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ECHOES

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# Head-Related Transfer Functions

*by William M. Hartmann*

Ever since the third edition of Lord Rayleigh's *The Theory of Sound* (1907), it has been known that a listener can make use of both interaural differences in level and interaural differences in timing to localize sound. If a sound source is to the left of the listener, the right ear is in the shadow of the head so that the signal level in the left ear is more intense. Also, with the source to the left, a signal arrives sooner at the left ear, creating an interaural time difference for each waveform feature.

Over the years, psychoacousticians have verified the roles of interaural differences in level and timing in great detail. But it has also been clear (to Rayleigh too) that there must be more. Interaural level and timing are not enough to disambiguate all different source locations. For example, locations in the median-sagittal plane (includes the points directly in front, directly in back, and overhead) are symmetrical with respect to the two ears so that interaural differences are small or absent. Yet listeners can readily distinguish between different sources in this plane. Further, when an experimenter presents signals by headphones using carefully controlled interaural differences in level and timing, listeners do not experience a sound that is correctly localized in space. Instead, the sound often seems to be within the head. The signal is said to be lateralized to the left or right. It is not externalized and localized. What is missing from the simple interaural-differences model of sound localization is the head-related transfer function.

The head-related transfer function (HRTF) is the frequency response, like the response of a filter, between a point in space, where a source might be, and an ear, attached to a head in the normal way. A HRTF is measured in an otherwise free field to avoid room effects, and the receiving microphone is normally a probe inserted well into the ear canal to capture the spectral details of the entire external ear. The frequency response of the external ear (pinna) is directional. In particular, it discriminates between source locations in the median-sagittal plane. The pinna is so important that HRTFs are sometimes called pinna response functions. However, its small size limits its directional response to the frequency range above 5 kHz. By contrast, psychoacoustical localization experiments exhibit some spectrally mediated directional effects at frequencies as low as 500 Hz. Therefore, the HRTF might be thought of as an *anatomical* transfer function.

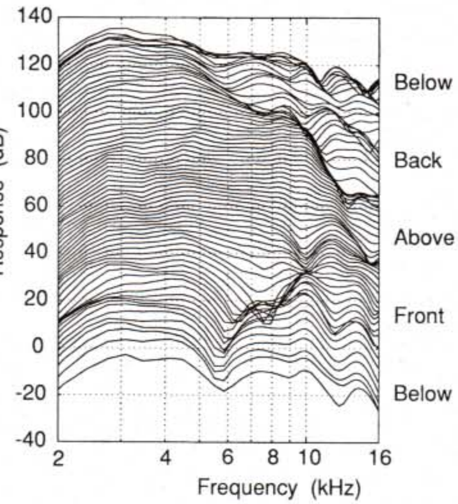


*Figure 1: Frequency response curves for a KEMAR head for about eighty different source positions distributed around a circle that runs directly below the head, in front, directly overhead, in back, and below again. The KEMAR is the Knowles Electronics Manikin for Acoustic Research. It has silicone pinnae and microphones where the inner ears should be. (Courtesy of R.O. Duda)*

HRTFs measured in the median-sagittal plane are shown in Figure 1. The curves show a broad maximum near the ear canal resonance, 2-4 kHz. Most significant is the *pinna notch* which occurs near 6 kHz when the source is below, and which occurs at ever higher frequencies as the source is elevated. When the source is overhead, the notch tends to disappear leading to a relatively flat frequency response.

The HRTFs in Figure 1 correspond well with psychoacoustical measurements of human localization ability. Increasing the frequency of a characteristic spectral feature like the notch is known to lead to a sense of increased elevation. The flat frequency response for locations overhead agrees with the psychoacoustical fact that listeners find it most difficult to distinguish between slightly different locations for

*continued on page 6*

## *We hear that...*

■ **James West** was named "Distinguished Engineer" by the National Society of Black Engineers at their Golden Torch Awards ceremony held March 27 during their 24th National Convention in Anaheim. This award is the Society's most prestigious honor, and is bestowed upon individuals who have demonstrated exceptional leadership and outstanding achievement in an engineering or technical field. Jim was honored for his pioneering work on foil electret transducers and their applications to microphones.

Jim has been a member of the Acoustical Research Department at Bell Labs, now the research and development arm for Lucent Technologies, for more than 40 years. During this time, he has earned more than 40 US and 100 foreign patents on microphones and techniques for permanently charging polymers. He has authored or contributed to many technical papers and books on acoustics, solid state physics and materials science.

Earlier this year, West was elected into the National Academy of Engineering. He received an honorary doctoral degree from the New Jersey Institute of Technology and was awarded the ASA Silver Medal in Engineering Acoustics. He is a fellow of ASA and of IEEE, and currently is president-elect of ASA.

■ The four-volume **Encyclopedia of Acoustics** edited by **Malcolm J. Crocker** (John Wiley & Sons, New York, 1997) was chosen as the winner of the 1997 Professional/Scholarly Publishing Division Annual Awards Competition for Excellence in Professional and Scholarly Publishing by the Association of American Publishers.

The 166 chapters in the Encyclopedia, divided into 18 parts, cover nearly every area of acoustics. In preparing this monumental work, the editor was assisted by an Editorial Board of 28 acousticians and several hundred authors, nearly all of them members of the ASA. In the foreword, Sir James Lighthill compares the importance of this work with Lord Rayleigh's *Theory of Sound*, which appeared in two volumes in 1876 and 1877.

ECHOES

Newsletter of the Acoustical Society of America
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■ A **NATO Advanced Study Institute on Computational Hearing** will be held in Il Ciocco (Tuscany), Italy, July 1-12, 1998. This institute, directed by Steven Greenberg, International Computer Science Institute, Berkeley, "will focus on integrating recent advances in computational modeling and analysis with more traditional perspectives on hearing, with the intent of fostering a more computational approach towards studies of auditory function, physiology and anatomy, as well as defining emerging fields of inquiry derived from these innovative methods."

Other members of the organizing committee are Phil Green, Gerald Langner, and Malcolm Slaney. Further information is available at: http://www.icsi.berkeley.edu/real/ComHear98.

■ **David Middleton**, consulting physicist and applied mathematician, was elected to the National Academy of Engineering in February 1998. David, who is an ASA Fellow, was cited for his pioneering work in statistical communications theory and its applications.

■ The International Symposium on Musical Acoustics (ISMA98) has received a grant of $5000 from the **Experience Music Project Foundation** of Seattle. ISMA98, sponsored by ASA and the Catgut Acoustical Society, will be held in Leavenworth, Washington, June 26-July 1 following the Seattle ASA/ICA meeting (see http://www.boystown.org/isma98/).

The Experience Music Project, an interactive music museum opening at Seattle Center in 1999, has Jody Patton as Executive Director and is largely supported by Paul Allen, co-founder of Microsoft. The 130,000-square-foot museum, designed by architect Frank Gehry, will house a variety of interactive exhibits, educational programs, workshops, live performances and popular attractions that celebrate creativity and innovation in rock 'n' roll and other forms of American popular music. The grant to ISMA98 came about largely because of conversations between ISMA organizer Doug Keefe and a former student, James Fricke of The Experience Music Project.

■ The **Endangered Language Fund** has given ten small grants in its annual first annual round of grants. Among the ten projects for support, selected from 54 proposals, are efforts to preserve Kuskokwim, Klamath, and Jingulu. Another will help to produce a comprehensive diction of Tohono O'odham, an Indian tongue spoken by roughly 12,000 people in southern Arizona and northern Mexico.

Some linguists predict that half of the approximately 6,000 languages spoken today will be extinct within the century. The problem of disappearing languages was addressed in an article by Peter Lagefoged in the Spring 1995 issue of *Echoes*. Lagefoged and his colleagues are making recordings of disappearing languages. The Endangered Language Fund, set up by Douglas H. Whalen, ASA member and linguist at Yale University and the Haskins Laboratories, supports projects to preserve endangered languages (http:/www.ling.yale.edu/~elf).

## ASA Workshop on Classroom Acoustics

*by David Lubman*

An ASA sponsored workshop entitled "Eliminating Acoustical Barriers to Learning in Classrooms" was held December 6-7, 1997 at the House Ear Institute in Los Angeles. The intense, interdisciplinary, 1fi-day workshop, which drew nearly 100 participants, opened with a keynote speech "Classroom Communication or Classroom Chaos" by Robert Apfel, past president of ASA. This ASA outreach effort drew a dozen co-sponsoring organizations from the ranks of architecture, audiology, education, acoustical engineering, government and parents.

The Workshop was a follow-up to a special session on classroom acoustics held at the Penn State ASA Meeting in the Spring of 1997. (Some of the papers given at that session can be accessed through on-line archives at the ASA web site). The Workshop was overseen by an ASA Task Force on Classroom Acoustics consisting of representatives of four technical committees:

David Lubman, Architectural Acoustics; Peggy B. Nelson, Psychological Physiological Acoustics; Louis Sutherland, Noise; and Sigfried Soli, Speech Communication. Because ASA Technical Initiative seed money was supplemented by contributions from co-sponsoring organizations and exhibitors, the workshop generated a surplus.

The Workshop had both educational and strategic purposes. Its educational purpose was to convey the facts about poor acoustics in classrooms, usually caused by excessive noise or reverberation. The Workshop identified those affected and showed how to avoid or correct these problems by enlisting the combined efforts of parents, educators, school facilities people, audiologists, architects and acousticians. The strategic purpose was to forge a coalition for change.

Healthy young children just learning to read are found to be especially vulnerable to the effects of poor classroom acoustics. Children suffering from ear infection and its aftermath are also impacted, as are the growing number of students with limited English proficiency and others with hearing, learning and language disabilities. The extent of the problem of poor classroom acoustics was a surprise finding of a 1995 General Accounting Office (GAO) survey of 10,000

American schools. This survey discovered that poor acoustical quality was the largest single environmental complaint in American schools, affecting 28.1% of the schools surveyed and over 11 million students. An indication of the extent to which acoustical quality in classrooms has been ignored is the absence of national Standards or guidelines. The absence of acoustical Standards together with the surprise GAO finding seem especially significant for a nation embarking on the largest program of school construction and renovation in its history, estimated at over $12B in 1996, an increase of 16.4% over 1995 spending.

*David Lubman, Mark Schaffer, and Donna Sorkin listen to Karen Anderson describe problems children have learning in reverberant and noisy classrooms.*

A summary and recommendations from breakout group discussions was made,consisting of 16 viewgraph. Copies are available at ASA headquarters. An extensive package of presentation materials from the Workshop is also being compiled for distribution to all participants and others on request. Copies of slides from a July 1997 presentation to architects of the Los Angeles Unified School District are also available for review from the Technical Committee on Architectural Acoustics.

Key findings of the Workshop are:

-Poor classroom acoustical quality is a problem for which engineering solutions exist.

-Good classroom acoustical quality is best achieved by planning rather than repair.

-A broad alliance of interested organizations is needed.

-Ongoing public education is needed to ensure that an aware public asks for better listening environments.

-Classroom acoustical guidelines and standards are needed. They must be simple and enforceable at the local, state and national level.

*David Lubman, an acoustical consultant in southern California, is a fellow of the ASA and past chair of its Technical Committee on Architectural Acoustics. He organized the special session on classroom acoustics at the Spring 1997 ASA meeting and serves as co-chair (with Louis Sutherland) of a new ANSI S12 Subcommittee on Classroom Acoustics.*

# Chain Reaction

The movie "Chain Reaction," released last August and now available in video stores, will probably not win any "Oscars," but it has created a few waves in the scientific community, and it has led to a lot of amusing stories. Featuring Keanu Reeves as a would-be physicist and Morgan Freeman as a philanthropist gone astray, the film uses sonoluminescence to extract hydrogen from water and blow up a good portion of Chicago's south side, all to the great interest of the FBI and CIA.

*Photo Courtesy 20th Century Fox*

Much of the filming was done at Argonne National Laboratory in a large empty building known as CWDD (for Continuous Wave Deuterium Demonstrator, built to do ground-based Star Wars research but never activated), where the film producers constructed "a fake multi-million-dollar laboratory in a week," according to Catherine Foster, Director of Science and Technology Communication at Argonne. "The set was magnificent: A giant hydrogen tank in the center of the lab, surrounded by a control room with banks of computers and video monitors. An elaborate laser light arrangement sits on a nearby table, and dozens of smaller work stations do the rest of the set."

The plot of the movie centers on a discovery by a University of Chicago physicist, who is developing a way to separate water so that the hydrogen can be used as fuel. The technology is a combination of lasers and ultrasound, culminating in a special nozzle designed and built by undergraduate technician Keanu Reeves. Once the technology is developed and demonstrated, the physicist wants to make a worldwide announcement, but evil corporate and government forces have the physicist killed, the laboratory destroyed, and the idealistic young technician framed for the crime. He escapes in the company of a glamorous post-doc, who is kidnaped by the bad guys. Reeves traces them all to a clandestine underground laboratory in Virginia, which in real life is the CWDD facility at Argonne.

Argonne workers were initially excited about having actors such as Keanu and Morgan on site, but paid less attention as the filming dragged on. They quickly learned that movie making is time consuming. For the big evacuation scene, about 200 people (mostly Argonne employees or their relatives) spill out of the laboratory, running down a ramp for the cameras. Shooting this scene took about six hours, Foster reports, with some people making the trek about two dozen times.

Scientists, such as Seth Putterman (UCLA), who are experts on sonoluminescence were less than enthusiastic about the science in the film. "I was sort of sensitive to having my research portrayed as potentially dangerous," Putterman is quoted as saying in a story by Jim Dawson in the *Minneapolis Star Tribune*. "And in fact, they [the actors in the movie] said 'this is more dangerous than scientists realize.' In reality sonoluminescence isn't dangerous." Morgan Freeman is reported to have asked then-Argonne Director Alan Schriesheim if the process in the film would really work. Schriesheim responded that if it did, it would violate at least a couple of laws of thermodynamics.

Several months before the filming began, Ken Suslick, Professor of Chemistry at the University of Illinois at Urbana-Champaign, was visited by the set director for the proposed movie. He wanted to see what a real chemistry lab looked like. When Ken took him into a basement storage area, his interest picked up. In return for a donation to the University, he ended up with a truckload of obsolete equipment, much of which was used to create the ersatz facility at Argonne.

Larry Crum, ASA president and sonoluminescence researcher at the University of Washington, was pretty disappointed that the movie writers didn't consult any scientists to ensure the movie didn't abuse the science. "When they do lawyer or doctor shows on TV, they almost always hire some "expert" who makes most things sound pretty real. They didn't do that with this movie, and I think it was one of the reasons it bombed...it was just too unrealistic. My daughter, who saw it with her high school friends said the science stunk." The irony of this is that Larry went out of his way to offer technical advice (see essay on p.5). So did Ben Stein and his colleagues at AIP, who put out a press release which aimed to separate fact from fiction in the movie.

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locations directly overhead. The frequency response curves show an approximate, but not exact, symmetry between locations in front and in back. This agrees with the fact that front-to-back confusions are the most difficult to eliminate in attempts to synthesize precise source locations using headphones.

Psychoacousticians have now mastered the techniques of measuring individual HRTFs and reproducing their effects with headphones. The results can be dramatic. Sound images from headphones are no longer confined to the head or to an indeterminate space having a diffuse leftness or rightness. It is possible to use headphones to synthesize sound images that are externalized, compact, and correctly localized in azimuth, elevation, and (to some degree) distance.

The sense of reality can be made still more striking by including the dynamical effects of head motion. It is tricky to to this, and it requires high-speed dedicated digital convolvers, but it can be done. First, HRTFs are measured for left and right ears for source locations over the full 4p steradians of solid angle (a grid with 10-degree spacing will work). The functions are stored as impulse responses in digital memory ready for use. The listener wears a head tracker, which regularly informs the controlling computer of the pitch angle, yaw and roll of the head. The computer then calls up the appropriate left and right HRTFs, or interpolates among neighboring HRTFs, so that the location of the virtual sound source, created by headphones, is fixed as the head rotates. Listeners, it seems, are forever running subconscious tests on their auditory sensations. A virtual sound image that passes the head-motion test is perceived to be more convincing than an image that is untested.

Because of its ability to simulate sources of sound located in space, the HRTF technique opens the way to virtual auditory reality. The head-related impulse response combined with the response of a concert hall can create the impression of listening to a live performance in the hall. Computer modeling of the impulse response of the hall for different listener locations can, in principle, enable a listener to evaluate the quality of sound in the hall before it is built.

Simulating auditory images in space can lead to enhanced audio for entertainment or multimedia use. A helicopter on a video screen can be made to sound as though it is flying overhead by moving the pinna response features together with the screen image. In fact, a major television network has processed audio signals to do exactly this. Meanwhile, scientists at Wright Patterson Air Force Base have used HRTFs to provide vital information to military pilots, whose sensory channels are overloaded during combat. Localized auditory images have been used for targeting information and to indicate the location of an approaching missile.

Back in the lab, HRTFs are helping acousticians understand the basis of sound localization and the sensations of externalization and distance. HRTFs in the horizontal plane are shown in Figure 2. There is a lot of detail there, and in addition to the magnitude informa-

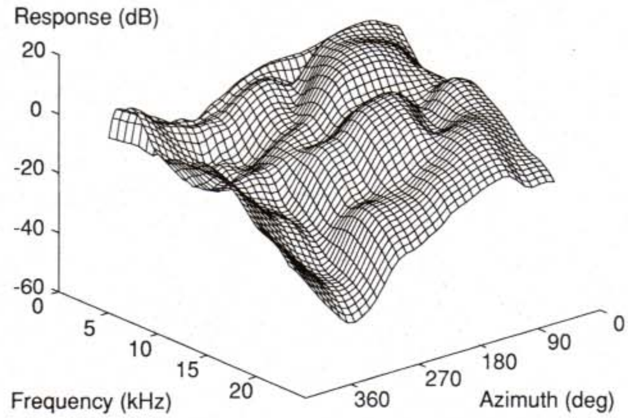


*Figure 2: Frequency response curves for a KEMAR head for sources in the horizontal plane, distributed around the complete circle. The nose points at zero degrees, and the measuring ear is at 90 degrees. (Courtesy of R.O. Duda)*

tion in the figure, there is also phase information. One wonders whether all that detail is really necessary. Experiments show that considerable information reduction is possible with negligible effect on perception. Although physical measurements of phase show significant dispersion, it appears that phase shifts can be modeled as frequency-independent delays without adverse effect. Further, the frequency response curve for a single location can be modeled by a Fourier sum with as few as eight coefficients, at least for low signal levels. On the other hand, additional detail, in the form of a radial dependence, is required to synthesize images that are within a meter of the head.

As would be expected for an anatomical feature like the HRTF, different listeners have different features. Also, perhaps unfortunately, individual differences in HRTFs are perceptually important. Experiments at the University of Wisconsin in which subjects listen through someone else's ears find increased confusion in localization, especially between sources in front and back. Images made with imperfect HRTFs can become diffused in space; although they are localized they are not compact. They often appear much closer to the head than they should be.

Widespread application of HRTF technology may

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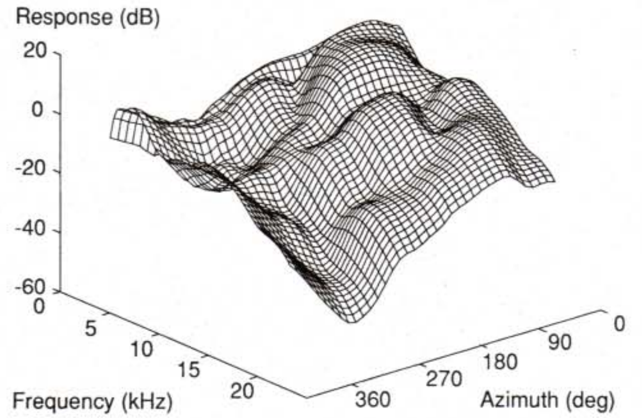


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Widespread application of HRTF technology may

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# Acoustics in the News

• Although progressive hearing loss impairs a large proportion of our populations (e.g., 16% of adults and more than one-third of those over 60 years old having a hearing loss of 25 dB or more), yet we know almost nothing about the reasons for this progressive loss, according to a paper in the March 20 issue of *Science*. Any clue to its genetic basis is useful, so the report that a mutation in the transcription factor *POU4F3* causes progressive hearing impairment in a large Israeli family is welcome news to researchers, according to Karen Steel who summarized the report.

Sensory hair cells in the inner ear are sensitive mechanoreceptors that sport a precise array of specialized microvilli, the setereocilia, at their upper surface. These hair cells can detect sound vibrations, which move the stereocilia as little as a single angstrom (0.1 nm). The sensitive arrangement at the top of each hair cell requires a precise molecular architecture that needs constant maintenance, and so it would not be surprising for a transcription factor to participate in the maintenance schedule. *POU4F3* may be required for continued maintenance.

• The duration of sonoluminescent (SL) pulses has now been determined and is independent of wavelength, according to two recent papers in *Physical Review Letters*. Researchers at the University of Stuttgart adapted the technique of time-correlated single-photon counting to SL and announced that SL pulses lasted from 50 ps to more than 250 ps and presented evidence that the length of the pulse for a given bubble is identical in the red and the ultra-violet parts of the spectrum (*Phys.Rev. Lett.* 79, 1405, 1997). Applying the same technique, researchers at UCLA were able to confirm

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depend on solving the individual difference problem. It is clear that some individual HRTFs are more successful than others. One commercially available device, intended to enhance television sound (the Auri from Virtual Listening Systems) gives the user a switch to choose among 15 representative HRTFs. Other techniques, some described at the ASA meeting at Penn State in June 1997, allow the listener to deform HRTFs to optimize localization. However, the space of possible HRTFs is so vast that an unrestricted search is bound to fail. Physical or psychoacoustical constraints must be judiciously placed to have any chance of getting close to the right answer. Perhaps one day we shall all routinely visit the HRTF-metrist who will fit us with individual virtual reality filters. Then we will be able to plug in to an expanded three-dimensional world of information and entertainment.

*Acknowledgements: Information in this article was borrowed from work by Fred Wightman and Doris Kistler, Elizabeth Wenzel, Robert Butler, Richard Duda,Abhijit Kulkarni and Steven Colburn, Richard McKinley and Timothy Anderson, also Andrew Wittenberg and myself.*

*Bill Hartmann is a professor of physics at Michigan State University. His research is on the perception of sound, particularly sound localization and the perception of pitch. He is the author of the textbook "Signals, Sound, and Sensation" (AIP Press/Springer-Verlag, 1997) and is currently vice-president elect of the Acoustical Society.*



## Now Hear This...Hiss

*To the Editor*

During a demonstration of an ultrasonic source at the "Free-for-All" session on "Education in Acoustics" in San Diego, I was reminded of an unusual auditory sensation experienced some 40 years ago. Perhaps someone can explain the phenomenon, or at least confirm its existence and eliminate my concern that it was a hallucination.

Several atmospheres of acoustic pressure at 25 kHz were being generated at the center of a large, spherical glass flask filled with water to study ultrasonic cavitation in the water.[1] The 25- kHz sound was inaudible to me but, to my surprise, I sensed a hiss in my ears whenever I moved around in the room–but only while moving.

My first hypothesis was that non-linear rectification in my hearing mechanism caused the inaudible ultrasound in the air to develop a steady component of pressure, and motion through the 25-kHz standing-wave pattern in the reverberant room modulated this pressure so it was sensed as sound. However, a quick calculation indicated that this mechanism, even if it existed, would only result in modulation at a low frequency which would vary with my speed of motion. The wavelength of 25-kHz sound in air is about 1.3 cm. Moving through the standing-wave pattern at 50 cm/sec would result in low-frequency fluctuations below 40 Hz instead of a high-frequency hiss.

Moreover, the ultrasonic level in the air does not seem high enough to result in nonlinearity. Although the level in the air was not measured, a rough estimate can be made based on the measured pressure gradient in the water shown in Fig. 4 of the reference.[1] For a sound pressure of one atmosphere in the water at the center of the sphere, the sound level in the air is estimated to be about 80 dB re 20 μPa one meter from the sphere. This is a loud sound at audible frequencies. Could motion somehow increase the sensitivity of my ears enough to detect ordinarily inaudible 25-kHz sound at this level?

1. M. Strasberg, "Onset of ultrasonic cavitation in tap water," *J. Acoust. Soc. Am.* **31**, 163-176 (1959)

*Murray Strasberg, David Taylor Model Basin, NSWC*
*9500 MacArthur Blvd.,W. Bethesda, MD 20817-5700*

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the result and found that the flash width varies by less than 3 ps from 200 nm to 800 nm (*Phys. Rev. Lett.* 80, 1090, 1998). The different pulse widths for different bubbles depend on the composition of the gas and on the intensity of the emitted light. The color-independence of the pulse duration appears to rule out the "adiabatic heating" hypothesis, because black body radiation should last longer at the longer wavelengths.

• Dipen Sinha and his colleagues at the Los Alamos National Laboratory have built an ultrasonic device that can identify the contents of a container of almost any shape or size, according to a note in the December issue of *Scientific American*. The "swept frequency acoustic interferometer" listens for resonant peaks in the sound emitted by an object subjective to ultrasonic waves that rise gradually from one to 15 megahertz. By analyzing how the peaks and valleys in the spectrum change as the frequency rises, the device calculates the density of the hidden material, the speed of sound, and the material's ability to absorb sound at different frequencies. Among the possible applications are weapons identification, monitoring water inside tanks for pollution, and detecting bacterial growth inside food containers, according to Sinha.

• After a decade of debate about noise pollution, Los Angeles has banned the use of leaf blowers in residential neighborhoods, according to a story in the Jan. 11 *New York Times*. Gas-powered blowers first became popular in California during the droughts of the 1970s when residents were forbidden to hose down driveways, parking lots, and other paved areas. Almost 1.5 million were sold in the USA in 1997, according to the industry's trade association, but little has been done to make quiet machines. Blowers run at speeds up to 9000 rpm, creating more noise than automobile engines that run around 3000 rpm and include efficient mufflers in their exhaust systems. Furthermore, many of these small air-cooled engines use fuel as a coolant, spitting unburned gasoline into the air to keep from overheating.

• In order to design new products, producers must anticipate how customers will react to the products. This is done, in part, by measuring various physical properties of the product and correlating these with subjective reactions. For one perceptual attribute, the sound of the product, experience and information are sadly lacking, according to an editorial by Richard H. Lyon in the March issue of *The Industrial Physicist*.

Some physical features of sound correlate well with perception (calculated loudness, for example, correlates very well with perceived loudness), but when sounds have some cognitive value that situation changes. Equal levels of sound from my neighbor's lawn mower (which is keeping our neighborhood attractive) and the motorcyclist racing along my street provoke quite different emotional responses.

Last September, about 30 participants from the automotive, aircraft, and appliance industries described their experiences and methods of dealing with product sounds in a workshop sponsored by ASA and the Institute of Noise Control Engineering (INCE). According to the participants, algorithms for correlating physical correlates and product perception (such as fluctuation strength, sharpness, and roughness) do not work as well as the loudness algorithm.

• New results on acoustic thermometry of ocean climate (ATOC) reported at the 1998 Ocean Sciences Meeting in San Diego Feb. 9-13 indicate that temperature readings of the Pacific Ocean are even more precise than projected and that marine mammals apparently aren't bothered by the sounds, according to a report in the Feb. 27 issue of Science. Data from the first 15 months of ATOC project indicate that 195-dB broadcasts from a source off the central California coast are picked up surprisingly well by arrays of sensitive hydrophone at Christmas Island, 5000 km away. Variations as small as 20 ms in the hourlong travel time of the pulses can be detected, and that's accurate enough to deduce the average ocean temperature along the sound path to within $0.006^{\circ}$ C. "That's far better than we expected," commented ATOC project director Peter Worcester of the Scripps Institution of Oceanography.

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