Low-frequency underwater hearing sensitivity in belugas, *Delphinapterus leucas*

Frank T. Awbrey
Biology Department, San Diego State University, San Diego, California 92109

Jeanette A. Thomas[a] and Ronald A. Kastelein[b]
Sea World Research Institute/Hubbs Marine Research Center, 1700 South Shores Road, San Diego, California 92109

The underwater hearing sensitivity of three captive belugas (*Delphinapterus leucas*) was measured at octave intervals between 125 Hz and 8 kHz. The average threshold of the three animals was 65 dB *re*:1 μPa at 8 kHz, which is in excellent agreement with previously published data [White *et al.*, HSWRI Tech. Rep. No. 78-109, Sea World Research Institute, San Diego, CA (1978)]. Below 8 kHz, sensitivity decreased at approximately 11 dB per octave, and was 120.6 dB at 125 Hz.

PACS numbers: 43.66.Gf, 43.66.Cb [NFV]

INTRODUCTION

Underwater audiograms are available for only a few odontocete cetacean species: *Phocoena phocoena* (Andersen, 1970), *Inia geoffrenis* (Jacobs and Hall, 1972), *Tursiops truncatus* (Johnson, 1967), *Delphinapterus leucas* (White *et al.*, 1978), *Orcinus orca* (Hall and Johnson, 1971), and *Pseudorca crassidens* (Thomas *et al.*, 1988). Only Johnson (1967) measured thresholds below 1 kHz. Thresholds below 2 kHz are difficult to measure accurately because testing is usually done in small, very shallow pools where problems with standing waves and interference are nearly insurmountable. Also, most underwater transducers cannot produce the high amplitudes needed with low enough distortion. To avoid this problem, we used airborne speakers to measure the underwater hearing sensitivity of three captive belugas during 1983. We report three low-frequency audiograms, with new data at 125, 250, and 500 Hz and data at 1, 2, 4, and 8 kHz that agree with those measured for belugas by White *et al.* (1978).

I. METHODS

We tested the subjects in the underwater theater at Sea World in San Diego. Dimensions of the pool were 13 m (l) × 13 m (w) × 4 m (d). The adult male was one of the subjects in the underwater hearing tests conducted by White *et al.* (1978). The adult female and subadult male had not been tested before.

A Rogersound Lab "Outsider" loudspeaker projected test signals at frequencies between 500 Hz and 8 kHz. An RCA LC1-A loudspeaker in a vented enclosure was used for frequencies from 125 Hz to 1 kHz. These speakers were suspended in air 1.9 m directly above the animal's station and projected test signals into the pool. These loudspeakers were driven by one channel of a 17-W stereo amplifier (Kenwood

KA-3700) that was driven by a function generator (Wavetek 148). This system generated a low-distortion sinusoid at sound-pressure levels as high as 130 dB *re*: 1 μPa at the whale's station. Sound-pressure levels in the vicinity of the whale's head varied no more than 5 dB at any of the frequencies we used. Test signals and ambient noise were monitored with an ITC 6050-C hydrophone (frequency response 5 Hz to 50 kHz, ± 3 dB). Sound-pressure levels of the test signal, any harmonics, and the ambient noise were measured using a Spectral Dynamics 345 spectrum analyzer with a 75-Hz bandwidth. An Apple II + personal computer served as the central controlling and data-recording device for the study. A BASIC program controlled a special voltage generator board installed in the computer. This, in turn, controlled the signal frequency, rise/fall time (50 ms), and amplitude through the function generator's VCG and amplitude modulation features. Duration of the resulting sine wave (0.5 s) was set in the program.

We used a variant of the ascending form of the method of limits (Robinson and Watson, 1973) to test seven frequencies at octave intervals from 125 Hz to 8 kHz. Each whale was trained to a station with its rostrum against a target that was 0.5 m below the water surface and to remain there until it either heard the test signal or was called back by the trainer's whistle. We defined improper responses as leaving the station at any time other than immediately after a test signal or as remaining at the station when called back by the trainer's whistle. Such improper responses were discouraged by withholding the fish reward. Two 30- to 45-min sessions were conducted every weekday for a month. In a session, each of three whales was given ten test series. For each of four different frequencies, an ascending series of at most six amplitudes was presented in 2-dB steps and each frequency was repeated twice. The ten test series included two silent catch series. The order of the frequencies and catch series was random.

At the beginning of a series, the trainer used a hand cue to send the whale to the station. When the subject was properly positioned at the station, the trainer pushed a start but-

TABLE I. Beluga hearing threshold data in decibels. Reference pressure = 1 μPa; here, N = number of ascending series used for determining thresholds and the total number of "catch" series; FA = number of false alarms.

	125 Hz	250 Hz	500 Hz	Frequency 1 kHz	2 kHz	4 kHz	8 kHz	Catch
Adult male								
Mean	124	126	108	102	99	78	66	
Range	121–127	125–127	104–112	97–111	97–99	76–80	65–67	
N	2	2	18	20	7	8	3	28
FA								4
Adult female								
Mean	122	122	109	102	103	76	65	
Range	121–123	121–123	94–116	97–107	101–111	76–78	63–67	
N	7	3	14	7	6	5	5	25
FA								2
Juvenile male								
Mean	118	114	106	100	101	77	65	
Range	115–121	111–121	100–114	97–107	99–103	76–78	63–67	
N	7	9	13	18	11	5	7	30
FA								3
Combined								
Mean	121	118	108	101	101	77	65	
Range	115–127	111–127	94–116	97–111	97–111	76–80	63–67	
N	16	15	41	46	26	17	15	83
FA								9

ton. After a random time delay of 1 to 15 s, a 0.5-s test signal was presented at a level 6 dB below the mean response level during past presentations of that frequency. If the animal detected the test signal, it had to back from the target within 2 s and swim to the trainer to get a fish reward. Otherwise, it remained at the station, the amplitude was increased by 2 dB, and the stimulus presented again. This stepwise increase in level continued until the subject responded or until six levels (12-dB range) were presented. Thus every frequency was tested by a series of from one to six ascending levels. A catch series was identical to a test series except that six "levels" of silence would be presented. Responding to a catch series as if a test signal were present was a false alarm (FA). Data from an individual's session were rejected if both catch series yielded false alarms or if a whale responded inappropriately more than once during the session. Assuming that a whale responded to the first stimulus it could hear, every ascending series in which a subject responded to any but the first level gave a detection threshold. We assumed that the actual threshold was midway between the level the whale detected and the previous, lower level. The average level of all responses at a particular frequency is the 50% probability estimate of hearing sensitivity.

II. RESULTS AND DISCUSSION

Table I summarizes our low-frequency hearing data for three belugas. The hearing curves for the three subjects are very similar, with the greatest variation (12 dB) at 500 Hz. The young male was slightly more sensitive to low frequencies than either of the adults. The adult male's hearing was somewhat less sensitive at 4 and 8 kHz than it was when tested in 1978 by White et al. False alarms and other inappropriate responses were infrequent. We rejected only two of the adult male's sessions and one session for each of the others. The whales also displayed other behavioral problems on those days. This and the agreement of our data with those of previous researchers who used a more conventional method give us confidence that our threshold measurements are valid.

Figure 1 shows the average low-frequency sensitivity curve for our three whales and the entire, average sensitivity curve of two whales from White et al. (1978). At 1 kHz, our mean estimate for beluga hearing sensitivity was the same as
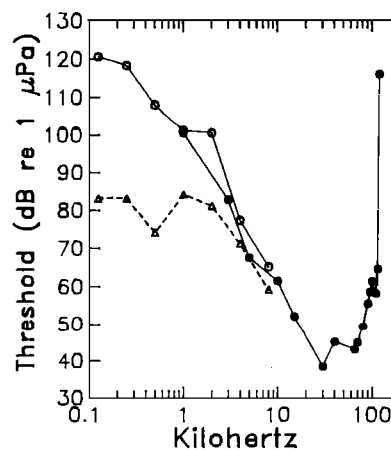

FIG. 1. The line with open circles is our average low-frequency hearing threshold curve of three belugas at octave intervals from 125 Hz to 8 kHz. The solid circles show the average hearing threshold curve from 1 to 120 kHz established 6 years earlier by White et al. (1978) for an adult female and the same adult male used in our study. The dashed line connects the sound-pressure levels (open triangles) of ambient noise in a 75-Hz band at the test frequencies.

the threshold that White *et al.* (1978) measured with the up–down staircase method. Our 4- and 8-kHz thresholds lie less than 3 dB above the line connecting their points at 3, 5, and 10 kHz. The reason for the 11-dB difference in the curves at 2-kHz is unknown, but we suspect a standing wave or constructive interference problem. The calibration tone consistently read 10 dB higher for a given voltage than those an octave above and below it.

The hearing thresholds that White *et al.* measured decrease at about 11 dB/oct, beginning at 30 kHz. We found the same decline. Hearing in *Orcinus orca* shows a similar trend below 15 kHz (Hall and Johnson, 1971), although they caution that their figures may have been noise limited. The caution applies to our study also.

ACKNOWLEDGMENTS

Andersen, S. (1970). "Auditory Sensitivity of the Harbour Porpoise, *Phocoena phocoena*," Invest. Cetacea **2**, 255–258.

Hall, J. D., and Johnson, C. S. (1971). "Auditory Thresholds of a Killer Whale, *Orcinus orca* Linnaeus," J. Acoust. Soc. Am. **51**, 515–517.

Jacobs, D. W., and Hall, J. D. (1972). "Auditory Thresholds of a Fresh Water Dolphin, *Inia geoffrensis* Blainsville," J. Acoust. Soc. Am. **51**, 530–533.

Johnson, C. S. (1967). "Sound Detection Thresholds in Marine Mammals," in *Marine Bio-Acoustics*, edited by W. N. Tavolga (Pergamon, New York), Vol. 2, pp. 247–260.

Robinson, D. E., and Watson, C. S. (1973). "Psychophysical Methods in Modern Psychoacoustics," in *Foundations of Modern Auditory Theory*, edited by J. V. Tobias (Academic, New York), Vol. 2, pp. 99–131.

Thomas, J., Chun, N., Au, W., and Pugh, K. (1988). "Underwater audiogram of a false killer whale (*Pseudorca crassidens*)," J. Acoust. Soc. Am. **84**, 936–940.

White, Jr., M. J., Norris, J. C., Ljungblad, D. K., Barton, K., and di Sciara, G. N. (1978). "Auditory Thresholds of Two Beluga Whales *Delphinapterus leucas*," HSWRI Tech. Rep. No. 78-109, Sea World Research Institute, San Diego, CA.

Influence of ground reflection on measurements involving bands of noise

Henry E. Bass, Richard Raspet, and John Noble
Physical Acoustics Research Group, The University of Mississippi, University, Mississippi 38677

It has been shown [L. C. Sutherland and H. E. Bass, J. Acoust. Soc. Am. **66**, 885–894 (1979)] that frequency-dependent atmospheric absorption can lead to a propagation loss for a band of noise that is much different from that for a pure tone at band center. In the presence of a ground surface, interference can also cause the sound amplitude to vary rapidly with frequency. When this occurs, the level measured for a pure tone can differ dramatically from that measured for a band of noise. Accurate treatment of this difference requires integration over the bandpass of the fractional octave band filter used in the measurement. Example calculations have been performed for a typical filter. These examples form a basis for general guidelines to be used when comparing theory to measurements.

INTRODUCTION

The basic problem addressed here is the difference between predictions of outdoor sound propagation, which generally are made at a single frequency, and experimental measurements, which are often made with a relatively broadband filter averaging over many frequencies. It has been shown that frequency-dependent atmospheric absorption can lead to a propagation loss for a band of noise that is much different from that for a pure tone at band center.[1] Another physical phenomenon that has a strong frequency dependence is the ground effect important for geometries similar to those in Fig. 1.

When a pure tone is propagated over a ground surface, there are certain frequencies where the direct and reflected rays interfere destructively. Figure 2 shows a typical spectrum that illustrates the problem. The interference dips at 250 and 800 Hz show that the ground surface can cause rapid variations in the relative sound-pressure levels with frequency. This spectrum shaping compounds the problem of spectral measurements of broadband noise signals that propagate over the ground. A finite bandwidth filter will perform some type of average over these dips. When this occurs, the level measured for a pure tone can differ dramatically from that measured for a band of noise.