

My wife Shelley and I have three sons, two of whom live in Victoria. We enjoy traveling when time allows, often associated with national/international conferences. A highlight for us last year was walking the 800-km historic Camino de Santiago pilgrimage route in northern Spain.

Getting back to the main subject of this column, a first question could be, Why are ASA conferences important to members? Perhaps most obviously, conferences provide a prime opportunity to share your work with an audience of peers and represent an effective way to get both your work and you known more broadly in your field. And questions and feedback at your presentation can help make your work stronger, more relevant, and more accessible. This is, of course, a two-way street, as attending others' presentations exposes you to concepts and applications that can generate new ideas for your own work and also help you to keep up-to-date with general advances and evolving trends in your field.

Outside the technical sessions, conferences provide the opportunity to meet with colleagues, old and new, to engage in deeper discussions and exchange of ideas, and to develop your scientific networks. The social aspects of making new acquaintances, staying in touch with colleagues, and developing collaborations and friendships are invaluable and often deeply satisfying. Conferences can also provide opportunities to meet in person with sponsors, industry/business contacts, and potential graduate students, academic supervisors, or employers whom you might not otherwise see.

I remember being told early in my career that although the value of attending a single, specific conference could be debatable, relative to the cost and effort involved, the value of regular conference attendance over a career is profound, and I fully agree.

Conference attendance can be particularly important for students and early-career researchers in terms of developing communication and social skills, meeting other researchers, and gaining visibility in their field. However, attending a conference for the first time can be intimidating! The ASA tries to provide a positive, welcoming conference experience with a variety of programs, including Student and First-Time Attendee Orientation Sessions on the first conference day, Student Meet and Greet Receptions, and the Fellows Meet Students for Lunch program. Furthermore, the ASA School, a 2+ day event for students and early-career acousticians held in conjunction with spring ASA meetings in even-numbered years, is designed not only for academic content but also to introduce participants to ASA meetings and to help create a sense of community and belonging among young attendees. Many TCs offer Student and/or Young Investigator Presentation Awards to encourage and recognize high-quality work (and provide a valuable distinction on CVs). Recognizing that financial cost can be a barrier for attendance, the ASA offers Student Transportation Subsidies and Young Investigator Travel Grants and helps organize room-sharing arrangements.

However, it is important to recognize that, besides students, there are many other ASA members for whom attending conferences is difficult or impossible for a variety of reasons, including costs, family care, or other commitments that don't allow travel and that these often disproportionally affect already disadvantaged groups. Broadly speaking, the ASA has about 6,000 members, but only 1,000 or so attend each meeting. Although a precise breakdown is not available, from experience it's apparent that there is a subset of ASA members who attend conferences regularly, whereas many others attend rarely or not at all. Whether this is due to costs, inability to travel, or lack of interest, we would like to reduce barriers to attendance and increase the perceived value of our meetings, increasing participation and diversity.

A particular challenge here is that costs associated with all aspects of conference attendance have increased substantially compared with prepandemic times. In particular, average business-class hotel rates are reported to have increased by roughly 20% in North America and 30% in Europe, and airfares have increased by a similar amount, with the environmental cost (carbon footprint) of conference air travel also of increasing concern. (I recently heard from a European colleague whose university no longer allows conference travel outside their continent due to environmental cost.) Furthermore, the costs associated with running a conference (e.g., meeting room rental, food and beverage expenses, A/V contracts) increased by about 30% in 2022 relative to prepandemic times, with another 7% increase predicted for 2023. Although the ASA has gradually increased meeting registration fees in recent years, these fees have not kept pace with rising meeting costs, such that the ASA has run substantial deficits in putting on meetings for a number of years. While these deficits are presently supported through reserves, this cannot continue indefinitely, and approaches to decrease conference costs and increase revenues are being actively investigated and implemented.

To address many of the points above, the Meetings Reimagined Committee chaired by Scott Sommerfeldt was convened in April 2021 and met biweekly until June 2022. It was tasked to review all aspects of ASA meetings and provide recommendations to the Executive Council. In approaching this task, the Committee considered the following guidelines and goals:

(1) Recommended changes should not detract from the positive "feel" (sense of community) that exists at ASA meetings.
(2) To identify possible new ways of doing things to increase enthusiasm and/or lead to improved efficiencies in holding meetings.
(3) To reduce the "clutter" (overprogramming) often associated with meetings, in particular, to free up evenings and lunch hours where possible to provide attendees more discretionary/social time.
(4) To structure meetings to be as accessible as possible to a broad and diverse constituency of members.
(5) To work toward eliminating, or at least greatly reducing, the financial deficits associated with

meetings. However, in addressing this, items 1-4 must remain at the forefront of all considerations.

The Meetings Reimagined Committee made many recommendations, big and small, that are under consideration. Some that are planned to be implemented within the next few meetings include moving from Tuesday and Thursday evening social (buffet) events to a single social to be held on Wednesday, the peak conference attendance day. In this plan, Wednesday afternoon would become the ASA's signature "celebration" event, starting with a keynote speaker, followed by the ASA Plenary/Awards Session, the social, and, later in the evening, the ASA Jam. The majority of TC meetings that are held on Tuesday and Wednesday could then be scheduled in the late afternoon, immediately after the last session of the day, rather than reconvening midevening; this would provide attendees with a free evening to make dinner or other plans with colleagues after the TC meeting.

Many academic/professional societies are considering how to best approach conferences in the post-Covid world, given experience gained and technologies developed during the pandemic. In such considerations, the Meetings Reimagined Committee recommended against holding hybrid ASA meetings (meetings that combine in-person and virtual participation), because of much higher costs, complexity, and potential for technical problems. But the Committee did recommend considering occasionally holding virtual (fully online) meetings. Of course, the ASA ran two virtual meetings during the Covid-19 pandemic. However, those were emergency replacements for in-person meetings cancelled at late stages. The idea here is to evaluate the pros and cons of a virtual meeting planned well in advance to take best advantage of the rapidly developing virtual format. In fact, the ASA is planning a trial virtual meeting for fall 2024 (three years after the last Covid-related virtual meeting). The goals of this meeting are to:

- Improve accessibility for the many members who are unable to attend in-person meetings;
- Prioritize opportunities for students and early-career acousticians to showcase their work;
- Expand our reach broadly to nonmembers who may be interested in acoustics;
- Design innovative sessions and social interactions that take best advantage of the virtual format, such as lightning rounds, panel discussions, tutorials, games/contests, and virtual lab tours as well as more-traditional presentations with live Q&A; and
- Decrease travel/conference costs and environmental impact (for both attendees and the ASA).

The actual composition of sessions at the virtual meeting will be up to the TCs, so please get involved and be imaginative!

But before this virtual meeting, we have two exciting "regular" ASA conferences.

- December 2023, in Sydney, Australia (joint with the Australian Acoustical Society), to be held in the state-of-the-art International Convention Centre on spectacular Sydney Harbour (with 100 special $1,000 grants for student travel).
- May 2024, in Ottawa, Ontario, Canada (joint with the Canadian Acoustical Association), to be held during the Ottawa Tulip Festival, the world's largest such event (a post-World War II thank you gift from the Netherlands to Canada).

These are a few of the benefits and ongoing issues, challenges, and plans associated with ASA conferences, a vitally important component of the Society's mission. I'd welcome any ideas or feedback. Send them to sdosso@uvic.ca.

# Measuring Sound Absorption: The Hundred-Year Debate on the Reverberation Chamber Method

*Jamilla Balint, Marco Berzborn, Mélanie Nolan, and Michael Vorländer*

## A Seemingly Simple Question

When we enter a concert hall, we enjoy the music that resonates through the space; when we enter a classroom, we want to understand what the teacher explains; and in an office, we need a quiet environment to focus on work. For these and all other spaces, the acoustic design of the room is critical. Sound waves travel through the space and are reflected many times at the surfaces where a fraction of the wave's energy is absorbed. Accordingly, when designing a concert hall or any other space, we have to ask how much energy is absorbed or how much absorptive material should be installed in a room to achieve adequate acoustics. If the classroom sounds like a church, we will not understand the teacher; if the office space is too loud, we cannot concentrate; and if a concert hall is not designed properly, we will not enjoy the music.

On the face of it, this question may seem easy to answer. More than 100 years ago, W. Sabine (1922) (for a short biography, see t.ly/1tw4) derived the well-known reverberation formula and showed that provided the sound field is diffuse, the reverberation time of a room is inversely proportional to the amount of absorption. Based on this theory, the acoustics of a room can be predicted if one knew how much sound energy can be absorbed by a given material, something referred to as the absorption coefficient. It is a seemingly simple quantity, but its measurement has caused perhaps the most controversial and long-lasting debate in the history of acoustics. This article gives an overview of the many discussions and difficulties related to sound absorption measurements and presents some of the ensuing research findings.

## The Beginnings of Absorption Measurements

The simple question of "How much sound can be absorbed by a certain material?" can also be answered using W. Sabine's (1922) theory of reverberation, with measurements conducted in a reverberation chamber. Reverberation chambers are typically large rooms with hard exposed surfaces, and they are designed to create a diffuse sound field, something that is required for Sabine's theory to apply. In a diffuse sound field, sound energy is independent of the receiver position in the room and the energy strikes the test material equally from all directions. Despite the method being fairly simple, proving that the underlying theoretical assumptions are fulfilled has been an elusive task.

In 1913, the Riverbank Laboratories for Acoustics (Geneva, Illinois) initiated the construction of the first reverberation room for the measurement of sound absorption (**Figure 1**, *right*). The room was designed by Wallace (Clement) Sabine but was only finished after his death in 1919. His cousin, Paul Sabine, continued the work and the experiments in the reverberation room. The measurement procedure, which was called the ear-and-stopwatch method, was conducted as follows. The trained observer sat inside a wooden box placed in the reverberation room (**Figure 1**, *left*). The box was used to mitigate the influence of the observer on the overall absorption in the room because a wooden box absorbs much less energy than a human body. A rotating vane (the object that looks like a flag in **Figure 1**, *left*) was installed in the middle of the room to guarantee a uniform distribution of sound intensity in the chamber.


https://doi.org/10.1121/AT.2023.19.3.13

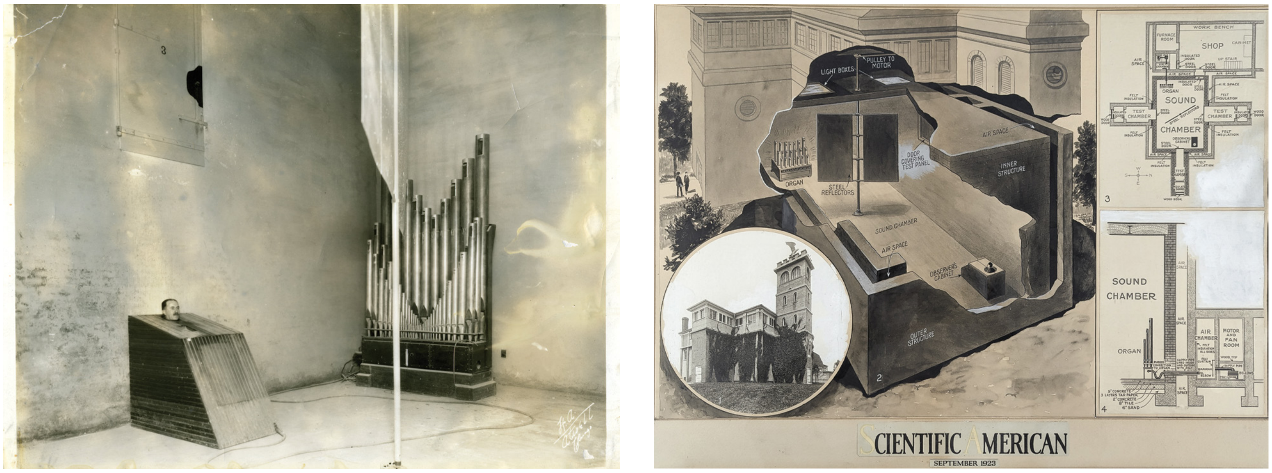



**Figure 1.** ***Left:*** *ear-and-stopwatch method to measure the absorption coefficient of a material at the Riverbank Laboratories in the 1920s. The experimenter is sitting in a wooden box listening to the sound decay emitted by organ pipes. Reproduced from Kopec (1997), with permission of the Acoustical Society of America, Copyright 1997, John Kopec.* ***Right:*** *drawing of the Riverbank Laboratories with a detailed view of the reverberation chamber. First published in Lescarboura (1923). Courtesy of JSTOR and Eric Wolfram, Riverbank Acoustical Laboratories*

Organ pipes in the room emitted a single tone. When the room was filled with sound, the tone was stopped and the time was recorded. The experimenter listened to the sound decay in the room and, once the sound was inaudible, again recorded the time. The interval between the two recorded times gave the reverberation time that could be measured with a precision of up to 0.01 seconds. An internal report by the Riverbank Laboratories for Acoustics (1919, p. 2) mentioned the exhaustive training needed: "Trials by a number of observers showed that considerable practice is required before the observations of a novice are reliable." The observer had to listen to the sound decay 1,100 times to obtain a reliable result for a single reverberation time at a given frequency (Riverbank Laboratories for Acoustics, 1919).

The procedure was repeated with and without the material under test (most likely some kind of porous fiber such as mineral wool) in the room, and the difference in reverberation times used to calculate the amount of absorbed sound energy, also known as the *random-incidence absorption coefficient,* via W. Sabine's (1922) formula. A value of 1 meant complete absorption, whereas a value of 0 meant that no energy was absorbed by the material.

## Technological Advancements and Round-Robin Tests

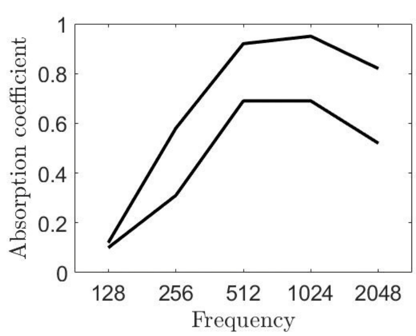
In the following years, technological advances in measurement techniques paved the way for simplification and improvement of the chamber method. In 1928, the US National Bureau of Standards (now the National Institute of Standards and Technology [NIST]) completed the construction of their 15,000-ft$^3$ (427-m$^3$) reverberation room that has contributed to knowledge in this field (Chrisler and Snyder, 1930).

By 1928, the interrupted-noise method replaced the ear-and-stopwatch method for measuring the reverberation time. In this method, noise was emitted by a loudspeaker instead of an organ pipe and the sound decay process was recorded by a microphone instead of an ear. Although the measurement procedure was much quicker than the ear-and-stopwatch method, it had to be repeated many times because of the stochastic nature of the excitation signal. However, it is one of the methods that is still in use today for measuring reverberation time.

The novel technologies allowed for more precise reverberation time measurement. Unfortunately, large discrepancies between the values of absorption coefficients assigned to the same material by different laboratories were found to exist and rapidly became concerning, to the point where this period (1925–1933) is known as the *battle of coefficients* (Hunt, 1939). As a matter of fact, this so-called *absorption coefficient problem* was among the motivating influences that led to the formation of the Acoustical Society of America (ASA) in 1929 (Hunt, 1939).

Soon, the first systematic investigation followed. To do this, a round-robin test was conducted in 1933 among seven laboratories to quantify the discrepancies in the measurement results from different laboratories on presumably identical materials (although the authors of this article could not find detailed documentation as to the precise nature of the round-robin tests). For these tests, samples of identical test material were sent to different testing laboratories to measure the absorption coefficient, and the results were reported back to the chairman of the round-robin committee. The results of the round-robin test were later presented by P. Sabine (1939), indicating large variations (see **Figure 2**). It turned out that despite using the same material, there were substantial discrepancies in the findings. For example, at 512 Hz, 1 laboratory reported an absorption coefficient of 0.69 and another laboratory a value of 0.92, results that would make the room acoustic design process very challenging. Many round-robin tests followed in the course of history, verifying the poor reproducibility of absorption coefficient measurements.

**Figure 2.** *Results from the first round-robin test conducted in the United States. Absorption coefficients at different frequencies are shown for the highest and lowest values obtained by seven testing laboratories. Data taken from P. Sabine (1939).*




## The Lack of Sound Field Diffuseness

At the 10-year anniversary of the ASA in 1939, where an entire session was dedicated to the absorption coefficient problem, Hunt (1939, p. 39) noted that something was "gravely wrong, either with the language, with the theory, or with the experiments." He suggested avoiding the term absorption coefficient as a unique measurable property of a material. Instead, he introduced the term *chamber coefficient*, which would be obtained "when certain numbers are placed in a certain formula, the numbers being obtained by means of certain specified operations performed under specific conditions" Hunt (1939, p. 40). It became clear that the condition of sound field diffusion had to be strictly satisfied to be able to use the term absorption coefficient for which it was intended.

Although many attempts were undertaken to increase the diffuseness in a reverberation room by adding diffusing elements like panel or volume diffusers, the absorption coefficients of the same material measured in different laboratories remained in disagreement. Hunt, even then, intuited that it would not be possible to achieve a satisfactory state of diffusion for reverberation theories to hold true.

Diffusion however, proved to be elusive to define. Schultz (1971, p. 17) described the problem of sound field diffusion in the following way: "Almost any man would feel insulted if told he lacks a sense of humor; but "humor" and "sense of humor" have stubbornly resisted definition for years. Similarly, to tell an acoustical laboratory operator that he hasn't adequate diffusion is likely to offend him, although acousticians have not settled on a practical, meaningful definition of diffusion." Cremer (1961, p. 22), on the other hand, was convinced that "the construction of a reverberation room is comparable with building a violin, such that the reverberation room too requires the subtle work of a violin maker who has to build an instrument that responds to all notes in the same manner."

Across the sciences, there is no unique definition of "diffusion." In physics and chemistry, it is the process of equalizing concentration differences in mixtures of substances. The particles in the substances can be atoms, molecules, charge carriers, photons, or even free neutrons. Transferring this concept to a sound field in a reverberation chamber, one imagines that the diffusion (mixing) effect is achieved by the superposition of waves arriving from all directions so that no specific direction of sound incidence can be determined anymore. This is thought to be achieved by numerous reflections off the walls. The term diffuse is used when referring to the type of sound field, whereas the term diffuseness is used when it comes to the quantification of the sound field diffusion.

## Direct Quantification of Diffuseness

Closely related to sound field diffusion is *isotropy,* a concept that relates to the directional uniformity of the sound field. In a diffuse sound field, sound waves arrive at the receiver with equal intensities from all directions (aka isotropically) and with random phases. Hence, a diffuse sound field is also always required to be isotropic.

To quantify sound field isotropy, considerable experimental effort has been spent during the last century and different methods have been developed. These methods try to quantify sound field isotropy based on the spatial characteristics of the sound field directly.

A particularly interesting and well-accepted approach consists of measuring the directional distribution of sound energy. The core idea behind this approach is that, in a perfectly isotropic sound field, an equal amount of energy is observed for every direction. The idea goes back to the early 1950s when Thiele (1953) and Meyer and Thiele (1956) captured the angular distribution of arriving acoustic energy using a concave mirror coupled with a single directional microphone. They presented the data in the form of directional "sound hedgehogs (hedgehogs are small spiny animals; when they feel threatened, they roll up into a tight ball and their pointy spines stand erect"; see t.ly/Az1o), showing the directions of sound incidence and corresponding energy in a room (see **Figure 3**). Every spine represents incident sound energy for the given direction where the length of the spine is proportional to the squared amplitude. Based on such directional energy distributions, a measure for the isotropy of the sound field was derived. In a fully isotropic sound field, the hedgehog would possess full spherical symmetry where all the spines would be equal in length and uniformly distributed. Contrastingly, a hedgehog with varying spine length or patches without spines results in reduced isotropy. A hedgehog with only a single spine would indicate full anisotropy. In **Figure 3**, waves with a higher amplitude arrive in the right hemisphere compared with the top or the bottom. The method by Meyer and Thiele (1956) is highly impressive given the simple equipment they had available (one microphone combined with a concave mirror).

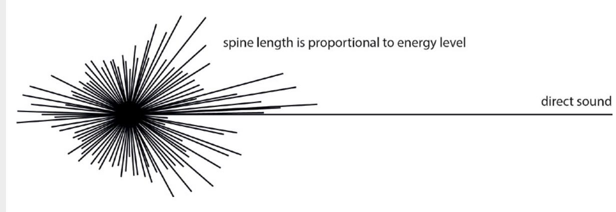



**Figure 3.** *Hedgehog representation of the directional distribution of sound energy in a room. Schematic drawing after Meyer and Thiele (1956). Spines indicate the direction of incident energy (length is proportional to energy level). The sound field is not fully isotropic because the hedgehog is not fully spherically symmetrical but shows distinct maxima in incident energy for some directions (spines of greater length).*

Over the past few decades, technical developments in sensing methods have facilitated the three-dimensional analysis of sound fields. Different methods have been proposed for the estimation of sound field isotropy from measurements with arrays of microphones. Gover et al. (2002) adapted the method proposed by Meyer and Thiele (1956) to do measurements with a spherical array of microphones. They could deduce the energy arriving at the receiving position as a function of direction and time as well as the rate of the energy decay. An analogous approach was suggested by Berzborn et al. (2019) who calculated the sound field isotropy on directionally dependent decay curves. An alternative criterion for quantifying sound field isotropy in reverberant sound fields was proposed by Nolan et al. (2018) by analyzing the symmetry of the angular distribution of arriving sound energy in the spherical Fourier domain.

Recent studies by Nolan et al. (2020) and Berzborn et al. (2019) applied the aforementioned microphone array-based methods to quantify sound field isotropy in reverberation chambers. These experimental studies showed qualitatively comparable results and confirmed that the sound field in standardized reverberation chambers is not isotropic (maximum 80% isotropy recorded). They also showed that the addition of an absorbing sample drastically influences the isotropy of the wave field (which drops to approximately 50%). In a different study, the distribution of incident acoustic energy on the measuring sample was also recorded, confirming that the sample was not exposed to isotropic sound incidence (Nolan et al., 2019).

Altogether, these findings demonstrate the shortcomings of the *averaging* implicitly contained in W. Sabine's (1922) absorption coefficient. Because sound does not strike the sample equally from all directions, the absorption coefficient measured according to W. Sabine's equation does not properly account for the distribution of sound energy at the sample's surface. Furthermore, the incident directions are highly specific to the respective chambers, which partly explains the fundamental problem of interlaboratory reproducibility associated with the measurement of sound absorption, and only produces new evidence that the measured sound absorption is inseparable from the laboratory room in which the measurements are performed.

## A Matter of Standardization

Many attempts were made to standardize the procedure of absorption measurements to guarantee a controlled laboratory environment and improve the interlaboratory reproducibility. The standards have specific requirements on the measurement procedure, the room volume, the sample size, and the procedure to ensure a diffuse sound field. As an example, an International Organization for Standardization (ISO)-certified chamber is shown in **Figure 4**, where a certain number of diffusing elements (e.g., hanging panels and built-in boundary diffusers on the walls and ceiling) are included with the aim of increasing the sound field diffuseness (Kosten, 1960). An indirect measurement procedure for evaluating the state of diffusion depending on the absorption coefficient is also included in ISO 354-2003 (2003). However, this procedure requires a diffuse sound field for the absorption coefficient to be correctly determined: a vicious cycle.

**Figure 4.** *Reverberation chamber at the Technical University of Denmark, Kongens Lyngby. The chamber is equipped with hanging panel diffusers (**left**) and built-in boundary diffusers (**right**) to create a diffuse (mixed) sound field. Photo by Torben Nielsen.*

Indeed, this method was deemed inadequate to ensure diffusion because the maximal achievable absorption is still a relative quantity, specific to the laboratory (Bradley et al., 2014). In ISO 354-2003 (2003), the measurement procedure to determine the reverberation time is carried out either with the interrupted-noise method or with the integrated room impulse response method developed by Schroeder (1965). The latter has the advantage that it allows for a fast measurement method and reduces uncertainties inherent to the excitation signal.

More recently, the possibility of using a so-called well-characterized reference absorber to calibrate the reverberation room was discussed. However, additional research and round-robin measurements showed that the calibration method only improves the results in a limited number of cases (Scrosati et al., 2020). Unfortunately, all these specifications on room volume, sample size, or measurement procedures could not improve the interlaboratory reproducibility. Even in the latest round-robin test, the issues remain unchanged (Scrosati et al., 2020).

In North America, the ASTM C423 (2023) standard serves as a guideline to measure absorption coefficients in a reverberation room. Although the challenges are the same, the standard acknowledges the difficulties and added a section "Precision and Bias" where the latest round-robin results are shown, and uncertainties are reported in the form of repeatability and reproducibility values. A revision is on the way, where it is suggested to extend the measurement procedure and include the integrated room impulse response method suggested by Schroeder (1965) instead of only allowing the interrupted-noise method. This would greatly improve the

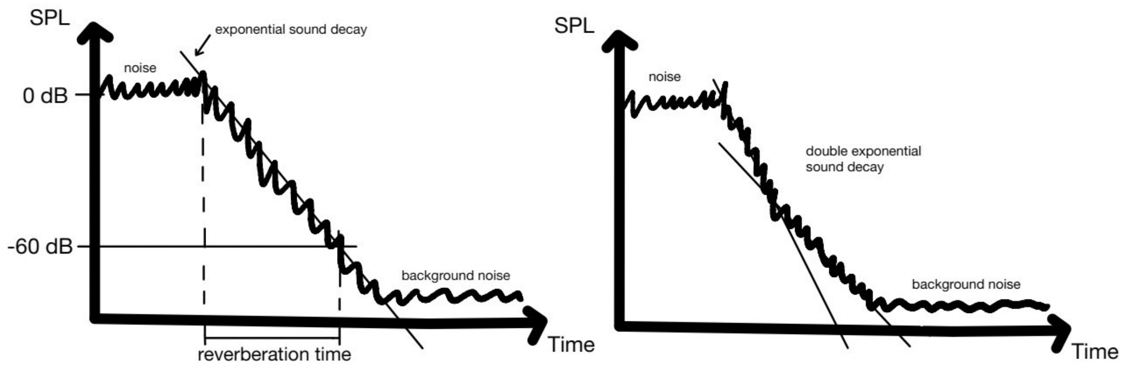



**Figure 5.** ***Left:*** *estimating the reverberation time from a single exponential sound decay by measuring the time for the sound level to drop 60 dB.* ***Right:*** *when the sound decay is of multi-exponential nature, estimating a single reverberation time is not possible anymore. Here, two simultaneous decay processes are present. SPL, sound pressure level.*

repeatability of measurements by removing the stochastic nature of the excitation signal.

## Further Challenges

To determine the absorption coefficient in the reverberation chamber, the measurement of the reverberation time is based on the diffuse field theory. In the case of a perfectly diffuse sound field and even distribution of absorption, the energy decay is linear when plotted on a logarithmic scale and the unique determination of a single reverberation time is possible (see **Figure 5**, *left*). The time for a sound energy level drop of 60 dB corresponds to the reverberation time.

Sadly, in most cases, we deviate from this assumption. As an example, if the absorption in the room is distributed unevenly (e.g., only the ceiling is absorptive), modes in the vertical direction will be attenuated fast, whereas modes in the horizontal plane will be reflected by the sound hard surfaces. Consequently, the assumption of a uniform damping of modes is not valid anymore. The resulting sound field decay will not be a single exponential function anymore but rather a sum of the latter (see **Figure 5**, *right*). In that case, calculating a single reverberation time is not sufficient anymore and multiple decay times must be estimated.

Hunt et al. (1939) suggested using a decay function with at least two to seven decay terms when measuring the absorption coefficient in the reverberation room . They argued that introducing an absorptive sample on the floor will always result in a sound field where at least two groups of decaying modes are present. Experimental results by Berzborn et al. (2021) confirmed the theory by Hunt et al. (1939). Different damping rates were detected for waves traveling almost parallel to the absorbing surface (slow-decaying grazing waves) and waves having oblique incidence (fast-decaying nongrazing waves). This experimental result confirmed the presence of at least two simultaneous but spatially separate decay processes during the absorption measurements theoretically considered in the past (Hunt et al., 1939; Kuttruff, 1958). The results directly contradict the assumption of a uniform damping of all modes required for application of Sabine's (1922) equation.

Schroeder (1965) noted that the integrated impulse-response method (he called it the integrated tone-burst method) to measure the reverberation time would be suitable for detecting multiple sloped-decay curves. He concluded that in most cases, we will not encounter a sound field where the decay is exponential in time. For example, his method revealed the double-sloped nature of the sound decay in the Boston Symphony Hall (see **Figure 6**). He estimated the two reverberation times ($T_1$ and $T_2$) by straight-line fits to the first 10 dB and the remainder of the decay. The results mean that an initial short decay is followed by a longer late decay, resulting in two simultaneous decay processes.

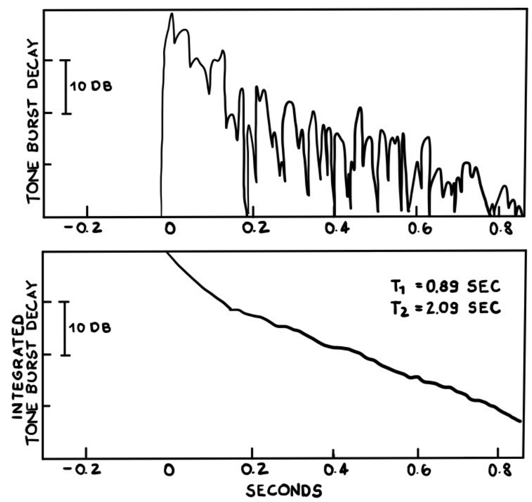



**Figure 6.** *Energy decay curves obtained at Boston Symphony Hall using the tone-burst method (**top**) and the integrated tone-burst method (**bottom**) suggested by Schroeder (1965). The latter method reveals the double-sloped nature of the decay curve, which results in two reverberation times,* $T_1$ *and* $T_2$*. Reproduced from Schroeder (1965), with permission of the Acoustical Society of the America, Copyright 1965.*

Unfortunately, calculating multiple decay times from one decay function is a very challenging task because it results in an inverse problem with infinitely many solutions. Luckily, Bayesian analysis provides the right framework to analyze experimental data that are subject to uncertainties and randomness (Xiang and Fackler, 2015). Xiang et al. (2011) developed a procedure where they introduced Bayesian statistics to calculate multiple decay times to characterize the decay process.

Yet, the question remains as to which of the decay times is physically meaningful to be used for calculating the absorption coefficient. Kuttruff (1958) derived theoretically that the reverberation time can be calculated from the sound decay curve by applying the inverse Laplace transform and that the beginning of the decay function contains the weighted mean of all modes. Based on Kuttruff's theory, Balint et al. (2019) used Bayesian statistics to estimate the initial decay time for calculating the absorption coefficient in a reverberation chamber. Good agreement could be achieved when comparing values of the measured absorption coefficient with theoretically calculated values.

In addition to the systematic issues associated with the lack of sound field diffusion and the nonuniform damping of modes, the reverberation chamber method is known to cause artifacts related to diffraction at the edges of the test specimen, also referred to as the *edge effect*. Absorption values exceeding unity have repeatedly been reported throughout the history of absorption measurements, indicating that the test specimen absorbs more energy than contained in the sound field present in the laboratory. Thomasson (1980) derived a model for the prediction of the *Sabine absorption coefficient* for finite-sized samples and suggested a correction term for rectangular test samples. Nonetheless, a correction term is not yet considered in measurements according to the current standards (ISO 354-2003, 2003; ASTM C423, 2023). Instead, ISO 11654-1997 (1997) suggests using the *practical absorption coefficient*, which is simply truncated to unity, a solution which is of practical nature rather than physically meaningful, especially because systematic measurement errors of materials with low absorption go unnoticed.

The implications of the edge effect are especially problematic for test specimens such as framed materials, slabs of mineral wool, or similar things that are measured in mounting conditions different from their typical applications. Having said that, the reverberation chamber method would still appear to be the most suitable method for measuring the absorption of bulky objects, such as furniture or people.

## Final Remarks

Accurately measuring the properties of sound-absorbing materials in reverberation chambers has been a recognized problem in acoustics since the 1920s. Nevertheless, the reverberation chamber method remains in widespread use for measuring sound absorption coefficients and is arguably the most frequently used. There is no doubt, however, that our acoustics community would benefit from the development of novel methods that measure sound absorption more accurately. In computer simulations for room acoustics, for example, experience has shown that absorption coefficients measured in reverberation chambers yield uncertainties that are insufficient for high-precision simulation results because they produce larger systematic deviations than would be allowed by the just-noticeable differences of human hearing (Vorländer, 2013). In computational acoustics, this is even more relevant because the complex boundary impedances determine the sound pressure field. Depending on the application, uncertainties in the boundary conditions may lead to errors in the local sound pressure by orders of magnitudes. For this reason, more accurate methods for determining limiting impedances and absorption coefficients are urgently needed.

Recent developments in array technology and statistical analysis have helped us gain more insights into the physical processes in reverberant sound fields. Yet, many open questions remain. How much diffusion is enough diffusion? Can existing reverberation chambers be improved? The idea of deriving calibration or compensation methods, similar to the approaches in the currently standardized method (ISO 354-2003, 2003; ASTM C423, 2023), based on direct quantifications of sound field diffusion is also widespread. However, there are no investigations on such methods yet.

It may be necessary to clarify the different terms and their usability. Because the conditions for obtaining a *random-incidence absorption coefficient* are not verified in our reverberation chambers, one could use the term Sabine absorption coefficient to emphasize that the calculation was carried out with W. Sabine's reverberation formula and its intrinsic limitations. Another possibility, as Hunt (1939) suggested, is to the use the term *chamber coefficient*, which would describe a material measured in a given chamber.

Regardless, one may question the use of a random-incidence absorption coefficient in rooms where specific angles of incidence dominate the losses (that is, in most ordinary rooms like classrooms, office spaces, and restaurants). Shouldn't the effective use of sound-absorbing materials in room acoustical design require the use of angle-dependent coefficients as opposed to random-incidence coefficients to properly account for the dissipation of sound energy at the room's boundaries? Most likely! Unfortunately, very few data of this kind are available. Would the surface impedance be a more suitable measure of a material's absorption properties? When it comes to computational acoustics, certainly, as the absorption coefficient does not contain information on angle or phase dependency.

In 2029, the ASA will celebrate its 100th anniversary. Will the absorption coefficient problem be solved? Probably not. We are, however, at the forefront of providing some answers and some alternative solutions, to help create good sound environments with even more precision.

## Acknowledgments

We thank Markus Mueller-Trapet at the Research Council National (NRC) Ottawa, Canada, and Volker Wittstock at Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany, for their valuable discussions on this topic from the viewpoint of testing laboratories. We thank Eric Wolfram from the Riverbank Laboratories for providing historical documents on early absorption measurements and Arthur Popper for his helpful comments and suggestions for the manuscript.

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# Extended High Frequency in Hearing and Speech[1]

*Ewa Jacewicz, Joshua M. Alexander, and Robert A. Fox*

## Elephants to Bats and the Range of Human Hearing

The audible frequency range specific to humans, known as the human hearing range, can extend from 20 Hz to 20 kHz depending on how good a person's hearing sensitivity is at higher frequencies. Yet, the understanding of human hearing capabilities has been limited to an upper limit of about 8 kHz because the primary explorations of these capabilities have historically been in the context of speech communication. After all, humans speak to be understood, and they need to hear well to perceive the sounds of speech.

Indeed, hearing loss is associated with difficulty understanding speech, and the standard clinical measurement of hearing is limited to tone sensitivity up to 8 kHz. Thus, does the human hearing range above 8 kHz have limited utility because it is unnecessary for speech communication? What is the advantage of having extended hearing up to 20 kHz? To better understand these issues, this article discusses recent research in speech and hearing and explores the potential of extended high-frequency hearing and the availability of high-frequency speech information in the audible range of human hearing.

Before we delve into issues related to human speech and hearing, let us pause and reflect on the audible frequency ranges in mammalian hearing because high- and low-frequency sensitivity is common to both humans and animals, irrespective of species-specific frequency limits. When interacting with animals, humans can easily hear cats and dogs because their vocalizations fall within the human hearing range, but humans may not be aware that the upper limit of hearing in these (and most other mammals) is much higher than theirs (Fay, 1994). To compare human and animal hearing, the hearing range is typically defined as the ability to detect sounds 50% of the time at the intensity level of 60 dB of sound pressure level (SPL) (Heffner and Heffner, 2007). Using this criterion, many mammals have better high-frequency hearing than humans, with the upper limit of about 45 kHz for dogs, about 80 kHz for cats, and about 85 kHz for the domestic house mouse.

High-frequency hearing in other mammals can even be higher. Bats are the most famous example, reaching or exceeding 200 kHz (Davies et al., 2013). The nonhuman mammalian ability to hear sounds at frequencies higher than humans is referred to as ultrasonic hearing (i.e., hearing high-frequency sounds inaudible to humans). Conversely, hearing sounds at frequencies below the lower limit of the human range is called infrasonic hearing (**Figure 1**). We note that what constitutes ultrasonic and infrasonic hearing is anthropocentric.

A hallmark example of infrasonic hearing is the low-frequency sensitivity of the elephant, reaching 16 Hz at 65 dB and 17 Hz at 60 dB SPL (Heffner and Heffner, 1982). In general, an elephant has good low-frequency hearing but poor high-frequency hearing (unable to hear sounds above 12 kHz). Indeed, research has established that mammals with good high-frequency hearing have poor low-frequency hearing (and vice versa), and the mammalian limit of low-frequency hearing varies directly with the high-frequency limit (Jackson et al., 1999). These variations are species specific.

The best human hearing sensitivity is from 2 to 4 kHz. In the 2- to 4-kHz range, humans can hear very soft sounds;

[1] *For additional information on extended high frequency, see the upcoming special issue of* The Journal of the Acoustical Society of America *on "Perception and Production of Sounds in the High-Frequency Range of Human Speech."*



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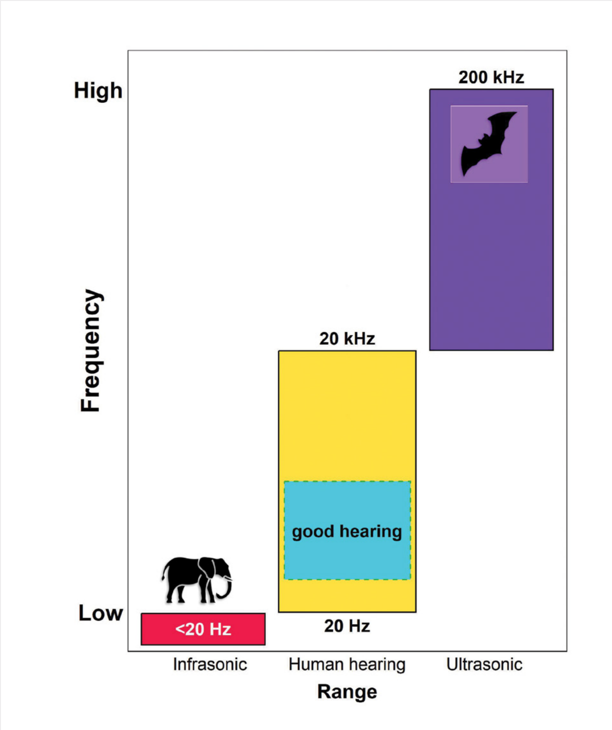



**Figure 1.** *A schematic illustrating species-specific good high- and low-frequency hearing relative to the human hearing range.* ***Left:*** *good hearing in elephants is in the infrasonic range of human hearing, below 20 Hz, but their high-frequency hearing also overlaps with humans, up to 12 kHz (not shown).* ***Center:*** *the audible frequency range for some humans is from 20 Hz to 20 kHz, but the good hearing range (i.e., good hearing sensitivity) is from about 250 Hz to 8 kHz.* ***Right:*** *bats have good hearing in the ultrasonic range (can hear sounds higher than humans), although their low-frequency hearing overlaps with the upper frequencies of the human range (not shown).*

pure tones can be audible at a level of −10 dB SPL (Jackson et al., 1999). Extending this highest sensitivity range, human hearing is still very good from 250 Hz to 2 kHz and 4 kHz to 8 kHz, with pure tones being audible at 10 dB SPL. However, sensitivity drops below 250 Hz and above 8 kHz, and sounds must be much louder to be perceivable, even by individuals with uncompromised hearing. Using the 60 dB SPL criterion in comparing the ranges of human and animal hearing, the human range can extend from 31 Hz to 17.6 kHz. Above 17.6 kHz, sounds can still be audible for some, but they need to be even more intense. In Jackson et al. (1999), only 3 of 6 adult listeners could hear 20-kHz pure tones at 91 dB SPL. Thus, compared with the hearing ranges of most high-frequency hearing mammals, human hearing sensitivity places humans as having good low-frequency hearing but relatively poor high-frequency hearing.

However, even if human hearing sensitivity at higher frequencies may not be as good as it is in the 250-Hz to 8-kHz range, humans can hear moderately intense signals, such as those produced in a normal conversation, at higher frequencies. Unfortunately, knowledge of how humans may utilize high-frequency information in speech communication is severely limited. This article discusses the historical reasons for the lack of interest in exploring the potential of high-frequency information for communication purposes and considers several areas of recent research that collectively make a case for a more important role of high frequency in hearing and speech than previously thought.

## Can You Hear Me Now? The Range of Telephones, Then and Now

Because hearing in humans is very good in the 250-Hz to 8-kHz range, how much high-frequency information is needed for successful speech communication? When humans hear someone speaking, they listen for comprehension, attending to words and phrases to understand the overall message. Early research at Bell Telephone Laboratories, Murray Hill, New Jersey (e.g., French and Steinberg, 1947) established that acoustic energy from 250 Hz to 4 kHz is essential to speech intelligibility because it contains most cues to vowels and consonants. This work also established 7 kHz as the upper frequency limit contributing significantly to spoken language comprehension.

The focus of this early work was both theoretical and practical because theoretical models were needed to improve telecommunication devices. Consequently, the finding that intelligibility does not suffer when the speech spectrum above 4 kHz is experimentally removed led to the general acceptance of the "telephone bandwidth" in traditional narrowband telephony.

Remember the old phones from the precellular times? They transmitted voice using a narrow bandwidth between 0.3 and 3.4 kHz and it worked! This bandwidth still preserved those speech characteristics considered necessary and sufficient for successful communication, to talk on the phone or make public announcements over loudspeakers. Listen to a sentence low-pass filtered at 4 kHz, approximating the narrowband telephone bandwidth (see **Multimedia File 1** at acousticstoday.org/JacewiczMedia). As you may have found, the sentence "I work for the school system" is fully intelligible despite the loss of acoustic energy above 4 kHz.

In recent years, however, audio media technologies (e.g., videoconferencing, voice of internet protocol, or cellular telephony) have steadily moved toward wideband or high-definition (HD) audio, with the upper frequency band extended to 7 kHz. This wideband audio coding not only improves voice quality, but the additional high-frequency information provided for specific speech sounds such as "s" can disambiguate words such as "thick" and "sick."

Indeed, this wideband audio meets today's needs and is now considered sufficient for telecommunication purposes. Listen to the same sentence low-pass filtered at 7 kHz and notice how the sound quality has improved (see **Multimedia File 2** at acousticstoday.org/JacewiczMedia). The advantage of increasing the frequency limit to 7 kHz is not as much in improved speech intelligibility but in reduced listening effort in processing the "s" sounds. Impressionistically, the words sound "crispier" (particularly the last word, "system"), and the message conveyed is easier to follow. The wider frequency bandwidth may be particularly useful in processing the sounds of foreign names or unfamiliar terminology.

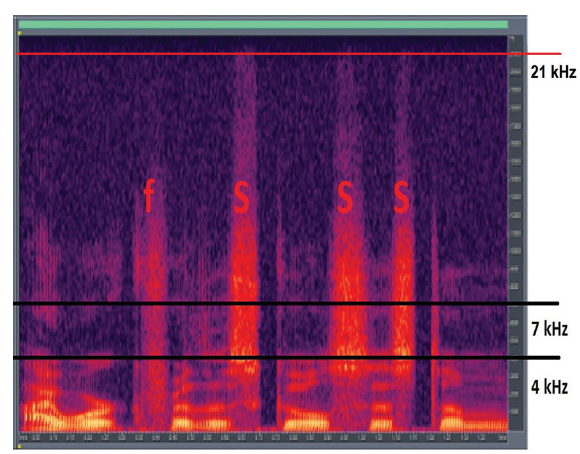
Based on the foundational research at Bell Telephone Laboratories (e.g., Fletcher and Galt, 1950) and many subsequent studies, the frequency range past 7 kHz is not expected to further improve speech intelligibility. Listen to the same sentence that has not been modified (see **Multimedia File 3** at acousticstoday.org/JacewiczMedia). The sentence was recorded at a 44.1-kHz sampling rate, the standard rate for audio CDs, and contains frequency information up to the limit of human hearing at 20 kHz. You probably do not notice any difference between examples 2 and 3. This is because even if some spectral information is missing, listeners can use a form of top-down (or "big picture") processing based on their prior knowledge and experience with pronunciation variability across different speakers to mentally "fill in" predictable information.

## Pushing the Limit: Extended High-Frequency Speech Sounds

If unnecessary and more than sufficient, can the upper-frequency range above 7 kHz, the extended high-frequencies, still be useful for speech perception or increase our understanding of speech acoustics? Consider how much spectral energy is still available between 7 kHz and 20 kHz in the spectrogram of our unmodified sentence "I work for the school system" (**Figure 2**). The four consecutive noise bars represent "noisy" consonants called fricatives, emphasized here in red for illustration purposes: I work ***f***or the ***s***chool ***s***y***s***tem. Fricatives are classified as high-frequency sounds because their spectral energy peaks are in the high-frequency range (near or above 8 kHz for some sounds).

**Figure 3** shows the average spectrum of the fricative "s" in words produced by a female talker (Alexander, 2019). As shown, a significant amount of extended high-frequency energy for "s" is produced by adult females; the average

**Figure 2.** *A spectrogram of the sentence "I work for the school system" recorded by a male talker. The sentence has energy up to at least 21 kHz. The low-frequency band marked at 4 kHz has been considered "necessary" to understand speech, and it approximates the 0.3- to 3.4-kHz bandwidth in traditional narrowband telephony. The higher band marked at 7 kHz is currently considered "sufficient" to understand speech in modern telecommunication devices. Note how much spectral energy is still available above 7 kHz, especially in fricatives "s" and "f."*



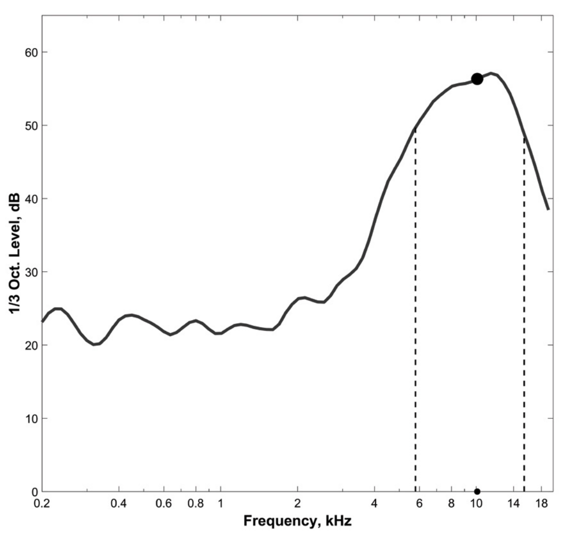



**Figure 3.** *Composite spectrum of the "s" sound extracted from 66 words spoken by a female talker.* ***Closed circles:*** *mean of the peak frequency.* ***Dotted lines:*** *means of the lower and upper shoulder frequencies (10 dB down from the peak).*

peak frequency of the "s" in this talker's words exceeds 10 kHz. As a rough estimate of the usable bandwidth for perception, the lower and upper shoulder frequencies, 10 dB down from the peak, are shown **Figure 3**, *dotted lines*. For this talker, the mean frequency of the high-frequency shoulder of "s" is 15.4 kHz.

The spectrum shown in **Figure 3** is a typical case because the range of values for the peak and upper shoulder frequencies across six female talkers was within an approximately one-third octave (Alexander, 2019). Although the peak frequency across the talkers, with a mean of 9.4 kHz and a range of 7.9-10.6 kHz, are consistent with previous reports, the frequencies of the upper shoulder are remarkably high, with a mean of 13.7 kHz, a range of 12.2-15.4 kHz, and a handful of reproductions exceeding 18 kHz. Although it is not a new finding (e.g., Tabain, 1998), the extent of high-frequency energy in "s" produced by female talkers has not been frequently reported. This is likely because the digital sampling rates used by many previous studies limited the amount of energy above 11 kHz.

The acoustic characteristics of "s" and other fricatives have been studied systematically since the early 1960s (e.g., Strevens, 1960). However, interest in frictives has intensified in speech research over the last three decades because modern computers offer greater computational possibilities. In the case of fricatives, a significant technological advancement was that speech recordings could be sampled at higher rates (44.1 kHz or even 48 kHz), which allowed for the development of new acoustic measures of fricatives that included spectral information up to 20 kHz. Even in the early 2000s, fricatives were recorded at the then-standard 22.05-kHz rate and their spectral content could only be analyzed up to 11 kHz. The seminal comprehensive acoustic analysis of English fricatives by Jongman et al. (2000) is a fitting example of this approach.

What have we learned from analyzing the acoustic spectra of fricatives in the entire range of human hearing, up to 20 kHz? More detailed measures characterizing fricatives have been proposed, with parameters defined specifically for use with sampling rates of 32 kHz or higher (Shadle, 2023). Indeed, using modern analytics, large corpora of speech, and machine-learning approaches, studies compared the effectiveness of various fricative measures (e.g., Kharlamov et al., 2023) or acoustic variation in individual speaker's pronunciation (Ulrich et al., 2023).

Investigating children's speech, full-spectrum-based measures uncovered significant acoustic differences between the pronunciation of fricatives in children with typical and distorted pronunciation (Miodonska et al., 2022). Children who were born deaf and were later fitted with cochlear implants (CIs) were found to pronounce fricatives differently from children with normal hearing (Yang and Li, 2023); this is because CI devices typically cover the speech spectrum only up to 8 kHz (Svirsky, 2017), making learning the fine-grained distinctions in the high-frequency sounds challenging for CI users.

## Extended High-Frequencies Benefit Perception

Having established that there is sufficient speech energy in the extended high-frequency region for people with good hearing to detect, the question remains whether they can use this information to help comprehend speech. To address this question, we first highlight pathological and experimental cases where the high and extended-high-frequency bands almost exclusively transmit the speech signal. Then, we discuss the ways information in the extended high frequencies can benefit people in everyday listening situations.

### *That's Incredible!*

Although most cases of sensorineural hearing loss have the earliest and most severe impact on the high-frequency range of hearing, there is a small subgroup of individuals with the opposite pattern of hearing loss: little-to-no usable hearing through 8 kHz with normal-to-mild hearing loss in the extended high-frequencies. In the mid-1970s, Charles Berlin was introduced to a young adult with significant hearing loss in the classic "speech frequencies," with normal thresholds in the extended high-frequency region.

Before being diagnosed by Berlin, this individual's audiological record baffled doctors and clinicians. For the previous 10 years, the only explanation was hysteria, so she was consequently treated with psychiatric and psychological care (Berlin et al., 1978). The dilemma was that she could detect speech at levels 50 dB lower than would be predicted by her detection thresholds for pure tones through 8 kHz, which were in the severe-to-profound range. In addition, she had nearly "perfect" pronunciation of the fricatives and "superb lip-reading ability" (Berlin, 1985). She could also respond to very soft, high-frequency sounds, such as when being called from another room (Berlin, 1985).

Berlin's previous work on ultrasonic hearing in animals led him to question her extended high-frequency hearing; however, the limits of human hearing in this range were not well-known at the time. Therefore, he had to improvise with what he could find; he started by modifying his ultrasonic transducer for animal testing to measure her hearing (Berlin et al., 1978). His work was so pioneering that normative threshold values in the extended high-frequency range had to first be developed only after finding a suitable audiometer with a low signal-to-noise ratio in this range. Ultimately, Berlin discovered that she had normal thresholds for frequencies at 12 kHz and higher, which could explain her anomalous communication abilities. Therefore, he commissioned an upward frequency-shifting hearing aid for her that transposed low-frequency sounds up to 12 kHz, which she successfully used for decades (Berlin, 1982). Her hearing loss and success with Berlin's device earned her a story in *Time* Magazine (1982) and a cameo on the popular 1980s TV show *That's Incredible!*

### *Perhaps Not So Incredible But Ordinary*

Although Berlin's star patient, one of the dozens of patients he later reported on, had an unusual pattern of hearing loss, her ability to exploit speech information from the extended high-frequency range in the face of sparse information from the typical speech frequency range is not. Under experimental conditions with severe signal degradation, individuals with normal thresholds throughout most of the range of human hearing have also been shown to harness extended high-frequency acoustic energy to support speech understanding.

Using normal-hearing subjects, Lippman (1996) tested the perception of nonsense syllables spoken by a female talker. The recordings were band-stop filtered, so the only acoustic energy was below 0.8 kHz and above a variable high-frequency cutoff between 3.15 and 10 kHz. Results indicated that speech recognition was 44% with just the low-frequency band but improved to almost 90% when combined with information from the high-frequency band above 4 kHz. Speech recognition remained relatively high at 74% when the high-frequency band was above 8 kHz; recognition of "s" in this condition was 100%. Recognition for several other consonants remained high when the high-frequency filter cutoffs were set at 8 and 10 kHz. These findings suggest that normal-hearing individuals can accurately perceive many speech sounds without midfrequency cues by combining information from the high-frequency speech spectrum with a limited range of information from the low-frequency speech spectrum.

### *Spatial Hearing*

Besides detecting and recognizing specific speech sounds in experimentally narrow conditions, how else do humans use information from the extended high-frequency range? The extended high-frequency spectrum can enhance spatial hearing by helping people and animals to localize sound sources. This is because high-frequency sounds have shorter wavelengths than low-frequency sounds. Shorter wavelengths are more directional, so they are more easily affected by the shape of the outer ear, the head, and the surrounding environment, making it easier to determine the location of a sound source. One classic example is the head shadow effect, whereby high-frequency sounds originating from the left or right are reflected off the head and cast a sound shadow on the opposite side. For example, if you are standing in a room and someone is talking to you from the left, the high-frequency sounds in their voice will be louder in the left ear compared with the right ear. The difference in loudness between the two ears will depend on the talker's location. The auditory system can use these loudness differences to help determine the direction of the sound source.

The extended high-frequency spectrum also provides critical cues for the localization of sounds varying in elevation since auditory comparisons of the sound arriving at the two ears are ineffective because each ear receives the same information. Instead, cues for localizing sound in the vertical dimension depend heavily on the diffraction of sound around the small folds and ridges of the outer ear (Middlebrooks and Green, 1991). Because the diffraction of sound waves is only significant when the object or opening is about the same size as the wavelength of the sound wave, the high and extended high frequencies carry the most relevant information about the elevation of sound sources (Hebrank and Wright, 1974).

### Speech Perception in Challenging Conditions

Most clinical and laboratory tests of speech perception do not reflect real-world communication environments. For example, talkers are limited in number and dialectal variability and are recorded in sound-treated rooms. In addition, recording methods such as the sampling rate, microphone style, and microphone position are not ideally suited to capture the extended high-frequency spectrum. Furthermore, when multiple talkers are combined or presented to the listener, they are often mixed in a single channel and/or played from a single loudspeaker.

These elements diminish the estimated contributions of extended high-frequency hearing in our everyday lives, particularly in challenging communication situations. Communication challenges can come from various sources, including background noise, reverberation, competing talkers, and language/cultural differences. These challenges reduce the redundancy of a talker's message as provided by contextual cues and predictability at every linguistic level (e.g., coarticulation of speech sounds to higher level information at the sentence and talker level). In general, the less predictable and contextually rich the spoken message is, the more extended high-frequency information will contribute to its understanding. This occurs because signal degradations often more adversely affect the lower frequency cues that significantly contribute to top-down processing, hence the ability of the listener to compensate for missing information in the acoustic signal.

Listening to speech in the presence of other competing talkers is one of the most challenging listening conditions, in part because the target (talker of interest) and maskers (other talkers) are more likely to share similar spectral and temporal characteristics compared with other masker sources (e.g., the sound of a fan or a backup warning beep on a truck). These commonalities can make it difficult to hear the target (energetic masking) and segregate the talker from the others (informational masking).

Monson and colleagues (Trine and Monson, 2020; Monson et al., 2023) demonstrated that the extended high-frequency spectrum contributes more to speech perception in these conditions than previously thought. They identified limitations of most experimental methods involving multiple talkers. One major limitation is that talkers are often recorded with the microphone directly in front of the mouth, which assumes that all the talkers face the listener and directly speak to them. Another limitation is that multiple talkers are often presented to the listener from a single loudspeaker in the front, similar to the talkers being in precisely the same position when speaking.

Although seemingly benign, these methodological details neutralize the differences in the extended high-frequency spectrum between the target and maskers (Trine and Monson, 2020; Monson et al., 2023). When a talker (target) speaks to someone, they usually face them, allowing the short wavelengths of the extended high-frequency speech to reach the listener's ear. However, other talkers (maskers) in the same environment are likely to be speaking to someone other than the listener, so they will face slightly off angle from the listener, even if they are in front of them. Thus, the extended high-frequency speech from the maskers will be reduced when it reaches the listener's ears, thereby boosting the signal-to-noise ratio in this region.

Monson et al. (2023) suggest that this release from energetic masking in the extended high-frequency region can increase the understanding of the talker facing the listener in ordinary conditions by providing additional access to the cues for vowels and consonants, including those not typically associated with the extended high-frequency spectrum. Additionally, increased access to the extended high-frequency spectrum can promote segregation and selective listening of the talker facing the listener by exploiting the synchronized pattern of amplitude changes across the entire spectrum.

## Future Directions

To what extent high-frequency energy in speech sounds can improve real-world speech communication is still unknown. Although laboratory experiments show that certain acoustic cues can be useful in perception, it is also the case that listeners adapt to contextual variation in speech and compensate for a loss of specific acoustic cues. More work is needed to better understand the perceptual importance of high-frequency energy in noisy sounds such as fricatives. It has been recently proposed that "human auditory system features, including the upper limit of hearing, have developed because of their ecological utility for detection and processing of speech" (Hunter et al., 2020, p. 3). Investigations using languages with a much richer inventory of high-frequency sounds than English (e.g., Mandarin, Polish, Russian, Greek, or Dravidian languages spoken in parts of India, Sri Lanka, and Pakistan) would be particularly insightful in providing evidence that hearing the fine-grained acoustic distinctions when learning a language is key to articulatory precision in producing them.

Speaker characteristics (not only vowels and consonants) are integral to human speech. When processing spoken language, we not only listen to what is being said but also who is talking. Perception studies have shown that high-frequency energy provides information about a speaker's gender (male or female), even in the absence of low-frequency cues. The primary cues to voice gender are in the low-frequency range, up to about 3 kHz, including the voice's fundamental frequency and the lower vowel formants. However, listeners can identify gender accurately even when speech is high-pass filtered at 5-12 kHz and the low-frequency content is removed (Donai and Halbritter, 2017). Moreover, they can identify gender only from brief vowel segments high-pass filtered up to 8.5 kHz. Similar results for gender identification have been reported in several other studies, which further underscores the usefulness of high-frequency information in speaker recognition (see Monson et al., 2014, for a comprehensive review). More recent research added that gender cues in the high-frequency range are almost as strong as in the low-frequency range, and information about a speaker's regional dialect is available in the 6- to 11-kHz range despite intelligibility loss (Jacewicz et al., 2023). Whether information about other speaker characteristics, physical, psychological, and social, is retained at the high end of the speech spectrum is still unknown, and future work is needed to explore this possibility.

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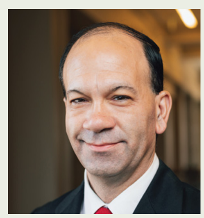


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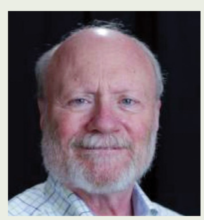


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# Incisionless Brain Surgery: Overcoming the Skull with Focused Ultrasound

*Meaghan A. O'Reilly*

## A "Focus" on the Brain

The brain is the command center for all our thoughts and actions and can be considered the essence of who we are, housing our personalities and the lifetime of memories that define us. For that reason, brain diseases and disorders are frightening in a way unlike those impacting other parts of the body because we risk losing what makes us, us. What do you do when faced with one of these conditions? When it is necessary to operate, exposing and cutting into the brain, the treatment can seem as daunting as the illness. It is not hard to see why the idea of incisionless brain surgery, where a patient can be surgically treated for a brain disorder, precisely interrupting the problematic brain region with millimeter precision without even piercing the skin, is incredibly appealing. But is this vision for the future just science fiction?

### *Treating the Brain*

Let's take the example of essential tremor, a motion disorder that results in uncontrollable shaking that can make even basic tasks such as putting pen to paper or drinking from a cup impossible. In addition to the practical challenges faced by these patients due to their impaired motor function, the social impact is significant. Embarrassment about the condition, which cannot easily be hidden, can result in social withdrawal. Treatments for severe tremor cases can include invasive approaches such as radiofrequency ablation or deep brain stimulation, both of which involve opening a hole in the skull and penetrating the brain tissue with a probe or electrode. Radiosurgery provides a noninvasive treatment alternative but exposes the brain to damaging ionizing radiation. Certainly, given the very real risk of damage to the healthy brain tissue, none of these interventions seem ideal. Enter focused ultrasound.

### *Focused Ultrasound*

Focused ultrasound (FUS; not to be confused with functional ultrasound [fUS]) is a noninvasive treatment approach that can be directed through the intact skull without the use of harmful radiation. Instead, it uses large aperture ultrasound devices that can focus energy to millimeter-scale focal volumes with high focal gain. This highly focused beam can generate targeted bioeffects deep within the body. Bioeffects is a catch-all term that refers to temporary or permanent changes or responses by biological tissues exposed to ultrasound. At high powers, the ultrasound energy absorbed by the tissue at the focus causes rapid heating, tens of degrees Celsius, in under one minute (Jones et al., 2019). This energy destroys the targeted tissue by effectively cooking it.

It is this thermal destruction (termed "thermal ablation") that is the key to its use in essential tremor. The ultrasound energy is focused through the intact skull bone and then precisely to a specific deep brain target where it thermally destroys a small volume of brain tissue, interrupting the tremor. Outside the focal volume, the ultrasound waves undergo destructive interference, meaning that they cancel each other out due to phase mismatch. This destructive interference means that there is no damage caused to the intervening healthy brain tissue.

A simple internet search for "essential tremor" and "FUS" will return several remarkable videos (see youtu.be/6BR94G5tRLY). We can see patients before and immediately after FUS treatment, and observe a miraculous normalization of motor function on the treated side. Although there are many emerging applications for focused ultrasound in the brain (see **Beyond Thermal Ablation** and **Future Directions**), its use in treating essential tremor



https://doi.org/10.1121/AT.2023.19.3.30

provides some of the most compelling visual evidence of the power of this technology, and it was the first brain application to receive regulatory approval. First tested in tremor patients in the early 2010s (Elias et al., 2013), by 2016 the device, InSightec's Exablate Neuro, had received approval from both the US Food and Drug Administration and Health Canada for the treatment of essential tremor. Since then, this procedure has also become reimbursable, meaning that the costs are partially or fully covered by government or private health coverage, an even more important milestone for the ultimate longevity of a medical technology.

Many people have never heard of FUS and are surprised to learn that this seemingly futuristic "scalpel-less brain surgery" is an approved procedure. But what might be more surprising to those outside the field of focused ultrasound is that FUS neurosurgery was being tested in patients over 60 years ago. Brothers William and Francis Fry, considered founding fathers of the field of focused ultrasound, had a very active research program and early successes in neurosurgery patients (Fry and Fry, 1960). For more on the history of the Fry brothers, see O'Brien and Dunn (2015) and O'Brien (2018). Despite these successes, and subsequent clinical investigations in brain tumors by others through the early 1990s (Heimburger, 1985; Guthkelch et al., 1991), the technology failed to gain critical momentum, and it all came down to the skull bone.

## Overcoming the Skull Problem

Until the 1990s it was considered impossible to focus therapeutic ultrasound exposures through the intact skull, the reason being twofold. First is the distorting effect due to the bone. The skull bone is irregularly shaped with spatially varying thickness, resulting in different path lengths that sound can take when traversing it (**Figure 1**).

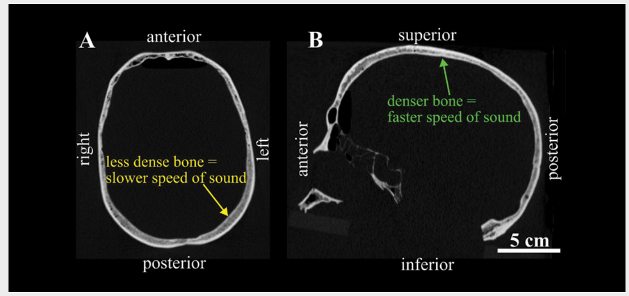


**Figure 1.** *X-ray computed tomography (CT) cross sections of a human skull illustrating the variability in bone thickness in a transverse view (**A**) and a sagittal view (**B**). The heterogeneity in bone density is observable in the pixel intensity, with brighter voxels reflecting denser bone and a higher speed of sound.*

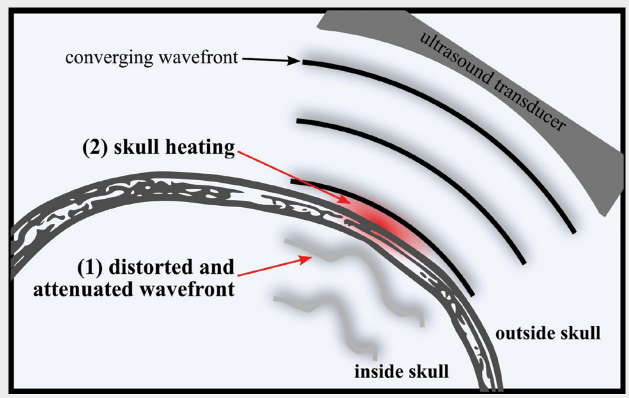


**Figure 2.** *Illustration of a focused ultrasound wave front passing through a section of skull bone. The spatially varying bone density and thickness result in distortion of the wave front (**1**). The strong absorption and scattering of ultrasound by bone attenuates the transmitted wave (**1**), illustrated here by a shift in the gray scale. The absorption also results in unwanted bone heating (**2**).*

Consider that the speed of sound in the skull bone can be double that in soft tissues (Fry and Barger, 1978) and the problem starts to take shape. Further complicating the situation is the fact that the sound speed in bone is density-dependent (Pichardo et al., 2011), and the bone density is spatially heterogeneous. Thus, due to the combination of varying path lengths and sound speeds, the skull bone acts as a complex aberrating lens, shifting and distorting the intended focus (**Figure 2**).

It is true that some regions of the skull bone, such as near the temples, have thinner, more uniform bone, enabling, for example, transcranial Doppler ultrasound imaging (Aaslid et al., 1982). Ignoring the limited field of view afforded by these acoustic windows, we are still faced with the second problem. Ultrasound absorption in the skull bone is an order of magnitude higher than in brain tissue (Pinton et al., 2012), meaning that achieving therapeutically relevant temperatures in the brain tissue runs the risk of even higher temperatures in the skull bone.

These two confounding factors, distortion and skull heating, mean that in order for the Fry brothers to conduct their groundbreaking neurosurgical studies using FUS, they needed to open a window in the skull to enable an unimpeded path for the ultrasound beams. The need to perform an invasive craniotomy prevented FUS from outcompeting other existing and new brain interventions, and so the technology stalled.

Fortunately, this was not the end. Interest in FUS for use in the brain was revitalized through major advances in methods and in magnetic resonance imaging (MRI), which occurred in the 1990s and 2000s. Specifically, the success of FUS for treating essential tremor was realized through three specific advances: the development of large-aperture phased-array transducer technology, the associated methods for correcting the beam distortions, and MRI thermometry.

## Large-Aperture Phased Arrays

Hynynen and Jolesz (1998) published a landmark study demonstrating that, contrary to existing dogma, it was indeed possible to achieve a focus through the human skull bone. It turns out that below 1 MHz, as the wavelength starts to become larger relative to the variations in bone thickness and the internal microstructure, the distortions and absorption are reduced and make generating a focus, albeit still somewhat distorted or shifted, possible. Breaking the transducer into an array of subelements further improved focusing because the timing of each element can be adjusted to compensate for the variations in skull transit time, enabling the waves from each element to arrive in phase at the intended focus (**Figure 3**).

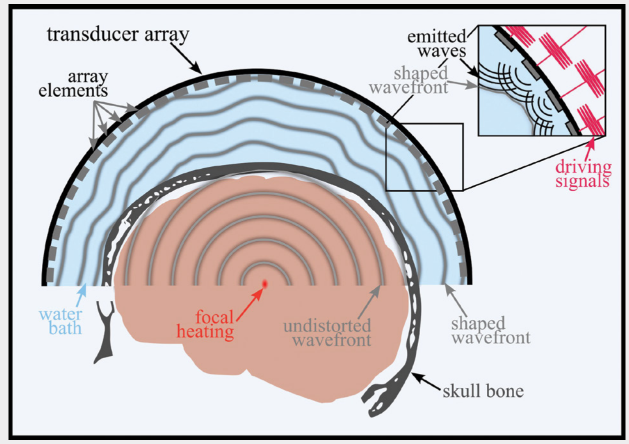


**Figure 3.** *Illustration of a large-aperture, hemispherical transducer array surrounding a human skull. The device is acoustically coupled to the head with a water bath.* ***Inset:*** *elements populating the surface. The timing of the electrical signals (**red waveforms**) can be adjusted to individually control the firing time of each element. For illustrative purposes, this is shown as short bursts. In practice, continuous sinusoidal waves are used for thermal ablation and the applied delays are subwavelength, adjusting the relative phase of the waves emitted by each element. The applied delays result in a shaped wave front that counteracts the skull distortions, resulting in an undistorted wave front after transmission through the bone. The large aperture also spreads the energy out over the entire skull surface, minimizing bone heating while achieving therapeutic levels of heating at the focus.*

Finally, by using a large aperture, the skull heating problem can be mostly overcome (Sun and Hynynen, 1998; Connor and Hynynen, 2004). The anatomy of the skull is conducive to the use of large hemispherical transducers (which resemble a bowl or a hairdressing helmet) that spread the ultrasound energy out over the entire skull surface (Clement et al., 2000). This reduces the absorption and associated heating experienced by a given location. Furthermore, high focal gains are achieved due to the waves emanating from a large-source surface area and all converging at the target.

## Aberration Correction

With the advent of these new phased arrays, it was also critical to develop methods to non-invasively predict the time for sound to transit through different points of the skull bone. Only in doing so could the necessary delays be applied to each array element to counteract the distorting effect of the skull bone. The first model derived skull geometry from a MRI (Sun and Hynynen, 1998), but models based on X-ray computed tomography (CT) data soon followed, allowing both geometry and bone density (hence, speed of sound) information to be incorporated into the models (Clement and Hynynen, 2002; Aubry et al., 2003).

Since then, many different computational models have been proposed that aim to improve accuracy, computational efficiency, or both. A recent benchmarking study of 11 transcranial acoustic propagation models found that, at least with respect to modeling the compressional wave component of transcranial sound propagation, there was reasonably good agreement, with the median values for focal pressure varying by less than 10% across all models and the focal position varying by less than 1 mm (Aubry et al., 2022).

In short, despite varied approaches for modeling the trans-skull propagation, existing models perform similarly for near-normal incidence where the main propagation mode is compressional. A caveat with this simulation-only study, however, is that it considered the skull bone to be homogenous. Yet, it has been shown separately that despite different equations determining sound speed from the bone density, the different published sound speed-bone density relationships all perform reasonably well (Bancel et al., 2021). With even the earliest computational models for calculating aberration corrections, positional errors less than 1 mm were achievable when measuring sound fields through bone samples (Clement and Hynynen, 2002), and similar results have been reported from clinical data (Moser et al., 2012).

But are these models accurate enough in practice to blindly apply them? Although the models have good positional accuracy, the restored focal pressure is more variable (Bancel et al., 2021), making it harder to predict tissue heating. Furthermore, the resulting heating depends on the local ultrasound absorption, and so heterogeneity in brain tissue can, in theory, results in the maximum pressure field not necessarily aligning perfectly with the location of maximum heating. Consequently, it is necessary to monitor the heating during the treatment, which is realized using MRI thermometry.

### *Magnetic Resonance Imaging Guidance*

FUS was first combined with MRI guidance to enable targeting and also spatial temperature mapping in the early 1990s (Cline et al., 1992; Hynynen et al., 1996). The temperature dependence of MRI parameters enables the use of MRI to image temperature changes in the body (Ishihara et al., 1995).

MRI thermometry is sensitive enough to detect small temperature elevations during FUS exposures. This allows the location of the treatment focus to be verified using a relatively low-power exposure that does not produce permanent changes in the brain. This is done prior to the therapeutic high-power exposure to ablate the tissue.

Temperature mapping also allows the temperature rise and thermal dose (a metric of the time spent at elevated temperature) to be quantified at the treatment target to ensure sufficient heat deposition. MRI thermometry can also assess unwanted heating outside the intended target. In practice, however, only a limited number of imaging planes are captured, providing an incomplete picture of heating outside the treatment volume.

### *Successes and Shortcomings*

Together, these technologies have enabled the success of thermal FUS in the treatment of essential tremor. Moreover, FUS thermal ablation is being used and studied clinically in other functional neurosurgery applications, including Parkinson's disease (Martínez-Fernández et al., 2018), chronic pain (Martin et al., 2009), obsessive-compulsive disorder (Jung et al., 2015), and major depressive disorder (Davidson et al., 2020). It would be safe to estimate that, worldwide, patients who have received this intervention number in the thousands (at my home institution alone, colleagues have treated over 300 tremor cases).

Indeed, by all measures, the technology appears to be a success and adoption is expected to continue to grow. But the success of FUS thermal ablation in these indications (deep brain ablation) is also because what is needed for the intervention conveniently aligns with the capabilities of FUS. That is to say, thermal ablation via FUS is ideal for generating lesions with sharp margins and in centrally located brain regions.

At the same time, once the focus moves too close to the skull, bone heating once again becomes a problem, despite the use of large apertures. Furthermore, despite early interest in using thermal ablation for treating brain tumors (McDannold et al., 2010), malignant brain tumors present the same challenges with FUS as with conventional surgery. Even after complete resection, some tumor cells remain and the tumor recurs. Add to these challenges the fact that there are many brain disorders that are diffuse and where tissue destruction would have no therapeutic role.

It is clear that high-intensity FUS thermal ablation has found an ideal niche in deep brain functional neurosurgery. However, what is also apparent is that an arsenal of other tools is needed to fully extend FUS to a broader set of brain conditions.

## Beyond Thermal Ablation

Transcranial FUS is being studied preclinically and clinically for many applications, some of which have been previously described in *Acoustics Today* (Pajek and Hynynen, 2012). One application that has reached the stage of clinical investigations is the use of ultrasound for targeted drug delivery.

## *Targeted Drug Delivery*

One of the greatest obstacles to the successful treatment of many brain conditions is the presence of the so-called "blood-brain barrier" (BBB). The BBB describes several features of brain endothelial cells (the cells that make up the walls of blood vessels) and their surroundings, which result in restricted transport of molecules from the bloodstream to the brain tissue. The purpose of the BBB is to preserve the privileged environment of the brain, warding off would-be invaders such as bacteria or viruses and ensuring a balanced chemical environment for brain cells. But a consequence of this robust natural defense system is that it also prevents most existing therapeutic drugs from getting into the brain in sufficient quantities to be useful (Pardridge, 2005).

Hynynen et al. (2001) demonstrated that FUS, in combination with diagnostic ultrasound contrast agents termed "microbubbles" (micrometer-size gas bubbles with a lipid or albumin shell to stabilize them and prevent rapid dissolution) could transiently and reversibly increase the permeability of the BBB to enable targeted drug delivery. Like the story of thermal ablation, investigations into the influence of ultrasound on the BBB actually predate this landmark study by over 40 years (Bakay et al., 1956).

However, what was critical about the 2001 study was that by employing pre-formed bubbles that could be administered intravenously and stimulated in combination with ultrasound, a reversible opening of the barrier was possible (**Figure 4**). Since then, several hundred studies have investigated and further developed this technique, and clinical investigations began in the mid-2010s.

An earlier *Acoustics Today* article (Konofagou, 2017) reported in greater detail on this approach for mediating drug delivery in the brain. A complete description is out of the scope of this article, but what is important to understand is that the mechanism by which the barrier is permeabilized is the oscillation of the bubbles in response to the ultrasound field. The vibrating bubbles stimulate the blood vessel walls through several mechanisms. This causes a transient increase in permeability as well as a suppression of the efflux mechanisms by which the barrier works to pump out unwanted molecules that do manage to find their way into the brain.

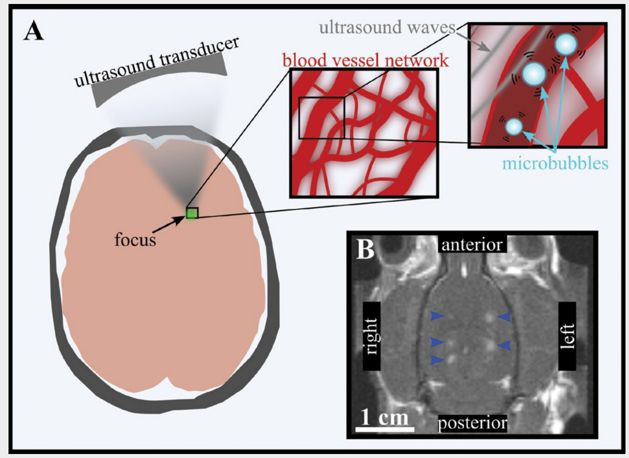


**Figure 4.** ***A:*** *conceptual image of ultrasound and microbubble-mediated blood-brain barrier (BBB) opening. Ultrasound is targeted to the brain (for simplicity, illustrated here using a small-aperture device). The callouts show the microvascular network. Microbubbles are injected intravenously and circulate through the vasculature. Where they interact with the ultrasound field, they oscillate, stimulating the blood vessel walls, resulting in a temporary increase in permeability of the vessels.* ***B:*** *example of a magnetic resonance imaging (MRI) image of a BBB opening in a rat brain. The bright spots within the brain (**blue arrowheads**) are discrete targets exposed to ultrasound. These are rendered visible by the local accumulation of a MRI contrast agent. The transient increase in vascular permeability caused by the ultrasound and bubbles allows the contrast agent, normally confined to the blood vessels, to reach the brain tissue.*

## *Technical Considerations*

The power levels needed to achieve a BBB opening are several orders of magnitude lower than what is used thermally and produce no significant thermal rise (Hynynen et al., 2001). That is, it is a purely mechanical effect that, in some ways, allows more flexibility with respect to the systems for delivering this therapy.

Because the time-averaged power of FUS BBB opening exposures is so low, these treatments avoid heating the skull bone, affording a much larger treatment envelope than for thermal ablation. This also enables use of simpler devices with smaller apertures, although still substantially larger than diagnostic ultrasound probes. Furthermore, if the number of treatment targets within the brain is relatively limited, transcranial treatment devices can be further simplified using three-dimensional (3D)-printed acoustic lenses to correct the skull distortions (Maimbourg et al., 2018). These lenses can be combined with single-element transducers, making them much more affordable and less complex than larger multielement devices.

MRI-guided interventions for FUS BBB openings are performed clinically with a system similar to that used for the thermal ablation studies (Lipsman et al., 2018). The BBB system operates at a lower frequency than the thermal ablation system (roughly 200-250 kHz vs. 600-700 kHz, depending on the specific system). The use of this lower operating frequency has several effects, including reducing the field distortion due to the skull and improving trans-skull transmission. Furthermore, the lower frequency slightly loosens the focal spot to enable opening over a larger volume for each focal location. Multielement phased arrays can be electronically steered, adjusting the firing timing of the different elements to move the focus around the brain, interleaving many spots to greatly increase the area of opening as desired.

### Treatment Monitoring

However, because this is a nonthermal procedure, MRI thermometry is no longer particularly useful for treatment monitoring. Instead, it is necessary to rely on the unique signatures of the oscillating microbubbles, which reemit not just the driving frequency of the ultrasound but also the harmonics and noninteger multiples of the driving frequency (sub- and ultraharmonics) (Neppiras, 1980). Furthermore, when these bubbles are driven to the point where they overexpand and violently collapse, they emit broadband noise, a signature of so-called "inertial cavitation" (the collapse of the bubble due to the dominant inertial forces of the surrounding medium).

By recording the scattered emissions from these bubbles and examining the spectral characteristics of their vibrations, it is possible to gain insight into the regimen of bubble behavior. It has been known for some time that changes in the spectral content of bubble emissions are correlated with the opening of the BBB (McDannold et al., 2006). Furthermore, it is possible to use bubble signals as feedback mechanisms to actively modulate the ultrasound pressure to ensure that the treatments remain in a safe, effective regimen (O'Reilly and Hynynen, 2012). Although MRI can still play a role in assessing the extent of barrier opening by visualizing the uptake of MRI contrast agents into the targeted region, the field is moving toward decoupling this technology from the treatments themselves. MRI is an expensive technology, and so by removing the need to occupy a MRI suite for the duration of the treatments, it is possible to reduce the cost to ultimately make this procedure more widely available. Therefore, in addition to studies using MRI-guided devices, neuronavigation-guided FUS is now being investigated clinically (Chen et al., 2021).

It is also worth mentioning that an implantable ultrasound device for a BBB opening exists that completely circumvents the skull bone by being surgically implanted at the time of conventional surgery to excise the tumor (Carpentier et al., 2016). However, due to the nature of it being implantable, the position of the device cannot be adjusted once it has been placed and it is suitable only for patients already undergoing surgical resection of a tumor. Thus, it lacks the flexibility afforded by transcranial devices.

A transcranial FUS BBB opening is being tested clinically for many different indications, including primary (Mainprize et al., 2019) and metastatic (Meng et al., 2021b) tumors situated in the brain, Parkinson's disease (Gasca-Salas et al., 2021), Alzheimer's disease (Lipsman et al., 2018), and amyotrophic lateral sclerosis (ALS) (Abrahao et al., 2019). These studies are expected to yield valuable clinical insight and hopefully pave the way for regulatory approvals for these treatments.

## Future Directions

It is an exciting time for FUS use in the brain. The clinical successes of this technology in functional neurosurgery and the translation of FUS BBB opening to clinical studies have been enabled by robust transcranial devices and methods for focusing through the skull bone. Beyond these treatments, new therapeutic ultrasound approaches for the brain are being studied, including the use of ultrasound to very precisely mechanically destroy tissue (Sukovich et al., 2018), to stimulate or modulate brain circuits (so-called "neuromodulation") (Legon et al., 2014), and to enable noninvasive biopsy by releasing tissue biomarkers into the bloodstream to be sampled by a simple blood draw (Zhu et al., 2018; Meng et al., 2021a).

No doubt the coming decade will see more "first-in-human" testing of these technologies and exciting new discoveries. With each new application of transcranial ultrasound, there is likely to be the need to refine the delivery approach. For example, our current models perform sufficiently well for MRI-guided thermal ablation and for BBB opening. However, both procedures have imaging readouts that can enable confirmation of targeting and that sufficient energy was applied. For neuromodulation, which lacks an imaging readout, these models may not yet be sufficiently accurate. Broadly, there is also a need to continue to innovate new approaches that can reduce the costs associated with this technology and therefore improve access. Certainly, given the strength and number of researchers working in this area, the field will rise to meet these challenges.

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# Move Me with Your Sound: Acoustic Streaming, Its Manifestations, and Some of Its Uses

*Raghu Raghavan and George Hrabovsky*

## Introduction

This article is about acoustic streaming, an intriguing phenomenon that is defined in **Acoustic Streaming**, and it has many uses, but this article emphasizes the application to enhance drug delivery to specific tissues of the body, with brief mention of other uses.

As background, the archetypal example of a wave on the surface of the water appears as a disturbance that moves across the surface without carrying the water along with it. In fact, there are several demonstrations of this on the Web, where an object experiencing the passing of a wave in a tank of water bobs up and down but does not really change its position (e.g., see bit.ly/BobUpnDn). In reality, the object does not quite return to where it started, but in most cases the motion of objects along the direction of the wave motion is too small for this discrepancy to be noticed in the short term. Over longer periods, however, sand or other materials in the water will move long distances from their original positions due to the motion of the waves because the object has drifted with the wave. This is often called the Stokes drift. See youtu.be/iPSC4Zt4l50 for a video illustrating the net motion that occurs.

There are many applications of streaming in biomedical technology. We discuss a fledgling application of enhanced drug delivery where acoustic streaming can be used to increase the concentration of the drugs to a region that might otherwise be hard to reach. We also mention other more mature applications. Due to the subtle difficulties of streaming, these applications will first require some background.

Sound is a longitudinal vibration that moves through air, water, or even solid objects. Such a vibration causes the particles in the medium to vibrate to-and-fro in the direction of the wave as the wave passes. This is different than the up-and-down motion of the water waves mentioned above that are transverse to the wave propagation direction. The drift behavior we saw with water waves can, however, also happen with sound waves traveling through air or liquids, like within tissue, blood vessels, or the fluid surrounding our brain. Fluids, unlike solids, have no fixed shape. Thus, sound waves can drive currents, causing the fluid to drift away from where it started and carrying things in it, like dust in air or dissolved drug molecules in a saline solution. The speed of drift is *much* smaller than the speed of the wave that, in turn, is essentially the speed of the *random* motion of the molecules due to the temperature of the medium, called the *thermal velocity*. On the other hand, the drift speed may well be comparable to the speed of the coherent motion of the particles due to the wave. We call the coherent motion of the fluid as a whole the *bulk velocity*. The result would then be a drift superimposed on the to-and-fro motion. Drift that occurs due to a sound wave is an example of what we call *acoustic streaming*. However, acoustic streaming is caused by an entirely different mechanism than the Stokes drift in water waves. We now discuss such matters in more detail.

## Acoustic Streaming

The scientific underpinnings of streaming are fascinating, and there is still much to discover. The heyday of the twentieth-century theories of streaming was immediately after World War II, and much of the work from this period was summarized in a watershed review (Lighthill, 1978) that not only established a context but pointed out that previous studies were quite inadequate. People had treated only those cases in fluid media where the intensity



https://doi.org/10.1121/AT.2023.19.3.38

of the sound waves was often unrealistically small. Since Lighthill's review (1978), the limitations he pointed out are being overcome.

We are accustomed to thinking of an acoustic wave as a cyclic process, with pressure and displacements returning to their rest values at the end of every cycle. For example, for a pulsed acoustic disturbance in ultrasonic medical imaging, we may think of the entire pulse duration as a cycle. The oscillatory pressure is a quite small disturbance to the resting pressure that is essentially the energy density of the thermal motion of the molecules. Acoustic streaming in a fluid is a *net* displacement of the fluid particles at the end of a cycle, and this displacement accumulates over cycles. This cannot happen in an ideal (linear) sound wave in an ideal fluid. For streaming to occur, some of the energy carried by the sound wave needs to be dissipated into the fluid medium, and we need to account for fluid motions beyond the linear approximation that accounts for the familiar harmonic vibrations.

We see a natural decrease in wave intensity as the sound wave covers an ever-expanding volume of fluid, resulting in less energy per volume element. This form of the *attenuation* of sound is due to simple geometry and does not result in acoustic streaming. When dealing with fluids, it is convenient to consider a small volume that is so large that the number of fluid particles in that volume can be treated as a constant. However, that volume is so small that it is smaller than the resolution of how we measure or model it. We will call such a small volume a (fluid) *parcel*.

### Bulk Velocity of the Sound Wave

The bulk velocity of the sound wave in the direction of the wave decreases transversely to this direction away from the axis of the sound beam. This directional change is the skewness or the shear of the velocity. As particles arrive across the shear, the skewness of the thermal velocity also increases and results in heating proportional to the kinetic energy in a parcel of the fluid. The coefficient that is needed to relate the kinetic energy of the bulk flow in a parcel to the rate of energy dissipation is called the shear viscosity. Furthermore, the sound wave alternately compresses and expands parcels of the fluid in its passage. This changes the balance of bulk velocity versus the thermal velocity. Such a change also results in dissipation due to what is sometimes called *bulk viscosity*. One result of all this is that the acceleration is no longer in phase with the force.

Another mechanism for dissipation, which also knocks acceleration and force out of phase, is due to transferring energy to the internal molecular vibrations of the fluid. This effect is mathematically of the same form as the bulk viscosity that helps in modeling these flows, although, of course, it is not physically the same at all. The sound wave over a cycle or several cycles brings in more velocity into one end of a fluid parcel than is taken out at the other end, thereby increasing the net rate of bulk momentum transfer across this parcel. This rate of change in momentum is a force, as Newton taught us, that causes some net motion called acoustical streaming. The effect is the product of two quantities oscillating in phase that does not vanish over a cycle, for example, like the square of a sine or cosine. This product is nonlinear. Consequently, acoustical streaming needs both dissipation and nonlinear considerations.

To make things even more complicated, dissipation and nonlinearity do not guarantee acoustical streaming. One reason is that while there is a transfer of momentum, we must also allow for the fluid pressure that is nothing but the energy density due to thermal motions. If the energy density can adjust itself spatially to counterbalance the bulk momentum transfer, the streaming will vanish. This can happen if the momentum transfer rate is of a certain form (Nyborg, 1965; Lighthill, 1978) or if boundary conditions force a vanishing as discussed in ***Spatial and Material Pictures***.

### Manifestations of Streaming

Sound waves can be traveling waves as in an unbounded space or they can be standing waves as in a closed tube or vessel of air or water. Circulatory streaming due to standing waves is shown in **Figure 1a**. **Figure 1a**, *arrows*, represents the directions of the streaming velocities produced by the waves. This first kind of streaming ever studied was by Lord Rayleigh (Strutt, 1884), and circulatory streaming due to the boundaries in a standing wave in general is often called Rayleigh streaming.

### Microstreaming Around Cells

A more extreme example of this situation is shown in **Figure 1b**, where the intensity of the sound is increased. In this case, the velocity produced results in a second

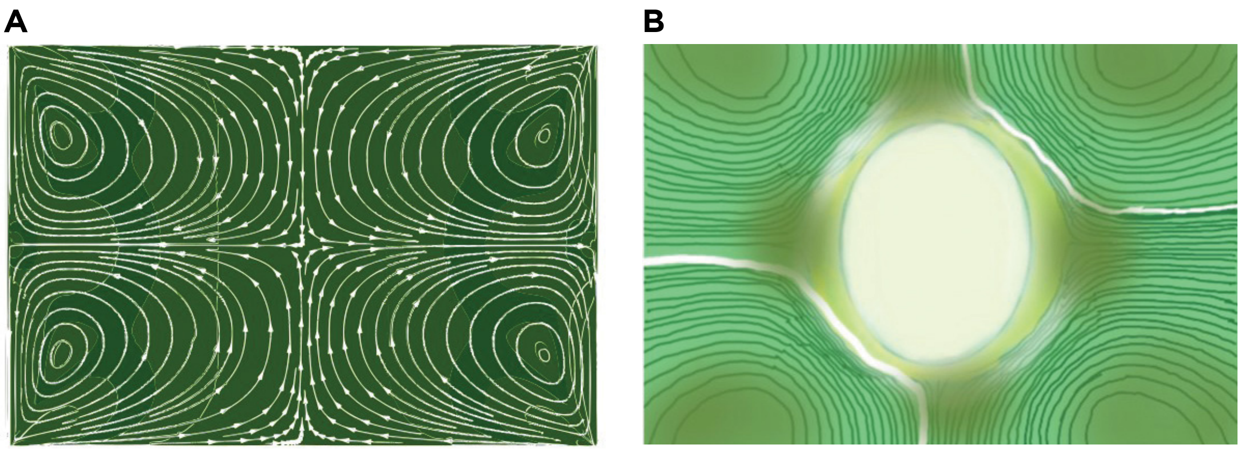



**Figure 1.** *Rayleigh-type acoustic streaming.* ***a:*** *Acoustic streaming in a standing wave is the form of streaming first analyzed by Lord Rayleigh.* ***Arrows:*** *directions of the streaming velocity produced by the wave.* ***b:*** *Circulatory streaming in a standing wave is the same as in* ***a*** *but at higher acoustic intensities. This is shown by four regions of circulation away from the cell (**white ellipse**) where the contours represent streamlines in these outer regions; there is also a region of circulation in the immediate vicinity of the cell whose streamlines are not apparent. It is this inner circulation that makes it different from the lower intensity in* ***a****. See text for details.*

circulatory region close to the body, where we must take into account a further term in the equations describing acoustic streaming that could be neglected for very low intensities (not shown in this article).

These are our first examples suggesting a biomedical application. The circulatory streaming from **Figure 1**, either **a** or **b**, is the norm near boundaries, particularly around cells in tissue and bubbles and is termed *microstreaming*. Microstreaming is effective in enhancing drug delivery as we describe further in **Biomedical Applications of Acoustic Streaming**.

Far away from boundaries, traveling waves can also be effective in streaming. See bit.ly/3TrdKT0 for a video of a sound transducer in a tank of water. A drop of dye introduced into the water and acted on a traveling sound wave generated by the transducer produced a velocity that moved the dye marker through the water. This is an example of a kind of acoustic streaming called *Eckart streaming*.

We now revisit our insistence that dissipation is necessary. The Stokes drift example in the video referenced in the **Introduction** illustrates an effect dependent on the phase of the wave and can happen without dissipation (but it *is* nonlinear) for a sound wave in a fluid as well. Technically speaking, this is not acoustical streaming, although it is related. To better understand these distinctions, let us examine the causes of the phenomena not related to dissipation but instead to phase.

## *Spatial and Material Pictures*

In general, when looking at modeling a gas or a liquid such as water, we can either follow the motion of a collection of molecules or establish an imaginary grid of points fixed in space. Following the particles of fluid or the parcels is traditionally called the Lagrangian approach or material picture. Establishing the grid and keeping track of the velocity at each grid point, is called the Eulerian approach or spatial picture.

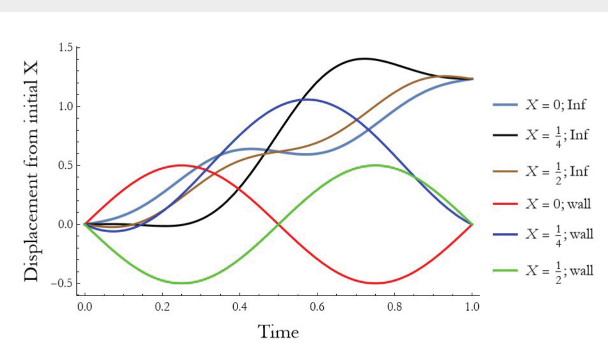
A velocity field describes the velocity at every grid point (and hence of that parcel that happens to be at that point) in a spatial picture at any given time. If we track the parcel as it is pushed by the appropriate velocity at each of the points at the appropriate times, we would be able to compute the velocity of the parcel. We refer to this as the material velocity. However, when we have a wave in the medium, not keeping the distinction between the pictures would lay traps for the unwary.

This is illustrated in **Figure 2**. The *first* case *assumes* that the spatial velocity, the velocity at a fixed point in space, is a simple harmonic (*not* attenuating) traveling wave.

Irrespective of the starting point of the three curves in this case, the fluid particle in one cycle of the wave has drifted to the right. This implies that with the passage of the wave, the fluid would just move in the direction of propagation. On the other hand, if the *spatial* velocities over a period were averaged, the averages would clearly be zero because at any point we have a simple harmonic motion. This contrasts with the cycle average of the material velocity, which does not average to zero. In other words, the spatial velocity must not be averaged or the difference between it and the material velocity must be accounted for. Stokes drift is an example of this at the surface of a body of water.

One would think that fluids obligingly flow in the direction of the wave. Paradoxically, this generally does not occur. This paradox can be resolved by considering the mechanism that produces such a wave, a vibrating wall, for example. In the *second* case, let us assume that the wall vibrates with precisely the same simple harmonic velocity (displacement of the wall per unit time) as the spatial velocity of the first case discussed above. At the wall, the fluid parcel "sticks" to the wall and must move with it. Then the curves show that a fluid parcel will always return to exactly the spot that it came from. Here the average *material* velocity is zero. This is not shown here, but a calculation of the spatial velocity will show that its average does not only not vanish but is exactly the same magnitude as the material velocity of the first case but is pointing left, *opposite* to the traveling wave in the direction of the wall.

**Figure 2.** *Theoretical subtleties. The difference between spatial and material velocities (often called Eulerian and Lagrangian, respectively) is illustrated for a fluid through which an acoustic wave is propagating from left to right. The curves are for a fluid in an infinite medium (no boundaries;* ***inf****). There is an oscillating wall and only the fluid motion to the right of the wall is considered (****wall****). The displacements of a particle in these two geometries (starting from position X) are shown. In the open space, the particles are all displaced over a cycle (Stokes drift) and end up at a different position from the starting one (lines that end higher up). By definition, the spatial velocity has a zero average (see text for more details) and since the particles are displaced to the right, this says the material velocity average is positive. But when there is an oscillating wall and the wave propagates in the half-space, a particle returns to its original position (lines that return to the same level): the material velocity averages to zero over a cycle. The* ***horizontal short bars*** *(line segments;* ***right****) indicate the position of the wall at various times in the cycle.*




Note that this picture would also pertain to a vibrating *solid*. Namely, the material velocity must average to zero (the atoms in a solid move around a fixed equilibrium position). This automatically means that the cycle average of the *spatial* velocity, which we observe if we gaze at a fixed point and measure the velocity there, does not vanish and points opposite to the wave propagation direction. We must be aware of this difference and its effects near the surface of an acoustic source to calculate the streaming effects correctly. Note that the effects mentioned are a consequence of the conservation of mass or matter, and the distinction between liquid and solid does not appear here. (They appear in the relationship of stimulus to response: liquids flow and solids don't or, more precisely, solids can support a shear stress and liquids flow in response to such a stress.)

## Biomedical Applications of Acoustic Streaming

We already mentioned one possible biomedical application of the idea of acoustical streaming to enhance drug delivery in specific tissues of the body. Perhaps the most widespread applications occur in the field of acoustofluidics (Green et al., 2014; Muller and Bruus, 2015; Rufo et al., 2022). Because a previous article in *Acoustics Today* (Nguyen et al., 2023) discussed acoustofluidics authoritatively, we do not discuss it here.

We have introduced the phenomena of microstreaming in ***Microstreaming Around Cells***. Despite its circulatory nature and its short range, it has important consequences derived from the pioneering work by Nyborg (1958). The

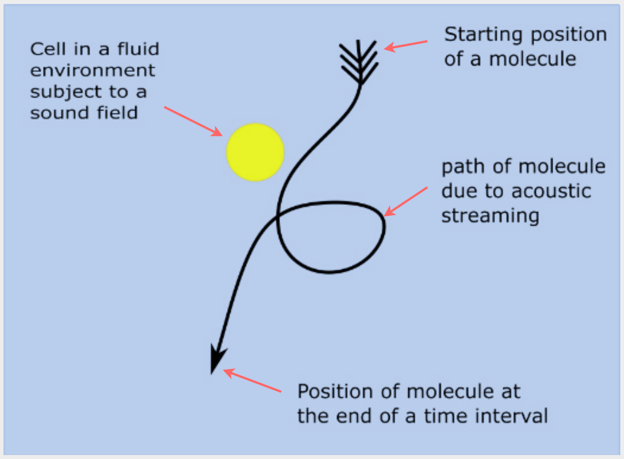



**Figure 3.** *Acoustic streaming in biology. Microstreaming is ubiquitous around cellular environments and plays a role in many ultrasound-assisted drug delivery applications and perhaps even in neuromodulation due to ultrasound (Kubanek et al., 2018). The movement of a marker particle near a cell (**yellow**) was followed for some time in the presence of a sound wave. The start (**tail of the arrow**) and end (**arrowhead**) positions indicate the limited time interval of observation. Inspired by Lee (2018).*

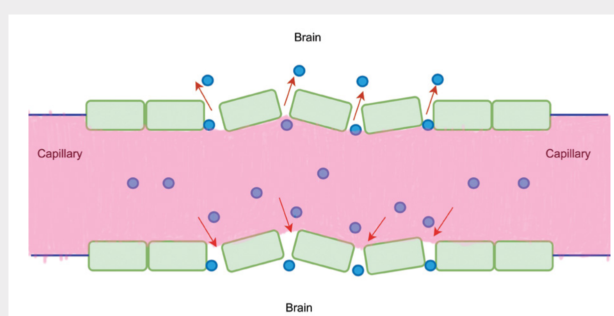
movement of a marker particle near a cell was followed for some time in the presence of a sound wave (**Figure 3**) (Lee, 2018). The start and end positions indicate the limited time interval of observation. The path is not random. Rather, it is characteristic of the complicated interaction of sound with the fluid medium. The path may develop a diffusion-type mixing if the medium consists of many cells whose placements are not regular. If this is the case, then the circulating path of a particle will not be closed (as in the case of the highly symmetrical situation in **Figure 1**) but will bifurcate so that its spread is effectively described as diffusivity enhanced by the streaming. The name for this is hydrodynamic dispersion (Bear, 1988).

One form of microstreaming used in drug delivery is called *sonophoresis*. It is believed (Collis et al., 2010) that the interaction of the sound waves with lipids in the cells opens a pathway in the cell membrane due to shear stresses, so that drugs can more easily enter the cell. Microstreaming may also play a role in opening the blood-brain barrier (BBB) for drug delivery (Konefagou, 2017) and in enhancing the delivery across it in the presence of microbubbles (Mo et al., 2012) (**Figure 4**). The microbubbles (between 1 and 10 micrometers) resonate strongly in acoustical fields used in biomedical systems. In **Figure 4**, the permeability of the capillary wall cells is represented by the gaps between the cells.

A biomedical application actively being investigated is enhancing drug delivery by the advection of therapeutic particles by a fluid streaming due to sonication. We now turn to such applications that will vastly extend the initial results such as those shown in **Figure 5**. This figure shows an example of a commercial sonicated catheter (Ekosonic Mach4). A drug was delivered via pores throughout the length of the catheter shown but sonicated only in the distal half; a color-coded concentration map of a contrast reagent shows greater radial penetration in the sonicated half.

Some delivery applications use the fact that particles such as drug molecules suspended or dissolved in a fluid can be carried by the fluid flow, called *advection*. The drug in suspension or solution with such a fluid carrier is directly delivered into tissue from a catheter port or ports by such advection. Such a process is called convection-enhanced delivery (CED) (Raghavan and Brady, 2011), and the driving force is the excess pressure from a pump used in infusing the fluid carrying the drug into the tissue. Biological tissues have a great deal of resistance to such flow due to various mechanisms (Brady et al., 2020). We may

**Figure 4.** *Ultrasound delivery across a blood-brain barrier (BBB). Microstreaming likely plays a role in the burgeoning field of disrupting the BBB to deliver drugs to the brain. Here we see how the sounds part the barrier, allowing a drug to pass through it. See text for references and explanation of the figure. **Blue circles:** microbubbles. **Light green rectangles:** capillary wall cells with their permeability represented by the gaps between the cells*



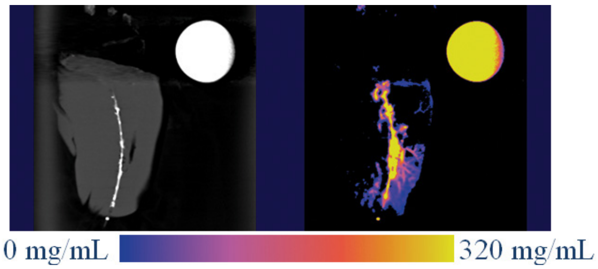



**Figure 5.** *Endovascular ultrasonic catheter. This example is from a catheter inserted into a blood vessel of a pig's liver ex vivo. The catheter is connected to a pump (not visible) and has ports along the side that can infuse fluid into which a contrast agent has been introduced. A contrast agent is a substance that shows up well in a CT scan.* ***Left:*** *black-and-white CT image of the catheter before the infusion. A calibration vial contains a known concentration of the contrast agent (****white circle****).* ***Right:*** *color-coded CT image of the infusion from a pump after 90 minutes. The concentration of the contrast agent is displayed (****yellow circle****), and the* ***color code*** *shows how colors match to concentrations. The bluish part of the background should be ignored as noise. In the distal (lower) half of the catheter are small ultrasound sources (not visible). The increased width around the middle of the catheter shows the increased spread of the agent due to sonication.*

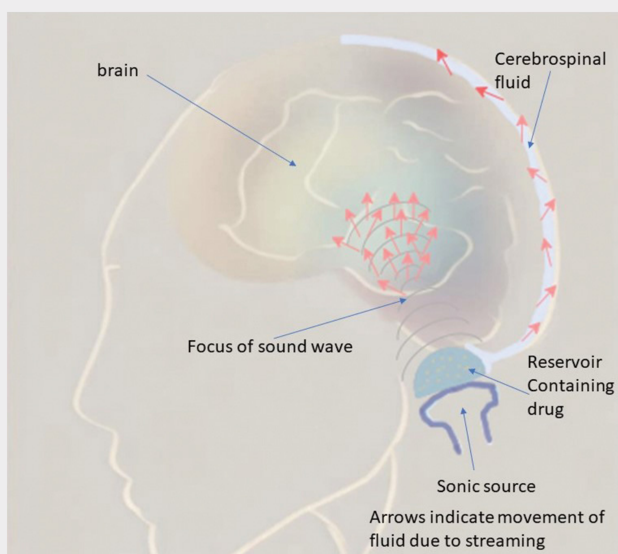
enhance the advection of the drug in the fluid by streaming driven by an acoustic beam. A stark difference from CED is that here the streaming force may be focused with adequate intensity anywhere, such as the regions further away from the catheter tip to where the CED is relatively ineffective because the pressure falls off very rapidly away from the infusion catheter. Using focused beams and steering the focus offers a way to enhance the spread of the drug (Raghavan, 2018), and this is the central promise of streaming for drug delivery. Delivery into the cerebrospinal fluid (CSF) spaces surrounding the brain known as intrathecal delivery is now becoming more widespread and streaming is expected to enhance this as well (Yoo et al., 2022).

**Figure 6** shows, in schematic form, the potential application of such an enhanced delivery system, although it should not be taken literally. A source of ultrasound generates waves going into both the tissue and the CSF, generating streaming therein to aid in drug delivery.

To make this quantitative, **Figure 7a** shows approximate calculations of streaming for in-tissue delivery, whereas **Figure 7b** shows this for delivery into the CSF, both in a "spherical" brain. We have used a simple model for the acoustic intensity patterns: a beam whose intensity follows a Gaussian distribution (see Kino, 1987, pp. 206-210). The plots are cycle averages of the *material* velocities of fluid in these respective spaces; see ***Spatial and Material Pictures***. A drug that floats in the fluid will be transported by these streaming speeds. The main message of these calculations (which need to be confirmed by experiment) is that therapeutic molecules, which would be advected by the fluid, can indeed be transported. Moreover, by varying the focus, it will be possible to attain higher fluid velocities throughout the desired region.

Let us recall the importance of boundary conditions. For results such as those shown in **Figure 7**, it is presupposed that a reservoir of fluid (containing the drug) is available for the process. In other words, a pump is not delivering a fixed amount of fluid per second but rather allows as much fluid to enter as the pressure conditions allow. We have also calculated (not shown here) fluid flow in the cochlea, proposed for drug delivery into the inner ear (Sumner et al., 2021) as well as for air into

**Figure 6.** *Future applications of streaming in medicine? This is an illustration of potential drug delivery in the brain enhanced by acoustic streaming. The fluid velocities that are the result of the acoustic streaming are quantified in* ***Figure 7****.*



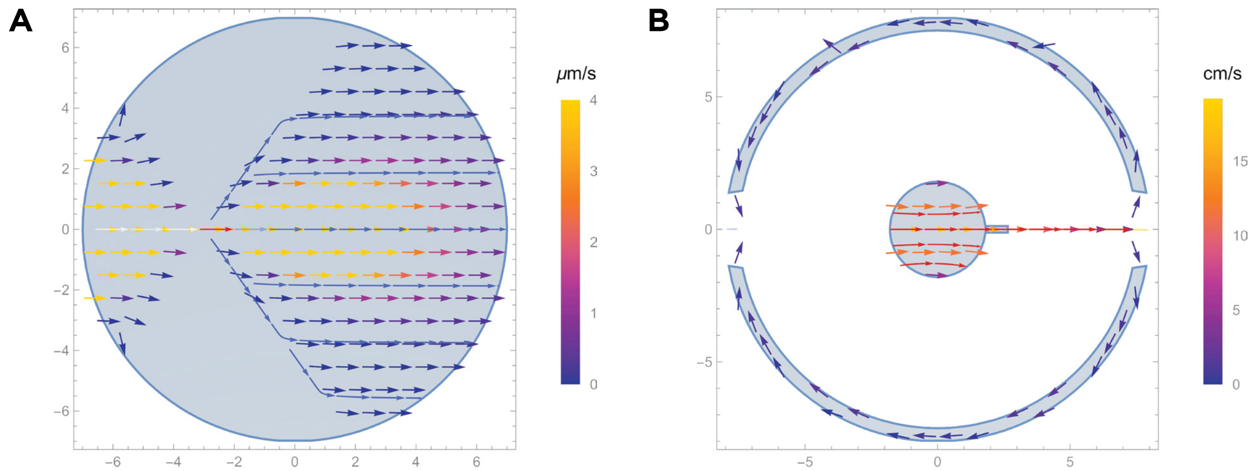



**Figure 7.** *Acoustic streaming calculations in tissue and in the cerebrospinal fluid (CSF).* ***a:*** *Acoustic beam focused in brain tissue.* ***b:*** *Beam in lateral ventricle to spread in the CSF. These simulated sonications are predicted to result in significant fluid flow that could be used to advect drugs in many therapies for the brain. Note the dramatic differences in speeds in liquid (**b**) and in tissue (**a**). These speeds are **color-coded arrows**, with the coding to speed matched with the bar.*

the trachea (Han et al., 2016). These calculations show more than adequate speeds of transport for safe-enough sound intensities. Although the latter application has not been realized (Meyers et al., 2019), there is potential for such development.

Many of the applications we have discussed are still in the research phase; thus, their efficacy is unverified. Although ultrasound disruption of the BBB has been known since the 1950s, the method is reaching the clinic only now because of the large investments made in the needed research and the development of monitoring technology (Flame et al., 2012). Similarly, the correlation between the promise of enhanced delivery due to acoustic streaming and the process of disease cure remains to be established. The first goal in establishing such a correlation would be to set a target and demonstrate a quantifiable improvement in coverage of the target region by a streamed drug compared with currently available delivery methods. The challenges are considerable; computing the sound fields in the environment of a living being is very difficult. Add to that further complication of predicting, not to mention calculating, the attendant streaming accurately is daunting enough. It seems inevitable that modern computational methods will play an increasingly important role in predicting the streaming. If efforts are initially promising, the entire process can be continually improved. However, just as in the case of BBB disruption, necessary investment into these improvements will be needed.

## Conclusions

We have briefly reviewed the context within which acoustic streaming is situated as a nonlinear effect and the interesting mechanisms that underlie it. Although much progress has been made to treat nonlinearities (Sadhal, 2014; Catarino et al., 2016; Joergensen and Bruus, 2021) (for nonperiodic acoustic sources, see Perelomova, and Wojda, 2009), a unifying theoretical treatment of the phenomena and its varied manifestations is still lacking. We described some of its biomedical applications. Lighthill's authoritative discussion (1978) was the start of newer aspects of acoustic streaming. We hope that the impetus from new technologies and new modeling methods in this millennium that will be brought to studies of streaming will also yield interesting and useful developments.

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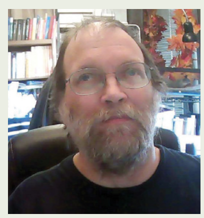

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# Conservation Bioacoustics: Listening to the Heartbeat of the Earth

*Aaron N. Rice, Marissa L. Garcia, Laurel B. Symes, and Holger Klinck*

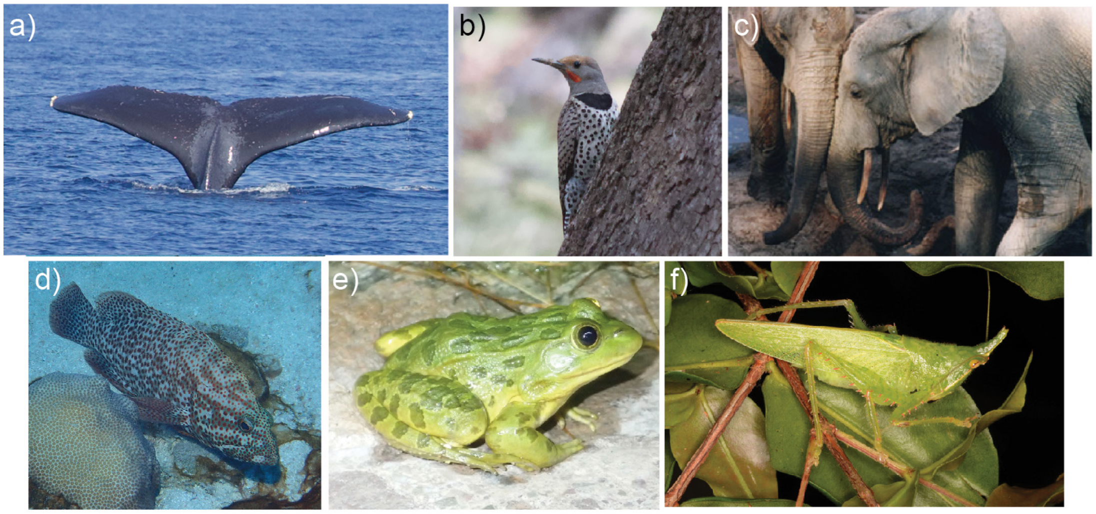
## What Is Conservation Bioacoustics?

If you close your eyes and just listen to an outdoor environment, the sounds that you hear provide ever-changing details about the world around you. These sounds of biological (e.g., animal calls), geophysical (e.g., thunder), and human-made (e.g., traffic) origin comprise what is often referred to as the soundscape (examples in *Acoustics Today* include Miksis-Olds et al., 2018; Slabbekoorn, 2018; also see acousticstoday.org/soundscapes).

As popularized by Rachel Carson's *Silent Spring*, the loss of calling frogs in wetlands was an immediate and audible indication that frogs had changed their behavior. This important observation led to a profound realization: the frogs' ecological community and ecosystem integrity were deteriorating (Carson, 1962). Indeed, we can glean a wealth of information from the ever-shifting composition of a soundscape, wherein both silence and sounds reveal the health of an ecosystem. How a soundscape transforms across days, seasons, and years can ultimately inform the conservation of the habitat and the animals calling within.

Just as many indigenous groups have recognized the importance of listening to nature for stewarding natural resources for millennia (Gray et al., 2001), scientists are now developing and implementing technologies that allow the study of sounds from a wide diversity of

**Figure 1.** *Bioacoustics has been used for conservation of a wide variety of taxa, originating with cetaceans (**a**,* Megaptera novaeangliae*; photo by Ben Gottesman) and birds (**b**,* Colaptes chrysoides*; photo by A. Rice), but has quickly expanded to forest elephants (**c**,* Loxodonta cyclotis*; photo by E. Rowland), groupers vulnerable to overfishing (**d**,* Cephalopholis cruentata*; photo by A. Rice), endangered frogs (**e**,* Lithobates chiricahuensis*; photo by A. Rice), and important ecological indicator species in tropical forests such as katydids (**f**,* Acantheremus major*; photo by M. Ayres).*



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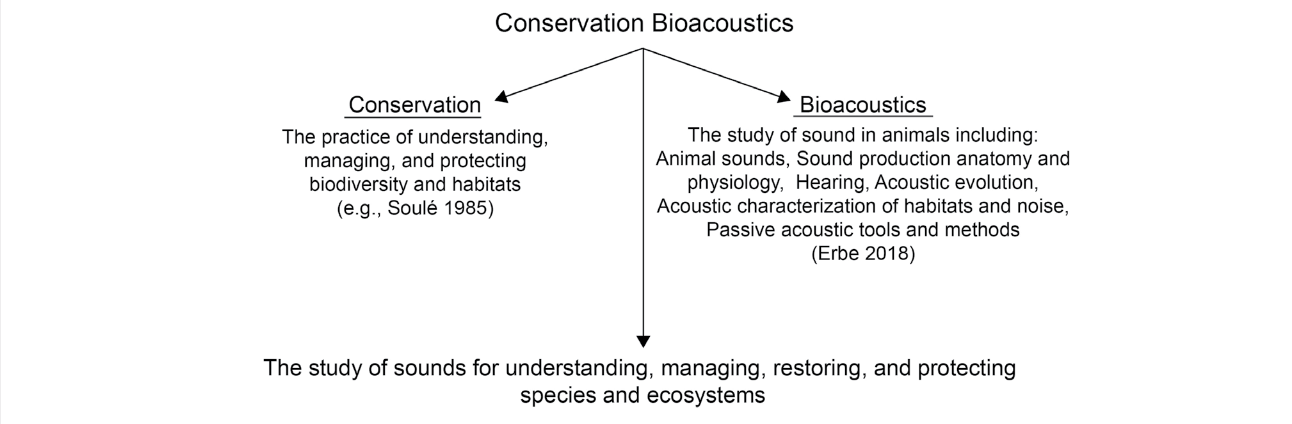



**Figure 2.** *Flowchart showing the conceptual relationship between the scientific fields of Conservation (e.g., Soulé, 1985) and Bioacoustics (Erbe, 2018) and how the two can be integrated to create the field of Conservation Bioacoustics.*

taxa and ecosystems at the vast spatial and temporal scales necessary to enable effective conservation actions (**Figure 1**). This growing field combines the disciplines of Conservation Biology (Soulé, 1985) with Bioacoustics (Erbe, 2018) to create a new, integrative field of Conservation Bioacoustics (Laiolo, 2010).

Based on Laiolo (2010), we use a working definition of "Conservation Bioacoustics" as applying the study of sounds in nature for understanding, managing, restoring, and protecting species and ecosystems (**Figure 2**). Currently, passive acoustic monitoring (PAM) is a primary application of Conservation Bioacoustics. PAM is enabled through autonomous recording devices, which record sounds within the environment and often focus on monitoring sounds of protected species (Van Parijs et al., 2009; Sugai et al., 2020; also see tinyurl.com/ASA-PAM). The recorders are placed noninvasively in environments, such as being buckled to a tree or suspended on the seafloor, and passively record sound in these environments. This is in contrast to "active acoustics," where devices emit a sound and the reflection pattern is the signal of interest. Because of its noninvasive nature, PAM is especially geared toward studying vulnerable species, where permitting is difficult and minimizing stress on the organism is essential.

What distinguishes Conservation Bioacoustics is its inherent motivation to shape ecological research into fuel for conservation success. For example, acoustic methods have played a key role in the identification and conservation of a unique population of New Zealand blue whales. These methods allowed a research team from Oregon State University, Corvallis, to establish that a group of blue whales were permanent, not seasonal, residents of the South Taranaki Bight in New Zealand (Barlow et al., 2018). This Bight also overlaps with mounting human pressures on natural resources, including petroleum exploration and potential seabed mining, with noise pollution that shrinks the range over which the whales can communicate. Knowledge of this newly documented population has helped activate and inform a social movement in New Zealand to enact the protection of these whales. The researchers developed models forecasting whale presence throughout the Bight (Barlow and Torres, 2021). From there, they can identify prime whale habitats, inform industrial limits, and successfully couple the scientific output to a conservation outcome.

Although the example of New Zealand blue whales represents a promising pathway to conservation success (di Sciara and Gordon, 1997; Tyack, 2001), translating a bioacoustics output to a conservation outcome is not always as intuitive or straightforward. Here, we illustrate a conceptual map documenting our working vision of how Conservation Bioacoustics can help span the research-implementation gap (**Figure 3**).

## *Translating Bioacoustics into Conservation*

Conserving biodiversity is a multidisciplinary and iterative process that entails a variety of stakeholder

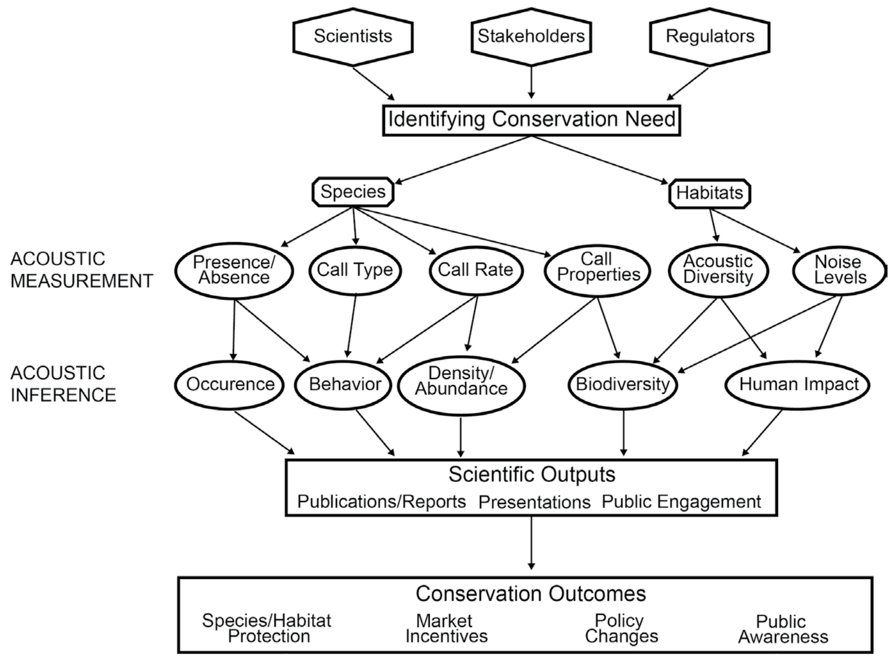



**Figure 3.** *Flowchart representation of the overall process of Conservation Bioacoustics, leading from constituents identifying conservation needs through to data collection, scientific outputs, and conservation outcomes.*

perspectives spanning biology, economics, environmental engineering, politics, and local communities. To initiate this process, a combination of these stakeholders identify an urgent or emerging conservation challenge. From there, they can define the species and/or habitats that are the conservation targets. Then, they can devise a plan for using acoustic data to shed light on these conservation targets.

Acoustic data can be the source for ecological information that directly aligns with conservation needs. Researchers can analyze acoustic data to learn when a vocally active species is occupying an ecosystem. Acoustic data can also capture the "noise footprints" that humans generate in ecosystems. For example, in forest landscapes, the sounds of gunshots on PAM recordings can demonstrate where and when poachers may be attempting to hunt forest elephants and noise from chainsaws can reveal legal and illegal logging activity (Wrege et al., 2017). In coastal environments, recordings of vessel noise or pile-driving activity can be used to estimate the time that whales are exposed to elevated anthropogenic noise levels and if those noise levels either exceed regulatory thresholds or represent a threat to the recovery of depleted populations (McKenna et al., 2016).

### *Transforming Outputs to Outcomes*

Translating bioacoustics to conservation requires a fundamental understanding of the distinction between outputs and outcomes. Traditionally, the scientific method has data synthesized into a strictly scientific output. Outputs typically take the form of peer-reviewed publications, conference presentations, or materials for public engagement. However, to achieve effective and impactful conservation, these outputs are but a stepping stone to an ultimate conservation outcome. These outcomes can take the form of protective legal measures, revision of management practices, strategic deployment of patrols to reduce illegal activity, financial incentives to conserve species or habitats, or greater public awareness and community stewardship.

Fundamentally, Conservation Bioacoustics is highly interdisciplinary and integrates ecological research, technology, and education; this combination forms three foundational components of a Conservation Bioacoustics framework. Technological advancements and education through training students and practitioners around the world (capacity building) are also key pillars driving the acceleration of conservation research, critical toward moving the field forward and fulfilling the goals of conservation success.

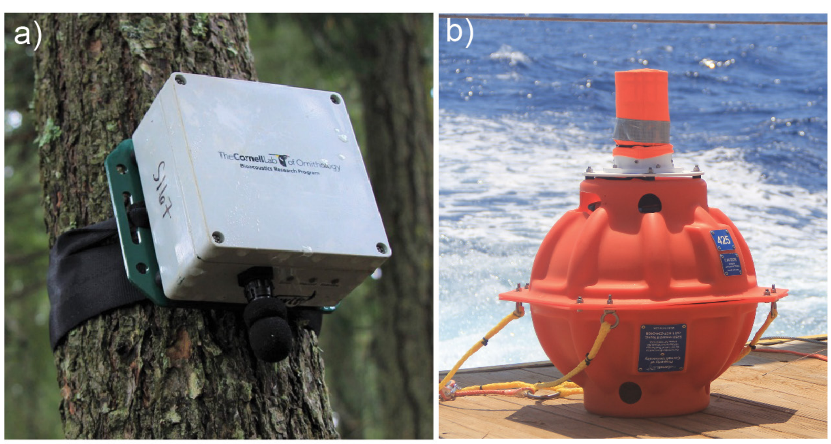
## Technological Advancements

Pursuing any scientific inquiry in Conservation Bioacoustics relies on constantly evolving recording technologies. In the early days of bioacoustics, recordings were analog, capturing no more than two hours on media such as tape. These recordings would then be transformed into spectrograms, which are visualizations of the recorded acoustic signals. The analysis to come could be long and tedious. With printouts of spectrograms scattered about, scientists would use rulers to measure the durations and pitches of each signal.

When analog audio transitioned to being digital in the mid-1980s, scientists saw many improvements in how acoustic data were collected, including the capability to record higher quality sound for longer intervals (Pavan et al., 2022). With the digital-recording revolution, increasing battery life, and larger data storage capacity, acoustic data could now be collected at previously unthinkable durations. In this accelerating era of PAM, the equipment could be left recording unattended for days or weeks at a time, with recent feats even managing years (**Figure 4**). Leaving rulers behind, computer-based analysis software such as Cornell's Raven Pro Software (see ravensoundsoftware.com) makes it possible to easily create spectrograms and annotate signals of interest, including relevant acoustic measurements and metadata. Conservation assessments often call for acoustic data that cover multiple seasons across several years to understand the seasonal patterns of important life history events of focal species (such as breeding or migration), and in an era of increasing human influence on the world's ecosystems (the epoch now referred to as the Anthropocene; e.g., Slabbekoorn, 2018), how those temporal patterns might be fluctuating because of climate change.

These technological innovations have expanded the potential for conservation impact by empowering people from across different backgrounds to exercise environmental stewardship via bioacoustics, using tools designed for citizen scientists like BirdNET (see birdnet.cornell.edu) or Haikubox (see haikubox.com) that help nonscientists automatically identify birds through artificial intelligence (AI)-based song recognition. The ability for recording devices to operate longer directly translates to less frequent deployment and recovery of equipment. For example, although remote regions are often the most biodiverse, collecting data in these environments can be costly in both logistical expenses and human effort. Because acoustic devices can record longer, researchers now have the opportunity to pursue in-depth studies in these ecologically significant remote areas. These devices offer greater returns on investment with their ability to collect data in quantities from which ecologically meaningful insights can be derived. With ecosystem monitoring now made accessible to smaller

**Figure 4.** *Representative recording devices developed at Cornell and used in Conservation Bioacoustics, including a terrestrial "Swift" recorder deployed in a tree (**a**) and a marine "Rockhopper" recorder device (**b, orange sphere**) on the stern of a research vessel awaiting deployment at sea.*



field teams globally, Conservation Bioacoustics could be the catalyst for localized conservation success.

Historically, most Conservation Bioacoustics recordings have been archival, meaning that the data can only be analyzed once the devices (or recording media) are returned to the laboratory. However, with increasing global connectivity (satellite, cellular, and WiFi), newer recording devices can detect signals of interest live from the field, reporting acoustic detections to practitioners and managers in near real time. Real-time detection marks a striking step forward from the field's traditional reliance on archival audio data, where it could take months or even years to access and analyze the data. Advancements like these facilitate data-driven decision making and conservation interventions.

With the exponential growth of acoustic data available to analyze, AI approaches (e.g., machine listening) have transformed the analytical capabilities in the Conservation Bioacoustics workflow (Tuia et al., 2022). Public data repositories of acoustic data (Parsons et al., 2022) have provided validated reference sounds for training and improving the performance of AI models (Kahl et al., 2021). Notably, the BirdNET algorithm, a deep convolutional neural network, can recognize over 6,000 bird species from raw acoustic data (Kahl et al., 2021). BirdNET is just one example among a growing pool of AI models (Tuia et al., 2022). The impact of these emerging AI models will be profound, dramatically increasing the ability to automate and expedite parts of the Conservation Bioacoustics analysis pipeline. The timeline from field recordings to conservation action will be accelerated, generating conservation outcomes at a pace relevant to rapid environmental, ecological, and climatological changes.

## Capacity Building and Engagement

To maximize success, conservation practitioners around the world must be empowered with the necessary tools to conduct bioacoustic monitoring in the ecosystems significant to their livelihoods and well-being. Although the importance of crafting university curricula at both the undergraduate and graduate levels cannot be overlooked, we need to look beyond traditional educational institutions. On-the-ground conservation practitioners should have the same access to relevant extensive training as the ones who often feel the effects of biodiversity loss and climate change first.

Despite the valuable insights that the acoustic data provide for conservation solutions, Conservation Bioacoustics remains an elusive skill set for university students, given its rare presence in higher education curricula. Consider, for example, the authors' home institution, Cornell University in Ithaca, New York. Although Conservation Bioacoustics has been a prominent research direction at Cornell for over three decades, a course bridging the field to students had yet to be offered. Where there was a gap, we saw an opportunity. In the fall semester of 2022, we taught Cornell's inaugural "Introduction to Conservation Bioacoustics" course. In a semester, we presented students with the theory and application of bioacoustics and conservation, recording technology, sound propagation, analytical approaches, signal processing, and acoustic detection across diverse taxa and ecosystems. At the end of the semester, students applied their new knowledge by implementing their own Conservation Bioacoustics projects during a Hawai'i-based field course during the winter session.

In the next course iteration, we will record key lectures and interactive laboratories to disseminate them publicly. As an international community, we prioritize supporting access to equipment and expertise in places where the utility of Conservation Bioacoustics runs high but resource investment historically runs low. To help make bioacoustics approaches more accessible, the K. Lisa Yang Center for Conservation Bioacoustics (Yang Center) at Cornell University (see bioacoustics.cornell.edu) has developed in-person and online acoustics workshops as well as a Bioacoustics Training and Mentorship Program that provides equipment and a year of training and mentorship to teams (see birds.cornell.edu/ccb/education). Our initial efforts have focused on Indonesia and Malaysia, where we are about to complete our first annual training and mentoring cycle. The program ends with an in-person symposium, where participants will present their Conservation Bioacoustics projects. The feedback from this first cohort has been positively energizing. Building on the momentum, we are working to expand this program to the Pantanal wetlands of South America and the tropical rainforest regions in Central Africa.

Conservation science has long suffered from "parachute science," the act of scientists conducting research in a country that is not their own without investing in the community or sharing results in the places where the work was conducted. To achieve the greatest impact, capacity building in Conservation Bioacoustics endeavors must follow an entirely different paradigm. Capacity-building efforts are most successful when community members have the skills and resources to conduct their own Conservation Bioacoustics projects.

## Where the Field Is Headed

### *Conservation Impacts from Bioacoustics*

Over the last decade, the rapid expansion of Conservation Bioacoustics has risen in parallel with a diversity of bioacoustics-informed conservation outcomes. We have accomplished scales of analyses previously unthinkable of 10 or 20 years ago, fueled by the maturation of technology for longer term and less expensive data collection.

In terrestrial habitats, the initial discovery of infrasonic vocalizations by elephants by Payne et al. (1986) led to the widespread use of PAM for understanding and managing forest elephant populations in Central and Western Africa (Wrege et al., 2017). Extended use of PAM in the Western North Atlantic Ocean has enabled the long-term study of occurrence patterns of North Atlantic right whales, documentation of shifting migration patterns, and new management strategies to promote their conservation, including increasing the size of protected areas and seasonal exclusion zones to minimize the impact of human activities (Davis et al., 2017). Yet, although progress in the field has been substantial, these successes have nevertheless tested the limits of existing systems and, in turn, highlighted emerging challenges.

### *Technological Challenges*

Although it is now possible to collect large quantities of information, data collection is still primarily constrained by storage, power, and the ability to share large quantities of data. Storage continues to become cheaper and larger, but battery technology has not seen comparable advancements in maximizing longevity or minimizing environmental impact. Lower power devices are still being developed, but battery life remains the limiting factor and solar power is not yet practical for many applications. Because many imperiled/exploited species and human activities (e.g., traffic, hunting) are detectable through sound, real-time acoustic detection enables rapid response and intervention of conservation managers (Van Parijs et al., 2009). However, battery life and connectivity remain key issues, particularly in densely forested areas or remote locations.

### *Expanding Scales of Data Collection*

Once long-term data are collected, it still needs to be stored in a way that can be accessed by multiple people, often across a geographically distributed area. Cloud data storage may seem like the best path forward because it makes data sharing more intuitive, but it entails significant costs for long-term storage. And when the funding for a project reaches the end of its cycle, what becomes of the data? Without ongoing project funding, there is often no path for ongoing data storage, which constrains the ability to aggregate cumulative datasets for more comprehensive PAM efforts.

In the United States, one institutional model that has begun to tackle these challenges successfully is the National Center for Environmental Information (NCEI), which is located within the National Oceanic and Atmospheric Administration (NOAA). NCEI has established a large data repository for the long-term storage and public accessibility of passive acoustic data from US government-funded marine PAM projects within US waters (see ncei.noaa.gov/products/passive-acoustic-data) (Wall et al., 2021). However, comparable repositories still need to cover long-term terrestrial passive acoustic data as well as passive acoustic data collected in other regions outside of the United States.

Moreover, machine listening has rapidly changed the prospects for automatically detecting sounds of interest, even with small amounts of initial training data (Tuia et al., 2022). Nevertheless, there are substantial ongoing challenges to automating analysis of bioacoustics data. These challenges include evaluating model performance when detection events are challenging for humans to confirm or refute (faint calls) (e.g., Digby et al., 2013), training effective models when training data are limited (few-shot learning), and deciphering complex soundscapes with many overlapping signals in time and frequency as well as the limited ability to aggregate and exchange training data across research groups while accurately attributing credit to the original data sponsors and collectors.

### *Translating Bioacoustics Sounds into Population Estimates*

How to best translate Conservation Bioacoustics data into policy remains an area for further optimization. Because many regulatory measures are centered around population size or the number of individuals of a particular species, it is desirable to apply bioacoustics for density and abundance estimation (Marques et al., 2013). Inherent to density estimation approaches is knowing a species' detection probability, detection range, and call rate (Marques et al., 2013). However, these parameters are not yet well-established for many marine and terrestrial species deemed a conservation priority.

### *Bioacoustics and Conservation Outcomes*

Finally, for Conservation Bioacoustics to reach full maturity, the connection between Conservation Bioacoustics and conservation action must be enhanced. Additionally, researchers must deliver acoustic insights with sufficient speed and interpretability to facilitate effective management action. Conservation Bioacoustics has seen rapid growth and emerged from a nascent and obscure subdiscipline into an increasingly accepted and promising field with transformative potential for natural resource conservation in both scale and scope. The continued acceleration of technology, examples of successful conservation outcomes through research, the growing number of students and experts, and the increased public awareness of the opportunities and importance of Conservation Bioacoustics all point to the field's continued growth and impact potential in our current crisis of global biodiversity loss.

## Acknowledgments

We thank Christopher W. Clark for his vision for using bioacoustics to achieve conservation opportunities and the importance of integrating biology, technology, and education for the success of Conservation Bioacoustics as an emerging field. Further development of the conceptual framework for integrating bioacoustics and conservation came from extensive discussions with Susan Parks and David Luther. We also thank K. Lisa Yang for providing generous support to ensure the continued success of Conservation Bioacoustics for years to come.

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# A Century of Acousto-Optics: From Early Discoveries to Modern Sensing of Sound with Light

*Samuel A. Verburg, Kenji Ishikawa, Efren Fernandez-Grande, and Yasuhiro Oikawa*

## Introduction

*Acousto-optic sensing* refers to the measurement of acoustic phenomena using *light*. The interaction between *sound* and *light* enables us to visualize and measure a wide range of acoustic phenomena that are difficult to observe with the most common type of acoustic sensors, the microphone. Such phenomena include, for example, the sound generated by a fast-moving source (e.g., a high-speed train), the three-dimensional (3D) sound field over a large volume (e.g., the reverberant field inside a room), or the interrelationship between acoustics and fluid dynamics (e.g., the combined sound field and airflow in front of a whistle).

Because no physical devices, such as conventional microphones and transducers, are introduced in the measured area, this type of measurement is remote and *noninvasive*. Such noninvasive measurements are relevant for a broad range of fields within acoustics, including metrology, underwater acoustics, architectural acoustics, bioacoustics, noise control, education, and generally all areas where the visualization and measurement of acoustic fields are of interest.

Still, acousto-optic sensing is relatively unknown to many acousticians; presumably, the application of these techniques has been limited by the lack of suitable technology and instrumentation. At present, however, we are witnessing substantial advances in optical technologies that are unlocking a vast domain of opportunity in the field. In this article, we describe the basics of acousto-optic sensing, summarize the historical development of optical methods to observe sound, and give an account on the-state-of-the-art through a few selected examples and current applications. We finalize with an outlook, looking ahead into some of the exciting prospects in the field.

## The Acousto-Optic Interaction

In a transparent homogeneous medium, light rays travel uniformly and follow a straight path. However, media like air or water are rarely perfectly homogeneous; the propagation of light is affected by disturbances such as flow, turbulence, heat transfer, density changes, and sound waves. Therefore, light propagating through a given medium contains information about the inhomogeneity of that medium. Researchers in optics have been utilizing this effect for visualizing invisible phenomena. Changes in the propagation of light caused by inhomogeneities are described by the *refractive index* (Feynman et al., 1964), a quantity that represents the *slowness* of light propagation.

As acousticians, what we are interested in the most is how the presence of sound waves modifies the propagation of light, a phenomenon called *acousto-optic interaction*. In this article, we focus on the frequency range from 20 Hz to 20 kHz (i.e., the audible range for humans) propagating in air at "normal" sound levels (e.g., below 130 dB re 20 μPa).

The different ways in which light and sound interact are illustrated in **Figures 1** and **2.** Acousto-optic effects can be classified into three phenomena: diffraction, refraction, and retardation.

A laser beam traveling across a high-frequency sound wave experiences *diffraction* (**Figure 1a**). The laser beam gets diffracted into several beams, with directions that depend on the acoustic (sound) and electromagnetic (laser) frequencies. Acousto-optic diffraction occurs when the width of the laser beam is larger than the acoustic wavelength (i.e., when the laser beam is "thicker" than the distance between the wave crests). In this case,



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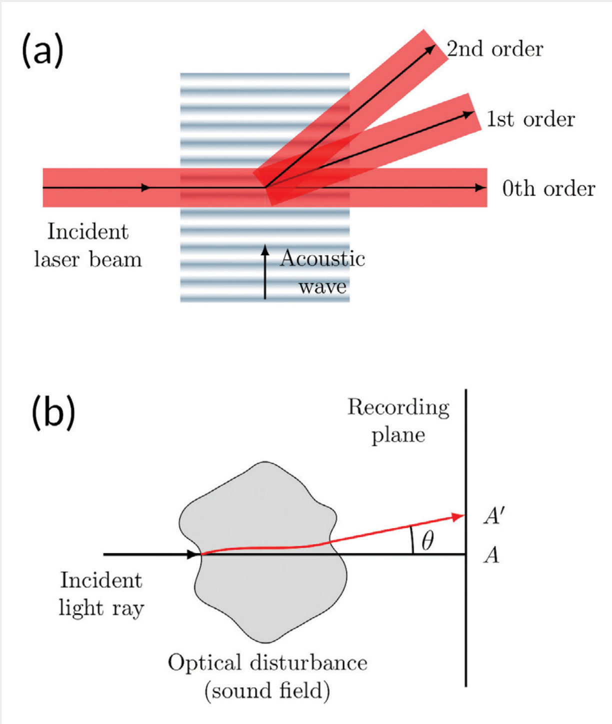



**Figure 1.** *Two types of interaction between acoustic waves and light.* ***a:*** *Diffraction of a laser beam by ultrasonic waves.* ***b:*** *Refraction of a light ray by an optical disturbance. See text for explanation.*

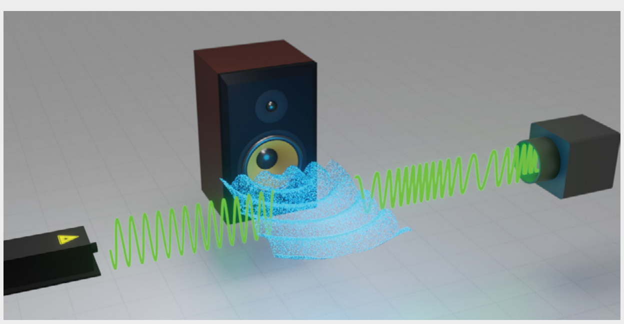


**Figure 2.** *Acousto-optic sensing of sound based on changes in the phase of the electromagnetic wave (light) due to acoustic waves. The electromagnetic wave (**green**) traveling through a sound field (**blue**) experiences a phase shift. The change is detected by optical means (e.g., a high-speed camera).*

the acoustic wave causes the light beam to diffract as if it was passing through a grating. The acousto-optic diffraction is the underlying principle of many devices used in modern laser technology to modulate light and generate ultrafast laser pulses.

Light rays traveling through a sound field also experience *refraction* (**Figure 1b**) when the sound field produces gradual variations of the medium's refractive index on the laser path. As shown by Fermat's principle, when light travels between two points, it will always take the path that requires the shortest time (formally, the path of minimum *optical path length*, defined as the integral of the refractive index over the geometrical path). Therefore, light rays *refract* or *bend* toward regions of smaller refractive indices.

Two classical visualization techniques based on the refraction of light are *shadowgraphy* and *schlieren*. Shadowgraphy consists of recording the displacement of the light rays (distance $A$-$A'$ in **Figure 1b**). In schlieren, an optical image of the angular deflection ($\theta$ in **Figure 1b**), is formed (Settles, 2001).

In addition to diffraction and refraction, light also experiences apparent *retardation* or a *phase shift* when traversing a sound field (**Figure 2**). Monochromatic light can be described as an electromagnetic wave, with a frequency, amplitude, phase, and polarization. Acoustically induced changes in the refractive index change the apparent velocity at which light propagates, as if light would travel slightly slower in areas of high pressure and slightly faster in areas of low pressure (Torras-Rosell et al., 2012). These changes translate into a phase shift of the electromagnetic wave, which can be measured via *interferometry* (interferometry refers to the superposition of two light beams, one that is exposed to the sound wave and one that is undisturbed and acts as a reference).

Of the three phenomena, refraction and phase shift have been used for visualizing audible sound fields. The refraction caused by acoustic waves is so small that very high sound pressure levels are typically required to record shadowgrams and schlieren images of sound waves. Although the phase shifts induced by acoustic waves are also small, optical interferometers are very precise and they can capture such phase shifts. Interferometry is often used in today's state-of-the-art methods for measuring audible sound. Some of them are be presented in **Acousto-Optic Sensing Today**.

## Historical Background of Acousto-Optic Sensing

### *First Visualizations*

The visualization of sound fields is a powerful means to understand how sound propagates. Early records dating as far back as classical Greece and Rome (Kilgour, 1963) contain analogies between water waves and sound fields to build an intuitive understanding of how sound "fills a space." It was not, however, until the nineteenth century that specific techniques to visualize audible sound and other invisible phenomena were developed. The underlying principle of these visualization methods is the refraction of the light rays caused by changes in the air density, something similar to a mirage over a heated road on a sunny day.

Wallace Clement Sabine pioneered the optical visualization of pressure waves in the field of acoustics. In the 1910s, Sabine built several scale models of theaters and auditoria and then generated shock waves inside the models using fulminate mercury explosions and electric sparks. Sabine was able to obtain surprisingly detailed photographs of the waves reflecting off the surfaces of the scale models using shadowgraphy (Sabine, 1913; see bit.ly/3XlfSiK).

Following Sabine's experiments, Swiss engineer Franz Max Osswald further developed the technique to photograph sound (Von Fischer, 2017). **Figure 3** shows one of Osswald's shadowgrams depicting the horizontal cross section of an auditorium model (side view) where the lines within the gray region are the pressure waves radiated by a source (**Figure 3**, *black circle*). One can clearly see the progression of the wave fronts and how they reflect and diffract from the different surfaces. The type of visualization techniques used by Sabine and Osswald, such as shadowgraphy and schlieren, offered very low sensitivities though, and consequently, their use was limited in the scientific study of acoustics.

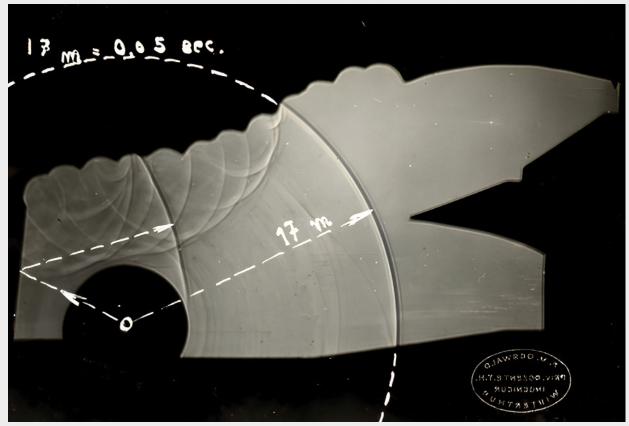



**Figure 3.** *One of Osswald's experiments with shadowgraphy in an auditorium model (doi.org/10.3932/ethz-a-000986431). From the Image Archive, ETH Library Zurich, Switzerland. See text for explanation.*

### *The Birth of Acousto-Optics*

The work of French physicist Léon Brillouin was a landmark in the field of acousto-optics. In 1922, Brillouin postulated that as light passes through a medium (e.g., a crystal, water, or air), it interacts with waves traveling in that medium (e.g., an acoustic wave) in a very particular way. Specifically, the waves cause the light beam to diffract (Brillouin, 1922).

The diffraction of light by ultrasound was observed for the first time in 1932 by Debye and Sears (1932) in the United States and by Lucas and Biquard (1932) in France. In the 1930s, Indian physicists Raman and Nath (1935) developed the theory for the diffraction of light due to ultrasonic waves, referred to as the acousto-optic diffraction. The first applications of the acousto-optic diffraction coincide with the onset of the use of lasers in the 1960s. A plethora of devices that use sound waves to modulate, deflect, and focus beams were developed, and continue to be widely used today (Adler, 1967).

### *The Second Half of the Twentieth Century*

During the 1960s and 1970s, various visualization methods based on laser interferometry were proposed. Developed in 1965, *holographic interferometry* offered a noncontact way of visualizing the vibration of objects as well as invisible phenomena in transparent media (Vest, 1979). In a double-exposed hologram, the light reflected by an object at two different deformation states was recorded on a single photographic plate so that the reconstructed hologram displayed interference fringes that correspond to the deformation. Holographic interferometry evolved rapidly, yet the process was complicated and time consuming, involving the exposure and development of photographic plates.

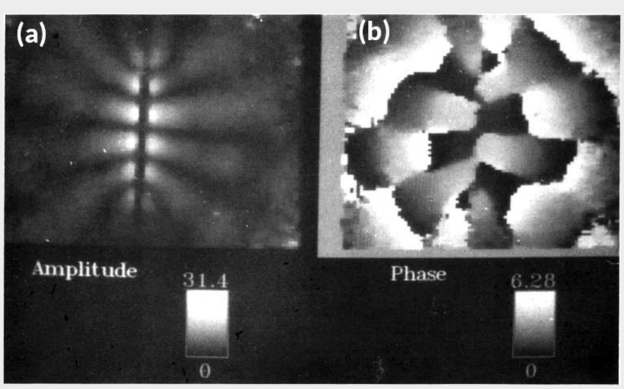
The use of electronic recording devices was introduced in the 1970s. In a method called *electronic speckle pattern* *interferometry*, a video camera recorded the speckle pattern formed when illuminating an object with coherent light. The recorded images were then processed to visualize the phenomena. The use of digital cameras in the 1980s further advanced the development of imaging techniques. However, it was still difficult to retrieve quantitative information of acoustic pressure waves. It was not until the 1990s and early 2000s that systems sensitive to the amplitude and phase of the acoustic signals began to be adopted.

**Figure 4** shows one of such experiments (Løkberg, 1994). The sound field radiated by a vibrating metal plate was recorded using a version of electronic speckle pattern interferometry. The images show a side view (i.e., looking at the plate's edge) with the amplitude of the projected field seen in **Figure 4a** and the phase seen in **Figure 4b**. This type of quantitative acousto-optic measurement was only possible due to the technological maturity achieved in the 1990s.

### *The New Century*

From the start of the new century, technological developments and research in the field have made it possible to quantitatively measure, visualize, and reconstruct audible sound of "normal" amplitude. One of the most popular of devices currently used for acousto-optic sensing is the laser Doppler vibrometer (LDV), an interferometer originally designed to measure the vibration velocity of objects (see bit.ly/3Nr2hSq). LDVs are a popular way to measure and visualize acoustic fields (Oikawa et al., 2005), partly because off-the-shelf LDV units are compact and easy to set up compared with other ad hoc interferometric arrangements.

**Figure 4.** *Visualization of the sound field radiated by a vibrating plate using electronic speckle-pattern interferometry. The* ***gray scales*** *represent nanometers for the amplitude (****a****) and radians for the phase (****b****).* ***a:*** *Plate profile appears as a* ***black line*** *in the center. The sound radiated by the plate appears as* ***white streaks*** *on the sides of the plate.* ***b:*** *Phase map shows phase values increasing linearly from 0 (****black****) to 2π (****white****), indicating the directions in which sound waves are traveling. Reproduced from Løkberg (1994), with permission of the Acoustical Society of America, Copyright 1994.*




LDVs can provide measurements of a sound field *projected* along a laser beam. Projections of a sound field on a two-dimensional (2D) plane can be also obtained using a scanning LDV, which is a LDV with a set of moving mirrors that can steer the laser beam in multiple directions. Because LDVs essentially provide a single-point measurement, it is necessary to scan the field to obtain 2D projections. Because of this, the visualized sound fields are limited to those that can be generated repeatedly, such as the sound field radiated by a loudspeaker.

In recent years, the use of polarized high-speed cameras has removed the need for scanning LDVs. As the camera captures 2D images of the sound field on thousands of pixels simultaneously, the sound fields that can be measured are no longer limited to those that can be repeated. A high-speed camera captures 2D sound fields with tens or hundreds of thousands of frames per second, making it possible to film a slow-motion video of propagating sound in real time. In particular, parallel phase-shifting interferometry (PPSI) has demonstrated impressive visualizations of airborne acoustic phenomena due to its high sensitivity and spatiotemporal resolution (Ishikawa et al., 2016).

## Acousto-Optic Sensing Today

### *Three-Dimensional Sound Field in Rooms with a Laser Doppler Vibrometer*

Measuring and visualizing sound fields in three dimensions is central to many aspects of acoustics. However, acquiring sound fields over large volumes of space using conventional microphones is challenging. Acousto-optic sensing provides a remote, noninvasive, and high-resolution way of acquiring volumetric sound fields.

For example, in a recent study (Verburg and Fernandez-Grande, 2021), the 3D sound field inside a reverberant

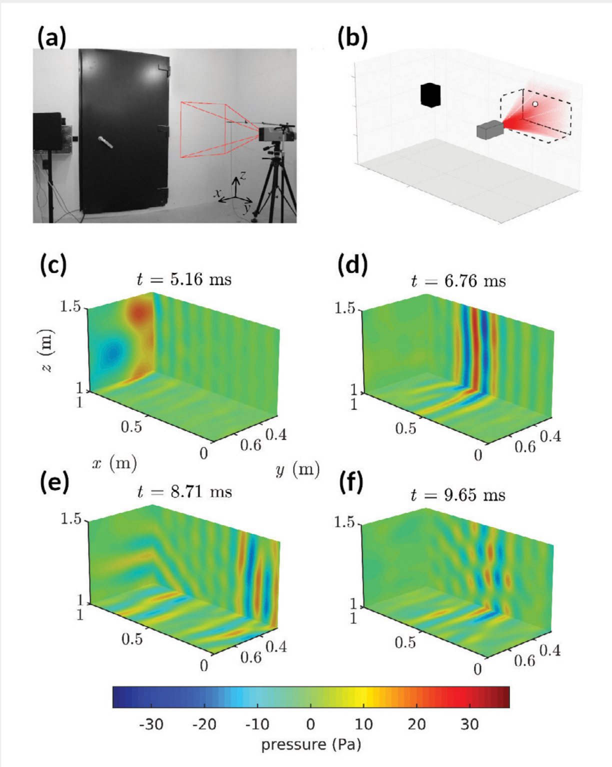



**Figure 5.** *Three-dimensional sound field inside a reverberant room reconstructed from remote acousto-optic measurements.* ***a and b:*** *Experimental setup. The LDV (**b, gray box**) was used to acquire acousto-optic measurements of the sound field radiated by a loudspeaker (**a, black box**). The sound field was sequentially scanned over a square-pyramid volume (**red**). The sound field was reconstructed in a 1- × 0.5- × 0.5-m³ rectangular volume (**b, dashed line**), and the acoustic pressure is displayed on three planes corresponding to three sides of such volume.* ***c-f:*** *Four snapshots of the acoustic pressure over time.* ***c:*** *Sound arriving from the source.* ***d:*** *Wavefront as it travels.* ***e:*** *Two reflections, one from a wall and one from the floor.* ***f:*** *Interference pattern between the two reflections. The color map represents the amplitude of the acoustic pressure. Reproduced from Verburg and Fernandez-Grande (2021), with permission of the American Physical Society, Copyright 2021.*

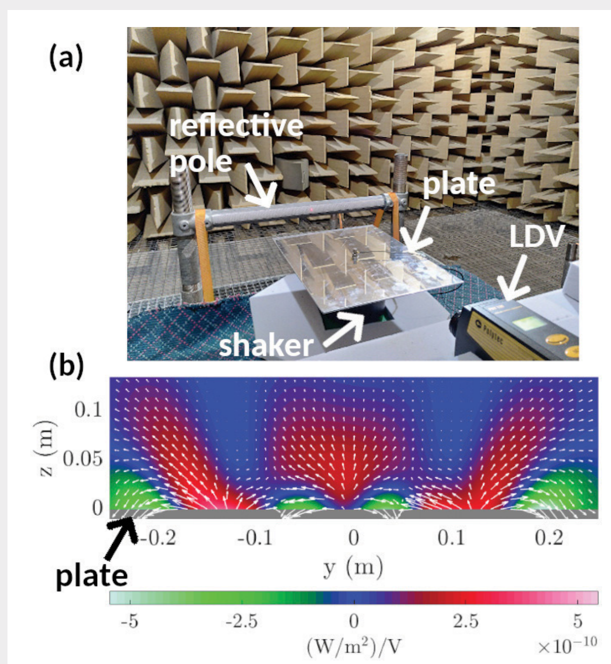
room was reconstructed from acousto-optic measurements using a scanning LDV (**Figure 5a, b**). The LDV (**Figure 5b,** *gray box*) was used to acquire acousto-optic measurements of the sound field radiated by a loudspeaker (**Figure 5b**, *black box*). **Figure 5c-f** corresponds to four snapshots of the acoustic pressure over time (see bit.ly/44wgbKm for a video).

## *Near-Field Acoustic Holography with a Laser Doppler Vibrometer*

Near-field acoustic holography (NAH) is a powerful technique that makes it possible to examine and visualize how acoustic sources radiate sound into the medium. In NAH, the sound pressure near a source is normally measured using an array of microphones. However, at high frequencies, the microphone spacing needs to be increasingly small, and the sound scattering due to many closely spaced microphones introduces significant measurement errors (i.e., the microphone array can no longer be assumed to be "acoustically transparent").

The use of acousto-optic sensing for near-field measurements has recently been examined as a noninvasive alternative to conventional microphones by Verburg et al. (2022). The experimental setup of this study is shown in **Figure 6a**. The acoustic pressure at 3.5 cm above a

**Figure 6.** *Optical measurements of the sound field above a vibrating plate.* ***a:*** *Experimental setup. LDV, laser Doppler vibrometer.* ***b:*** *Intensity field above the plate.* ***White arrows:*** *direction and amplitude of the vector intensity field. The color map indicates the amplitude of the intensity field in the direction normal to the plane. Reproduced from Verburg et al. (2022), with permission of the Acoustical Society of America, Copyright 2022.*



vibrating aluminum plate was optically measured using a LDV. The plate was mounted on a shaker to excite vibrations. The laser beam was directed at a steel reflective pole covered with retroreflective tape. The setup was installed inside an anechoic chamber.

As an example, **Figure 6b** shows the sound intensity field (i.e., the flow of acoustic energy) *above* the plate when it was vibrating at a resonance frequency. To visualize how the plate radiates sound energy into the medium, **Figure 6b** shows a vertical cross section passing through the center of the plate (the *x-y* plane with $z = 0$ corresponds to the position of the plane). It is possible to observe complex radiation phenomena such as the nonpropagating circulation of acoustic intensity close to the plate. Such fine details are difficult to capture using conventional microphone arrays, especially at mid- and high frequencies.

## Aeroacoustics and Moving Sources with Parallel Phase-Shifting Interferometry

Measuring sound fields in the presence of airflow with conventional microphones is very challenging. First, introducing a device in the measurement area will undoubtedly disturb the airflow. And second, the flow of air around the microphone will generate a high noise (we have all tried to have a phone call on a windy day). Acousto-optic sensing is suitable for measuring sound fields in the presence of airflow; because light is the sensing element, no physical device is introduced in the measurement area. Interestingly, the technique enables one to observe acoustic waves and the fluid dynamics simultaneously, a practice that is not possible with conventional acoustic instrumentation.

**Figure 7** visualizes both the airflow and the sound waves emitted from a whistle using PPSI and a high-speed camera (Ishikawa et al., 2018) (see bit.ly/3XWkFaG for a video). At 0 ms, we can start to see the flow of air coming from the opening of the whistle. As time progresses, the turbulent flow develops, showing a seemingly chaotic structure. At 33.3 and 38.1 ms, a spherical acoustic wave radiating from the whistle opening can clearly be seen. It is interesting to observe that the two types of perturbation (acoustic and flow) present very different temporal and spatial scales. The airflow evolves more rapidly and presents a finer structure over space. The combined analysis of flow and acoustic waves is only possible due to the recent advances in acousto-optic sensing and PPSI.

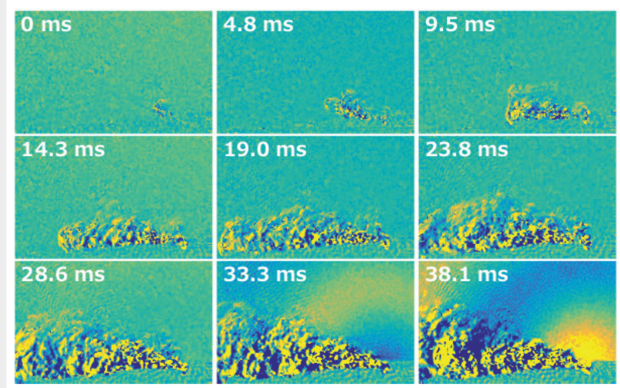



**Figure 7.** *Simultaneous visualization of the airflow and the sound waves emitted from a whistle using parallel phase-shifting interferometry (PPSI) and a high-speed camera.* ***Bottom right of each panel:*** *position of the whistle. The color map represents changes in the phase of the laser beam used to visualize the phenomenon. Reproduced from Ishikawa et al. (2018), with permission of The Optical Society, Copyright 2018.*

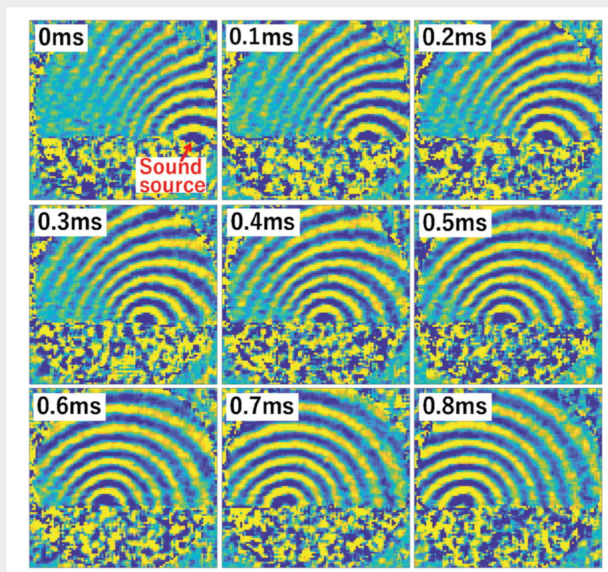



**Figure 8.** *Visualization of fast-moving sound sources. The wavefronts can be observed as* ***blue and yellow semicircles****. Adapted from the results of the joint research by Waseda University and the Railway Technical Research Institute in Japan. See text for explanation.*

A related application is the visualization of fast-moving sound sources such as high-speed trains. A fast-moving source generates airflow itself, and the acoustic pressure that it radiates is difficult to capture. In a recent study, Akutsu et al. (2022) used PPSI to visualize the sound field generated by the scale model of a train. A sound source was flush mounted on the scale model and launched at a speed of 280 km/h (174 mph). The source was emitting a pure tone of 40 kHz. **Figure 8** shows the resulting phase changes of light captured with a high-speed camera (see bit.ly/46S5CmG for a video). As the sound source travels from right to left, the wavefronts are "compressed" in front of the model and "expand" at the back. This behavior, known as the Doppler effect, is typical of moving sources.

### *Acoustic Metrology with Light*

Acoustic metrology is the area of acoustics that deals with the definition of measurement units (e.g., the Pascal in the case of acoustic pressure) as well as the traceability and calibration of measurement devices. Although several standardized methods exist to calibrate acoustic measurement devices, none of them is free of limitations.

One common calibration method is the *free-field calibration* in which a pair of microphones are positioned facing each other at a fixed distance in a free field (e.g., an anechoic chamber). A major source of uncertainty in free-field calibration is knowing the exact distance between the *acoustic center* of both microphones (which is different from the physical distance between them). Hermawanto et al. (2023) were able to determine the acoustic center of a microphone with high accuracy, leveraging the noncontact nature of acousto-optic sensing.

In the past, the relatively high noise level of optical measurements hindered their application to acoustic metrology. However, recent advances in acousto-optic measurements have achieved equivalent noise levels of 0 dB sound pressure level (SPL)/Hz (Ishikawa et al., 2021), which is comparable with standard high-precision measurement microphones. It all seems to indicate that optical measurements will play a crucial role in next-generation acoustic metrology due to their precision, universality, and noncontact nature.

### *Other Applications*

Acousto-optic sensing has found multiple other applications in recent years, just a few of which are discussed now. One of the aims of research in bioacoustics is to reveal the mechanisms by which animals generate sound because this sheds light on the evolutionary processes of the animals that produce it. It is sometimes difficult to measure and visualize such bioacoustic signals, and acousto-optic sensing can help to do so. Optical, noncontact PPSI measurements have recently been used to visualize the sound generated by the cicada (*Tanna japonensis*), a sound-producing insect (Oikawa et al., 2018) (see bit.ly/3DjQq45). This type of visualizations can be used to observe the spatial and temporal features of bioacoustic signals, deepening our understanding of how animals produce sound. Other videos of acoustic phenomena captured using PPSI can be seen on Professor Oikawa's laboratory YouTube channel at bit.ly/3rrsUzq.

The high spatial and temporal resolution offered by PPSI as well as its noncontact nature make it a convenient tool to investigate the sound radiation from musical instruments. For example, Ishikawa et al. (2020) investigated the sound produced by *castanets*, a small percussion instrument used in traditional Spanish music. The castanets are composed of two wooden shells that produce a strong clapping sound when played. Because of the way it is constructed, no measurement device can be placed in between the two shells where the sound resonates. Due to the noncontact nature and high resolution of optical measurements, it was possible to unveil the sound-generation mechanism of castanets (see bit.ly/3Di1miI). A better understanding of the mechanisms in which musical instruments generate sound can help us craft better sounding and more-durable instruments as well as guide us in the restoration of historical instruments.

Acousto-optic sensing can also help address long-standing problems in engineering acoustics, such as the characterization of acoustically absorptive materials. Classrooms, hospitals, and offices are usually treated with acoustic panels that absorb unwanted sound. A common way of quantifying the absorption of the acoustic materials used for the panels is the *impedance-tube* method. The method consists of placing a sample of the material on one end of a rigid tube while sound waves are generated with a loudspeaker placed on the other end. The sound energy absorbed by the sample is then monitored with a pair of microphones mounted on the tube's wall. However, the impedance-tube frequency range of operation is limited by the tube's width. Acousto-optic sensing has made it possible to largely extend this frequency range, facilitating the characterization of acoustic materials. Vanlanduit et al. (2005) measured the sound field inside a transparent tube using a LDV and characterized different materials. Because the sensing element (light) does not interfere with the acoustic field, tubes narrower than the standard ones could be used, effectively extending the frequency range of validity.

## Outlook

Although it might still be a relatively unknown technique, we expect to see a broader understanding and use of acousto-optic sensing in the acoustics community. After all, many fields within acoustics can benefit from remote, noninvasive acoustic measurements and visualizations. For instance, optical visualization of sound can be directly applied to, for example, education, musical acoustics, and bioacoustics where the visualization of invisible phenomena can help build an intuition.

The measurement and visualization of sound using light is a relatively new area that has an extraordinary potential for exploration across the field of acoustics. State-of-the-art acousto-optic measurements are already able to achieve very low noise levels as well as render detailed visualizations. Further technological advances will make it possible to address long-standing acoustic problems, find new applications, and unveil complex acoustic phenomena. In particular, the field of *quantum photonics* is experiencing a very rapid development, with increasing capabilities to generate, manipulate, and detect light at the level of individual quanta. Detectors can count individual photons, and ultrafast lasers can send femtosecond ($10^{-15}$ s) light pulses, thus pushing the limits of what is possible in experimental physics. It will be exciting to see how acousto-optic sensing benefits from these advances in the near future.

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# Recent Acoustical Society of America Awards and Prizes

*Acoustics Today* is pleased to present the names of the recipients of the various awards and prizes given out by the Acoustical Society of America. After the recipients are approved by the Executive Council of the Society at each semiannual meeting, their names are published in the next issue of *Acoustics Today*.

Congratulations to the following recipients of Acoustical Society of America medals, awards, prizes, and fellowships, who will be formally recognized at the Fall 2023 Plenary Session. For more information on the accolades, please see acousticstoday.org/asa-awards, acousticalsociety.org/prizes, and acousticstoday.org/fellowships.

*Wallace Clement Sabine Medal*

**Peter D'Antonio**
(RPG Acoustical Systems LLC) for contributions to theory, design, and application of acoustic diffusers

*Rossing Prize in Acoustics Education*

**Scott D. Sommerfeldt**
(Brigham Young University, Provo, Utah)

*Silver Medal in Acoustical Oceanography*

**Stan E. Dosso**
(University of Victoria, Victoria, British Columbia, Canada) for contributions to Bayesian inference methods in ocean acoustics and marine geophysics

***David T. Blackstock Mentorship Award***
*(Awarded by the Student Council)*

**Mark F. Hamilton**
(University of Texas at Austin)

Congratulations also to the following members who were elected Fellows in the Acoustical Society of America in Fall 2023.

- **John L. Davy**
  (RMIT University, Melbourne, Victoria, Australia) for contributions to modeling of sound insulating wall boards and modal theories of rooms and structures
- **Libertario Demi**
  (University of Trento, Trento, Italy) for contributions to lung ultrasound
- **Lixi Huang**
  (The University of Hong Kong, Pokfulam, Hong Kong) for contributions to biomedical noise control, aeroacoustics, and acoustics
- **Amanda M. Lauer**
  (Johns Hopkins University School of Medicine, Baltimore, Maryland) for multidisciplinary contributions to hearing and hearing impairment in wide-ranging animal models
- **Benjamin E. Markham**
  (Acentech, Cambridge, Massachusetts) for leadership and teaching in the field of architectural acoustics
- **Thomas J. Royston**
  (University of Illinois at Chicago) for furthering understanding of anisotropy and acoustoelasticity in dynamic elastography

## Erratum

Two errors were found in the article "Uncertainty in Acoustical Modeling," by Sheri L. Martinelli, D. Keith Wilson, Andrew S. Wixom, and Chris L. Pettit, which appeared in the summer 2023 issue (volume 19, issue 2). The caption for figure 3 should read, "Frequency dependence of the Lloyd's mirror transmission loss (TL) interference pattern. a: Wavelength ($\lambda$) = 2 m or 170 Hz; b: $\lambda$ = 1 m or 340 Hz; c: $\lambda$ = 0.5 m or 680 Hz. Darker regions indicate destructive interference (high TL), whereas lighter regions indicate constructive interference (low TL)." Additionally, the sentence starting on line 10 of page 31 should read, "These values correspond to wavelengths of 2 m, 1 m, and 0.5 m, respectively."

# Conversation with a Colleague: Jennifer Cooper

*Jennifer Cooper*
*Conversation with a Colleague Editor:*
*Micheal L. Dent*

## Meet Jennifer Cooper

**Jennifer Cooper** is the next acoustician in our "Sound Perspectives" series "Conversation with a Colleague." Dr. Cooper is currently a program scientist at the Johns Hopkins Applied Physics Laboratory (APL), Laurel, Maryland, and was a member of the Executive Council of the Acoustical Society of America (ASA). Jennifer received her BS from the University of North Texas, Denton, with a major in physics. She received her MS and PhD from The Pennsylvania State University, University Park, in acoustics. We asked Dr. Cooper to give us her elevator pitch and then to elaborate on her inspirations, contributions, and hopes for the future.

### *Give your "elevator speech" about the thrust(s) of your scholarly work over your career.*

Light and other electromagnetic waves tend to not travel very far underwater due to a variety of environmental and sensor limitations, but sound does. As a result, hydrophones (underwater microphones) provide an excellent sensing system for all things emanating sound into the ocean. The Navy uses SOund NAvigation and Ranging (SONAR) to extend their sensing capabilities beyond those possible with electromagnetic and electro-optic systems to maintain their operational situational awareness. There are multiple acoustic signals in the ocean that we can observe, including marine mammals and other biologics along with man-made vessels and wind, rain, and seismic phenomena. By using arrays of hydrophones, we can break up that noise into smaller subsets based on the direction that each signal is coming from and hopefully separate out the signal we are interested in from the others. My work over the past 15 years largely centers around the research, design, testing, and employment optimization of sonar systems used by the Navy. This differs somewhat from the arrays used purely for research because longevity, cost, reliability, manufacturability, and usability in real time by a crew without advanced acoustics degrees all come into the equation. For example, we may be concerned about the precise relative calibration between hydrophones in an array and how that calibration changes with time, temperature, or depth. Ultimately, it's my job to predict how those variations will impact system performance.

### *What inspired you to work in this area of scholarship?*

Like many acousticians, I was interested in both music and science in school and attempted to double major in jazz and physics. I briefly thought that perhaps I would someday design concert halls and then perform in them. Of course, that is extremely difficult within the constraints of financial aid limits on the number of course hours, and I ended up not completing the music degree. But it led to a work-study assignment helping to teach labs for the Musical Acoustics course that was designed to meet the lab science requirement for musicians. From there, I learned about other areas of acoustics and decided to go to graduate school. Playing in big bands gave me many opportunities to practice leading from the middle without a formal leadership role.

My first graduate research project at Penn State, with Jiri Tichy, focused on computational models of active noise cancellation. My PhD research, with Dave Swanson, focused on computational models of the long-range propagation of sound in the atmosphere over a complicated terrain. Those topics were appealing to me because



https://doi.org/10.1121/AT.2023.19.3.64

the approach started from fundamental principles and was worked through by adding more complexity. We can use simulation to build an intuition of what to expect in a given situation. Because we can "turn all the knobs," we can assess sensitivity to each parameter independently, even when those parameters do not vary independently in real life. During graduate school, my research was primarily independent, with guidance from my advisors. Working through the problem sets for the courses was a good exposure to the benefits of working with a team from different backgrounds; my classmates with electrical engineering backgrounds helped me understand signal-processing problems and I helped with some of the math problems.

When I came to APL, my focus shifted to modeling the even longer range propagation of sound underwater and how that is affected by oceanographic variables, including mesoscale eddies, as well as how our predictions of propagation are influenced by imperfect knowledge of the environment. More recently, I've been leading teams working on the development of new sonar arrays, which makes use of our understanding of the properties of both signal and noise.

As much as I enjoy working with a team of dedicated colleagues, as an introvert, I feel most productive when diving deep into the weeds alone; I need to block out the distractions and listen to some good music. Increases in workplace flexibility over the past few decades, accelerated by Covid, make it easier to shift my schedule to tend to personal things in the early morning (when many of my coworkers work the best) and then stay a bit later in the evening when I focus best and the others have gone home. Computational acoustics is an area that lends itself well to lots of alone time.

### *Of all your contributions during your career, which are you most proud of and why?*

From the first time I worked on trade-offs between different array design options for arrays that actually got built and tested at sea, I was hooked. It's very satisfying to be involved in a large team with people who have diverse skill sets (mechanical engineers, electrical engineers, oceanographers, Naval officers, acousticians, and the experienced ship's crew) all working together to design, build, deploy, and use a sonar system in a sea test. Getting the first data back that confirms your predictions (or not; sometimes we learn new things!) must be one of the most thrilling things I have ever been part of. I've been fortunate to be involved in the process at all stages, from ideation and research, to initial concept development, to setting requirements for a prototype to validate the concept, to testing the prototype and refining the requirements, and to ultimately testing a final production array and developing displays and training materials for the crews.

Along the way, I've learned a lot about how arrays in the real world can be vastly different from the simple models physicists are taught to use to start a problem. And that means we get to constantly increase the fidelity and complexity of the models to include things like sources that have complex directionality or range-dependent sound speed fields with internal waves, or even the idea that sharks or marine mammals might be so interested in the array that they investigate closely.

As with anything that exists in the real world, occasionally a test does not go as expected and the interdisciplinary team must work together to determine the cause. Is there a physical phenomenon unaccounted for in the model, are there some flukes in an electrical connection, or perhaps damage was sustained during deployment?

Because APL is doing new things that have not been done before, we constantly run into new challenges. In particular, when developing new sonar systems, I am often asking if the engineering or manufacturing teams can make a component with lower self-noise, lower power, rated to go deeper, or with a tighter relative calibration than has been required in the past simply because the prior systems were not trying to exploit the same signal. One area I have been looking at a great deal in recent years is that real arrays do not contain truly identical hydrophones nor are they in precisely the desired locations within the array, especially for an array moving through the water. There are always (hopefully small) differences in calibration from phone to phone as well as (again, hopefully small) deviations in array shape. The engineering team needs specifications about how large those imperfections can be, worded in a way that lends itself both to a measurement to verify that the specification was met and to guarantee the desired acoustic performance. It becomes an iterative process, where I describe what I think is needed and they reply with what they think is possible. And in the end, we work together to describe metrics that can actually be met and tested for a system that advances the state of the art.

### *What are some of the other areas in which you feel you made substantive contributions over your career?*

I really enjoy mentoring early-career scientists and helping them develop their skills, background knowledge, and confidence to increase their impact. That includes coworkers and folks I meet at events like round-table discussions. Although I do not teach courses aside from an occasional guest lecture and do not work with students, I do get to interact with a variety of people, including sponsors and colleagues from interorganizational teams, and share with them specific problems they should be concerned about and why. Often that also means explaining why those will be hard problems.

I've been involved in the ASA since graduate school, and throughout the years, I've participated in a number of different committees. At one of the first meetings I attended (the fall 1999 meeting in Columbus, Ohio), I wound up at the Noise Technical Committee meeting and was, as one of the only students in the room, elected as their Student Council representative. Now, almost 25 years later, I'm finishing up a term on the Executive Council, having served alongside several of the other Student Council representatives with whom I first started. Along the way, I've been involved in Women in Acoustics and now Member Engagement and the Committee on Practitioners and Industry, working to increase diversity and representation in the Society. I helped with the push to make computational acoustics a full technical committee and have chaired sessions for computational acoustics, underwater acoustics, and physical acoustics. I've served in all the officer positions in the Washington, DC, regional chapter and am currently the treasurer. Because the ASA has always felt very welcoming to me, I want to make sure it feels welcoming to everyone.

### *What do you think are the most pressing open questions that you would like to focus on over the next 5-10 years?*

Utilizing new sensors optimally requires aiding crews in understanding how the sensors work in different environments. Typically, this means lots of time-consuming performance model runs or using models that have been so simplified to improve speed that the results can be misleading. Climate change and increasing shipping contribute to the complexity because crews are unable to rely on prior performance or historical databases of model inputs (such as sound speed profile and wind speed) as indicators of what will happen now. So, there is a modeling aspect. But there is also work to be done in areas like automated signal processing and displays that help highlight where operators should look.

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# *POMA*, An Underutilized Opportunity

*Megan S. Ballard, Kent L. Gee, and Helen Wall Murray*

The *Proceedings of Meetings of Acoustics* (*POMA*) fulfills a unique role within the collection of Acoustical Society of America (ASA) publications, which also includes the *Journal of the Acoustical Society of America* (*JASA*), *JASA Express Letters* (*JASA-EL*), and *Acoustics Today*. *POMA* supports the ASA's mission to generate, disseminate, and promote the knowledge and practical application of acoustics by providing an archival published record of work presented at ASA meetings. (For more on *POMA*, see bit.ly/POMA-2020.)

However, despite the added value *POMA* brings to the ASA, *POMA* is underutilized by the Society. Of the over 2,000 oral presentations and posters presented annually at ASA meetings, only about 150 have associated *POMA* articles. With the many demands on researchers, practitioners, and students, it can be difficult to find the time postmeeting to write a *POMA* article. Nevertheless, presenters that do take advantage of *POMA* enjoy rapid publication of their research, social media buzz, and widespread attention to their articles within the ASA community as well as a broader audience due to scholarly indexing. In 2022 alone, published *POMA* articles received over 160,000 downloads. It is important to also note that *POMA*'s rolling submission policy enables authors to submit papers from all past ASA meetings without deadline.

A good *POMA* article provides readers with a complete written summary of their oral presentation or poster. *POMA*'s written format lets the author formalize their results and provide additional details, such as a more complete theoretical derivation or a more in-depth analysis. A *POMA* article allows someone who was not able to watch the oral presentation or who wants to revisit the content afterward to learn more about the author's research. In principle, an article based on any ASA oral presentation or poster, including case studies and preliminary or limited-scope investigations, is suitable for publication in *POMA*. *POMA* is an excellent venue for research that might not merit a standard peer-reviewed journal article but is still of interest to the scientific community. Furthermore, *POMA* also provides an opportunity for authors to stake their claim on their own original ideas while a project is still in progress. You can learn more about the components of a good *POMA* article from our *POMA* associate editors (AEs) at bit.ly/good_POMA.

Although *POMA* has always been considered an online "open access" journal, plans have been made to transition to Creative Commons Attribution 4.0 International license (CC BY 4.0; see creativecommons.org/licenses/by/4.0) in the future. This allows *POMA* to meet emerging funder and institution requirements. Authors retain the copyright and grant a CC BY 4.0 license to their articles. The CC BY 4.0 licensing allows for liberal reuse as long as proper attribution under the license terms is given. As before, publication in *POMA* is included in the ASA meeting registration fee, and there is no direct cost to authors.

As an editor-reviewed journal, *POMA* balances the scope of a proceedings journal with the quality standards of ASA publications. Submissions are evaluated by the assigned AE for correctness and clarity. Although manuscripts are frequently returned to the authors for minor revisions, the eventual acceptance rate of *POMA* is above 90%. Moreover, because articles are not sent for peer review, *POMA* is able to maintain a high speed of publication, with the median time to first decision averaging approximately 20 days over the past 5 years.

*POMA* is especially well poised to provide early publishing opportunities for the student authors who represent our next-generation acousticians. In particular, *POMA* has a highly qualified editorial board who dedicate their time and expertise in providing useful feedback to all authors, with a bit of extra emphasis on student authors. Additionally, *POMA*'s simple submission portal and rapid editorial process benefit students in building their CVs. Furthermore, the *POMA* publishing experience equips students with technical writing skills and serves as stepping stone toward a peer-reviewed paper in *JASA* or


https://doi.org/10.1121/AT.2023.19.3.67

*JASA-EL*. To hear more real-time student perspectives on publishing in *POMA*, visit the ASA YouTube channel at bit.ly/POMA_Students.

Starting with the 182nd ASA meeting in Denver in the spring of 2022, *POMA* introduced a Society-wide student paper competition for a *POMA* submission based on a presentation or poster from the meeting. For each competition, up to 5 student authors received an award of USD $300. The first two *POMA* Student Paper Competitions were successful, bringing in 13 contenders for the 2022 Denver meeting, representing 10 different technical committees (TCs). Five awards were granted. For the 2022 Nashville meeting, six papers were submitted, representing five different TCs. Three awards were given. To date, the eight winning papers represent six different TCs, with one interdisciplinary (ID) paper. The quality of all the student submissions has been very high, as noted in comments from the AEs involved and the judging team (*POMA* editor, *POMA* assistant editor, and *POMA* manuscript manager). We hope the timing of the upcoming Chicago meeting will lend more opportunity for students to prepare their articles and take advantage of this unique opportunity. The winners of the first two *POMA* Student Paper Competitions are listed.

## Denver Winners

- **Samuel David Bellows**
  Musical Acoustics, Brigham Young University, Provo, Utah; https://doi.org/10.1121/2.0001586
- **Kyle S. Dalton**
  Underwater Acoustics, The Pennsylvania State University, University Park; https://doi.org/10.1121/2.0001605
- **Jeffery Taggart Durrant**
  Physical Acoustics, Brigham Young University, Provo, Utah; https://doi.org/10.1121/2.0001579
- **Jiacheng Hou**
  Physical Acoustics Utah State University, Logan; https://doi.org/10.1121/2.0001604
- **Trigun Maroo**
  Engineering Acoustics, University of Arkansas at Little Rock; https://doi.org/10.1121/2.0001609

## Nashville Winners

- **Lara Díaz-García**
  Interdisciplinary, University of Strathclyde, Glasgow, Scotland, United Kingdom; https://doi.org/10.1121/2.0001715
- **Mara Salut Escarti-Guillem**
  Noise, Universitat Politecnica de Valencia, Valencia, Spain; https://doi.org/10.1121/2.0001716
- **Kanad Sarkar**
  Signal Processing, University of Illinois Urbana-Champaign; https://doi.org/10.1121/2.0001707

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# STEM Substitute Teaching: Making a Contribution After Retirement?

*Steven L. Garrett*

After retiring from my academic position at The Pennsylvania State University, University Park, I returned to California to resume my life on the Monterey Peninsula. I was surprised by how much I liked Salinas, my neighbors, the bilingual culture, and the excellent fresh food that comes with having the most expensive agricultural land/acre in the United States and a very large fraction of the population with roots in Mexico. As a retiree, I wanted to contribute to this community but knew that with a half-century of academic experience, there must be a better use of my experience than collecting trash along the highway.

Like almost every town in the United States, Salinas had a shortage of STEM (Science, Technology, Engineering, and Math) teachers in their public schools. I thought my most valuable form of "community service" might be as a substitute teacher when the regular teacher was absent. After two years of working as a substitute in the Salinas Union High School District, I am still pleasantly surprised by how much I enjoy every assignment I accept. The purpose of this "Sound Perspectives" essay is to tell other retired (or soon to be retired) *Acoustics Today* readers about some of my experiences in the hope that others might give this option a try.

Before relating a few personal anecdotes, the first thing worthy of mention is that substitute teaching is a perfect "job" for a retiree; you only take the assignments you want, when you want, for as long as you want, and you also get paid for your service. In my district, substitute teacher vacancies are "advertised" on a website that tells the name of the teacher you will be replacing, their "specialty area" (e.g., math, science, physics, astronomy, English, history, construction technology, special education), the teacher's email address, and how long you will be needed. My shortest assignment was just two classes on one afternoon and my longest was four consecutive full days (which was too long because I needed to wake up at 6:00 a.m. to be ready for class at 8:00 a.m.); I really only have sufficient stamina for a rare three-consecutive-day assignment.

Although the "job requirements" (beyond the degree and teaching experience) vary among different school districts, the qualification process was rather easy and not particularly burdensome. I needed to get fingerprinted (for a background check) and get tested for tuberculosis. I had to take six online courses that ranged from 10 minutes to 1 half-hour each, then pass an online test after watching each presentation. As you might suspect, those courses covered sexual harassment, suicide prevention, "trafficking" (i.e., the exploitation of poor or immigrant students for illicit purposes), reporting suspected child abuse, coronavirus, and accident protocols (e.g., blood, urine, or vomit in the classroom). The test questions mostly just required a commonsense choice among a multiple-choice list of responses. After that, it's just you and the substitute vacancy website.

Finally, being a substitute is not like being a real classroom teacher. You don't make lesson plans, grade papers, or serve on committees. As far as I can tell, the only official duty required of a substitute is to take the roll at the start of each class. Because you know the regular teacher's email address, you can communicate in advance and discover the topic for each class you'll be covering.

As an example, I signed up for a math class and the teacher said that day's topic was graphing. With that advanced notice, I decided to bring one of my laboratory notebooks to class because it contained at least one graph per page on average. I made some comments about the history of graphing (i.e., the genius of Rène Descartes), which is a fairly new concept in human history, the importance of graphical data representation, and the role of least-squares fitting of a function (usually linear). Then I passed my notebook around the class while they were working at their desks on that day's in-class exercise. A few students looked


https://doi.org/10.1121/AT.2023.19.3.69

through more than just one or two pages, but one student, an agricultural mechanics major, spent at least 10 minutes asking me about the graphs as well as the schematic diagrams of op-amp signal-conditioning circuits, apparatus sketches, and transducer calibrations.

Another example is an earth science course that I was told would be covering volcanos. With that advance knowledge, I got a copy of Tom Gabrielson's brilliant animations of the infrasonic pressure wave that was detected on barometers and traveled around the globe five times after the eruption of Krakatoa in 1883 (Gabrielson, 2010). That animation and the idea that a sound wave could travel around the Earth five times is something those students would probably never have seen or thought about if a member of the Acoustical Society of America (ASA) wasn't their substitute that day.

In the United States, Black History Month is celebrated in February. One class that month had a "Black Minds Matter" assignment. The students had to identify a black scientist or inventor to study. James West came to the rescue that day! He's both a scientist and an inventor (Bush, 2007), and I got to talk to them about the electret condenser microphone and my visit to Bell Labs to see Jim. Every student knows what a microphone is, but none know how it works. Again, something to motivate students that they would likely not have occurred had an ASA member not been in their high-school classroom.

Does this matter? I've not attempted a scientific randomized study, but I know that students in every one of those classes appreciated the enthusiasm I had for each of those topics and they learned a little extra about something that wasn't in their textbooks.

Possibly the most rewarding part of this experience is summarized in the words of the great contemporary stand-up philosopher, Allan Stewart Kronigsberg (also known as the as the American comedian, actor, and Oscar-winning filmmaker, Woody Allen): "80% of success in life is just showing up." One day, an assignment appeared on the substitute vacancy website for a teacher whose specialization was listed as "pre-engineering." Having placed experiments on navy ships and submarines, had an experiment go into low-Earth orbit on the Space Shuttle *Discovery*, put a fission-heated thermoacoustic engine in the core of a nuclear reactor, and built

**Figure 1.** *Two students in a pre-engineering class during their aerospace engineering unit with their exploded rocket (**left**) that was destroyed by the launcher (**right**). That launcher was powered by 60 psig (500 kPa) of air pressure to accelerate the rocket. The blue handle on the launcher actuates a quick-release valve.*

two thermoacoustically cooled ice cream sale cabinets for Ben & Jerry's with my research group, I figured I was a good enough engineer to take that assignment, at least by high-school standards.

It turned out that the teacher's pre-engineering classes had students fabricate and test devices that introduced them to various engineering fields. For aeronautical engineering, they built paper rocket ships, sized to fit around a 1.5-inch PVC pipe. (The room must have had at least 40 pieces of pipe for them to wind their construction paper into tubes of the correct diameter and several hot glue guns.) The rockets were launched with 60 psig (500 kPa) of air pressure. **Figure 1**, *left*, shows two students and the rocket that exploded, which was their failed first attempt. Some of those rockets actually flew more than 100 m. It made for a very exciting morning, whether those rockets glided gracefully through the air, almost out of sight, or exploded on the launcher (**Figure 1**, *right*).

In another pre-engineering class for the hydraulic engineering module, the students were constructing the hydraulically actuated scissors jack (**Figure 2**, *top*). You know the students are enthusiastic about learning in those hands-on classes because they start working on their projects *before* the bell rings to announce the start of class. In that classroom/lab, they have access two drill presses and two band saws plus a nice variety of hand tools, soldering irons, and measuring instruments (**Figure 2**, *bottom*).

I really had to marvel at the cleverness of those projects. They were challenging at the appropriate level but also inexpensive enough so that 80 students could build them every semester. I also was pleased to see that the enrollment was about equally split between those students who were in a "vocational education" curriculum and those who were planning to attend college.

What I didn't know was that the pre-engineering teacher also taught two classes of Construction Technology (i.e., woodshop) after lunch. I also did not know that any high-school woodshop would be as well-equipped as what I found (**Figure 3**). (None of the other four high schools in the district have anything comparable.) I have so much fun helping those students with their projects that I needed to set the alarm on my cellphone so I don't forget to call "clean-up" 10 minutes before the end of class period.

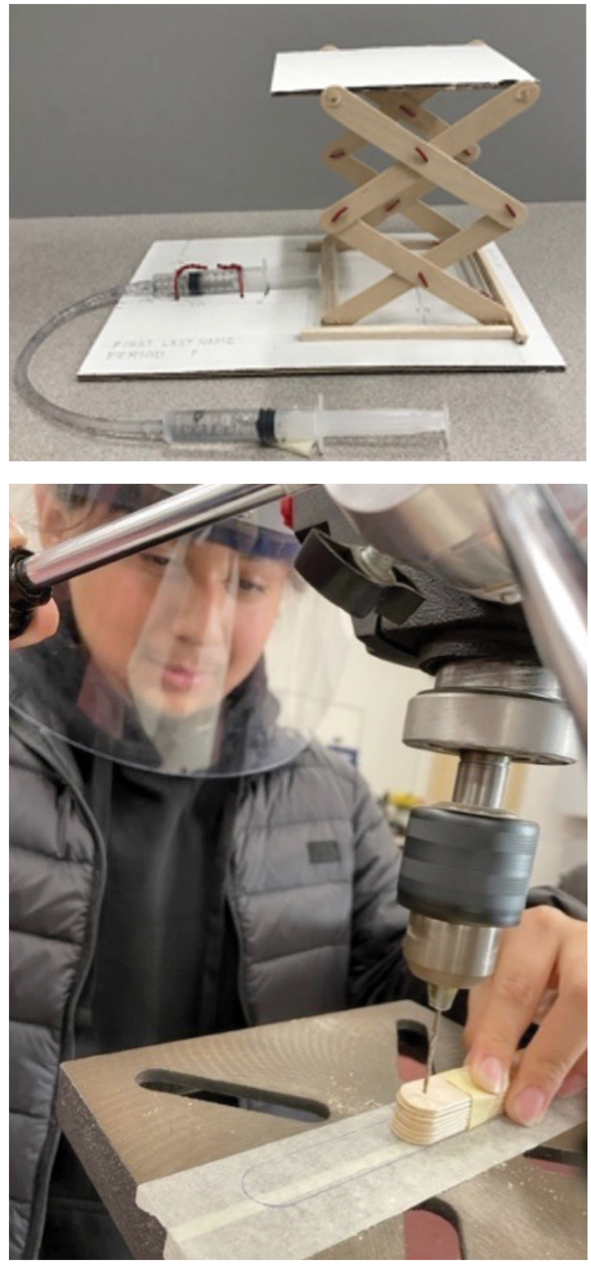

**Figure 2.** ***Top:*** *hydraulically actuated scissor jack that uses two 10-ml syringes to raise and lower the jack.* ***Bottom:*** *a student is drilling the holes used as bearings (with copper wire) in all eight tongue depressors at once.*

A further step was required before I was able to supervise students using power tools, but it was well worth the day of on-site "training." Because I'm now one of only a few substitutes in the district who holds that qualification, all engineering and shop assignments are now offered

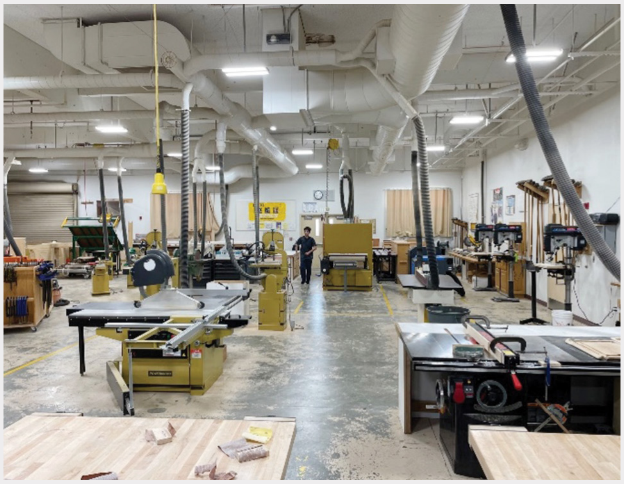

**Figure 3.** *I was amazed by the woodworking machinery (with active sawdust capture hoses) that was available in this high school. In the foreground are two of three table saws. Behind the right one is a 6-foot-long 6-inch-wide belt sander and behind the sliding table saw are two band saws. Against the right wall are three drill presses and a couple of chop saws, then to the left are six router tables and a surface sander.*

directly to me before they would be posted on the substitute website.

I cannot say that substitute teaching is the best or only approach to giving K-12 students exposure to practicing scientists and engineers. I also cannot claim that anything I've done has helped any student. That would take a long-term controlled study of a randomized group of students to see if they seek further STEM education after leaving high school and what they chose as their careers. I can say that I always find each assignment to be personally rewarding in some way, and I have plenty of anecdotal evidence that the students *feel* that they receive some immediate added benefit from my interventions. Several have told me I'm "the best substitute they ever had"; some have written letters to thank me. One such letter said, "Listening to you talk about the cool things you were able to accomplish, where you taught, and where you got your degrees made me superhopeful and want to study physics further. It was like a spark ignited when you talked." Occasionally, a student will tell me that (s)he wishes I were their regular teacher. All that definitely makes me feel good but that doesn't prove that there was any long-term benefit to any student.

There are organized programs that bring retired scientists and engineers into the classroom. The American Association for the Advancement of Science (AAAS) has a "STEM Volunteer Program" that began in 2004 (see aaas.org/programs/STEM-volunteers). It currently has 110 retired volunteers in 4 school districts in the Washington, DC, metropolitan area (Rea, 2023). Each volunteer commits to a few hours once each week throughout the school year. In early September, the list of new volunteers is sent to the science supervisor. (S)He makes assignments to teachers, and a training session is held in late September or early October. The teachers attend a lunch to enable them to chat with their new volunteers and explore joint activities. This requires coordination with the teacher to arrange the times and attempts to integrate the "special topics" with curricular goals. There is substantial administrative overhead!

A similar program is run by the Santa Fe Alliance for Science, New Mexico (see sfafs.org). Again, like the DC program, it relies on the large local engineering and scientific population created by the Los Alamos National Laboratory. These two examples exist in areas with a large existing indigenous concentration of STEM professionals. Anyone, anywhere, can do what I do on an individual basis. Integrating into an ordinary classroom environment is a much stealthier way to influence potential STEM students by "swimming under the sonar."

I suspect becoming a STEM substitute may not be a good option for some retirees, but the administrative overhead (e.g., fingerprinting) is not extensive and the opportunities are flexible, so you can try it out. See if you feel the same way as I do when I walk home after a day teaching high school?

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# ExploreSound.org: Acoustics Education for Everyone

*L. Keeta Jones*

Imagine a world where the wonders of sound come alive, capturing the imaginations of young learners and providing a wealth of educational resources for teachers. ExploreSound.org was created by the Acoustical Society of America (ASA) to open a world of sound exploration and learning. From the melodious tunes of a favorite song to the echoes that bounce off the walls, sound has the power to captivate young minds and spark their curiosity. To that end, ExploreSound.org makes sure acoustics education is for everyone. In this article, I provide a brief overview of ExploreSound.org to encourage members of the acoustics community to visit the site and help spread the word about this educational platform.

Whether an instructor is using these materials for K-12 students or college students, the website takes learning beyond textbooks and lectures, providing hands-on exploration opportunities that foster active engagement. The platform utilizes interactive simulations, virtual experiments, and online laboratories that allow educators to help their students manipulate sound waves, explore musical instruments, and understand the science behind various acoustic phenomena. These interactive elements not only make learning enjoyable but also deepen conceptual understanding and develop critical thinking skills.

At the core of the site lies curated content tailored specifically for K-12 educators. ExploreSound.org hosts a rich collection of interactive lesson plans (see ow.ly/ouCx50OW57F), educational videos (see ow.ly/3IhQ50OW59o), hands-on experiments (see ow.ly/AZf750OW5aS), and engaging activities (see ow.ly/cKMI50OW5cA), all designed to make learning about sound an exciting and immersive experience. From exploring the physics of sound waves (see ow.ly/qzNf50OW5es) to discovering the role of sound in health (see ow.ly/xfsR50OW5fw), the content covers a wide range of topics that align with various curriculum standards. ExploreSound.org even offers a dedicated section (see ow.ly/5Nci50OW5gG) filled with resources specifically designed to enhance teaching practices. Educators can access these resources for free to bring into their own elementary, middle, and high school classrooms to create dynamic and engaging learning experiences that bring the science of sound to life.

Postsecondary educators can also leverage ExploreSound.org as a valuable resource to enhance college courses. For example, the previously mentioned lesson plans can be modified for college students as suitable introductory activities. The extensive library of lay-language research papers (see ow.ly/aiYO50OW5Y6), *Acoustics Today* articles (see ow.ly/jMkm50OW61R), acoustician profiles (see ow.ly/Kv5L50OW646), and many other things can serve as supplementary readings for college students. By incorporating these materials into a course syllabus, instructors can provide students with a deeper understanding of acoustics, its applications, and career options. Whether one is teaching a course in physics, engineering, music, biology, oceanography, or any other field related to acoustics, ExploreSound.org can be a valuable tool to supplement instruction and engage college students in practical applications of acoustical concepts.

By offering comprehensive lesson plans, collaborative idea sharing, and multimedia resources, ExploreSound.org empowers all educators with the support they need to effectively teach acoustics and sound-related topics. The platform equips educators with the necessary tools and knowledge to inspire students' curiosity, deepen their understanding, and foster a lifelong passion for sound exploration.

ExploreSound.org also offers accessible, engaging, and relevant content for elementary, middle, and high-school students, aligning with their cognitive abilities and interests. The organization of the content encourages students to explore and discover sound-related topics at their own pace and on their own time. Curious learners of all ages can delve into any aspect of sound,


https://doi.org/10.1121/AT.2023.19.3.73

such as musical instruments (see ow.ly/vcLX50OW6oH), sound waves (see ow.ly/svwP50OW6rh), hearing (see ow.ly/Xjc950OW6us), and animal communication (see ow.ly/Oznc50OW6x2). This autonomous exploration fosters a sense of curiosity, independent learning, and the development of a personal connection to the subject matter. By providing a variety of learning materials, interactive tools, and real-world examples, ExploreSound.org supports people with different learning preferences, ensuring that they can engage with the content in a way that best suits their individual needs.

ExploreSound.org is an invaluable resource that empowers educators and learners alike to explore acoustics. Members of the acoustics community have the opportunity to make a significant impact by visiting the site, discovering its wealth of resources, and sharing it with others. Spread the word about ExploreSound.org to fellow ASA members, colleagues, friends, and anyone who can benefit from its engaging content. Additionally, ASA members can contribute their expertise and ideas to improve ExploreSound.org even further by getting involved with the ASA Education in Acoustics Committee (Edcom). ASA Edcom enhances acoustics education and paves the way for a world where the wonders of sound are understood and appreciated by all. Together, we can ensure that acoustics education reaches a wider audience and continues to inspire future generations.

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## BECOME INVOLVED

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# High-Schoolers Receive ASA Awards at the 2023 International Science and Engineering Fair

*Abbey L. Thomas and Peter F. Assmann*

**Figure 1.** ***Left to right:*** *Michelle Hua, Peter Assmann (ASA Lead Judge), Shodai Tanaka, and Anton Bulancea.*

Acoustical Society of America (ASA) members representing the Society as a Special Awards Organization presented high-school finalists with prizes for outstanding acoustics projects at the Regeneron International Science and Engineering Fair (ISEF) held in Dallas, Texas, on May 13-19, 2023. The ASA judging team included Peter F. Assmann (lead judge), Abbey L. Thomas, Satwik Dutta, and Nursadul Mamun from the University of Texas at Dallas, Richardson, Texas, and Christopher Ainley from Wrightson, Johnson, Haddon & Williams, Inc. Fifteen acoustics projects were selected from over 1,600 projects for an in-person review by the ASA judges, and the finalists who received awards from the ASA each demonstrated an in-depth understanding of acoustic principles relevant to their projects. The projects by this year's winners of the ASA awards showcased acoustic theories and applied them in innovative ways.

**Shodai Tanaka** (Sapporo Kaisei Secondary School, Sapporo, Hokkaido, Japan) was awarded first prize for his project *A Mathematical Study About the Sustaining Phenomenon of Overtone in Flageolet Harmonics on Bowed String Instruments*. Shodai demonstrated impressive knowledge of and passion for this complex topic. His presentation was clear and informative despite the complex equations his model included. Shodai will receive a cash prize of $1,500.00. The ASA will also send $500.00 to his mentor and $200.00 to his school.

**Anton Bulancea** (Pushkin Lyceum, Chisinau, Moldova) won second prize for his project *Designing and Building an Acoustic Levitation Prototype*. The judges were amazed by Anton's enthusiasm for the project and his grasp of the physics of acoustic levitation. Anton demonstrated extensive work and initiative in building and testing his system. Anton will receive a cash prize of $1,000.00. The ASA will also send $250.00 to his mentor and $100.00 to his school.

**Michelle Hua** (Cranbrook Kingswood School, Bloomfield Hills, Michigan) was awarded the ASA third prize for her project *3D Acoustic Simulation and Optimization Algorithms for Transcranial Focused Ultrasound Delivered with Robotic Systems.* The judges were impressed by Michelle's understanding of how different materials affect the propagation of ultrasonic waves. Michelle will receive a cash prize of $600.00, and her mentor will receive $150.00.

**Anu Iyer** (Little Rock Central High School, Little Rock, Arkansas) won the honorable mention for the second consecutive year. Anu's current project, *VAST (Voice and Spiral Tool): A Novel Multimodal Machine Learning Method to Detect Parkinson's Disease and Assess Severity*, built on her work from the previous science fair. Anu demonstrated a thorough understanding of the unique acoustic features of voices of patients with Parkinson's disease. The judges commend Anu for her dedication to this project.

All awardees, including the honorable mention, are invited to attend the next ASA meeting, with waived registration fees. Please see exploresound.org/isef-asa-winners to read the abstracts of these ASA awardees. The judging team was inspired by the quality of the studies produced by these young scientists and their fellow finalists. The judges commend these students for their enthusiasm and devotion to scientific study and look forward to seeing their future contributions to the field of acoustics and beyond.

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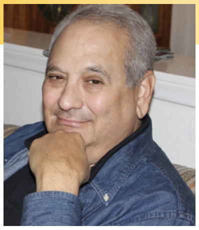
https://doi.org/10.1121/AT.2023.19.3.75

## Obituary
# Sanford A. Fidell, 1945–2023



**Sanford A. (Sandy) Fidell**, Fellow of the Acoustical Society of America and an associate editor of *The Journal of the Acoustical Society of America*, passed away on February 27, 2023, at the age of 77. Sandy was born in New York, New York, on May 11, 1945, and graduated from Trinity College, Hartford, Connecticut. He completed his PhD from the University of Michigan (Ann Arbor) Experimental Psychology Program in 1968 under the supervision of Wilson P. "Spike" Tanner, John Swets, and David Green. His doctoral thesis demonstrated that by presenting auditory (headphone) and visual (oscilloscope) sensory sine wave stimuli simultaneously, detection performance was improved over either input in isolation. In August 1968, he began work at Bolt Beranek and Newman (BBN), Van Nuys, California. Sandy's hobbies included music and amateur film making.

Sandy's professional interests lay primarily in auditory signal detection and community noise exposure-response relationships. As a former head of BBN's Psychoacoustics Department and then of his own company, Fidell Associates, Inc., he pursued both interests with equal vigor. He always engaged a core group of diversely skilled individuals who aided in bringing his ideas to fruition.

Sandy's broad range of clients came from both the public and private sectors. He was instrumental in developing BBN's psychoacoustic laboratory where he conducted numerous cutting-edge auditory detection experiments. Among many others, very low frequency auditory bandwidth tests to guide helicopter aural detection models were used by both NASA and the US Army. Sandy also conducted emergency warning signal audibility and noticeability tests to establish predictive models for both phenomena. He also designed and guided aircraft auditory detection software development for the US Army, Air Force, and National Park Service.

Sandy's interest in community noise exposure-response relationships began with collaborations with Theodore (Ted) Schultz. After considering several functional forms for such relationships, he championed the concept of a community tolerance level (CTL) in which the slope of the function was fixed and determined by a growth of loudness model. By so doing, differences in noise tolerance between communities could be numerically evaluated. For 24 years, Sandy was a presenter at the annual University of California, Berkeley short course on Airport Systems Planning and Design. Based on his broad experience studying aircraft noise impacts and noise management actions at many airports across the United States, he provided an understanding of people's reactions to aircraft noise as well as of mitigation strategies to airport professionals.

Sandy's ability to focus on the big picture as well as small details is exemplified by his guidance to NASA's upcoming low-boom supersonic overflight community-reaction study. Sandy demonstrated smartphone technology's ability to acquire immediate reactions to individual booms while also examining the entire data collection and analysis process to recommend an integrated, cost-effective, least-risk approach to real-time integration of aircraft trajectory, boom sound level, and subjective-response data.

Sandy was a prolific writer, with over 60 journal publications and over 100 conference presentations. His extensive vocabulary (foreign and English) along with his fastidious attention to grammatical correctness will be missed.

### *Selected Publications by Sanford A. Fidell*

Fidell, S., and Mestre, V. (2020). *A Guide To U.S. Aircraft Noise Regulatory Policy*, 1st ed. Springer Cham, Cham, Switzerland.

Fidell, S., Horonjeff, R., Teffeteller, S., and Green, D. (1983). Effective masking bandwidths at low frequencies. *The Journal of the Acoustical Society of America* 73(2), 628-638.

Fidell, S., Schultz, T. J., and Green, D. (1988). A theoretical interpretation of the prevalence rate of noise-induced annoyance in residential populations. *The Journal of the Acoustical Society of America* 84(6), 2109-2113.

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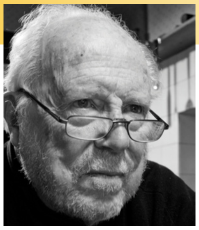
## Obituary

# Ivan Tolstoy, 1923–2023



**Ivan Tolstoy** was a Renaissance man: scientist, writer, athlete, epicure, and more.

He was the author of two technical monographs and over 100 publications and was a winner of the Acoustical Society of America (ASA) Pioneer Medal in Underwater Acoustics. He made contributions not only in underwater acoustics but also in geophysics and astrophysics. From the ocean floor to earth to space.

But he was also a writer of books that helped to popularize science, such as a biography of James Clerk Maxwell, a book on the philosophy of science, and a geophysics introduction for the general public. He was also involved in alerting people to the dangers of nuclear waste disposal.

In his youth, Ivan was a vigorous athlete, a self-taught classical guitarist, an amateur sailor, an artist (usually pen and ink), a superb chef, a wine connoisseur, and a passionate chess player. He was also a speaker of multiple languages and was fluent in French, Russian, and English. He was born in Baden-Baden, Germany, to Russian nobility who fled Russia during the revolution, but he was raised in Paris (finishing first in his class at the Sorbonne University, Paris, France, with a degree in geology).

Ivan was given United States citizenship in 1945, as a result of helping downed US airmen escape from the Nazis during World War II and subsequently went to Columbia University, New York, New York, for graduate studies with Maurice Ewing. He was a discoverer of T phases in underwater seismology (some say they were named after him but he always claimed that it was T for tertiary waves). After his doctorate, he became a professor at Columbia University and associate director of their Hudson Labs. He later became a professor at Florida State University, Tallahassee, and subsequently at Leeds University, Leeds, United Kingdom. He lived in the countryside of Scotland for over 45 years. He loved it there.

Ivan was a codiscoverer of the mid-Atlantic Ridge, and this was groundbreaking, so to speak. It supported other evidence coming in at the time for tectonic plates and seafloor spreading. This was, however, contrary to much of the thinking then (late 1940s). But Ivan loved ruffling feathers.

He was also the discoverer of T phases that were unnoticed by previous investigators of seismic records. We have all heard of P waves (primary arrivals) and S waves (secondary arrivals), but T phases were new observations seen only in underwater signals. He found them and proposed that they be used for tsunami warnings.

Tony Biot was a significant mentor and friend with whom Ivan learned much about elastic media, vector equations, Hamiltonians, elasticity, normal modes, porous media, and edge diffraction. They coauthored numerous papers, with Ivan paying tribute to Biot on his death by publishing a collection of Biot's works. Ivan's full list of his publications can be found on www.ivantolstoy.com.

Ivan also discovered superresonances and investigated ideal wedge modes, atmospheric gravity waves, and rough surface boundary waves. He was an AAAS life member.

Ivan died on February 18, 2023, after a brief illness and would have been 100 on March 30, 2023. He retained an interest in science, art, music, and life up to the end.

He is survived by three daughters, each a scientist and the authors of this obituary, and a grandson.

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# Obituary
## Lisa M. Zurk, 1962–2022

**Lisa M. Zurk**, Fellow of the Acoustical Society and first woman chair of the Acoustical Society of America (ASA) Technical Committee on Underwater Acoustics, passed away on January 12, 2022.

Lisa started her career not in acoustics but in computer science, receiving her BS degree from the University of Massachusetts, Amherst, in 1985. She spent some of her early years in industry before moving on to graduate school. She earned a MS degree in electrical and computer engineering in 1991 from Northeastern University, Boston, Massachusetts, and a PhD in 1995 in electrical engineering from the University of Washington, Seattle, with a study on electromagnetic scattering with applications to remote sensing of snow.

Lisa had a highly accomplished research career. In 1996, she returned to the Boston area as a technical staff member at the Massachusetts Institute of Technology Lincoln Laboratory, Lexington, where she began splitting her research between acoustics (sonar systems) and electromagnetics (radar systems). Lisa was one of those rare individuals who was considered an expert in both electromagnetics and acoustics, and she simultaneously contributed to these two fields and drew key insights from each. She left the Lincoln Laboratory in 2005 to join the faculty of the Electrical and Computer Engineering Department at Portland State University (PSU), Portland, Oregon. She was recruited away from PSU in 2016 by the Defense Advanced Research Projects Agency (DARPA) to become a program manager. During her time at PSU, Lisa published numerous research articles related to electromagnetic scattering in the terahertz frequency band. At the same time, she and her students published 12 articles in *The Journal of the Acoustical Society of America*. In 2017, she was hired as the first woman to lead the Applied Physics Laboratory at the University of Washington as executive director.

In electromagnetics, Lisa's most impactful work was related to propagation and scattering in the terahertz frequency band. In acoustics, she is best known for developing innovative active and passive signal-processing methods to improve underwater sonar systems. She had a particular talent for using physics-based insights to improve signal-processing methods. In some cases, the processing she employed included a physics-based model of the ocean acoustic waveguide that is generally referred to as matched field processing (MFP). In other situations, she used simple phenomena like the Lloyd's Mirror effect caused by interference between sound produced by an underwater source and its reflection off the sea surface. She developed processing methods that exploited these interference effects to determine the source depth and, in some cases, also the range. She applied these methods to both passive and active sonar scenarios and supported results with measurements from at-sea data collections. She, along with her students, even applied MFP concepts to electromagnetic terahertz applications of nondestructive testing. Lisa's legacy includes the lasting impact she had on so many of her colleagues and students. She left us too soon and will be greatly missed.

***Selected Publications by Lisa M. Zurk***

Kniffin, G. P., Boyle, J. K., Zurk, L. M., and Siderius, M. (2016). Performance metrics for depth-based signal separation using deep vertical line arrays. *The Journal of the Acoustical Society of America* 139(1), 418-425.

Quijano, J. E., Zurk, L. M., and Rouseff, D. (2008). Demonstration of the invariance principle for active sonar. *The Journal of the Acoustical Society of America* 123(3), 1329-1337.

Zurk, L. M., and Rouseff, D. (2012) Striation-based beamforming for active sonar with a horizontal line array. *The Journal of the Acoustical Society of America* 132(4), EL264-EL270.

Zurk, L. M., Lee, N., and Ward, J. (2003). Source motion mitigation for adaptive matched field processing. *The Journal of the Acoustical Society of America* 113(5), 2719-2731.

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