Acoustics Today

Fall 2024 Volume 20, Issue 3

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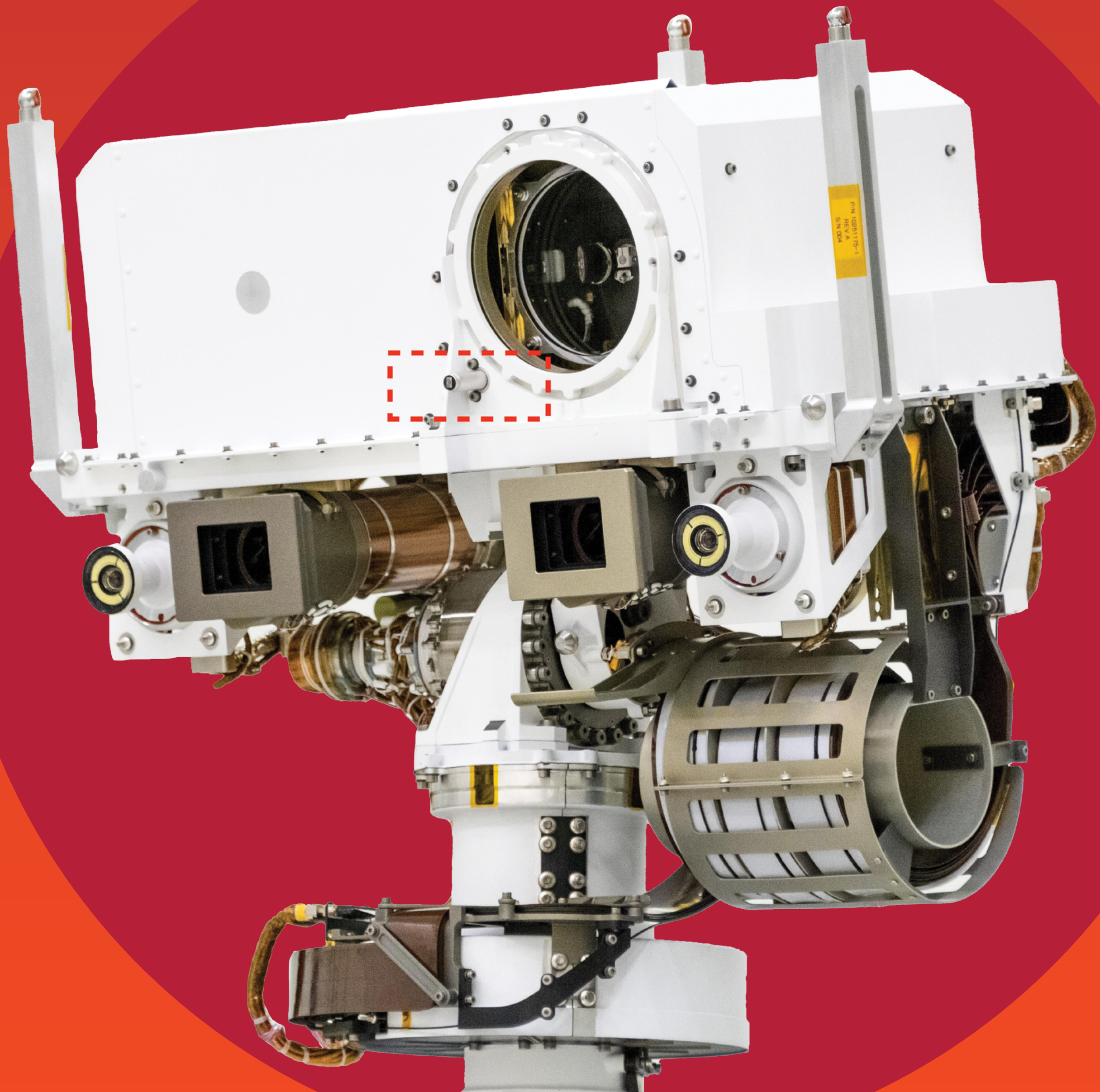
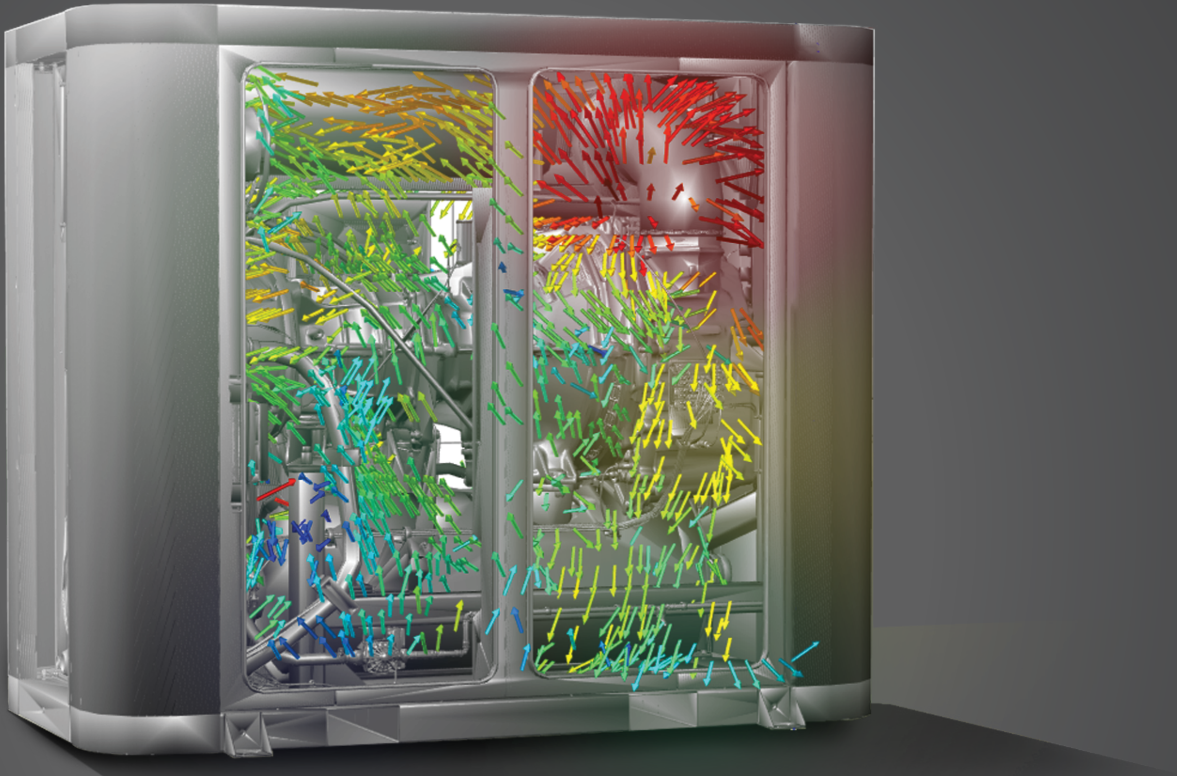
Unveiling Mars: Sounds of the Red Planet






Yeah! That's the feeling when you know
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Featured Articles

Sound Perspectives

Departments

About the Cover

Photo of the SuperCam instrument (dotted rectangle) on the Perseverance rover, which allowed scientists to study the Red Planet's surface in unprecedented detail. From the article "Unveiling Mars: Sounds of the Red Planet," by David Mimoun, Ralph Lorenz, and Sylvestre Maurice (page 39). Image courtesy of NASA/JPL-Caltech.

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From the Editor

Arthur N. Popper

As you have no doubt heard, D. Keith Wilson will be the new editor of *Acoustics Today* (*AT*) starting January 1, 2025. I am a bit saddened to be giving up the magazine but delighted that we could entice Keith to take over. He has written several excellent articles for *AT* (e.g., see bit.ly/3W7SlSn) and has a broad understanding of acoustics and a strong devotion to the Acoustical Society of America (ASA).

As for my plans, I'm still cogitating. I was thinking of fully retiring, (e.g., stop all research, editing, writing) and look for new things to explore. But when I shared this idea with my family, and particularly with our grandkids, the laughter and disbelief was rather raucous. And the truth is, I still enjoy ties to science and colleagues, and so while I will slow down and do other things, I'm still planning on keeping my hand on several projects. And I've promised Keith that I'd be around to share experiences as he gets involved with *AT*, and if he wants.

Serendipity in Acoustics

Before I talk about this issue of *AT*, I want to mention that the next issue is going to be rather different, and I hope, quite interesting and fun. One of the ideas I've been most intrigued with in my career is serendipity, how things just happen in life. And I've particularly been intrigued with how you recognize a serendipitous event, and how following up on it can lead to whole new directions in your scholarly and personal lives. Just think about it; how many times in your life, from a very young age, did something unexpected happened that, because you recognized it, changed your life path?

Just to give one example to get you thinking about serendipity. One day, while in my third year in college, I walked into a new pet store in my neighborhood and wandered among the fish tanks. I "discovered" a tank of fish that had no eyes. They were Mexican blind cave fish (see bit.ly/4bXYHtx). I was totally fascinated. Seeing these fish was a serendipitous moment for me, particularly since once I started to think about them, I could not get them out of my mind.

As soon as I got to campus (the now-defunct Heights Campus of New York University, Bronx, New York), I walked into the office of my undergraduate mentor, a biologist by the name of Douglas Webster and asked if he knew anything about the fish. Doug (we later became good friends and even published a book together) said he'd not heard of these fish, but he suggested that I do some research about them, and he offered me a place in his laboratory to do that work. Had I not serendipitously seen those fish, my whole life from that day on would likely have been very different!

But the influence of that serendipitous moment went on. Because of doing work on Mexican blind cave fish, Doug introduced me to the curator of ichthyology at the American Museum of Natural History, New York, New York, who then offered me a part-time research job in the department. One day while working in the laboratory, I was visited by another curator who was interested in a parrotfish I was working on. He did a brief dissection and showed me a dense structure in the head called the otolith, and he told me that it was part of the ear.

And that serendipitous encounter with a fish ear let me to discover Willian N. Tavolga, a faculty member just three floors above where I worked. Tavolga was a pioneer in the study of fish hearing, and when we discussed a research project for my doctoral work, we had the idea that my Mexican blind cave fish would be perfect subjects!

I tell this story as a prelude to our winter issue. Perhaps, as you read of my serendipitous moment (and I have had many more), you will start to think about how serendipity has impacted your career and how many times this has taken place. But keep in mind that serendipity impacted your nonscholarly life as well—perhaps how you picked your college, how you met your spouse, how you found your first job, and even how you moved forward in your career! Indeed, serendipity is a fascinating, and critical, part of the paths of our lives.

This Issue

This issue of *AT* has five articles, and although I did not ask the authors, I would "bet" that any number would agree that various serendipitous events in their lives led to the work that they write about.

In our first article, Philip Blom and Jordan Bishop introduce us to infrasound and its role in detecting nuclear testing. The article focuses on the history of using infrasound in monitoring nuclear tests but also shares insights into some of the difficulties of doing this (and solutions to problems) as nuclear testing has changed. Related articles are found at bit.ly/3xY6KIT.

Going to the other extreme in the size of sound waves, Matthew R. Lowerison, YiRang Shin, and Pengfei Song share insights into the use of ultrasound in the imaging of microvessels in humans. They point out that understanding the flow of blood in these very tiny parts of the circulatory system provides invaluable insights into the monitoring and treatment of a wide range of diseases from cancer to dementia. See bit.ly/AT-ultrasound for other articles on use of ultrasound in medicine.

Our third article moves from using sound to listening for it to understand the behavior of dolphins and whales. Here, Eduardo Mercado III describes many cetacean sounds. But he goes well beyond simple description and considers the perceptual world of these animals from communication to echolocation. Related articles are at bit.ly/ATC-Bioacoustics.

Over my years as editor of *AT*, we have had a few articles that considered sound in other parts of the solar system and universe (see bit.ly/3Wr8V0S). In this issue, David Mimoun, Ralph Lorenz, and Sylvestre Maurice take us onboard a Mars lander to learn about, and actually hear, the sounds of the Red Planet. Although many of our articles include sounds, I don't often encourage readers to make sure to listen to them, but in this case, hearing the sounds of another planet is "something else."

In our last article, we return to the use of ultrasound in medicine when Natasha D. Sheybani introduces us to the use of sound for cancer therapy. Although this article focuses on ultrasound, it also gives a broad introduction to a variety of cancer treatments and shows how ultrasound is becoming an important tool in fighting disease. Other articles on biomedical uses of ultrasound are at bit.ly/AT-ultrasound.

This is followed by my last Conversation with a Colleague (CwC) essay, and features Michael R. Haberman, a long-time contributor to *AT*. Of course, CwC has been developed and edited by our associate editor, Micheal L. Dent. Over the past 10 issues of *AT*, we have tried to feature one member of ASA from as many Technical Committees (TCs) as we could. Micheal and I thank not only the authors, but also the TC chairs who have guided us in selecting colleagues to invite to participate. You can see the complete CwC series at bit.ly/AT-CwC. (And to learn about other ASA members, see bit.ly/3FjTCeL.)

There is a growing interest in the archives of biological sounds on the web. In his essay, Jack Greenhalgh gives a perspective on these archives and includes a table that gives links to 14 such archives. I particularly appreciate Jack pulling together this listing because the original intent of his essay was to focus on an archive on freshwater fishes that he works on, I suspect that this essay will be of greatest interest to a very wide range of scholars and students.

Our final "Sound Perspective" essay is another in our series from the ASA Student Council. The essay, by Marissa L. Garcia, focuses on student researchers who won awards at the 2023 Sydney meeting. You can see many other interesting essays about students at bit.ly/ATC-Students.

From the President

Barbara Shinn-Cunningham

As I step into the role of president of the Acoustical Society of America (ASA), I am filled with both pride and humility. My journey with the ASA began when I started graduate school under the mentorship of dedicated ASA members whose guidance and collaborative spirit profoundly shaped my professional and personal growth. For over three decades, this Society has been more than just a professional association to me; it has been a cornerstone of my career, a source of lifelong friendships, and a wellspring of scientific inspiration.

Recognizing the immense responsibility of this role, I am committed to steering the ASA forward, honoring our rich legacy while embracing the challenges and opportunities ahead. I am particularly enthusiastic about ongoing initiatives to diversify our membership and nurture the next generation of acousticians. This includes our Committee to Improve Racial Diversity and Inclusivity and our Summer Undergraduate Research or Internship Experience in Acoustics (SURIEA) program (information about how to get involved as a SURIEA mentor is at acousticalsociety.org/suriea).

Ensuring the ASA's vitality over the next 30 years requires fiscal responsibility and innovative thinking. Unlike many societies that profit from meetings, the ASA faces unique financial challenges due to our structure of simultaneous, parallel sessions. The need for many small meeting rooms limits venue options and escalates audiovisual costs, presenting ongoing fiscal hurdles.

To address these challenges, discussions have begun across all levels of the Society to explore creative solutions. During the recent Ottawa, Ontario, Canada, fall meeting, the Executive Council and Technical Council initiated discussions on ideas aimed at mitigating meeting costs while recognizing and honoring the diverse needs of our technical committees. Ideas, such as shifting some oral presentations to poster sessions and optimizing session scheduling throughout the conference week, were presented at individual technical committee meetings in Ottawa to get feedback and inform future plans. We recognize that each technical committee has different needs and that any particular suggestion may not work across all committees. Rest assured, we are committed to respecting the unique needs and cultures of each technical committee and will introduce changes only gradually, guided by our members' needs.

Another proposal is to move from two annual meetings per year to one; however, this cannot be implemented for a few years given already planned meetings, many of which are joint. A less drastic alternative would be to hold occasional fully virtual meetings instead of traditional in-person gatherings. Although such virtual sessions cannot fully replace in-person conferences, they provide inclusive, cost-effective engagement opportunities and help reduce our environmental footprint. Our upcoming virtual meeting in November will serve as a testing ground for this idea, allowing us to evaluate different virtual session formats. We eagerly await your feedback to guide future decisions.

In late July, around 60 society members from every technical committee and spanning all levels of seniority gathered for an ASA Think Tank. The goal was to lay the foundation for an updated strategic plan to guide our society forward. A professional strategist facilitated discussions, which culminated in identifying three primary areas of focus for the next five years: Meetings, Member Support, and Education and Outreach.

Meetings have always been central to the ASA's identity. They serve as critical platforms for sharing knowledge, fostering interdisciplinary collaboration, and building our community. Maintaining the vibrancy of these meetings is essential — yet we must ensure they don't impose financial strain on the society. We discussed the growing competition from specialized meetings that vie for our members' time and travel budgets. Creative ideas emerged, such as holding 1–2-day interdisciplinary workshops or enhanced regional meetings to complement our traditional large-scale events. These approaches offer exciting possibilities for augmenting our existing meeting structures in the coming years.

Member Support is another crucial area that encompasses all the activities we undertake to advance our members' careers and provide valuable services. During our discussions, there was a strong emphasis on the need to better support early-career investigators. These individuals represent the future of our society, and their success is vital to our long-term health. Additionally, we recognized the importance of continuing and expanding efforts to increase diversity within our membership. By fostering a more inclusive community, we can ensure that the ASA remains a vibrant and welcoming organization for all.

Education and Outreach emerged as the third key area of focus. There is significant potential for the ASA to expand its efforts in advocating for our science and promoting scientifically informed policy, particularly with government agencies. We also discussed the importance of engaging with K-12 education to inspire the next generation of scientists. Creating online resources to educate professionals on key topics and developing a coherent communication strategy for the society were also highlighted as important goals.

The Executive Council (EC), most of whom attended the Think Tank, will soon draft a consensus report on these discussions, which will be shared with all members. Stay tuned for more details, and don't hesitate to reach out to your TC chair or any EC member (including me) with your thoughts!

As we embark on this new chapter, I invite you to engage with the ASA's initiatives, share your insights, and consider volunteering your time and expertise. Together, we will navigate the challenges ahead, ensuring that the ASA remains a vibrant, innovative, and inclusive community for generations to come.

Thank you for your trust and support. I am honored to serve as your president and am excited about the accomplishments we will achieve together.

Listening for a Boom You Can't Hear

Philip Blom and Jordan Bishop

Introduction

On the morning of July 16, 1945, seismic and acoustic signals were recorded across the southwestern United States from an excessively energetic event. These signals emanated from a location roughly 50 km south of Socorro, New Mexico. Microbarographs 45 km away near San Antonio, Texas, recorded a local overpressure from the event of more than 780 Pa (Manley et al., 1945). This overpressure exceeds 150 dB sound pressure level and is equivalent to being in the immediate vicinity of a shotgun blast or large firework explosion. Seismic and acoustic signals from this event were observed more than 1,000 km away near Mount Wilson in southern California and numerous other locations across the southwestern United States (Gutenberg, 1946).

The source of these observations was the test of an implosion-design plutonium bomb called Trinity (see bit.ly/Blom1) that was conducted as part of the Manhattan Project to develop a nuclear bomb. The bomb design was the product of years of research by J. Robert Oppenheimer and other scientists at Los Alamos Laboratory, Los Alamos, New Mexico. The device was nicknamed "the gadget" and released an explosive energy equivalent to 21,000 tons of TNT (US Department of Energy [DOE], 2015). The fireball produced by the explosion (**Figure 1**) was visible more than 100 km away. Trinity was the first of more than 2,000 nuclear tests that would be detected and characterized via seismoacoustic means over the following decades through the nuclear arms race and into the modern era.

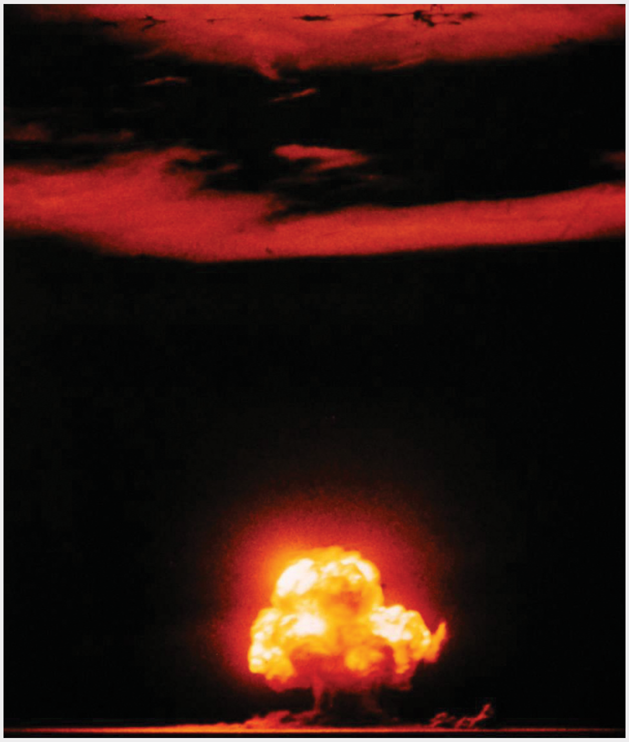

Figure 1. *The fireball produced by the Trinity nuclear test. Photo by Jack W. Aeby, captured as part of the Manhattan Project. Available at bit.ly/3ySMzMD.*

Subaudible Acoustic Waves

The acoustic signals produced by Trinity and other nuclear tests contained significant amounts of energy at subaudible frequencies (below 20 Hz). Such acoustic waves are termed "infrasound" and although they cannot be heard by the human ear, they are a remarkably useful means of passively monitoring energetic phenomena in the atmosphere. Any phenomena that displace a large volume of air in the atmosphere can produce these subaudible acoustic waves. Infrasound is generated by both natural and anthropogenic events, and many of these sources are of interest to natural hazard monitoring (e.g., volcanic eruptions, earthquakes, tornadic and maritime storms) as well as to national security interests (e.g., explosions, rocket launches, supersonic aircraft).

Infrasound waves exhibit efficient long-range propagation that makes them ideal for remote sensing applications. Thermoviscous absorption of acoustic waves by the atmosphere decreases with frequency. This decreased loss of energy into the propagation medium, combined with the

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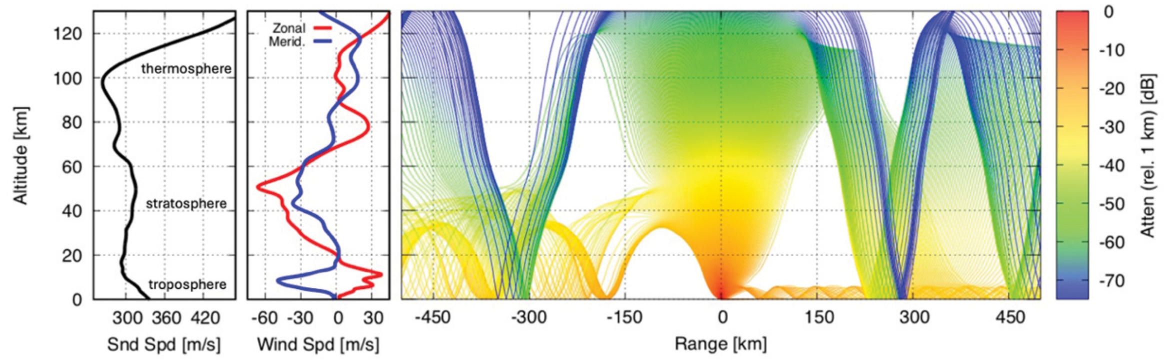


Figure 2. *Example of infrasound propagation including tropospheric, stratospheric, and thermospheric refractions. Tropospheric and stratospheric waveguides are driven by the atmospheric winds, whereas temperature gradients in the thermosphere produce refraction. Snd Spd, sound speed; Atten, Attenuation.*

energetic source mechanisms required to displace air volumes on the scale of infrasonic wavelengths, results in acoustic waves that can remain detectable hundreds or even thousands of kilometers from the source.

Infrasonic waves propagate through the atmosphere and are refracted by gradients in the wind and temperature as shown in **Figure 2**. Temperature gradients in the atmosphere (**Figure 2**, *left*) are relatively weak so wind gradients are typically needed to produce waveguides through which infrasound can efficiently propagate. The jet stream near the top of the troposphere (12 km altitude, where airplanes fly) can produce enough refraction to return infrasound waves to the ground surface. Further up, strong winds in the stratosphere (12-50 km altitude) are produced by the polar vortex (the same one often associated with sudden weather fluctuations during the winter).

In **Figure 2**, *middle*, the zonal (east and west component) and meridional (north and south component) winds are shown. Due to global circulation patterns, wind-driven waveguides are typically oriented east/west around the globe and are strongly dependent on the zonal winds. The propagation plane shown in **Figure 2**, *right*, is oriented east/west and shows a westward stratospheric waveguide (negative range values) and eastward tropospheric waveguide (positive range values).

In the thermosphere (above 85 km altitude), strong temperature gradients produce refraction of infrasound waves from the upper atmosphere. Thermospheric infrasound waves are particularly complicated as they extend beyond the Kármán line at 100 km, which astrophysical conventions define as the edge of space. Infrasonic refractions from the thermosphere can be thought of as sound waves that have been to outer space and back. At these altitudes, the atmospheric density decreases significantly, and linear acoustics does not fully capture the propagation physics.

Infrasound in Early Nuclear Nonproliferation

Following the conclusion of World War II, the United States held a monopoly on nuclear weapons, although that would only last a few years. Many of the scientists and engineers who had worked on the Manhattan Project speculated that the US nuclear monopoly would be short-lived and that "the fundamental physics of the bomb are well-known to all nations" (Marshak, 1946).

On August 29, 1949, the first Soviet nuclear test was conducted. This test was codenamed "Joe-1" in United States reports in reference to Joseph Stalin. Prior to Joe-1, in September 1947, General Dwight D. Eisenhower ordered the Army Air Forces to investigate technologies that would enable the United States to detect nuclear explosions across the globe. This effort to monitor and deter nuclear weapon development by foreign nations is termed "nuclear nonproliferation." The decision to assign this task to the Army Air Forces was based on the need to sample the atmosphere for radioactive debris that was indicative of a fission reaction that would identify a nuclear test. Initial deployments were targeted at the Soviet Union, and such debris was detected by a modified B-29 Superfortress aircraft when the first Soviet test was conducted in 1949 (Ziegler, 1988).

The detection of fission debris from Joe-1 demonstrated the capability of the Air Force Office of Atomic Testing (AFOAT-1) to detect foreign nuclear tests; however, the aim to monitor the entire globe for nuclear tests was more challenging than focusing on a single region. Aerial sampling for radioactive debris across the entire globe was simply not an option.

Thus, additional signatures were needed that could detect explosive events and inform aerial sampling. Seismic and infrasonic monitoring methods were identified as candidates for detecting the explosive waves from nuclear tests. Any belowground or near-surface explosion would couple energy into both the seismic and infrasonic wavefields, and airbursts would produce infrasonic signatures observable at significant standoff distances.

The need to consider these and other emplacement scenarios, as well as the need to discriminate conventional chemical explosives from those of nuclear origin, led to a multiphenomenological capability development. A combination of mechanical sensing modalities (seismic, infrasonic, and underwater acoustic) alongside radiochemical sampling was developed to detect explosions and then discriminate whether the explosion was conventional or nuclear.

AFOAT-1 evolved through the subsequent decades into its current form as the Air Force Technical Applications Center (AFTAC). AFTAC is based at Patrick Space Force Base near Satellite Beach, Florida, roughly 40 km south of Cape Canaveral. AFTAC maintains and utilizes a network of sensors across the globe, called the United States Atomic Energy Detection Systems, that enable its mission to monitor the globe for nuclear explosions.

Changing Nuclear Nonproliferation Challenges

The landscape of nuclear explosion monitoring shifted notably in August 1963 when the Partial Test Ban Treaty (PTBT), also known as the Limited Test Ban Treaty (LTBT), was signed by the United States, the United Kingdom, and the Soviet Union. The PTBT prohibited nuclear test detonations except those conducted underground, which limited the usefulness of infrasound as a sensing modality.

Infrasound was still utilized in monitoring applications to ensure no aboveground tests were conducted that would violate the PTBT. However, its primarily day-to-day use shifted to that of a supplement to seismic methods. When a possible explosion was identified, the presence of infrasound signatures was used to aid in discrimination between deep and shallow belowground sources. Deep sources were likely earthquakes, but shallower sources that coupled energy into the atmosphere could be explosions.

Around this same period, the US Defense Advanced Research Projects Agency (DARPA) initiated Project Vela in September 1959. Project Vela was aimed at monitoring compliance of foreign nations with the in-development PTBT. It included seismic monitoring capabilities (Vela Uniform) as well as satellite-borne sensors monitoring the atmosphere and space (Vela Sierra and Vela Hotel, respectively) (Penman, 1999).

Thus, following significant use of infrasound as a sensing modality for more than 450 atmospheric nuclear tests conducted from the late 1940s to the 1960s, the introduction of satellite sensing platforms and the shift of nuclear tests to exclusively below ground limited how useful infrasound would be in future nuclear explosion monitoring. With few other applications in the greater scientific community, infrasound research diminished in the early 1970s, and the field went relatively dormant for several decades.

An Infrasound Renaissance

During the 1990s and early 2000s, the field of infrasound underwent what some have referred to as a "renaissance" (Garces, 2008; Evers and Siegmund, 2009). This renewed interest in infrasound was due to a combination of newly identified applications of infrasound monitoring, newly available data, improvements in atmospheric specification accuracy, and advances in computational capabilities.

Infrasound Applications

Infrasound studies of volcanic eruptions became more frequent in the 1980s following subaudible recordings of the eruptions of Mt. Saint Helens, Mt. Tokachi, and Sakurajima volcanos among others (Johnson and Ripepe, 2011). The ground motion produced by earthquakes was shown to couple into the atmosphere and produce infrasonic waves that aid in magnitude estimation and other characterizations (Mutschlecner and Whitaker, 2005).

Studies have also identified infrasound signals produced by tornadic (Frazier et al., 2014) and maritime (Hetzer et al., 2008) storms that can potentially be leveraged for early warning and monitoring for such natural hazards. Planetary science researchers have leveraged infrasound in analyses of exceptionally bright and energetic meteors that produce fireballs in the sky, termed bolides. The resulting studies have provided information about the distribution of such objects in the solar system (Ens et al., 2012).

In scenarios where source information is known, infrasound propagation effects can be analyzed and used to estimate wind speeds in the atmosphere. Infrasound paths extend into the middle and upper atmospheres, which can be challenging to probe using ground- or space-based radar and similar platforms due to atmospheric opacity (Blom and Marcillo, 2017).

The Comprehensive Nuclear-Test-Ban Treaty and the International Monitoring System

Innovative applications of infrasound monitoring helped renew interest in the field, but a global source of high-quality infrasound data supported and enabled many of these new research areas. Ongoing security concerns drove additional nuclear treaty negotiations following the success of the PTBT, including the 1968 Nuclear Non-Proliferation Treaty that prohibited nonnuclear nations from developing such capabilities and the 1974 Threshold Test Ban Treaty that banned nuclear tests with yields greater than 150-kilotons equivalent TNT.

Additional negotiations continued intermittently through the 1980s and 1990s, leading to the eventual drafting of the Comprehensive Nuclear-Test-Ban Treaty (CTBT). The CTBT bans all nuclear weapons tests in any environment and was adopted by the United Nations in September 1996; however, it has not entered into force due to several nations having not yet ratified the treaty. A more detailed discussion of the history and nuances of the CTBT can be found in Dahlman et al. (2009).

The International Monitoring System (IMS) is a global network of geophysical and radionuclide sensing platforms that monitor for signatures of nuclear tests and is operated by the Preparatory Commission for the CTBT Organization. This organization is tasked with developing the capability and verification regimen for enforcing the CTBT once it has entered into force. The IMS is a global network of seismic, infrasonic, and hydroacoustic and radionuclide particulate and noble gas sensors and laboratories that monitor the globe looking for signatures of a nuclear explosion. It is also frequently leveraged for more general scientific studies.

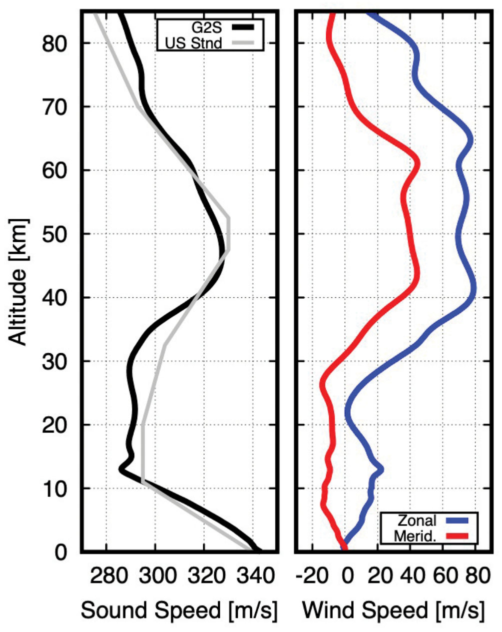
The IMS includes 60 planned infrasound stations distributed across the globe (Christie and Campus, 2010). Global security infrasound research resumed at US DOE laboratories in the 1980s, including analysis of infrasonic signals from belowground nuclear explosions and their capability to aid in characterization of such sources. Part of the work at the DOE laboratories included construction of a prototype IMS infrasound array to test and evaluate the performance of the sensing platform in 1997, jointly undertaken by the Los Alamos National Laboratory (LANL), Los Alamos, New Mexico, and the Sandia National Laboratories (SNL), Albuquerque, New Mexico. In recent years, the IMS has become a treasure trove of useful infrasound data with signals captured from the Chelyabinsk superbolide (Pilger et al., 2015), the Hunga Tonga-Hunga Ha'apai volcanic eruption (Matoza et al., 2023), and numerous other energetic events in the atmosphere.

Improved Atmospheric Data

Simulating and understanding infrasound propagation effects requires knowledge of the atmospheric structure through which waves propagate. Infrasound paths extend into the middle and upper atmospheres so that temperature, pressure, and density as well as the ambient wind fields from the ground into the stratosphere and thermosphere are needed to accurately predict and model propagation. During the early decades of nuclear explosion monitoring, atmospheric data were limited, and idealized atmospheric models were used to understand infrasound observations. A series of atmospheric models were developed and refined by the US National Oceanic and Atmospheric Administration (NOAA) through the 1950s and 1960s and culminated in the US Standard Atmosphere 1976. The model was moderately useful for modeling infrasonic propagation but did not include any seasonal variations and the altitude resolution was overly coarse.

Atmospheric measurements improved over the subsequent decades and by the 1990s and 2000s, atmospheric specifications could be obtained for specific locations and times to simulate and understand infrasonic propagation effects more accurately. A comparison of the US Standard Atmosphere 1976 and a modern Ground-to-Space (G2S) atmospheric specification (Drob et al., 2003) is shown in **Figure 3**. **Figure 3**, *gray line*, shows the sound speed profile in the US Standard Atmosphere, and **Figure 3**, *black line*, shows the sound speed as well as the zonal (**Figure 3**, blue line) and meridional (**Figure 3**, *red line*) wind fields, respectively, as specified in the sample from G2S. The US Standard Atmosphere captures the general trends of the atmospheric sound speed but has less than 10 reference altitudes and assumes linear variations between them. In comparison, available G2S atmospheric data has 100 m-altitude resolution and includes wind information in addition to sound speed. The more detailed atmospheric data result in significantly improved prediction capability. G2S atmospheric data, useful for infrasound propagation analysis, is openly available through a University of Mississippi National Center for Physical Acoustics (NCPA), Oxford, web service (see bit.ly/4ch59vZ).

Figure 3. *Comparison of historical US Standard (Std;* ***gray line****) with modern Ground-to-Space (G2S;* ***black line****) atmospheric model resolution. Year-round averaged pressure, density, and temperature were specified in the US Std atmosphere, whereas G2S specifies such information as well as zonal (****blue line****) and meridional (****red line****) winds (east/west and north/south, respectively) on a nearly hourly basis using data from weather prediction tools (****red and blue lines****).*



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acousticstoday.org/infrasound-henry-e-bass

This article from an early issue of *Acoustics Today* gives an overview of the field of sub-audible sounds.

Complicated Physics Requires Advanced Computational Tools

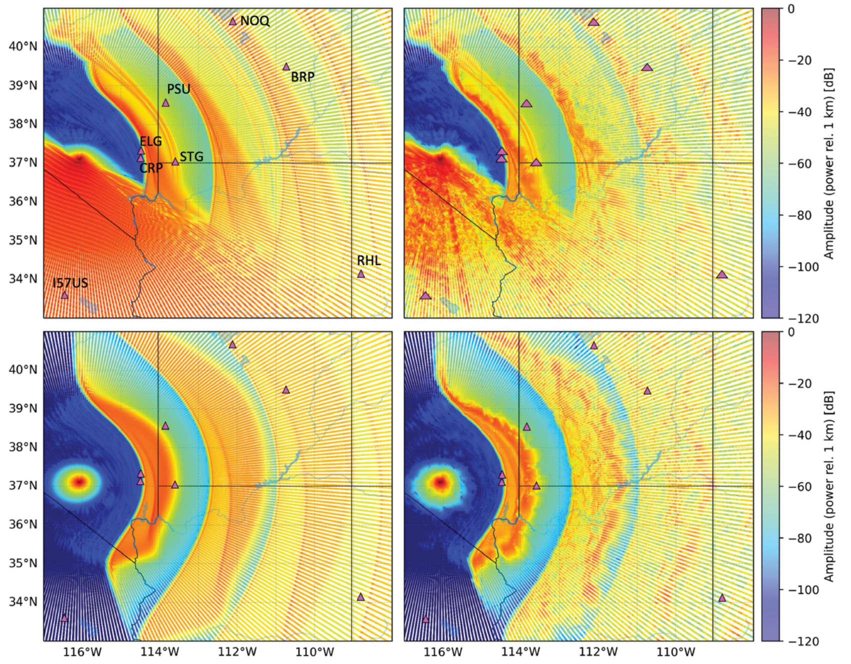
Simulations of infrasonic waves as they propagate through the atmosphere are computationally intensive partially due to the sheer spatial scale of the problem. Although some applications can deploy sensors in the immediate vicinity of sources of interest (e.g., a network of sensors around an active volcano), remote sensing applications of infrasound, such as nuclear explosion monitoring, leverage a network of stations covering a region extending hundreds or even thousands of kilometers from the individual stations. Infrasonic wavelengths range from a few tens of meters to a few kilometers and simulating all the complicated interactions of infrasonic waves with atmospheric structure and terrain over relevant spatial scales requires advanced numerical capabilities.

Even numerically efficient simulation methods such as ray tracing can be challenging when considering infrasound scenarios. The atmosphere is a dynamic, inhomogeneous moving medium. The geometry of the atmosphere is a spherical layer surrounding the globe in comparison to a Cartesian geometry that can be used for small-scale simulations. Infrasound waves interact with mountains, valleys, and other large-scale terrain structures as they propagate. Furthermore, when energy propagates into the thermosphere, the atmospheric density decreases so much that simple linear acoustic physics is no longer accurate. Despite this, several infrasonic propagation tools have been developed using ray-tracing algorithms. Additionally, several methods utilized in underwater acoustics have been adapted to infrasound applications including parabolic equation and horizontal wave number (modal) methods.

Current Infrasound Simulation Capabilities

The improved accuracy of atmospheric data combined with the advanced propagation simulation capabilities discussed in ***Complicated Physics Requires Advanced Computational Tools*** have provided continued momentum to the so-called renaissance of infrasound research and development (R&D). **Figure 4** shows propagation simulations for a pair of conventional chemical explosions conducted at the Nevada National Security Site (NNSS) (formerly the Nevada Test Site) in the fall of 2020. These explosions were part of the Large Surface Explosion Coupling Experiment (LSECE) and were conducted less than 72 hours apart. The first explosion, Artemis, occurred just after 6:30 a.m. local time on October 27, 2020, and the second, Apollo, just after 3:30 p.m. on October 29, 2020. In the relatively short time between the two explosions, the jet stream winds changed from strongly southward to much weaker so that the infrasonic waveguide dissipated and propagation to the south became inefficient. A definite infrasonic signature was observed at the I57US IMS station to the south for the first explosion but not for the second. Propagation simulations for these two events are shown in **Figure 4**, *top and bottom rows*, and capture this difference in propagation due to the temporal variations

Figure 4. *Propagation simulations using a parabolic equation method for two surface explosions conducted 2 days apart during the Large Surface Explosion Coupling Experiment (LSECE). The LSECE-Artemis (**top row**) and –Apollo (**bottom row**) events are shown. The differences when considering flat ground (**left column**) and realistic terrain (**right column**) simulations are shown. From Blom (2023, Figure 9).*



in the atmospheric structure, thus explaining the observed signal during Artemis and lack of signal from Apollo.

At several stations, infrasonic signals that required higher fidelity propagation simulation methods were identified. **Figure 4**, *left and right columns*, shows the difference in predicted propagation effects when considering flat ground and realistic terrain, respectively, using a parabolic equation algorithm. The impact is most notable for the tropospheric waveguide to the south because those propagation paths interact with the ground surface more extensively than those refracted in the middle atmosphere. Following several ground reflections, however, the propagation of energy to the east also exhibits notable focusing and defocusing of energy due to the interaction with the terrain. As noted in Blom (2023), the focusing and defocusing are impacted by both the static terrain structure and dynamic atmospheric state. Thus, high-resolution atmospheric data as well as advanced numerical methods are required to fully understand the infrasonic signals observed in remote-sensing applications. The availability and continuous improvement of both atmospheric data and numerical simulation capabilities have enabled infrasound to become a useful remote-sensing capability for natural-hazard monitoring, global security, and other applications.

Modern Infrasound Research and Development for Global Security

AFTAC continues to conduct the operational monitoring and reporting aspects of treaty and nuclear nonproliferation verification for the United States. R&D supporting that mission is conducted both by subject matter experts at AFTAC and across multiple fronts outside AFTAC. This includes significant efforts by the US DOE that supports work nationwide at US DOE laboratories, other government facilities, and through various industry and academic partners. US DOE programs maintain the scientific and technical base needed to advance nuclear threat reduction via detection and monitoring of foreign nuclear weapons development activities.

Infrasound research sponsored by the US DOE improves AFTAC's explosion monitoring mission and other aspects of nuclear nonproliferation and global security. These efforts support a combination of analysis and software development as well as experiment-driven efforts at the NNSS. Software and method development includes the tools mentioned in ***Complicated Physics Requires Advanced Computational Tools*** as well as development and evaluation of signal-analysis tools. Both traditional and machine-learning frameworks are being considered for identifying and understanding infrasonic signatures.

The United States conducted more than a thousand nuclear tests between 1945 and 1992, ceasing nuclear explosive testing activities prior to the start of negotiations for the CTBT in 1993. This has led to a need to leverage historical or "legacy" nuclear data for empirical nuclear nonproliferation research or to investigate and develop chemical-to-nuclear source relationships to continue R&D supporting nuclear explosions monitoring without conducting nuclear explosive tests.

A similar challenge exists in US DOE efforts to ensure that the existing US nuclear weapon stockpile is safe, secure, and reliable (a mission often referred to as "stockpile stewardship"). Advanced materials science and computational analyses are utilized to provide confidence in the US nuclear stockpile. A significant effort has been made between the 1990s and today to maintain the stockpile and conduct nuclear nonproliferation research that ensures treaties are enforceable, all without the need to conduct nuclear explosive tests.

Nuclear Nonproliferation Field Experiments

Several campaigns of large-scale field experiments have been undertaken using conventional chemical-explosive sources to continue development of source models for above- and belowground explosions in support of nuclear nonproliferation and related global security applications. Two large-scale and enduring efforts aimed at such investigations are currently supported by the US DOE.

The Source Physics Experiment

The first of these programs is the Source Physics Experiment (SPE) that has completed two series of conventional explosions at the NNSS (Snelson et al., 2014). Phase I of the SPE was conducted in a hard-rock granite geology between 2010 and 2016, whereas the second was conducted in a softer dry alluvium geology (DAG) between 2017 and 2019.

The first two phases of the SPE focused on understanding the generation of seismic shear energy by explosive

Figure 5. *Workers at the Nevada National Security Site (NNSS) emplacing the DAG-2 explosive during the Source Physics Experiment (SPE). DAG-2 was a 50-ton equivalent TNT explosion at a depth of 385 m below the ground surface. Photo from US Department of Energy, taken by a representative of the Nevada National Security Site.*

sources (in theory, a purely compressional source) as well as various other investigations related to the seismoacoustic wavefield produced by such sources. Phase III of the SPE is ongoing, and the focus has shifted to a direct comparison of seismoacoustic signatures from several shallow earthquakes and colocated explosions to evaluate models for discrimination of earthquakes and explosion sources.

A significant amount of R&D has been conducted as part of SPE investigating how seismic energy propagates from the explosion to the ground surface and couples into the acoustic wavefield (Blom et al., 2020; Kim et al., 2022). This research has shown that acoustic signals produced by belowground explosions are strongly dependent on the scaled depth of burial (SDOB; the physical depth divided by the cubic root of the explosive yield). A similar trend is known for aboveground explosions where blastwaves from different explosions are found to be similar at corresponding scaled propagation ranges.

Figure 5 shows the emplacement of the canister for the DAG-2 explosion by the high-explosives team at NNSS. This chemical explosion was 50-ton TNT equivalent at a depth of 385 m below ground level. Despite the relatively large 50-ton equivalent TNT yield of DAG-2, ground-based microbarometers within 2 km of surface ground zero did not detect an acoustic signal from the explosion. In contrast, Phase I experiments SPE-2 and SPE-3 were shallower and smaller explosions at depths of just over 45 m and yields of 1-ton equivalent TNT. Both events produced infrasonic signatures observable more than 5 km from surface ground zero.

As discussed in Blom et al. (2020), DAG-2 produced significant ground motion, but the spatial extent of the motion (i.e., the radius of the effective speaker cone or piston in an acoustic analysis of the ground motion) is much larger than the radiated acoustic wavelengths. In such a case, radiated energy is highly directional and focused perpendicular to the ground surface. This dependence of the seismoacoustic coupling of energy from a belowground explosion on the SDOB implies that information contained in the infrasound signal from such a source could be used beyond a simple shallow versus deep discriminate.

Low Yield Nuclear Monitoring and Multi-Phenomenological Explosion Monitoring

The second ongoing experimental effort sponsored by the US DOE is the Low-Yield Nuclear Monitoring (LYNM) program. LYNM looks to extend a multiphenomenology approach to better detect and characterize smaller nuclear explosions at shorter distances. **Figure 6** shows an idealized realization of such multi-phenomenological explosion monitoring (often referred to as "multi-PEM").

Leveraging these various phenomenologies to detect and characterize nuclear explosions is challenging due to the huge range of timescales. Electromagnetic signals propagate at the speed of light, mechanical signals at a few kilometers per second to a few hundred meters per second, and radionuclide signals at the speed of atmospheric advection. Despite this challenge, there are numerous advantages and information gains available through combinations of phenomenologies such as utilizing acoustic observations to constrain the boundary layer winds that impact the diffusion and transport of radionuclides. Furthermore, when considering small nuclear explosions, the number of sensors close enough to detect signals is often limited. In such scenarios, the ability to combine small numbers of signatures from disparate phenomenologies can mean the difference between identifying and missing an event of interest.

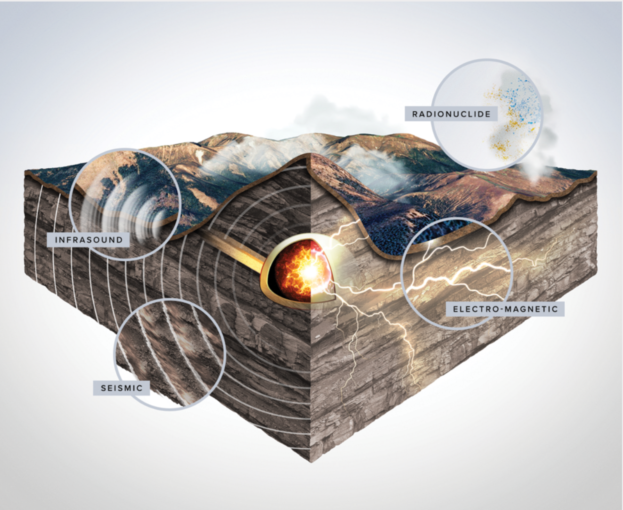


Figure 6. *Multi-phenomenology explosion monitoring (multi-PEM) is a growing focus of Department of Energy-supported Defense Nuclear Non-Proliferation Research and Development. In addition to the mechanical (seismoacoustic) and atmospheric radionuclide signatures historically leveraged to identify a nuclear explosion, electromagnetic signatures are being investigated to provide additional means of discriminating conventional and nuclear explosions. Figure created by Los Alamos National Laboratory.*

In addition to a significant amount of scientific work supported by the LYNM program, a series of experiments have been undertaken to generate data for testing in-development physical models and data-analysis methods. The LYNM Physics Experiment One (PE1) is an ongoing effort at the NNSS including testing of an electromagnetic source, various atmospheric releases of tracers for radionuclide transport model development, and a recent chemical explosion including radiotracers (Myers et al., 2024). These experiments are expected to provide additional data useful in developing and validating predictive models for multi-PEM research.

A Community Effort

Throughout the so-called infrasonic renaissance and into the current research landscape, infrasound experts have made increasing efforts to share the products of their work not only through peer-reviewed journal publications but also through sharing of datasets and software. The US DOE nuclear nonproliferation field experiments (e.g., SPE and LYNM-PE) have a policy of holding data for 2 years while US DOE scientists complete their work and then upload the data for others to utilize via platforms like EarthScope (see earthscope.org).

Several universities include infrasound in their regional networks for earthquake- and volcano-hazard monitoring (e.g., University of Utah, Salt Lake City; University of Alaska, Fairbanks) and make that data available to others. In addition to such institutional sources of infrasound data, "citizen scientist" data are a growing resource following the introduction of cheap seismoacoustic sensors built from Raspberry Pi platforms (Raspberry Shake, 2016).

Similarly, many scientists within the infrasound community have taken steps to establish open-source software licenses for algorithms and tools they have developed to share such methods more easily with the community. GitHub and similar software-sharing and-collaborative development platforms have been increasingly used to host R&D products.

A number of software tools for infrasound propagation simulation and data analysis are available through GitHub channels supported by LANL (see bit.ly/3XmeDlq), LLNL (see github.com/LLNL/AC2Dr), the University of Mississippi NCPA (see bit.ly/4b0MVOv), the University of Alaska (see bit.ly/4cgiBAr), and others.

The broader scientific community has been moving toward an "open science" mindset, and the infrasound community has adopted such an approach as well. Whether it's natural-hazard monitoring to keep communities safe or global security applications to protect the nation, the infrasound research community is providing needed data as well as tools and software to identify and understand signatures of interest.

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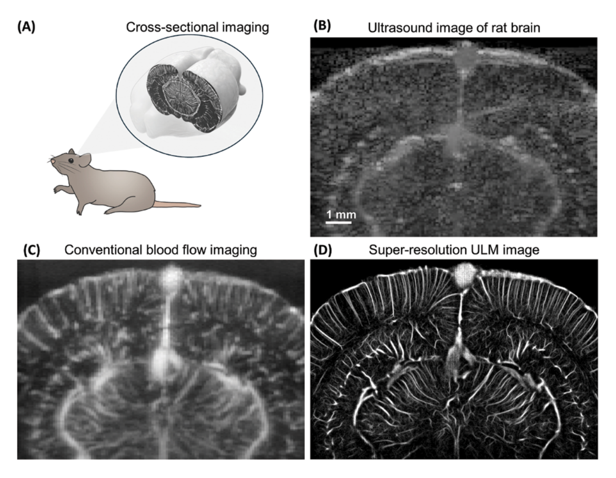
Super-Resolution Ultrasound Imaging: The Quest for Microvessels

Matthew R. Lowerison, YiRang Shin, and Pengfei Song

Everything you do, from climbing stairs to drinking a cup of coffee to reading this article, relies on oxygen to fuel your actions. Oxygen is delivered throughout your body via red blood cells that travel along the highway of your vascular system. The last stop in their journey are the microvessels, small blood vessels where oxygen and other gases are exchanged with the cells in your body. Understanding this microvessel blood flow is critical to the treatment and monitoring of numerous pathologies, from heart disease to cancer to dementia. However, microvessels are very small and often very deep in tissues, making them especially difficult to see using conventional biomedical imaging technologies. So, there is an ongoing pursuit to give clinicians ready access to microvascular flow information.

One potential approach to solve this critical imaging issue is a technique referred to as super resolution ultrasound imaging, often referred to as ultrasound localization microscopy (ULM). ULM is a recently developed solution to this "quest for microvessels" that uses FDA-approved microbubbles to greatly improve imaging resolution without losing imaging depth (**Figure 1**). But how does ULM do this? In this article, we discuss the ULM image reconstruction process using real in vivo example data taken from one of the most metabolically demanding organs, the brain.

Figure 1. ***A:*** *example of cross-sectional imaging of a rat brain.* ***B:*** *ultrasound tissue imaging gives a view of the different types of tissue where the differences in image intensity depend on changes in acoustic properties (e.g., density, sound speed).* ***C:*** *conventional blood flow imaging, such as power Doppler processing, reveals vasculature but is still limited by the wavelength of ultrasound.* ***D:*** *super-resolution ultrasound localization microscopy (ULM) imaging can break past this barrier and provide an imaging resolution at the microvascular scale.*



The "Crowd" Inside Our Body

Envision yourself lost in a crowd surrounded by people who are talking. Close your eyes and rely on your ears to distinguish individual voices and identify your colleagues. If everyone is speaking at once, distinguishing and locating specific individuals becomes a formidable challenge (**Figure 2**). But if only a handful of people are speaking, the task is much more manageable because of the separation and isolation of sound sources. Likewise, if your colleagues use something to help them stick out in the crowd (e.g., a whistle, which has a different pitch and volume from voices), the task of finding them is also more manageable. Super-resolution ULM imaging works in a similar way, detecting and localizing isolated microbubble signals that are distinct from tissue to generate detailed microvascular images.

Consider biomedical ultrasound imaging in this context of mapping the location of voices in this crowd. You are the ultrasound transducer, positioned on the surface of the body, and the various tissues and organs inside our body are the various individuals. (Of course, a caveat with this analogy is that we do not have active "voices"

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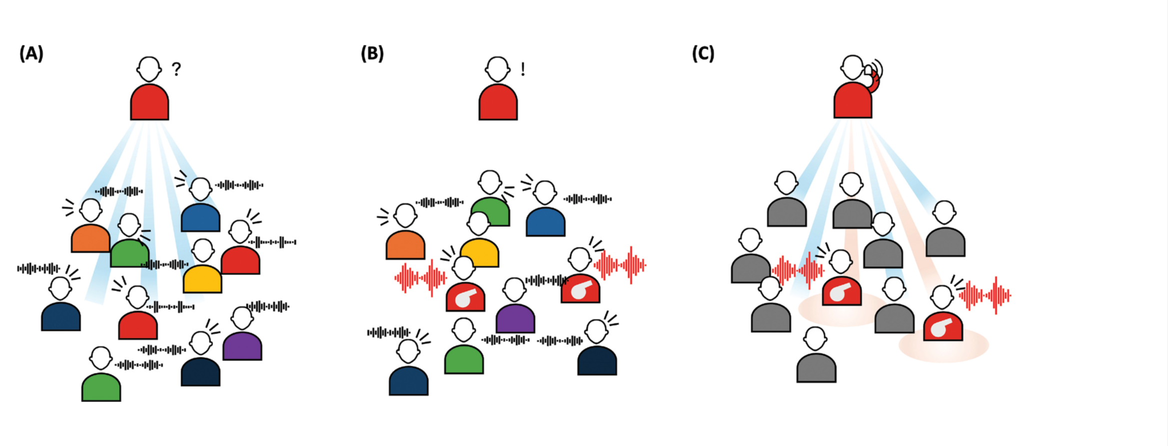


Figure 2. *Lost in the crowd.* ***A:*** *with everyone speaking at once, it is impossible to identify the locations of individual voices based on sound alone.* ***B:*** *if we give our colleagues (****red shirts****) a whistle, then we can locate them based on the pitch and loudness of the sound (****C****). Identifying each person's individual location is easier if our colleagues are far apart from one another or if they are moving around in the crowd.*

that speak in our body; specifically, ultrasound has a frequency range of ~1-15 MHz, well above the human voice frequency range of 90-255 Hz and the upper human audible range of 20 kHz). The transducer sends an ultrasound wave into the body to generate echoes from tissue(s) that consist of tiny "scatterers." Scatterers arise from changes in the acoustic impedance of tissue (which depends on tissue density and tissue sound speed) as the ultrasound wave travels through the body (e.g., different cell types, different orientations of tissues, different tissue structures such as connective tissues).

As one can probably guess, there are too many voices, all speaking at once and with similar tones and timbres, making the task of localizing each scatterer difficult. In real biological tissues, the number of scatterers is several orders of magnitude higher than we have considered in this analogy, presenting an even larger challenge to differentiating between tissues. The best we can hope to accomplish is to map out the general location(s) of a group of voices. For example, there may be denser groups where voices are loudest or the pitch of voices can provide us with information about the composition of the group (such as the ratio of men to women to children in our crowded room analogy). But the "problem" is that it is impossible to pinpoint the location of a single voice or scatterer with conventional ultrasound imaging. Our ability to resolve these fine details is compromised.

Microbubbles as Unique "Colleagues"

So how do we improve the technology? Can we pinpoint our colleagues within the crowd if they are all simultaneously speaking? No. We need a way for our colleagues to stick out in the crowd. And so, continuing with our analogy, we hand our colleagues a whistle (microbubble) to play. We are also asking them to walk around in the crowd and, ideally, to stay far apart from one another to make our task easier.

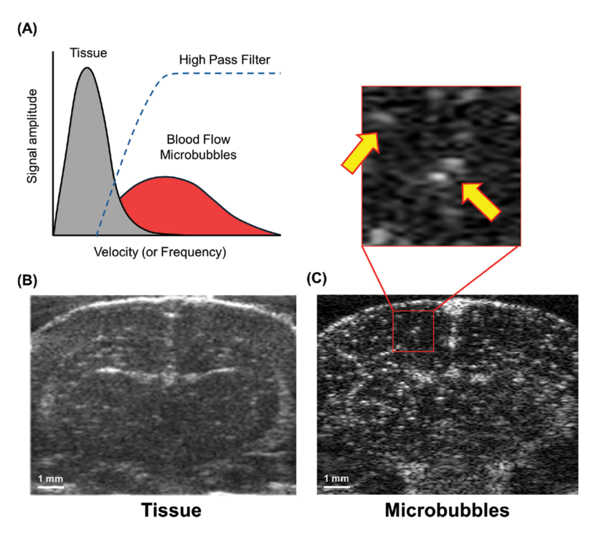
In biomedical ultrasound imaging, there is a well-established technology called contrast-enhanced ultrasound (CEUS) in which tiny microbubbles are injected into the bloodstream to enhance blood flow signals; these microbubbles function as the whistle in our crowded room analogy. Blood flow signals tend to be much weaker than the surrounding tissue(s), so microbubbles were designed to help image the vasculature. These microbubbles are typically 2-5 μm in size and made from lipid shells encapsulating an inert gas (e.g., perfluorocarbon). The size of the microbubbles was specifically chosen to mimic the size of red blood cells. This design ensures that microbubbles are small enough to smoothly circulate in the blood flow system without blocking vessels (even capillaries) but are also too large to leak out of the vascular space. Microbubbles are clinically approved around the world and are widely and safely used for numerous clinical applications such as cardiac imaging and cancer diagnosis.

Microbubbles have some unique acoustic properties that distinguish them from tissue scatterers. First, they are highly compressible, approximately four orders of magnitude more compressible than regular soft tissue. This makes microbubbles very bright under ultrasound imaging because ultrasound backscattering intensity is proportional to the difference of compressibility between microbubbles and the surrounding medium (i.e., blood). In our analogy, this means that the whistle is louder than the surrounding voices.

Second, microbubbles are highly nonlinear acoustic resonators. When hit with ultrasound waves, microbubbles generate nonlinear signals that are not produced by soft tissue. This unique property provides an opportunity to separate microbubble signals from native tissue signals during ultrasound imaging (the whistle is a much higher pitch than a typical voice, making it stand out in the crowd). Isolation is also essential to the task of pinpointing the individual locations of our microbubbles and colleagues. That is, if the whistles are too close together, the sounds overlap, causing confusion and impairing our ability to locate each individual precisely.

Third, microbubbles are highly mobile because they circulate within the body via the bloodstream; similarly, our colleagues with whistles are walking around while others remain stationary. This property provides another opportunity for creating separation between the microbubble signal and native tissue signal by means of filtering based on motion (**Figure 3**).

Figure 3. ***A:*** *using filtering, we can separate out the tissue components in the data (**B**) from a video of moving microbubbles (**C**).* ***C, inset:*** *handful of isolated microbubbles in one imaging frame (**yellow arrows**).*



Combining the three unique properties of microbubbles and envisioning their behavior in biological tissues, microbubbles manifest as a group of sounds that are loud (Property 1), with distinct tones (Property 2), and are constantly moving (Property 3) within the crowd. Importantly, the typical microbubble concentration in the bloodstream is several orders of magnitude lower than that of red blood cells, which gives rise to much greater distances between microbubbles, making them easier to localize in vivo (e.g., **Figure 3C**, *yellow arrows*, highlights the microbubbles).

Recognizing these unique advantages provided by microbubbles, Couture et al. (2011) and Siepmann et al. (2011) first introduced the idea of super-resolution imaging based on localizing microbubbles (ULM). The seminal papers by Christensen-Jeffries et al. (2015) and Errico et al. (2015) then marked the beginning of a new era of deep tissue microvascular imaging enabled by the combination of ultrasound and microbubbles. We detail how ULM imaging works, how it impacts basic science and clinical research, what shortcomings and limitations need to be overcome, and what is on the horizon for super-resolution ultrasound imaging.

How Does Localization of Microbubbles Work?

Microbubble “localization” is the process of estimating the subwavelength position of an individual microbubble within an ultrasound image, pinpointing the position of this whistle in the crowd. The usual workflow involves two main stages: an initial, quick estimate of the rough position of some “candidate” microbubbles and then a finer, subpixel algorithm of these candidates to get the super-resolved location.

It is important to note that there are usually several microbubbles within an ultrasound imaging frame (**Figure 4**), so we need a strategy for getting that first rough estimate of all microbubble positions simultaneously. A simple method is to identify isolated bright spots in the ultrasound image, which is sometimes called

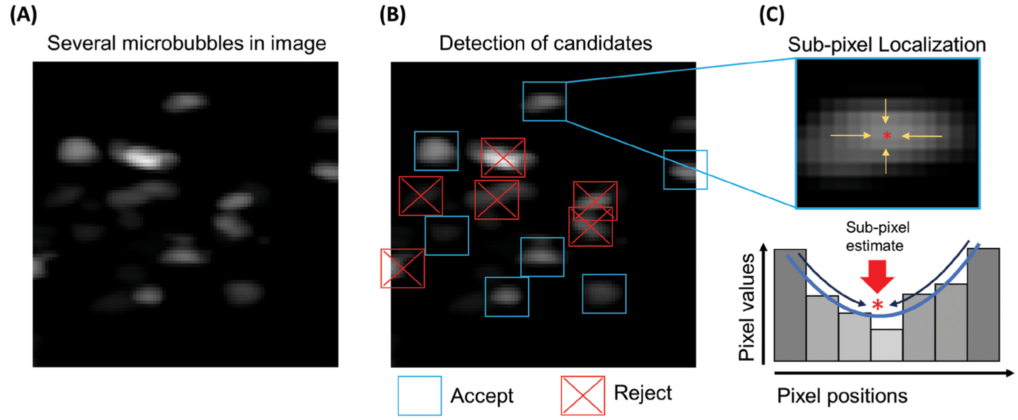


Figure 4. *Two phases of microbubble localization.* ***A:*** *example image with several microbubbles within the field of view from which the first stage of localization is applied to identify microbubble candidates (**B**). Some candidates may be rejected at this stage before being passed to the second stage that calculates the subpixel position of each valid candidate (**C**).*

a local maxima search. Other strategies include cross-correlation with a hypothetical microbubble point spread function, sometimes referred to as template matching. Deep learning plays a role here, with many networks designed to perform both microbubble detection and subpixel localization in a single step, as demonstrated by van Sloun et al. (2021) and Shin et al. (2024). Each strategy has several parameters that must be tuned for the specific imaging setup. Generally, there are assumptions made about the shape and size of a microbubble, how bright it is in comparison to the background, and the variability of the appearance of the microbubble. These assumptions are used to exclude candidates that seem too different than expected, with the assumption that these are likely false detections due to noise and other sources of error.

These candidate microbubble positions are then processed using a subpixel algorithm to achieve super-resolution. One of the most common super localization strategies for microbubble images is the "intensity weighted centroid" algorithm, sometimes also referred to as the "center of mass," in which a subpixel microbubble position is inferred based on the pixel intensities within a local region of interest surrounding the microbubble image. Other strategies to estimate the subwavelength position have been proposed, each with different advantages and disadvantages, such as processing time required, appropriateness of microbubble physical model, and assumptions made to simplify the problem. These new subpixel positions are then fed into the next stage of super-resolution ultrasound processing, a microbubble tracking algorithm.

How Does Microbubble Tracking Work?

As mentioned in **Microbubbles as Unique "Colleagues,"** microbubbles travel inside blood vessels, following the flow of blood plasma to circulate through the body. One of the conditions for good microbubble localization is that they are relatively spatially sparse to avoid any distortion of the microbubble shape by other nearby microbubbles. If we were to only accumulate the microbubble positions on every frame into an image, we would end up with a collection of discontinuous points within the lumen of blood vessels. Luckily, we know that the microbubbles are only within the vascular flow so we can make some assumptions about their locations between imaging frames and then use this information to interpolate or "fill in" the missing space between positions, a process often referred to as microbubble linking and tracking.

The simplest form of microbubble tracking is a nearest-neighbor search. For every imaging frame, we take each microbubble and pair it with the closest microbubble in the next imaging frame and then continue this process iteratively until all microbubbles within our reference frame are either paired or until we have exhausted all potential candidates. We then move onto the next frame and pair those microbubbles with the candidates in the frame after that and so on until we run out of imaging frames. Each "chain" of pairs becomes a track, which can then be interpolated to get the super-resolved spatial positions.

From this track data, we can estimate valuable physiological metrics of the vasculature. The distance traveled by the microbubble over time is the flow velocity. Tortuosity, a measure of the "disorganization" of the vasculature, can be estimated by how chaotic the trajectory is and has applications in cancer and neuroimaging.

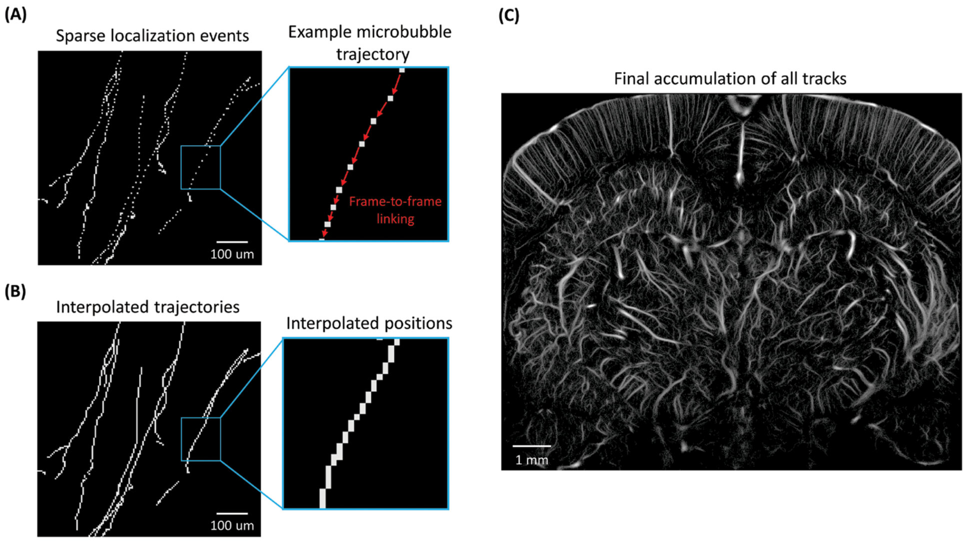
There are also features in addition to position that can be used for pairing. Several algorithms have been used that also match microbubbles, characterized by intensity, shape, or cross-correlation based on the assumption that a microbubble will look most similar to itself in the next imaging frame.

As with microbubble localization, there are several parameters that must be selected to complete this process. Some of these include the maximum allowable velocity of a microbubble, the minimum track length that is considered valid (i.e., short tracks are probably noise), the amount of acceleration and/or changes in direction in the microbubble flow, and threshold value(s) for the microbubble "similarity" metrics used to pair microbubbles. More advanced tracking algorithms also have a "gap filling" option in the pairing step that allows a microbubble to be paired with another that is more than one frame away to account for the occasional missed detection.

Now that we have the microbubble tracks, the final step is to convert it into a super-resolution image. This is done by selecting a desired interpolation factor to generate a pixel grid and then filling in all of the pixel positions for each track. The selection of the interpolation factor needs to be done judiciously because a pixel grid that is too coarse will lead to loss of information (separate blood vessels being merged together) and a pixel grid that is too fine will leave spaces inside vessels.

The ULM microbubble tracking is demonstrated using a real-world experimental dataset from a rat brain (**Figure 5**). In **Figure 5A**, we see an example accumulation of microbubble localization events for a single 1,000 frame acquisition of data from the cortical region. Although there are obvious vessel-like features,

Figure 5. *In vivo example of microbubble tracking.* ***A:*** *in this accumulation image, the sparse localizations of microbubbles lead to discontinuous vessel segments. The zoomed-in subregion demonstrates a chain of microbubbles that can be linked frame-by-frame into a trajectory.* ***B:*** *this microbubble track is interpolated to fill in these gaps in the data.* ***C:*** *this process is repeated for every microbubble track in the dataset, accumulating all the track data to produce the final super-resolution image.*



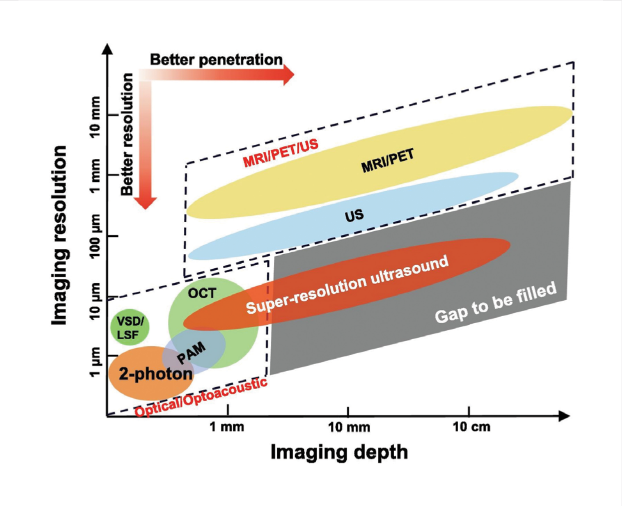


Figure 6. *Comparison of imaging resolution and penetration depth across various vascular imaging modalities, including two-photon microscopy (2-photon), laser speckle-flow imaging (LSF), magnetic resonance imaging (MRI), optical coherence tomography (OCT), photoacoustic microscopy (PAM), positron emission tomography (PET), ultrasound (US), and voltage-sensitive dye imaging (VSD). Reprinted from Song et al., 2023, licensed under CC BY-NC-ND 4.0 (see creativecommons.org/licenses/by-nc-nd/4.0h).*

the sparse microbubble data have led to discontinuous vessel segments that can be difficult to interpret. A subregion was selected to show diagrammatically the process of frame-to-frame microbubble linking to produce a trajectory. This trajectory is then interpolated to fill in the missing microbubble positions and plotted onto a pixel grid (**Figure 5B**). Finally, all the interpolated track data is accumulated across all acquisitions into a final super-resolution ULM reconstruction (**Figure 5C**), which required 50,000 frames in total.

What Are the Representative Applications of Super-Resolution Imaging?

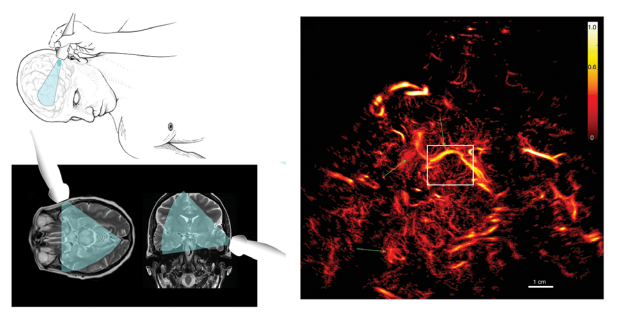
Super-resolution ULM imaging is essentially a microvascular imaging technique. Therefore, any applications that benefit from in vivo imaging of the tissue microvasculature are candidate applications for super-resolution ultrasound. Detailed summaries of preclinical and clinical applications of super-resolution imaging are provided in these reviews by Christensen-Jeffries et al. (2020), Chen et al. (2021), and Song et al. (2023). Here we provide a brief overview of some of the most prominent ones.

The brain has been one of the most popular organs for super-resolution imaging because of the importance of cerebral blood flow (CBF). This is not surprising because the brain is one of the most metabolically demanding organs, requiring a tightly regulated CBF to maintain normal function. CBF is a highly complex process that spans many different brain regions and across many different size vessels; thus imaging and monitoring of CBF presents a formidable challenge because it demands an imaging modality that has both large imaging territory and high spatial resolution.

Over the past several decades, many brain vascular imaging technologies have been developed, including optical imaging, photoacoustic imaging, magnetic resonance imaging (MRI), X-ray computed tomography (CT), and Doppler ultrasound. However, none of these methods provide both brain-wide imaging coverage (e.g., whole brain imaging provided by MRI and CT) and high spatial resolution (e.g., at micrometer scale provided by optical imaging) at the same time. Super-resolution ultrasound, on the other hand, nicely bridged this gap (**Figure 6**); it allows brain-wide spatial coverage while providing a micrometer-scale spatial resolution as well as the capability of measuring blood flow velocity for individual vessels.

These new imaging capabilities have created many new possibilities in many brain applications such as a stroke (**Figure 7**), shown by Demené et al. (2021) and Chavignon et al. (2022), aging by Lowerison et al. (2022), Alzheimer's disease by Lowerison et al. (2024), hydrocephalus and ischemia by Zhang et al. (2022), and functional imaging

Figure 7. *In vivo human brain super-resolution imaging. The schematic diagram depicts the handheld ultrasound imaging setup and reconstructed microvessel density map. Adapted from Demené et al., 2021, with permission. © Springer Nature.*



of neural activities in the brain by Renaudin et al. (2022). Both animal and human brain imaging results have been reported (see Song et al., 2023), and the brain remains as one of most promising and active areas of research for super-resolution ultrasound.

Another prominent application of super-resolution ultrasound is associated with cancer imaging. As aberrant growth of microvessels is one of the hallmarks of cancer, super-resolution ultrasound presents an enticing tool from cancer basic research to clinical management of cancer (e.g., early detection, diagnosis, and therapy response evaluation). Thanks to the high spatial resolution, super-resolution ultrasound is capable of characterizing and quantifying the abnormal microvascular flow, which serves as a functional tumor microenvironment biomarker because impaired flow is indicative of elevated intratumoral pressure and hypoxia, reported by Lowerison et al. (2020). Translational research of cancer super-resolution ULM in humans is under way and early promising results have been reported in breast (Opacic et al., 2018) and lymph node (Zhu et al., 2022) tissues.

What Are the Limitations?

Similar to its optical counterpart, fluorescence photoactivation localization microscopy, the primary limitation of super-resolution ULM lies in its slow imaging speed or low temporal resolution. In contrast to conventional ultrasound imaging, which is known for providing real-time imaging speed, ULM requires tens of seconds for data acquisition and hours for postprocessing to generate a single image. The slow imaging speed poses a formidable challenge for practical application because ultrasound imaging is typically conducted via free-hand scanning, and therefore the long data acquisition time makes ULM very susceptible to probe and tissue motion. Pragmatic solutions to this problem have included fixation of the transducer to reduce motion and correction of motion artifacts in postprocessing, although this is ideally done with three-dimensional (3D) imaging that is not as accessible as two-dimensional (2D) imaging in practice.

However, despite the low imaging speed, significant progress has been made in accelerating data acquisition. This includes developing algorithms for identifying overlapping signals under high microbubble concentration, boosting localization rates with high-frame-rate ultrasound imaging, exploiting temporal and spatial correlation of microbubbles, and inventing new super-resolution techniques that bypass microbubble localization or tracking. Hardware approaches, such parallel computing and algorithmic improvements driven by deep learning, have also been implemented to achieve faster postprocessing. Although real-time ULM without compromising spatial resolution remains a challenge, ongoing advancements hold the promise to narrow this gap and ultimately establish super-resolution ultrasound as a routine tool in biomedical research and clinical practice.

Another pragmatic challenge of ULM imaging is its dependence on microbubbles, which are intravenously injected into the bloodstream in vivo. Although intravenous injection is not an inherently complicated procedure, it is invasive and requires knowledge of anatomy and proper techniques to ensure it is done correctly and safely. In small animals such as mice, tail vein or jugular vein injections can be challenging because of the small vessel size. In humans, intravenous injections require designated medical staff and monitoring of adverse reactions to microbubbles. Contrast microbubble-free super-resolution imaging approaches offer the best practicality (and also real-time imaging), but they do not yet provide the same spatial resolution as microbubble-based techniques (demonstrated by You et al., 2023).

The next frontier of ULM is to extend its capabilities beyond imaging tissue microvasculature. Microbubbles only travel within blood vessels, which precludes super-resolution ultrasound from imaging the extravascular (outside blood vessel) space. The next-generation ultrasound contrast agents based on nanoparticles, nanodroplets (Thomas et al., 2021), and gas vesicles (Bourdeau et al., 2018) are being actively developed to open new doors for future, extravascular super-resolution ultrasound imaging.

The Outlook

Since 2015, the field of super-resolution ultrasound imaging has been experiencing an exponential growth propelled by advancements in techniques and their consequential impact on both preclinical and clinical domains. Looking ahead, a pivotal area for further development lies in high throughput imaging, enabling swift in vivo examination of tissue microvasculature. This endeavor necessitates overcoming two primary obstacles: long data acquisition (e.g., from tens of seconds to several seconds or less) and postprocessing time (e.g., from hours to minutes or even seconds). Enhanced microbubble localization and tracking techniques that sustain a high-fidelity performance under high microbubble concentrations remains the key to shortening the data-acquisition time. Although real-time ULM based on localizing individual microbubbles faces challenges due to the inherent slowness of accumulating sparse signals (similar to coloring a picture with ultrafine tipped markers), alternative techniques that bypass localization or tracking offer real-time imaging capabilities but sacrifice spatial resolution (demonstrated by Chen et al., 2023). The different available super-resolution techniques provide a complementary set of tools for effective imaging. For example, one can utilize the localization-free approach to obtain a real-time, comprehensive view of the vasculature, while employing localization-based methods to capture "close-up," high-resolution details of tissue microvasculature. For both approaches, a robust computational resource with adequate computing power to handle the high data rate associated with ultrafast imaging (e.g., several to tens of gigabytes per second) and postprocessing pipeline for super-resolution imaging (e.g., beamforming, tissue clutter filter, microbubble localization and tracking, neural networks for deep learning-based algorithms, and other ancillary processing steps) is necessary. In the meantime, ongoing efforts will focus on the continual development of more efficient algorithms aimed at reducing the computational expenses associated with super-resolution imaging.

Once high throughput imaging becomes available, super-resolution ultrasound will transition into a much more practical technology and be utilized by a much broader user base in both basic and translational research. On successful commercialization and integration into clinical ultrasound scanners, super-resolution imaging will become readily available to clinicians worldwide. This accessibility will enable clinicians to explore a myriad of clinical applications, ultimately revealing the clinical impact of super-resolution ultrasound. Another promising avenue for future growth of super-resolution ultrasound imaging lies in the domain of neuroscience, particularly in brain imaging. The unique combination of a large imaging territory (e.g., whole brain), ultrafine spatial resolution, and the portable and wearable nature of ultrasound imaging renders a compelling vision of a wearable brain imaging device that provides real-time, high-fidelity functional brain imaging in freely moving and naturally behaving subjects, including animals and humans. The longitudinal, in vivo imaging capability also presents a crucial tool for investigating the progression of neurological diseases and responses to therapy, particularly in relation to cerebral blood flow. Moreover, when coupled with therapeutic ultrasound techniques, such as focused ultrasound-based drug delivery, ablation, and neuromodulation, super-resolution ultrasound offers a compelling avenue for monitoring and assessing responses, including the opening of the blood-brain barrier, passive cavitation detection and localization, and neural activities triggered by focused ultrasound stimulation. By reducing reliance on MRI for imaging guidance and response monitoring and offering an all-acoustic solution for both therapy and imaging, super-resolution ultrasound holds the potential to significantly enhance the accessibility of these innovative therapeutic techniques, benefiting diverse populations worldwide across various demographics.

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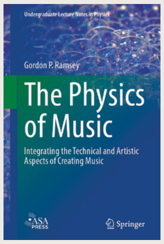

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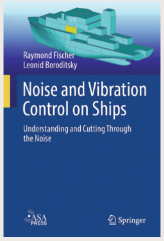

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Perceptual Soundscapes of Dolphins and Whales

Eduardo Mercado III

Thousands of hours of oceanic recordings have revealed whales and dolphins (collectively referred to as cetaceans) to be an exceptionally vociferous group of animals (for examples of vocalizations, see bit.ly/Dosits_Whale). These aquatic mammals produce complex patterns of vocalizations, possibly for communication, social interaction, navigation, or other purposes. However, even after decades of study, many of the sounds that cetaceans produce remain enigmatic.

How would one know if a whale or dolphin is vocalizing to reveal its inner thoughts, to probe its environment, or to pass the time? Simply dropping a hydrophone in the water and recording vocalizations won't reveal what animals are perceiving. Watching how animals behave while vocalizing is also unlikely to shed light on the issue because a cetacean vocalizing to communicate may behave similarly to one vocalizing to echolocate.

In fact, there are three main factors that one needs to consider in detail when attempting to answer questions about how dolphins and whales use sound: (1) How flexibly are the animals varying the physical features of their vocalizations? (2) Do the ways in which sound propagates underwater affect how cetaceans use sound? and (3) How do listening cetaceans encode, perceive, and interpret variations in received sounds? (**Figure 1**).

Figure 1. *Whales and dolphins are immersed in a sea of vibrations. A subset of these vibrations enters the animals' perceptual awareness. Cetaceans may perceive sounds as objects, events, agents, feelings, or in other ways that are unfamiliar to human observers, such as experiencing them as colored waves. Listeners may use their auditory experiences to gain information about vocalizers' movements, identity, emotional states, and potential future actions (Herman, 1980). Vocalizing individuals and groups shape their acoustic environment in ways that depend on how they vocalize, where they vocalize, and on how the surrounding environment reacts to those vocalizations. Predicting the reactions of listeners' brains to vocalizations is particularly critical to understanding how dolphins and whales use sounds in their daily lives.*

One cannot know how cetaceans are using vocalizations without some indication of what perceptual soundscapes they are constructing. The broad range of sound fields that vocalizing dolphins and whales produce afford numerous perceptual possibilities. Sorting vocalizations based on observers' subjective impressions can bias investigation and interpretation of cetacean vocal behavior. Analyzing the full physical spectrum of what happens in oceans and in animals' bodies during and after sound production is key to identifying the properties of sound fields that listening whales and dolphins are encoding and perceiving as well as the perceptually salient scenes and objects that their internal representations of sounds make real.

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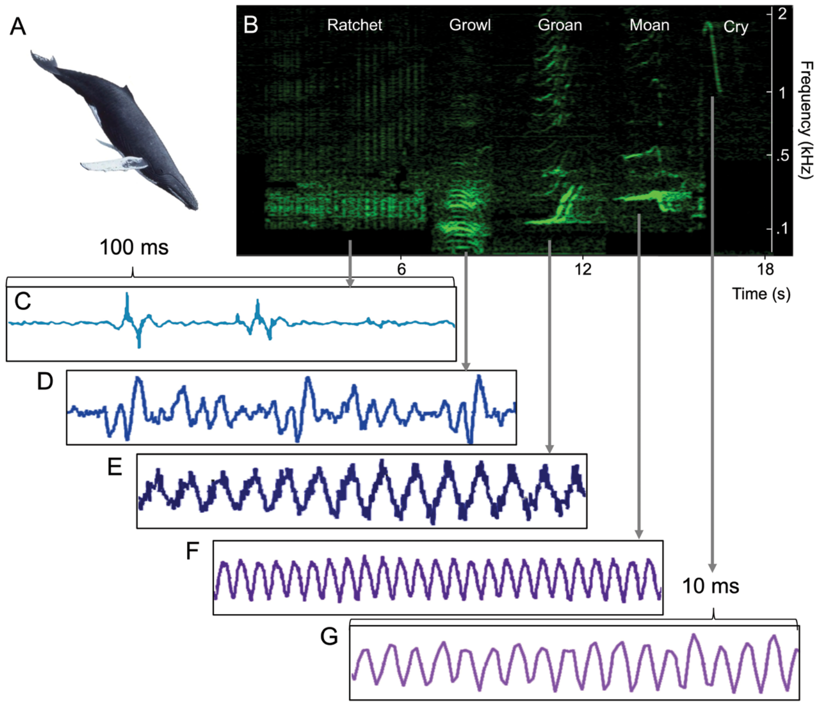
Vocal Flexibility

Whales and dolphins make sounds in many ways. One is to make percussive sounds by striking the water with body parts. They also vocalize by pushing air through vibrating membranes (Reidenberg, 2017). Cetaceans may vocalize reflexively in reaction to internal states (e.g., pain) or external events (e.g., threats). They can also modify properties of their vocalizations based on sounds they have recently heard (Mercado et al., 2014).

Sound Repertoires

Many past descriptions of cetacean vocalizations split them along the lines of the species making them: odontocetes, cetaceans with teeth such as bottlenose dolphins (*Tursiops truncatus*) and sperm whales (*Physeter macrocephalus*), produce clicks, burst-pulse signals, and whistles, whereas mysticetes (toothless whales) produce calls and songs (Au and Lammers, 2014). These categories highlight features that are perceptually salient (i.e., obvious) to human observers. For example, researchers may listen to recordings and sort vocalizations into auditory categories that they learned as a child (e.g., "whistles, "clicks," and "moans"), or may inspect spectrograms (two-dimensional images highlighting the spectral and temporal properties of sounds; see **Figure 2**) and categorize them based on their distinctive visual forms. Sometimes researchers also sort vocalizations based on the context within which the vocalizations were produced, leading to categories like "feeding call." This subjective approach to classifying vocalizations may obscure cross-species similarities that are relevant to understanding how cetaceans perceive or use their vocalizations.

Figure 2. ***A:*** *singing humpback whales produce a wide variety of sounds within their songs. Image by Larry Foster.* ***B:*** *different vocalizations produced by a singing humpback can appear quite distinctive in spectrograms. Researchers often label vocalizations based on preexisting auditory categories (see* ***Multimedia File 1*** *at acousticstoday.org/Mercado-Media).* ***C:*** *the discrete pulses within a "ratchet" are commonly referred to as "clicks" when produced by smaller cetaceans.* ***D:*** *when the duration between pulses is comparable to the pulse duration, then these vibrations are considered continuous. In dolphins, such vocalizations are referred to as "burst pulses."* ***E:*** *as the frequency of pulsation increases, the distinctions between individual pulses decrease, leading to wave patterns that are more regular and triangular. Such vocalizations produced by orcas are called "pulsed calls." Spectrograms of such vocalizations commonly show stacks of horizontal bands.* ***F:*** *further increases in pulse frequency make the waveform of a vocalization appear more regular.* ***G:*** *ultimately, the vocalization begins to approximate a sinusoid. Comparable vocalizations in dolphins are called "whistles."*



Within a species, perceptually distinctive features of signals can be directly related to changes in the vibratory modes of the membranes generating the sounds. This continuum from discrete pulses (clicks) to more sinusoidal tonal sounds (whistles) can be modeled as relaxation oscillations with properties determined by membrane tension and air pressure differences that cause the membranes to vibrate in different ways (Amador and Mindlin, 2023). The vocal repertoires of well-studied cetacean species such as bottlenose dolphins, orcas (*Orcinus orca)*, and humpback whales (*Megaptera novaeangliae*) all include vocalizations spanning the same continuum of membrane oscillations (**Figure 2**) (Murray et al., 1998). A subset of tensions and pressures can lead to more complex membrane movements, producing vocalizations with "nonlinear" features (Cazau et al., 2016).

Communicative Clicks

One category of cetacean vocalizations that has received a disproportionate amount of scientific attention over the last half century are clicks. Many cetaceans produce extended series of clicks in a variety of contexts. In odontocetes, click trains tend to be associated with echolocation (reviewed by Au, 1993). However, studies of stereotyped click trains produced by sperm whales, called codas, have increased awareness that click production and echolocation are not synonymous (Jacobs et al., 2024). Initial reports of click production by mysticetes such as humpback whales and gray whales (*Eschrichtius robustus*) were rare and seldom associated with echolocation (Fish et al., 1974). Mysticetes do not produce ultrasonic clicks. However, they commonly produce short-duration sounds with the impulsive and audible features characteristic of clicks (**Figure 2, B** and **C**) (Stimpert et al., 2007).

When odontocetes use clicks to echolocate, they may time click production such that echoes of interest return during the intervals between clicks or they may produce a burst of clicks, called a packet (Finneran, 2013). Clicks within a series tend to be highly similar, although individuals may vary click features when echolocating in noisy conditions (Au, 1993). Belugas (*Delphinapterus leucas*) and bottlenose dolphins typically switch to using packets when searching for targets at long distances.

Changing Vocalizations Over Time

The vocal repertoires of cetaceans appear to be graded, meaning that their vocalizations vary continuously across one or more acoustic dimensions rather than consisting of a fixed set of stereotyped sounds. Singing humpback whales, for example, continuously morph the acoustic features of individual sounds ("units"), dynamically shifting the pitch, duration, form, and spectral shapes of units as they progress through a song cycle (see **Multimedia File 2** at acousticstoday.org/Mercado-Media). Singers also vary how they morph units from one song to the next (Mercado and Perazio, 2022).

Some of the ways that whales shift the features of their vocalizations accumulate over seasons and years. Blue whales (*Balaenoptera musculus*) around the world have gradually decreased the pitch of units within their songs every year for over a decade (Rice et al., 2022). They vary unit properties while producing them in relatively fixed sequences. Singing humpback whales, in contrast, vary both units and unit sequences from one year to the next (Payne and Payne, 1985). Singers typically produce unit patterns in a predictable order and rhythm, with all singers in a population converging on similar sequences (see **Multimedia File 3** at acousticstoday.org/Mercado-Media). Singing humpbacks progressively and collectively vary the patterns they produce over months and years, with the degree of variation changing from one year to the next (Payne et al., 1983).

Learning to Use Novel Sounds

Like humans, cetaceans possess the rare ability to vocally imitate novel sounds immediately after hearing them. Vocal imitation requires not only flexible control of air pressure and membrane tension but also the capacity to transform perceived sounds into the vocal actions required to reproduce those sounds. Bottlenose dolphins can match not only time-varying changes in the frequency content of individual sounds (Richards et al., 1984) but also the number of sounds in a sequence (Lilly et al., 1968) and the rhythm of sound patterns (Mercado and DeLong, 2010). Both mysticetes and odontocetes sometimes engage in coordinated vocal interactions. Such interactions can even happen across species, leading some to wonder whether it might someday be possible to translate delphinid discussions or engage in interspecies conversations.

Unlike humans, cetaceans are not limited to vocally interacting with a few individuals that they are facing and that are facing them. Instead, cetaceans typically vocalize while

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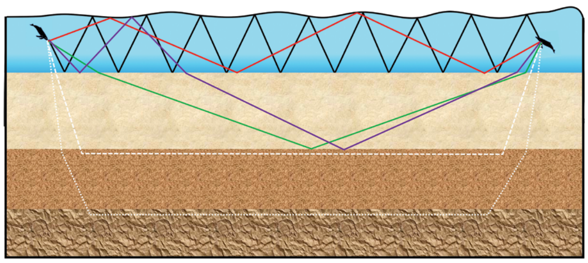
on the move in a fluid, spatially open environment where potential listeners are only occasionally visible. Moreover, cetaceans' movements and selection of sounds can affect how their vocalizations disperse in ways that are much more complex than is true for human speech. A vocalization produced at depth will have different properties from the same vocalization produced near the surface, will produce different echoes, and will reach different subsets of listeners. These are not conditions humans naturally experience. For researchers to understand how cetaceans use sound, it is critical that they identify what listening is like for the individuals using those sounds as well as the various ways that underwater sound transmission has shaped what vocalizing cetaceans hear.

Affordances of Vocalizations

When you hear people vocalizing around you, the specific sounds you hear determine the kinds of reactions you are likely to have. For instance, hearing your name yelled from a distance might provoke you to look in the direction of the caller. Hearing a number called out in a waiting room might lead you to either continue to wait or to initiate an interaction with the caller. Hearing your own voice echoing back from the walls of a canyon might encourage you to yell "Hello!" to yourself. In each case, the sounds you experience set the stage for what you're likely to do next. Psychologists describe the opportunities that objects, events, or environments provide to an individual as *affordances*. Affordances suggest possible future actions. For example, some affordances of beach balls are that they are throwable, rollable, kickable, floatable, deflatable, and huggable.

By vocalizing, cetaceans alter the affordances of their oceanic habitats to better suit their needs. Any sound they make will reveal a host of behaviorally relevant cues to other nearby (and perhaps more distant) group members. A vocalizing cetacean broadcasts where it's located, where it's going, when it's likely to arrive at future locations, and what it's doing. The sound fields they generate make it possible for listening individuals to monitor ongoing events, coordinate actions, identify individuals, corral prey, and recognize the internal states of group members. If the vocalizer is aware of the movements and goals of listeners, then vocalizations can also reveal what the vocalizer expects other individuals to do. Dolphins and whales are using sound to actively construct their perceptual worlds in real time, in ways that guide future actions.

Figure 3. *Shallow water transmission of cetacean vocalizations is more complex than what happens when humans converse or hear birds singing outside a window. Sounds and their echoes will travel through multiple paths, including subterranean channels (Thode et al., 2000). What a listener hears will depend not just on what sounds others are producing but also on where the vocalization was produced relative to the location of the listener. Resulting vocalizations received from long distances will not simply be quieter. They may be distorted in ways that make the original form of the signal unrecognizable.* ***Top to bottom:*** *the four depicted layers (pathways) correspond to seawater, sediments, basalt, and gabbro, each of which differs in its sound transmission properties.*



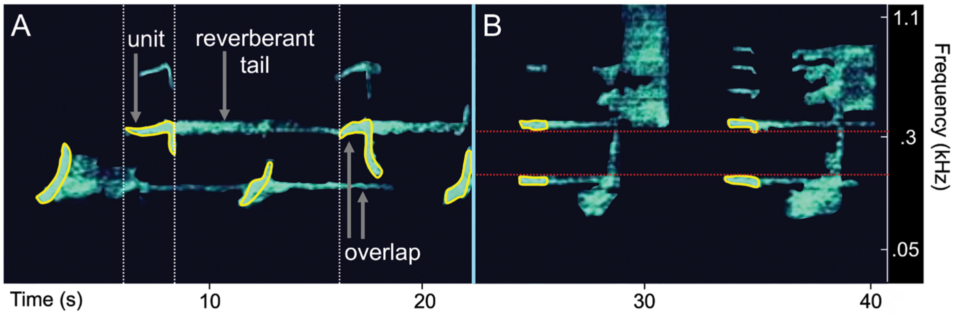


Figure 4. ***A:*** *alternating units produced by a singing humpback whale (****yellow outline****) generate long-lasting reverberant tails. When reverberation from a preceding unit minimally overlaps with the spectral properties of a subsequent unit, the units are spectrally interleaved.* ***B:*** *singers sometimes spectrally interleave tonal units with more broadband, chaotic units. In this example, the singer initiates broadband units at frequencies below those of the preceding unit, then rapidly shifts to higher frequencies. Such patterning may reduce cross-unit interference and/or enhance sound localization. Adapted from Mercado (2021), with permission of the Acoustical Society of America, © 2021.*

Environmental Constraints on Sound Usage

Once a cetacean initiates tissue oscillations within its head, those vibrations will begin propagating into the surrounding seawater. How vocalizations propagate will depend on several factors, including (1) the relationship between the acoustic properties of the vocalization and the anatomy of the vocalizer; (2) the external environment; and (3) the individual's location within that environment. The same click or whistle produced by both a bottlenose dolphin and a beluga will propagate differently based on differences in their bodies, behaviors, and habitats.

A major determinant of how cetacean vocalizations propagate is how intensely the animal vocalizes. That's not the only factor, however. Vocalizations also vary greatly in their directionality and in their susceptibility to degradation during transmission. Propagation gets particularly complicated when the water depth is less than the distances that the vocalizations can travel (**Figure 3**).

Cetaceans can move their bodies in ways that directly influence the form and function of the sound fields they produce and experience (Mercado and Frazer, 1999). For instance, when bottlenose dolphins inspect an object with echolocation, they often move their head from side to side while producing clicks, thereby controlling the properties of echoes that will be generated by the object as well as the acoustic properties that will register at their ears (Au, 1993). The dynamic forms of sound fields that vocalizing cetaceans generate and perceive remain largely unknown. The extent to which vocalizers accommodate, control, or derive useful affordances from such fluctuating fields is similarly obscure.

Vocal Reverberation: Noise or Signal?

Cetaceans' vocalizations sometimes produce significant *reverberation*, reflections that persist within an environment. Reverberation could increase ambient-noise levels, making reception more difficult. However, cetaceans might also use reverberation to guide their actions (Ellison et al., 1987). For example, singing humpback whales often produce consecutive units in ways that minimize overlapping frequencies, a behavior referred to as *spectral interleaving*. Spectrally interleaved units generate reverberation in quite narrow frequency bands that can persist for periods longer than the intervals between units (**Figure 4**). Reverberating units create new affordances for spatially processing sounds that can potentially enable listening whales to more accurately judge their distance from a singer (Mercado, 2016).

The affordances that cetaceans create by vocalizing supplement the oceanic sounds that they experience daily. These affordances are not directly observable from either acoustic recordings or from observations of behavior.

They depend on what cetaceans perceive in the present and on their memories of past acoustic events. Any cetacean's use of sound fields ultimately is a function of the internal neural and mental activity evoked by those fields. This activity, referred to as an individual's *auditory representations* of experienced sounds (Cheung et al., 2016), may differ significantly from what occurs when a terrestrial mammal is exposed to the same sounds.

Cetaceans' Auditory Representations

A soundscape consists of the combination of all sound fields detectable from a specific point in space over some duration (see articles at bit.ly/3yGZoJK). A perceptual soundscape, in contrast, corresponds to what an individual apprehends from a specific vantage point. Identical soundscapes presented to two individuals could evoke radically different perceptual soundscapes. For example, if you were to stick your head underwater as a dolphin echolocates or listen using a hydrophone, you and the dolphin would be exposed to similar soundscapes. However, the dolphin's experience of that received soundscape will differ substantially from yours. These differences arise because the auditory representations that a dolphin constructs as it produces click trains are qualitatively different from those formed by a human exposed to those same clicks.

The full scope of auditory representations and associated perceptual landscapes formed by listening cetaceans remains unknown. Their experiences likely extend beyond the norm for human listeners and other terrestrial animals. For example, sound waves reach sensory receptors within cetaceans' heads through pathways quite different from those typical of terrestrial mammals. Behavioral experiments indicate separate reception channels for ultrasonic versus sonic vocalizations in odontocetes (Norris, 1964). Mysticetes also seem to receive sounds through multiple tissue channels (Yamato et al., 2012). The complexity of pathways through which vocalizations propagate within a cetacean's body likely leads to dynamic interactions between incoming sounds that shape the formation of auditory representations.

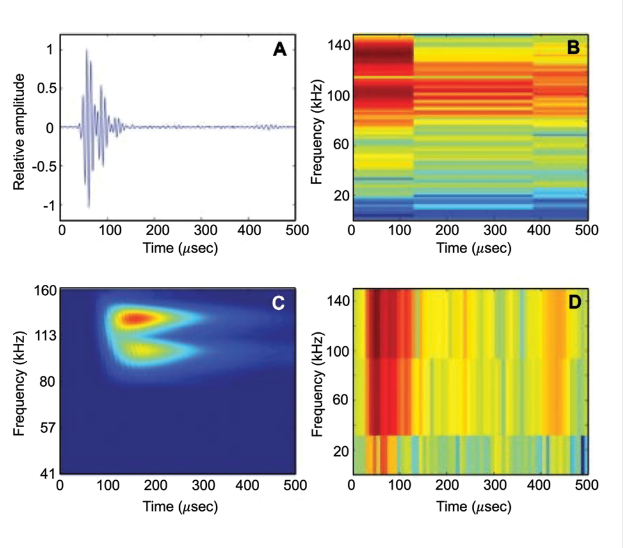
Simulating Sound Reception

One way to reveal aspects of a given species' auditory representations is by simulating cochlear reception of sound and subsequent neural reactions to sensed signals (Branstetter et al., 2007). Representing vocalizations as *cochleagrams*, spectrogram-like images of simulated sensory responses, makes the acoustic features emphasized by the relevant listeners' ears more salient (**Figure 5**).

Mapping Neural Sensitivities

Simulations of sound reception can extend far beyond what happens at the ear. Electrophysiological studies of neural activity have revealed that sensitivities to behaviorally relevant features of vocalizations are spatially organized within sensory cortical networks in the brain. For example, some echolocating bats possess cortical maps organized based on the timing of echo arrivals, emphasizing delays that correspond to distances from which bats track and capture targets while foraging (Moss et al., 2014). Although less is known about cortical maps in cetaceans, the basic principles of auditory cortical processing in other mammals likely generalize to auditory

Figure 5. ***A:*** *an echo from a single click produced by an echolocating dolphin shows rapid oscillations within a short period.* ***B:*** *spectrogram set for fine-frequency resolution reveals periodic structure within these oscillations. In this color scale,* **red** *indicates frequencies at which the energy in the echo is most intense and* **blue** *corresponds to frequencies where there is little energy.* ***C:*** *cochleagrams display how a dolphin's ear reacts to the echo over time based on theoretical models of inner ear function.* ***D:*** *spectrographic parameters could be set to achieve comparable temporal resolution but at the cost of reduced frequency resolution. Adapted from Branstetter et al. (2007), with permission of the Acoustical Society of America, © 2007.*



representations in whales and dolphins. In particular, whether a whale or dolphin perceives a sound as coming from a friend, foe, or food will depend on how incoming sounds are cortically represented.

The Role of Changing Neural Circuits

The specific auditory representations that any individual forms will also depend on the sounds that individual has heard during development and on how the individual produces and uses similar sounds. Vocalizing cetaceans are not only constantly constructing their personal auditory experiences but also creating the neural infrastructure for auditory perception and cognition in future generations. The collaborative process of vocal repertoire building is evident not only in the shared use of dolphin whistles and orca calls but also in the constantly morphing song sequences produced by singing humpback whales. Use of vocalizations as part of coordinated foraging strategies in humpbacks (Bryngelson and Colonius, 2020) and spinner dolphins (*Stenella longirostris)* (Benoit-Bird and Au, 2009) further suggests that learning experiences not only shape which sounds cetaceans produce but also how and when vocalizations are used during social interactions.

Interpreting Echoic Scenes

Few investigators have considered the perceptual implications of the dynamic, learned vocal repertoires used by cetaceans. Instead, hearing has been treated as analogous to spectrographic analysis, with incoming sounds triggering fixed computations. In reality, however, cetaceans' auditory representations are constantly changing in the short and long term. For example, the songs of blue and humpback whales vary within the lifespans of individuals. Consequently, their auditory representations of songs will change over years. As singing whales change their songs over time, both singers and listeners will need to familiarize themselves with new properties to be able to make best use of the vocalizations that they sense.

The auditory representations that form the foundation for any cetacean's perceptual soundscapes are much more dynamic than the vocalizations that they hear or produce. This asymmetry in complexity and flexibility between produced and received signals is most evident in the case of echolocation. For instance, bottlenose dolphins can repetitively produce highly stereotyped clicks to produce an almost limitless variety of perceptual soundscapes, enabling them to form distinctive representations of complex objects they have never experienced before (Pack and Herman, 1995). These dynamic properties of echoic representations in cetaceans are entirely hidden from outside observers.

Seeking with Sound

Electrophysiological and computational analyses of auditory representations in bats currently provide the best indications of how cetaceans might extract spatial information from echoes. Although there are many differences between the vocalizations used by bats and cetaceans, both groups actively control sound production and reception in ways that affect their ability to resolve the positions and movements of sound sources (Moss et al., 2014). Like dolphins, bats often adjust the timing of their vocalizations while foraging, including producing cries within packets (Mayberry et al., 2019). Both groups also show some ability to form perceptual soundscapes using echoes produced by conspecifics' vocalizations (Xitco and Roitblat, 1996).

As noted in ***Communicative Clicks,*** echolocating cetaceans often vary properties of click trains depending on the echoes that they're experiencing. Some echolocating bats gradually morph the forms of their sonar signals based on the perceptual context, for example, by shifting the frequency content of cries as they approach a target (Moss et al., 2014). Although echolocating dolphins do not change their vocalizations in this way, other cetaceans, such as singing humpback whales, do gradually morph consecutive vocalizations (Mercado et al., 2022). Such vocal variations will shift emitted sound fields in a manner analogous to the changes produced when echolocating bats adjust properties of their cries. Might humpback whales benefit from morphing their vocalizations in the same way that echolocating bats do?

Most mysticetes produce structured vocal sequences (songs), with the complexity of sequences seeming to vary depending on the oceanic conditions within which the sequences are produced (Širović and Oleson, 2022). Mysticetes could potentially use echoes from songs to perceive behaviorally relevant environmental features (Ellison et al., 1987) or to monitor the movements of prey (Yi and Makris, 2016) and conspecifics (Mercado, 2018). The kinds of sound fields and auditory representations that would enable whales to construct echoic soundscapes over vast distances may differ significantly from those that enable dolphins to track and capture fleeing prey. By modulating temporal and spectral features of vocal sequences, mysticetes may selectively enhance aspects of their perceptual soundscapes.

Comparative studies of auditory representations in bats that focus on long-range echolocation and on recognition of faint signals within background reverberation can potentially clarify the auditory mechanisms mysticetes might use to construct spatial scenes from sonic echoes. Bats detect targets from long ranges when they are searching (Moss et al., 2014), and they can recognize faint echoes buried within reverberation when they are foraging from a perch (Neuweiler et al., 1987). During search flights, bats may repetitively produce a stereotyped cry or may alternate between two to three different vocalizations (Jung et al., 2014). Bats that hunt from perches often produce tonal cries in rapid succession, leading researchers to refer to them as high-duty-cycle bats. In both cases, bats generate relatively stable sound fields from which variations in returning echoes can reveal the presence of relevant targets.

The vocal strategies used by perching and searching bats have widely been regarded as irrelevant to analyses of cetacean vocal behavior. It is well-established, however, that singing humpback whales often maintain a relatively stationary position in the water column while singing, sometimes even resting their heads on the ocean floor. Adopting such postures increases the stability of the sound fields the singer generates, providing streams of returning reverberation that are acoustically analogous to the sound fields experienced by high-duty-cycle bats hanging from a perch (Mercado, 2021).

In the past, researchers have assumed that singing humpback whales remain stationary to increase the communicative effectiveness of their songs. The fact that a singer's movements affect the perceptual soundscape that the singer experiences has largely been ignored. Some have argued that humpback whales make no use of the echoes that their songs generate (Au et al., 2001). Without more data on how cetaceans represent the sounds they hear, however, it is difficult to say what they perceive.

Final Remarks

Cetaceans are widely regarded as some of the most vocally versatile animals on the planet. Historically, their sophisticated vocal skills have been linked to the evolution of complex social ecologies requiring the exchange of detailed situation-specific information. No less impressive is their capacity to survey their surroundings using sound. Clarifying what dolphins and whales listen for and how they represent the sounds they hear can reveal new facets of the functions of their vocalizations.

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Unveiling Mars: Sounds of the Red Planet

David Mimoun, Ralph Lorenz, and Sylvestre Maurice

A Brief Journey Through Planetary Microphones History

The concept of capturing sounds from Mars has always sparked curiosity and excitement among the general public. The history of these ambitious attempts dates to the groundbreaking Soviet missions in the early 1980s. It was during this period that the Union of Soviet Socialist Republics (USSR) embarked on ambitious endeavors to explore our enigmatic planetary neighbor Venus (Ksanfomaliti et al., 1982; see bit.ly/4bFp5bm). These missions, officially launched in 1981, represented a significant leap forward in planetary exploration.

The spacecraft Venera 13 and 14 were designed to survive the harsh Venusian environment, characterized by crushing pressures (90 bar) and scorching temperatures (480°C). On their successful landing on Venus's surface in March 1982, these spacecraft became the first to transmit color images and valuable data back to Earth from the planet's surface. Integral to these missions was the Groza 2 instrument suite, tasked with characterizing the atmospheric and surface conditions of Venus, notably searching for thunder.

Despite the groundbreaking nature of these missions, the limited data sent back to Earth meant that only plots of sound amplitude, showing the presence of wind noise and sounds of spacecraft operation (notably, camera covers blowing off and operation of a drill) are their only acoustic legacies. They have sparked curiosity and speculation among scientists and space enthusiasts alike.

Sounds from Titan

A significant milestone in space exploration was later achieved with the Huygens probe (see bit.ly/46toZmi), part of the Cassini-Huygens mission when it successfully recorded the sounds of its descent through Titan's atmosphere in 2005. This mission, a collaboration between NASA, the European Space Agency (ESA), and the Italian Space Agency (ASI), marked the first time a probe landed on Titan, Saturn's largest moon.

The Huygens probe, named after the Dutch astronomer Christiaan Huygens, was equipped with a suite of scientific instruments designed to study Titan's atmosphere and surface. On January 14, 2005, the Huygens probe began its descent through Titan's thick (1.5 bar), cold (−180°C), nitrogen-rich atmosphere. As it parachuted down, the probe recorded the changing atmospheric conditions and a crude microphone picked up the noise of the air rushing past. These sounds, later processed and made available to the public, provided an unprecedented sensory experience of another world (see bit.ly/HuygensSounds).

The recordings quickly gained immense popularity, with thousands of downloads from the ESA's website. The Huygens probe also featured an active acoustic instrument, a 15-kHz sonar, intended to measure the depth of Titan's liquid methane seas in case the probe landed in a liquid. The probe landed in a desert, but it did pick up an atmospheric echo from the surface in the last seconds of its historic descent (Towner et al., 2006). Additionally, after 10 min on the surface, a speed-of-sound sensor detected a drop in sound propagation, perhaps due to sound-absorbing gases like ethane or carbon dioxide sweated out of the ground by the warm probe (Lorenz et al., 2014).

Going to Mars

In 1998, a groundbreaking project emerged from the Space Sciences Laboratory (SSL) at the University of California, Berkeley. Working in collaboration with The Planetary Society (see bit.ly/MarsMicrophone), with mostly outreach objectives, the SSL developed the Mars microphone

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for NASA's Mars polar lander (MPL) mission (Delory et al., 2007). This Mars Microphone was a marvel of engineering, designed to be small, robust, and capable of withstanding the harsh Martian environment. It was built to endure extreme conditions, including high levels of radiation and the frigid temperatures of the Martian surface. This microphone was expected to record a range of sounds, from the whisper of Martian winds to the potential crunch of surface material beneath the lander.

However, this innovative project faced a significant setback. On December 3, 1999, the MPL embarked on its descent toward the Martian surface. Tragically, contact with the spacecraft was lost shortly after it entered the Martian atmosphere.

The intense interest in capturing the sounds of Mars led to another promising opportunity for the Mars microphone with the Centre National d'Etudes Spatiales (CNES) on the NetLander mission. Scheduled for a 2007 launch, the NetLander mission was designed to deploy multiple landers on the Martian surface, each equipped with scientific instruments, including a Mars microphone, to study the planet's geology and atmosphere.

However, the ambitious NetLander mission (see bit.ly/NetLander) faced significant financial and logistical challenges. In 2001, the CNES announced the cancellation of NetLander, dashing hopes for the Mars microphone's deployment. This setback was a major disappointment for the scientific community, which remained eager to hear the sounds of Mars.

Undeterred, the team behind the Mars microphone sought another opportunity, this time with NASA's Phoenix Mars mission. The microphone was integrated into the Mars descent imager (MARDI) camera system, designed to capture high-resolution images during the spacecraft's descent and landing. The inclusion of the microphone promised to provide an audio accompaniment to the visual descent, offering a richer sensory experience.

As the Phoenix mission prepared for its 2008 launch, excitement grew once again. Yet, the Mars microphone faced another obstacle. Concerns arose about potential interference issues with other critical systems on the Phoenix lander. To mitigate these risks, mission planners decided not to activate the microphone during the mission. The disappointment was palpable, but the scientific community remained resolute.

Finally, the Mars 2020 Mission Microphones Were a Success

The NASA Mars 2020 Perseverance rover (see bit.ly/MarsLander) marked a significant milestone in the exploration of the Red Planet when it landed on February 18, 2021. Among its advanced suite of instruments, the mission payload included microphones designed to capture the sounds of Mars, contributing to the mission's scientific objectives. The Mars 2020 mission aimed to search for signs of ancient microbial life, study the planet's climate and geology, collect samples of Martian rocks and soil for potential return to Earth, and prepare for future human missions to Mars.

One of the most innovative tools of NASA's Perseverance rover is the SuperCam instrument (Maurice et al., 2021; Wiens et al., 2021). This advanced piece of technology combines several scientific techniques to study the Red Planet's surface in unprecedented detail. Central to SuperCam's capabilities is its use of laser-induced breakdown spectroscopy (LIBS). This sophisticated technique involves firing a powerful laser at Martian rocks and soils. When the laser hits the surface, it creates a small, intense burst of energy that breaks down the material into a glowing plasma. By analyzing the light emitted from this plasma, scientists can determine the chemical composition of the targeted materials. This process allows researchers to identify various elements and minerals present on Mars, offering crucial clues about the planet's geology and history.

The inclusion of a microphone in the SuperCam instrument (Mimoun et al., 2023) enhances its analytical power (e.g., Chide et al., 2019; Murdoch et al., 2019). When the LIBS laser fires, it generates shockwaves that produce sound. By recording these sounds, the microphone captures the acoustic signatures of the laser impacts. These recordings provide scientists with valuable information about the hardness and texture of Martian rocks and soils. For instance, different materials produce distinct sounds when struck by the laser, helping researchers distinguish between various types of geological formations.

The insights gained from SuperCam's analyses are vital for understanding Mars' geological past. By studying the chemical makeup and physical properties of Martian

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materials, scientists can reconstruct the planet's environmental history, including the presence and movement of water. This information is crucial for unraveling the mysteries of Mars's past climate and its potential for supporting life.

Moreover, the SuperCam plays a critical role in the Mars sample return mission. By identifying the most promising samples, the SuperCam helps scientists select the rocks and soils that hold the greatest scientific value. The audio data from the microphone adds another layer of precision, ensuring that the chosen samples provide a comprehensive snapshot of Mars' diverse geology.

Another microphone has been accommodated on the flank of the Mars 2020 Perseverance rover: the entry, descent, and landing (EDL) microphone. This microphone was specifically installed to record the sounds during the rover's dramatic descent through the Martian atmosphere and its subsequent landing on the planet's surface. The EDL microphone aimed to provide a new sensory perspective on the landing process. As the rover plunged through the thin Martian atmosphere on February 18, 2021, it experienced a series of intense and rapid events known as the "seven minutes of terror" (see bit.ly/4b16Cph). The EDL microphone was designed to capture these moments in real time, recording everything from the deployment of the parachute to the rover's final touchdown on Mars (Maki et al., 2020).

Behind the Scenes of SuperCam's Microphone: Technological Challenges

The decision to integrate a microphone, the move that would bring the sounds of Mars to Earth for the first time, was made in the late stages of developing the SuperCam mast unit (see bit.ly/MastUnit).

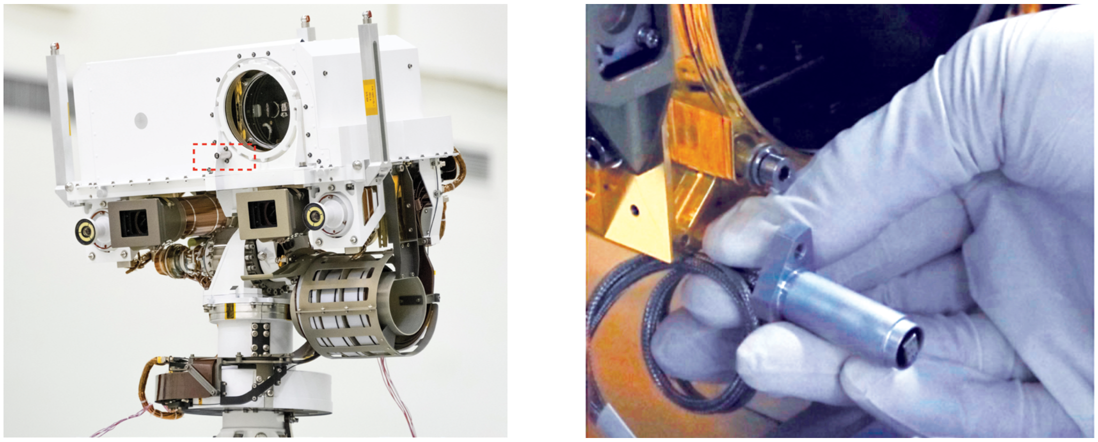


Figure 1. ***Left:*** *SuperCam instrument on the Perseverance rover.* ***Dashed red rectangle:*** *microphone location.* ***Right:*** *microphone during its tests. It is 3.4 cm long and weighs a mere 13 g!* ***Left*** *courtesy of NASA/JPL-Caltech;* ***right*** *courtesy of ISAE-SUPAERO.*

Every component of a space mission must meet exacting standards to survive the harsh conditions of space travel and operate reliably on another planet. There were concerns that the microphone might interfere with other critical parts of the SuperCam. Engineers and scientists faced a delicate balancing act. They needed to ensure that the microphone would not compromise the primary objectives of the mission. The decision to include it was continually reassessed, with the understanding that it could be removed if it posed any risk to the mission's success.

The design of the SuperCam microphone (Mimoun et al., 2023) was heavily influenced by this late addition to the unit (**Figure 1**). Instead of having a dedicated data-acquisition system, the microphone "piggybacked" on the existing system of the SuperCam instrument, sharing the same analog to the digital channel as the laser's housekeeping. One of its key features is its ability to operate at two different sampling frequencies: 25 kHz and 100 kHz. These frequencies determine how many times per second the microphone samples sound waves, influencing the quality and detail of the recordings.

This setup introduced minor operational constraints. The SuperCam team could not simultaneously use the laser temperature housekeeping and the microphone and the total acquisition volume, and therefore its duration was limited. Instead, each recording session could not exceed 8 megabytes, which is the same amount of memory required for a single image from the rover's remote micro-imager (RMI), an already existing feature of the instrument.

Depending on the chosen sampling frequency, this memory limit allows for a maximum recording duration of either 41 s at 100 kHz or 167 s at 25 kHz.

To manage this limitation and ensure efficient use of the rover's telemetry, engineers developed a sophisticated filtering algorithm. This algorithm, embedded in the SuperCam body unit's flight software, processes the audio data to optimize its transmission back to Earth, reducing the amount of data without losing essential information.

Given the unknown nature of Mars' acoustic environment, the microphone was designed to operate at four different gain settings. These settings adjust the microphone's sensitivity to capture sounds of varying intensities, from the faint whisper of Martian winds to the sharp crackle of the SuperCam's laser.

Additionally, the microphone includes a "pulsed" mode specifically designed to save data. In this mode, the microphone records only the brief sound bursts generated by the LIBS-induced shots. Although this mode conserves data, it is not suitable for continuous recordings, such as capturing the ambient noise or wind turbulence in the Martian atmosphere.

Physically, the microphone was strategically mounted beside the SuperCam telescope input window holder to optimize the recording of the incoming shockwave. As a result of this, despite the microphone part being omnidirectional at lower frequencies, the surrounding large-scale elements, such as the remote warm electronics box (RWEB), mast unit, and rover body, affected its directional performance once integrated.

Every day, this microphone is exposed to a dramatic range of temperatures, plunging to as low as −80°C at night and rising to around 0°C during the day. Despite these harsh conditions, the microphone is built to endure and operate effectively, even when temperatures fluctuate between −135°C and +60°C.

However, although the microphone itself can tolerate these extremes, its delicate electronics are far more sensitive. To protect these vital components, the electronics are housed inside the optics box, a specially designed enclosure on the rover. This box shields the electronics from the severe cold, keeping them within a safer operational range of −55°C to +60°C. This protective measure ensures that the microphone can continue to function reliably, capturing valuable audio data from the Martian surface.

To guarantee the microphone's resilience to Mars' relentless temperature cycles, engineers subjected a development model to rigorous testing. This model experienced more than 1,000 cycles of temperature variations, simulating the harsh daily changes it would face on Mars. These tests were crucial to verify that the microphone could maintain its performance and durability over time, even when exposed to the planet's extreme and rapidly changing conditions.

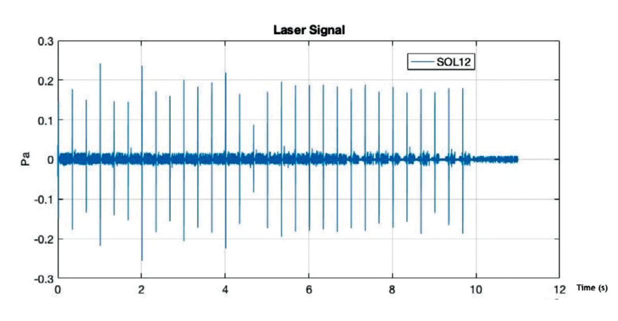


Figure 2. *Recording of the laser signal on Sol (Martian day) 12 of the mission. Reproduced from Mimoun et al. (2023). ©2023 D. Mimoun et al.*

This thorough testing process reflects the meticulous planning and engineering required to prepare instruments for the Martian environment. Each component of the Perseverance rover, including the SuperCam microphone, undergoes extensive validation to ensure it can withstand the rigors of space exploration. The ability to endure such extremes is vital for the success of the mission.

The Sounds of Science

The Mars microphones serve several objectives (Mimoun et al., 2023). The main microphone, part of the SuperCam instrument, supports both scientific and engineering goals. As described, its primary scientific objective is to enhance LIBS by analyzing the sounds produced when the laser vaporizes rock, generating a shockwave (see **Figure 2**). Additionally, the microphones record environmental sounds, such as the Martian wind and potential thunder from storms, providing insights into the Martian weather and atmospheric conditions. Also, engineering objectives include the monitoring of the rover's mechanical operations, such as the sound of wheels turning and the mast swiveling, which helps diagnose and troubleshoot mechanical issues. Finally, microphones also have significant public and educational value by adding an auditory dimension to the Mars exploration experience, making the distant planet more tangible and engaging for the public (see bit.ly/MarSound).

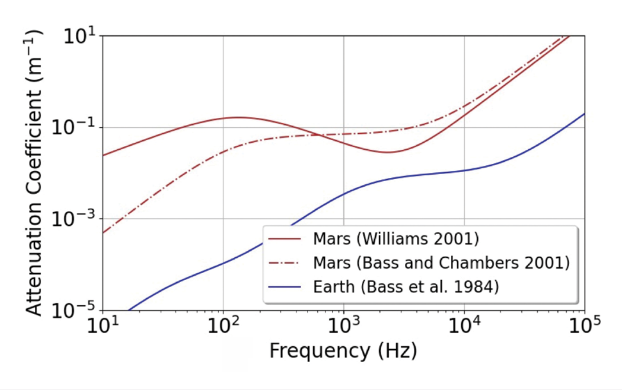
Propagation of the Sound in the Martian Atmosphere

One of the primary reasons for the relatively late integration of Mars microphones as part of the science payloads of Mars missions was the skepticism about whether there is enough sound to record due to the planet's low atmospheric pressure. Many scientists believed the thin atmosphere might render audio recordings impossible.

Sound on Mars behaves similarly to how it does in the Earth's stratosphere, where atmospheric pressure averages between 6 and 8 mbar (at 35 km altitude), and the mean temperature hovers around 240K. Attenuation on Mars was expected to result from both classical and molecular absorption processes. Studies on acoustic modeling of multicomponent gas mixtures predict a frequency-dependent sound speed and attenuation. Given Mars' cold, CO_2-rich atmosphere, significant attenuation is expected. Most sounds within the human hearing range may not be audible beyond a few tens of meters from the source.

However, the situation is different for lower frequencies. Infrasound, frequencies below the human hearing range, potentially caused by dust devils, meteor impacts, or other sources, can travel over kilometer ranges. For instance, the attenuation of a 50 dB sound at various frequencies demonstrates that high frequencies are more strongly attenuated, whereas infrasounds propagate well on both Mars and Earth (Gillier, 2024).

Figure 3. *Sound attenuation coefficient for an atmosphere of CO_2 at 240K and 740 Pa. The sound attenuation coefficient is a measure of how much sound decreases in intensity as it travels through a medium. Based on the models from Williams (2001) (**solid red line**), and Bass and Chambers (2001) (**dashed red line**). **Solid blue line:** frequency-dependent attenuation coefficient for the Earth. Reproduced from Mimoun et al. (2023). ©2023 D. Mimoun et al.*



In the quest to explore Mars, understanding how sound travels across its surface is crucial. A model of sound propagation on Mars is therefore essential for several reasons. First, to accurately interpret the acoustic properties of a sound source based on the received signal, the effects of sound propagation through the Martian atmosphere must be considered. Conversely, if the sound source is known, analyzing the received signal can reveal properties of the atmosphere. This dual approach necessitates a thorough understanding of how acoustic waves travel through Mars' atmosphere.

A sound propagation model is also pivotal for designing future acoustic instruments and experiments. The characteristics of the sound source intended for recording dictate the specifications needed for these instruments.

The SuperCam microphone, for example, was designed using existing models of sound propagation in the Martian atmosphere. These models (**Figure 3**) allowed scientists to calculate the attenuation coefficient and speed of sound for both a general Martian atmosphere and specific atmospheric profiles from the surface to the upper atmosphere. In the instrument design, the choice of the relevant model was crucial because it governs the level of sound expected at the microphone level and therefore the required gain tuning.

Capturing the Sounds of the Red Planet

Since the Perseverance rover's arrival on Mars, the SuperCam microphone has recorded approximately 27 h 20 min of audio (**Figure 4**) by Sol 1200 (a sol is the Martian equivalent of a day on Earth, slightly longer by about 40 min). Despite the generally quiet environment of Mars, the microphone has successfully documented notable events. These include the flight of the Ingenuity helicopter and the passing of a Martian dust devil. These recordings offer valuable insights into the Martian atmosphere and contribute to our understanding of the acoustic landscape on Mars.

Natural Sounds

Many of the "natural" recordings made by the SuperCam microphone are due to interactions between the Martian wind and the microphone itself. The microphone records pressure fluctuations generated by the instrument blocking the wind flow, known as the stagnation pressure, rather than by sound waves traveling through the Martian atmosphere (Chide et al., 2021).

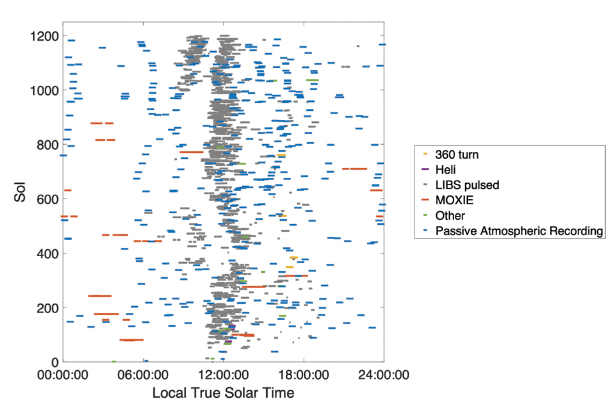


Figure 4. *A summary of the 1,200 first sols (about 2 years) of microphone recording. The various colors represent the types of recording identified. Heli, helicopter; LIBS (laser-induced breakdown spectroscopy), SuperCam; MOXIE (Mars oxygen in situ resource utilization experiment), oxygen production. Various sound descriptions are detailed in the text. Figure courtesy of Martin Giller, private communication.*

A remarkable milestone was achieved when the SuperCam microphone captured the sound of a Martian dust devil (Murdoch et al., 2022). This unique event was simultaneously documented by the Mars environmental dynamics analyzer (MEDA) instrument and the rover's navigation camera, which recorded meteorological data and images during the encounter. The sound of a Martian dust devil is available at bit.ly/dustsound.

Analysis combining the captured data with models revealed that the dust devil was approximately 25 m in diameter and at least 118 m tall. It passed directly over the rover, traveling at about 5 m/s. Additionally, valuable information about the density of dust grains within the vortex was collected.

This shows that microphones as atmospheric sensors complement traditional wind sensors with high-frequency measurements, addressing the dedicated sensors' slower response times that typically span several seconds. Moreover, the detection of grain impacts via the microphone offers an unprecedented opportunity to directly measure wind-blown grain fluxes on Mars. This capability provides new data on Martian surface dynamics and aeolian processes.

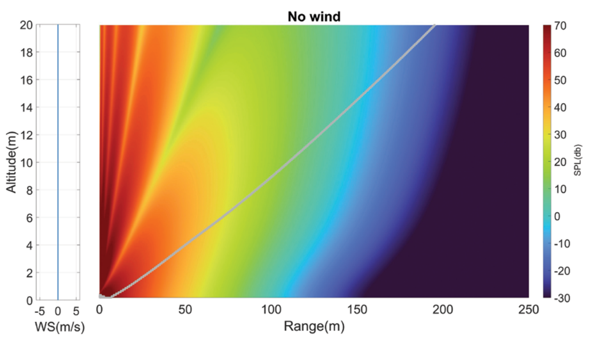
Anthropogenic Sounds

Anthropogenic sounds, or human-made noises, are the most common sources of noise on Mars. The microphone on Perseverance predominantly picks up human-made, or anthropogenic, sounds, a testament to its design. These sounds fall into two categories. First are internal rover sounds that include the hums and whirs from internal systems such as MOXIE (Mars oxygen in situ resource utilization experiment; see bit.ly/4dGyIYA), the remote sensing mast (RSM), and possibly the cooling system motors. The second set of sounds are from environment interaction. These include the sounds born from the rover's actions like the zaps from the LIBSshots, the crunch of its wheels against the Martian surface, and the buzz of the Ingenuity helicopter (see bit.ly/4cgMK2y).

Unexpected Acoustic Findings: Ingenuity Helicopter Sounds on Mars

In the first year of the Perseverance mission, one of the most puzzling surprises was the SuperCam microphone's ability to record the sound of the Ingenuity helicopter from distances exceeding 200 m. Simple propagation models, which consider ray-tracing methods, geometric attenuation, and empirical absorption, suggested that sounds should not be detectable beyond 80-100 m (see **Figure 5**).

Figure 5. *Amplitude of a Martian sound as a function of the distance to a sound source located at the (0,0) point.* ***Dark blue zone:*** *shadow zone where the sound is strongly attenuated. This is an effect due to the temperature gradient. Reproduced from Gillier et al. (2024); licensed under a Creative Commons Attribution 4.0 International (CC BY 4.0) license (creativecommons.org/licenses/by/4.0).*



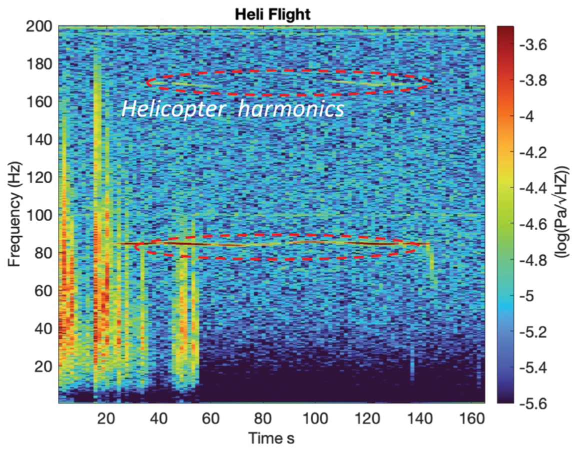


Figure 6. *This spectrogram recording of the Mars helicopter is like a visual map of the helicopter's sounds over time. There was a loud wind gust noise at the start (**vertical lines**), followed by specific sound patterns made by the helicopter at certain pitches (80 Hz and 160 Hz) that continue over time.* ***Colors:*** *sound intensity, with **red** and **yellow** representing the louder sounds. Vertical axis: SPL, sound pressure level. Reproduced from Lorenz et al., 2023; licensed under a Creative Commons Attribution 4.0 International (CC BY 4.0) license (creativecommons.org/licenses/by/4.0).*

However, the recordings defied these expectations. The sound of the helicopter was distinctly audible. Two harmonics were captured, one at 84 Hz and a second at 168 Hz. Although the 168-Hz tone is barely audible, the 84-Hz tone is distinct enough to measure the Doppler effect along with other acoustic phenomena (see **Figure 6** for the spectrogram). Higher harmonics are seen in tests on Earth, but those higher frequencies are inaudible after about 100 meters of propagation on Mars. A detailed analysis of the helicopter recordings (Lorenz et al., 2023) discusses the Doppler and attenuation effects and also discusses a modulation of the tones due to an unexpected small difference in the spin of the two coaxial rotors. These findings provide new insights into sound propagation in the Martian atmosphere, challenging existing models and enhancing our understanding of acoustic behavior on Mars.

Unveiling Martian Turbulence

By capturing the sounds of wind turbulence dust devils, and other atmospheric phenomen, the microphone provides valuable data on Mars' surface environment. One aspect that is worth stressing here is the fact that acoustic recordings have proven to be exceptionally effective for characterizing turbulence and resolving the wind structures of vortices. The wind sensors so far sent to Mars have a sample frequency of about 1 or 2 samples/s and can easily miss high-frequency effects. This is not the case with the microphones. This tool allows scientists to explore Martian turbulence on scales that were previously inaccessible.

With the microphone, we have been able to investigate how the spectral slope and regime transitions vary with different factors such as wind speed, wind direction, local time, and season (**Figure 7**). As more data are collected, these investigations will provide deeper insights into the complex atmospheric dynamics of Mars.

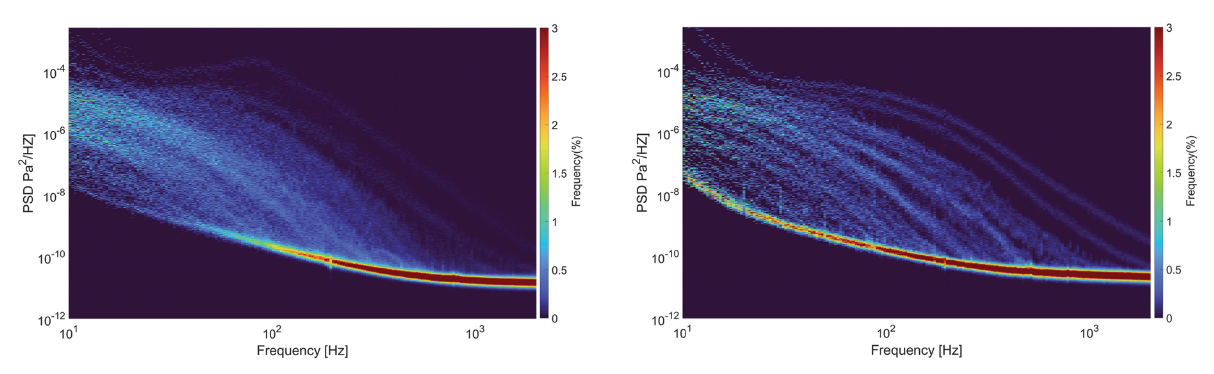
This advancement not only enhances our knowledge of the Martian environment but also paves the way for future explorations and potential habitability studies on the Red Planet. The SuperCam microphone stands as a testament to the innovative spirit driving space exploration, transforming abstract scientific inquiries into tangible discoveries.

The Future of Planetary Acoustics

The Mars microphone represents a significant technological and scientific advancement in planetary exploration. Initially thought of as an add-on to a SuperCam dedicated to rock hardness properties, its most significant applications have been in atmospheric science. Acoustic signatures also provide an important situational awareness tool, recording interaction of vehicle systems with planetary environments that may be diagnostic of the health of the equipment such as pumps or wheels. The Chinese Zhurong rover that landed on Mars just a few weeks after Perseverance also carried a microphone that recorded the clanking sound of the rover driving down a ramp onto the surface (e.g., see bit.ly/3Y6EXke). From an acoustic perspective, Mars is probably one of the most challenging planetary surface environment. Due to both the low pressure and the attenuation of carbon dioxide in the audible range, Martian sounds are faint.

However, other locations in the solar system may be much more promising. Scientists are already considering the prospects for using balloon-borne infrasound observations on Venus to detect seismic events. Looking even further afield and into future decades, several moons of the outer planets (like Jupiter's Europa or Saturn's Enceladus) may have internal water oceans beneath their icy surfaces, and acoustic methods have considerable appeal for geophysical and astrobiological studies (Dziak et al., 2020) should it one day be possible to access those environments. As well as an internal water ocean, Titan has surface liquid (methane) forming lakes and seas, rivers and rain, bringing additional interesting possibilities (Leighton and White, 2004).

Figure 7. *Spectral distribution of the Martian environment sound in the 11th- to 16th-h local time period (**left**) versus the 21st- to 6th-h period (**right**). It shows all the different frequencies of a sound and how intense each one is. Nights are generally quieter than days. Reproduced from Gillier et al. (2024); licensed under a Creative Commons Attribution 4.0 International (CC BY 4.0) license (creativecommons.org/licenses/by/4.0).*



Concrete new steps in planetary acoustics are already being taken. The NASA Dragonfly mission (see dragonfly.jhuapl.edu), under development for launch in 2028 with arrival at Titan in 2034, will include a microphone suite (Wray et al., 2024). Its designers benefit from the experience of Perseverance (e.g., using three microphones to enable better determination of sound sources and characterization of sound propagation and the use of more flexible sampling and data-compression schemes). The mission's long cruise in space subjects the instrumentation to a higher radiation dose than Perseverance, and the bitterly cold Titan environment (−180°C) has demanded careful part selection. However, Dragonfly, an octocopter lander (e.g., Lorenz, 2022) using rotor flight to visit dozens of sites with a sampling drill, promises a rich spectrum of both artificial and natural sound sources. The pioneering Perseverance experience suggests the soundscape will be full of surprises. Listen up!

Acknowledgments

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How Sound Waves Could Revolutionize Cancer (Immuno)therapy

Natasha D. Sheybani

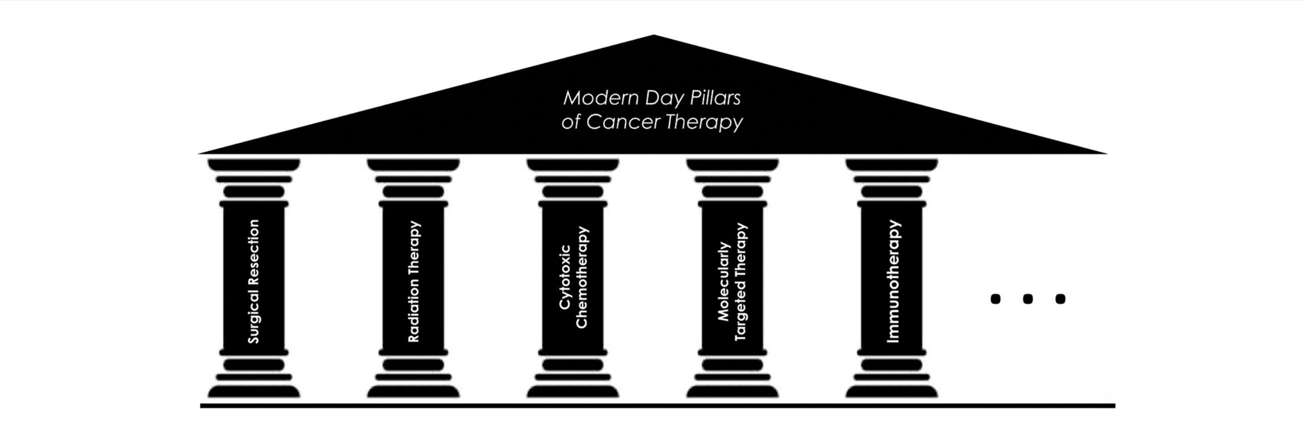
The Existential Threat of Cancer

In *The Emperor of All Maladies*, Siddhartha Mukherjee (2010) conveys the intimate and inextricable connection between cancer and the human body: "Cancer's life is a recapitulation of the body's life, its existence a pathological mirror of our own." Indeed, cancer, most simply defined as the uncontrolled growth and spread of abnormal cells in the body, represents a distorted reflection of our own biological processes. It is a formidable disease that touches every life, directly or indirectly, and the continued quest to conquer this common adversary binds us all in a profound way. Indeed, cancer affects millions of people each year, and according to the American Cancer Society, it is the leading cause of death in the United States for the population below age 85 (Siegel et al., 2024). Alarmingly, the incidence of several common cancers is rising worldwide, and, despite age historically being among the strongest risk factors for diagnosis, cancer patients are getting younger (Siegel et al., 2024). These trends underscore a dire need for safer, more effective cancer treatments. As this article highlights, sound waves are poised to play a transformative role in fulfilling this need.

Cancer Treatment 101

Before diving into the role of acoustics, however, it is necessary to introduce the current state of cancer therapy. Standard cancer therapies encompass a versatile array of treatments designed to target and eliminate cancer cells, ultimately aiming to cure the patient, prolong life, or reduce symptoms (**Figure 1**). The therapeutic mainstays for cancers vary across anatomical region, subtype, and stage but generally include surgery, chemotherapy, and radiation therapy. Surgery involves highly invasive physical removal of the tumor and, in some cases, surrounding tissue to prevent further cancer spread. Chemotherapy, discovered in the early 1940s, uses potent small-molecule drugs to destroy rapidly dividing cells, a downside being that this can also affect healthy cells and harbor significant side effects. Radiation therapy (i.e., radiotherapy) found its origins in the 1890s and employs high-energy ionizing radiation to target and

Figure 1. *Modern-day pillars of cancer treatment. These pillars include the mainstays of surgery, radiotherapy, chemotherapy, molecularly targeted therapy, and immunotherapy.*



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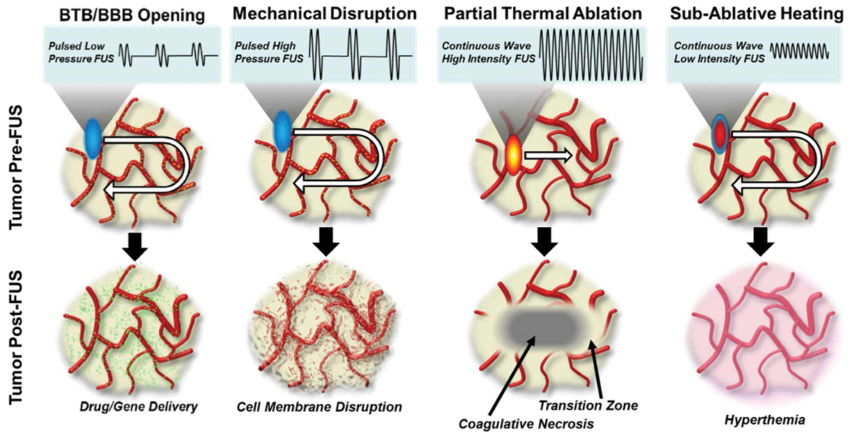
kill tumors by damaging the DNA of cancer cells but with off-target toxicity risks similar to chemotherapy (Sudhakar, 2009). Collectively, these treatment modalities have borne a profound impact on cancer outcomes. However, the safety risks and toxicities of these treatments remain a significant disadvantage for patients (Shanholtz, 2001). Although surmountable in some cases, these risks can fundamentally impact both short- and long-term quality of life, causing physical discomfort, emotional and psychological distress, and disruption of normal activities.

The late twentieth century has ushered in a transformative shift in cancer treatment with the introduction of molecularly targeted therapies and immunotherapies that are revolutionizing the way we combat malignancies with more specific targeting of cancer cells or by harnessing the eradicative power of the immune system. By honing in on specific molecular targets, these therapeutic categories offer radical potential for more precise and effective treatments with reduced damage to normal cells, leading to improved outcomes and fewer side effects for cancer patients (Min and Lee, 2022). Specifically with the advent of immunotherapies, a class of drugs designed to engage the body's own surveillance system, the immune system, to recognize and attack cancer cells (discussed in greater detail in **Cancer Immunotherapy: Promise and Problems**), there is newfound promise not just for combatting primary tumors, but also for elaborating immunological memory to drive effective responses against the chief cause of mortality in most advanced cancer settings, metastases (Davis, 2000). Despite the marked impact of these advancements on cancer care, challenges remain. The success of both molecularly targeted therapies and immunotherapies has been limited by such factors as tumor heterogeneity, physical barriers to delivery, complex mechanisms of tumor evolution, and off-target effects (Huang et al., 2014; Whiteside et al., 2016).

Despite innumerable advances in cancer care, a clear need remains for therapeutic options that balance the need for improved efficacy with prioritization of minimal risk to patients. If we peer into the "constellation" of cancer therapy options, a particular "star" shines bright as being a powerful asset to both conventional and novel cancer treatment paradigms due to its uniquely nontoxic and versatile nature, therapeutic ultrasound.

Figure 2. *Examples of thermal or mechanical therapeutic ultrasound regimens applied in tumors. Focused ultrasound (FUS) waves (**top, light blue:** representative sound wave patterns) can be tuned to ablative or subablative exposure levels to result in a broad range of bioeffects to tumor tissue (**tan; red:** blood vessels). These include (**left to right**) blood-brain/tumor-barrier (BBB/BTB) opening with microbubbles for drug or gene (**green dots**) delivery; mechanical disruption (i.e., mechanical ablation) resulting in cell membrane disruption and tissue fractionation; thermal ablation resulting in coagulative necrosis, i.e., "burning" of tissue (**gray oval**); and subablative heating resulting in hyperthermia, i.e., "warming" of tissue (**pink**). Sonications can be applied in a variety of patterns to achieve total or subtotal tumor coverage (**white arrows**). Not pictured are other known mechanisms of action such as radiosensitization and sonodynamic therapy. Adapted from Curley et al. (2017), copyright Ivyspring International Publisher; licensed under a Creative Commons Attribution-Noncommercial 4.0 International (CC BY NC 4.0) license (creativecommons.org/licenses/by-nc/4.0).*



The Multifaceted Marvel of Therapeutic Ultrasound

Not to be confused with ultrasound for biomedical imaging applications, therapeutic ultrasound (TUS) has emerged as a promising modality for transforming cancer treatment, offering a nonionizing, noninvasive, precisely targeted, and highly tunable approach for acoustic energy deposition that can be leveraged to destroy cancer cells, facilitate delivery of cancer therapeutics, and even modulate the tumor-immune landscape (**Figure 2**). Utilizing high-energy ultrasound waves, this technique generates thermal and/or mechanical bioeffects that can be targeted to tumor tissues with submillimeter precision while sparing intervening or surrounding healthy tissue. In addition to its precise and minimally toxic nature, perhaps one of the greatest strengths of TUS is its versatility, herein described.

Thermal Disruption of Tumors

TUS can yield controlled and localized heating that induces thermal ablation, where continuously applied acoustic energy is concentrated to confer rapid temperature elevations >55°C on average. This results in destructive "burning" of the targeted area, characterized by protein denaturation and cell death. Often, this ablated zone is surrounded by a transitional zone of irreversible heat-mediated cell damage, termed the "peri-ablative margin." By carefully controlling the duration, intensity, and location of the ultrasound energy, clinicians can achieve precise and customizable ablation zones while minimizing damage to surrounding healthy tissues. Real-time imaging guidance, often involving ultrasound or magnetic resonance imaging (MRI), ensures accurate targeting and monitoring of the ablation process. Continuous sound waves can also be tuned to lower exposure conditions to yield hyperthermic temperatures, typically between 40° and 45°C. This moderate "warming" can have several biological effects, including increasing blood flow, enhancing local drug delivery, and sensitizing tumor cells to radiation therapy and chemotherapy.

Mechanical Disruption of Tumors

TUS can also achieve tissue disruption through mechanical forces rather than thermal affects. At high amplitudes, the interaction of pulsed ultrasonic waves with endogenous microscopic gas bubbles in the targeted tissue microenvironment can result in localized acoustic cavitation activity through the oscillation and rapid collapse of bubbles, generating shock waves and microstreaming forces that exert mechanical stresses on the surrounding tissue (see Maxwell et al., 2012). The mechanical forces produced by cavitation can cause physical fragmentation of cells, tissues, and even subcellular organelles, yielding yet a different mechanism of tumor ablation.

At lower intensities, TUS can also be applied in tandem with the administration of exogenous cavitation nuclei such as nano- or microbubbles (e.g., Matula and Chen, 2013). The amplification of mechanical exposures in this case originates within the blood vessels and exerts forces on the surrounding tissue via induction of shear stresses, microjets, and localized pressure changes. The mechanical disruption brought about by micro- or nanobubble-assisted TUS can have various effects, including enhancing drug delivery through increased vascular permeability (e.g., transient opening of the blood-brain barrier; highlighted by Konofagou, 2017), promoting tissue permeabilization for targeted therapies and even facilitating tissue ablation.

Physical Sensitization of Tumors

Aside from classically thermal or mechanical perturbations, TUS offers numerous other mechanisms of action with an emerging promise for cancer therapy. Sonodynamic therapy (SDT) leverages small molecule agents (e.g., 5-aminolevulinic acid) that are preferentially taken up by metabolically active cancer cells. The activation of these agents by low-intensity ultrasound waves can induce tumor killing through oxidative damage and eventual cell death in targeted cancer cells, enabling a modality for tumor cell-specific killing with TUS.

Alternatively, efforts are underway to use TUS as a strategy for making tumors more sensitive to radiotherapy. Known as "radiosensitization," this involves leveraging the mechanical or thermal bioeffects of TUS to enhance susceptibility of cancer cells to killing via ionizing radiation energy. Through mechanisms that are still being uncovered, TUS can heighten the susceptibility of cancer cells to radiation-induced damage, thereby offering promise to improve "standard of care" outcomes or mitigate toxicities by enabling titration of radiation doses.

The versatile mechanisms of TUS have given way to numerous advancements in the treatment of cancer, including nonsurgical tumor debulking, cancer-associated pain palliation, and combinatorial treatment with radiotherapy, chemotherapies, molecularly targeted therapies, and immunotherapies. However, to cover all these topics in meaningful depth would be infeasible within the scope of this article. The remainder of this article thus focuses on TUS for enabling the strategy that is submitted as having the most curative potential in the fight against cancer, *immunotherapy*.

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Cancer Immunotherapy: Promise and Problems

Heralded by *Science Magazine* as "Breakthrough of the Year" in 2013 and the topic of the 2018 Nobel Prize in Physiology or Medicine awarded to James Allison and Tasuku Honjo, cancer immunotherapy represents a revolutionary frontier in cancer treatment (Loontz, 2013). The origins of cancer immunotherapy can be traced much farther back than the early 2000s, however, specifically to around 1891 with the pioneering work of William Coley, often referred to as the "Father of Cancer Immunotherapy" (Dobosz and Dzieciątkowski, 2019).

Inspired by observations that some cancer patients who developed infections unexpectedly experienced tumor regression, Coley experimented with intentionally infecting patients with bacteria to stimulate an immune response against their tumors. He developed a mixture known as "Coley's toxins," which demonstrated some success in treating certain cancers.

Despite initial skepticism and subsequent decline in use of his methods with the advent of radiation and chemotherapy, Coley's work laid the foundation for modern cancer immunotherapy. The resurgence of the immunotherapy field in the late twentieth century has brought with it an accelerated pace of discovery yielding novel immune targets and the development of various immunotherapy drugs including antibodies, engineered immune cells, and cancer vaccines, all uniformly aimed at unleashing the immune response for precise recognition, targeting, and elimination of cancer cells throughout the body. With its many modes of action, immunotherapy holds great potential for achieving durable and long-lasting remissions, even cures, across various cancer types (Harris et al., 2016).

Although the impact of cancer immunotherapies has been transformative in select cancers, an unfortunate reality remains: they are ineffective against most tumors. Indeed, most solid cancers create a particularly daunting set of diverse and complex challenges, which still need to be addressed for the promise of immunotherapy to be fully realized. Recent statistics suggest only ~20-40% of patients, depending on solid cancer type, respond to immunotherapy drugs (Pilard et al., 2021). This excludes a significant proportion of patients and motivates the continued quest to extend the benefits of immunotherapy to the broader cancer patient population.

One of the primary hurdles to effective immunotherapy is the heterogeneity of tumors, where genetic and molecular differences within and between tumors can result in variable responses. Additionally, many tumors leverage sophisticated mechanisms to evade the immune system before, or even after, the ramping up of a response that can limit the effectiveness of immune-based treatments. The risk of immune-related adverse effects is another challenge, because activating the immune system can sometimes lead to unintended inflammation and damage to healthy tissues, known as immune-mediated toxicities. Moreover, identifying reliable biomarkers to monitor treatment progress or predict which patients will benefit from immunotherapy remains a critical need. Finally, manufacturing and delivering specific immunotherapeutic agents, such as engineered immune cells, also present logistical and cost barriers due to their complexity. Overcoming these obstacles is paramount, requiring innovative strategies to enhance immune response specificity and durability as well as development of combination therapies that prioritize both efficacy and safety profiles (P. Sharma et al., 2017).

Potentiating Immunotherapies with Therapeutic Ultrasound

It has been widely posited that rational combinatorial strategies hold the key to advancing immunotherapy outcomes (Yap et al., 2021). TUS is remarkably well-suited to be a promising combinatorial strategy due to the numerous ways in which it can be leveraged to potentiate different immunotherapy classes. As discussed in this section, TUS is capable of evoking immunogenic signatures that intersect with the classical "cancer immunity cycle" (Sheybani and Price, 2019), which is a conceptual framework describing the steps required for the immune system to effectively recognize and eradicate cancer cells, fully explained in Chen and Mellman (2013). The earliest observations supporting the immunogenicity of TUS date back to the early 1990s when local hyperthermia or thermal ablation exposures unexpectedly mobilized host immune responses in preclinical or clinical cancer settings. Since then, we have also learned that TUS can augment immunotherapy delivery and even remotely control immune cells. Taken together, these capabilities hold profound implications for improving the effectiveness and precision of immunotherapy paradigms.

Inducing Immunogenic Cell Death

Many cells in our bodies are constantly dying and turning over. It would be a major problem if that natural homeostatic process elicited an immune response every time. As such, our bodies have evolved special mechanisms for alerting the immune system to cell death that warrants a response. We call this immunogenic cell death (ICD). ICD describes a specific mode of cell death that can be recognized by the immune system. ICD is essentially one of the first crucial steps in the cancer immunity cycle because it sets the stage for an effective immune response coordinated to recognize and attack cancer cells.

Unlike conventional cell death, which can occur without eliciting an immune response, ICD is characterized by the release or exposure of specific "danger signals" (otherwise known as alarmins) and the exposure of antigens (discussed in ***Priming Innate Immunity***) that enhance the visibility of dying cancer cells to the immune system (Hayashi et al., 2020). To this end, the concept of ICD is thus critical for cancer immunotherapy because it converts the tumor into its own vaccine, thereby enhancing the effectiveness of immune-based treatments. Some of the ablative modes of TUS, such as thermal and mechanical ablation, have been shown to result in the widespread translocation of key alarmins and heat shock proteins within and surrounding the ablation zone (Hu et al., 2005). Other approaches have also utilized nanoparticles decorated with alarmins (Sethuraman et al., 2020) or the help of agents like chemotherapy (Ya et al., 2023) to elaborate more robust ICD signatures in TUS applications.

Priming Innate Immunity

The "first responders" of the immune system are known as innate immune cells. The innate immune response plays a crucial role in the body's initial defense against cancer, serving as the first line of immune surveillance and attack. Central to this response are innate immune cells, known as dendritic cells (DCs), which are key antigen-presenting cells capable of bridging the innate and adaptive immune systems. On encountering cancer cells, DCs ingest tumor antigens (molecules produced by cancer cells that can be recognized by the immune system), and these antigens are then processed and presented on the surface of DCs in conjunction with major histocompatibility complex (MHC) molecules. The mature antigen-loaded DCs migrate to distal sites like the lymph nodes or spleen, where they cross-pollinate with naive T cells and present them with specific tumor antigens. This "priming" event activates T cells to become tumor specific, rendering them capable of recognizing and killing cancer cells bearing the specific antigens. Unfortunately, tumors have sophisticated ways of rendering innate immunity aberrant by limiting antigen availability or repertoire, downregulating MHC molecules, or conferring immunosuppressive signals that limit productive DC function. This is excitingly where TUS has again demonstrated promise for overcoming these critical barriers.

For example, thermal ablation has been demonstrated across numerous solid tumor settings to promote DC maturity and function by elevating DC representation in draining lymph nodes, upregulating MHC and activation molecules, and promoting intratumoral antigen cross-presentation (Chavez et al., 2018). Mechanical TUS regimens have displayed a similar capacity across tumor settings within (Curley et al., 2020) and outside (Hendricks-Wenger et al., 2021) the brain. Recent work has even demonstrated that mechanical ablation shapes innate immune responses through marked improvement of tumor-associated antigen availability and promotion of antigen acquisition by conventional DCs (Thim et al., 2024). Several approaches have strategically coupled TUS with innate immune adjuvants such as CD40 agonists, toll-like receptor (TLR) agonists, and cancer vaccines to more robustly invigorate the early stages of the "cancer immunity cycle" (Singh et al., 2019).

Improving Immunotherapy Delivery and Persistence

The transport of systemically administered immunotherapies to and within solid tumors faces several significant barriers that directly limit therapeutic efficacy. One primary obstacle is the abnormal and often poorly organized blood vessel network within solid tumors, known as the blood-tumor barrier, which impairs effective drug delivery and distribution. In brain tumors, an additional layer of complexity is introduced by the protective blood-brain barrier (Arvanitis et al., 2019). Solid tumors also typically exhibit high interstitial fluid pressures and possess dense extracellular matrices that further hinder the penetration of therapeutic agents into the tumor core. Hypoxia and acidic conditions within the tumor can also negatively affect immune cell function and survival. TUS has been variably utilized as a strategy to overcome these barriers.

For example, thermal ablation has been demonstrated to reduce interstitial fluid pressure and improve macromolecule penetrance into tumor tissues (Sassaroli and O'Neill, 2014). Mechanical perturbations, with or without microbubbles, have been exploited for breaking down dense extracellular matrix, as in the particularly challenging setting of pancreatic cancer (Maloney et al., 2017). Meanwhile, both thermal and nonthermal bioeffects of TUS have been shown to increase tissue oxygenation, holding critical implications for the treatment of hypoxic tumors (D. Sharma et al., 2022). A known effect of microbubble-assisted TUS is transiently overcoming the blood-brain and/or blood-tumor barriers, which has given way to a rich tapestry of studies demonstrating improved delivery of immunomodulatory chemotherapies (Arrieta et al., 2024), immune checkpoint inhibitors (Lee et al., 2023), adoptive cellular therapies (Sabbagh et al., 2021), gene therapies (Ilovitsh et al., 2020), and more. Early-phase clinical trials have also demonstrated the capacity of TUS-mediated blood-brain/-tumor barrier opening to augment delivery of adjuvant chemotherapies and immunotherapies into brain tumors and even improve the local persistence of the latter (Meng et al., 2021).

Chasing the Abscopal Effect

In cancer treatment, there is a phenomenon known as the abscopal effect (from the Latin words "ab," meaning "away from," and "scopos," meaning "target"). This describes a situation where localized therapy, such as TUS, leads to the regression of cancerous lesions at sites distant from the primary treatment area; put another way, the abscopal effect refers to the systemic impact of a localized intervention. To this end, the abscopal effect is widely regarded as the "holy grail" for locoregional therapies, and TUS is no exception in this regard.

The abscopal effect has been reported sporadically in clinical cases implementing TUS for ablation, and research is ongoing to better understand the mechanisms behind abscopal responses and how they can be reliably induced for more comprehensive metastatic disease control and improved patient outcomes. Combining localized treatments like TUS with systemic immunotherapies is proving to be a promising strategy for elaborating abscopal effects.

Numerous preclinical studies deploying thermal or mechanical TUS have reported elaboration of productive T cell responses, and even abscopal responses, across varying immunophenotypes including melanoma, breast cancer, and other settings (van den Bijgaart et al., 2017). Promisingly, anecdotal observations of the abscopal effect have been made in the clinic, as in the example of a recent hallmark case report that reported abscopal control following mechanical ablation of liver cancer (**Figure 3**) (Vidal-Jove et al., 2021). The number of these observations is continuing to grow as global clinical adoption of TUS technology expands.

Sonogenetics

When peering into the future of TUS and cancer therapy, a new area on the horizon, sonogenetics, can be appreciated. Sonogenetics is an emerging field that involves the use of TUS to modulate cellular function and activity through the introduction of genetically encoded ultrasound-sensitive proteins. This technique holds significant potential for cancer immunotherapy by providing a noninvasive and highly precise method to control and enhance the action of

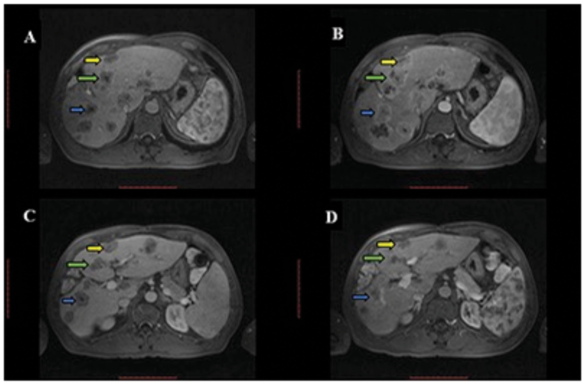


Figure 3. *Representative magnetic resonance imaging (MRI) images illustrating abscopal effect following mechanical ablation in liver cancer. Images depict one week prior to treatment (**A**), one day posttreatment (**B**), one week posttreatment (**C**), and eight weeks posttreatment (**D**). **Colored arrows:** three different untreated liver tumors tracked over time, displaying apparent volume shrinkage after mechanical ablation of a separate mass. Originally adapted from Vidal-Jove et al. (2021), with permission of IEEE; reproduced from shorturl.at/KL5Uw.*

immune cells against tumors. The basic concept of sonogenetics involves genetically engineering immune cells, such as T cells or dendritic cells, to express ultrasound-sensitive ion channels or mechanoreceptors that enable direct response to an acoustic stimulus. A compelling example of this was the recent engineering of "remotely controllable" chimeric antigen receptor (CAR) T cells, wherein CAR domains could be switched on or off via ultrasound exposure, thereby offering a novel strategy for localized T cell engagement and cytotoxicity as well as mitigation of on-target, off-tumor toxicities (**Figure 4**) (Y. Wu et al., 2021). The convergent innovations in TUS and synthetic biology that are giving way to sonogenetics offer the potential to enhance the specificity, efficacy, and safety of immunotherapies, paving the way for more effective treatments for various cancer types.

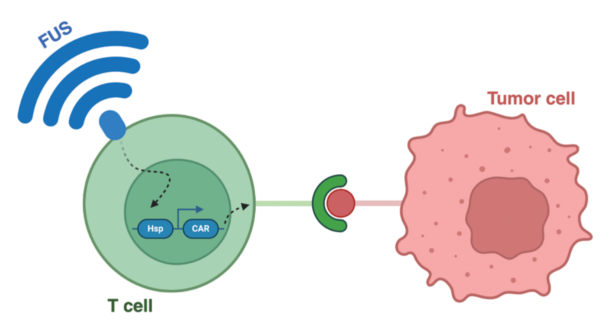
Clinical Advancement

TUS has been steadily advancing over decades as a clinical modality for oncology applications, with some of the earliest clinical observations of immunomodulation dating back to the mid-1990s and early 2000s (Rosberger et al., 1994; F. Wu et al., 2004). Despite the disruptive intersection with immuno-oncology having come online in just the last several years, clinical investigations have accelerated at an unprecedented pace. The "first-in-human" trial to combine TUS with immunotherapy (now completed) was launched at the University of Virginia, Charlottesville, in 2017; this trial assessed the combination of thermal ablation and pembrolizumab (Keytruda) in metastatic breast cancer patients. Presently, multiple clinical trials across the globe are taking aim at solid cancers, including breast, brain, skin, pancreatic, prostate, and others, to assess the safety, feasibility, and preliminary efficacy of combining TUS with immunotherapies. Furthermore, numerous ongoing early-phase clinical trials have demonstrated a commitment to further knowledge by integrating immunological assessments into primary or exploratory endpoints. Importantly, this has given rise to timely consensus dialogues addressing the critical need for field-wide standardization of immunology analyses (Padilla et al., 2023). Given the accelerated pace of advancement in this field, the coming years are certain to see clinical evidence build rapidly and the portfolio of novel immunotherapy combinations with TUS continue to grow.

Conclusions and Future Directions

A twisted echo of our cellular functions gone awry, cancer is a stark and persistent reminder of our shared vulnerability and mortality as human beings. There is a growing recognition of the need for precision and individualization in the management of this formidable disease.

Figure 4. *Mechanism of action for sonogenetically controllable chimeric antigen receptor (CAR) T cells. The T cell (**green**) is engineered with a genetic circuit linking expression of the T cell receptor (CAR) to heat shock protein (HSP), which can be induced through remote heating of the tumor via ultrasound (FUS). With FUS exposure, the CAR is expressed on the surface of the T cell, enabling tumor antigen recognition and targeted tumor cell (**pink**) killing. Adapted from Y. Wu et al. (2021), with permission of Springer Nature.*



Fortunately, the promise of delivering on this need has never been greater than it is today. TUS is positioned to play an exciting role therein, as a readily accessible, non-invasive, non-ionizing focal therapy modality and the only of its kind to converge tunability, spatial precision, and marked versatility in the treatment of cancer. In an emerging scientific era where physics is being used to control and manipulate biology, we are rapidly appreciating the depths of TUS' capabilities in allyship to immunotherapies. While this is already transforming hope for the more effective, if not someday curative, treatment of primary and disseminated cancers (in particular, anatomically challenging or advanced metastatic tumors), the hard work is not yet complete.

More studies are needed to optimize treatment protocols and advance control and prediction of the many mechanisms of action elaborated by TUS. Furthermore, systematic investigations are needed to determine the favorability of thermal versus mechanical immunostimulation across cancer immunotherapy applications. Finally, better response metrics will be needed to enable rational decision-making for combinations and improved real-time adaptation of treatment paradigms where needed. That said, the momentum in this field is nothing short of inspiring, and the next decade will surely deliver on these needs with the advent of new TUS technologies and discoveries. TUS stands at the cutting edge of next-generation cancer therapies, with tremendous promise for improving patient outcomes and markedly expanding the horizons of cancer immunotherapy.

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Conversation with a Colleague: Michael R. Haberman

Michael R. Haberman
Conversation with a Colleague Editor:
Micheal L. Dent

Meet Michael R. Haberman

Michael R. Haberman is the next acoustician in our "Sound Perspectives" series "Conversation with a Colleague." Mike is currently an associate professor in the Walker Department of Mechanical Engineering at The University of Texas (UT) at Austin, with a courtesy appointment at the Applied Research Laboratories, UT Austin. He received his bachelor's degree from the University of Idaho, Moscow, in 2000 and his master's and PhD from Georgia Institute of Technology, Atlanta, in 2001 and 2007, respectively. In addition, he holds a Diplôme de Doctorat in Engineering Mechanics from the Université de Lorraine in Metz, France, which was awarded in 2006. Between 2001 and 2003, Mike was a research and design engineer at GN ReSound, Chicago, Illinois, where he worked on a team that introduced additive manufacturing as a tool for mass customization of hearing aid shells, the mechanical casing that encases the electronics and has a shape that is custom for each person to fit within their ear canal. He is a Fellow of the Acoustical Society of America (ASA) and served as the chair of the Technical Committee on Engineering Acoustics between 2018 and 2024. He has also been an associate editor for *The Journal of the Acoustical Society of America* since 2014. We asked Mike to give us his elevator pitch and then elaborate on his inspirations, contributions, and hopes for the future.

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

Waves can be found everywhere in nature. They allow the communication of information in many forms, notably in our ability to hear and see. From the standpoint of engineering and scientific research, the ability to control wave motion enables technological advances and fuels scientific discovery across all areas of acoustics. I have always found it fascinating that the structure of matter dictates every aspect of wave motion: propagation speed and direction, energy dissipation, and even the motion of particles that make up the whole. This interest has driven my study of material structure via acoustic and elastic wave propagation since my time as a graduate student.

I like to think of my research as having both a "top-down" and a "bottom-up" perspectives. What do I mean by that? The top-down approach is one in which we seek to infer unknown or evolving material structure by measuring acoustic waves transmitted through or reflected from the material. This is a classical nondestructive testing paradigm, which was central to me becoming interested in acoustics and has numerous applications in industry and scientific research. The bottom-up approach is effectively materials design for acoustics. My research in this area began in the field of composite materials and spilled into the exciting field of acoustic metamaterials (AMM). AMM are materials that are designed with small-scale structures that enable the control of acoustic and elastic wave propagation in ways that we once thought impossible.

What inspired you to work in this area of scholarship?

I would have to say my interest in acoustics was first sparked by an introductory course on fracture mechanics that I took in 1999 as an undergraduate mechanical engineering student at the University of Idaho! As strange as that may seem, it was during this course that it first became clear to me that acoustics is a field of study

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with broad utility for both engineering and scientific research. Specific to the content of that course was the use of ultrasonic nondestructive testing as an essential tool for damage detection and characterization in elastic components. As a student, I was astonished that we could use ultrasonic waves to monitor crack growth and even damage that is much smaller than a wavelength using this specialized technique. The next semester, I took an undergraduate-level acoustics course from Michael Anderson where I began to appreciate that while the field of acoustics encompasses physics, engineering, musical performance, human health, biology, and many other areas, all subfields of study ultimately rely on similar physical phenomena. I was hooked and Anderson convinced me to apply for graduate school to learn more, which is exactly what I did.

While in graduate school in a dual-degree program at the Georgia Institute of Technology and the Université de Lorraine, I was lucky to have had a wonderful PhD advisor, Yves Berthelot, who taught me to spend time learning from other areas of science to gain inspiration and insight to help address current research challenges. He also taught me that doing good research is a matter of asking the right questions and to not be constrained by what we think is currently possible. He instilled the idea in me that knowledge gained from other areas of science and engineering drives creativity in research and accelerates progress. His insights and encouragement during those years is what provided me with the tools that helped me see the potential in the field of acoustic metamaterials and to link my initial interests in ultrasonic testing to the design and discovery of new materials to control acoustic fields.

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

Of all of my previous and ongoing work, I am proudest of my work in the area of acoustic metamaterials (AMM). This includes my scientific contributions to the field and my efforts to promote this relatively new area of research to the acoustics community. Below I only focus on a few specific contributions by my research group.

I did not begin my research career in the field of AMM. As a matter of fact, the word "metamaterial" had only very recently been introduced into the scientific lexicon (in 1999 by Roger Waxler) when I started my graduate degree. At the time, metamaterial research was concentrated in the fields of electromagnetics and optics. My graduate research, which started in 2000, was focused on wave propagation in composite materials and was inspired by efforts to model ultrasonic waves in these heterogeneous materials for the purposes of improving nondestructive testing (NDT). Although my interest in acoustics was sparked by this "classical" area of acoustics, I was quickly drawn to the idea of designing materials to control acoustic waves. Fortunately for me, these two fields of study are in many ways two sides of the same coin. Both ultrasonic testing and AMM operate within the same physical domain and the behavior is bounded by the fundamental physical laws of elastic wave motion. The difference is ultimately the objectives of each field. AMM research seeks to design and create structured materials to manipulate the waves for a desired performance, whereas the research in ultrasonic NDT aims to characterize a structure using the information encoded in elastic waves propagating through complex structures of a given mechanical component. I ultimately found that the design of novel materials to manipulate acoustic and elastic waves captured my interest and made me excited for its potential for long-term impact in the field of acoustics.

My earliest published research that was explicitly in the field of AMM was on the topic of acoustic cloaking. My first publication on cloaking was an article in *The Journal of the Acoustical Society of America* (*JASA*) in 2011 in collaboration with Andrea Alù. This topic was clearly very compelling. I felt as though we were trying to turn science fiction into science. Our unique approach, which we called scattering cancellation, consisted determining a layering scheme for materials surrounding an object that minimized the scattered field over a specific frequency range. Though our work in this area was fruitful and showed promise to make acoustic sensors that minimally perturb the field the measure, most of the outcomes were theoretical and it has been left for future work to turn those ideas into reality.

My interests then turned to more general concepts. This included Willis materials, pentamode materials, and materials that enable nonreciprocal acoustic wave propagation, which I highlight briefly below.

Willis materials are a class of acoustic and elastic materials that have unique behavior due to the fact that the small-scale structure of the material (structure that is much smaller than the wavelength of propagating acoustic waves) is asymmetric. As a result, the momentum and stress fields of the material are functions of both the strain and velocity fields. In a classical material, the stress would only be a function of strain and the momentum would only be a function of velocity. These materials are named in honor of John Willis, who was the first one to predict this unusual material response in 1981 but only through mathematical models.

We first experimentally observed this behavior in 2017 using a simple impedance tube measurement. We simultaneously developed dynamic multiscale theoretical and numerical models to describe the emergence of this behavior from small-scale asymmetries and how it may be exploited to control scattering from objects, create more efficient acoustic lenses, and design materials that have direction-dependent absorption coefficients. Research in this area is still very active, with regular new demonstrations of concepts that make use of this novel material response.

Pentamode materials (PM) are elastic lattice materials that behave as fluids with direction-dependent properties over very wide frequency ranges. These materials were hypothesized in 1995 by Graeme Milton and Andrej Cherkaev but were considered something of a theoretical novelty until it was shown that they could enable acoustic cloaking and other exotic devices. My group, in collaboration with Andrew Norris and Preston Wilson, was the first to model, design, fabricate, and acoustically test two-dimensional (2D) and three-dimensional (3D) pentamode materials created from additively manufactured metals in the underwater environment. We demonstrated underwater acoustic focusing using 2D PM lenses and 3D PM materials with anisotropic longitudinal sound speeds over a wide bandwidth using additively manufactured structures.

Finally, I want to highlight our work on what has come to be known as “nonreciprical materials.” The principle of reciprocity essentially states that if you can hear someone, they can hear you. The ability to purposefully break this restriction on wave propagation could lead to exciting new capabilities in acoustics, such as the ability to simultaneously transmit and receive acoustic signals from the same device at the same time. My research with Benjamin Goldsberry and Samuel Wallen has made several key contributions to this area, primarily in the use of waves propagating through mechanical lattices with deformations that change in time and space. We showed that slowly varying nonlinear deformations of lattice structures could be leveraged to generate nonreciprocal elastic wave propagation and generalized our computational tools to address this problem to consider nonreciprocal beam vibrations and elastic wave mode converters. The generality of the concepts we have demonstrated on this topic will enable exploration of realistic elastic media and structures for improved control of vibroacoustic motion.

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

In my mind, one of the best aspects of the field of acoustics is the wide range of engineering and science that it touches. Though I was initially inspired to study acoustics by concepts in ultrasonic nondestructive testing, the reality is that most of my research career has focused on more fundamental topics of acoustic and elastic wave propagation through the study of metamaterials. However, I have continued to do research in ultrasonic methods for material characterization and damage detection. Two specific examples are my work with Jinying Zhu on the use of acoustics to detect damage in concrete bridge decks and ongoing work with Ofodeke Ezekoye where we are using ultrasonic waves to detect damage in lithium-ion batteries (LIB).

Soon after my arrival at UT Austin in 2007, I began to interact with several colleagues whose research focused on nondestructive testing. One project, led by Jinying Zhu, who is currently at the University of Nebraska-Lincoln, involved the creation of air-coupled ultrasonic testing methods to search for damage in concrete bridge decks. We focused spark-generated N-waves using an ellipsoidal reflector system to excite resonances in concrete that indicate long horizontal cracks known as delaminations that can be found 10-20 centimeters deep within the structure. Interestingly, the ellipsoidal reflectors were inspired by previous work in nonlinear acoustics by David Blackstock and Wayne Wright at UT Austin. The resulting surface motion, amplified by the resonance associated with the depth of the delaminations, radiate acoustic waves that we detected using microphones placed at the focus of parabolic reflectors. The entire system was demonstrated on interstate highway bridges and the data was fused with ground penetrating radar to improve the efficiency and accuracy of bridge deck inspection. Versions of this system are being developed by industry for future use in infrastructure projects throughout the U.S.

More recently, I began working with Ofodeke Ezekoye to leverage ultrasonic waves to detect damage and to monitor the state of charge and state of health of LIB to ensure safe operation. This work is an essential component in recent efforts to develop testing methodologies that merge electrical, chemical, mechanical, and ultrasonic information to help ensure the safety of existing LIB systems. Furthermore, we are working with colleagues at the National Renewable Energy Laboratory in Boulder, Colorado, to integrate ultrasonic testing into testing protocols for the next generation of batteries, such as solid-state batteries, in order to assess battery safety when subjected to different charging protocols, environmental conditions, and other factors prior to the widespread integration into the market.

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

The field of acoustic metamaterials finds itself at an inflection point where further advances requires more direct engagement with researchers and practitioners in areas outside of acoustics, particularly in the areas of materials science and advanced manufacturing. I intend to do so in order to address open questions involving the creation of acoustic materials that can adapt their properties to a changing environment. This requires an understanding of wave propagation through materials whose structure changes with time and an ability to work across disciplines in science and engineering to make it possible. Interestingly, this knowledge is also applicable to open questions in application-driven research on the use of ultrasonics to detect changes and classify damage in energy storage systems like lithium-ion and next-generation batteries.

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The Importance of Biological Sound Archives

Jack Greenhalgh

Central to the effort to understand sounds produced by the natural world is the effort to document and catalogue sounds produced by animals and plants (see **Table 1** for examples of many of the sounds and sound libraries mentioned in this article). As such, the establishment and maintenance of biological sound archives is an integral part of deriving ecologically meaningful conclusions from large acoustic datasets. Since the creation of the Macaulay Library see (macaulaylibrary.org) by Cornell University, Ithaca, New York, in 1929, which is primarily dedicated to the cataloguing of bird sounds, many other biological sound libraries have since been established encompassing a wide array of ecosystems and species, such as marine mammals in the ocean, bats in woodlands, and frogs in rainforests (see examples in **Table 1**). The purpose of this essay is to get to the heart of why biological sound archives are essential, not just for the study of the natural world but for maintaining our connection with it, by hearing directly from the people involved in their creation and ongoing maintenance. In addition, to see how the creation of a biological sound archive is helping to unlock the secrets of a sonic frontier, the freshwater soundscape, a mysterious and often overlooked underwater acoustic world.

The Importance of Documenting Biological Sound

"[Biological sound] archives are vital as they provide data that is fundamental to the work many folks are doing" (Kieran Cox, cofounder of the online database Fish Sounds, personal communication, 2024) (see fishsounds.net/index.js). Fish Sounds is an online repository that was established in 2020 in the wake of the Covid pandemic and now hosts sound recordings from over 1,000 species of fish from around the world (Looby et al., 2023). "It may not be evident, but archives are a form of long-term monitoring, and this type of research is vital to identifying ecological change, supporting novel research, and training the next generation of scientists" (Cox, personal communication, 2024): "Understanding long-term trends requires long-term datasets. There's a very good chance that they will be used for things we can't yet imagine" (Ed Baker, a data researcher at the Natural History Museum in London, personal communication, 2024). In 2014, Baker established BioAcoustica (see bit.ly/3XFOpuF), the biological sounds data archive for the museum. One of the many benefits acoustic monitoring provides is the opportunity to store large amounts of data for reanalysis in the future when new methodologies have been developed. "The Natural History Museum collection was started in the 1950s, made on tape, and analysed with an oscillograph. Now it's being used to train machine learning models inconceivable at the time the recordings were made. The value of well-made collections increases over time" (Baker, personal communication, 2024).

Beyond their scientific value, biological sound archives offer a unique chance for people to connect with the environment through an accessible medium: sound. Baker has recently helped establish the Nature Discovery Garden at the London Natural History Museum, which uses biological sound recordings to engage visitors in new and exciting ways. "In the Nature Discovery Garden, visitors can listen to environments where they might not think sound has a function, such as soils, timber and ponds. There are massive untapped opportunities to use biological sound archives to engage blind and partially sighted audiences with nature" (Baker, personal communication, 2024).

Exploring the Unknown: The Freshwater Soundscape

A new initiative in collaboration with Fish Sounds and led by me, The Freshwater Sounds Archive (see fishsounds.net/freshwater.js) is now seeking to catalogue the underwater sounds produced by freshwater species. The sounds of marine mammals, birds, and bats are fairly well studied and documented in biological sound archives. However, the mysterious underwater soundscapes of freshwater ecosystems remain poorly

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Table 1. *Notable biological sound archives*

Name	Target Realm	Target Taxa	Institution(s)	Country	Link
Discovery of Sound in the Sea	Marine	Marine mammals, marine fishes, marine invertebrates, anthropogenic sounds	University of Rhode Island and Inner Space Center	United States	dosits.org
Fish Sounds	Marine, Freshwater	Fish	University of Victoria, University of Florida, University of São Paulo, Meridian, FishBase	N/A	bit.ly/4crWuXV
The Freshwater Sounds Archive	Freshwater	Freshwater fish, freshwater invertebrates, freshwater plants	University of Victoria, University of Florida, University of São Paulo, Meridian, FishBase	N/A	bit.ly/4cv8VCk
British Library Sounds Archive	All	All	The British Library	United Kingdom	bit.ly/4ezlgac
BioAcoustica	All	All	Natural History Museum (London)	United Kingdom	bit.ly/3XFOpuF
Macaulay Library		Birds	Cornell University	United States	bit.ly/45Bd59C
Amphibiaweb	Terrestrial, freshwater	Amphibians	University of California, Berkeley	United States	bit.ly/3VvRGKk
Fonoteca Zoológica	Terrestrial, freshwater	Frogs	Consejo Superior de Investigaciones Científicas, National Museum of Natural Sciences (Madrid)	Spain	bit.ly/4cMLK6L
Frog Call Library	Terrestrial, freshwater	Frogs	Herpetological Society of Singapore	Singapore	bit.ly/3VQvLyD
Global Library of Underwater Biological Sounds	Marine	Marine mammals, marine fishes, marine invertebrates, anthropogenic sounds	28 Different institutions globally	N/A	glubs.org
ChiroVox	Terrestrial	Bats	Hungarian Natural History Museum (Budapest), Southeast Asian Bat Conservation Research Unit	N/A	chirovox.org
Bat Conservation Trust Sound Library	Terrestrial	Bats	The Bat Conservation Trust	United Kingdom	bit.ly/3XwpnOs
Xeno Canto	Terrestrial, freshwater	Birds, grasshoppers, bats, frogs	Xeno-canto Foundation, Naturalis Biodiversity Center	The Netherlands	xeno-canto.org
Avisoft Bioacoustics	Terrestrial, freshwater	Bats	Avisoft Bioacoustics	Germany	bit.ly/4evLDOi

understood. Recently, some researchers have been turning their attention to the study of the underwater soundscapes of ponds, rivers, and lakes to unlock their secrets (Linke et al., 2018).

Freshwater soundscapes are packed full of bizarre sounds produced by a wide array of species; it is like an underwater disco (Greenhalgh et al., 2023). Some sounds are more familiar, such as the croaking of frogs, and the drumming of fish (see tinyurl.com/va249nu4) because they use specialised muscles to vibrate air inside their swim bladders to communicate. However, many sounds are otherworldly and surprising, such as the strange whining and ticking sounds (see tinyurl.com/va249nu4) produced by submerged aquatic plants as tiny oxygen bubbles are released into the water. In addition, aquatic insects produce strange scratching, scraping, and rasping sounds as they rub hard body parts together in a process called stridulation. One particular aquatic insect is known for making the loudest sound in the animal kingdom, when scaled to body size, by rubbing its penis against its abdomen (Sueur et al., 2011).

We have known for a long time that different species of aquatic insects must be able to produce different sounds because identification guide books draw on the differences in their sound-producing anatomy to distinguish between species (Greenhalgh et al., 2020; Desjonquères et al., 2024). If different species have different instruments, then logically it follows that they must be producing species-specific sounds. However, we know very little about which species are producing which sounds. This is important because many species of aquatic insects function as indicator species, meaning that they are indicative of specific ecological conditions and have been used by freshwater ecologists for decades to reliably assess the condition of rivers, lakes, and ponds (Hawkes, 1998).

The next big challenge in freshwater soundscape research therefore is to begin to catalogue the species-specific sounds produced by key indicator species groups, such as aquatic insects. As such, the creation of The Freshwater Sounds Archive is essential for understanding the associations between freshwater biodiversity, acoustic diversity, and ecosystem condition.

Conclusion

Biological sound archives are essential for unpicking the hidden complexities in soundscapes and for establishing meaningful links between biodiversity and acoustic monitoring. Moreover, the value of well-designed and maintained archives only increases in time as data are added and new methods for analysis are developed. However, the value of biological sound archives reaches far beyond its importance for biodiversity monitoring and extends into museum exhibits and classrooms around the world, reinforcing connections with people and the environment. Madeline Reilly works for the Lake Champlain Basin Program in Vermont and uses biological sound recordings while working with children. Reilly said it best while talking about the value that biological sound recordings have to engage and inspire a new generation: "People need tools to feel connected and hopeful — sound recordings provide a reminder of what we're trying to protect" (personal communication, 2024).

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Celebrating Best Student Research Winners from Acoustics 23 in Sydney, Australia

Marissa L. Garcia

Students are a life force in the Acoustical Society of America (ASA), and ASA meetings represent one such venue where this is evident. The semiannual cadence of ASA meetings allows students multiple chances to showcase their research with the broader acoustics community over the course of their degree program. For each of the 12 technical committees in the ASA, dozens of students, spanning both undergraduate and graduate degree programs, share their findings via poster sessions and oral presentations. This opportunity allows students to receive rich feedback from field experts that directly feeds back into enhancing their research and cementing promising career outcomes long term.

Best Student Presentation Awards are a most striking example of how the ASA supports students. Often, for at least one ASA meeting each year, each technical committee grants a Best Student Presentation Award to a few students for exceptional research. Several of these awards were granted at the Acoustics 23 meeting in Sydney, Australia.

The Student Council seeks to celebrate these students and feature their work. Here, you can learn more about the cutting-edge research of some of these award winners:

Animal Bioacoustics: Acoustic Catalog of Fish Sounds

Audrey Looby (alooby101@gmail.com) will graduate in Summer 2024 with a PhD in fisheries and aquatic sciences from the University of Florida, Cedar Key. In her undergraduate research at the University of Southern California, Los Angeles, Audrey conducted biodiversity monitoring in California kelp forests. She earned her master's degree at the University of Florida, where she studied the effects of submerged aquatic vegetation. Her studies evolved into her PhD under Charlie Martin and Laura Reynolds, where she focused on fish sound production and soundscape-habitat interactions in coastal habitats. Now, she is the colead of the FishSounds (see fishsounds.net/index.js) effort to compile global fish sound production information and recordings, which she shared in her award-winning presentation, "FishSounds: A Data-Sharing Website of Global Soniferous Fish Diversity," at the Sydney conference.

> "Fish sounds serve wide-ranging ecological roles and monitoring applications, but despite extensive endeavors to document them, the field of fish bioacoustics has been historically constrained by the lack of a comprehensive inventory of known fish sound production. To create such an inventory, I extracted information from over 900 references from the years 1874–2021, finding over 1,000 fish species that have been shown to produce active (i.e., intentional) sounds. This information is available on the FishSounds website at FishSounds.net alongside representative recordings of fish sounds that can be easily searched through and accessed by users. FishSounds has since launched new initiatives to develop regional acoustic catalogs for fisheries management applications as well as a free education program that has reached over 2,500 participants across the United States and Canada. The data available on FishSounds can be similarly adapted to meet other research or management needs, improve public awareness of underwater soundscapes, and aid in the discovery of novel soniferous behaviors across fishes globally" (adapted from abstract).

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Physical Acoustics: Acoustic Detection of Ice Fractures

John Case (jackcase97@gmail.com) is in his sixth year of his PhD in acoustics in the Graduate Program in Acoustics at the Pennsylvania State University, State College. He received his BS in mechanical engineering from the University of Hartford, West Hartford, Connecticut. Under the guidance of Andrew Barnard and Daniel Brown, he researches ice fracture acoustic detection and classification using machine learning, which he presented in part in his award-winning Sydney presentation, "Marine and Lacustrine Ice Fracture Detection."

> "In recent years, the need to detect and classify ice-fracturing events has become increasingly important to fisheries and climate science as well as to local communities. Fractures primarily occur due to stress relief within an ice sheet during temperature shifts and ice movement. These events create mechanical waves within the sheet that couple into the water column, which manifest as pressure and particle velocity fluctuations that we can acoustically detect. In this study, we used machine-learning algorithms to detect and classify ice-cracking events through their acoustic signature. We compared multiple models to assess efficiency and accuracy along with an extensive preprocessing algorithm. We automatically detected acoustic signatures of ice fracturing events in several different locations, including Northern Alaska and the Great Lakes" (adapted from abstract).

Underwater Acoustics: Passive Acoustics in Aid of Autonomous Underwater Vehicle Navigation

Junsu Jang (jujang@ucsd.edu) is a fourth-year PhD candidate in oceanography at the Scripps Institution for Oceanography, La Jolla, California. Hailing from South Korea, he received a BS in electrical and computer engineering from Carnegie Mellon University, Pittsburgh, Pennsylvania. He then pursued an MS in media arts and sciences at the MIT Media Lab at the Massachusetts Institute of Technology, Cambridge. At MIT, he grew his interest in oceanography through researching an underwater stereo-imaging system to track marine snow in the twilight zone. In his PhD research, he develops and applies statistical signal-processing methods to process various oceanographic data. Some of this research was featured in his talk, "Waveguide Invariant Navigation of an Autonomous Underwater Vehicle."

> "Passive acoustics is a nonintrusive yet powerful approach to a wide variety of oceanographic applications, ranging from ecosystem monitoring to situational awareness. In my research, I have been investigating the use of passive acoustics to supplement the navigation of an autonomous underwater vehicle (AUV) equipped with a hydrophone and relatively low-budget navigation sensors. I am interested in leveraging the acoustical recordings of a source of opportunity, such as a passing container ship, in shallow water.
>
> "The interference pattern of the propagating acoustic fields (modes) in a waveguide form striations of intensity bands as a function of frequency and range, which can be summarized by a scalar parameter called the waveguide invariant. Using this parameter, the range information between the source and the receiver can thus be extracted from the spectrogram. I have been investigating the estimation and incorporation of this range information into the AUV navigation.
>
> "At the ASA meeting in Sydney, I proposed a new statistical model of the received signals that allows us to perform range estimation and implemented a sequential Bayesian filter to fuse the range information with the onboard navigation sensor measurements. This capability was demonstrated using both simulations and real data."

Speech Communication: English Speakers Adapting to Tonal Language Learning

Yanping Li (yanping.li@westernsydney.edu.au) is in the final year of her PhD at Western Sydney University, Penrith, Australia, where she is completing her research on accent variability in Mandarin lexical tones and its effects on tone perception by English learnings. Uniquely, as a PhD candidate in the Covid-19 generation, Yanping used virtual resources such as E-Prime Go and Zoom to collect her data. Her past academic training includes a BA in Chinese linguistics and literature from Xinyang Normal University, Xinyang, China, and an MA in linguistics and applied linguistics from Beijing Language and Culture University, Beijing, China. Her thesis research was shared in part through her talk, "Categorization and Discrimination of Mandarin Lexical Tones by Naive English Listeners."

> "Unlike tone languages such as Mandarin, English lacks tones at the sublexical level. Accordingly,

English listeners have difficulty perceptually assimilating tones as categorized or uncategorized native segments (perceptual assimilation model [PAM). While English listeners can categorize the four lexical tones of Mandarin, i.e., level contour, rising, dipping, and falling, when given *question, statement, exclamation*, and *uncertainty* intonations as category choices. This does not address tone assimilation at the segmental level. We reasoned that they might assimilate tones as nonassimilable nonspeech patterns if given visual icons as tone category choices (flat, rising, dipping, and falling lines, respectively) with no reference being made to English intonation categories. Accordingly, 76 monolingual English listeners (Mage = 24.85 years, 50 females) were set two tasks: to use visual icons to categorize Mandarin tones in naturally produced tone words (/ga, ti, tu, gu/ × 4 tones) and to discriminate all six pairwise tone contrasts. All tone pairs showed ceiling-level discrimination, and listeners split their categorizations of falling and level stimuli between the falling and flat icons, suggesting that when given visual icons, tone-naïve English listeners perceive Mandarin tones as nonspeech acoustic patterns, which is consistent with PAM's nonassimilation predictions" (from abstract).

Noise: Noise Limit Explorations for Civil Supersonic Aircraft

Joshua Kapcsos (jlk642@psu.edu) is a fifth-year PhD candidate in the Graduate Program in Acoustics at the Pennsylvania State University, State College. He is a Joseph and Irene Tobis Graduate Fellow in Acoustics in the College of Engineering, advised by Victor Sparrow. Born and raised in Bethlehem, Pennsylvania, he received his BS in physics right in his hometown at Lehigh University. His thesis research was in part featured in his invited paper, "Progress Update on Inclusion of Atmospheric Profiling for Sonic Boom Propagation Through Turbulence."

"With the recent unveiling of experimental supersonic aircraft such as NASA's X-59 Quesst (see nasa.gov/mission/quesst), which seeks to demonstrate that sonic "booms" can be mitigated to "thumps," international efforts continue to push for development of civil supersonic aircraft. To revise the governmental restrictions on civil supersonic flight by exchanging the existing Mach 1 speed limit for a noise limit, simulations must closely match real-world data produced by the demonstrators. While the KZKFourier tool developed at Penn State simulates sonic boom propagation through turbulent atmospheric boundary layers, the original only supports homogeneous atmospheres. I modified the code to take in humidity profiles by looping through matrices of each value's solutions, providing a more realistic simulation.

"Thus far, uniform layers of humidity values were used in the newly modified propagator, and the results presented in Sydney are consistent with the known results that higher humidity leads to higher peak pressure. Additionally, compared to homogeneous atmospheres of 10% and 80% relative humidity, profiling the atmosphere between these values yields results that intuitively fit in between. I continue to implement more realistic profiles, thicker boundary layers, and the shaped boom waveforms of demonstrators, which will help develop technical standards to aid in certifying civil supersonic aircraft.

"This research was funded by the US Federal Aviation Administration (FAA) Office of Environment and Energy through ASCENT, the FAA Center of Excellence for Alternative Jet Fuels and the Environment, and project 57 through FAA Award Number 13-C-AJFE-PSU under the supervision of Sandy Liu. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the FAA."

Signal Processing in Acoustics: Active Noise Control in Vehicles

Jun Young Oh (eric6518@snu.ac.kr) is in the fourth year of his PhD in mechanical engineering at Seoul National University, Seoul, South Korea. He pursued his undergraduate studies at the Korea Advanced Institute of Science & Technology (KAIST), Daejeon, South Korea. His PhD research focuses on active noise control and vehicle noise, vibration, and hardness (NVH), which he investigated in his commended talk, "Updating the Secondary Path Using Deep Learning Models to Enhance the Performance of Active Road Noise Control."

"The accuracy of the secondary path estimate significantly influences the performance of active noise control (ANC) in vehicles, especially in dynamic environments that alter the secondary path. We proposed deep learning-based methods to update the secondary path estimate in real time, addressing fluctuations caused by head movements. These methods showed high estimation accuracy and low data storage requirements, with the principal component analysis (PCA)-based approach using only 1.5% compared to storing all cases. Updating the secondary path estimate in real time led to reductions of 10.2 and 17.2 dB in road noise and 500- 1,000-Hz random noise, respectively. The improvement was notable for both types of noises, indicating that the suggested method can expand the frequency range of ANC.

"For future research, we are adapting our application to real driving cases. In these cases, where installing microphones at ear positions isn't feasible, virtual-sensing technology is used to estimate acoustic pressure at these locations using surrounding microphones. This approach necessitates updating much more transfer functions in real time, which is expected to benefit significantly from the update method proposed in this study."

Summary

Ranging from fish ecology to ice fractures, from autonomous underwater vehicle navigation to tone languages, from noise control for both civil supersonic aircraft and vehicles alike, students in the ASA are paving their paths in their respective fields. We at the Student Council look forward to seeing how these students continue to advance knowledge as they wrap up this stage in their educational journey and progress further into their careers. You can learn more about the Student Council, its activities, and many other outstanding students at the Council's website (see asastudents.org) and at the AT Connections website (see bit.ly/3TYFaU7).

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Obituary
William A. Kuperman, 1943–2024

William (Bill) A. Kuperman, former Acoustical Society of America (ASA) President and Gold Medal recipient, died at his home in La Jolla, California, on June 30, 2024, at the age of 81. He was known especially for his work on ocean acoustics.

Bill was born in The Bronx, New York. After graduating from The Bronx High School of Science, he got a BS from Brooklyn Polytechnic, New York, before completing a master's degree at the University of Chicago, Illinois. He then joined the Acoustics Division at the Naval Research Lab (NRL) in Washington, DC, where he was mentored by R. H. Ferris. Recognizing Bill's talents, Ferris nominated him for an NRL Edison Fellowship that supported his PhD work at the University of Maryland, College Park, in statistical physics. He published a classic paper at NRL with Frank Ingenito that incorporated sea-surface roughness into waveguide propagation.

Bill spent 10 years at NRL before taking a trip to the NATO SACLANTCEN in La Spezia, Italy, to install some of the NRL acoustic propagation models. He fell in love with the place that led to a new phase of his career as head of the Environmental Modelling Group. He published another classic paper with Ingenito, simulating ocean wind noise by coupling an infinite sheet of monopoles to the ocean waveguide. In another famous paper (with Finn Jensen), he showed how sound propagating upslope in a wedge led to beams of energy injected into the ocean subbottom.

Employment terms at SACLANTCEN typically last 3-5 years so Bill contemplated his return to the United States. He saw there were important opportunities connecting ocean acoustic and oceanographic models. With changes in the Navy system, both areas had become seated at the Naval Ocean Research and Development Activity (NORDA) in Stennis Space Center, Mississippi. So Bill moved his family to New Orleans, Louisiana, taking the position as head of the Numerical Modeling Division.

In 1985, Bill returned to the NRL in Washington and became the senior scientist of the Acoustics Division. Here he did pioneering work on matched-field processing that uses the waveguide physics for source localization and environmental inversion.

In 1993, Bill was hired by the Scripps Institution of Oceanography, UC San Diego, La Jolla, California, as a professor and the director of the Marine Physical Laboratory. This started a 30-year career in academia where he supervised research, including many graduate dissertations. He developed new ideas with applications to time-reversal acoustics, underwater acoustic communications, adjoint methods, global sound propagation, and waveguide invariants.

He received many honors over his career, including the Pioneers of Underwater Acoustics Medal (1995) and the Walter Munk Award (2011). He was elected to the National Academy of Engineering (2004) and was also a SECNAV/CNO Chair for Ocean Science (2004).

He is survived by his wife of 54 years, Gaby Kuperman, children Mark and Rachel, and three grandchildren.

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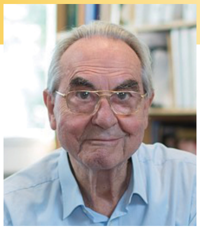
Obituary

Gunnar Rasmussen, 1925–2024



Gunnar Rasmussen was an acoustician and inventor from a time when "innovation" and "disruption" were a lifestyle driven by desire and curiosity. He was a shrewd and modest person with a voracious appetite for the unknown, character traits that helped him throughout his life.

Born in Esbjerg, Denmark, in 1925, Gunnar attended Aarhus Teknikum, Aarhus, Denmark, where he was captivated by Jacobsen's lecture on the rapid postwar technological development in the United States. After completing his studies in 1950, Gunnar joined Brüel & Kjær and moved to the United States, where he gained insight into the advanced automotive and aircraft industries and the important standardization of laboratories.

Inspired and full of ideas, Gunnar returned to Denmark and soon after revealed his invention in 1956 of the one-inch measurement microphone. It was superior to all previous microphone types in terms of precision, durability, and stability. It quickly became the go-to reference microphone and was the basis for the International Electrotechnical Commission (IEC)-1094 series of standards for measurement microphones and still is today.

Gunnar's quest continued, and he developed the half-inch measurement microphone. It is still the world's most widely used measurement microphone and has been copied countless times. But as Gunnar said: "It's never a shame to be copied — then you know you've done something right." Gunnar's microphone is on display at the Metropolitan Museum of Modern Art (MoMA) in New York, New York.

Gunnar further developed and created an impressive number of diverse acoustic measurement instrumentation. All of these are notable milestones in the acoustic world. Additionally, Gunnar was deeply engaged in standardization work and knowledge sharing, and he could be found at conferences and conventions around the world.

Gunnar had been nicknamed "Mr. Microphone" by industry colleagues, professors, and close customers who had all benefited from his seminars, white papers, and inexhaustible application knowledge. In 1994, at the age of 68, he and his wife Hanna Hertz founded GRAS Sound & Vibration. With this, Gunnar seized the opportunity to develop new ways of producing microphones in new materials, and thus another generation of measurement microphones was born, this time in his own name. The family business thrived and grew from a few handpicked employees to more than 90 by 2011.

Gunnar was driven and passionate to the very end. He was honored with several awards and honorary titles throughout his life; of great importance and meaning was his title as an Acoustical Society of America Fellow. He leaves a lasting imprint on all our lives, from the smallest hearing aid to the largest rockets. When we want a quiet hedge trimmer or a quieter dishwasher or simply want to improve our hearing and social life with a small discreet hearing instrument, then Gunnar has played a role. All these products were developed, approved, and produced using measurement microphones and thus Gunnar Rasmussen's very sustainable microphone design.

Gunnar joins the ranks of inventors and entrepreneurs who had committed themselves to making a difference for the rest of us. He will be deeply missed by his wife, children, grandchildren, and great-grandchildren, many of whom were inspired and involved in acoustics because of him.

Selected Publications by Gunnar Rasmussen

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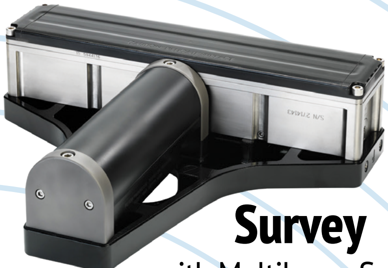

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