Marine mammal audibility of selected shallow-water survey sources

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Abstract: Most attention about the acoustic effects of marine survey sound sources on marine mammals has focused on airgun arrays, with other common sources receiving less scrutiny. Sound levels above hearing threshold (sensation levels) were modeled for six marine mammal species and seven different survey sources in shallow water. The model indicated that odontocetes were most likely to hear sounds from mid-frequency sources (fishery, communication, and hydrographic systems), mysticetes from low-frequency sources (sub-bottom profiler and airguns), and pinnipeds from both mid- and low-frequency sources. High-frequency sources (side-scan and multibeam) generated the lowest estimated sensation levels for all marine mammal species groups.

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1. Introduction

Regulatory agencies, environmental advocacy organizations, the navies of the United States and Great Britain, the oil and gas industry, and others recognize that sound sources used to support various human activities have the potential to harm or disturb marine mammals in some circumstances. Certain sound sources, such as powerful mid-frequency sonars used by naval vessels and airguns used by the oil and gas industry, have attracted more attention than the multitude of other sound sources used in the world's oceans, but other sound sources warrant further consideration. Recent studies have examined the audibility of detonations[1] and ultrasonic transmitters[2] to marine mammals. In this Letter, we compare estimated marine mammal sensation levels (i.e., levels above hearing threshold) of sounds from seven commonly used acoustic survey sources, including six electromechanical projectors and one small airgun array (Table 1).

The scope of this study has been limited to a standardized sound propagation environment with a constant and relatively shallow (40 m) water depth, an isovelocity sound profile, and a topographically uniform profile of seafloor geoacoustic properties. This approach allowed a functionally consistent set of acoustic sources to be selected and compared under a single set of sound transmission conditions. The beam pattern of each source was modeled based on manufacturer specifications and supplemented by transducer theory. The lateral source output along the azimuth of maximum signal strength was used as input to a computational propagation model suitable for the frequency range of each source. A parabolic equation model was used for airguns and a beam-trace model was used for electromechanical sources. To estimate sensation levels for six species of marine mammals, sound pressure levels (SPLs) predicted by the propagation model were weighted according to hearing sensitivity and auditory integration time.

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Table 1. Selected geophysical survey sources and their modeled specifications.

Type	Model	Frequency (kHz)	Beam width (−3 dB)	Beam orientation	Source level (rms dB re 1 μPa @ 1 m)	Rep. rate (/sec)	Pulse length (ms)
Low-frequency (<10 kHz)							
Airgun array	Bolt 4×40 in^3	0.005-2 (pulse)	n/a	n/a	229[b]	0.1	100
Sub-bottom profiler	EdgeTech DW-106	1–6 (chirp)	28°–36° circular	vertical	200	15	33
Mid-frequency (10 to 100 kHz)							
Communications transceiver	Simrad HiPAP 500 USBL	23	10° circular	2° from horizontal[a]	206	1	1000
Fish finding sonar	Simrad SX90	26	7° circular	2° from horizontal[a]	215	1	72
Hydrographic echosounder	Simrad EA500	38	7° circular	vertical	232	0.5	0.1
High-frequency (>100 kHz)							
Multibeam echosounder	Simrad EM2000	200	150° × 1.5° rectangular	vertical	218	10	0.2
Side-scan sonar	EdgeTech 4500DF	230	50° × 0.15° rectangular	30° from horizontal	229	10	20

[a] Sonars with steerable beams were oriented toward the horizontal.
[b] Maximum source level in horizontal plane.

2. Acoustic source modeling

Electromechanical sources use directive transducers to focus beams of sound energy toward a specific target. We modeled the far-field pressure directivity patterns of circular and rectangular elements using well-known formulas from transducer theory:[3]

$$D_{\mathrm{circ}}(\varphi) = 2\cdot J_1(\pi L\sin(\varphi))/\pi L\sin(\varphi),\ L = 60/\Phi, \tag{1a}$$

$$D_{\mathrm{rect}}(\varphi_x,\varphi_y) = \mathrm{sinc}(\pi L_x\sin(\varphi_x))\times\mathrm{sinc}\big(\pi L_y\sin(\varphi_y)\big),\ L_{x,y} = 50/\Phi_{x,y}, \tag{1b}$$

where φ is the angle from the transducer axis, Φ is the −3 dB beam width of the transducer, in degrees, and J_1 is the Bessel function of the first kind.

Directivity patterns were modeled by superimposing the contributions of one or more discrete elements, according to Eqs. (1a) and (1b). Transducer theory is only generally applicable in front of a transducer head, since the backing structure limits acoustic radiation in the back half-space ($\varphi > 90°$); we applied therefore an attenuation factor so the pressure level directly behind the transducer was 40 dB lower than the pressure level in the direction perpendicular to the main beam. This approach does not assume any shading of the transducers; as such, it is expected to provide a conservative estimate of spatial side lobe leakage. All electromechanical sources, except the sub-bottom profiler which produces a multi-tonal chirp signal, were assumed to be single-frequency sources. This assumption is reasonable because these sources typically have highly resonant transducers ($Q \sim 10$) that only emit in a very narrow frequency band.[3]

Airguns use the rapid release of compressed air to generate low-frequency pulses in water. Multiple airguns are towed in planar arrays to direct sound energy toward the seabed. For this study we considered a small 4×40 in^3 airgun array, laid out in a 0.8×2.5 m T-shaped configuration and towed at 2.5 m depth. We used a physical model of airgun bubble oscillation and radiation[4] to compute broadband source levels for the airgun array in 1/3-octave bands from 5 Hz to 2 kHz. An array of this size would typically be used for a two-dimensional geotechnical survey rather than a three-dimensional (3D) hydrocarbon exploration survey. Source levels for a full 3D survey array would be approximately 10 to 15 dB higher than what was modeled here.

3. Sound propagation modeling

We modeled sound propagation in a 40-m-deep waveguide, with constant sound speed profile ($c = 1500$ m/s) and bottom composed of sandy sediment (grain size $\phi = 2.45$, porosity $N = 39\%$) with frequency-dependent geoacoustic profiles estimated using Buckingham's Grain-Shearing model.[5] We computed transmission loss for the airgun array using a split-step Padé parabolic equation model[6] modified to account for bottom losses due to *S*-wave conversion,[7] and for the six electromechanical sources using a Gaussian beam-trace model[8] with frequency-dependent volume absorption.[9] Beam amplitudes were shaded according to modeled directivity patterns. We modeled transmission loss for broadband sources (airgun array and sub-bottom profiler) at 1/3-octave band center frequencies, and computed maximum-over-depth SPL for each source in the direction of maximum source strength.

4. Temporal weighting

For pulsed sounds, frequency, signal duration, and repetition rate strongly influence audibility. The mammalian ear behaves analogously to an energy integrator, which sums sound intensity with a frequency-dependent time constant.[10] Available audiometric data suggest broad similarities between integration times for different species of marine mammals.[11] An integration time of 200 ms has been proposed as a suitable choice for low-frequency sources like airguns,[12] but this would likely underestimate sensation levels above 10 kHz where measured τ-values are typically 10 to 100 ms.[11]

For this study, we assumed that cetaceans and pinnipeds shared a common frequency-dependent integration time curve, which transitioned from $\tau = 200$ ms below 5 kHz to $\tau = 50$ ms above 50 kHz (Fig. 1). We applied an exponential intensity-weighting factor, W_τ, to account for the influence of integration time on the audibility of received pulses:[13]

$$W_\tau = (1 - \exp(-t/\tau))/(1 - \exp(-T/\tau)), \tag{2}$$

where t is pulse length, T is pulse repetition period, and τ is the integration time constant.

While this model may overestimate hearing thresholds for odontocetes exposed to mid-frequency pulses with very short repetition periods ($T < 100$ ms), all sources

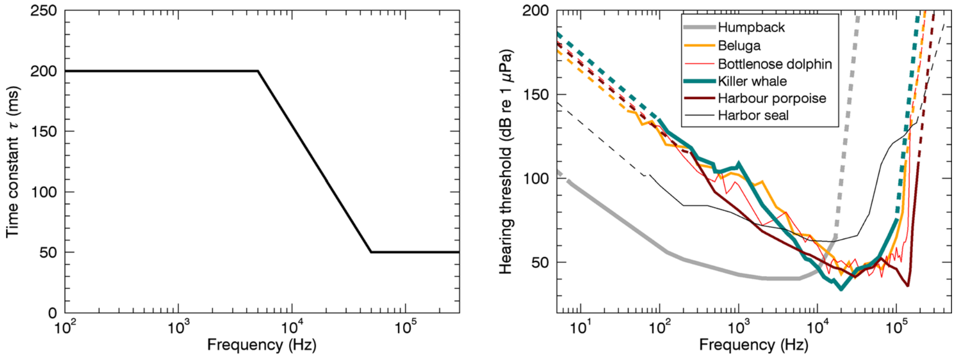

Fig. 1. (Color online) Left: Plot of modeled temporal integration time constant versus frequency. Right: Modeled audiograms for six species of marine mammals [root-mean-square (rms) SPL]. Dashed lines indicate extrapolated thresholds.

considered in this study have sufficient pulse spacing that any dependence of τ on T can likely be neglected.

5. Audiogram weighting

We applied audiogram weighting to modeled SPLs for six species of marine mammals, a representative sampling across hearing groups (Fig. 1). Audiograms for bottlenose dolphin (*Tursiops truncatus*), harbor porpoise (*Phocoena phocoena*), beluga whale (*Delphinapterus leucas*), killer whale (*Orcinus orca*), and harbor seal (*Phoca vitulina*) were compiled from summaries of published behavioral data.[14] For the humpback whale (*Megaptera novaeangliae*), we used a hypothetical audiogram that was estimated based on vocalization frequencies, ear anatomy, and behavioral reactions to sound.[15,16] At very high frequencies, we extrapolated hearing thresholds for cetaceans and pinnipeds according to the average slope of the audiograms in each of the two groups. At very low frequencies, we extrapolated audiograms based on a 12 dB/octave slope, which is believed to represent mammalian hearing roll-off toward the infrasound range.[17]

6. Results and discussion

We modeled sound level above hearing threshold as a function of horizontal distance for seven acoustic sources. The resulting curves (Fig. 2) represent estimated sensation levels for six different species of marine mammals and therefore relate to the ability to hear sounds produced by the sources. While this analysis does not directly relate to potential for behavioral response or auditory injury, weighting sounds according to hearing sensitivity allows assessment of relative risks associated with exposures to different sources.[18]

Our model shows that low-frequency sources (airguns and sub-bottom profiler) are the most audible sources to humpback whales at all ranges. Mid-frequency sources (fisheries, communication, and hydrographic systems) are the most audible sources to odontocetes at ranges below 3 km, but low-frequency sources begin to dominate between 3 and 10 km. Low- and mid-frequency systems have similar estimated audibility for seals due to their broad hearing range. For all species, modeled sensation levels

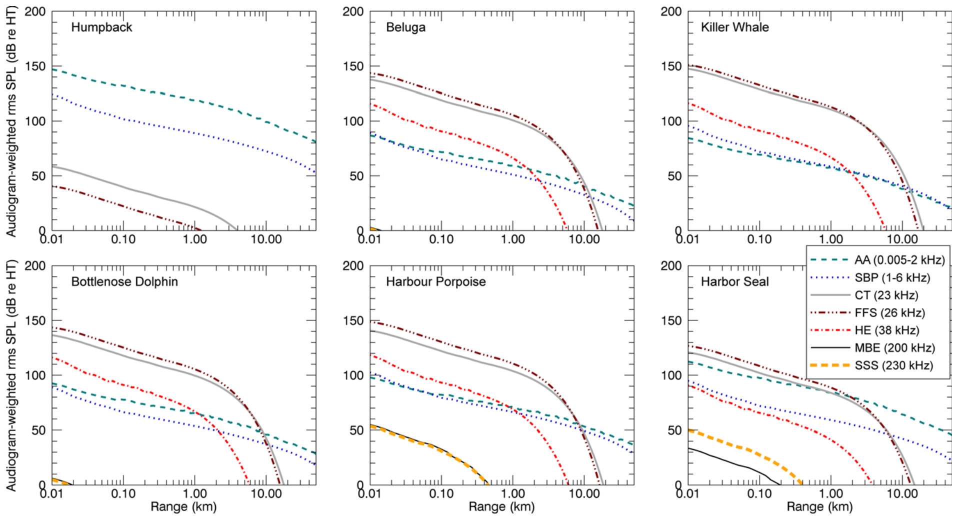

Fig. 2. (Color online) Modeled sound levels (relative to hearing threshold) versus horizontal range for seven geophysical survey sources weighted according to the estimated hearing abilities of six marine mammal species. AA = airgun array, SBP = sub-bottom profiler, CT = communications transducer, FFS = fish finding sonar, HE = hydrographic echosounder, MBE = multibeam echosounder, SSS = side-scan sonar.

are lowest for the high-frequency sources (side-scan and multibeam), which operate at the upper limits of the audible spectrum. The estimated zone of audibility for all species is largest for the low-frequency sources (airguns and sub-bottom profiler), which propagate over longer distances relative to the rapidly attenuating high frequencies.

Although animals cannot respond to sounds that they cannot hear, all sources that are audible could, in the right context, elicit behavioral responses. While sensation level alone may not be a good predictor of behavioral responses,[19] it is reasonable to expect that higher levels above the threshold of audibility, in combination with the same contextual setting, would be more likely to elicit responses than lower levels. Thus, according to our model, and assuming a constant contextual setting, mysticetes should be more likely to respond to sounds from low-frequency sources while odontocetes should be more likely to respond to sounds from mid-frequency survey sources than from airguns, at least at certain distances. The harbor seal results indicate that pinnipeds, unlike cetaceans, may be equally likely to respond to both kinds of sources.

Our audiogram weighting calculation assumed negligible sideband leakage for the high-frequency sources (side-scan and multibeam). Because these sources operate at the upper end of the audible spectrum, even a small amount of sideband leakage could result in higher sensation levels than our model predicts. Nonetheless, modeled sensation levels for these systems were so far below the other sources that we would not expect even a moderate increase to change their comparative ranking.

Our model did not consider sensation levels in the presence of background noise. Clearly, at least natural ambient noise and the sounds generated by the vessels associated with the modeled sound sources will be present. Calculating masked thresholds in the presence of other sounds requires careful consideration of critical bands and prevailing background conditions. The true threshold of audibility in the presence of background noise is specific to species, sound sources present, and location. Qualitatively we expect background noise will more readily mask wide-band sounds (e.g., from airguns) than narrowband sounds (e.g., from sonars) because less sound energy is concentrated inside a single critical band. Further investigation would be required, however, to quantify how the many sounds often present in the ocean would affect the audibility of the sources considered here.

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References and links

[1] R. A. Kastelein, R. Gransier, L. Hoek, and C. A. F. d. Jong, “The hearing threshold of a harbor porpoise (*Phocoena phocoena*) for impulsive sounds (L),” J. Acoust. Soc. Am. **132**(2), 607–610 (2012).

[2] A. E. Bowles, S. L. Denes, and M. A. Shane, “Acoustic characteristics of ultrasonic coded transmitters for fishery applications: Could marine mammals hear them?,” J. Acoust. Soc. Am. **128**(5), 3223–3231 (2010).

[3] X. Lurton, *An Introduction to Underwater Acoustics: Principles and Applications*, 2nd ed. (Springer, New York, 2009).

[4] A. O. MacGillivray, “An acoustic modelling study of seismic airgun noise in Queen Charlotte Basin,” M.Sc. thesis, University of Victoria, B.C. (2006).

[5] M. J. Buckingham, “Compressional and shear wave properties of marine sediments: Comparisons between theory and data,” J. Acoust. Soc. Am. **117**(1), 137–152 (2005).

[6] M. D. Collins, “A split-step Padé solution for the parabolic equation method,” J. Acoust. Soc. Am. **93**(4), 1736–1742 (1993).

[7] Z. Y. Zhang and C. T. Tindle, "Improved equivalent fluid approximations for a low shear speed ocean bottom," J. Acoust. Soc. Am. **98**(6), 3391–3396 (1995).

[8] M. B. Porter and H. P. Bucker, "Gaussian beam tracing for computing ocean acoustic fields," J. Acoust. Soc. Am. **82**(4), 1349–1359 (1987).

[9] R. E. Francois and G. R. Garrison, "Sound absorption based on ocean measurements. Part II: Boric acid contribution and equation for total absorption," J. Acoust. Soc. Am. **72**(6), 1879–1890 (1982).

[10] R. Plomp and M. A. Bouman, "Relation between hearing threshold and duration for tone pulses," J. Acoust. Soc. Am. **31**(6), 749–758 (1959).

[11] R. A. Kastelein, L. Hoek, C. A. F. d. Jong, and P. J. Wensveen, "The effect of signal duration on the underwater detection thresholds of a harbor porpoise (*Phocoena phocoena*) for single frequency-modulated tonal signals between 0.25 and 160 kHz," J. Acoust. Soc. Am. **128**(5), 3211–3222 (2010).

[12] P. T. Madsen, M. Johnson, P. J. O. Miller, N. A. Soto, J. Lynch, and P. Tyack, "Quantitative measures of air-gun pulses recorded on sperm whales (*Physeter macrocephalus*) using acoustic tags during controlled exposure experiments," J. Acoust. Soc. Am. **120**(4), 2366–2379 (2006).

[13] R. Plomp, "Hearing threshold for periodic tone pulses," J. Acoust. Soc. Am. **33**(11), 1561–1569 (1961).

[14] J. R. Nedwell, B. Edwards, A. W. H. Turnpenny, and J. Gordon, "Fish and marine mammal audiograms: A summary of available information," *Subacoustech* (2004), 278 p.

[15] D. S. Houser, D. A. Helweg, and P. W. B. Moore, "A bandpass filter-bank model of auditory sensitivity in the humpback whale," Aquat. Mamm. **27**, 82–91 (2001). Available at http://www.aquaticmammalsjournal.org/share/AquaticMammalsIssueArchives/2001/AquaticMammals_27-02/27-02_Houser.PDF.

[16] C. W. Clark and W. T. Ellison, "Potential use of low-frequency sounds by baleen whales for probing the environment: Evidence from models and empirical measurements," in *Echolocation in Bats and Dolphins*, edited by J. A. Thomas, C. Moss, and M. Vater (The University of Chicago Press, Chicago, 2004), pp. 564–582.

[17] T. Marquardt, J. Hensel, D. Mrowinski, and G. Scholz, "Low-frequency characteristics of human and guinea pig cochleae," J. Acoust. Soc. Am. **121**(6), 3628–3638 (2007).

[18] J. J. Finneran and C. E. Schlundt, "Subjective loudness level measurements and equal loudness contours in a bottlenose dolphin (*Tursiops truncatus*)," J. Acoust. Soc. Am. **130**(5), 3124–3136 (2011).

[19] W. T. Ellison, B. L. Southall, C. W. Clark, and A. S. Frankel, "A new context-based approach to assess marine mammal behavioral responses to anthropogenic sounds," Conserv. Biol. **26**(1), 21–28 (2012).