UNDERWATER AMBIENT NOISE

Peter H. Dahl
Applied Physics Laboratory, University of Washington
Seattle, Washington 98105

James H. Miller
Department of Ocean Engineering, University of Rhode Island
Narragansett, Rhode Island 02882

Douglas H. Cato
Defence Science and Technology Organisation
and University of Sydney Institute of Marine Science
Sydney, NSW 2009, Australia

Rex K. Andrew
Applied Physics Laboratory, University of Washington
Seattle, Washington 98105

Introduction

Underwater ambient noise, long an important area of study in underwater acoustics and acoustical oceanography, has recently entered the forefront of public awareness. A renewed emphasis on its study is driven in part by basic questions concerning the relation between anthropogenic noise and the ecology of marine mammals. For example, there is concern about the degree to which marine mammals are possibly habituating to, or otherwise being affected by increasing anthropogenic noise contributions. Natural ambient noise has always provided the background noise limitation on the use of sound by marine mammals, but now ambient noise contains a significant anthropogenic component.

Here we provide a brief overview and perspective on the subject of underwater ambient noise, of interest to a diverse set of behavioral, biological and physical science professionals involved in its analysis. In addition, this article may also serve as an introduction of the subject to those involved in the analysis of human community noise, and motivate a useful information exchange. That said, we state up front that this article is neither comprehensive nor exhaustive on the topics presented.

We quote directly from the National Research Council's 2003 report, *Ocean Noise and Marine Mammals*[1] to define ambient noise as "The noise associated with the background din emanating from a myriad

"Is there a convenient and physically correct way to compare measurements of sound in air and water? This question has caused a number of interesting discussions involving air and underwater acousticians, journalists, and the general public."

of unidentified sources. Its distinguishing features are that it is due to multiple sources, individual sources are not identified (although the type of noise source—e.g., shipping, wind—may be known), and no one source dominates the received field." This definition excludes the anthropogenic noise due to individual sources more localized in both time and space. Such sources are, for example, close shipping, sonars, seismic air guns, and pile driving and dredging devices. Suffice to say that an understanding of such noise sources including their potential impacts on marine mammals requires an understanding of the background, ambient noise conditions.

This article begins with a restatement of some important definitions relating to the use of decibel notation in both the air and underwater noise communities. Next, underwater ambient noise is described in terms of its spectrum, or frequency content. This is a useful and informative summary of underwater noise, but here we can only briefly allude to the noise field's variation in time, space and angle of arrival (angular intensity distribution). The major anthropogenic and natural constituents of the spectrum are itemized, and two spectra, corresponding to nominal high and low ambient noise levels, are introduced to illustrate the dynamic range of underwater ambient noise. These spectra are then compared with several examples of field measurements, and some historical trends in field measurements are mentioned.

Finally, an interesting perspective is gained by a brief examination of ambient noise as we might experience it in air, including a familiar impact concept, speech intelligibility. For this, measurements of noise originating from highway traffic that also exemplifies time variation and contributions from multiple sources, which is common in underwater ambient noise, are used. Of course, discussion of sound in air and in an underwater environment has frequently led to confusion, so we tread carefully, using genuinely comparable physical units. The intent here is to provide some background to understand the effects of noise on marine mammals by comparing sound in air and water, and the ambient noise in the two environments.

Definitions: The use of decibel notation

We recall that decibels in acoustics were defined originally at Bell Labs as 10 times the logarithm of the ratio of the sound intensity to a reference intensity.[2] Sound intensity has units of W/m² and is given by

$$I = p^2/(\rho c) \tag{1}$$

where p is the rms (root-mean-square) pressure in Pa obtained from measurements, ρ is density in kg/m³ and c is sound speed in m/s. Eq. (1) assumes that pressure is measured sufficiently far from its source such that a plane wave approximation applies.[3] The reference intensity for sound in air (ρ_{air} is about 1.2 kg/m³ and c_{air} is about 340 m/s) is

$$I_{\text{ref-air}} = p_{\text{ref-air}}^2 /(\rho_{air} c_{air}) \tag{2}$$
$$= 1 \times 10^{-12} \text{W/m}^2$$

where $p_{\text{ref-air}}$ equals 20 µPa, corresponding to the rms pressure at the nominal threshold of human hearing at a frequency of 1000 Hz. The reference intensity for sound in water (ρ_{water} is about 1025 kg/m³ and c_{water} is about 1500 m/s) is

$$I_{\text{ref-water}} = p_{\text{ref-water}}^2 /(\rho_{water} c_{water}) \tag{3}$$
$$= 6.5 \times 10^{-19} \text{W/m}^2$$

where by accepted convention, $p_{\text{ref-water}}$ equals 1 µPa.

Note that the reference intensity levels in air and water differ by more than 6 orders of magnitude. It is this reason why air and water measurements in decibels (dB) are not the same, as the references themselves differ by 62 dB. The characteristic impedance of air, $\rho_{air} c_{air}$, and water, $\rho_{water} c_{water}$, have units of rayls named in honor of Lord Rayleigh. The standard characteristic impedance for air is approximately 415 rayls and for water is about 1,500,000 rayls. Impedance in acoustics is the ratio of acoustic pressure to particle velocity for plane waves. It plays the same role as resistance does in electric circuits, the ratio of voltage and current. Ohm's law applies to electricity and acoustics.

Sound pressure can also be expressed as a level in dB, and consistent with the above definition regarding ratio of intensities, sound pressure level (SPL) in dB is thus defined as:

$$\text{SPL(dB)} = 10\log_{10}\frac{p^2}{p_{\text{ref}}^2} \tag{4}$$

Equation (4) defines SPL in terms of the square of the pressure amplitude, and to emphasize the all-important reference pressure level, the shorthand "dB re 20 µPa²" is required if measurements of p were made in air and "dB re 1 µPa²" if they were made in water. It has, however, become convention to express the reference levels as "dB re 20 µPa" in air and "dB re 1 µPa" in water, in view of the fact that SPL in Eq. (4) can also be obtained from the ratio of rms pressures, i.e, by 20 times the logarithm of the ratio p/p_{ref}. We will also refer to SPL values in this manner.

The approximate magnitude range of the pressure spectral density for underwater ambient noise

The underwater ambient noise field depends both on the strength and density of sources of sound and on the propagation to the receiver, which in turn depends on the particular underwater environment as set by sound speed, bathymetry, acoustic properties of the seabed, and ocean dynamics. We expect and indeed observe large fluctuations in the level of underwater ambient noise upon a change in time, location, or depth. Still, it is possible to sketch out a function describing the approximate magnitude range for the pressure spectral density of underwater ambient noise in very general terms. The *pressure spectral density* gives the mean-squared pressure of noise measured within a given frequency bandwidth, divided by the measurement bandwidth Δf, and thus the ordinate is in units of pressure squared per hertz.

For underwater acoustics, the decibel unit for pressure spectral density is dB re 1µPa²/Hz, which is called the *spectral level*. To obtain SPL in dB from spectral level values, a particular bandwidth of interest needs to be identified. For example, if the spectral level were a constant N, over the bandwidth B, in Hz, SPL would be N + $10\log_{10}$(B). If the spectral level is not constant over the bandwidth of interest, integration of the pressure spectral density in linear units (i.e., mean square pressure per hertz) is instead performed to recover the mean-squared pressure.

The earliest studies of underwater ambient noise were made during World War II and were quite extensive, covering a wide range of locations and conditions, and were published in a substantial report and later in a scientific paper.[4,5] These established that surface-ship radiated noise, sea surface noise (mainly breaking waves and what was later found to be the ensuing bubble production), and the sounds of the marine animals contribute most to the ambient noise field. In a later study, Wenz[6] recognized that ships across an ocean basin could produce a general low frequency background noise that may not in fact be recognizable as coming from shipping; he called this "traffic noise" to distinguish it from noise from readily identifiable shipping sources. His noise summary curves have formed the basis of many prediction systems.

As a consequence of their location near the surface, the radiation efficiency of both shipping and sea surface noise sources diminishes for sound rays (representing the direction of sound propagation) that have decreasing angle relative to horizontal. On the other hand, long range propagation favors ray angles close to the horizontal, and this tends to dominate in the case of low frequency, distant shipping noise. The vertical angular distribution of sound from distant shipping sources will be enhanced at shallow grazing angles, despite the fact that the initial radiation efficiency for such angles was small. Sea surface noise, however, is mainly generated by bubbles very close to the sea surface, much closer than ship noise sources. Because the sea surface is a "pressure release" surface with a substantial impedance mismatch, the radiation from the bubbles and their surface images is effectively dipole with maximum radiation downwards. As a result, most of the noise at a receiver comes from nearby sources and steep angles, often leaving a gap that is observed in the vertical angular distribution near horizontal, known as the "ambient noise notch."[7]

There is a dichotomy between *deep water* and *shallow water* ambient noise, based largely on the nature of sound propagation from sources located near the sea surface. Deep water ambient noise is from an environment for which there is no bottom interaction of sound from distant sources (typically commercial shipping). This occurs if there is a critical depth (also called a conjugate depth) at which the sound speed is equal to the sound speed at the sea surface.[8] A ray is refracted following Snell's law towards the water mass with lower sound speed, and those with small initial, or launch, angles become trapped between the sea surface and (approximately) the critical depth. This is illustrated using a sound speed versus depth profile based on the climatology[9,10] at location 33.42° N 173.68° W, which puts the critical depth around 4000 m (Fig. 1). The noise level below the critical depth is reduced, but does not vanish altogether.

On the other hand, shallow water ambient noise is that associated with an environment for which there is no critical depth and there is interaction of sound with the seabed. A critical grazing angle, α_c, equal to arccos(c_w/c_b) can usually be identified, where c_w is the sea water sound speed at the water–sediment interface, and c_b is the sound speed in the sediment and $c_b > c_w$. Sound rays with grazing angles greater than α_c penetrate the seabed and are attenuated, and thus the angular distribution of distant shipping noise remains nominally within $\pm \alpha_c$.[11] Furthermore, for a seabed with moderate reflectivity (as is often the case), the angular distribution of wind-generated surface noise may not change appreciably,

but the area of contributing sources enlarges as a result of multiple reflections. A typical α_c for the seabed is 20–30°, and the association of the angular distribution of the noise field with the bottom critical angle is the basis for inversion of ambient noise measurements for both sound speed and attenuation in the seabed.[7,11]

The more reflective the bottom the greater the α_c; this combined with an ambient noise field concentrated within a shallower water column, generally means shallow water ambient noise levels exceed those in deep water. How much? Wenz[6] noted that shallow water noise levels are "…about 5 dB greater than corresponding deep water levels at the same frequency and same wind speed," which is a reasonable value to assume for purposes of this discussion.

To be sure, this simple dichotomy does not accommodate all littoral and pelagic conditions, and it tends to gloss over distinct acoustic environments from the standpoint of both propagation and the nature of the noise sources. Nevertheless, let us proceed towards describing typical magnitudes for the pressure spectral density of underwater ambient noise, and take this description to be broadly applicable to both deep and shallow water conditions, with the caveat that on average shallow water ambient noise levels will be higher. Our description consists of the two curves (solid, and dashed gray lines) in Fig. 2 for the pressure spectral density of ambient noise that are assembled as follows. The curve of higher level is an amalgamation of Wenz's "heavy traffic noise" spectral density plus the spectral density of wind-speed related noise associated with Beaufort wind speed scale 8 or 34–40 knots (gale force winds).[6] Note that sea state is often used as a broadly based environmental input parameter for noise models, even though the noise from the sea surface correlates much better with wind speed than with sea state. The World Meteorological Organization (WMO) sea state code 6 corresponds to Beaufort scale of 8, and WMO sea state 0 corresponds to glassy calm conditions. Similarly, the curve of lower level represents a combination of "light shipping" plus the spectral density of ambient noise associated with WMO sea state 0.[12] Shipping activity and sea state are combined in this rather artificial way to obtain our two curves, approximately 25 dB apart, that describe the general nature of underwater ambient noise in terms of pressure spectral density, as would be measured by an omnidirectional hydrophone. We take these two curves to represent nominal high and low pressure
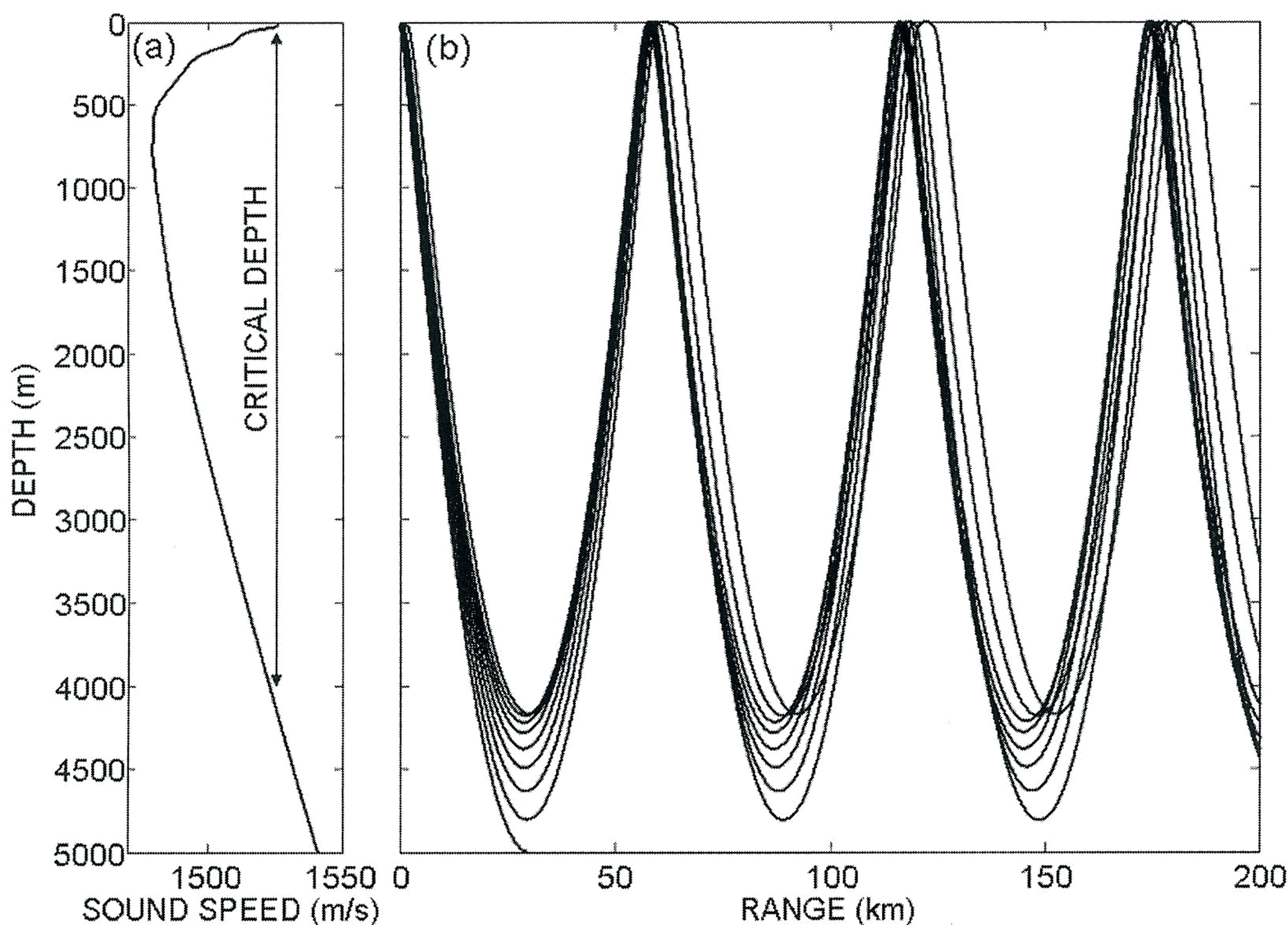

Fig. 1. Illustrating the critical depth for a pelagic environment. (a) Sound speed versus depth based on climatology at 33.42° N, 173.68° W (see Refs. [9,10]). In this example the critical depth is 4000 m and the sound speed here equals the sound speed at the sea surface and is less than the sound speed at bottom depth (5000 m). (b) Rays launched from a source near the sea surface will refract towards the water mass with lower sound speed. Rays with launch angle greater than 7° will intersect the bottom and do not propagate to long distances owing to bottom attenuation (one such ray is shown). Sound from distance shipping is effectively trapped between the sea surface and the critical depth. The clustering of rays at quasi-regular intervals is called a convergence zone.
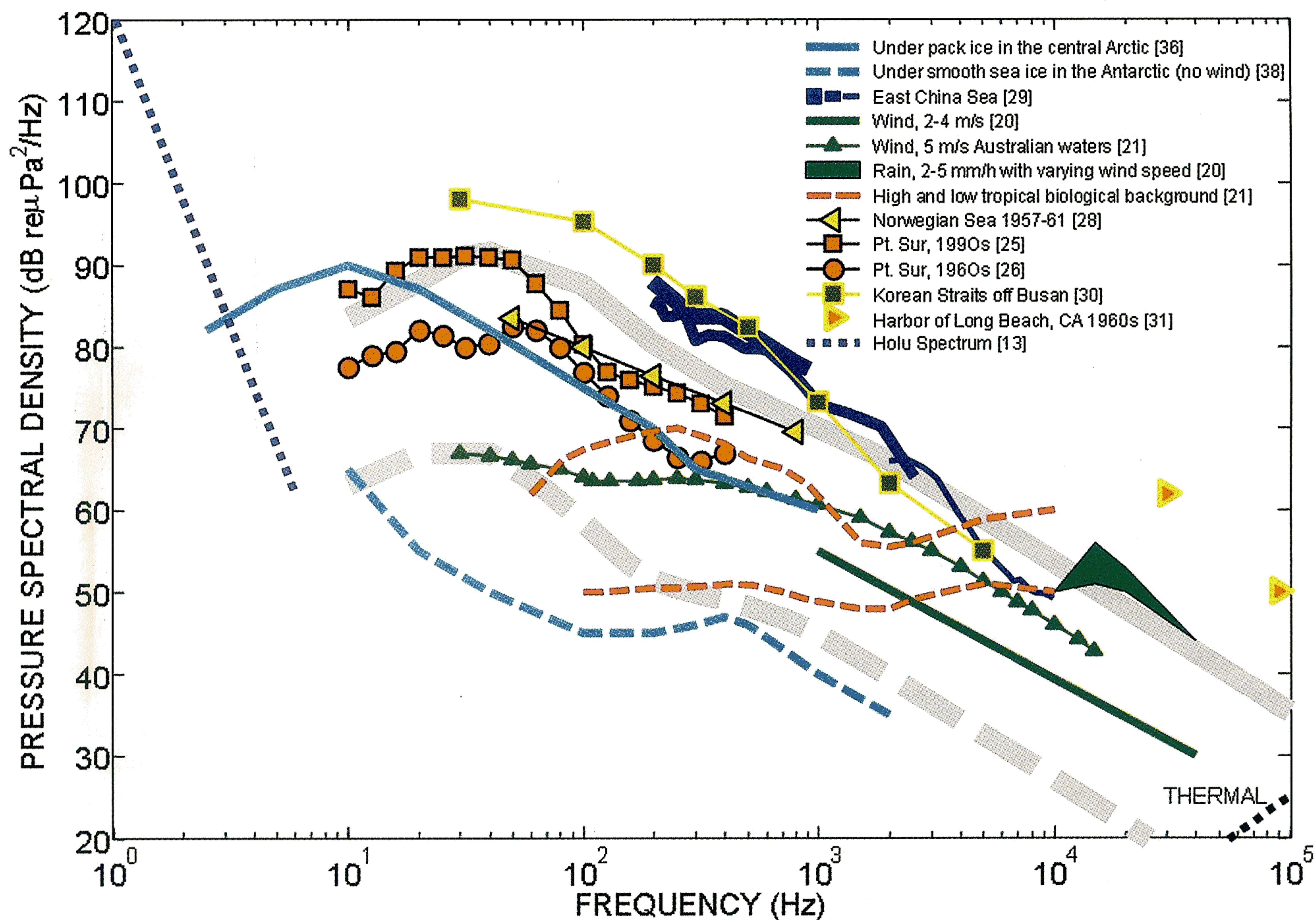
Fig. 2. Curves representing the nominal high (solid gray) and low (dashed gray) magnitude of the pressure spectral density of underwater ambient noise. The nominal high curve is based on a combination of heavy shipping activity plus sea state 6, and the nominal low curve is based on a combination of light shipping activity plus sea state 0 (see text for explanation on construction of curves). Several examples of measurements of the ambient noise pressure spectral density are plotted with references identified in the legend. (These represent different averaging periods and measurement bandwidths, and use of either symbols or lines does not reflect frequency resolution of measurements.) The spectral density of thermal noise is shown in the lower right corner for reference.

spectral density levels for underwater ambient noise in the 10–100,000-Hz band.

The starting frequency of 10 Hz is motivated more by simplicity and need to limit the scope of this discussion. The infrasonic band of < 10 Hz is also more strongly influenced by shallow water waveguide effects that establish a cutoff frequency for effective sound propagation.[1] However, it is worth noting here that in pelagic, open waters, the general trend for frequency dependence and spectral level within the nominal 1–10-Hz band is reasonably described by the Holu Spectrum (observed to apply between 0.4 Hz and 6 Hz), from the Hawaiian word for deep ocean,[13] and which is shown for reference in Fig. 2. Ambient noise in this spectral band is associated with the dynamics of ocean surface waves. Shorter wavelength ocean waves exhibit a saturation beyond which they no longer increase in waveheight, and this is mirrored in the Holu Spectrum insofar as the spectral density remains roughly constant for a given frequency.

The ending frequency of 100,000 Hz (100 kHz) is largely set by thermal noise generated by the random motion of water molecules. Thermal noise ultimately establishes the lower limit of measurability of pressure fluctuations associated with truly propagating sound waves, and is also shown for reference in Fig. 2.

In regions of the world with high shipping densities, the frequency band between about 10 Hz and 200 Hz is primari-

ly associated with distant shipping activity, and this source typically constitutes the largest anthropogenic contribution to underwater ambient sound in terms of mean-squared pressure.[1,6] The majority of the noise power radiated into the water by surface ships comes from propeller cavitation.[14,15] Above 200 Hz, depending on wind speed, and extending up to ~100 kHz, wind-generated sea surface agitation governs much of the ambient noise field. Wind-speed related noise rather consistently shows an approximate 5 dB reduction in average pressure spectral density per factor of two increase in frequency, which is reflected in the Wenz curves.[6] Wind-generated noise largely results from bubbles created in the process of wave breaking. At lower frequencies (< 500 Hz) it is the oscillation of bubble clouds themselves that are considered to be the source of sound,[16,17] while at higher frequencies the excitation of resonant oscillations by individual bubbles is the source of sound.[18,19]

Several ambient sound data sets are shown in Fig. 2 to illustrate both some degree of consistency, and discrepancy, with the two curves describing nominal high and low noise pressure spectral density. These data sets represent different averaging periods and measurement bandwidths (discussion on the related topic of frequency resolution and spectral variance, which can be found in many standard texts, is beyond the scope of this article). The data curve for a wind speed of 2–4 m/s (4–8 knots),[20] corresponding to WMO sea state

between 1 and 2, is clearly parallel to our high and low curves for frequencies > 1000 Hz. The increase in spectral level with decreasing frequency does not continue; instead a spectral plateau, or even a slight decrease in spectral level with decreasing frequency (i.e., the opposite trend), is characteristic of purely wind-speed dependent noise, although this is difficult to see in data owing to shipping related noise that tends to dominate lower frequencies. However, this is clearly evident in the wind-related noise data curve corresponding to a wind speed of 5 m/s[21] taken in Australian waters where shipping traffic is much reduced. Furthermore, a recent refined analysis of the wind dependence of low-frequency (< 500 Hz) ambient noise measurements from the 1975 Church Opal data set taken midway between Hawaii and California[22] displays the same trend.

Rain can produce a peak in the ambient sound pressure spectral density in the vicinity of 15 kHz, as is shown by the range of data depicted by the green shaded area, corresponding to rain rates from 2 to 5 mm/hr measured at different wind speeds.[20] The spectral peak is associated with acoustic resonance from the dominant bubble sizes created through the impact of rain drops;[23] at higher rain rates, however, this peak tends to be obscured and the spectrum flattens out and may reach levels of 80 dB re 1 μPa^2/Hz at 10 kHz.[24] The Wenz curves do not reflect the contribution from rain *per se*, and thus the explicit contribution from rain is not included in our simplified descriptive curves for high and low noise pressure spectral density.

Underwater ambient sound from commercial shipping is typically quite variable given that this contribution is strongly modulated by both shipping activity and environmental conditions for long range acoustics propagation. A maximum in spectral level, in the vicinity of 50–100 Hz, is often observed with a decay in frequency thereafter at a rate somewhat higher than that observed for wind-related noise;[6] this is apparent in analysis of data taken from the bottom mounted SOSUS array (depth ~2000 m) located on the continental slope off Point Sur, California.[25] These data, from 1995–2001, represent *long-term averages* that can reflect seasonal and yearly trends. Their higher level is postulated to be associated with increases in anthropogenic noise due to shipping over recent decades as evidenced by a comparison (also in Fig. 2) of measurements made using the same receiver but over the years 1963–1965.[26] A more recent study,[27] also involving continental slope waters off California, reports a similar increase in noise level believed to be associated with increases in commercial shipping activity. Not necessarily comparable to these data, but still of interest, is the data curve in Fig. 2 representing measurements taken in the Norwegian Sea over 40 years ago[28] using bottom mounted hydrophones in waters of depth 600 m. The noise spectral levels are a combination of "moderately heavy traffic composed of diesel-engine trawlers and smaller fishing craft," and rough seas and high winds.

Ambient noise levels readily exceeding the nominal high spectral density curve in Fig. 2 were measured by three experimental groups[29] involved in the 2001 Asian Seas International Acoustics Experiment (ASIAEX) in the East China Sea in waters of depth ~100 m. A composite pressure spectral density composed of the three different but overlapping frequency ranges measured by each group is shown by the three blue-colored lines of varying thickness. In this case the primary source of noise is a fleet of ~30-m-long fishing trawlers (as wind speed during the observation period was less than 3 m/s) operating constantly in the immediate experimental area with a vessel density of approximately 1–2 vessels per square kilometer. Like intense fishing activity, busy harbors in shallow water invariably possess high ambient noise levels, as seen in the data taken in the Korean Straits (depth ~100 m) within the shipping lanes of the large port of Busan,[30] representing a spectral average over 30 min, during which the wind speed was 2 m/s. Also shown in Fig. 2 are measurements made at very high frequency (30 and 90 kHz) within the confines of the port of Long Beach, California.[31] Interestingly, similar high frequency measurements from other ports are reported in Ref. 31 and the general tendency of the noise level to increase with decreasing port latitude was observed and presumed to be associated with a greater abundance of snapping shrimp (more on this below). We nevertheless anticipate that noise spectral levels from a typical port environment, or otherwise from waters of concentrated commercial shipping or fishing activity, and derived from a suitably long-term average (say, 30 min or more), to exceed our nominal high spectral density curve by ~10–20 dB.

A view of underwater ambient noise based on the combination of sea state and commercial shipping contributions (including fishing or recreational boating) alone is, of course, far from complete. Biological noise from fish, invertebrates and whales is an important component of ambient noise.[5,32-34] The most ubiquitous biological contribution is that produced by snapping shrimp, which abound in shallow temperate and tropical waters.[35] Biological noise may form the major background noise in some areas. The "tropical biological background" in Fig. 2 shows the range of background noise in waters north of Australia where the ambient noise is mostly from biological sources and is dominated by snapping shrimps above 2 kHz. Biological choruses that result when large numbers of animals are calling, typically of a few hours duration, are common, especially following sunset. In the range of a few hundred hertz to a few kilohertz, levels over a wide area can be as high as the highest levels in Fig. 2.

In ice-covered waters that are often far removed from distant shipping sources, a very different picture emerges. In the central Arctic, low frequency (10–20 Hz) noise is correlated with stresses applied to the pack ice by a combination of winds, currents, and pack ice drift,[36,37] and levels near the spectral peak (~15 Hz) can reach those produced by shipping sources. In conditions where these stresses are reduced, under-ice conditions can produce very low levels of underwater ambient sound. For example, measurements made under smooth, 3-m thick Antarctic sea ice in McMurdo Sound during the austral summer of 1969[38] fall well below our nominal low noise spectral density curve. In this case, the smooth surface of the McMurdo ice sheet is thought to have minimized the effect of the wind, and wind speed itself was minimal during the measurement period. The spectral peak near 400 Hz is a biological component associated with phonations of Weddell seals. Were we to remove the light shipping activity contribution from our low noise curve, the
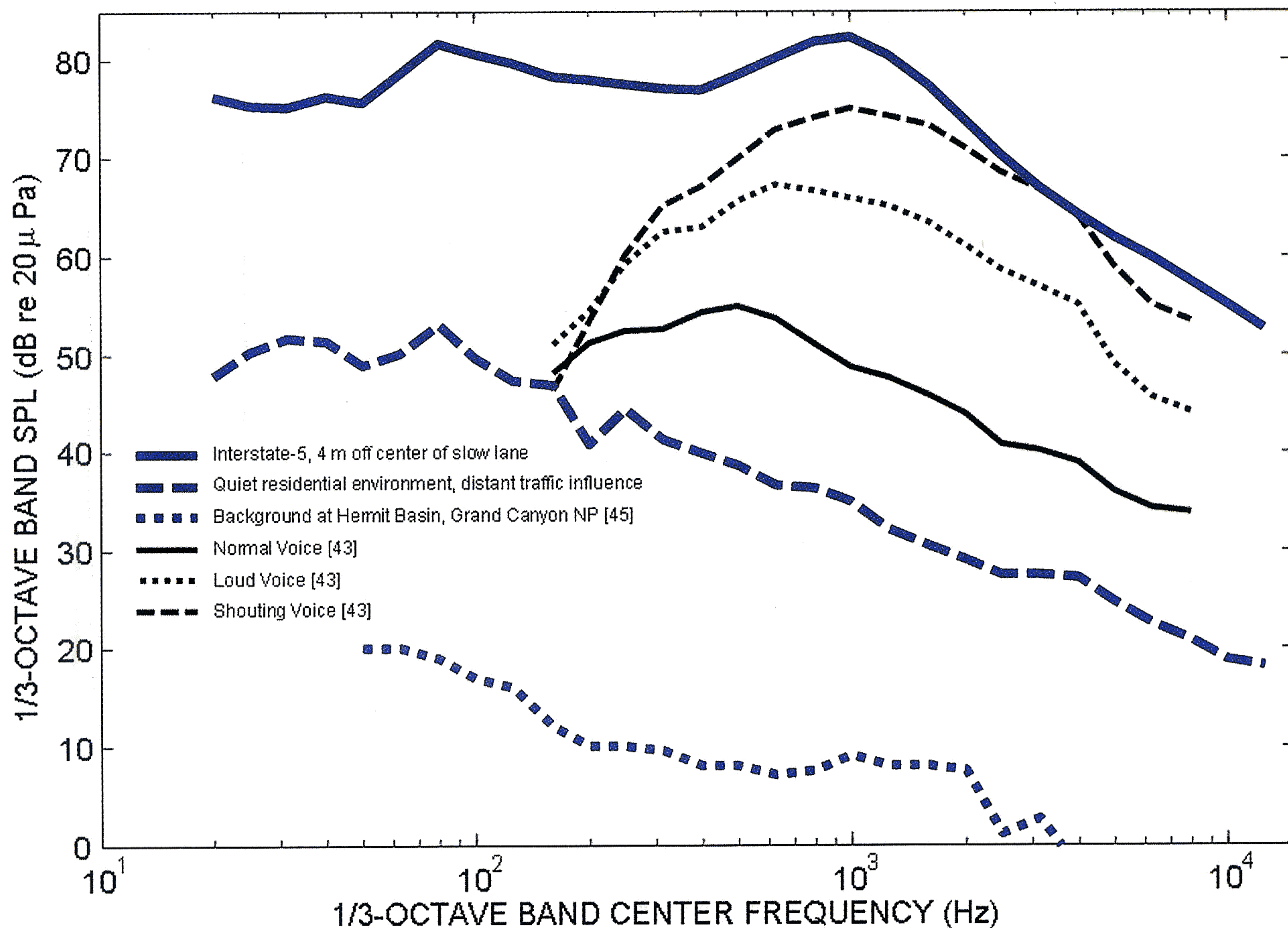
Fig. 3. One-third-octave spectra of noise measurements for three environments in air (blue lines), compared to spectra for standard speech according to ANSI standard 3.5 (black lines).

result would be closer to the Antarctic measurements for the 10–100-Hz band.

In summary, the basic trend conveyed by Fig. 2 is consistent with the notion of the ocean behaving as a "low pass filter" for sound transmission. This can be understood in view of the increase in attenuation for underwater sound with increasing frequency, e.g., at 100 Hz the attenuation is 0.02 dB per km where as for 1000 Hz it is 0.06 dB per km.[1] We have previously remarked on the prevalence of near-surface sources in the composition of underwater ambient noise. Interestingly, for a uniform distribution of such sources, a reduction of intensity due to geometrical spreading is exactly compensated by the increase in the number of noise sources with increasing area.[7] Thus, attenuation, rather than geometrical spreading loss, ultimately governs the picture.

Perspective: Background, ambient noise as we might experience it in air

Underwater ambient noise is not something we ordinarily experience, unless it interferes with, or otherwise involves, the operation of underwater acoustic devices. There are numerous exceptions of course, e.g., snapping shrimp can be heard easily when diving near coral reefs. Still, it is of interest to examine examples from airborne, community noise if only to broaden our perspective on the subject.

Highway traffic noise represents for many populations the largest contribution to community noise. Figure 3 is a spectrum of noise originating from high-speed highway traffic

measured at 11:00 a.m. on a weekday in February 2006[39] along the busy Interstate-5 (I-5) corridor north of Seattle, Washington. The spectrum represents the average of two, 10-min averaging periods that produced nearly identical spectra. The measurement was made at a height of 1.5 m above the pavement and at a distance 4 m offset from the center of the nearest lane (the slow lane). This height follows approximately the Federal Highway Administration guidelines[40] for measuring highway noise, but the offset is less than the recommended 15 m, and a cylindrical spreading model[2] for highway noise suggests these measurements would be reduced by ~7 dB were they to have been made at the longer range. Vehicle passage rate was about 100 per min in each direction (combined rate of 200); a high rate, but not enough to reduce the average speed below the limit of 96 km/h (60 mph), and the peak in the vicinity of 1000 Hz is typical for high speed traffic spectra for which tire-related noise is a major contributor.

The A-weighting filter that is commonly applied to measurements of community noise was purposely not used here, and the result is a spectrum that shows a second spectral peak in the vicinity of 80 Hz, corresponding to truck engine noise at cruising speed. The A-weighting function (Fig. 4) can be loosely thought of as an approximation to nominal human hearing sensitivity, relative to that at 1000 Hz, and A-weighted noise measurements are considered to provide improved correlation with metrics associated with community noise annoyance. For sound measurements made with A-weighting, the contribution from sound fre-
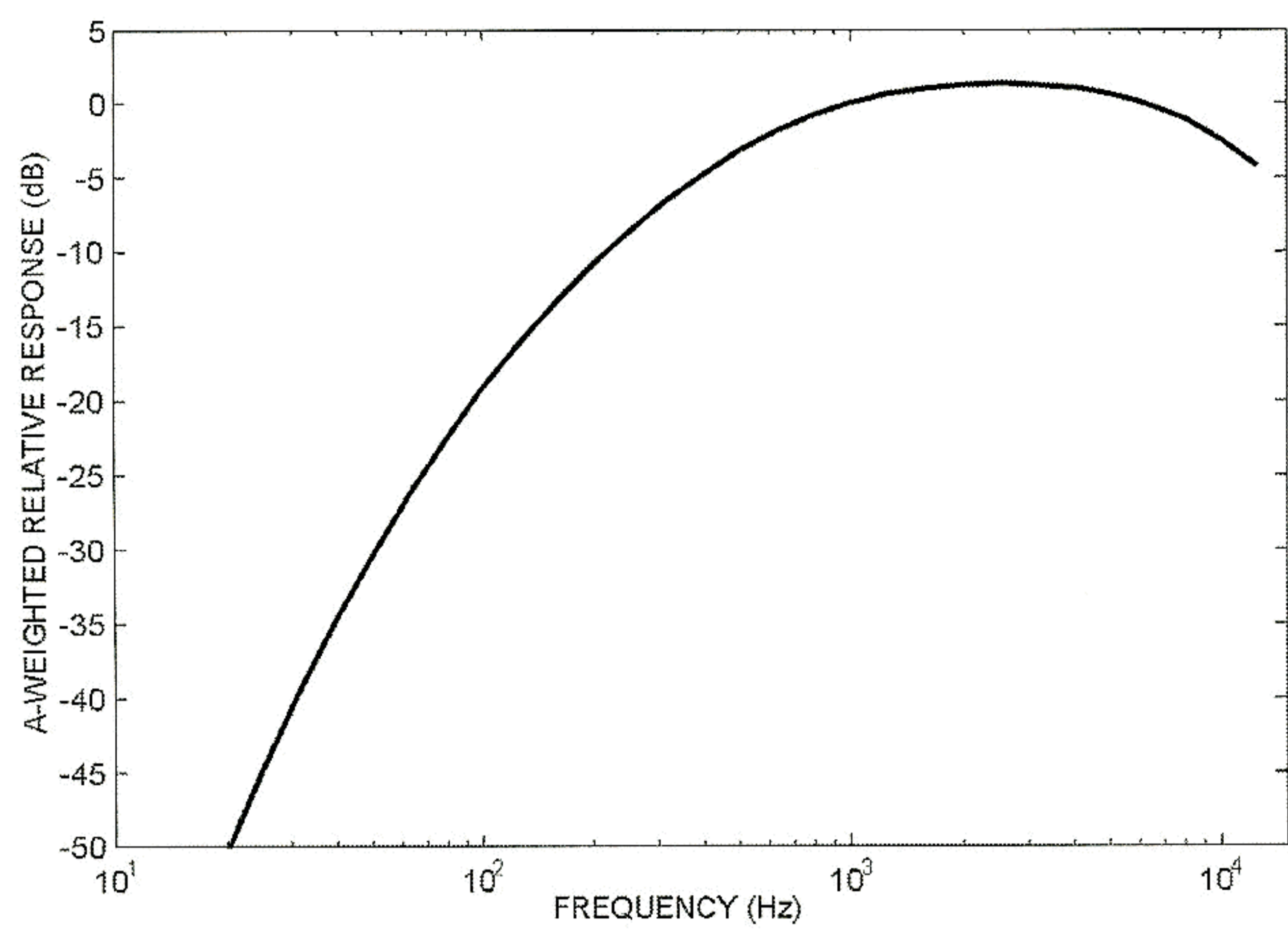
Fig. 4. A-weighting expressed in decibels as a function of frequency.

quencies less than 1000 Hz is reduced, reflecting our reduced hearing sensitivity in this frequency band, and a small gain is applied to frequencies between 1 and 5 kHz that corresponds to the frequency range of greatest hearing sensitivity. Thus, the engine noise spectral peak would not usually show up in an A-weighted traffic spectrum owing to the ~20 dB attenuation applied in this frequency range.

The ordinate in Fig. 3 is labeled "third-octave band sound pressure level (dB)," meaning the values represent the mean-square pressure output from each of the sound level meter's third-octave filter bands, expressed in dB re 20 μPa. This is to be contrasted with the *pressure spectral density* of Fig. 2, a display more common to the underwater acoustics community. Third-octave filtering, however, is a method common to both air and underwater noise analysis, and originates from studies on human hearing for which the ear can be viewed as a series of band pass filters (called critical bands) about a third octave wide. The bandwidth is a constant fraction of the band's center frequency (about 23% for third-octave bands), e.g., at the center frequency of 1000 Hz the bandwidth is 230 Hz. Thus, for the third-octave measurement data the measurement bandwidth is increasing with frequency, and were the data in Fig. 3 to be expressed in terms of a pressure spectral density both spectral level and spectral slope would change. To obtain the total (broad band) SPL, i.e., one that includes contributions from all frequencies measured, the sum of the third-octave band levels (SPL_i) is taken as follows,

$$SPL = 10\log_{10}\sum_i 10^{SPL_i/10} \tag{5}$$

which gives 92 dB re 20 μPa for this location. The corresponding A-weighted value, for which the truck noise is effectively removed, is 88 dBA. (Given the averaging period of 10 min, this number would thus be commonly be reported as 88 dBA, $L_{eq,10\,min}$ for A-weighted, equivalent continuous noise level.)

The noise field at the I-5 location would exceed typical upper bounds of tolerable community noise. More representative of traffic noise impacting living areas is the spectrum measured in a residential area close to a busy road (prior to construction of a noise barrier)[41] that is very similar in shape to the I-5 spectrum in Fig. 3 but with spectral levels 18-20 dB

less. On the other hand, measured broad band noise levels up to 88 dBA L_{eq}, 30 min, associated with traffic noise in living and studying environments in Hong Kong have been reported.[42] While being immersed in the I-5 noise field normal voice communication is clearly impacted such that one must either shout or use a loud voice, and be generally closer, to communicate effectively with another person. This is evident by the three black curves in Fig. 3, which are the third-octave band spectra for human speech at range 1 m from the speaker's mouth, for normal, loud, and shouting vocal efforts according to ANSI standard 3.5.[43]

In the first issue of *Acoustics Today*, Long[44] discusses some simple ways to quantify speech intelligibility using A-weighted measures. For such a quantification the A-weighted spectral density of the signal and the noise must be roughly similar (in shape), and this is approximately the case for the highway noise and loud vocal effort. The corresponding A-weighted broad band SPL for the loud voice is 74 dBA, which is not significantly less than the unweighted SPL owing to the shift to higher frequencies associated with the increase in vocal effort (Fig. 3). The four of us at the I-5 site carried out strained conversation at a position ~3 m further offset from where the measurements were made, which would put the traffic noise level at this point equal to 85 dBA. A minimum signal-to-noise ratio equal to negative 6 dB is needed for adequate intelligibility according to the criterion that 60% of the sentences are correctly identified in the presence of background noise.[44] To obtain adequate intelligibility, we needed to close our speaking distance to about 1/2 m, putting the loud voice SPL closer to 80 dBA, and within 6 dB of the traffic noise level.

For reference, Fig. 3 also shows a spectrum of background noise measured outside a residential home in northeast Seattle at 5:00 p.m. on the Saturday evening following the I-5 measurements (by the first author and under similar meteorological conditions as the I-5 measurements), and of background noise from Hermit Basin in Grand Canyon National Park,[45] representing an extremely quiet environmental noise background in air. For the residential case there remains a hint of the din of lower-frequency engine noise from I-5, located 4 km to the west, and perhaps from Interstate-405, located 6 km to the east, but otherwise the higher frequency tire noise has been largely attenuated, and the total SPL is 60 dB re 20 μPa, which corresponds to 46 dBA. This dBA value is typical of that representing a quiet residential environment[2] and the high-pass filtering influence of A-weighting is significant given that the noise contribution is predominately from frequencies < 1000 Hz. For Hermit Basin, the total SPL is 27 dB re 20 μPa, which corresponds to 17 dBA.

Our simple demonstration of a noise impact insofar as the approximate quantification of reduced speech intelligibility and subsequent adaptation (raised voices and closer range), is straightforward enough to do given the ANSI standard plus direct measurements of the noise environment in effect. Our intention is not to imply this quantification is equally straightforward in the case of underwater noise and marine mammals. Nor do we indicate this kind of impact represents a perfect analogy, e.g., in addition to communication impacts, the underwater ambient noise field can impact

a number of important marine mammal functions, e.g., feeding,[46] migration,[47] and physiological impacts.[48] Nevertheless, we take the quasi, steady-state din and multiple-source quality of the road traffic noise field, and, to a limited extent, the impacts that it presents to humans, as interesting if not somewhat useful analogies to consider in the context of underwater ambient noise.

Comparison: Ambient sound levels in air and underwater

Acoustically, the atmosphere and the ocean are two very different environments and this is reflected in differences in the nature of the ambient noise. The absorption attenuation of sound in air is far greater than in water, typically hundreds of times greater at the same frequency, and thus for frequencies in the 100-1000 Hz range, absorption is more of a significant limitation on sound propagation in air than in water. The cap on the underwater environment provided by the air–water interface, besides causing a dramatic change in acoustic impedance, can change geometrical spreading losses from spherical (factor of 4 reduction in intensity per doubling of distance, or 6 dB reduction) to cylindrical spreading (factor of 2 reduction, or 3 dB reduction) for ranges roughly greater than the water depth. However, this depends on the acoustical characteristics of the bottom and also acoustic frequency; a highly reflective bottom will maintain the energy in the water column while an absorptive one will remove it. On the other hand the usual situation in daytime air is upward refraction

and there is nothing to return the ray paths back to the ground, which tends to limit the area of sources contributing to airborne noise. (Important exceptions include weather dependent and nighttime temperature inversions, wind, and other features of propagation of sound in the atmosphere—see Volume 2 of *Acoustics Today* for discussion.[49])

These differences in propagation mean that we can expect contributions from sources over a much wider area in the case of underwater noise than for airborne noise. Consequently, the spatial correlation scales for the intensity of underwater sound are expected to be greater than for sound in air. For example, the noise environments at the I-5 locality and the city residence, separated by a few kilometers, are manifestly different, whereas one can expect to find large expanses of the North Atlantic presenting very similar noise environments. Shipping traffic spread over the entire ocean can contribute significantly to the ambient noise at any position, whereas high noise environments on land such as around busy highways and airports are much more localized.

Nevertheless, is there a convenient and physically correct way to compare measurements of sound in air and water? This question has caused a number of interesting discussions involving air and underwater acousticians, journalists, and the general public. From the previous discussion, intensity can be computed for plane waves in air and water by taking into account the rms pressure of the wave and the acoustic impedance of the media (see also ref. 50). From a physical point of
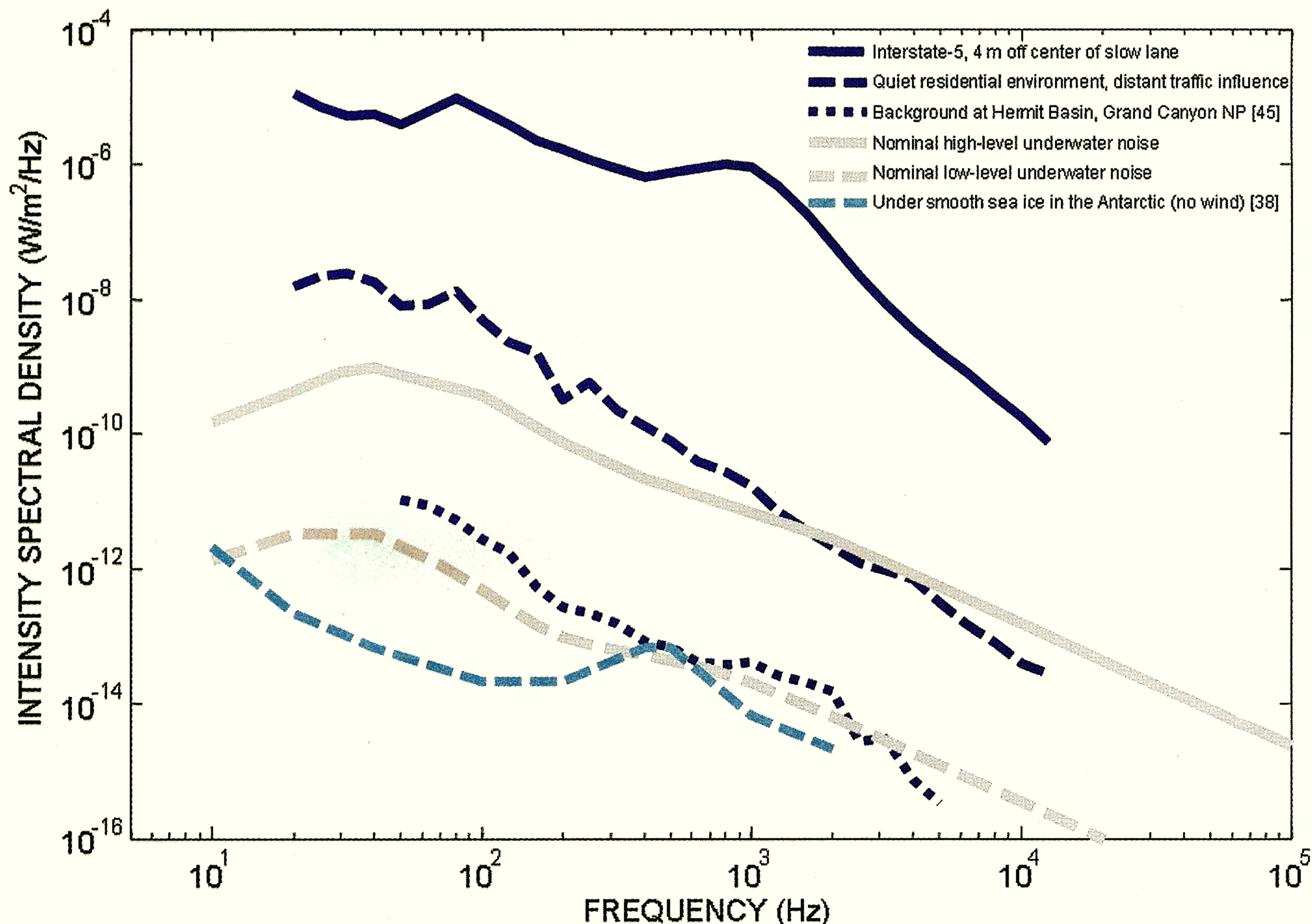

Fig. 5. Intensity spectral density of noise for different environments in air and underwater. Solid and dashed gray curves represent nominal high-level and low-level underwater ambient noise, respectively, as originally discussed in context of Fig. 2. Note: each tick mark on the ordinate is equivalent to a change of 20 dB (air or water).

view, a comparison of intensities, rather than pressures or measures of particle motion, is appealing. From the point of view of the sensitivity of mammals to noise in the two environments, it may also be the most appropriate comparison.[51] Terrestrial mammals have evolved a complicated auditory system that matches the impedance of the air to that of the liquid filled cochlea, the sensing part of the inner ear. Marine mammals have a similar adaptation to their environment. The impedance matching allows the optimal transfer of energy from the sound wave in the medium into the cochlea, irrespective of the relative pressures. For the same rate of flow of energy (per unit area) into the cochlea, the pressure in the medium will be about 35 dB higher in water than in air (this results from the ratio of impedances from Eq. 1 because intensity equals the rate of flow of energy per unit area). Let us now proceed with the comparison of ambient noise environments in air and water by revisiting some of the results in Fig. 2, concerning the pressure spectral density of underwater noise, and in Fig. 3, concerning the one-third octave spectrum of background noise measurements made in air, viewing each on the same plot with ordinate having a dimension of $W/m^2/Hz$. This view is an *intensity spectral density.*

For this, both kinds of data must be stripped of their decibel notation, converted to pressure spectral density in terms of Pa^2/Hz, then divided by their respective acoustic impedances. For the third-octave measurements of airborne noise, the aforementioned measurement bandwidth that increases with frequency must also be taken into account. In any case the conversion is straightforward, and the results allow comparisons among the I-5 traffic, quiet residential, and Grand Canyon noise environments with our nominal high and low underwater noise levels, plus the case of extremely low level underwater noise measured under smooth Antarctic ice (Fig. 5).

It is somewhat remarkable that the intensity spectral density of noise representing a quiet residential environment can exceed that of nominal high-level underwater ambient noise conditions. However, the residential environment is only 4 km from a busy highway and it is difficult to find an underwater environment to match that in terms of density of mechanical sources. Perhaps a site at a similar distance from a constant stream of boats or ferries would be appropriate, but even that is unlikely to match the number of vehicles per hour on the highway. To be sure, we showed that pressure spectral density of underwater noise from waters close to busy commercial shipping harbors readily exceed the high level curve by 10 to 20 dB. Thus the intensity spectral density from the harbor environment is nominally similar to that from the quiet residential environment at frequencies near 100 Hz and exceeds the residential case for frequencies greater than about 1000 Hz. Note that our labeling of the residential environment as "quiet" is somewhat subjective. It appears to be quiet to us because much of the energy is filtered out by the response of the human auditory system,

"It is somewhat remarkable that the intensity spectral density of noise representing a quiet residential environment can exceed that of nominal high-level underwater ambient noise conditions."

as suggested by the A-weighted level being about 14 dB below the unweighted level.

The ambient noise in the Grand Canyon could be considered to be representative of very low level noise, possibly among the lowest in an open environment in air. The case of low shipping plus sea state 0 could be considered to be representative of the lowest noise in the open ocean and is remarkably similar to the noise in the Grand Canyon, considering the differences in the acoustics of the two environments. The under-ice noise levels are even lower, but are less typical of ambient sea noise.

It is tempting to infer from Fig. 5 that the dynamic range of quasi, steady-state airborne ambient noise, insofar it can be represented by the difference between the I-5 and Grand Canyon environments, is greater than that for underwater ambient noise. For example, to reach the intensity spectral density levels as measured along I-5, the nominal high-level underwater noise curve must be increased by more than 4 orders of magnitude (40 dB). We cannot find examples of time-averaged, underwater ambient noise possessing an intensity spectral density of such magnitude. On the other hand, it would be quite rare to find a similar spatial concentration of high energy human sources in the ocean. Even busy harbors do not have a similar density of sources. The closest comparison seems to be marine dredging, which produces sustained noise that may sometimes reach intensity levels in the 20–1000-Hz band that are comparable to those near I-5.[52]

Concluding remarks

Underwater ambient noise is a complex subject of keen interest to a diverse set of scientists in underwater acoustics, biology, and oceanography, and public stakeholders in the area of marine mammal biology and conservation. Here we have only touched upon the subject, with particular focus on the approximate magnitude and frequency dependence of underwater ambient noise and a partial inventory of its primary sources. A comparison of typical underwater ambient noise levels with some examples of airborne noise has been made possible by recasting results in each environment in terms of an intensity spectral density, providing useful context for the ongoing discussion concerning the relation between anthropogenic underwater noise and the ecology of marine mammals.

In spite of the substantially different acoustic environments in air and water, examples of ambient noise spectra representing a range of air and water environments are similar in spectral shape, and the spectral intensity levels are broadly similar when both environments are far removed from human activities. Levels vary over a wide range (in excess of 30 dB) in both environments as conditions change. Underwater ambient noise originates from a much larger spatial distribution of sources than ambient noise in air because of the lower transmission loss in water, and thus underwater ambient noise associated with human activities is more wide spread than it is in air. **AT**

References and further reading

1 National Research Council (NRC), *Ocean Noise and Marine Mammals* (National Academies Press, 2003).

2 L. E. Kinsler, A. R. Frey, A. B. Coppens, and J. V. Sanders, *Fundamentals of Acoustics*, 3rd Edition (John Wiley & Sons, New York, 1982).

3 H. Medwin and C. S. Clay, *Fundamentals of Acoustical Oceanography* (Academic Press, San Diego, 1998).

4 V. O. Knudsen, R. S. Alford, and J. W. Emling, *Survey of Underwater Sound, Report No. 3, Ambient Noise*, OSRD Report No. 4333, Sec. No, 6.1-NDRC-1848 (1944).

5 V. O. Knudsen, R. S. Alford, and J. W. Emling, "Underwater ambient noise," J. Marine Res. 7, 410–429 (1948).

6 G. M. Wenz, "Acoustic ambient noise in the ocean: spectra and sources," J. Acoust. Soc. Am. 34, 1936–1956 (1962).

7 C. H. Harrison, "Formulas for ambient noise level and coherence," J. Acoust. Soc. Am. 99, 2055–2066 (1996).

8 G. B. Morris, "Depth dependence of ambient noise in the northeastern Pacific Ocean," J. Acoust. Soc. Am. 64, 581–590 (1978).

9 S. Levitus and T. Boyer, World Ocean Atlas 1994, Vol 4: Temperature, NOAA Atlas NESDIC Vol. 4 (U.S. Dept of Commerce, Washington, D.C. 1994).

10 V. A. Del Grosso, "New equation for the speed of sound in natural waters (with comparison to other equations)," J. Acoust. Soc. Am. 56, 1084–1091 (1974).

11 M. J. Buckingham and S. A. S. Jones, "A new shallow-ocean technique for determining the critical angle of the seabed from the vertical directionality of the ambient noise in the water column," J. Acoust. Soc. Am. 81, 938–946 (1987).

12 R. J. Urick, *Principles of Underwater Sound* (McGraw-Hill, New York, 1983).

13 C. S. McCreery, F. K. Duennebier, and G. H. Sutton, "Correlation of deep ocean noise (0.4 – 30 Hz) with wind, and the Holu Spectrum - A worldwide constant," J. Acoust. Soc. Am. 93, 2639–2648 (1993). The first author wishes to thank Ralph Stephen (Woods Hole Oceanographic Institution) for providing additional information on this topic.

14 D. Ross, *Mechanics of Underwater Noise* (Pergamon Press, New York, 1976).

15 S. C. Wales and R. M. Heitmeyer, "An ensemble source spectra for merchant ship-radiated noise," J. Acoust. Soc. Am. 111, 1211–1231 (2002).

16 A. Prosperetti, "Bubble-related ambient noise in the ocean," J. Acoust. Soc. Am. 84, 1024–1054 (1988).

17 W. M. Carey and D. G. Browning, "Low-frequency ocean ambient noise: measurements and theory," in *Sea Surface Sound*, edited by B.R. Kerman, (Kluwer Academic, Dordrecht, 1988), pp. 361–376.

18 M. L. Banner and D. H. Cato, "Physical mechanisms of noise generation by breaking waves–a laboratory study," in *Natural Physical Sources of Underwater Sound – Sea Surface Sound* (2nd Edition), edited by B.R. Kerman, (Kluwer, Dordrecht, 1993), pp. 429–436.

19 H. Medwin and M. M. Beaky, "Bubble sources of the Knudsen sea noise spectra," J. Acoust. Soc. Am. 89, 1124–1130 (1989).

20 B. B. Ma, J. A. Nystuen, and R-C. Lien, "Prediction of underwater sound levels from rain and wind," J. Acoust. Soc. Am. 117, 3555–3565 (2005).

21 D. H. Cato, "Features of ambient noise in shallow water," in *Shallow Water Acoustics*, edited by R. Zhang and J. Zhou, (China Ocean Press, 1997), pp. 385–390.

22 R. D. Gaul, D. P. Knobles, J. A. Shooter, and A. F. Wittenborn, "Ambient noise analysis of deep ocean measurements in the Northeast Pacific," IEEE J. Oceanic Eng. (in press).

23 J. A. Scrimger, D. J. Evans, G. A. McBean, D. M. Farmer, and B. R. Kerman, "Underwater noise due to rain, hail, and snow," J. Acoust. Soc. Am. 81, 79–86 (1987).

24 J. A. Nystuen, C. C. McGlothin, and M. S. Cook, "The underwater sound generated by heavy rainfall," J. Acoust. Soc. Am. 93, 3169–3177 (1993).

25 R. K. Andrew, B. M. Howe, J. A. Mercer, and M. A. Dzieciuch, "Ocean ambient sound: Comparing the 1960s with the 1990s for a receiver off the California coast," Acoust. Res. Lett. Online 3, 65–70 (2002).

26 G. M. Wenz, "Low-frequency deep-water ambient noise along the Pacific Coast of the United States," U.S. Navy J. Underwater Acoust. 19, 423–444 (1969).

27 M. A. McDonald, J. A. Hildebrand and S.M. Wiggens, "Increases in deep ocean ambient noise in the Northeast Pacific west of San Nicolas Island, California," J. Acoust. Soc. Am. 120, 711–718 (2006).

28 H. M. Walkinshaw, "Measurements of ambient noise spectra in the South Norwegian Sea," IEEE J. Oceanic Eng. 30, 262–266 (2005).

29 These measurements were made by three of the teams participating in the Asian Seas International Acoustics Experiment conducted in the East China Sea in May/June 2001, approximately 500 km east of the China coastline off Shanghai. Lowest frequency band (thickest, blue line) are from the Marine Physical Laboratory, Scripps courtesy of C.-F. Huang and W.S. Hodgkiss. Mid-Frequency band (thick, blue line) are from the Institute of Acoustics, Beijing courtesy of Renhe Zhang, Zhaohui Peng, Zhenglin Li, and Fenghua Li. Highest frequency band (thinnest, blue line) are from the Applied Physics Laboratory, University of Washington.

30 J. Na, J. Kim, and J. Choi, "Characteristics of ambient-noise in the shallow coastal area," J. Acoust. Soc. Korea 10, 58–63 (1991).

31 A. L. Anderson and G. J. Grubert, "Ambient-noise measurements at 30, 90, and 150 kHz in five ports," J. Acoust. Soc. Korea 49, 928–930 (1971).

32 M. P. Fish, "Biological sources of sustained ambient sea noise" in *Marine Bio-Acoustics*, edited by W.N. Tavolga, (Pergamon, Oxford, 1964).

33 D. H. Cato, "Marine biological choruses observed in tropical waters near Australia," J. Acoust. Soc. Am. 64, 736–743 (1978).

34 W. W. L. Au, J. Mobley, W. C. Burgess, M. O. Lammers, and P. E. Nachtigall, "Seasonal and diurnal trends of chorusing humpback whales wintering in waters off Western Maui," Marine Mammal Sci. 16, 530–544 (2000).

35 F. A. Everest, R. W. Young, and M. W. Johnson, "Acoustical characteristics of noise produced by snapping shrimp," J. Acoust. Soc. Am. 20, 137–142 (1948).

36 I. Dyer, "Speculations on the origin of low frequency arctic ocean noise," in *Sea Surface Sound*, edited by B.R. Kerman (Kluwer Academic, Dordrecht, 1988), pp. 513–532.

37 N. C. Makris and I. Dyer, "Environmental correlates of pack ice noise," J. Acoust. Soc. Am. 79, 1434–1440 (1986).

38 A. C. Kibblewhite and D. A. Jones, "Ambient noise under Antarctic sea ice," J. Acoust. Soc. Am. 59, 790–797 (1978).

39 The measurements were made by P.H. Dahl (using an Ono Sokki LA-5111 Type I sound level meter) who received assistance at the site from colleagues Per Reinhall and Jee Woong Choi from the University of Washington, and from Jim Laughlin from the Washington State Dept. of Transportation, who provided us with unique access to Interstate-5. Meteorological conditions were represented by wind speed < 5 m/s, temperature 5° C, and relative humidity 70%.

40 C. S. Y. Lee and G. G. Fleming, *Measurements of Highway Related Noise*, U.S. Department of Transportation Federal Highway Administration Final Report FHWA-PD-96-046 (1996).

41 M. E. Nilsson and B. Berglund, "Noise annoyance and activity disturbance before and after erection of a roadside noise barrier," J. Acoust. Soc. Am. 119, 2178–2188 (2006).

42 W. M. To, R. C. W. Ip, G. C. K. Lam, and C. T. H. Yau, "A multiple regression model for urban traffic noise in Hong Kong," J. Acoust. Soc. Am. 112, 551–556 (2002).

43 *Methods for Calculation of the Speech Intelligibility Index.* American National Standards Institute ANSI S3.5 (1997).

44 M. Long, "Dinner conversation (an oxymoron?)," Acoust. Today 1, 25–27 (2005).

45 N. P. Miller, "Transportation noise and recreational lands," Noise/News International 11, 9–21 (2003). The first author wishes to thank Nicholas P. Miller (Harris Miller Miller & Hanson Inc.) for providing additional information on this data, and Gilles Daigle (National Research Council, Canada) for discussions on this topic.

46 J. Miksis-Olds and J. H. Miller, "Transmission loss in manatee habitats," J. Acoust. Soc. Am. 120, 2320–2327 (2006).

47 C. I. Malme, P. I. Miles, C. W. Clark, P. Tyack, and J. E. Bird, *Investigations of the Potential Effects of Underwater Noise from Petroleum Industry Activities on Migrating Gray Whale Behavior: January 1984 Migration.* Final Report No. 5586 report prepared by Bolt, Beranek and Newman Inc., Cambridge, MA, for the U.S. Minerals Management Service, Anchorage, AK. BBN, Inc. NTIS PB-86-218377 (1984), 297 pp.

48 D. R. Ketten, "Marine mammal auditory systems: a summary of audiometric and anatomical data and implications for underwater acoustic impacts," Polarforschung 72, 79–92 (2004).

49 T. B. Gabrielson, "Refraction of Sound in the Atmosphere," Acoust. Today 2, 7–17 (2006).

50 W. Carey, "Sound Sources and Levels in the Ocean," IEEE J. Oceanic Eng. 31, 61–75 (2006).

51 B. S. Miller, A. L. Zosuls, D. R. Ketten, and D. C. Mountain, "Middle-ear stiffness of the bottlenose dolphin, *Tursiops truncates*," IEEE J. Oceanic Eng. 31, 87–94 (2006).

52 W. J. Richardson, C. R. Greene, Jr., C. I. Malme, and D. H. Thomson, *Marine Mammals and Noise.* (Academic Press, San Diego, 1995).
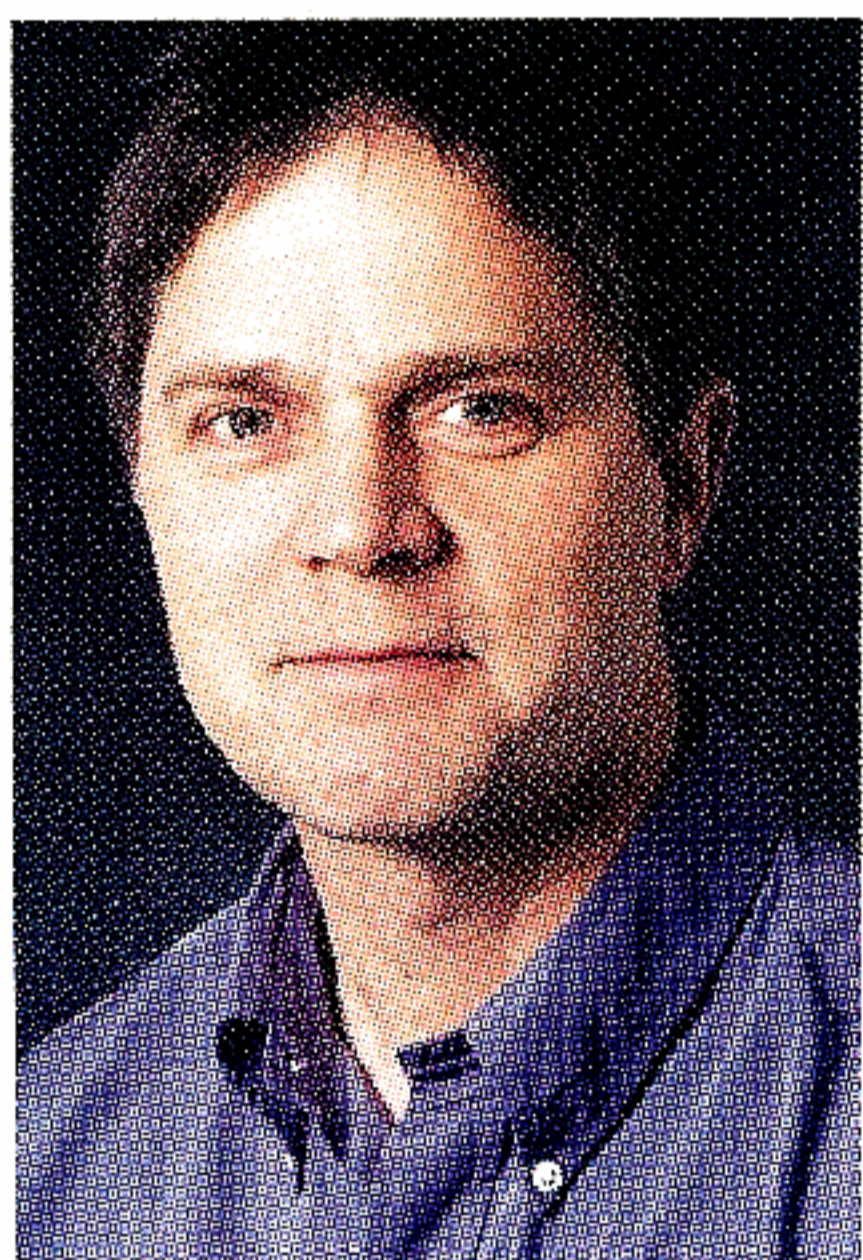
Peter H. Dahl received the Ph.D. degree in ocean engineering from the Massachusetts Institute of Technology, Cambridge and Woods Hole Oceanographic Institution, Woods Hole, MA, Joint Program in Oceanography and Oceanographic Engineering in 1989. He is a Principal Engineer at the Applied Physics Laboratory, University of Washington, Seattle, where he has been since 1989, and conducts experimental and theoretical research in underwater acoustics. He is a Research Associate Professor in Mechanical Engineering, where he teaches graduate courses in acoustics and advises graduate students. For the past three years he has presented a month-long course, *What is Sound?*, to freshman as part of the University of Washington's fall early start program. He was an Associate Editor for the IEEE Journal of Oceanic Engineering from 1997-2003, and served as Guest Editor for its recent Special Issue on Asian Marginal Seas. He is also a Fellow of the Acoustical Society of America, and recently completed serving as Chair of the Technical Committee on Underwater Acoustics.

James H. Miller earned his B.S. in Electrical Engineering in 1979 from Worcester Polytechnic Institute, his M.S. in Electrical Engineering in 1981 from Stanford University, and his Doctor of Science in Oceanographic Engineering in 1987 from Massachusetts Institute of Technology and Woods Hole Oceanographic Institution. He was on the faculty of the Department of Electrical and Computer Engineering at the Naval Postgraduate School from 1987 through 1995. Since 1995 he has been on the faculty of the Department of Ocean Engineering at the University of Rhode Island where he is Professor of Ocean Engineering and Oceanography. He has more than 100 publications in the area of acoustical oceanography, underwater acoustics, signal processing and marine bioacoustics. In 2003, he was elected Fellow of the Acoustical Society of America. He has served as Associate Editor for Underwater Sound for the *Journal of the Acoustical Society of America* responsible for scattering, inverse methods, and fish acoustics. He is a member of Sigma Xi, Tau Beta Pi, Eta Kappa Nu, the Institute of Electrical and Electronics Engineers, the Acoustical Society of America, and the Marine Technology Society.
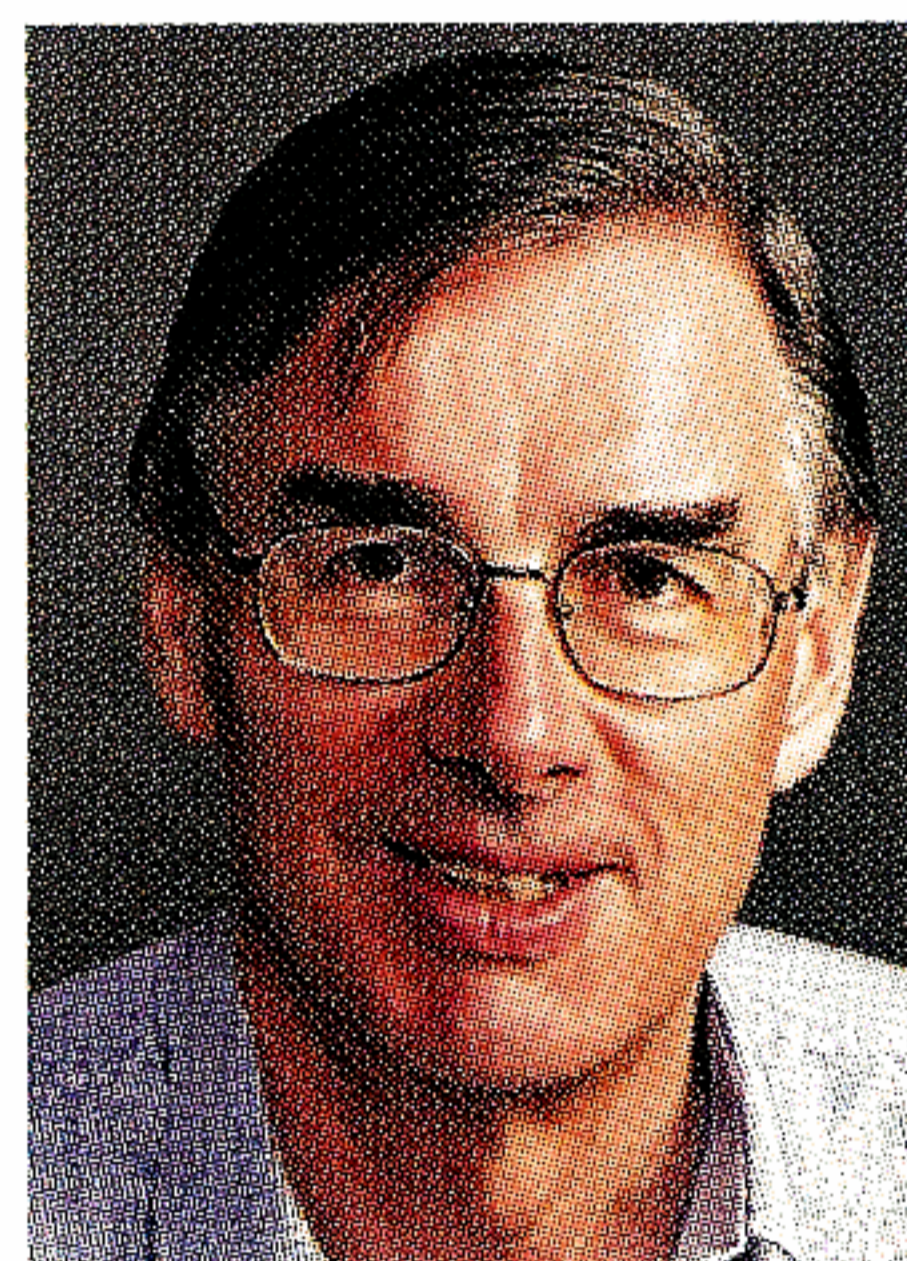
Douglas H. Cato is with Australia's Defence Science and Technology Organisation in Sydney, and is Adjunct Professor and Director of the University of Sydney Institute of Marine Science. He is a Fellow of the Acoustical Society of America. His main research interests are ambient sea noise, marine bioacoustics and the effects of noise on marine animals.

Rex K. Andrew received the B.S (physics) and M.S.E.E. degrees from the University of Washington, Seattle, in 1981 and 1987 respectively, and the Ph.D/E.E. degree from the University of Victoria, Victoria, B.C., Canada, in 1997. From 1987 to 1991, he was with the Naval Undersea Warfare Engineering Station, Keyport, WA, where he led an effort to develop large-aperture discrete-element over-the-side acoustic measurement systems. From 1997 to 1998, he was with the Department of Radiology, University of Washington, where he developed diagnostic ultrasound video codecs using 3-D wavelets. From 1997 to 1999 he developed 2-D image registration and alignment algorithms with Ioptics, Inc. He joined the Ocean Acoustics Department at the Applied Physics Laboratory, University of Washington, in 1999, where his major interests are statistical signal and array processing, ambient noise, acoustical wave propagation in random media, and acoustical oceanography.