Volume 10 | Issue 3 Summer 2014

Acoustics Today

A publication of the Acoustical Society of America

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About the Cover

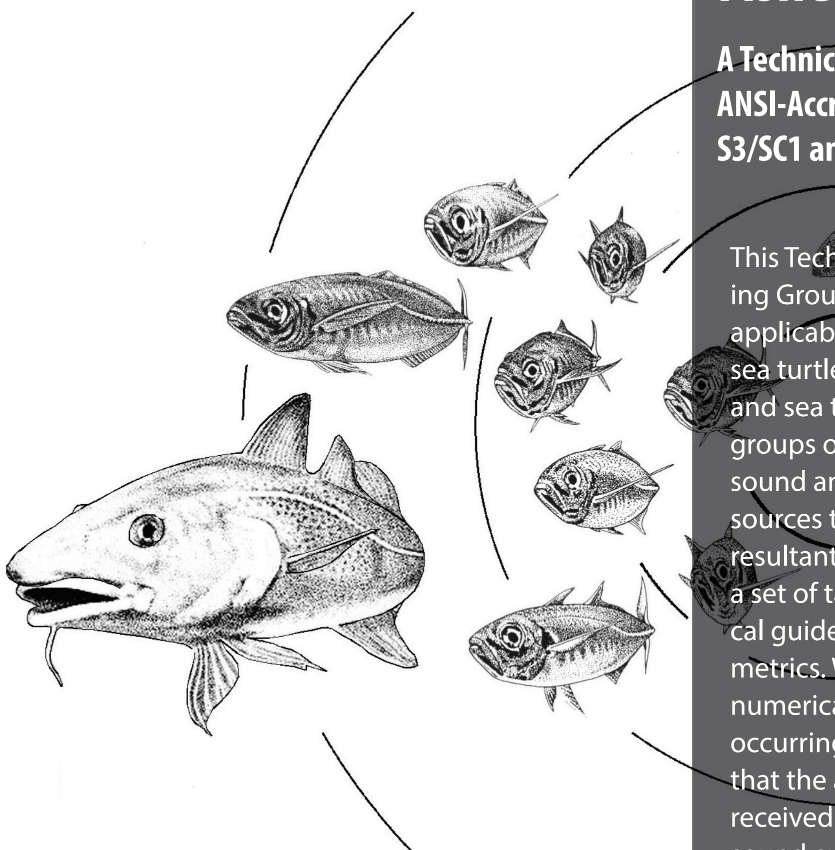
The cover photo and inset scan are from the article Sonars and Strandings: Are Beaked Whales the Aquatic Acoustic Canary? (pg. 46) by Darlene R. Ketten. The photograph is of a male Blainville's beaked whale. Inset is the 3D reconstruction from CT scans of the head of a *stranded* male Blainville's beaked whale. More information about both and photo credits can be found on page 51. To view videos that accompany the CT scan visit http://acousticstoday.org/?p=2315.

TECHNICAL REPORT

ASA S3/SC1.4 TR-2014

Sound Exposure Guidelines for Fishes and Sea Turtles:

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



This Technical Report presents the outcome of a Working Group that was established to determine broadly applicable sound exposure guidelines for fishes and sea turtles. After consideration of the diversity of fish and sea turtles, guidelines were developed for broad groups of animals, defined by the way they detect sound and related to the different types of sound sources to which the animals might be exposed. The resultant sound exposure guidelines are presented in a set of tables, by source type. In some cases numerical guidelines are provided, expressed in appropriate metrics. When there were insufficient data to support numerical values, the relative likelihood of effects occurring was evaluated, although it is made clear that the actual likelihood of effects depends on the received level. The report carefully notes that these sound exposure guidelines, which are based on the best scientific information at the time of writing, should be treated as interim. This interim status is emphasized because the expectation is that these guidelines can be refined as new and updated information becomes available. In addition to the guidelines, recommendations are put forward defining the research requirements of highest priority for refining, and adding to, these interim exposure guidelines.

ASA S3/SC1.4 TR-2014

TECHNICAL REPORT

This Technical Report is available on the ASA online store in PDF for $39.99.
ASA members may use their member carnets (coupons) to obtain this report for FREE or apply the 25% ASA member discount.

Hard copies can be ordered via www.springer.com for $54.99.
PDFs are also available from Springer.

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Acoustical Society of America

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

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

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

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

ACOUSTICS TODAY *(ISSN 1557-0215, coden ATCODK) Summer 2014, volume 10, issue 3, is published quarterly by the Acoustical Society of America,* ***Suite 300,1305 Walt Whitman Rd., Melville, NY 11747-4300****. Periodicals Postage rates are paid at Huntington Station, NY, and additional mailing offices. POSTMASTER: Send address changes to Acoustics Today, Acoustical Society of America,* ***Suite 300, 1305 Walt Whitman Rd., Melville, NY 11747-4300****.*

This issue of *Acoustics Today* has an eclectic series of papers that includes consideration of climate change and bioacoustics, microphone arrays and the analysis of animal movement, the prehistoric origins and evolution of the flute, non-destructive testing of materials using acoustics, and effects of man-made sound on marine mammals. Several of the papers take advantage of our ability to use multimedia to enhance articles. In each case, we give the URL for the multimedia in the articles, and they are linked directly from the PDF of the issue on our web page (www.AcousticsToday.org). Though most of the multimedia is visual, do make sure to listen to the wonderful music that accompanies our article on flute evolution by Jelle Atema.

This issue also features what I hope will be regular pieces about the various ASA Technical Committees. The first, about Musical Acoustics, was written by former TC chair Thomas Moore. Thom is also a member of the *Acoustics Today* advisory committee and so when the idea for having TC reports came up, Thom volunteered and then worked with me to figure out the "kind" of content and thrust we want for these articles. We decided that these reports should give an overview of the technical area and an idea of the kind of background that is needed to pursue the areas of interest for the TC. The goal is not only to inform members about the great diversity of interests within ASA, but to help "educate" non-members who may read the article about the excitement of pursuing acoustics careers. We hope you find this article, and future articles, interesting and useful.

As many of you may recall, we ran a survey in late spring to elicit feedback about *Acoustics Today* and our web site. Almost 800 people responded. We also had a drawing for ASA books from among the responders (who provided email addresses). The "winners," selected randomly, were Keith Adams, Dave Mellinger, Matthew A. Nobile, and Jeff Rector.

We have not yet completed analysis of the survey since it contains so much material, but you might find a few facts of interest. Note, this was not a "scientific" survey since people self-selected about responding. Accordingly, the results do not necessarily reflect the distribution of ASA members. I did find it interesting that 43.4% of the responders identified themselves as being in an educational institution, while 19.3% are in industry and exactly the same number are self-employed. Every Technical Committee was represented in the survey, ranging from 3% of responders for one group to 12.1% for a second and 15.2% of the third.

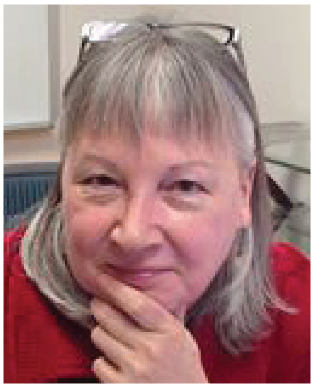
One of our interests was, in this day of reading on the web, e-readers, etc., how our members prefer to receive and read AT. It turns out that a substantial majority (73.1%) prefer to read the print issue of the magazine, though 44.5% (we allowed multiple answers) like the downloadable PDF from our web site. Of readers, 61.7% read 50% or more of the magazine, while the remainder read less. Hopefully, over time, this readership will go up as articles are written more and more for the broader ASA membership. This certainly is an important goal for all of us associated with the magazine.

The most popular parts of the magazine are the articles (97%) and news (65.5%). This is useful to know. Realizing that ASA members value getting news and announcements (as indicated by the survey), we are enhancing the News page of www.AcousticsToday.org in order to provide more, and more timely, information of interest to members. In future issues, most news will appear on the web site rather than in the print edition, since our "news" has been out of date due to the gap between our receiving the information and quarterly publication. We encourage you to check www.Acousticstoday.org regularly for up-to-date material. And, feel free to send us material you think would be of interest to the ASA membership for consideration for inclusion on the web page.

I was also pleased to see that the vast majority of responders thought that the articles in the Winter Issue were above average for ease of reading, appropriate for broad audiences, and scientifically accurate.

There was a lot more in the survey, and we will share more qualitative results in future "From the Editor" columns. But, I do want to thank all of you who took the time to respond to the survey. The information is interesting and valuable as we continue to try and make *Acoustics Today* a magazine for all ASA members.

Arthur N. Popper



As mentioned in the spring issue of *Acoustics Today*, ASA engaged the services of Cate Bower and Marybeth Fidler of Cygnet Strategy, LLC to help guide the Society in planning for the future. The goal of this 18-month process is to put us in a position to harness and leverage our capacities toward a common set of goals.

As a first step we developed a central question to consider and explore:

> *"How will ASA need to change the way it does business, if at all, within a rapidly changing environment and uncertain publishing future, in order to maintain our position as the premier scientific society in acoustics?"*

We also will consider these subsidiary questions:

- How can ASA best prepare to meet future challenges in publishing and beyond, especially by building on and amplifying its past success?
- How can ASA best expand and maximize our value to members and to the field of acoustics in the future?
- How can ASA best translate our wealth of good ideas, activities, and programs into the highest impact priorities for practical action and "make them so?"
- How can ASA capitalize on our transition to a new senior staff team that included key additions of our new Executive Director, Editor-in-Chief, Editor of *Acoustics Today*, and our new Web Developer?
- What organizational structures and processes will be needed to execute well in these areas in the future?

At the spring Providence meeting, Marybeth Fidler led both the Executive and Technical Councils in an exercise designed to cull and articulate key strengths and concerns about ASA today and in the future. Some of those factors included the uncertain future of ASA publishing in light of open access, competition from other scientific societies, the aging of membership, and the pressure on time required to attend meetings.

The result of those discussions will help inform the second phase of this process, which is to gather information from a broad spectrum of key stakeholders. This will be accomplished through telephone interviews, guided group discussions, a member survey, and further interaction with the Executive and Technical Councils. In January 2015 we will convene a group of about 60 people to spend two and a half days using information gathered earlier to develop a vision for the future of ASA. This will include a discussion of the environment within which ASA and our members operate, confirmation of our mission, creation of the vision, and developing agreement on major areas of focus to achieve the vision.

A report of this summit will serve as the working document for a planning team to develop into a final plan. The goals and objectives developed here would then be brought to the Executive Council for final approval.

We intend to have wide input by members, associate members, students, and all interested parties. I hope that you will give us the benefit of your time and your perspective when asked for your input. There will be several opportunities to do so. In addition, I am always pleased to hear from members about their thoughts, concerns, and ideas. So, please do not hesitate to contact me by email: sfox@acousticalsociety.org or phone: 516-576-2215 (direct) at any time and about any issue.

Susan E. Fox

Bioacoustic Monitoring Contributes to an Understanding of Climate Change

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Both direct and indirect effects of climate change will impact acoustics, especially in the fields of acoustical oceanography, animal bioacoustics, noise, and underwater acoustics.

Introduction

From policymakers, to funding agencies, to the general public, there is a push to understand more about how anthropogenic activities are impacting our climate, how the changing climate affects our planet, and how we can mitigate these effects. At first glance, acoustics and climate change may seem to have little in common. The reality, however, is that both direct and indirect effects of climate change will impact acoustics, especially in the fields of acoustical oceanography, animal bioacoustics, noise, and underwater acoustics. How can we, as acousticians, identify and understand the impacts in our field so we can contribute to the science and dialogue of climate change?

The earth is warming, and anthropogenic activities are to blame. The latest Intergovernmental Panel on Climate Change report states with 95% confidence that "more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together" (IPCC, 2013). Although already warming, climate models predict further global warming of up to 4° C by the year 2100 (Figure1).

In addition to increases in global temperature, other effects of climate change include losses of ice on sea and land, a rise in sea level, changes in the distribution of organisms within ecosystems, ocean acidification, changes in weather patterns, and increased threats of disease (IPCC, 2013; CCSP, 2008). These biotic and abiotic effects of climate change may also influence the acoustics of an environment and alter the communication of animals. This, in turn, leads to variations in entire soundscapes of regions and to changes in biodiversity, as some species adapt while others do not. Here, we explain how these effects of climate change may impact bioacoustics and discuss some recent findings on the impact of climate change on underwater and aerially communicating animals.

Effect on Underwater Communicating Animals

One of the better-known impacts of climate change on acoustics derives from increasing ocean acidification. The combustion of fossil fuels has driven atmospheric CO^2 levels from a pre-industrial level of approximately 280 ppm to a present-day level of higher than 400 ppm worldwide (IPCC, 2013). However, only about half of the CO^2 that has been produced still resides in the atmosphere. The rest is absorbed by the ocean, which results in ocean acidification.

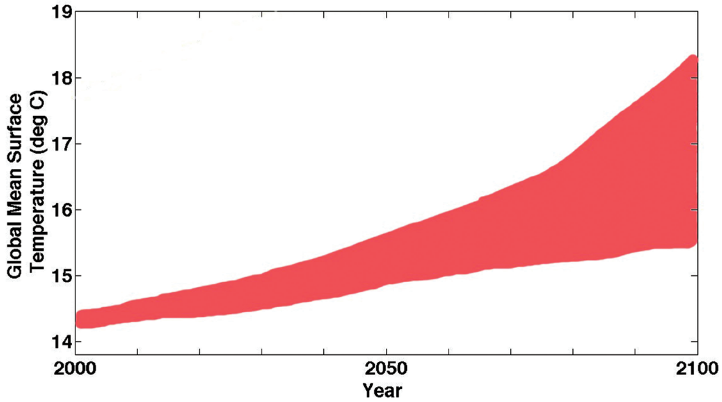

Figure 1: *Range of predicted global mean surface temperatures (in Celsius) based on the 2007 IPCC climate models. Temperatures are predicted to increase between 1 and 4 degrees Celsius between the years 2000 and 2100.*

Sound naturally attenuates in the ocean, and this acoustic absorption is dependent on temperature, pressure, salinity and acidity. This natural attenuation can be further affected by changes in pH. Figure 2 illustrates that the dependence on absorption and pH changes nonlinearly depending on pH and sound frequency. The left panel shows how the absorption (in dB) between a pH of 7.5 and 8.5 changes nonlinearly across a frequency range from 500 Hz to 10 kHz. Changes in

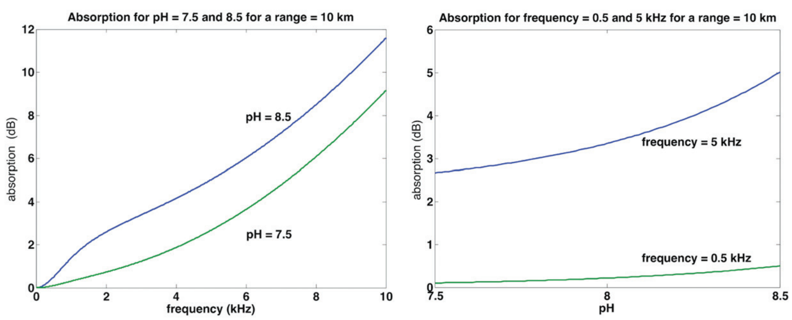

Figure 2: *Left panel shows the absorption (in dB) at 10 km for pH values (7.5 and 8.5) as a function of frequency. The right panel shows the absorption (in dB) at 10 km at two frequencies 0.5 and 5 kHz for pH values 7.5 from 8.5. (Miller et al., 2014).*

absorption that depend on pH occur for frequencies below 3 kHz, and the maximum difference in absorption for a range of 10 km is approximately 2 dB. The right panel shows how the absorption between a frequency of 500 Hz and 5 kHz changes nonlinearly across a pH range from 7.5 to 8.5. For a pH value of 7.5, the difference in absorption between the low (500 Hz) and high (5 kHz) tone is approximately 2.5 dB, but at a pH value of 8.5 the difference in absorption may be as high as 4.5 dB (Miller et al., 2014).

The global average surface ocean pH is approximately 8.0, but continued solution of CO^2 in the water is expected to reduce pH by 0.3 or more by the end of the century (Orr et al., 2005). Climate projections estimate future CO^2 will decrease the open ocean pH by 0.3 units or more in the next 100 years, resulting in a decrease of sound absorption, particularly for low frequencies, by as much as 40% in 100 years (Brewer and Hester, 2009; Hester et al., 2008).

Saltwater Species

The reduction of sound absorption in the ocean means that sounds, both natural and anthropogenic, will travel farther. The increase in anthropogenic sound levels will contribute more noise to the ocean. These changes can impact the acoustic communication behaviors of many marine species, including invertebrates, fishes, and marine mammals. We already know that anthropogenic noise impacts the acoustic behavior of marine mammals. In noisy environments, whales lengthen the duration of their communication sounds (Miller et al., 2000; Foote et al., 2004), increase the intensities of these sounds (Au et al., 1985; Parks et al., 2011), and adjust their sound frequencies (Au et al., 1985). Increased ambient noise levels can lead to other changes in behavior, such as aborting foraging dives (Aguilar Soto et al., 2006; Cox et al., 2006). These results highlight the negative implications of reduced sound absorption, but potentially there could be positive effects of reduced sound absorption. Baleen whales produce low-frequency communication sounds that travel long distances. These whales currently take advantage of low-attenuation regions of the ocean (SOFAR channels), occasionally singing in these regions so that their songs travel several kilometers (Payne and Webb, 1971). Because these animals use songs to communicate with members of their own species, an acidification-caused reduction in sound absorption may be beneficial to them because it will allow them to remain in communication over longer distances.

Regardless of whether reduced absorption is harmful or beneficial, some investigators disagree over whether ocean acidification will result in changes in absorption large enough to cause measurable changes that will affect animals (Joseph and Chiu, 2010). Additionally, it is important to point out that these predictions are based around theoretical calculations and not experimentation. These predicted changes in sound absorption have yet to be empirically tested in the ocean because logistics have prevented scientists from acidifying the large volumes of seawater necessary to observe decreases in absorption.

In addition to the decrease in sound absorption, the reduction in ocean pH may affect oceanic animals in other ways. Larval fish are thought to rely on sensory cues such as olfaction and hearing for predator avoidance and for localizing reef settlement sites. Noisy reefs indicate the presence of predators, so most larval fish will avoid these noisy sites. Larval clownfish reared in waters with elevated CO^2 levels did not avoid noisy sites; instead, they demonstrated no preference for sites depending on noise level (Figure 3; Simpson et al., 2011). This suggests that ocean acidification may result in a breakdown of predator avoidance among fish species by disrupting their ability to detect and localize sound sources.

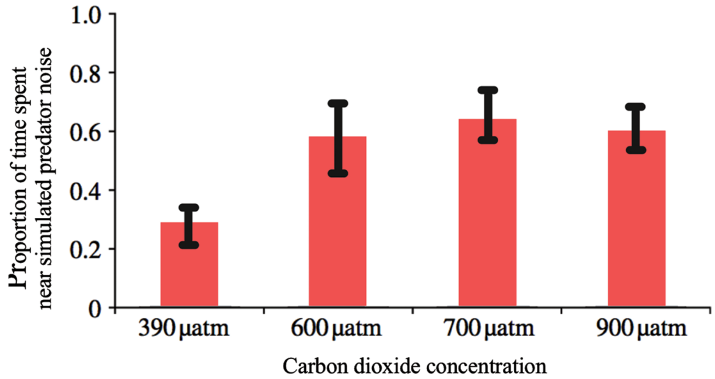

Figure 3: *Effect of carbon dioxide concentration on auditory behavior of juvenile clownfish. Fish reared in ambient CO^2 conditions avoided simulated predator noise, whereas fish reared in elevated carbon dioxide environments did not avoid the noise. Figure adapted from Simpson et al. (2011).*

Freshwater Species

Predicting the impact of climate change on freshwater species is more difficult. The size of many freshwater systems is below the resolution of Global Climate Models (GCMs), which constrains the accuracy of climate projections for these environments (Hobday and Lough, 2011). Additionally, unlike the relatively homogenous oceans, freshwater systems are enclosed and habitat specific. Because climate models predict droughts in some regions and heavier rainfall in others, we cannot create a unifying prediction as to how climate change will impact freshwater species (Hobday and Lough, 2011). For example, streams associated with melting glaciers may increase in flow and volume as the planet warms, whereas lakes and ponds in other regions may desiccate as those environments experience droughts. Increased temperatures can result in a decrease in aquatic mixing and turnover, resulting in stratified regions with hypoxic conditions and low pH. Acidification of freshwater systems is predicted, but it is not known if significant changes in sound absorption will occur due to the small size of most freshwater systems. Clearly more data are needed.

An additional factor to consider in predicting the impact on climate change in freshwater environments is the effect of ambient temperature on the auditory system. Fishes are ectotherms that regulate their body temperature by reference to external temperature, rather than by internal physiological setpoints. The water temperature at which animals were housed affects the hearing sensitivities of two species of catfish, the channel catfish (Ictalurus punctatus) and the tropical catfish (Pimelodus pictus). Thresholds of neural responses from auditory nuclei in the brain varied with housing temperature (Wysocki et al., 2009); at high temperatures, thresholds increased and hearing sensitivity decreased. The magnitude of these changes varied between the two species, and was further affected by how long the fishes were kept at a particular temperature. These results have particular implications for how fishes may respond to climate change. First, temperature will not affect the hearing sensitivity of all species to the same degree, and second, if animals can acclimate to temperature variations, then the negative consequences of increased temperature on hearing sensitivity may be lessened (Wysocki et al., 2009).

Effect on Aerially Communicating Animals

Climate change impacts terrestrial species as well as aquatic species. Changes in temperature (Figure 1- *see page 9*), precipitation, and CO^2 levels, combined with the increased climatic variability caused by global warming, can initiate or exacerbate habitat loss and thus affect biodiversity by altering species distribution, behaviors, and viability. As discussed above for aquatic species, studying these impacts in terrestrial species is also not trivial, because these impacts vary between different habitats (tropical and temperate zones, high and low elevations; Navas, 1996; Deutsch et al., 2008), and between different species (longer-lived species such as birds may be affected in a different manner than shorter-lived species such as insects; Şekercioğlu et al., 2012). Because of the complexity and variability of different habitats and the different life histories of species living in these habitats, we still do not know which species will acclimate and adapt to a changed habitat, which will disperse to other habitats, and which may go extinct. This is where animal bioacoustics can play a major role, both by providing methods for tracking habitat modification and species distribution by acoustic monitoring, and by quantifying animal sounds and behavioral responses to these sounds as an index of species health.

Many terrestrial species, including insects, frogs, birds, and mammals, use vocalizations as part of their social and reproductive behaviors (Bradbury and Vehrencamp, 1998). Mating calls, advertisement calls, and territorial calls are essential for maintaining reproductive isolation between different species and for regulating aggressive interactions within species. Sounds, either self-generated or from the environment, are also used for foraging, orientation, and navigation. The acoustic content of animal vocalizations is molded by constraints imposed by the physical features (temperature, precipitation, vegetation) of the species' local habitat (Wiley and Richards, 1978). Throughout evolutionary time, sounds used for long distance communication between members of the same species have been molded by the environment so that they can transmit efficiently from the sender to the receiver, with minimal interference and degradation ("acoustic adaptation" hypothesis; Morton, 1975). The implication of these environmental constraints on the acoustic structure of communication sounds is that, as the environment changes, the sounds themselves may need to change, too.

Vegetation is a particularly significant environmental constraint on the structure of animal vocalizations. It provides perches from which animals can call, but it can also affect the acoustic parameters of the call. As one example, songbirds living in forests tend to produce long tonal, whistle-like songs with low modulations while songbirds living in more open habitats tend to produce songs with rapid modulations (Morton, 1975). The presence and type of vegetation interacts with atmospheric conditions such as temperature gradients, absorption, scattering, refraction and reflection to influence call propagation and degradation (Bradbury and Vehrencamp, 1998). As patterns of vegetation become modified by climate change, will communication sounds still propagate efficiently in these changing habitats?

The physical environment also impacts the receiver of the vocalization. The receiver must detect the call at various distances from the source (the sender) and against environmental noise that can mask it; otherwise, communication will fail. One strategy to make the receiver's job easier has been identified in some orthopteran insects (crickets, grasshoppers, katydids) and anuran amphibians (frogs and toads). These animals have evolved an auditory system (ear, auditory nerve, and auditory brain areas) that are specialized to detect (that is, are maximally tuned to) important frequencies in their species' mating and advertisement calls (Gerhardt and Huber, 2002). In the Puerto Rican coqui frog Eleutherodactylus coqui, the two notes in the male's advertisement call are at frequencies of about 1000 Hz and 2000 Hz. The second, higher qui note is important for attracting a female to the calling male, and the female's auditory nerve responds best to this note. In this way, the male sender and the female receiver are coupled, suggesting that the vocal production system and the acoustic processing system have co-evolved (Narins and Capranica, 1976). But, will climate change disrupt this balance between the sender and the receiver? Will the receiver's hearing change quickly enough so that any communication sounds that have been modified by the environment can still be detected and discriminated? If not, then acoustic communication essential for reproductive behaviors and species viability will be disrupted.

Sound Absorption

Some researchers are now beginning to address the effects of the changing climate on the acoustic structure of vocalizations. Snell-Rood (2012) analyzed acoustic features of songs from 50 species of North American wood warblers and of echolocation sounds from 11 species of Southwestern bats, and correlated these features with levels of atmospheric absorption at various locations in the geographic ranges of these species. She found small but significant correlations between some acoustic features and atmospheric absorption. In wood warblers, the frequency bandwidth of song was narrower in habitats with greater sound absorption. Differences in absorption were on the order of 0.03 dB/m to 0.1 dB/m, which translate into differences in the intensity of the song by as much as 10 dB over a 100 m propagation distance, a typical communication range for these birds. Mean frequency of the echolocation calls in the 11 bat species was lower in habitats with higher absorption. For two representative species of bats, absorption ranged from 1.53 to 1.73 dB/m, which translate into a change of about 4 dB in intensity for a prey 5 m away (10 m travel time, from the bat to the prey and back), a distance over which these small bats can detect prey.

Precipitation

Changes in patterns of precipitation produced by climate change can impact animal sounds both by varying humidity and thus sound absorption by the atmosphere, and also by altering the times at which animals will vocalize. Snell-Rood (2012) observed that in the same bat species, acoustic features of echolocation calls differed between rainy and dry seasons. In rainy seasons, when precipitation and humidity were high, absorption was higher (0.58 dB/m greater than in the dry season) and echolocation sounds were both longer in duration and lower in frequency. An increase of this magnitude would translate into about 6 dB greater absorption, and thus a lower sound intensity, for a bat detecting a prey 5 m away. Such changes may impact the bat's foraging success by altering the distance over which its echolocation operates.

The calling behavior of tawny owls *(Strix aluco)* also is affected by precipitation. During dry days with lower sound absorption, these birds showed better signal-to-noise ratios for detection of their territorial calls and thus a larger communication range (Lengagne and Slater, 2002). Tawny owls did not call during nights of heavy rain, even within the breeding season. The authors estimated that to maintain the same communication range during rainy and dry nights, the owls would need to increase the intensities of their calls by 20 dB, increases that are not physiologically realistic (Lengagne and Slater, 2002). Thus, if overall precipitation levels increase and rainy seasons become longer, then owl acoustic behaviors will become less efficient.

Precipitation also affects communication by its impact on vegetation. Moller (2011) compared the location of calling sites ('song posts') in 34 species of Danish birds in the period 1986-89 and in 2010. Over this time span, local ambient temperatures increased on average by 2° C (20%), precipitation increased by 75 mm (30%), and vegetation was overall higher. Over all species sampled, male birds sang on average from higher perches in 2010 than in 1986, an 18% (1.2 m) increase in "song post height." Moller (2011) suggested that the increased precipitation and temperature produced increased vegetation which in turn triggered changes in song post height. The extent to which an individual species of bird moved to higher perches was related to their local microhabitat: Birds singing in forested areas showed larger increases in song post height than birds singing in grassland. We do not know how these changes in song post height affect the propagation or degradation of song. Details of the mating interactions within a species as well as their susceptibility to predation also influenced the magnitude of the changes in song post height. Because not all species reacted in the same way to similar climatic changes, this suggests that local ecosystems might become unbalanced by favoring some species over others.

Temperature

Like fishes, ectotherms such as insects, reptiles, and amphibians are physiologically vulnerable to external temperature fluctuations (Deutsch et al., 2008; Paaijmans et al., 2013). Ectotherms living in temperate zones have been shown to have a broader tolerance range for changing temperatures than those living in the tropics (Deutsch et al., 2008). Because of this broader tolerance range, these species might suffer fewer physiological, and thus behavioral, consequences of increased temperatures than tropical species (Navas, 1996).

Laboratory studies in both insects and anuran amphibians have shown that temperature affects call production and the operation of the ear and auditory nerve (Stiebler and Narins, 1990; Gerhardt and Huber, 2002; Meenderink and van Dijk, 2006). For example, wing-stroke rate in stridulating, singing insects is linearly related to temperature over a fairly broad range. And in some anurans, the rate and duration of the male's advertisement call vary with temperature, although these effects are not always linear but show considerable individual and species variability (Gerhardt and Huber, 2002). Currently, we have little information as to how these effects would manifest in the natural environment under conditions of global warming.

How a changing thermal environment affects calling behavior in temperate zone anurans has been examined by Llusia et al. (2013). These investigators monitored atmospheric temperatures and calling temperatures (atmospheric temperatures during the times the animals were actively vocalizing) of 10 species of Iberian anurans for a continuous three year period. Males of all of these species vocalized across a range of environmental temperatures, exhibiting a wide "thermal breadth" of activity. These data suggest that anurans can adapt to changing environmental temperatures. Species living in habitats with hotter temperatures had longer calling seasons and longer periods of calling than those living in habitats with cooler temperatures. For both hotter and cooler habitats, when ambient temperatures rose, so did calling temperatures. Llusia et al. (2013) suggested that temperate zone anurans can acclimate to increased external temperatures by shifting their preferred calling temperatures, but again, different species do not all react in the same way.

The onset of the breeding season in temperate zone frogs is typically indexed acoustically, by the beginnings of chorus formation and advertisement calling (Blair, 1961). Gibbs and Breisch (2002) showed that over the time periods 1900-

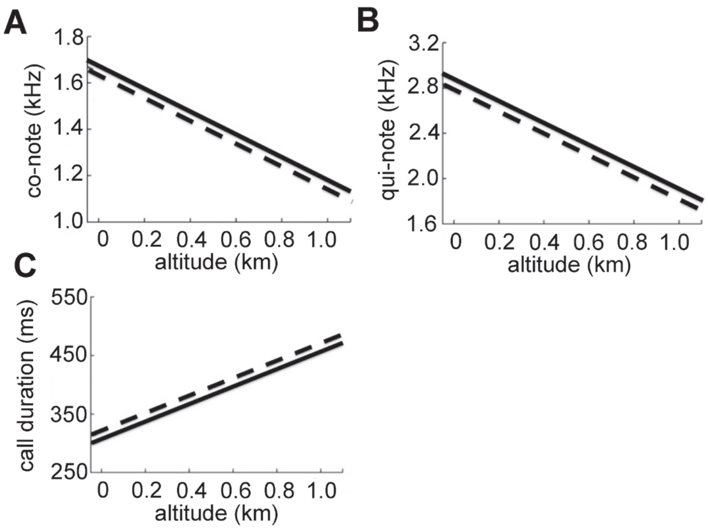

Figure 4: *Relationship between acoustic parameters of the two note (co qui) advertisement call of male Puerto Rican coqui frogs and altitude at which the animals live, sampled in 1983-1984 (dashed lines) and again in 2006 (solid lines). Lines represent the best-fitting linear regression through the data for each time period. (A), the "co" note in the advertisement call decreases in frequency as altitude increases. (B), the "qui" note decreases in frequency as altitude increases. (C), total call duration (both notes together) increase as altitude increases. Regression lines for the two time periods are parallel, but shifted. Over the 23-year span, mean ambient temperatures increased by 0.37° C. Figure adapted from Narins and Meenderink (2014).*

1912 and 1990-1999, four of six frog species acoustically censused in the area around Ithaca, New York, began calling earlier in the spring, by10-13 days. This shift towards the earlier onset of advertisement calling was correlated with an average increase of 1-2.3° C in the springtime mean daily temperatures. What effect this earlier breeding has on population size or viability is not known.

Changing environmental temperatures can also impact acoustic communication in tropical anurans. Narins and Meenderink (2014) compared advertisement calls of male Puerto Rican coqui recorded in 2006 to those recorded 23years earlier, in 1983-84. These frogs are found at different altitudes in their natural habitat, and the acoustic parameters of their advertisement calls vary over this altitudinal gradient. At both time periods, the frequencies of the two notes in the advertisement call decreased with elevation (Figure 4), and the duration of the entire two note call increased with elevation, and at similar rates. That is, the best-fitting regression lines through the data from both time periods are parallel, but are offset. Note frequencies are higher in 2006 but call duration is shorter. These shifts are mirrored in an upward shift in mean local temperatures of 0.37° C (range 0.34-0.41° C) over this 23 year span. Although laboratory studies have shown that temperature affects the ability of some species of female frogs to discriminate advertisement calls (Gerhardt and Huber, 2002), it is not known if the hearing sensitivity of female coqui frogs has shifted in a manner paralleling the shift in the male coqui's call. Any disconnect between the male's vocal output and the female's hearing sensitivity would have severe negative consequences for species reproduction and survival.

Unlike ectotherms, endotherms (birds and mammals) regulate body temperature by internal physiological means. There are few data that address the question of how acoustic communication in endotherms is affected by global warming. This is a particularly important question in species such as songbirds, whose social and reproductive behaviors are largely regulated by vocal cues (song). Aside from the small influence of sound absorption on song bandwidth (Snell-Rood, 2012), it is not known if other acoustic parameters of song, like those of frog advertisement calls, vary with temperature over geographic gradients.

Increasing temperatures may affect acoustic communication in temperate zone songbirds indirectly, by advancing the breeding season (Torti and Dunn, 2005). Seasonal variability is an important component of the communication system in these animals. In some songbird species, the brain nuclei controlling song production and song perception are larger in the spring than in the fall (Tramontin and Brenowitz, 2000). These volume changes have been linked to changes in day length and levels of circulating hormones. The potential contributing factors of temperature or of precipitation, which also vary seasonally, on these volume changes have not been explicitly examined. It is not known if seasonal variations in the sizes of brain areas occur to the same extent in years where springtime comes earlier, due to global warming.

Bioacoustic Monitoring

In addition to understanding how climate change can impact the acoustic behavior of species, we can use acoustic techniques to monitor changes in the distribution and viability of species in different habitats. For example, birds are considered an indicator species for climate change since community-based bird watching datasets provide extensive historical data on the distribution and timing of behaviors. Bird species most vulnerable to climate change, however, are located in the tropics and are not as well observed as their temperate counterparts (Şekercioğlu et al., 2012). Acoustics can provide key information on these species and their habitats: by recording bird songs in critical habitats, species abundance and distribution can be monitored and linked to environmental parameters to determine the impact of climate change in specific regions. Avian bioacoustic monitoring has been proven successful for identifying species and determining population density (Frommolt and Tauchert, 2014), as well as determining species richness in regions (Towsey et al., 2014). Bioacoustic monitoring can also be fruitful for examining the relationship between climate change and changing distribution of other species that rely on acoustic communication, including those living in aquatic and in terrestrial environments. Developing semi-automated approaches into fully automated approaches can provide rapid, real-time information on species identification, distribution, and behavior in habitats vulnerable to climate change.

Conclusions

This article has focused on the impact of climate change on the acoustics of individuals or species, but it is important to emphasize that an individual in any habitat is one link in a network of interactions with other individuals and species. This collective interaction of biological, geophysical, and anthropogenic sound, termed "soundscape ecology," is studied to understand the dynamics of acoustics in environments across space and time (Pijanowski et al., 2011). We are only just beginning to understand how climate impacts the acoustic behavior of species. The evidence so far suggests that any acoustically communicating animal is at risk for climate-change induced modifications. For marine animals, ocean acidification may result in increased ambient noise, which can affect communication, foraging, and predator avoidance. For terrestrial animals, changes in precipitation and temperature can result in modifications to emitted vocalizations, modifications in the auditory system, and modifications to the balance between the sender and the receiver. Together with changes in species' distribution due to environmental parameters, all these factors may result in changes to the entire soundscape of regions. New methods and approaches are allowing for rapid analysis of soundscapes in the marine (Denes et al., 2014; Parks et al., 2014), freshwater (Gage and Axel, 2014), and terrestrial environments (Farina and Pieretti, 2014; Rodriguez et al., 2014). As the planet continues to adapt to climate change, it is important that all bioacoustic studies document environmental parameters and climate conditions. With this information, we can begin to understand how the sounds of entire habitats and ecosystems will change in response to our changing climate and how this will impact bioacoustics on a global scale.

Biosketches

Laura N. Kloepper is a National Science Foundation Postdoctoral Fellow with dual appointments at Brown University and the University of Massachusetts Dartmouth. Her research focuses on the sensory and behavioral processes underlying echolocation in toothed whales and microchiropteran bats. She obtained her Ph.D. from the University of Hawaii, investigating the dynamics of echolocation in odontocetes using laboratory animals and hydrophone arrays. She currently uses new technological approaches and mathematical techniques to understand adaptive vocal-motor behavior in echolocating bats. She recently taught a course on climate change biology at Brown University, and is interested in linking bioacoustics and climate science.

Andrea Megela Simmons is Professor of Psychology, with a secondary appointment in Neuroscience, in the Department of Cognitive, Linguistics, and Psychological Sciences at Brown University. Her primary research interest is in analysis of the development of the octavolateralis (auditory, vestibular, lateral line) systems in developing anurans across the metamorphic transition. She also studies vocal interactions and dynamics in frog choruses using microphone array techniques. A new line of research concerns the impact of anthropogenic noise on communication in frogs and echolocation in bats.

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Observing the Invisible: Using Microphone Arrays to Study Bat Echolocation

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Acoustic arrays have become an essential tool for investigating the behavior of echolocating animals in the field and the laboratory.

This paper was presented by Dr. Simmons as a Hot Topics at the San Francisco meeting of ASA on December 4, 2013.

Introduction

Sound is produced and sensed by nearly all animals. It provides a fundamental means of communication, detection and classification of predator and prey, localization of sound sources, and orientation relative to the environment. Most animals rely upon sound for survival, but a select few have developed a precise sense of hearing. Nocturnal birds such as the barn owl (Tyto alba) excel at passive localization of prey-generated sounds for capturing prey at night. A specialized group of mammals (e.g. bats and toothed whales, including dolphins) have evolved to use acoustics as their primary active sense in the absence of visual information. These echolocating mammals have developed an extreme acuity and agility with which their external world is precisely reconstructed from the stream of echoes received; however, the exact physical and neuronal mechanisms responsible for this precision are not well understood nor are they matched by any existing technological system.

The biosonar system of echolocating bats (Figure 1) and toothed whales represents the most advanced acoustic imaging solution known to exist. The sophistication of biosonar lies not in its complexity, but in the real-time performance that is achievable by a minimalistic set of hardware – a few acoustic baffles[1] and a compact network of neural circuitry.

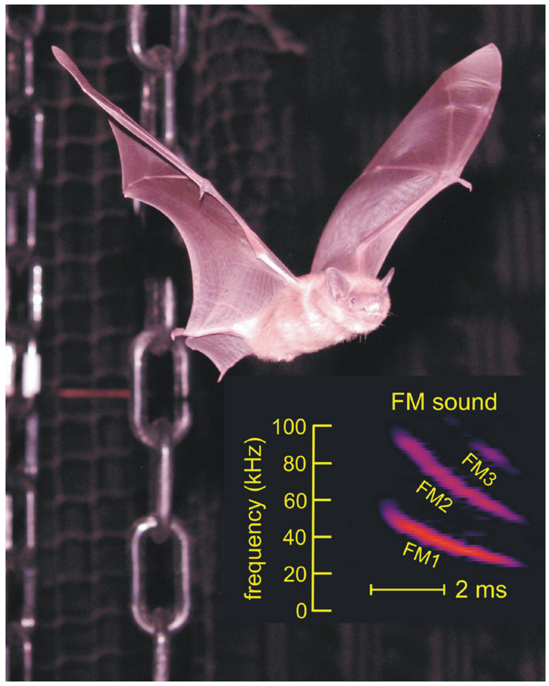


Figure 1: *Close-up view of big brown bat, Eptesicus fuscus, flying through an array of vertically hanging chains in tests of steering through cluttered surroundings. Inset shows spectrogram of FM biosonar sound with three down-sweeping harmonics. The signal's broad bandwidth provides for sharp registration of arrival-time at microphones, while the high frequencies largely preclude the occurrence of multipath reverberation—a major problem for underwater array measurements to locate cetaceans or in air for triangulation of lower-frequency animal sounds, such as birdcalls, in forests.*

[1] *e.g. nose, ears, mouth for bats*

Echolocation is a complex active sensory system in which animals forage and navigate in their environment primarily using emitted acoustic signals. By producing intense, ultrasonic signals and receiving their returning echoes, these animals can identify, discriminate, and track prey, often in highly cluttered environments. Bats and toothed whales are two distinctly different suborders of mammals that convergently evolved echolocation, and both have been intensely investigated to understand their mechanisms that may translate to man-made sonar and radar systems.

Bioacoustics researchers apply a variety of advanced tools to improve our understanding of animal echolocation. These tools range from mathematical signal processing algorithms to physical hardware and technology. This article focuses on the latter, which includes multi-sensor arrays. A primary objective when designing any measurement apparatus is to sense without affecting the phenomenon being sensed. This is especially important in acoustics, where strong reflections off the array itself can interfere with the free-field response being measured.

Designing Specialized Microphone Arrays for Bioacoustics Research

Microphone arrays consist of two or more spatially separated sensors that convert acoustic pressure waves into a series of electrical signals. Common usage of microphone arrays in biosonar research might include monitoring biological activity in the field, tracking animals by estimating the source position of emitted sounds, measuring and visualizing the spatiotemporal directivity patterns, estimating head aim, and analyzing the time-frequency structure of bioacoustic waveforms.

Although the array sensing requirements are often unique, the specific solutions almost always consist of the same set of general hardware: sensing transducers, mechanical support and alignment, power and signal conditioning circuitry, digital converters and processors, and data storage. Invariably, there are numerous technical considerations to account for when defining the system requirements. The range of frequencies used by a particular animal species is a fundamental characteristic since it impacts the selection of all components in the signal chain from sensor to data storage. For example, many species of bats emit ultrasonic echolocation and communication signals that span the upper end of human hearing to the limitations imposed by acoustic absorption over several meters in air (20 – 200 kHz). Unfortunately, the majority of commercially available microphones, amplifiers, and converters are designed to work within the range of frequencies audible to humans (20 Hz – 20 kHz) such that selection of components with suitable ultrasonic performance can prove difficult.

Integrating video with acoustic data collection is essential in many experimental scenarios. Synchronized audio and video greatly facilitate the process of analyzing acoustic recordings, because a human can quickly filter out dead-time and focus on interesting events by scanning through a video track much more quickly than browsing multiple channels of audio data. Furthermore, if localization and tracking accuracy is needed beyond what the acoustic array can provide, a pair of overlapping video streams may be used to stereoscopically estimate the position of one or more objects in three dimensions. The major challenge here is that acoustic events are generally sparse and irregularly spaced in time; however, video tracking provides continuous discrete-time estimates. These disparate sets of data may be combined into an improved tracking algorithm using Kalman filtering or smoothing techniques.

Algorithms for Acoustic Localization and Tracking with Arrays of Microphones

By far, the most common bioacoustic application of a microphone array is passive monitoring and tracking. In these scenarios, an array is used to estimate the position of one or more animals from the acoustic waveforms they produce. Fortunately, most signals emitted by echolocating bats have a stereotypical time-frequency signature. This allows researchers to both classify the species with high confidence and apply time-correlation techniques to filter out extraneous noise.

A variety of array signal processing algorithms are used for bioacoustics tracking problems. When real-time tracking is necessary, highly efficient algorithms such as frequency-domain beamforming from an array of closely spaced sensors are ideal. Frequency-domain methods require that the array have excellent phase agreement at every stage including mechanical alignment, matching transducer frequency response, and synchronous digital sampling. Furthermore, array elements must be spaced no greater than a half wavelength of the highest frequency to avoid grating lobes, or spatial aliasing.

Alternatively, when acoustic sensors can be deployed in advance at fixed known locations, tracking can be accomplished by time-domain beamforming with a distributed array. Time-domain beamforming has the advantage that grating lobes and other spatial aliasing effects are eliminated, because aliasing is an artifact of the processing rather than physical manifestations of the sound field. Within the context of a distributed array and time-domain processing, there are several options for array signal processing. The most straightforward is cross-correlation followed by time-difference-of-arrival (TDOA) (Brandstein et al., 1996; Gillette and Silverman 2008). Steered response power (SRP) and its variants (Silverman et al., 2005) are a bit more computationally expensive, but this class of algorithms can provide a one-step solution for localizing sound sources.

Although there are numerous beamforming algorithms to estimate sound source locations and produce acoustic images, the information used is largely the same – the relative time delay of a correlated signal arriving at multiple array sensor elements. Perhaps more important is the array bandwidth. Increased bandwidth translates to improved localization accuracy and resolution over a narrowband approach, because resolution in time is inversely proportional to signal bandwidth. For passive arrays, the bandwidth of the bioacoustic signal itself will determine the upper bound on array accuracy and resolution.

Honey, I Shrunk the Technology

Recent developments in micro-electromechanical systems (MEMS) offer a low-cost solution to the acoustic measurement problem. MEMS devices are continuously improving through advancements in silicon integrated circuit manufacturing. Today, MEMS sensors are widely commercialized and have numerous benefits. Ultrasonic MEMS microphones, for example, have an effective aperture on the order of 1 mm or 0.04" (Figure 2). By comparison, precision condenser microphones have an aperture of 1/4" or 1/8". By reducing the acoustic aperture MEMS microphones offer a more omnidirectional response.

As a technology, MEMS does have limitations. All mechanical devices have resonances and stress related concerns; MEMS pressure sensing microphones are no exception. The acoustic sensitivity, dynamic range, and spectral noise floor of current devices does not yet match the specifications for any precision microphone devices; however, MEMS microphones are also 2 to 3 orders of magnitude lower in cost. MEMS vector sensors are also being developed for air and water. These sensors can be used to couple acoustic particle velocity measurements along with the traditional pressure-only measurements. Not only do vector sensors improve sound source location estimates, but also dense arrays of these sensors may be used to provide new insight into the near-field acoustics in close proximity to biosonar structures.

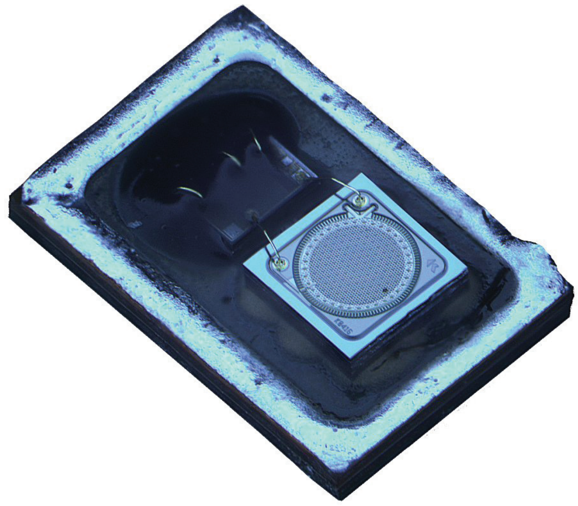


Figure 2: *A close-up photograph of a Knowles MEMS microphone sensor. The pressure-sensing surface is the approximately 1 mm diameter circle at the center of the MEMS substrate. Acoustic waves actuate the surface of the sensor and small changes in capacitance are translated into electrical signals that can be amplified and conditioned. Photograph is courtesy of Knowles Corporation.*

Until approximately a decade ago, large-scale acoustic measurement systems would be nearly impossible to construct without a substantial research budget. Aside from the large cost of pressure sensors and their associated electronics (i.e. preamplifiers, analog-to-digital converters, transceivers, memory storage), the collection of data across hundreds of sensor elements requires synchronized control of variable-gain amplifiers and analog-to-digital converter devices. This control can be performed in one of two basic ways: A very high-speed processor (such as a programmable digital signal processor) or custom parallel digital electronics. Hybrid solutions also exist in the form of graphical processing units (GPUs). The fully parallel solution is obviously more scalable to higher density measurements, but traditionally requires a significant investment in building specialized electronic circuit boards or application specific integrated circuits (ASIC) – both of which are expensive in development time and material cost. Commercial data acquisition systems that implement these solutions are abundant for applications requiring tens of channels recorded simultaneously, but not hundreds. Commercial systems that embrace

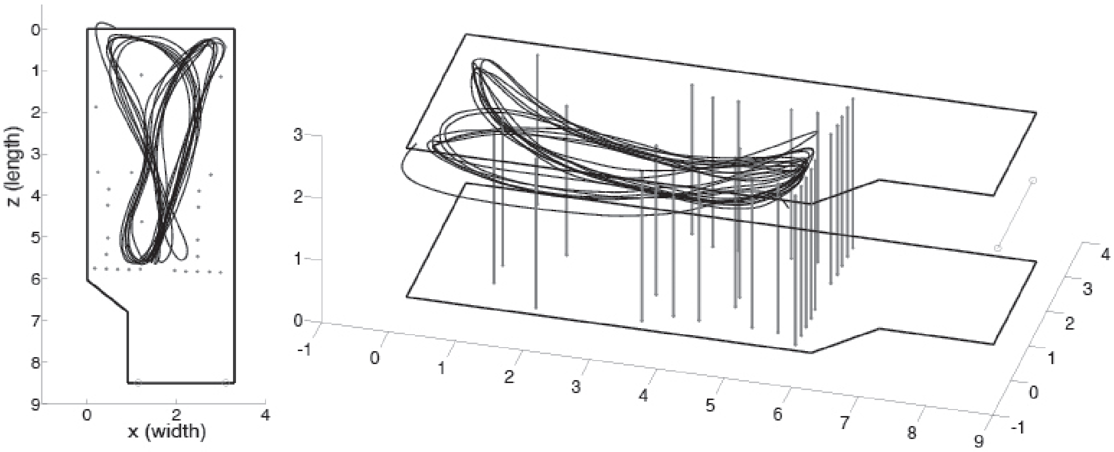


Figure 3: *Looping flight track of bat steering around the room with hanging chains. The bat is tracked from TDOA at 20 MEMS microphones distributed around the room. Left, plan view, right, diagonal view (Barchi, Knowles, and Simmons, 2013).*

the modular approach can be expanded to achieve the desired performance, but not without tradeoffs between cost and performance. Now that field programmable gate array (FPGA) technology has matured into a compact, highly integrated system-on-a-chip platform, the significant amount of time invested in building and debugging custom hardware solutions can be replaced by writing software-defined hardware. Reconfigurable FPGA devices are ideal as a rapid prototyping platform, because they take only seconds or minutes to download a new design configuration, all from the developer's keyboard. With the use of FPGAs, the ability to replicate numerous customized digital hardware blocks is trivial and concerns of repeatability and reliability are minimized.

Microphone Arrays in Controlled Laboratory Environments

In a controlled laboratory environment, microphone arrays are ideal instruments for reconstructing the flight tracks of echolocating bats during an experiment. Due to the high pulse-rate of echolocation signals in flight, the animals' trajectories can be estimated fairly accurately by localizing each pulse and fitting spline curves to successive positions. Auxiliary uses of microphone arrays include simultaneously estimating behavioral parameters, such as head aim leading up to a prey capture, and acoustic parameters, such as the spatial directivity patterns (Ghose and Moss 2003; Matsuta et al., 2013; Surlykke et al., 2013).

In the Simmons' Lab at Brown University, echolocating big brown bats *(Eptesicus fuscus)* are tracked during flight experiments using a distributed array of 24 microphones that completely surround the 7.6 x 4.3 x 2.7 m semi-anechoic room environment. This species of bat emits high intensity (approx. 134 dB SPL re 20 µPa @ 1 m) broadband FM echolocation signals with a pulse repetition rate between 10 and 100 pulses per second during flight. Obstacles such as plastic chains or nets are configured in specific positions and densities to test various aspects of echolocation behavior (see video 1 at http://acousticstoday.org/?p=2413).

Custom microphone circuit boards are positioned around the room in a loosely uniform configuration and staggered between two vertical heights. This positioning provides a near field aperture that completely encloses the space and yields excellent coverage of the animal's directional sounds throughout the room. The microphones are commercially available ultrasonic MEMS pressure sensors (Knowles Acoustics, Ithaca, NY) that can be machine soldered to the surface of the printed circuit boards. A professional audio system (V4HD and pair of HD192, MOTU, Cambridge, MA) is used to integrate the audio stream sampled at 192 kHz and stereo thermal infrared video (Merlin and/or Photon 320, FLIR Systems, Boston, MA) running at 30 frames per second (see video 2 at http://acousticstoday.org/?p=2413). During experiments, a user controls the recording system through the MOTU and AudioDesk software and all data are recorded directly to a standard internal hard drive. All data are post-processed by using MATLAB (Mathworks, Natick, MA), since real-time tracking is not required. After detecting the sound sources with simple energy detection, echolocation signals received at each microphone must be paired across the entire array. Cross-correlation and TDOA estimation is implemented by a relatively simple algorithm (Gillette and Silverman, 2008).

Figure 3 shows an example flight track of E. fuscus during one experimental trial. The flight room recording system was jointly designed and constructed by Jonathan Barchi, Jeffrey Knowles, Jason Gaudette, and James Simmons, with a significant amount of assistance by many current and former members of the lab. To date, the flight room array has been used in studying the spatial memory and flight dynamics of big brown bats (Barchi et al., 2013), and is currently being used to understand acoustic and behavioral adaptations in varying degrees of dense clutter.

Arrayzilla Lives!

Distributed arrays of microphones allow researchers to reconstruct the spatiotemporal directivity of bats' echolocation beams. This directivity is not only defined by azimuth and elevation, but also critically depends on frequency due to the broadband nature of these signals. These bioacoustic beam patterns are also time-dependent because, unlike man-made transducers, acoustic baffle structures such as the ears and mouth are constantly moving.

To visualize this multi-dimensional acoustic information with sufficient fidelity requires a very large number of sensors and supporting equipment to sample the space. Ideally, these detailed acoustic beam measurements would be made with high quality, precision calibrated microphones, which have a wide frequency response, low directivity, and excellent gain and phase matching. All of these characteristics are important for accurately measuring the broadband sound field relevant to animal echolocation, which spans over a decade of frequencies in many cases. Unfortunately, the expense of such high-quality equipment limits the number of elements in the array and therefore the angular coverage and spatial resolution that is achievable.

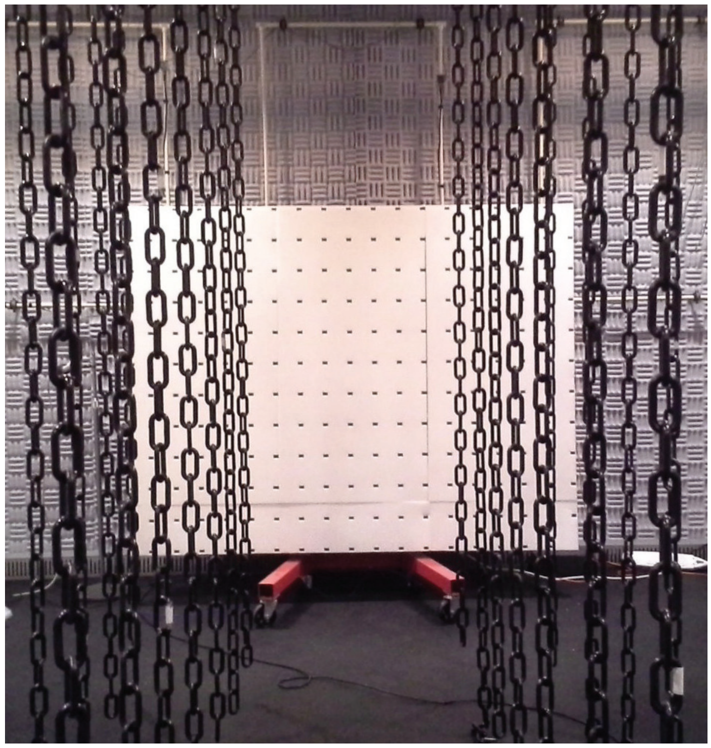
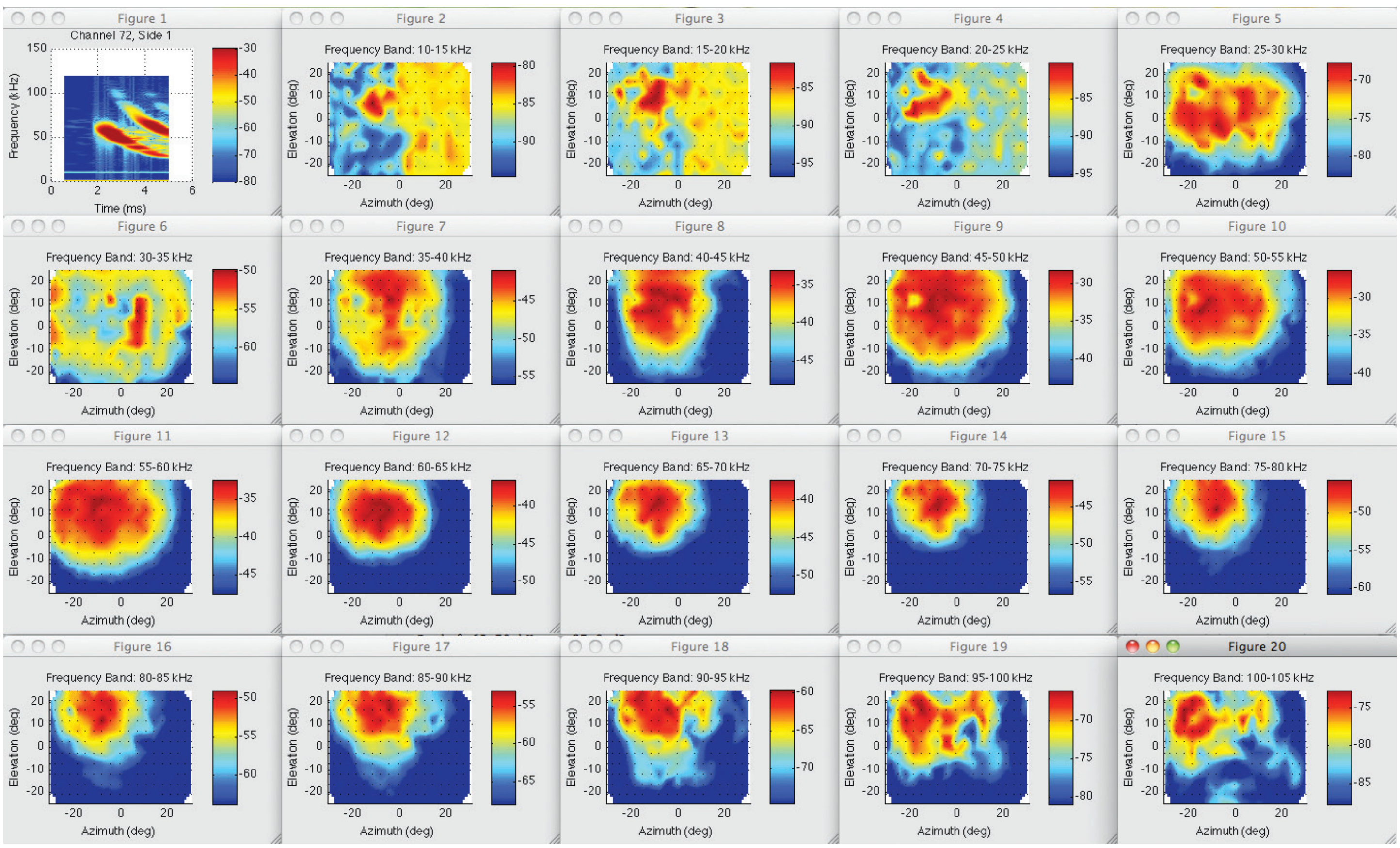


Figure 4: *Multiple-microphone "Arrayzilla" in-situ for visualizing broadcast beam patterns of bats flying through a corridor between rows of vertical chains.*

Figure 5: *Broadcast beam patterns (azimuth, elevation) for an FM biosonar sound (see Figure 1). Individual plots show a series of frequencies in 5-kHz bands from 10 to 105 kHz.*



Large-scale sensing requires that many concurrent requirements are met: Numerous spatially distributed sensors, sufficient bandwidth and synchronization of data acquisition equipment, adequate data transfer speed (both, throughput and latency), abundant storage, and automated software for rapid online or offline data analysis. Without meeting these requirements, researchers will spend less time searching for evidence of adaptive echolocation techniques and more time finding ways to compensate for the limitations imposed by their experimental design.

New and creative approaches to designing arrays with advanced technologies have enabled high-density acoustic sensing systems suitable for beam pattern measurements. Our lab has recently designed, built, and tested a large reconfigurable microphone array with up to 224 ultrasonic microphones along with supporting acoustic signal processing software (Gaudette et al., 2014). The broadband array has been used in a variety of experiments with bats from both, a stationary platform and in flight (see Figure 4). Due to its immense size and density, the array was affectionately named Arrayzilla (see video 3 at http://acousticstoday.org/?p=2413). This measurement array achieves unprecedented fidelity of bats' echolocation beams in the laboratory—a spatial sampling resolution between 3 and 6 degrees in azimuth and elevation. Figure 5 shows data from a single echolocation pulse during a stationary platform experiment with *E. fuscus*.

Acoustic Measurements and Flight Tracking in the Field

Despite the large amounts of data that can be collected conveniently in a controlled laboratory environment, the behavior of bats in natural conditions still constitutes ultimate "ground truth" about the capabilities of biosonar. Laboratory studies can focus on aspects of echolocation behavior by creating conditions and measurement devices that emphasize one kind of response while minimizing variability, but there is no substitute for field observations of bats actually deploying their sonar. Field research involves bringing acoustic instrumentation into conditions beyond the reach of power connections, to situations where portability, battery power, and simplicity of operation are essential. The functional equivalent of the acoustic measuring equipment used in the laboratory must be transported to field sites where bats are known to fly in pursuit of prey, to engage in bat-to-bat chases, to fly in cluttered surroundings, or to aggregate in swarms. Prior scouting helps to locate study sites so that setting up apparatus is not wasted time. At a minimum, field recordings can be performed with a single microphone device, and, in fact, for half a century nearly everything we have learned about the behavior of bats in natural conditions has come from listening to their sonar sounds with "bat detectors" or recorded with only one microphone. The capability to process multiple-microphone recordings and exploit them as true arrays only became feasible when personal computers and the necessary applications programs became commonly available. The microphones in an array have to be located with respect to each other for processing the recordings to determine the direction of the sound sources. In a flight room, they can be mounted permanently on the walls around the room and their locations measured to provide 3D coordinates. In the field, it is often difficult to find corresponding features on which to anchor the array. One solution is to mount several microphones together on a frame, which can then be placed to face the area where bats are flying. To cover a larger area, several such frames can be arranged to surround the location. Then, the problem is to measure the distance and orientation between the frames. This method has been used especially effectively in studies of foraging by Japanese house bats (*Pipistrellus abramus*) in a well-defined feeding area (Fujioka et al., 2011; Hiryu et al., 2008). In many field sites, the location is irregular in shape, and there are trees, banks, or other features that constrain the placement of microphones. It then becomes necessary to position the microphones in a loosely defined grid and measure their positions as they happen. Figure 6 illustrates an array placed in a clearing in rain forest, next to a Mayan temple. The microphones are placed on poles of different heights to fill the clearing, and the locations of the microphones measured separately each time the array is emplaced. The processing algorithms have to take into account the grid formed by the microphones.

We have used a variety of microphone configurations to record bats in natural conditions (e.g., Eastman and Simmons, 2005). For example, using an array of 4 microphones in each of two towers, a design obtained from Japanese colleagues (Fujioka et al., 2011; Hiryu et al., 2008), we track big brown bats (*E. fuscus*) flying near each other at a foraging site. Figure 7 shows sample tracks for two bats flying past the two array towers at the same time. The method successfully follows each bat, in large part because the duty-cycle of the bats is low enough that their sounds do not coincide to obscure which bat is where. Besides just tracking the bats, which helps to locate capture maneuvers from the rapid burst of broadcasts accompanying interceptions, the characteristics of their sounds are available from the recordings. Figure 8 shows several acoustic parameters extracted from the two tracks. Big brown bats emit FM sounds with two harmonic sweeps (Figure 1). The first harmonic, FM1, at lower frequencies, is more broadly beamed and less susceptible to propagation losses due to atmospheric absorption. The plots show the starting frequency, the center frequency, and the ending frequency of the FM1 sweeps, plus the duration of FM1. These two bats differ in the frequencies of their recorded sounds, while the durations are about the same. However, due to the bats' movements relative to the microphones and to distances, only the ending frequency of the sweeps represents reliable data. From the distribution of ending frequencies, it is evident that these two bats differ in the span of frequencies in their broadcasts.

Several important findings have emerged from microphone array recordings in the field. The first use of a true array was to determine the elevation of foraging serotine bats *(Eptesicus serotinus)*

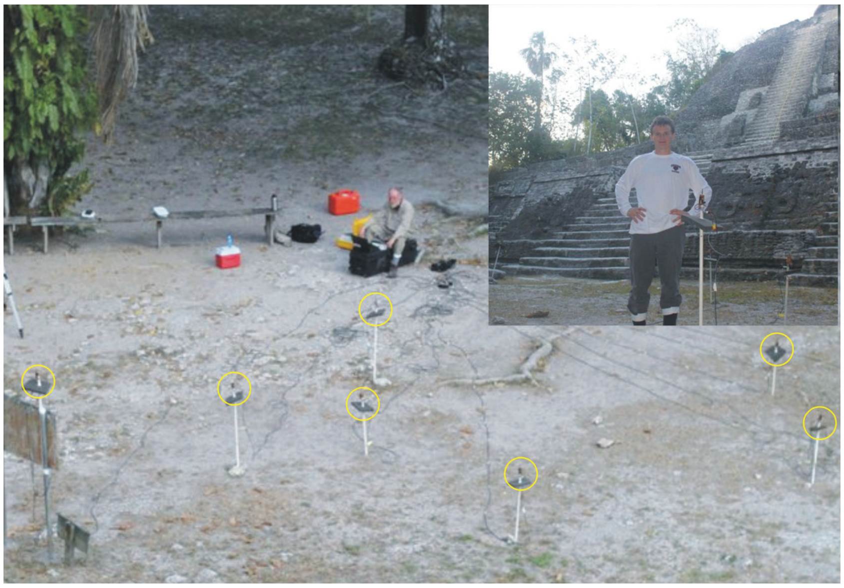


Figure 6: *Setting up an array of microphones (yellow circles) deployed as a tracking array in the field. Inset shows view back towards location of camera, and single microphone with Jeff Knowles. Field set-ups commonly have to conform to local topography, such as the Mayan temple, so there is no standard pre-configuration. Coordinates of each microphone are measured using a laser-equipped reflector-less total-station theodolite.*

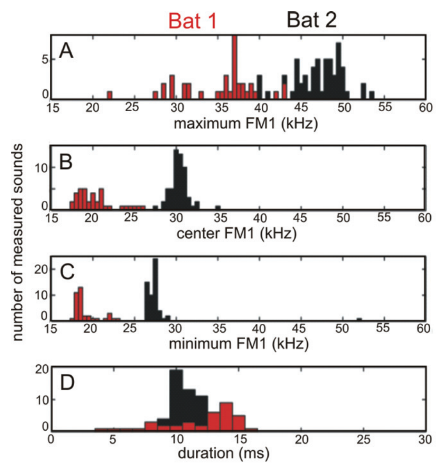


Figure 8: *Acoustic features extracted from sounds on the flight tracks plotted in Fig. 6. (A, initial FM1 frequency; B, center FM 1 frequency; C ending FM1 frequency; D, duration). These plots embody not only useful information but also potential pitfalls for using microphone arrays in the field, where the animals often are relatively far from the microphones. Bat 1 emitted biosonar sounds with lower frequencies in FM1 than Bat 2, but only the ending FM1 frequencies represent reliable frequency measurements. Data are limited to frequencies in FM1 (see Figure 1) to minimize artifacts related to broadcast beaming and distance for these rapidly moving bats. The bats' broadcast durations are similar.*

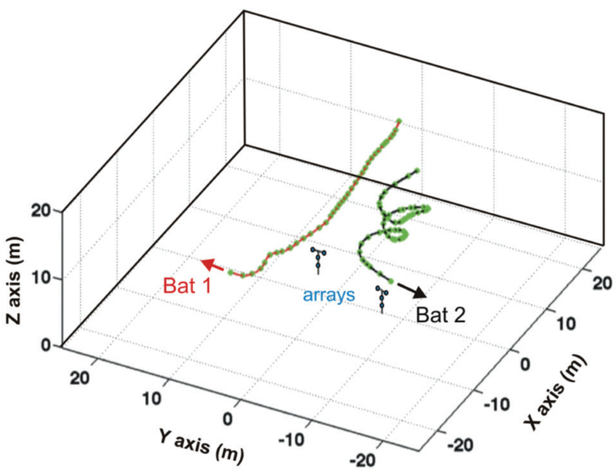


Figure 7: *Flight tracks of two big brown bats traced by TDOA measurements using two 4-microphone tower arrays of the Japanese design (Fujioka et al., 2011; Hiryu et al., 2008). The low duty-cycle of each bat makes it easy to separate their paths (data from Jeff Knowles).*

to correlate the characteristics of their biosonar sounds with flight altitude (Jensen and Miller, 1999). When flying higher than 8-10 m above the ground, their broadcasts were of constant duration, while bats flying lower changed the duration of their sounds correlated with height. The important finding was that the bats sense their distance from the ground and treat the size of the foraging space partly in terms of their altitude.

Another example of the utility of microphone arrays for tracking bats comes from a study of the adaptive changes bats make in their sounds depending on the distance to nearby objects (Holderied et al., 2006). The question is significant because bats may make adjustments to their broadcasts to sharpen their images for objects a particular distance—a potential "distance of focus." To assess this hypothesis, recordings were made with an array of 8 microphones to track individual whiskered bats *(Myotis mystacinus)* while they commuted along a row of vegetation to reach their feeding areas. The distance from the bats to the vegetation induced the bats to change their sounds in a manner consistent with the distance of focus.

One of the most extensive uses of microphone arrays to track bats in the field has been done by a Japanese group (Fujioka et al., 2011; Hiryu et al., 2008). They set up multiple frames of microphones to completely surround the foraging area used by Japanese house bats. Their array consisted of up to 32 microphones in clusters of two to four microphones mounted on frames deployed around the feeding area. The entire sequence of tracks and sound emissions was recorded across sequences of interceptions, revealing how the bats change their sounds and pace themselves during hunting.

Conclusion

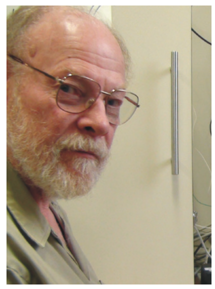
The implications of understanding the underlying mechanisms of biosonar are profound and far-reaching. Biosonar is not a theoretical development; it is a proven high-resolution acoustic imaging system that is functional and robust. The exceptional performance and adaptability by animal echolocators in the midst of dense clutter is what draws engineers and scientists to marvel at its simplicity.

Acknowledgments

The authors would like to thank the Office of Naval Research and the Naval Undersea Warfare Center for supporting their continued interest and endeavors in bioacoustics research.

Biosketches

Dr. Jason E. Gaudette is a research engineer at the Naval Undersea Warfare Center in Newport, RI. In May 2014 he received the Ph.D. in Biomedical Engineering from Brown University under the guidance of Dr. James Simmons. Jason received the Electrical Engineering degrees of M.S. from the University of Rhode Island in 2005 and B.S. from Worcester Polytechnic Institute in 2003. He has been an active member of the Acoustical Society of America since 2010. Jason's current research interests include acoustics, neural information processing, and reconfigurable computing for embedded applications.



Dr. James A. Simmons is a professor of Neuroscience at Brown University, in Providence, RI. He has been carrying out research on echolocating bats since 1965. He received the Ph.D. from Princeton University and previously has held faculty appointments at Washington University in St. Louis and the University of Oregon. In recent years, the Simmons Lab has collaborated with Prof. Hiroshi Riquimaroux and Dr. Shizuko Hiryu, at Doshisha University in Japan, to understand how bats form biosonar images of desired targets while preventing off-side clutter from interfering with these images but still allowing bats to steer through the off-side scene.

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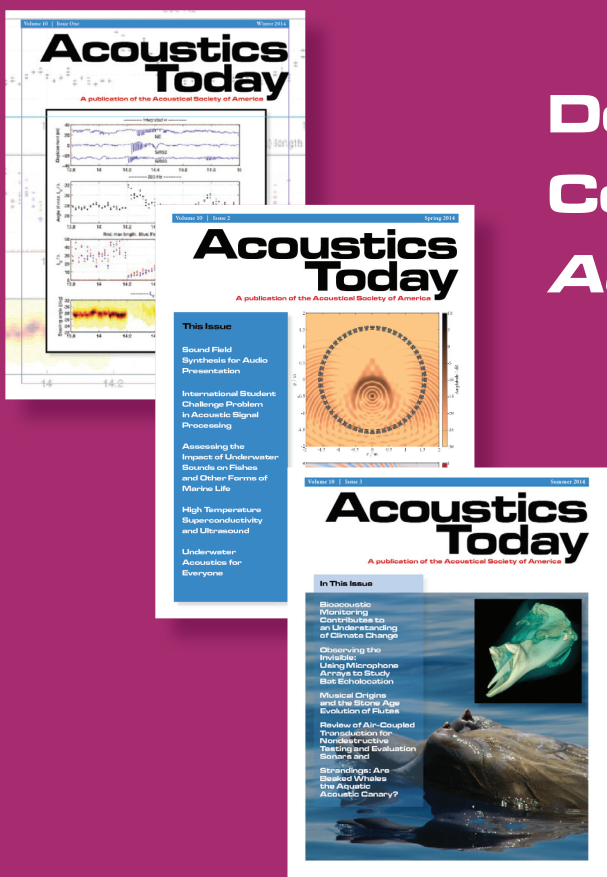

Musical Origins and the Stone Age Evolution of Flutes

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When we, modern humans, emerged from Africa and colonized Europe 45,000 years ago, did we have flutes in fist and melodies in mind?

Introduction

Music is an intensely emotional subject and the origins of music have fascinated people for millennia, going back to early historic records. An excellent review can be found in "Dolmetsch Online" (http://www.dolmetsch.com/musictheory35.htm). Intense debates in the late 19th and early 20th century revolved around the origins of speech and music and which came first. Biologist Charles Darwin, befitting his important recognition of evolution by sexual selection, considered that music evolved as a courtship display similar to bird song; he also felt that speech derived from music. Musicologist Spencer posited that music derived from the emotional content of human speech. The Darwin–Spencer debate (Kivy, 1959) continues unresolved. During the same period the eminent physicist Helmholtz-following Aristotle-studied harmonics of sound and felt that music distinguished itself from speech by its "fixed degree in the scale" (Scala = stairs, i.e. discrete steps) as opposed to the sliding pitches ("glissando") typical of human speech. As we will see, this may not be such a good distinction when analyzing very early musical instruments with our contemporary bias toward scales. More recent symposia include "The origins of music" (Wallin et al., 2000) and "The music of nature and the nature of music" (Gray et al., 2001). All sides of this ancient debate agree that music connects to human emotions. All agree also in the assumption that music started with vocalization--song. I will, however, avoid the tangle of perspectives and introspectives that characterizes this debate and focus on musical instruments, which are tools produced specifically for making music. I will also not now enter the debate of what constitutes music. According to composer John Cage, music is "organized sound." This organization can take the form of rhythm, melody or harmony as well as dynamics and timbre and any combination of these music variables. Finally, music is in the ear of the beholder.

Prehistoric Musical Instruments

With that, the quest moves to the historic and particularly the pre-historic origin of musical instruments emerging from archeology. The oldest instruments that can be discovered are necessarily those that are preserved over the centuries and millennia. Historical and biblical records describe and depict musical instruments going back over 5,000 years. (We will refer to early dates as 5kyBP, five thousand years before present). East Indian literature from 3.5kyBP describes a transverse flute. Both pictorial evidence and actual instruments are known from these early settled cultures. Most were made of wood and other perishable materials. But only bone and ivory flutes go back into pre-history, specifically to a period between the Middle and Upper Paleolithic around 40kyBP, when in Europe the invasion of modern human culture (previously referred to as Cro-Magnon) replaced Neanderthal culture after a brief period of overlap, known as the Chatelperronian. It is thus of considerable interest to know more about these earliest preserved instruments that represent the only reliable evidence of music. Who invented them and why? What is involved in flute making? What kind of flutes did they make? What sound did they produce? And, most intriguingly, what music did they play?

To this end in the early 1980's, I began studying and reconstructing such preserved instruments and played them in the French caves along the river Vezere, where I was asked how I knew what to play. I gave two equally improbable answers: "The flute guides me" and "The rocks are full of dot patterns for notes." Together, these flip statements hide a sad truth: we do not know and *cannot* know. Even on a flute with finger holes that suggest a scale, the pitch is not reliably constrained. Finger combinations and blowing direction/strength can form intermediate pitches, and sliding fingers can create a complete "glissando" of all the instrument's possible pitches: the player makes music by organizing sound according to personal preference. However, it seems likely that any personal preference would be deeply engrained in the player's cultural context similar to local languages and dialects. Of course, preferences can have deep cultural roots, but they are not preserved. The oldest known music notation, carved in stone, dates from Greek and Roman culture over two millennia ago revealing familiar sounding melody; notation took its current form with the Roman philosopher Boethius (c. 480–524 AD).[1] Efforts to recreate Paleolithic music thus become a hybrid of recreating old instruments played by today's musicians. A similar effort has recreated the dinosaurs: bones and bone fragments can reasonably suggest body form and even motion, but not skin color and vocalization. For those aspects we rely on today's dinosaur relatives, the lizards, birds and crocodiles.

To appreciate the evolution of flutes it is instructive to sketch a series of developmental stages in flute construction that may have taken place to arrive at today's refined instruments. Each of these stages reflects a new invention and achieves a higher level of musical complexity. Instrument evolution emphasizes the importance of music in the cultures where they originated or where they were copied and became established. While the evolution of musical instruments is not driven by Natural Selection as are survival tools for hunting and fishing, the Rolling Stones and many other performers agree with Darwin that music emerged due to Sexual Selection: pleasing the opposite sex.

[1] *http://www.cengage.com/music/book_content/049557273X_wrightSimms_DEMO/assets/ITOW/7273X_0 1_ITOW_Boethius.pdf*

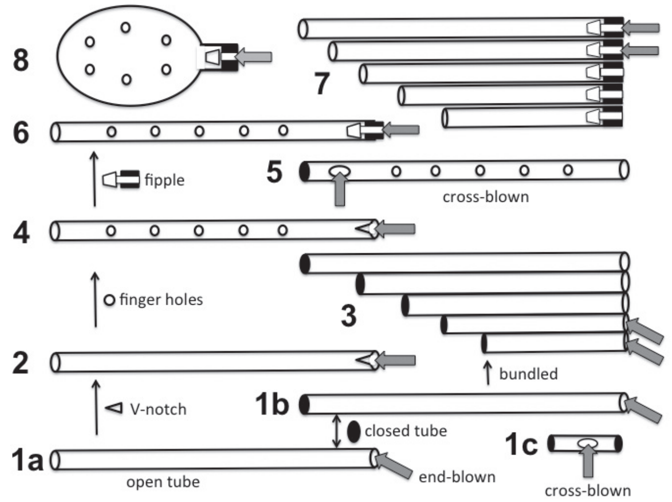

Figure 1. ***Evolution of Flute Technology***
Evolution of flutes; all but two are end-blown as in quenas, neys and recorders. 1a. open tube, 1b. closed tube, 1c. cross-blown whistle, 2. open tube (V-notch), 3. closed tube bundled: Pan pipes (depicted without V-notches), 4. open tube (V-notch) with finger holes: quena, ney, 5. cross-blown, closed tube with finger holes: transverse flute, 6. fipple with finger holes: recorder, 7. bundled open tube fipples: organ pipes. 8. closed vessel fipple with finger holes: ocarina.

1) *Found sound.* The simplest flute is not made but found: a hollow tube making sound by blowing across one of the two open ends (Figure 1-1a); its variant is closed at one end (Figure 1-1b). The player can blow the air stream straight or obliquely across the open top. Reeds, bamboo and bones, especially naturally hollow bird bones, provide ideal starting material. Such flutes do not require much modification to make sound. They produce one fundamental pitch with small fluctuations possible by varying air speed and blowing angle. Depending on tube dimensions, closed-end tubes can produce one or more harmonics. We might call this the "Coke bottle" stage. A simple variant is the cross-blown whistle, made of a small tube with both ends closed and a blowhole in the shaft (Figure 1-1c), often made from mammalian digits.

Note: Of course, one can also go to the trouble to *make* a tube, which can then be made into a flute. Incredibly, this is the case with some of the oldest instruments known. These are described below.

2) *V-notch.* The next stage is to carve a V or U-notch at one end of the tube and direct the airstream at the -sometimes beveled- notch (Figure1-2); notching facilitates sound production particularly in small, narrow-bore tubes.

3) *Panpipes.* To make it possible to play a series of different pitches, the stage 1 and 2 flutes above have been expanded in two directions. In one direction, bundling a series of closed-end tubes of different lengths forms the "Panpipe."

(Figure 1-3) The pitches of such pipes are constrained and would give a reasonable indication of the locally preferred musical scale. Alas, they are typically made of bamboo and other perishable materials.

4) *Finger holes.* In the other direction, different pitches were obtained by making finger holes in open-end tubes (with or without V-notches, Figure 1-4). Opening a finger hole has the same effect as shortening the tube to create a higher pitch. However, as mentioned above, different fingering combinations, finger placement, sliding over the finger holes, and airstream variation can all be used to create a "glissando" across the entire flute's range. The "scale" is thus not constrained and this makes the instruments unreliable indicators of any cultural scale. Of course, trained musicians almost automatically play "in tune" with a preferred scale. This flute stage forms the principle of the historically old as well as contemporary Quena (Balkans, S.America) and Ney (Egypt, Turkey).

5) *Transverse (cross-blown) flutes.* Another modification of the simple tube is to make a blow hole along the shaft and blow the airstream across the tube as in a whistle: the simplest transverse flute (Figure 1-5). Some complexity can be added by closing either or both ends (perhaps while playing), which changes the pitch in a few steps depending on tube length. Adding finger holes allows the playing of more or less discrete pitches. Still, fingering and blowing can produce a sliding pitch, and an uncertain scale. Transverse flutes, described from China (lacquered bamboo) and India ~2-3kyBP, have now reached their end point: today's gold and silver concert flutes are not different in principle. [Needless to say that the last 500 years have seen great technical improvements on the basic design.]

6) *Fipple flutes.* The transverse flute and the end-blown flutes of stages 1-4 in Figure 1 are easy to make but require good control of the air stream and are thus more difficult to play. Creating a more fixed airstream solves this problem. In fipple flutes, the blowing end is stoppered while cutting or leaving a narrow air channel that directs the player's air toward an –often beveled- edge of a hole just below the stopper (Figure 1-6). It is easy to see in today's recorders, penny whistles, etc. The flute is now as easy to play as breathing. Its sound power is typically enhanced as well. But who would have thought of a fipple? Here too, blowing and fingering can create variable pitches including glissandos.

7) *Organ pipes.* A different way to use fipple flutes is to "bundle" pipes of different lengths and diameters into a pipe organ (Figure 1-7). The oldest records (2kyBP) describe an air supply driven by water pressure; it was called a "hydraulis" presumably invented by Ctesibius of Alexandria[2] (~200 BC) and admired by the insane but musical Roman emperor Nero (37-68AD). Unlike fingered flutes, the pitch of a pipe organ is fixed and its scale tuned to the local culture.

8) *The Ocarina*, reputedly known for as much as 12,000 years and originating (independently?) in different cultures, uses a fipple mouthpiece, but the flute body is not a tube supporting standing waves but a closed, often ceramic, vessel (Figure 1-8). It functions as a "Helmholtz resonator" where pitch is determined by the number of open finger holes, not their position along a tube; it can play scales but does not produce reliable harmonics. Because it is played with fingers it can produce glissandos as well as scales.

Who Invented the Critical Steps in the Evolution of Flutes?

The sequence of major inventions from one-pitch whistles to pipe organs can be imagined as: V-notch, finger holes, bundling, and fipple (Fig. 1). Both finger holes and bundling allow the playing of several pitches and thus melodies, while V-notch and fipple designs facilitate both power and ease of sound production. We may reasonably assume that bundled flutes and flutes with finger holes are designed to play melodies, i.e. sequences of different pitches. This may signify an evolutionary step in music, or it may simply be an instrumental version of already established vocal music. Still, the earliest hard evidence for melodic music comes from bone and ivory flutes with finger holes. Since flute stoppers used in fipples are also likely to perish over time, it will be difficult-but not impossible- to recognize this design in the Paleolithic record.

None of this of course means that there was no music prior to bone flutes. Humans may have sung and danced for 200,000 years all across Africa long before invading Southern Europe and they may have made wooden flutes and a variety of drums and lyres made of wood and leather. Making complex instruments implies that music was important to the culture that devoted both time and imagination to develop the technology. It is not simple to "invent" a fipple and it makes no sense to carve an ivory flute from a solid

[2] *http://www.mlahanas.de/Greeks/Ctesibius1.htm*

mammoth tusk when ready-made hollow bird bones are everywhere. Yet, somehow it was done!

Before we review what is known about the recovered flutes that provide evidence about their playing potential, we need to establish what is a flute. How do we know that the object found buried under many layers of civilization and geological processes represents a flute? The designation “flute” is based primarily on finger holes, and most clearly on a series of at least 2 or 3 similar holes in a row. In addition, to function as flutes, both the tube length/diameter and the human-finger holes have constraints of size and spacing. By themselves, hollow tubes with or without V-notches are insufficiently constrained to know they were used as flutes. Tubes with one hole in the shaft can generate sound but also doubts: Was this hole made by humans and if so for what purpose? Fragments with human decorations and broken holes that are similar to decorations or parts of accepted flutes can still provide evidence for flute making (Conard et al., 2009). Of course, all reconstructions are physical models of the original according to the reconstructor’s concept of what it “must have been.” In addition, the dating of buried artifacts is an archaeological and physical art form in constant development leading to sometimes widely variable results (Higham et al., 2012). Therefore the dates presented here are closest available estimates with “oldest flute” dated 40-50kyBP (Table 1).

Table 1. Summary of the most complete flutes considered here.

Site	kyBP	found	mouthpiece	species	material
DivjeBabe	50	1995	V or fipple?	cavebear	femur
Geissen 1	35	1990	?	swan	radius
Geissen 3	43	1974-79	?	mammoth	tusk
HohleFels 1	35-40	2008	V-notch?	vulture	radius
Les Roches	30?	1878	?	mammal	ulna?
Isturitz	25?	1920-90	?	vulture	ulna
Jiahu	8-9	1980s	end	crane	ulna
Veyreau	4	1983	fipple	vulture	ulna
La Roque	1-30?	1920	fipple	mammal	ulna?

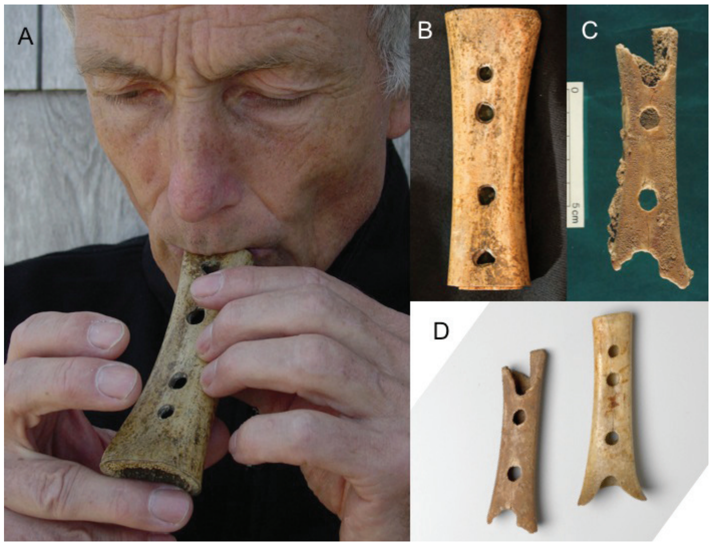

Figure 2. *The Divje Babe “flute”. A. The author playing his replica/model of the Divje Babe flute made from a partially fossilized cave bear femur with a fipple mouthpiece, shown also in B. C. The original “bone with holes”. D. Replica (left) and quena model (right), both made by Turk’s team in Slovenia. [A, B courtesy Atema. C, D courtesy Ivan Turk. B. Photo: Jeremiah Seymour.]*

Paleolithic and More Recent Flutes

The Divje Babe"fluete", Slovenia (~50kyBP), Figure 2.
In 1995, Ivan Turk and his team discovered the oldest known “flute” in a Slovenian cavebear cave called Divje Babe (“Wild Woman”). What makes this discovery particularly exciting as well as controversial is that it came from a Neanderthal site. Turk and his team published a careful description of the “bone with holes” and its archeological and zoological context (Turk et al., 1997). It was dated with electron spin resonance to 50-60kyBP and to 46kyBP by the radiocarbon method. In life, the bone was the shaft of a femur of a young cave bear. The remaining bone is about 12 cm long by 3 cm wide with two complete round holes and at least one broken round hole all in a row in line with a U-shaped notch at one end. At the other end two wedge-shaped chips are missing; one includes part of the third hole and another hole could have been part of the other chip (Figure 2). It looks like a flute, but others consider it a bone with a series of holes chewed by a carnivore. Finding similar “flutes” in the same location would greatly enhance the human hypothesis. For the purpose of this essay it is important to discuss the main arguments of the controversy; simply stated: Did Neanderthals make flutes and what kind of flute was it?

If we interpret this bone-with-holes as a human artifact, it would represent a flute with three finger holes that can be played as a V-notch quena or stoppered as a fipple flute: both reconstruction models work. This would place the instrument at an advanced technological level. It would also credit Neanderthals with this technical capability and interest, since there is no evidence of modern humans at the Divje Babe site, while Neanderthal artifacts were found there (Turk et al., 1997). This contradicts substantial evidence and strongly held views that Neanderthals did not develop complex tools and ornaments, and only started making even simple ornaments after the arrival of modern humans in Europe during a period of physical and cultural overlap known as the Chatelperronian (~40kyBP). In sum, while Divje Babe *flute* evidence is strong, its *Neanderthal* construction evidence is weak.

However, crediting an animal with this find may be more problematic than accepting human construction. Zoologists argue that scavengers looking for marrow crush bones with their molars or carnassials, which are located back in the jaw and are designed for this crushing job; in contrast, their dagger-shaped canines are designed for grasping prey. More importantly, the three holes are nicely lined up and fit human fingers (Figure 2A); also, there are no counter tooth marks on the opposite side of this bone suggesting a bite. To experimentally test the animal bite hypothesis, Turk et al. (2001) conducted an extensive series of biting tests using, in his words, *"mostly fresh bones of brown bear cubs and models of cave bear, wolf and hyena dentition (upper and lower jaw). We tested carnassials and canines of wolf and hyena and canines of cave bear. Sometimes, not always we succeeded in making one hole without cracking and splitting the bone. With multiple bites bones were split into two parts."* (Ivan Turk, pers. com., July 2014). A bone with one hole is thus difficult to recognize as a human artifact; two holes greatly increase the odds of human effort and three holes become highly unlikely to be made by a bone-crunching animal. The holes appear thus drilled not crushed. Still, Turk maintains the small possibility that his discovery was not man-made. When in 1997 I carefully examined this "bone-with-holes" I concluded that the likelihood of a human artifact is greater than the likelihood of animal damage. Of course, in science "never say never," but this holds for both hypotheses.

Based on my measurements and photographs, I tested the human hypothesis and reconstructed this "flute" (Figure 2) from a partially fossilized cave bear femur donated by Gernot Grabaeder in Vienna (Atema, 2004). In the reconstruction I assumed three finger holes and a mouthpiece at one end of the bone. I chose to make a fipple model, while Turk's team made quena models (Figure 2D). Both play well. The fipple reconstruction makes beautiful sounds (visit http://acousticstoday.org/?p=2370 to hear flute of Divje Babe). The Viennese cave bear bone was partially fossilized (presumably silicates replaced some of the carbon) resulting in a soft, hauntingly sweet and clear bell-like sound in the range of our current notation of D5-A5. In contrast, reconstruction from a fresh blackbear bone resulted in a still soft but dull, rough sound in a similar range. Being finger flutes, their pitch can slide along the entire range. The "bone with holes" can thus be used as a flute, but this does not prove it was.

Figure 3. *Swabian Alb flutes: A, B. Geissenkloesterle 3 re-assembled from recovered fragments; A. side view with carvings suggesting twine binding of the two ivory half-tubes, B. top view with two complete "finger" holes and two broken holes at each end. The spike suggests a fifth hole at the very end. C. Frances Gill playing an ivory model freely fashioned as a transverse flute (https://www.youtube.com/watch?v=PJjpHWo09tc). While the reassembled original (A, B) provides no evidence for cross blowing, this reconstruction shows the twine binding of the two ivory half pipes. D. Hohle Fels 1 reassembled from fragments showing four complete and one broken "finger" hole at one end and two "V-notches" at the other end. [A, B from Conard et al., 2009, C. courtesy Frances Gill, photo P. Geiger. D. Courtesy Nicholas Conard.]*

Flutes of Swabian Jura (35-43kyBP), Figure 3.

In contrast to the isolated discovery at Divje Babe, several flutes and other cultural artifacts (carved figurines and ornaments) have been excavated in the Upper Danube watershed of the Swabian Jura, in SW-Germany (Conard et al., 2009): the Ach river valley with the Geissenkloesterle and Hohle Fels caves and the nearby Lone valley with the Vogelherd cave. The finds include fragments of Aurignacian (the early modern human period) flutes (35-43kyBP) made of swan and vulture bones or carved from mammoth tusk ivory. Of these potential flutes, three could be reconstructed from pieces to provide sufficient evidence for the "flute" designation, while smaller fragments provide evidence of additional flutes. Extensive archaeological work at these sites provides cultural context and evidence that modern humans may have first entered Western Europe via the Danube river corridor (Conard et al., 2009; Higham et al., 2012). The discovery of both flutes and figurines provides strong evidence of Aurignacian culture and has led to imaginative but unverifiable speculations of Stone Age life. One hard fact is that people spent time and effort creating musical instruments of considerable complexity.

The well-researched and publicized **"Hohle Fels 1"** flute (Conard et al., 2009) was reassembled from 12 pieces; it is made from a griffon vulture (Gyps fulvus) wing bone (radius) and has five finger holes in a row (four plus a partial hole where the flute broke) and two apparent V-notches at one end (Figure 3D). The presence of two notches is so far unique and their function is unclear and perhaps not intentional. While seemingly far-fetched, it is possible that a now lost fipple was part of the original with one of the V-notches serving as the beveled edge of the sound hole. Unfortunately, I have not seen the Swabian flutes in person.

The **"Geissenkloesterle 1"** flute appears similar but is made of a swan radius. Friedrich Seeberger reconstructed this flute with a small single V-notch; copies are for sale at the local museum in Blaubeuren near Ulm and Steve Pollitt played one for me quena-style. He blew soft and sweet sounds using finger combinations to play improvisations tuned to our contemporary Western (diatonic) scale.

Ivory flutes such as **"Geissenkloesterle 3",** recently dated 43kyBP (Higham et al., 2012), present another level of complexity. Tusks are not natural flutes. Construction must therefore start with cutting and hollowing out an ivory rod split lengthwise. The bone halves then need to be bound (and glued?) together into a tube. To be playable this tube had to be completely airtight-sealed. This flute and some of the other ivory fragments show a series of -in one case 7- closely spaced grooves suggesting the location of thin ropes binding the two halves (Figure 3A, B). Either after, or more likely prior to, binding, the (4-5) finger holes need to be carved as well as the possible mouthpiece/blow hole. The half-pipe construction is astounding. Since ivory was used for figurine carving at the same sites, perhaps the material itself, coming from a formidable beast, had status/magic value. In addition, ivory is a different material from bird or mammal bone and this would affect sound quality (timbre), possibly making the sound "sweeter." Unfortunately, there is no evidence of a mouthpiece and playing mode cannot be established. The free reconstruction played by Frances Gill (Figure 3C) (https://www.youtube.com/watch?v=PJjpHWo09tc) shows a full-length ivory flute bound by twine, but there is no evidence that the original was a transverse flute.

The Isturitz flute(s) (~25kyBP)

In 1990 a 4-hole bird-bone flute (vulture ulna) was reconstructed from fragments that were originally recovered in the early 20th century from the cave of Isturitz in the Pyrenees area in SW France. This recovery history makes accurate dating impossible; a best guess is Upper Paleolithic "Gravettian" or ~25kyBP (Buisson, 1990). The reconstructed flute and other flute pieces from this site show interesting "decorations" in the form of wavy lines and series of parallel scratches. No mouthpiece can be determined, so that any playable reconstruction would remain imaginary.

Figure 4. *A. "Les Roche", B. "La Roque" reconstructed from a deer ulna, with four finger holes and a fipple in front and two thumbholes (not visible) in the back. The main addition is keeping the missing piece above the mouthpiece that is broken in the original C. There is evidence for a fifth hole at the bottom. Both originals have a museum label wrapped around. [A, C: Courtesy British Museum. B. courtesy Atema, photo Jeremiah Seymour.]*

The Vezere/Dordogne flutes: "Les Roches" and "La Roque" (1-30kyBP), Figure 4.

The British Museum has two mammalian bone flutes from the Dordogne area in France. The age of both pieces is uncertain. One flute (Figure 4A) has two holes and was excavated in 1878 in the valley known as Les Roches (or Castel Merle, near Sarlat). It looks similar to the Isturitz flutes and may be as old. The ends appear broken and worn and a playing method cannot be reliably reconstructed. The other flute, **La Roque**, (Figure 4C) has four (or five) holes on the front and two on the back. It was found at Pas du Miroir, now a popular tourist attraction known as Le Roc St Christophe.

In 1983, I studied the "**La Roque"** flute at the Museum and was then told it could be 32kyBP on the assumption that it had come from a remnant of Perigordian deposit that had survived intense human activity around the Medieval troglodyte settlement. However, the piece was found during 19th century road construction and in the absence of any record of its archaeological context this date -unfortunately- must be regarded as uncertain. The flute is made from a mammalian bone, 12.5 cm long and 2 cm diameter. From my sketches, photos and measurements I later reconstructed a playable copy from a deer ulna adding only one small piece of bone where it had broken off (Figure 4B) (Atema, 2004). The remarkable aspect of this flute is that it was in all likelihood a fipple flute: the broken hole at the top shows two clear break surfaces just where one would expect them at the weak points resulting from fipple construction (Figure 4B, C). This leaves four intact finger holes in front, evidence of a fifth hole at the bottom where the flute may have broken, and two thumb holes in back. It fits human hands perfectly and can play a range from B4-G#5, including an overblown second octave. If played in straight steps, i.e. without bending and sliding, it most resembles a diatonic scale (visit http://acousticstoday.org/?p=2370 to hear flute of La Roque). If reconstructed with an additional fifth hole the flute would have been ~14.5 cm long and its lowest note would have been around our current A4 (concert A 440 Hz). However, we must consider that this flute is perhaps only 1kyBP old. Given its importance as a fipple flute, accurate dating would be worthwhile as a document of evolving music technology.

Figure 5. *The Jiahu flute collection (from one grave), some of which are directly playable as end-blown quenas. From Jiang et al., (1999).*

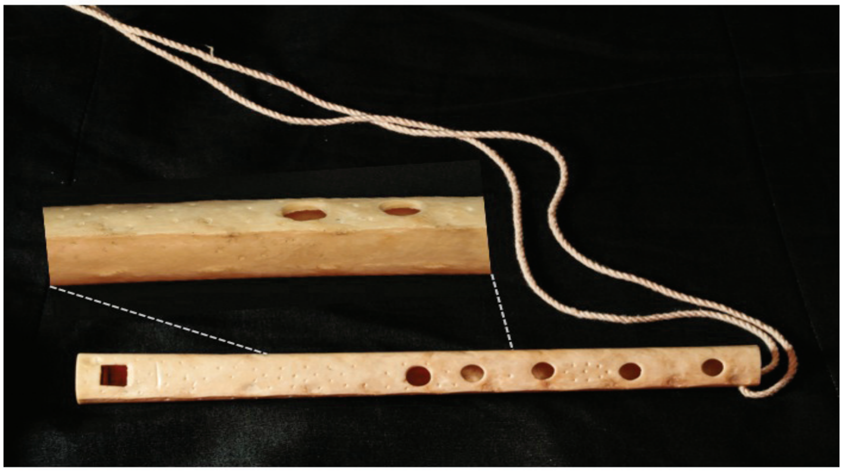

Figure 6. *The flute of Veyreau. Copy of the completely intact original, with square blowhole of the fipple and 5 finger holes. Note decorative dot patterns made as superficial pits (inset shows oblique side view). Carrying cord added to show probable function of small bottom hole. Cork stopper (added to create fipple) visible inside square blowhole. [courtesy Atema, photo Jeremiah Seymour.]*

The Jiahu flutes of China (8-9kyBP)

In the 1980's a large number of old flutes, 18-25 cm long, made from wing bones (ulnas) of red-crowned crane, were discovered in Jiahu (Hunan province, China) and -remarkably- some are playable (Jiang et al., 1999). They were cut and polished and had 5-8 finger holes in a row (Figure 5). The oldest two (9-8.6 kyBP, carbon-dated) were discovered in the grave of an adult man and have five holes; one can produce six, the other seven, pitches in an octave range starting at ~A440. The Chinese flutes are reported to play a pentatonic scale and from images appear to be end-blown without a stopper. There is no clear evidence of a V-notch for sound production. These flutes are remarkable in the number recovered at a single site and especially in the fact that some can still be played. Since they have finger holes and are approximately of the same length, their group-discovery is not evidence for Pan-pipes.

Only bone and ivory flutes go back into pre-history, specifically to a period between the Middle and Upper Paleolithic, when in Europe the invasion of modern human culture (previously referred to as Cro-Magnon) replaced Neanderthal culture after a brief period of overlap.

The flute of Veyreau (4kyBP), Figure 6.

The flute from Veyreau (Fages, Mourer-Chauvire, 1983) is 17.5 cm long with in front 5 round finger holes in line with a large square hole near one end. This fully intact flute is made of a wing bone (ulna) of a Griffon vulture; the front is beautifully decorated with dot patterns and one groove near the square hole (Figure 6). A tiny hole on the side at the very bottom suggests the flute was worn with a string around the player's neck. It was found in a burial cave in the South of France together with other artifacts and human bones from which the flute was carbon-dated at 4kyBP. The original is in the Cevennes Museum of Florac, France, where I studied it with Mr. Fages. It required only a (cork) stopper with a small air channel to start playing powerful sounds in a range of one and one half octave from A4 to D5 (visit http://acousticstoday.org/?p=2370 to hear flute of Veyreau). The large square hole at one end is the sound-generating hole of the fipple; there is no V-notch and when cross-blown it barely makes sound. It is a fipple flute. If we ignore "La Roque" due to dating uncertainty, it represents the earliest known "recorder." I made a copy from a contemporary vulture ulna including the subtle dot pattern decorations (Figure 6); it is essentially indistinguishable from the original. Of course, this flute is relatively recent by date but perhaps not by culture.

Interpretation of Flute Evolution

None of the flutes discussed here were primitive and all have *melodic* musical potential. But how our ancestors used this potential cannot be determined. There are many ways to make sound with a hollow pipe. Despite our fervent hopes to extract a musical scale from an instrument with holes that suggest discrete pitch steps, we cannot determine with certainty what scales local cultures favored. The one thing we can say with certainty about the finger holes is that they need to fit the human hand and fingers. All the recovered flutes show that they do, often perfectly. We can therefore suggest that finger hole size and spacing could have been more constrained by fingers than by pitch. The resulting pitches may have influenced cultural preference for certain intervals and harmonies. That preference in turn could later "fine-tune" the location and size of finger holes to facilitate playing "in tune." Interestingly, many people and particularly trained musicians, find it exceedingly difficult to NOT play in tune, "our" tune. This scale has become culturally engrained and affects us from birth or earlier; we do not know anything else. Replicas of the archeologically recovered flutes can easily accommodate the different scales and glissandos used in various cultures. Therefore we cannot credibly determine which scale if any was used in the Stone Age. Of the nine flutes in Table 1 only Jiahu can -apparently- be played as found, Veyreau only needed a stopper to complete the fipple, and La Roque required a small bone addition (and thus a modern copy) to complete the fipple. Hohle Fels 1 and Divje Babe suggest V-notch playing, as shown in modern reconstructions, but either could have been played also with a fipple. So far, the other flutes lack convincing signs of a playing mode. Despite the many uncertainties, the flute replicas and models can tell us something about three aspects of music: their range of pitches, their melodic potential and their dynamic range.

From the great spread of dates, materials and rare mouthpieces we cannot determine a chronology of flute making techniques as schematized in Figure 1. The only thing we can say with any certainty is that modern humans entered Europe with flute-in-hand. This was not a simple flute, but one that could play complex melodies over a span of 1-1.5 octaves. Such a flute would likely have evolved over long time periods from simpler instruments, which are difficult to recognize as flutes in the archaeological record. It is also clear is that we cannot extract their music with any certainty. Given the historic longevity of certain songs and the globally distributed use of the pentatonic scale, we can imagine that this scale reflects early human origin. But no facts back this up.

In addition to the flutes discussed here, people probably played flutes and other musical instruments made of perishable materials. Indeed, people make music with anything that produces sound. The carrot clarinet is an amusing and impressive example (https://www.youtube.com/watch?v=zrme04RIsE8#t=102), while personally, I play the lobster claw. This should tell us something about our interpretations of found objects that resemble flutes.

The Divje Babe flute presents a conflict that can be resolved only with further archeological discoveries. As it stands, the evidence for human construction outweighs the carnivore-gnawing hypothesis. The real question is if Neanderthal people made it or that it somehow derived from modern humans…stolen or copied. It is not uncommon in archeology to start with a weak signal (a single "flute") that can either fade away or gain credibility with new discoveries. Therefore we must be careful to not dismiss prematurely the Divje Babe flute as a joke played on us by scavenging Paleolithic carnivores. There is no evidence that Neanderthals did or did not make this flute. When "we" arrived in Europe 45,000 years ago we may have inspired Neanderthals to make flutes or they may have started to make bone flutes instead of wooden flutes. Perhaps we saw Neanderthals play bone flutes and copied them. In the spirit of "Jurassic Park," we can imagine approaching a Neanderthal camp while playing a flute. To our surprise we hear another flute in the distance playing quite different tunes. Like mocking birds, we imitate their sounds and they modify their tune. When we enter the camp we are shocked to recognize the great differences in appearance and we do not understand each other's speech, but music paves the way toward acceptance and peaceful coexistence. When we wake up and the movie is over, we see that the Neanderthals are gone.

Acknowledgments

I thank my friends John Pfeiffer, author of "The Creative Explosion", who inspired me to start playing the reconstruction of paleolithic flutes, and Arthur Popper who invited me to write this updated flute story. Nicholas Conard, Susanne Muenzel and Frances Gill of the University of Tuebingen and Jill Cook, curator of Paleolithic art at the British Museum educated me on a number of important new details. I enjoyed my earlier visit and discussions with flute discoverers Ivan Turk (Divje Babe) and M. Fages (Veyreau). Gernot Grabaeder of the University of Vienna supplied cave bear femurs for my reconstruction of the Divje Babe flute and Dominique Albouy sent me a present day vulture ulna for the Veyreau flute replica. Steve Pollitt played beautiful music on the Seeberger reconstruction of the Hohle Fels 1 flute. Charles Derby and Arthur Popper provided helpful comments on the manuscript. Atema sound recordings (https://soundcloud.com/ancient-bone-flutes) by Julian Lampert using DPA 2006-A microphones; mixed & Mastered by Seth Mintz—CBS/ABC.

Biosketch

Jelle Atema, born in the Netherlands, studied biology in Utrecht and music with French flute virtuoso Jean-Pierre Rampal. He has performed in Europe, China and the United States and commissioned compositions for flute and strings. He teaches Sensory Biology at Boston University and flute privately. He and his many students analyze the underwater sensory worlds of lobsters, sharks and reef fishes. For 14 years, he directed the Boston University Marine Program and currently has labs in Boston and at the Woods Hole Oceanographic Institution. He has published over 175 scholarly articles. Flutes and science combine in his Stone Age flute reconstructions.

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Review of Air-Coupled Transduction for Nondestructive Testing and Evaluation

The future of nondestructive testing lies in the ability to efficiently generate waves in structures without contact.

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Introduction

Nondestructive testing (NDT) of structures and mechanical parts is increasingly receiving attention as the need to monitor the health of aging infrastructure and quality controls on the manufacturing of mechanical parts is becoming more apparent. NDT is defined as using various tools, whether they be acoustic, electromagnetic, or thermally based, to inspect the structural integrity of these objects without damaging the object as a result of testing it. In the case of acoustic NDT techniques, a source transducer emits sound/vibrational waves into the structure under test and various techniques are then used to detect signatures of damage (such as micro or macro cracking, etc.).

In 1996, Delta Flight 1288 experienced engine failure when part of a fan hub entered the engine; this accident led to the death of two passengers. It was later determined that undetected micro-fractures missed during routine maintenance were the cause of the failure (Federal Aviation Administration, 2014). In 2002, a Boeing 747 operated by China Airlines catastrophically failed in flight, causing the death of 206 passengers and 19 crew members. The probable cause was the growth of incipient fractures, created during a previous noncritical accident that went undetected (Federal Aviation Administration, 2014). NDT techniques detected cracking and corrosion on the I-35W Mississippi River bridge in Minnesota prior to its collapse in 2007, yet measures were not taken to avoid the collapse that led to the deaths of 13 people (Wikipedia, 2014). In 2012, 16 workers at the Idaho National Laboratory were exposed to radioactive powder as a result of damaged stainless-steel cladding that housed the radioactive material (Associated Press, 2011). Each of these accidents, and many others, could likely have been avoided with the use of proper NDT techniques, along with appropriate intervention measures.

The vibration of solid structures for NDT, without contacting the structure, offers many advantages. As bonding between the source transducer and the structure is eliminated, along with the use of noncontact sensors (such as laser Doppler vibrometers and/or microphones), rapid imaging of large areas then becomes possible. Besides, it is not always desirable or feasible to use contact transducers on certain samples. The development of efficient air-coupled transducers, however, remains a challenge because of the large impedance contrast, by several orders of magnitude, between air and solids. Impedance is the product of the speed of sound and the density of the material or medium.

When there is a significant impedance change between two different media, in this case nearly 5 orders of magnitude difference between the face of the source transducer and the air, it is difficult to deliver energy into the air from the transducer's motion. Practically, this means that only a fraction of the energy generated by the source will be transmitted into the air and then only a fraction will be transmitted to the structure. Essentially, nothing can be done about the impedance mismatch between the air and the structure under test. Fortunately, a number of approaches have been proposed to improve the transmission of energy from the source into the air. Noteworthy reviews on this topic include the paper of Green (2004) and the recent one of Chimenti (2014). Both focus on non-contact transduction devices while the latter also discusses the implementation of several NDT techniques. The present paper provides an overview of recent advances on the development of air-coupled transducers for NDT applications, with some new techniques that are not reported in either of the aforementioned papers, and a brief review of many traditional types of air-coupled transduction.

"Developments in the next generation of air coupled sources, that utilize time-reversal focusing or a focused electric spark source, will provide more reliable excitation with higher amplitudes and allow the use of advanced NDT techniques."

Conventional Non-Contact Sources

Most commonly, generation of ultrasonic waves inside a material through air is achieved with piezoelectric transducers that are manufactured from a bulk piece of ceramic. A piezoelectric material is characterized by its ability to convert electric energy into mechanical energy, and vice versa. The large impedance contrast between the piezoelectric material and air can be mitigated with resonant matching layers that are glued onto the surface of the transducer and that basically act as an impedance transition between the piezoelectric material and the air. Initial work on the design of such layers suggested a single layer with two characteristics: (1) a thickness of one quarter of a wavelength at the resonance frequency of the transducer so that a standing wave can be established across the layer; and (2) an impedance close to the geometrical mean of the impedances of the piezoelectric material and the medium the source is radiating into (Lynnworth, 1965). For air-coupled applications, the impedance of the matching layer should range between 0.001 and 0.1 MRayl (Haller et al., 1994). Many porous materials with impedances approaching this range, including cork and balsa wood, cannot be used as matching layers because they exhibit high attenuation, which deteriorates the performance of the transducer (Schiller et al., 1994; Stor-Pellinen et al., 1989). Practical materials for this application include silica aerogel (Krauss et al., 1994), silicone rubber loaded with micro-spheres (Yano et al., 1987), and porous membranes (Kelly et al., 2001). Most of these materials have impedances close to 0.1 MRayl and relatively low attenuation. Note that silica aerogel is limited to applications below 100 kHz because it does not lend itself to machining at the thickness that would be required for higher frequency applications. A detailed review of the materials used in the design of matching layers, including their attenuation, impedance, and performance, is given by Gómez Álvarez-Arenas (2004). The matching layer can also be created using micro-fabrication techniques (Haller et al., 1994) for operating frequencies approaching 1 MHz. The main disadvantage of using a single matching layer is the reduced bandwidth and the subsequent ringing of the transducer. To address this limitation, the use of multiple layers has been proposed, where the intermediate layers increase the bandwidth with a reduced effect on the sensitivity (Goll et al., 1975; Desilets et al., 1978).

Alternatives to matching layers have been proposed to enhance the ultrasonic radiation of bulk piezoelectric transducers. Multiple ultrasonic horns obtained by chemical etching on a plate have been tested in the range of 20 to 100 kHz (Fletcher and Thwaites, 1992). Another strategy has been to reduce the impedance of the active element through the use of composites made of ceramic pillars embedded in a uniform filler material (such as epoxy) matrix (Reilly and Hayward, 1991; Smith and Auld, 1991). The mechanical properties of the composite can be adjusted with the volume fraction of ceramic. Impedance matching has also been achieved by constraining a thin layer of air between the surface of the piezoelectric element and a thin polymer membrane or a perforated plate (Toda, 2002). Last, some recent numerical work has suggested the possibility of using wedges of power-law profiles to provide a gradual impedance matching (Remillieux et al., 2014). Ideally, for a perfect wedge tip with no thickness, these profiles ensure that the elastic waves generated within the thickest portion of the wedge (or adjacent plate) by a bulk piezoelectric transducer propagate towards the wedge tip and never reflect back from it. In practice, the wedge tip has a finite thickness and reflects some of the energy back into the wedge. Despite this imperfection, power-law profiles provide a smooth impedance matching transition for the large-amplitude flexural waves observed in the thinnest region of the wedge (near the wedge tip), thus improving significantly the ultrasonic radiation in air. The experimental validation of this numerical work is underway.

Capacitive ultrasonic transducers are an alternative to bulk piezoelectric transducers. They were introduced in the 1950s (Kuhl et al., 1954). Their principle of operation is radically different from that of piezoelectric transducers. They typically consist of two components: (1) a fixed electrode - a conducting back plate with a microscopically rough surface of random profile; (2) an electrode allowed to deform - a thin dielectric polymer membrane coated on one side with a conducting layer and stretched over the back plate. A bias voltage is applied so that the oppositely charged electrodes attract. As a result, the membrane is stretched further and remains in contact with the back plate. Because of the varying surface profile of the back plate, the membrane is resting on point-like supports and small air gaps are formed beneath the membrane. Under a voltage signal, the membrane deforms and displaces the surrounding fluid, which generates ultrasonic waves. The transducer can also be used as a receiver under the reciprocal process. Capacitive ultrasonic transducers offer two advantages over piezoelectric transducers: a better impedance matching with air and a wider bandwidth (Schindel, 1996). Their performance depends mainly on the dimensions of the air gaps, the membrane properties (such as density, dimensions), and the bias voltage (Carr and Wykes, 1993). At high frequencies, such as above 1 MHz, it is not possible to control the size of the air gaps beneath the membrane through traditional manufacturing techniques. The subsequent variation of the membrane tension across its surface leads to reduced performance of the transducer.

The advent of micro-fabrication techniques led to the rapid development, since the late 1980s, of capacitive micromachined ultrasonic transducers (CMUTs). The interested reader is referred to the review of Khuri-Yakub and Oralkan (2011) on this topic. Microfabrication techniques provide control over the parameters for which there were uncertainties in traditional capacitive ultrasonic transducers: in-plane tension and air-gap size. Additionally, the reduction of the membrane and air-gap sizes allows reaching higher frequencies, in the tens of MHz, which was not possible previously. A photograph of a CMUT array is depicted in Figure 1a. The operating principle of CMUTs is identical to that of traditional capacitive ultrasonic transducers. However, there are three practical issues with CMUTs: (1) the bias voltage must be close to the collapse voltage to achieve the theoretical electromechanical coupling, which is not possible given the current tolerances in micro-fabrication techniques; (2) the design must be different for optimal transmitting and receiving operations: a small air gap is required to increase sensitivity when the CMUT is used as a receiver whereas the relatively large displacement of the membrane in a transmitter requires a much larger air gap; and (3) they have a small capacitance (large electrical impedance), thus making their operation sensitive to parasitic capacitances. To minimize the effect of parasitic capacitance and to limit the potential of interference on the cabling, the transmitter/receiver electronics should be kept close to the CMUT elements (ideally integrated on a single chip).

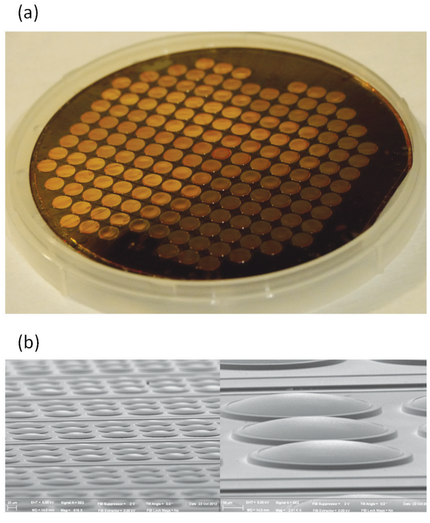


Figure 1: *Photographs of MUT arrays. (a) CMUT provided by Prof. Butrus (Pierre) Khuri-Yakub from Stanford University. (b) PMUT provided by Dr. Arman Hajati from FUJIFILM Dimatix.*

Piezoelectric micromachined ultrasonic transducers (PMUTs) are an alternative to CMUTs that still benefit from micro-fabrication techniques for miniaturization and precision control but do not need a conducting back plate to be operated. A photograph of a PMUT array is shown in Figure 1b. Essentially, they consist of an electroded thin piezoelectric film deposited on a (possibly multilayered) membrane resonator, which is typically on the order of microns in the thickness and tens of microns in the in-plane direction (Akesheh et al., 2004). An electric field is applied across the thickness of the piezoelectric film, which in turn induces a deformation of the membrane according to its bending modes. The piezoelectric film is used as an actuating element only while the ultrasonic radiation characteristics (such as operating frequency) are dictated by the membrane properties. Other advantages over CMUTs include: (1) a higher capacitance, which makes the transducer less vulnerable to parasitic capacitances and the use of coaxial cables possible; (2) lower power requirements due to the elimination of the bias voltage; and (3) lower sensitivity to fabrication accuracy. It is worth mentioning that PMUTs do not offer a perfect alternative to CMUTs as the deposition of a high quality thin piezoelectric film, free of defects, remains a challenge and therefore, an active topic of research. Defects in the thin film may include micro-cracks, pinholes, lattice misorientation, and non-uniform thickness.

Ultrasonic arrays of transducers have been increasingly preferred over single-element transducers because, when combined with appropriate signal processing techniques, they offer many attractive features, including some flexibility in the type of ultrasonic fields generated (such as plane waves, steered beams, and focused excitation) and better imaging capabilities. An extensive review on this topic for NDT applications, including transducer materials and array geometries, is given by Drinkwater and Wilcox (2006), with a particular focus on the phased array technology. The operation of phased arrays is based on the use of appropriate time delays between the signals applied to or received from the individual transducers. When parabolic delays are used, ultrasonic waves can be focused to a specific point in air or on the surface of a sample (Azar et al., 2000). This allows reaching relatively high amplitude levels at the focal point compared to what a single-element transducer can generate.

The performance of a phased array is not only affected by transducer material and signal processing but also by its geometry. Initially, arrays were one-dimensional, which means that their elements were aligned along a linear axis and beams could be steered only in the plane formed by the axis of the array and the normal to the surfaces of the transducers. Simplification of the electronics and availability of cheaper hardware has spurred the development of two-dimensional arrays in which the elements are usually arranged in a checkerboard format. This added dimension allows three-dimensional steering. Annular arrays are the third type of arrays commonly encountered. They consist of a set of concentric rings with varying width so as to keep the surface area of each element constant. They allow the beam to be focused to different depths but only along the normal to the array surface passing through its center. One important aspect to consider when designing the array is the spacing between the elements. If the element spacing is larger than one half of a wavelength ($\lambda/2$) at the operating frequency used for beam steering or focusing, then grating lobes will be generated. Grating lobes are essentially undesired side lobes resulting from the spatial under-sampling of periodically arranged elements. Usually, the $\lambda/2$ limitation can be overcome by keeping the gap between the elements small while increasing the width of the element. As the element shape deviates from a point-like representation, its radiation becomes more directional and the contribution of the grating lobes is reduced but so is the range of angles at which beams can be steered.

Another conventional technique for non-contact transduction is based on the thermoelastic effect. White (1963) demonstrated that the thermal expansion resulting from transient heating on the surface of a solid generates elastic waves within the solid, which is referred to as the thermoelastic effect. Pulsed lasers are commonly used for this purpose since they can create a focused excitation in space and time. The amplitude of the excitation is related to the energy density. If it becomes too large, material ablation may occur as a result of the melting and evaporation of the material in the area targeted by the laser. The effect of the heating rate was studied by Gauster (1971). The depth of the damage is on the order of a few microns. This may not be acceptable in some NDT applications. In this case, the pulsed laser should be operated within the thermoelastic regime, such as below the threshold of ablation. Typically, for NDT applications, the pulse duration approaches 10 ns, which provides a broadband perturbation with frequency content up to 100 MHz (Viertl, 1980). Pulsed lasers have been used to excite different types of waves in structures. Despite many advantages, the operation of a pulsed laser requires high power and appropriate safety measures to be taken. Therefore, it does not have the same practicality as air-coupled sources.

Time Reversal Acoustic Non-Contact Excitation

A high amplitude acoustic source has been developed at the Los Alamos National Laboratory (LANL) using the principle of reciprocal time reversal (TR) to focus energy in time and space on the surface of a sample without contact (Le Bas et al., 2013). A prototype of this source is depicted in Figure 2. The hardware essentially consists of a hollow cavity enclosed by thin metallic walls onto which some piezoelectric transducers are glued. The size(s) of the transducers will

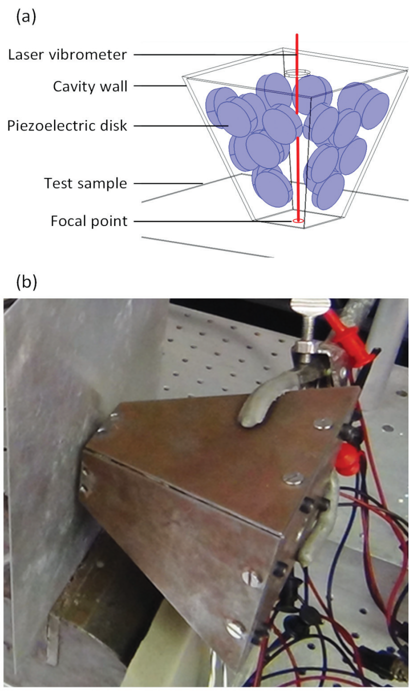


Figure 2: *The high-amplitude non-contact acoustic source based on reciprocal TR installed in front of a test sample: (a) drawing and (b) photograph of the experimental apparatus.*

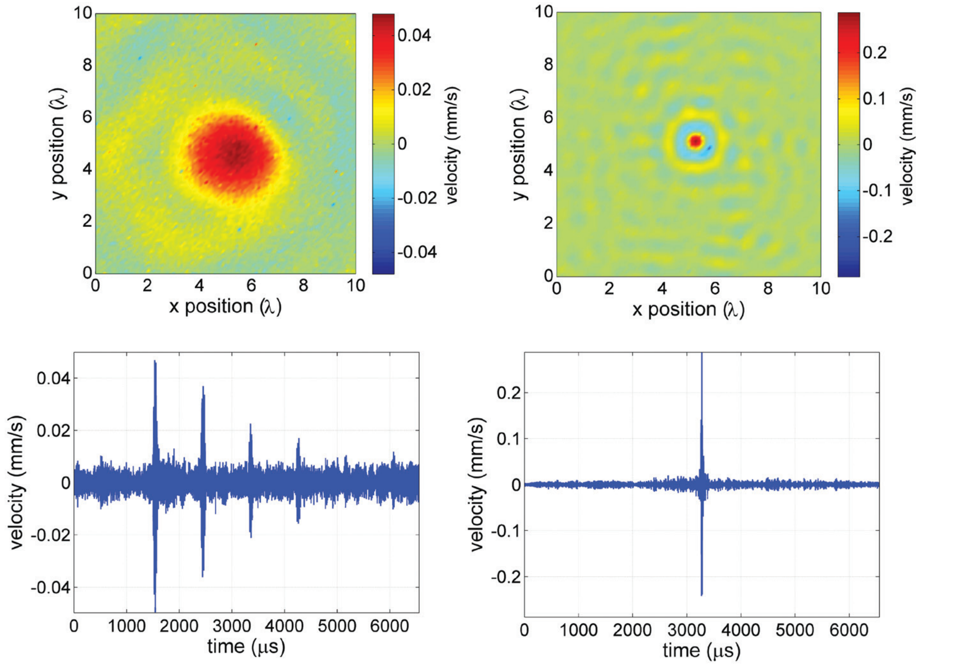


Figure 3: *Comparison of energy focusing on the surface of a thin metallic plate achieved with a Focused Ultrasound Transducer (left) and the TR non-contact source (right). Spatial extent of the focal spot in terms of wavelength (top) and time histories of the velocity at the focal point (bottom).*

determine the optimal operating frequencies of the source. The cavity creates a diffusely scattered wave field inside and contains an opening to allow a progressive emission of the scattered waves. The cavity has two holes in order to shine a laser vibrometer through it. The elastic response recorded by the laser at a point on the surface of the test sample is used to calibrate the source to focus energy at that point, as will be described below. The larger hole at the top of the pyramid is also the main sound transmission path from the source to the sample. Note that, in a TR experiment, scattering is beneficial to the ability of focusing energy in time and space because each reflection acts as a virtual source. In other words, a TR experiment can be conducted successfully with only one transducer as long as the medium is highly reverberant and weakly dissipative. This is clearly an advantage over phased arrays where scattering would deteriorate the performance of the array.

A standard TR experiment in a reverberant medium consists of two steps that can be briefly summarized as follows (Anderson et al., 2008). In the first step, or *forward* propagation, a known signal is emitted from a source at a point *A* while a receiver is recording the signal at a point *B*. The received signal is the convolution of the impulse response between points *A* and *B* with the source signal. This impulse response is rather complex due to the multiple propagation paths within the bounded medium. In the second step, or *backward* propagation, the received signal is reversed in time and remitted from point *B*. The invariance of the wave equation implies that the various broadcasts of energy from each virtual source will coalesce at point *A*, where the original source signal will be reconstructed (Fink, 1992). There are some imperfections in this reconstruction process, mainly because the directional information of the energy received in the *forward* signals is not typically used, attenuation that exists in a realistic system, and a limited (as opposed to infinite) acquisition time of the *forward*-propagation signal is used. It is possible to interchange the source and the receiver positions thanks to the principle of spatial reciprocity (Achenbach, 2003). In the *backward*-propagation step of a reciprocal TR experiment, the received signal is remitted from the source point *A* and coalesces at the receiver point *B*.

Experiments were conducted on a thin metallic plate (Figure 2) and the performance of the LANL source was compared to that of a commercially available Focused Ultrasound Transducer (FUT) that makes use of impedance matching layers and some geometry optimization. Figure 3 shows the velocity fields on the plate at an instant in time and the signals recorded at the focal point location. One advantage of the LANL source is the ability to generate only one distinct large amplitude pulse of energy whereas the FUT repeatedly produces pulses of energy due to the multiple reflections between the surface of the FUT and that of the test sample. The size of the focal spot is approximately five times smaller with the LANL source than with the FUT. Last, the LANL source also offers a significant gain of amplitude, in this case a factor eight times. Note that this gain was obtained with a prototype device that was not optimized in any way and that was built for the purpose of demonstrating that the concept was working. Optimization studies are under way. In particular, the effects of the wall thickness, layout of the transducers, and shape of the cavity are investigated. An additional gain of amplitude is expected from an optimized device.

Last, it is worth mentioning that the spot size (measured as full width at half maximum) achieved by a TR mirror in the far field cannot be smaller than half a wavelength as a consequence of the diffraction limit. Sub-wavelength components of the acoustic field cannot be recovered by TR in the far field of a homogeneous medium because they are carried by evanescent waves, which decay exponentially with the distance from the source. The diffraction limit can be overcome by using, for instance, a distribution of scatterers with specific sizes in the near field of the source, to achieve sub-wavelength focusing (Lerosey et al., 2007). Evanescent waves convert to propagating waves as they diffract off the scatterers.

Focused Electric Spark Source

Focusing can also be achieved by appropriately tuning the shape of the transducer: usually with an ellipsoidal shape. This strategy has been used for bulk piezoelectric transducers that are combined with impedance matching layers (Bhardwaj, 2001), with capacitive ultrasonic transducers (Song et al., 2006), and spark sources (Dai et al., 2013). The performance of the first type of focused transducer has been discussed in the previous section, in comparison with that of the LANL source (TR mirror). The second type of focused transducer can achieve diffraction-limited focusing, like the TR mirror. The third type is discussed in more details below, since it is a new apparatus that is neither based on bulk piezoelectric transducers nor capacitive ultrasound transducers.

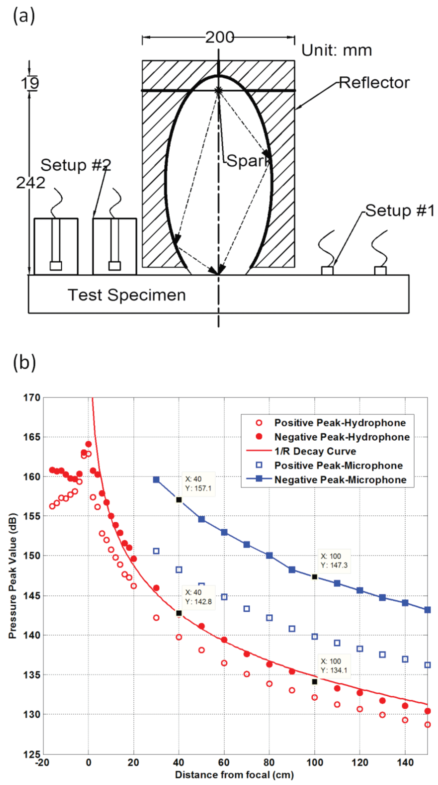


Figure 4: *(a) Schematic representation of the test setup including the spark source enclosed within the ellipsoidal reflector and (b) peak pressure amplitude versus distance along axis, measured by a hydrophone and a microphone. Hydrophone sensing was employed near the focus to enable measurement of high amplitudes without saturation (overloading).*

Recent efforts at The University of Texas (UT) at Austin have been focused on the generation of high amplitude air-borne acoustic signals for non-contact excitation of wave motion in concrete slabs to aid in the rapid inspection of the nation's infrastructure (Dai et al., 2013). The non-contact air-coupled NDT device devised by UT is schematized in Figure 4 and consists of a spark generator and an ellipsoidal focusing mirror. The spark generator consists of two electrodes separated by a small air gap which is collocated with the near focus of the ellipsoidal reflector. A high electric potential is generated across the electrodes of the spark generator by charging a large capacitor that is electrically in parallel with the electrodes. Discharge occurs when the electric field between the electrodes reaches a critical level and the ensuing spark creates a rapid and intense heating of the air resulting in a high amplitude acoustic disturbance that spreads outward with nearly omnidirectional directivity. This transient wave spherically diverges from the near focus until it encounters the ellipsoidal reflector, when it is then reflected and re-directed back to the far focus. The reflected wavefront converges at the far focus where the amplitude is proportional to the time-derivative of the spark-generated signal and some gain factor related to the geometry of the reflector (Hamilton, 1993). Because the spark-generated wave has a very short rise-time, and thus a high temporal derivative, the peak pressures at the far focus are very high and thus capable of generating elastic waves in the sample to be interrogated. In-air peak pressures as high as 180 dB re 20 μPa at the far-focus have been measured (Dai et al., 2013).

It is important to point out that the use of spark-generated signals to generate high amplitude acoustic waves is nothing new. Indeed, Wright and Blackstock (1997) used spark-generated signals to study on-axis wave field resulting from spark-generated air-borne N-waves that were focused by an ellipsoidal reflector. Further, use of a spark discharges for ultrasonic NDT has also been explored with some success (Cooper et al., 1984; Korolev et al., 1987). Those discharges result in intense, transient, and localized heating at the surface of the sample and a subsequent high frequency ultrasonic signal with amplitudes similar to those generated by pulsed lasers. This approach proved to be somewhat problematic, however, because numerous spark discharges on the surface of the interrogated sample resulted in damage due to ablation and thus alternative configurations were investigated.

Krylov and colleagues later investigated the use of air-borne acoustic waves generated by in-air sparks with some encouraging results for generating elastic wave motion in aluminum. Their studies included un-focused (Krylov, 1992) and spherically focused air-borne waves (Korolev and Krylov, 1988). Each of those had drawbacks which apparently discouraged further study. Curiously, no results were ever reported by Krylov and colleagues that employed an ellipsoidal reflector paired with spark-generated acoustic waves which enables wave focusing without requiring collocation of the source and focus points.

The ultrasonic source developed at UT has been used for impact-echo testing in concrete plates. This technique (impact-echo) consists of impulsively loading the surface of the plate, usually via contact such as a hammer blow, and recording the out-of-plane motion. The spectrum of the response contains a peak corresponding to the impact-echo frequency, which is proportional to the compressional wave speed in the material and inversely proportional to the sample thickness (Sansalone and Carino, 1986). Recent analysis has shown that these impact-echo frequencies are associated with zero-group-velocity (ZGV) Lamb modes that represent localized wave motion with non-zero phase velocity but zero group velocity and have high excitability (Gibson and Popovics, 2005; Prada et al., 2008). Because these modes have zero-group velocity, they represent wave motion that is trapped near the source point and thus is long lived and relatively easy to detect.

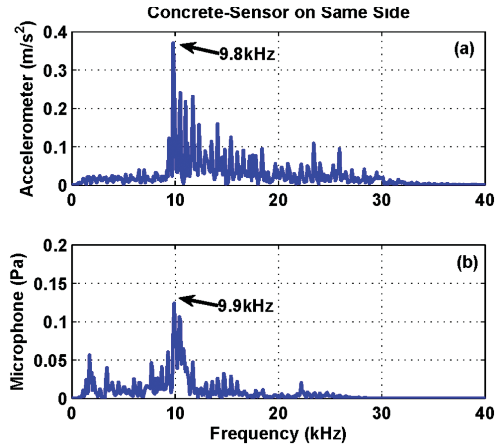
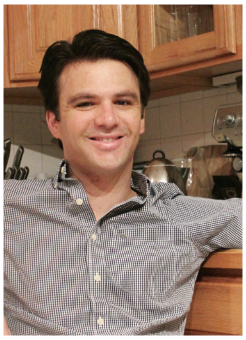


Figure 5: *Spectra showing the zero-group-velocity mode in a 25cm thick concrete plate measured using contact sensing and fully non-contact methods with spark-source excitation (Dai et al., 2013).*

Theoretical and experimental work at UT shows that the focused spark-generated air-borne signal has a sufficiently small spot size on the air-solid interface that broadband surface waves can be generated in concrete and detected using accelerometers on the surface (contact sensing) or microphones positioned close to the surface (non-contact sensing), as seen in Figure 5 for the case of a 25 cm thick concrete plate. The results clearly show that a spark-generated signal focused by an ellipsoidal reflector enables fully air-coupled interrogation of the surface of a specimen with high acoustic impedance. Other work exploiting the properties of ZGV modes was based on the use of traditional air-coupled ultrasonic transducers (Holland and Chimenti, 2004) and pulsed laser excitation (Cès et al., 2011).

Conclusion

Nondestructive testing (NDT) is increasingly relied upon for monitoring aging infrastructure and for evaluating transportation structures. Air-coupled (non-contact) transduction allows rapid testing of these structures and thus increases the practicality of NDT implementation. Developments in the next generation of air coupled sources, that utilize time-reversal focusing or a focused electric spark source, will provide more reliable excitation with higher amplitudes and allow the use of advanced NDT techniques.



Marcel Remillieux is a post-doctoral research associate at Los Alamos National Laboratory. He is developing, implementing, and using numerical techniques to solve elastodynamic problems with applications to nondestructive testing. Between 2005 and 2012, he conducted research on NASA funded projects at Virginia Tech, where he received his M.S. and Ph.D. degrees in mechanical engineering. He also holds an Engineer Diploma in mechanical engineering from the Université de Technologie de Compiègne, France. During his undergraduate education, he was selected for a year-long exchange program with the University of Pennsylvania (Ivy League). Since that time, he has been mostly living in the United States and has been enjoying most of his vacations in France. In his free time, Marcel enjoys outdoor activities, skiing being his favorite, in New Mexico with his family.

Brian Anderson is a research scientist at Los Alamos National Laboratory (LANL) in the Geophysics Group where he develops new nonlinear acoustic techniques, using time reversal, for the nondestructive evaluation of mechanical parts and structures. He is an associate editor for the *Journal of the Acoustical Society of America*. Prior to coming to LANL, Brian spent 3 years as a visiting assistant professor at Brigham Young University (BYU) in the Dept. of Physics & Astronomy conducting research and teaching courses. He worked for three years as a postdoctoral research associate at LANL. He received a Ph.D. in Acoustics from the Pennsylvania State University in 2006 while working at the Applied Research Laboratory there. He received his M.S. and B.S. degrees in Physics from BYU. Brian enjoys GPS-based geocaching in his spare time with his three sons and his wife Angela.

TJ Ulrich has been conducting research using time reversal and nonlinear elasticity at Los Alamos National Laboratory (LANL) for the past 10 years, first as a post-doc and now as a research scientist. During this time he has developed many international collaborations and enjoys traveling the world to work on various topics on acoustics, nondestructive evaluation, and materials characterization. Prior to coming to LANL, TJ attended the University of Nevada, Reno where he obtained degrees in Materials Science and Engineering (B.S.) and Physics (M.S. and Ph.D.). His current research focus is developing the next generation of acoustic tools for nondestructive evaluation of mechanical parts and structures, specifically for nuclear energy applications, as well as geophysical exploration tools and techniques for the oil and gas industry. When at all possible you can find TJ at his home away from home on the slopes of Taos Ski Valley with his family or down in town enjoying the blue corn and green chile.

Pierre-Yves Le Bas is currently a research scientist at Los Alamos National Laboratory. He obtained his Ph.D. in acoustics from the University of Le Havre, France in 2004. Pierre-Yves was one of the experimentalists in a European project called AERONEWS where he developed NDE techniques combining Time Reversal and nonlinear elasticity during a post-doc at KU Leuven, Belgium. His work includes the use of nonlinear acoustic techniques for nondestructive evaluation and borehole imaging. He is a certified LabVIEW architect for developing experimental systems. Pierre-Yves enjoys mentoring the Los Alamos High School FIRST robotics team, project Y.

Biosketches continued on next page.

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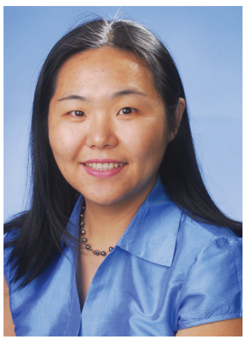

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Sonars and Strandings: Are Beaked Whales the Aquatic Acoustic Canary?

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"The basic question is simple: Are sonars or any other anthropogenic sound resulting in significant, population level impacts in the ocean? The answers are far from simple."

Figure 1. *A Cuvier's beaked whale stranded on the beach on Grand Bahama Island, March 2000. (Image courtesy of Nan Hauser, Center for Cetacean Research and Conservation).*

Introduction

On the morning of 15 March, 2000, phones began ringing in Washington, Virginia, and Massachusetts. Emails flew between the USA and the Bahamas. The event behind these communications was a mass stranding of beaked whales (Ziphiidae) in the northern Bahamas extending from Grand Bahama to the tip of Abaco (Evans and England, 2001). Over two days, 17 whales were reported on shore, of which nearly half succumbed to the stress and trauma of stranding. Four years earlier, in 1996, 12 overtly healthy Cuvier's beaked whales (Ziphius cavirostris) beached and died near ship based trials of mid and low frequency sonars in Kyparissiakos Gulf, off the Peloponnesian coast of Greece. It soon became evident that the Bahamian stranding, like the one in Greece, coincided with naval sonar exercises in nearby waters immediately prior to the beachings of these normally elusive, deep diving, deep water whales (Figure 1). Since then, there have been multiple similar events: Madeira (2000), Canary Islands (2002, 2004), Hawai'i (2004), Madagascar (2008), and again Greece (Corfu 2011, Crete 2014), some involving military vessels and sonars; others, industrial and research vessel sonars, fueling demands that scientists solve the question of the relationship between marine mammal strandings and intense sound sources (Frantzis, 1998; Freitas, 2004; Ketten et al., 2004; D'Amico et al., 2009; Fernandez et al., 2012).

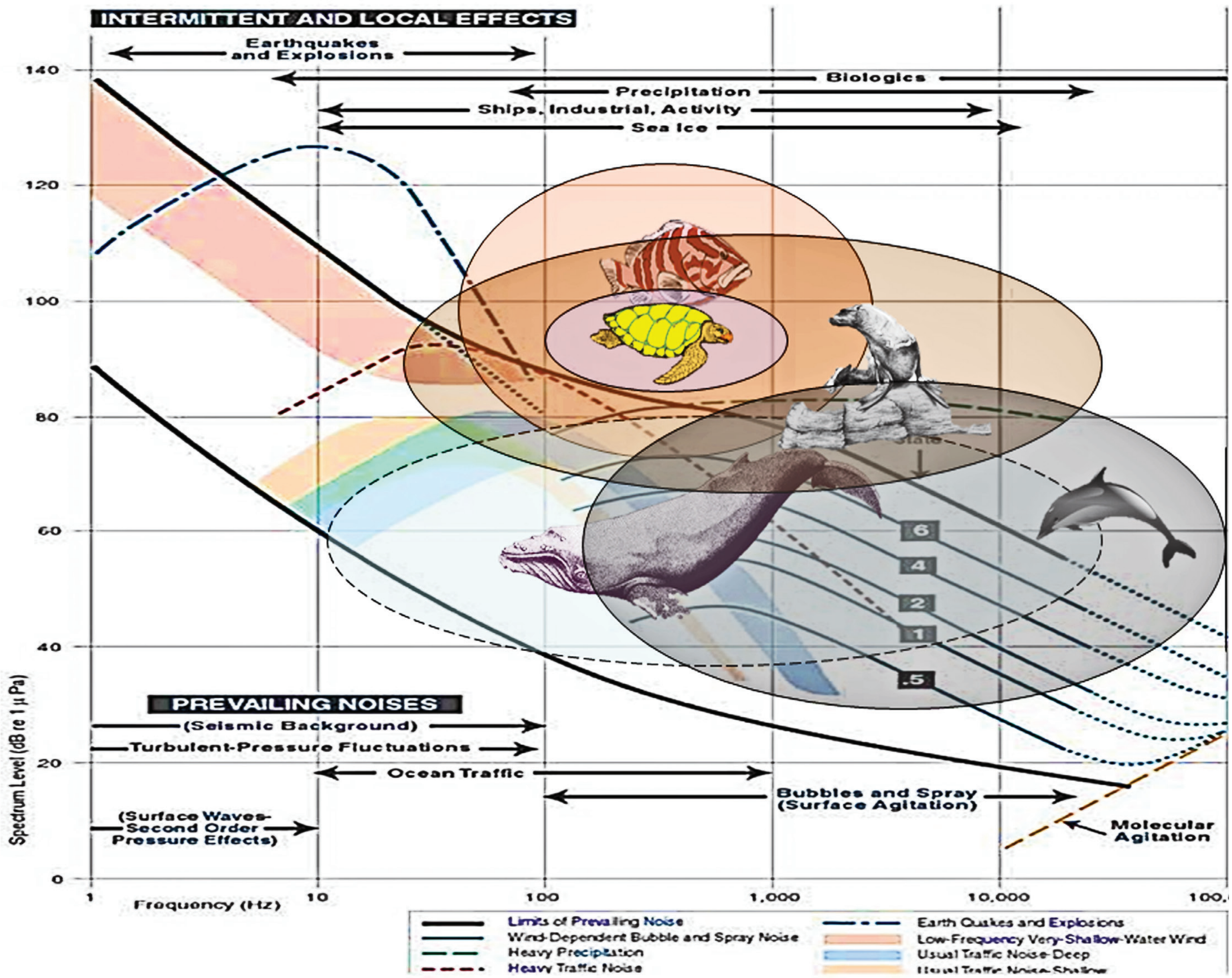


Figure 2. *Wenz curves illustrating the natural ambient and the relative contributions of some human underwater sound sources. The ovals approximate the total hearing range (frequency and sensitivity) of hearing in marine fishes (orange), sea turtles (lavender), seals and sea lions (brown), and toothed whales (gray). Baleen whale hearing (light blue, dotted line) is estimated from vocalizations. The units for the original Wenz curves were dB re 0.0002 dyne/cm^3. They are shown as converted to dB re 1 uPa in NRC (2003). (Adapted from Wenz, 1962; NRC, 2003).*

The events in Greece and the Bahamas were thoroughly investigated and followed by expert panel reviews (D'Amico and Verboom, 1998; Evans and England, 2001; Cox et al., 2006) that cited the simultaneity of the whale beachings and the absence of any apparent typical stranding cause, concluding that military sonar use debilitated the animals and precipitated the strandings.

Were these indeed acoustically driven events with a sole critical factor – the sound of the sonars - or were these strandings a perfect storm of colliding elements – sound, ship movements, bottom topography, sound profiles, species hypersensitive to sonar frequencies – or…what? After more than a decade of research, the problem remains perplexing. Although the primary question is how a group of whales came to die, it is important for the acoustic research community, with facets related to noise impacts, underwater sound propagation, and the design of underwater devices, and answers with repercussions for the future of acoustical research. At present, we do not have all the answers, but there has been progress.

Sonars and Ocean Noise

Among the important issues are what is the acoustic context of these events and what is the evidence for and against sonar as the critical agent.

The natural ambient in which marine mammals evolved is not silent. A quiet ocean is a dead ocean, and our global ocean is still very much alive. Natural sources of ocean noise are abundant and variable. Major geophysical events, such as undersea quakes and volcanic activity, produce intense and sometimes prolonged seismic to low frequency sounds. More constant, broader spectra noise comes from wave action, bubbles and cavitation, hydrothermal vents, substrate and ice movements, and surface events like lightening and storms. Some natural phenomena may increase local ambient levels by as much as 35 dB (Figure 2) (NRC, 2003, 2005).

The largest contributor to natural marine noise however is "life." All marine fauna produce and detect sounds that are critical survival cues. Biotic sounds range from infrasonic to ultrasonic frequencies, with source levels as high as 200 dB re 1 µPa rms, although most species hear and employ frequencies primarily at mid to higher frequencies, exploiting the range beyond lower frequencies common to natural abiotic ambient sources.

Anthropogenic sources increase the ocean's ambient "budget." There is no human activity in the ocean that does not add noise, intentionally or as a by-product. With the advent of machine- powered vessels, noise increased substantially. Modern human contributions to the ocean soundscape include vessel noise, industrial construction and operations, military activities, transport, fisheries, and research, many of which employ seismic, explosive, and impulse sources. Although ship-based military sonars, have, to date, received the greatest attention in the media, most NATO navies halved their fleets over the last two decades (McGrath, 2013). During this time, the global merchant marine fleet increased exponentially. Today, commercial shipping is by far the dominant anthropogenic source in the sea. It is estimated to have increased background noise by 15 dB in the last 50 years and accounts for over 50% of the total ocean noise budget in the northern hemisphere (NRC, 2003).

Seismic sources, such as air gun arrays (peak spectra below 100 Hz), are the mainstay of oil and gas exploration and the next largest source, followed by research and commercial sonar systems employing infra to ultrasonic frequencies. These are used as bottom profilers, scanners, navigational aids, and depth sounders in ocean exploration, transport, fisheries, tourism, and recreation. Commercial system source levels are difficult to determine because specifications are not conventionally provided by manufacturers, but they have been estimated to exceed 230 dB re 1 µPa at 1 m (Hildebrand, 2009).

Sounds we are adding may be soft or intense, intermittent or constant, static or mobile, varying by region, activity, and season. Consequently, our concerns about anthropogenic noise impacts are no longer just for immediate, acute impacts but also cumulative, long-term exposures. In effect, in some ocean areas and particularly along our fragile coasts, we may be creating an environment akin to that of human industrial workplaces. Much of this concern came about because strandings showed us underwater anthropogenic sound could have tragic environmental consequences.

The Case Against Sonar

Echo-ranging devices appeared in the early 20th century and were first used to detect submarines during World War I (D'Amico and Pittenger 2009). Hull mounted sonar systems proliferated during World War II; and by 1960, surface ship active sonars were using longer pings at lower frequencies (100 Hz to 8 kHz) and exploiting bottom bounce and convergence paths to increase detection range. Today, multiple military sonar systems are deployed worldwide, including low (LFA) and mid-frequency (MFA) active military sonars.

Most research on sonar precipitated strandings have focused on beaked whales as the prevalent whale group stranded in association with naval sonar exercises. Prior to 1950, beaked whales, especially Cuvier's beaked whales, did not commonly strand, singly or en masse. However, from 1874, when international stranding records began, to 2004, there were136 beaked whale strandings with 539 beaked whales in total distributed across multiple beaked whale species. Of these, 126 cases involving 486 animals, nearly all Cuvier's beaked whales, occurred after 1950 (D'Amico et al., 2009). The first post-1950 major stranding of Cuvier's beaked whales occurred near the NATO base in La Spezia in 1963, shortly after a new generation of MFA sonars were tested, followed by beaked whale strandings coinciding with NATO LFA sonar trials beginning in 1981 (D'Amico and Verboom, 1998)… then came the repeated incidents listed above.

Although the absolute number of sonar related beaked whale strandings is small, averaging fewer than 10 animals per year, it is not the raw number but rather the fact that the stranding incidence increased coincident with sonar exercises that is damning. Further, while Cuvier's are the dominant species, some are mixed species strandings involving also Blainville's beaked whales (*Mesoplodon densirostris*), and two stranding events have been reported with a non-beaked whale species. Two melon-headed whale (Peponocephala electra) strand-

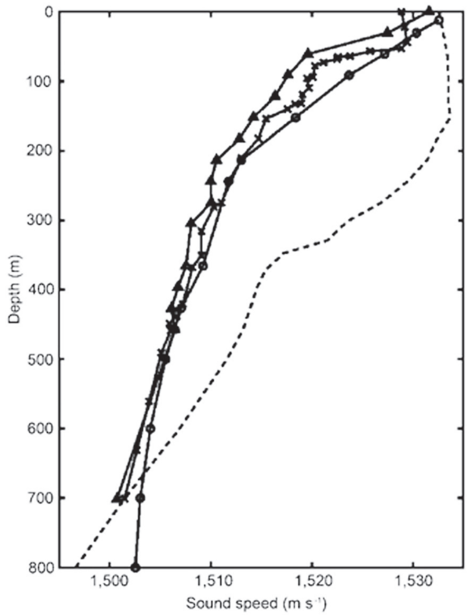


Figure 3. *Sound speed profiles taken from 3 expendable bathythermographs (XBT) in the Canary Islands (circles, triangles and 'x's) and in the Bahamas (dashed line) near the stranding events. Two datasets show a steady decrease with depth but one curve for the Canary Islands and the Bahamian curve suggest a surface duct that would "…trap mid to high frequency sound radiated by acoustic sources within the duct…;" i.e., ship mounted sonars. (reprinted with permission, d'Spain et al., 2006. Journal of Cetacean Research and Management)*

ings occurred while military and commercial sonars were in use in Hawai'i (NOAA 2004) and Madagascar (IWC 2013). Reviews of these events (NOAA, 2004; IWC, 2012) concluded sonar was the probable cause. If so, these events suggest that at least for several species, activities involving repeated, high intensity underwater sound sources, carries a serious, to the point of mortal, risk. This conclusion, in turn, has led to broader claims in the media, on blogs, and in lawsuits that far more animals are being harmed than have been seen and that a cacophony of anthropogenic underwater noise threatens extinction of already threatened or endangered species, many of which rely primarily on hearing for survival.

To understand if these concerns are valid, and to put bounds on the risks, it is important to try to understand exactly what precipitated the strandings by dissecting the events and the bodies. If there is a common cause, key questions become what underlying features are common to the events, what were the sound profiles, what other activities were underway, and what do the bodies tell us. We also need to understand why, considering the breadth and number of sonars in use worldwide, we are not seeing more strandings and why more abundant dolphin and whale species in the same area as the beaked whales were not similarly affected?

Acoustic Profiles

To understand what sound the whales that stranded could have encountered, we need an understanding of not just the received intensity, but also the peak spectra, duration, duty cycle, onset, and directivity, and how those vary with distance and depth, which amounts to a model of sound propagation specific to the source and environment in which it was deployed. Acoustic intensity decreases as sound travels through any medium according to spreading, absorption, and interaction with obstacles. Idealized losses are generally characterized as having spherical or cylindrical spread according to whether the medium is uniform or stratified. In the latter, a "duct" may trap sound, acting like a wave guide, decreasing the loss, for some frequencies, in comparison to the idealized models. The SOFAR channel is a classic example, however, of the wave guide that has been estimated for some of the stranding events differs in that it is in the upper waters (surface duct), which is not uncommon seasonally throughout the ocean (d'Spain et al., 2006).

For any real world situation, modeling the spreading can be difficult. A great deal of effort has gone into spreading models, both for the ideal and regional case as well as explicit models for several of the stranding events (see Fromm and McEachern, 2000, Zimmer, 2004; d'Spain et al., 2006). It is notable that in three major cases, Greece, Bahamas, and Canary Islands (2002), there were several common features: ships with active sources made near shore transects in waters deeper than 1km, traveling at > 5 knots while emitting periodic, high amplitude, transient pulses 15-60s apart with peak energy between 1-10kHz. The models created for all three sites indicate that variable ocean sound speed layering created an acoustic wave guide delimited by bottom refraction with sources positioned within the wave guide. Sound levels would not attenuate as rapidly as normally expected coupled with pulse integrity maintained with little scattering in calm weather (Figure 3); in effect, creating an anomalously high intensity acoustic cage. We have no data on the location of any of the animals prior to beaching, but at least in the Bahamian case, that "cage" was coincident with the preferred dive depths of Cuvier's beaked whales. We must also bear in mind that the "cage" was mobile, moving in repeated sweeps that came ever closer to shore. Thus we have several important elements: an acoustic phenomenon plus a movement pattern. That brings us to bodies on the beach.

Strandings

Our perception and response to strandings varies significantly according to culture and over time. Throughout the Ancient into Middle Ages, whales were largely seen as a food and fuel resource even while they were revered and a subject of curiousity (Aristotle, c 350 BC; Oppianus, c 150 AD). A 1324 law gave all rights to stranded or captured cetaceans in Britain to the Crown (BMNH, 2005) and drawings of crowds around stranded whales, some rather fancifully rendered, were common in Europe from the 15th century onward. Only in the last century did many countries turn away from whaling and initiate conservation efforts, including stranding response teams, for marine mammals.

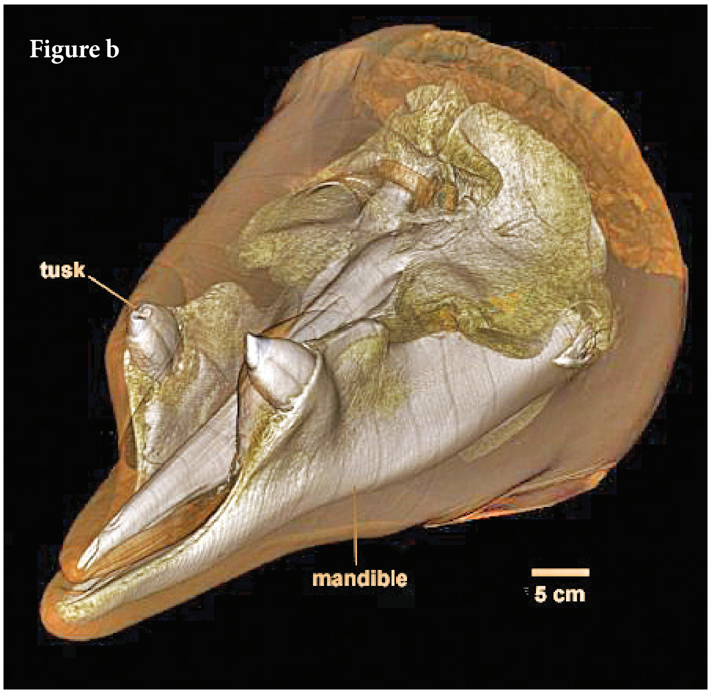
Approximately 4,000 marine mammals strand along U.S. coasts annually (https://mmhsrp.nmfs.noaa.gov/mmhsrp/html/seahorse_public.htm). It is important to understand that "stranding" is not synonymous with dead. "Stranding" is defined officially (http://www.nmfs.noaa.gov/strandings.htm) as an animal found dead or alive in an "inappropriate" location. In many cases, a stranded animal washes ashore after death or dies on or near shore; however, "stranding" also applies to animals in waters atypical for that species, such as pelagic species coming into a harbor. A "mass stranding" is defined as two or more animals that are not mother-calf or mother-pup pairs, stranding simultaneously or synchronously; i.e., a few animals or several hundred. Timing and proximity are critical. In the beaked whale cases, animals were found strung along a common arc several kilometers apart; in Hawai'i (2004) and Madagascar (2008), melon headed whales, an offshore species, came into a bay and swam up a major estuary.

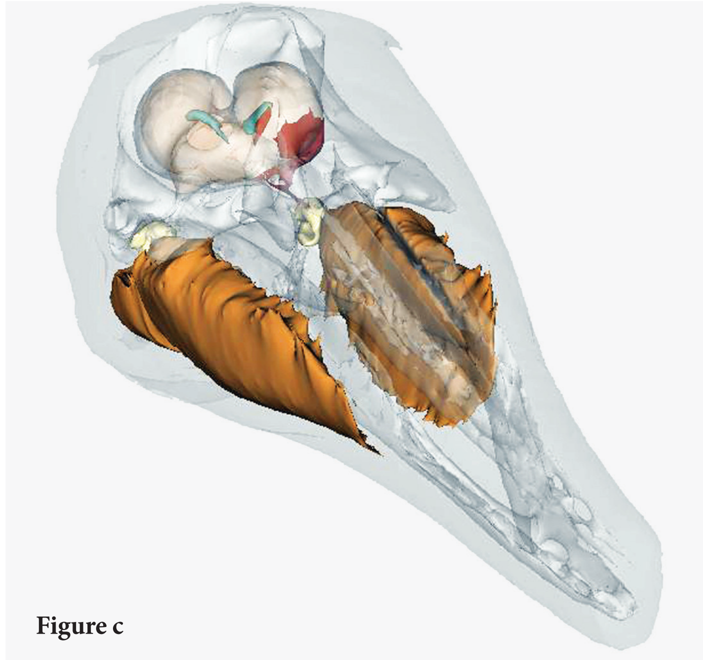
Animals succumb to disease, age, complications in calving, habitat disruption, food shortages, predators, and naturally occurring injuries and toxins, but of course many die or strand as a result human interactions, particularly from by-catch (caught in fishing operations), entanglements in gear and debris, ship strikes, and even intentional assaults, such as shootings, as well as from cumulative stressors, like chemical pollutants and noise. By-catch once accounted for as many as 100,000 cetaceans annually worldwide (Read, 2006, 2008), but in recent years, through gear improvements, the numbers have decreased to less than 2,000 annually, which is approximately equal to animals taken in commercial and scientific whaling fisheries. Drive fisheries, both today and in the past, have used sound to herd whales and dolphins around the world. Aristotle comments on such fishing methods as "…a loud and alarming resonance...induce the creatures (dolphins) to run in a shoal high and dry…on the beach and so …catch them while stupefied with …noise." Similar drives continue today in the Faroe Islands and Taiji fisheries. Depth and fish finders are also reported to bring whales to the surface (Payne, 1995). It is somewhat ironic that for millennia we exploited anthropogenic sound as a fishing tool and only now are attempting to understand the mechanism behind it in order to protect what was once our prey.

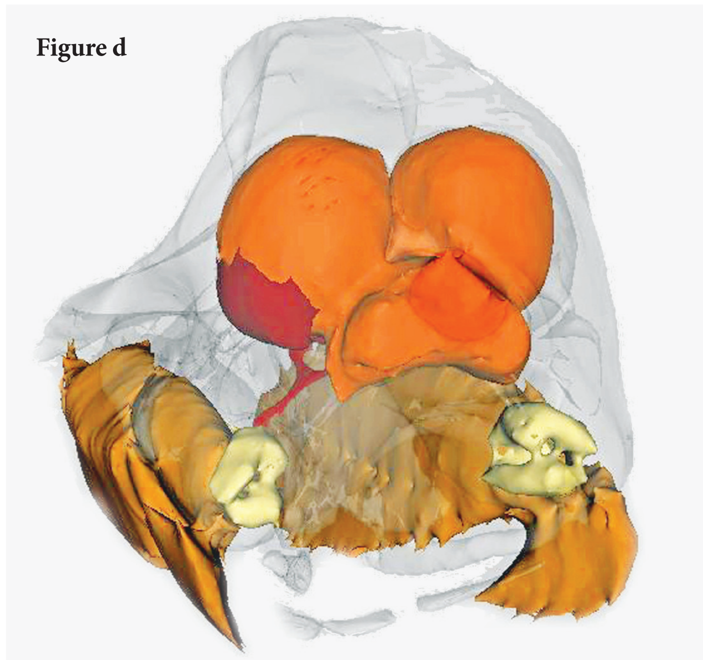
Anatomy of a Stranding: Cause, Mechanism, and Manner of Death

When a stranding occurs, local response personnel determine whether to assist the animal, if live, back into the water or transport to a rehabilitation facility. If it is moribund or dead, they will document its condition and collect the carcass to conduct a necropsy, a systematic examination of the body following an established protocol performed on the beach or in a dissecting facility. The goal of the necropsy is a comprehensive analysis of the animal's condition to obtain data related to its life history and any evidence related to its stranding and death.

As with a formal autopsy, the necropsy attempts to determine the "cause, mechanism, and manner of death." These are exact terms with well-defined clinical significance. Cause of death refers to an underlying physiologic condition, such as trauma or disease, critical to initiating the lethal event. Mechanism of death refers to the proximal physiologic process that the cause set in motion which resulted in death. Manner is a term for the category of the event, such as natural, accidental, or, in human cases, homicide or suicide. As an example, consider the case of an individual who steps off a curb into the path of a car and falls, striking his head on a curb, snapping his neck. The cause of death is a traumatic injury to the brainstem and severing of the spinal cord; the mechanism is neck extension and skull fractures resulting in hemorrhage and crushing and tearing of associated soft tissues; the manner of death is accidental from a collision with a car and resulting fall. Similarly, a diving fatality may have as a mechanism of death drowning, but the cause of death is cardiac arrest while diving, and the manner of death is then natural. These determinations, and the extensive, rigorous exam process behind them, are just as applicable and important for the analysis of strandings as in human cases.







Figures 4 (a,b,c,d). *Include live and CT images of adult male Blainville's Beaked Whale (Mesoplodon densirostris). (CT images courtesy of WHOI Imaging Facility. All rights reserved. http://csi.whoi.edu)*

Figure 4a. *Male Blainville's beaked whale swimming near Abaco, Bahamas. (Photo courtesy of Diane Claridge, Bahamas Marine Mammal Research Organisation, all rights reserved.)*

Figure 4b. *The 3D reconstruction from CT scans of the head of a stranded male Blainville's beaked whale shows the skin surface (translucent) and the characteristic male tusks and skull shape. The right tusk has lost its tip from trauma or decay. Two videos accompany this image, one showing a set of CT scans of the head and the second shows the reconstruction of the head built upon the CTs.*
To view videos visit http://acousticstoday.org/?p=2315.

Figures 4c and 4d. *Anterior and posterior views of the internal anatomy of the head of a beaked whale that stranded on Abaco, March 2000. The scans demonstrate the origin, location, and extent of a left subarachnoid hemorrhage (red) that traveled along the internal auditory canal to the left ear region.*

Because of practical limitations on examining large animals under field conditions, such as post mortem times and ambient conditions, tissue loss from scavengers and decay, limited resources for analyses, etc., comprehensive findings are not possible for every necropsy. In the last decade, clear cause of death could be assigned in only 30% to 40% of all stranding cases examined worldwide. Even for strandings that qualify as an Unusual Mortality Event (UME) because of the rarity of species or the location and numbers of individuals involved, answers can be difficult. In UMEs, a far more extensive necropsy and series of exams are undertaken. Nevertheless, despite the far more thorough analyses involving multiple specialists, a cause of death has been ascertained for only 53% of UMEs in the past five years.

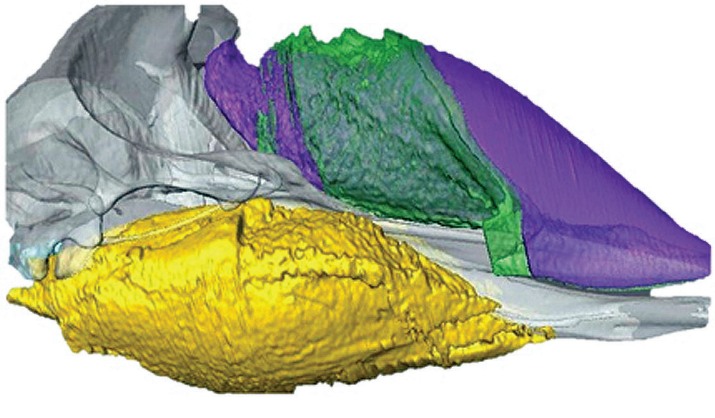


Figure 5a.(left) *Stranded Cuvier's Beaked Whale (Ziphius cavirostris) being prepared for necropsy.*

Figure 5b (above) *3D image of the head showing the skull (white), melon (purple) through which echolocation signals are emitted; surrounding dense collagen band (green); fatty tissues along the mandible that connect to the ear complex (gold).*

Figure 5c (right) 3*D CT scan image of the inner ear of the same animal. The difference in the auditory nerve (an) and the vestibular nerve (vn) diameters in this ear are typical of toothed whale VIIIth nerves. Their auditory nerve has approximately 20 times more nerve fibers than the vestibular nerve. The relatively small diameter of the vestibular canals (ssc = the juncture of the semicircular canals at the ampullae) in comparison to the cochlea and the change in scalae diameters along the cochlear canal are also typical of whale ears (sv = scala vestibule; ow = oval window). A video accompanies these images that examines the head of a stranded female Cuvier's beaked whale (Ziphius cavirostris) showing the surface (translucent) and the skull. Two tusks shown embedded in the lower jaw are typical of females and juvenile males of this species. Only the adult male has erupted, externally visible tusks. As the video image rotates to a ventral view the exceptionally dense ear bones (white) can be seen just inside and slightly posterior to the mandibles (lower jaw bones). To view video visit http://acousticstoday.org/?p=2315.*

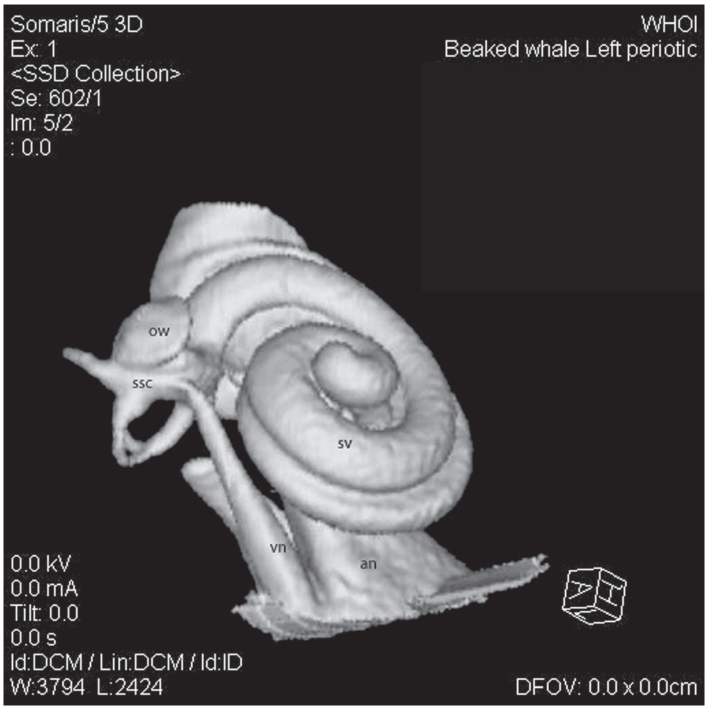
The Findings

It is important to appreciate that the sonar related stranding events are globally distributed and therefore the response and analyses depend upon the regulations and processes of the country with jurisdiction over the stranding event. Thus, there is substantial variability amongst the sonar stranding cases in the available data.

In Greece, in 1998, all 12 beached animals were found dead. It was reported that the bodies appeared to be overtly healthy, well nourished animals, but they were too remote for responders to obtain useful samples from the carcasses (D'Amico and Verboom, 1998). Several later stranding events had similar outcomes. In some cases, the bodies had extensive post mortem autolysis (breakdown of tissues) or the working conditions allowed only the most basic tissue samples; in others, local customs resulted in dismemberment or immolation that destroyed critical anatomy (Freitas, 2004; Ketten, 2005; IWC, 2012).

In the Bahamian cases, necropsies were performed on a few whole carcasses on Grand Bahama Island, but these bodies were not discovered until they had lain on hot sand on secluded beaches, in tropical heat, for 12 or more hours post mortem (Figure 1). Little could be gleaned that was not corrupted by postmortem artifacts. On Abaco, however, the story was quite different. Abaco lies to the south of Grand Bahama and is also the home base of the Bahamas Marine Mammal Research Organisation (BMMRO), which has a respected history of research on beaked whale ecology and behavior. Because BMMRO was alerted as soon as the beaked whales began coming ashore, of the 17 whales reported stranded, 10 were returned to deeper water. Of the remaining seven that died, six were preserved and necropsied.

As in Greece, the animals were in good body condition with no evidence of debilitating infectious disease, toxins, lacerations, fractures, or blunt trauma. The principal anatomical elements of underwater hearing common to high frequency,



echolocating, toothed whales were all there (Figure 4), and as later studies showed, there were no features suggesting they would be particularly sensitive at mid or low frequencies (Ketten, 2005). CT scans of the freshest intact heads from these specimens, however, showed blood deposits within the inner ears and hemorrhaging in the fluid of the subarachnoid spaces surrounding the brain that were confirmed on dissection (Figure 5). Similar hemorrhages in humans or land mammals would not likely have been fatal nor caused permanent hearing loss, but they could be at least temporarily debilitating. The intracochlear blood may have compromised hearing temporarily or caused disorientation. Ultimately, it was determined that these whales died as a result of cardiovascular collapse (mechanism) due to hyperthermia and high endogenous catecholamine release (cause) consistent with the extreme physiological stresses associated with beaching in an accidental stranding (manner) (Evans and England, 2001).

The strandings clearly coincided with a multi-ship exercise using tactical MFA sonars. The critical elements are there of both time and proximity, and there was no evident, alternative common cause for the strandings. The investigation panel concluded that tactical mid-frequency sonars in use aboard U.S. Navy ships during the sonar exercise in Bahamian waters were the force majeure, the most plausible instigating force for the strandings (Evans and England, 2001). The sonars in use have an operational source level of approximately 220 to 230 dB re 1 μPa @ 1m. Multiple sonar units were operating over an extended period of time, ensonifying a complex environment that included a strong surface duct and steep topography. To that, add beaked whales diving in the ensonified undersea canyons with sheer walls and limited exits.

In the Canary Islands, the topography was different but the pattern of events and results were similar. Multiple ships used MFA sonars in a box-like maneuver towards shore, followed by beaked whale strandings along that coast. In addition to similar hemorrhage sites in those bodies, some animals were reported to have widely disseminated intravascular bubbles (Fernandez et al., 2012). Bubbles were also reported in major organs of stranded animals in the United Kingdom in a retrospective study (Jepson et al., 2003). These reports have led to a number of speculations that exposure to sonars results in a rapid surfacing that promulgates decompression sickness (DCS). While these findings are worth noting, it is also important to bear in mind that the consensus of experts in diving fatalities and dive physiology is that "presence of gas in any organ or vessel after a scuba diving death is not conclusive evidence of decompression sickness or air embolism" (Caruso, 2014). It is critical for a diagnosis of DCS to have consistent trauma in lungs, ears, and brain and specifically interarterial and left ventricle high oxygen content, gas emboli, not simply broadly distributed bubbles (Brubakk and Neuman, 2002; Edmonds et al., 2002; Piantadosi and Thalman, 2004; Hooker et al., 2012; Caruso, 2014). Bubbles in post-dive, post-mortem animals are to be expected because normal off-gassing processes by the lungs are halted by death and they may occur also from decomposition. To date, we have no reports documenting the critical symptoms of DCS. Therefore, it is not yet possible to state with certainty that DCS or pathology from altered dives is present in these cases.

Concerning the two melon head whale stranding events investigated by the National Marine Fisheries Service (NMFS) and the International Whaling Commissions (IWC), in Hawai'i, a pod of these normally off-shore animals entered a shallow bay simultaneous with Navy vessels passing through the region. One calf in poor health died during the incident; the others left the bay several days later. In Madagascar, a large pod entered an estuary on the west coast coincident with sonar use during an oil and gas exploration operation. Most of these whales died over the next week, trapped by tidal flows and tangled in the mangroves and mud. The majority of bodies found were in very poor condition, and again, the necropsy findings were inconclusive, but, as in the Bahamian cases, some of the ears from the Madagascar cases were in sufficient condition to establish that there was evidence of longer term hearing loss associated with aging or infections but no evidence of recent, acute auditory or vestibular damage (Ketten, 2005; IWC, 2012).

In both of the melon head cases, as with the beaked whale cases, no typical stranding cause was found, which led the panel to implicate sonar use in the area as a probable cause. It should be noted, however, that in the Hawaiian case, a report was later published that documented a mass stranding of the same species simultaneous with the Hawaiian incident, but 5,000 miles to the West and with no nearby acoustic event, raising the question for the Hawaiian case at least of some unappreciated, underlying, non-acoustic trigger, such as prey movement or lunar cycles (Jefferson et al., 2006).

The Unusual Suspects

At this point, we have no clear causal impact phenomenon for these strandings, but there are a number of possible suspects. Cox et al. (2006) summarized proposed impacts as follows:

(1) behavioral avoidance responses to sound that leads to stranding;
(2) maladaptive dive responses (rapid ascent, or remaining at depth or surface longer than normal) leading to tissue damage (bubble formation, hypoxia, hyperthermia, cardiac arrhythmia, hypertensive hemorrhage, or other trauma);
(3) tissue damage or other direct physiological effects from sound exposure (acoustically mediated bubble formation, vestibular damage, tissue resonance, species disseminated diathetic coagulopathy, which is failure to clot exacerbated by stress).

Later panels eliminated some of these theories, such as resonance effects, as improbable for a variety of reasons. At present, the focus of research is on behavioral responses. The current large-scale Behavioral Response Study (BRS) is pursuing the difficult task of locating and tagging free-ranging beaked whales with data-loggers in order to measure changes in diving and acoustic behavior of whales exposed to test signals. Results to date show that beaked whales have a consistent avoidance response, not simply to sonar signals, but to novel sounds in general. This contrasts sharply with responses of other species, such as pilot whales which were attracted to the same stimuli (Southall et al., 2012). The BRS data also show that avoidance behaviors occur at relatively low sound levels, which suggests an avoidance response is not the result of inner or middle ear injury, consistent with the necropsy findings of no acoustic trauma or acute inner ear pathology in the stranded animals.

Conclusions: Mind the Gap

The basic question is simple: Are sonars or any other anthropogenic sound resulting in significant, population level impacts in the ocean?

There is no question that underwater anthropogenic noise has the potential to do harm, directly or indirectly, to marine animals, just as noise in air can harm humans and other animals (http://www.nidcd.nih.gov/health/hearing/pages/noise.aspx). The susceptibility of beaked whales to sonar-related stranding, set us the task to find out why and how they were impacted. It is not clear that there is a common cause or mechanism for the pathologies documented across the Bahamas, Greece, and Canary Island stranding cases nor to what extent acoustics were involved vs. ship movement or any other element. Questions remain about whether the focus of mitigation to prevent another event should be: (a) sonar exposures of all types; (b) novel sound exposures with parameters like those eliciting behavioral responses; (c) use of sonars and/or novel signals in beaked whale habitats; d) multi-ship and/or multi-sonars exercises near shore; or (e) some or all of the above.

The issue of potential impacts of sounds from sonars is real, and it raises a bigger question of whether we, as scientists, need to work to assure the perception of the risk is accurate and neither underestimates nor exaggerates the actual threat. The acoustic research community has seen the effects of public uncertainty before in reactions to the Heard Island and ATOC experiments (Munk et al., 1994; Potter, 1994). Since then, thinking has shifted from individual to population level effects (Hastings, 2008). The sonar cases raise legitimate concerns. Until a mechanism is determined, we cannot say definitively whether these strandings are limited to the cases we have observed, or if, as has been asserted, they are a shadow image of a far broader problem. At present, we have no direct evidence of a significant, population level impact from sonar or any other sources, but we must be alert to more subtle events than strandings, including changes in behavior, habitat use, and demographics.

In summary, we have several concerns. There is no denying the potential importance of anthropogenic sound impacts in our oceans and the appropriateness of regulating the deployment and use of sound sources. Hearing is considered the most important sensory system for many marine species. Shifting the noise budget of the oceans, as we are doing, can result in a significant hazard to not only marine mammals but other species, including fishes, turtles, and invertebrates (Popper et al., 2014; Hawkins and Popper, 2014). A robust research program on sound impacts is essential to protecting the marine environment and providing a balanced and scientifically informed risk assessment. If we are to continue to conduct essential ocean research, we must face the challenge of public education on the vital role of research for placing valid limits on sound use in our seas.

Acknowledgments

Much of the data included in this article were obtained through the support of NOAA/NMFS, ONR, Navy Environmental Division, LMR, NIH, the Seaver Institute, and the Mellon Foundation. The preparation of this manuscript, parts of which were adapted from a book chapter in press, was supported by support through a Western Australia Premier's Fellowship. Scott Cramer and Julie Arruda provided exceptional technical and imaging assistance for this effort.

Biosketch

Darlene Ketten is a neuroethologist who employs biomedical imaging techniques to study hearing and hearing loss in land and marine animals. She received a B.A. from Washington University, M.S. from M.I.T., and Ph.D. from the Johns Hopkins Medical Institutions. She currently holds joint appointments as Professor of Imaging and Applied Physics, Curtin University; Adjunct Professor, Veterinary Medicine, Murdoch University; and Assistant Clinical Professor, Harvard Medical School. She is the Chief Scientist of the WHOI Computerized Scanning and Imaging Facility (http://csi.whoi.edu) and is a Fellow of the Acoustical Society of America and of the Association for the Advancement of Science. (Photo courtesy livebetter Magazine/Bill Simone)

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TECHNICAL COMMITTEE REPORT

Musical Acoustics

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The Technical Committee on Musical Acoustics (TCMU) is made up of scientists and engineers interested in the application of science and technology to the study of music and musical instruments. Members of the committee are interested in the underlying science of how humans make and perceive music, including music created by the human voice. Topics of interest include the physics of musical sound production, the perception and cognition of music, the analysis and synthesis of musical sounds and composition, and the classification of music and musical instruments. A review of publications in the area of musical acoustics reveals work relating to a wide variety of instruments. There are reports of several investigations of the human voice and many familiar western orchestral instruments, but one can also find reports of more unfamiliar instruments such as the Southeast Asian khaen (Cottingham, 2011) and the Nigerian slit log drum (Cannaday, et al., 2012).

Interestingly, the vast majority of scientists who are working in the field of musical acoustics were not trained as acousticians. Most come to the field of musical acoustics from a variety of other scientific disciplines. Therefore, the TCMU is an eclectic mix of scientists with a wide array of backgrounds. At a meeting of the TCMU it is not unusual to find someone trained in high-energy physics discussing the physics of the trumpet with a colleague who was trained in nonlinear optics. This mix of backgrounds gives the TCMU a unique character that enhances both personal and professional interactions, and results in each person approaching the field from a slightly different perspective.

As one would expect, there are some musical acousticians who were trained in acoustics. This is more prevalent with the members living in Europe, where the field is supported financially by governmental organizations. However, we are beginning to see more young people from the United States studying musical acoustics. This increase can probably be attributed to the interesting and challenging problems presented to those who study the physics of musical instruments, as well as the welcoming attitude that the members of the TCMU have toward people new to the field.

Although the community of musical acousticians encompasses a wide variety of research topics, there are a few that have been receiving significant attention recently. There are also several topics that would be receiving attention if adequate funding was available. One of the research areas that fits in the former category concerns the ability to distinguish the quality of musical instruments deterministically. It is common for musicians to believe that one make or model of an instrument is better than another one that appears almost identical, and they often agree on which instruments are superior. Unfortunately, the goal of evaluating the quality of a musical instrument quantitatively has been elusive. The inability to objectively determine the quality of a musical instrument is partly due to the musician's inability to express the important qualities of an instrument in scientific language. It is also partly due to the acoustician's inability to determine what quantities to measure and how to measure them (see, for example, Campbell, 2013). The problem is exacerbated by the personal preferences and preconceived notions of many musicians. A prime example of the power of preconceived notions was recently published in *Proceedings of the National Academy of Sciences* by Claudia Fritz and her colleagues at *Lutheries-Acoustique-Musique* in Paris (Fritz, 2014). They reported that in double-blind tests professional musicians cannot distinguish between high quality modern violins and similar instruments made by Guarneri and Stradivari in the 18th century. Although the conclusions seem well supported, many musicians have been critical of the research simply because of the well-established bias toward violins made by the 18th century masters.

Another topic receiving significant attention concerns the effect of structural vibrations on the sound produced by wind instruments. Structural vibrations are clearly important in producing the sound of string and percussion instruments. The importance of structural vibrations on the sound produced by wind instruments, however, has been debated for over a century. Recent experimental results indicate that structural vibrations are important in producing the unique sound of some brass wind instruments, e.g., trumpets and trombones (Kausel, et al., 2010), but the effects are likely insignificant in woodwind instruments, e.g., flutes and clarinets (Nederveen and Dalmont, 1999). The current work in this area is primarily directed toward achieving a theoretical understanding of the processes governing the interaction between the structural vibrations and the air column that produces the sound in these instruments. The issue is complicated by the necessity of the human interaction with the instrument during performance, which means that the structural vibrations can affect the sound field directly or they may feed back to the lips of the player. Additionally, the player may unconsciously compensate for the effects of structural vibrations. Separating these effects and determining the physics of the coupling mechanism is a non-trivial problem that is currently being addressed by musical acousticians in several countries.

Research on the synthesis of musical sounds is another area in which a large number of musical acousticians are involved. The goal of such work is to model the full physical system of a musical instrument and produce an accurate simulation of the sound in real time. Current work in this area includes a wide range of instruments, but regardless of the instrument under investigation the effort always necessitates extensive theoretical, experimental and computational work (see, for example, Smith, 2010; Chabassier, et al., 2013). Although significant progress has been made over the past decade in real-time simulation of musical instruments, there is still much to learn. Many musical instruments are so poorly understood that there is not even enough information to begin constructing an algorithm that will result in an accurate simulation of the sound.

As was pointed out by Murray Campbell in a recent plenary address to the ASA, there is one area that is critical to the advancement of our understanding of music and musical instruments but has yet to be seriously addressed: the quantitative characterization of the vocabulary that musicians use (Campbell, 2013). Not only has this topic not been adequately addressed, there seems to be no consensus on how to address it. Musicians use such terms as dark, rich, resistance, powerful, etc. when describing a musical instrument or its sound, but the meanings of these terms are not clear. It is not even clear that musicians are using the same definitions, although surprisingly they often agree on the description of an instrument using such terms. An accurate translation of the vocabulary that musicians use to describe instruments into scientific terms would revolutionize the field of musical acoustics, however, it currently appears to be many years away. Unfortunately, until such a lexicon can be constructed the divide between the musician and the acoustician will never be adequately bridged.

There are many interesting problems in musical acoustics that relate to singing and the perception of songs by listeners. The scope of the research is impressive, which is not surprising given the prevalence of sung music in cultures worldwide. Research on the process of singing ranges from imaging vocal folds to electroglottography (see, for example, Bailly, et al., 2010; Bernardoni, et al., 2014). Research on the perception of sung music is similarly broad and involves investigations across the fields of physics, physiology and psychology. The study of sung music overlaps significantly with the study of human speech, but it has recently been shown that the two fields may be more closely coupled than one may suspect. Work by Diana Deutsch and her colleagues at the University of California, San Diego has revealed that when a spoken phrase is listened to several times in succession the listener perceives the phrase as being sung (Deutsch, 2011).

Most musical acousticians came to the field because of an abiding interest in music and the science of music. Many still maintain active research programs in other fields of physics and engineering while approaching musical acoustics as an

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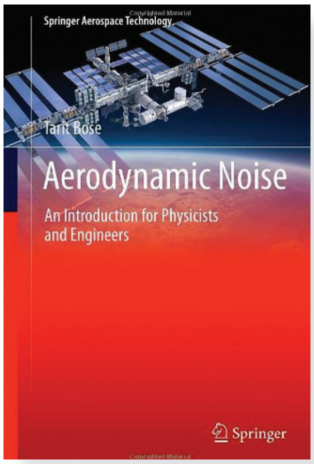
These reviews of books and other forms of information express the opinions of the individual reviewers and are not necessarily endorsed by the Editorial Board of Acoustics Today or the Journal of the Acoustical Society of America.
– Philip L. Marston, *Book Review Editor*



Aerodynamic Noise: An Introduction for Physicists and Engineers

Author: Tarit Bose
Publisher: Springer Science+Business Media, New York, NY
ISBN: 978-5-7036-0131-2
Pages: 165 pp.
Binding: Hardcover
Publication Date: 2013
Price: $89.95

***Review by*: Joe W. Posey**
121 Breezy Point Drive, Yorktown, Virginia 23692

The subject of this book is aircraft noise. It is a collection of notes from a graduate-level course taught by the author over the past few decades. He assumes no previous exposure to the study of acoustics by the students. Even though the text is brief, the scope is very broad, going from the fundamentals of acoustic theory to computational aeroacoustics (CAA).

The introduction, chapter 1, addresses acoustic propagation and noise metrics, then moves on to very brief discussions of the nature of aircraft noise, types of vehicular horns, and music theory. The next chapter covers the fundamental types of noise sources: monopoles, dipoles, and quadrupoles. Chapter 3 discusses Lighthill's 1952 paper including his "equation of sound" and his acoustic analogy. The brief chapters 4 and 5 are concerned with subsonic jet noise while the next chapter, the longest in the book (46 pages), is an exploration of various CAA schemes, concluding with short discussions of propeller and helicopter noise prediction. Supersonic jet noise, "sound at solid boundaries" (airframe noise?), combustion noise, and sonic booms are dealt with in 11 pages in chapter 7 before it concludes with 8 pages on measurement techniques and noise reduction.

Clearly, the author wishes to share the information he collected throughout his career which is related to aircraft noise, plus a few other aspects of acoustics. As the title indi cates, the book is intended to be an introduction to the subject, and that is a reasonable description of the contents. It could be used to show the student a sampling of work done in the area, but not to provide a foundation for further study. While the density of equations suggests rigorous treatment, the breadth of coverage and the brevity of the book necessitate cursory discussions of the many aspects of aircraft acoustics. Anyone seriously interested in the field would be well advised to first take a course in acoustics and then to study a systematic survey of the field such as that compiled by Hubbard (Aeroacoustics of Flight Vehicles, Theory and Practice–Volume 1: Noise Sources; Volume 2: Noise Control, edited by Harvey H. Hubbard, Acoustical Society of America, 1994) which was stringently reviewed.

The work chosen for presentation by Bose is curious indeed. Many of the references are non-refereed conference papers and theses or dissertations. For example, the only references for the extensively researched topic of propeller noise are a 1970 Jet Propulsion Laboratory report and an unspecified 1996 "time-domain calculation." Lengthy quotations from the references are given throughout the book, but they are usually taken out of context so that the reader has no basis for establishing the limitations or generality of the quote.

Nomenclature and symbology are not only unconventional, but often contradictory and confusing. For example, instead of using f (Hz) for frequency in cycles per second, ν is used and given the dimension of 1/s when it is clearly intended to be cycles/s. Further, even though the traditional ω is used for radial frequency, it is given the units of radians/s rather than 1/s. In the discussion on standing waves in tubes, α is given two different definitions. The second is called "spatial radian frequency" and defined as ω/c, which is traditionally called the wave number and given the symbol k. In fact, in the same discussion, ω/c is set equal to ν, α, and finally k in the space of little more than a page. To compound the confusion, the accompanying Fig. 1.4 erroneously shows pressure antinodes and velocity nodes at the open ends of a tube. All of this discussion and pointless collection of equations clouds one of the simplest concepts in acoustics, resonant frequencies of tubes. One need only note that a closed-closed tube will resonate at frequencies having an integral number of half wavelengths in the tube due to the requirement for a

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velocity node at each end. Similarly, an open-closed tube resonates with an odd number of quarter wave lengths due to the requirement for a pressure node at the open end and a velocity node at the closed end. Such obfuscation is typical of the entire book.

Nonsensical passages are found throughout the text. For example, here is a run-on sentence from section 1.8 talking about ducted fan noise: “It has been found that pressure noise distribution is less effective can decay [sic] exponentially in their passage through the duct, whereas in a supersonically spinning mode the noise distribution is less effective upstream and is zero under choking conditions.” Unfortunately, this and a short, equally cloudy discussion near the end of the book are the only inclusions of duct acoustics material, a very important consideration in turbofan noise prediction and control. For large, modern turbofan-powered transport aircraft, fan noise often is larger than jet noise, especially during landing approach.

Unfortunately, organization is also a major problem. For example, the brief section on “Measurement Techniques” includes an unrelated discussion of airframe noise sources as well as a paragraph on the increasing role of air traffic controllers in airport community noise reduction, including the imposition and enforcement of curfews.

So, this introduction to aerodynamic noise may have an audience, but it should not include anyone with a serious interest in establishing a foundation for the practice of aircraft noise control engineering.

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unfunded sideline. Some have no active research effort in musical acoustics but are merely interested in the physics and physiology associated with making and listening to music. The TCMU acts as a professional home for all of these people.

Biosketch

Thomas Moore is the Archibald Granville Bush Professor of Science and a Professor of Physics at Rollins College in Winter Park, Florida. He is the former chair of the Technical Committee on Musical Acoustics and has an active research program investigating the physics of musical instruments.

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Acoustical Society Foundation Fund

The mission of the recently established Acoustical Society Foundation Board (ASFB) is to support the mission of the ASA by developing financial resources, namely the Acoustical Society Foundation Fund (ASFF), for strategic initiatives and special purposes.

The Acoustical Society Foundation supports many of the prizes and stipends that are awarded to young professionals in the fields of acoustics to further their careers and reward outstanding achievements. With the amazing generosity of Dr. James and Betty (Horenstein) Pickett, the ASA, through the Foundation's support, awarded two 2014 Stetson Awards to outstanding young speech scientists. The purpose of the Stetson Scholarship is to facilitate the research efforts of promising graduate students. It was first established through a grant to the Acoustical Society Foundation in 1998, and honors the memory of Professor Raymond H. Stetson, a pioneer investigator in phonetics and speech science; this year's scholarships are for $20,000 each.

Patrick Reidy is a doctoral student in the Department of Linguistics at Ohio State University; his adviser is Dr. Mary E. Beckman. Mr. Reidy researches spectral dynamics in fricatives produced by children with and without hearing impairment. Mr. Reidy's previous work has focused on developing novel measures of degree of acoustic contrast in children's speech production. He has also developed software packages for acoustic analysis, and has conducted research evaluating the utility of different acoustic measures of fricative consonants.

Kyle Danielson is a doctoral student in the Department of Psychology at the University of British Columbia; his adviser is Dr. Janet Werker. Mr. Danielson's background is in psychology, phonetics, and psycholinguistics. His research examines the acoustic properties of infant-directed speech produced in bilingual households. His current investigation examines the role that vision and motor proprioception play during the perception of auditory speech sounds. This entails the study of English-learning infants for their ability to acquire speech contrasts from other languages.

The applications for the award are submitted to ASA (see www.acousticalscoiety.org) and are reviewed by the Speech Communication Technical Committee and its chair. Funding for this award is provided through the Acoustical Society Foundation Fund.

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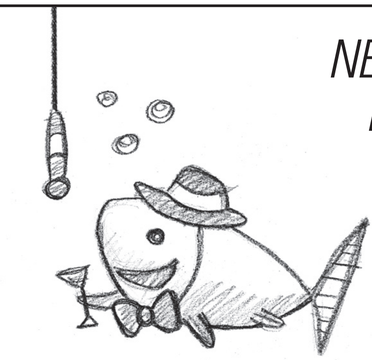
One column ad, $38.00 per line or fractions thereof (44 characters per line), $200 minimum, maximum length 40 lines; two-column ad, $50 per line or fractions thereof (88 characters per line), $350 minimum, maximum length 60 lines. (**Positions** desired ONLY – ads from individual members of the Acoustical Society of America receive a 50% discount)

Submission Deadline: 1st of month preceding cover date.

Ad Submission: E-mail: Christine DiPasca at cdipasca@aip.org; tel. : (516) 576-2434. You will be invoiced upon publication of issue. Checks should be made payable to the Acoustical Society of America. Mail to: Acoustics Today, Acoustical Society of America, 1305 Walt Whitman Road, Suite 300, Melville, NY 11747. If anonymity is requested, ASA will assign box numbers. Replies to box numbers will be forwarded twice a week. Acoustics Today reserves the right to accept or reject ads at our discretion. Cancellations cannot be honored after deadline date.

It is presumed that the following advertisers are in full compliance with applicable equal opportunity laws and, wish to receive applications from qualified persons regardless of race, age, national origin, religion, physical handicap, or sexual orientation.



Advertisers Index

Advertising Sales & Production

For advertisement reservations or further information please contact:

Debbie Bott
Advertising Sales Manager
Acoustics Today
c/o AIPP Advertising Department
1305 Walt Whitman Road
Suite 300
Melville, NY 11747-4300
Phone: (800) 247-2242
(516) 576-2430
Fax: (516) 576-2481
Email: dbott@aip.org

For advertisement production inquiries, please contact/send files to:

Christine DiPasca
Sr. Advertising Production Manager
Acoustics Today
c/o AIPP Advertising Department
1305 Walt Whitman Road
Suite 300
Melville, NY 11747-4300
Phone: (516) 576-2434
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