APPENDIX G
FUNDAMENTALS OF UNDERWATER SOUND

FUNDAMENTALS OF UNDERWATER SOUND

Most treatments of the effects of underwater sound are based on the Source » Path » Receiver concept. In the present case, the sound source is an airgun array that generates short pulses that contain large amounts of underwater sound. A seismic pulse is created by a burst of compressed air released from each airgun that makes up the array. Sound from the array radiates outward and travels through the water as pressure waves. Approximately 90% of the sound energy is focused downward, with some travelling radially in the horizontal plane. Water is an efficient medium through which sounds can travel long distances. The receiver of these sounds is a marine animal of interest (i.e., a VEC). The sounds received depend upon how much propagation loss occurs between the source and the receiver. Propagation loss can be much higher in shallow water because of attenuation. The ability of the receiver to detect these signals depends upon the hearing capabilities of the species in question and on the amount of natural ambient or background noise in the sea around the receiver. The sea is a naturally noisy environment, and this noise can "drown out" or mask weak signals from distant sources.

Humans hear sounds with a complicated non-linear type of response. The ear responds logarithmically, so acousticians use a logarithmic scale for sound intensity and denote the scale in decibels (dB). In underwater acoustics, sound is usually expressed as a sound pressure level (SPL):

$$\text{Sound Pressure Level} = 20 \log (P/P_o)$$

where P_o is a reference level, usually 1µPa (microPascal). Other reference levels have been used in the past, so the reference level needs to be shown as part of the SPL unit. A sound pressure (P) of 1000 Pa has a SPL of 180 dB re 1µPa and a pressure of 500 Pa has a SPL of 174 dB. In this scale, a doubling of the sound pressure means an increase of 6 dB. In order to interpret quoted sound pressure levels one must also have some indication of where the measurement applies. SPLs are usually expressed as received sound level at the receiver location or the source of the sound. A source level is usually calculated or measured as the SPL at 1 m from the source. A complete reference to a source level should read, e.g., 180 dB re 1µPa at 1 m (or 180 dB re 1 µPa·m). The unit of distance is necessary for comparison of source levels. Geophysicists usually refer to source levels of airguns in the units bar-m. In addition, the SPL can be expressed in different metrics: the difference in pressure between the highest positive pressure and the lowest negative pressure is the peak-to-peak pressure (p-p). The peak positive pressure, usually called the peak or zero-to-peak pressure (0-p) is approximately half the peak-to-peak pressure. The average pressure recorded during the pressure pulse can be expressed as the root mean square (rms) or average pressure. The rms pressure is integrated over the duration of the pulse. A difficulty with this type of measurement is that it is often difficult to interpret because for a brief pulse (and even a longer transient sound) it depends on the averaging time. For seismic sounds, the rms pressure is usually about 10 dB lower than the peak pressure (Greene 1997).

More recently, pulsed sounds like those from airguns have been described as sound exposure levels or SELs. This is directly proportional to the total energy density of the acoustic signal. Energy is proportional to the time integral of the pressure squared. Hence, SEL includes time as a dimension and is expressed in dB re 1 $\mu Pa^2 \cdot s$. Energy levels are not directly comparable to pressure levels. In most cases, energy values are less than "average pressure squared over the pulse duration", measured in dB re 1µPa, but the difference is variable (Richardson et al. 1995). As most of the literature on effects of sound on marine animals is presented as SPLs, the discussion in this EA focuses on pressure levels but includes SELs when available.

Sound measurements are often expressed as broadband, meaning the overall level of the sound over a range or band of frequencies. The level at a specific frequency will be lower than the broadband sound level for some bands containing that frequency because the broadband sound includes the components over a wide range of frequencies. Sound signatures from airguns consist of measurements of the sound level at each frequency (a sound spectrum). Sound level can also be measured and summed over groups or bands of frequencies (e.g., octaves or third octaves).

The majority of the literature describing the effects of sound on marine mammals deals with effects of low frequency sounds such those produced by ships, seismic exploration, or other activities related to offshore oil and gas exploration and development.

Pressure waves from airguns used in seismic exploration have slower rise times than traditional explosives and therefore cause much less injury to animals in water. Single airguns produce pulses with rise times on the order of 1 ms, an initial positive pulse of 2 ms duration, followed by a negative pulse of ~3–5 ms duration (Parrott 1991).

Current seismic data acquisition practices use arrays of airguns to achieve the penetration requirements needed to investigate the geologic subsurface. The distribution of the airgun elements within the array forms a geometry that increases the efficiency of the total energy source by directing its output downward into the subsurface by means of constructive interference of the signals from the individual guns. This happens at the expense of the amount of energy that propagates laterally because of geometric destructive interference. Approximately 90% of the useful energy is focused downward.

The sound from an array of airguns is received as a series of overlapping pulses from individual airguns. At long distances the pulse is further stretched out in duration by multipath, reverberation, and other propagation effects. After travelling several kilometres, the pulses can have durations of 250–500 ms (Greene and Richardson 1988; Richardson et al. 1995).

Sounds produced by the types of airgun arrays used to search for undersea petroleum reserves are broadband, which means that the sound is produced over a wide range of frequencies. However, the energy is unequally distributed over the frequency band. Sounds produced by an airgun have most of their energy at low frequencies. The strongest components of the sound are below 150 Hz, although there is significant energy up to 1 kHz. Energy diminishes progressively at higher frequencies (Richardson and Würsig 1997; Goold and Fish 1998).

Literature Cited

Goold, J.C. and P.J. Fish. 1998. Broadband spectra of seismic survey air-gun emissions, with reference to dolphin auditory thresholds. J. Acoust. Soc. Am., 103, 2177-2184.

Greene, C.R. 1997. An autonomous acoustic recorder for shallow arctic waters. J. Acoust. Soc. Am. 102(5, Pt. 2):3197.

Greene, C.R., Jr. and W.J. Richardson. 1988. Characteristics of marine seismic survey sounds in the Beaufort Sea. J. Acoust. Soc. Am. 83:2246–2254.

Parrott, R. 1991. Seismic and acoustic systems for marine survey used by the Geological Survey of Canada: Background information for environmental screening. Manuscript, Atlantic Geosci. Cent., Geol. Surv. Can., Dartmouth, N.S. 36 p.

Richardson, W.J. and B. Würsig. 1997. Influences of man-made noise and other human actions on cetacean behaviour. Mar. Freshwat. Behav. Physiol. 29(1-4):183-209.

Richardson, W.J., C.R. Greene Jr., C.I. Malme, and D.H. Thomson. 1995. Marine Mammals and Noise. Academic Press, San Diego. 576 p.

APPENDIX H:

SUMMARY OF CALCULATIONS FOR ESTIMATES OF PERCENTAGE OF POPULATIONS AND NUMBER OF INDIVIDUALS EXPOSED TO CHECK-SHOT/VSP ARRAY NOISE

Table H-1. Summary of values used to calculate the percentages of the narwhal population (and number of individuals) exposed to Check-Shot/VSP array received levels (RLs) of ≥198 dB re 1 µPa$^2 \cdot$ s M_{MFC}.

Stratum	Area (km^2)	Overlap with RL Modeling[a] (km^2)	Density (#/km^2)	Corrected Density (#/km^2)[b]	Numbers Exposed	Population Size	Percentage of the Population Exposed
Offshore	123,669	0.00	0.0026	0.0122	0.0	-	-
NPZ I[c]	23,814	0.00	0.0664	0.3162	0.0	-	-
Northwest	4860	0.00	0.0109	0.0519	0.0	-	-
Northeast	2755	0.00	0.0092	0.0438	0.0	-	-
Central	2133	0.00	0.0493	0.2348	0.0	-	-
South	6614	0.00	0.1635	0.7786	0.0	-	-
Total	163,845	-	-	-	0.0	15,060	0.00

[a] Area exposed to received level at Site 2 = 0.0006 km^2
[b] Corrected for availability bias by dividing by 0.21 (CV=0.09)
[c] Excluding the Heide-Jørgensen et al. (2010) survey blocks

Table H-2. Summary of values used to calculate the percentages of the narwhal population (and number of individuals) exposed to Check-Shot/VSP array received levels (RLs) of ≥160 dB re 1 μPa_{rms}.

Stratum	Area (km^2)	Overlap with RL Modeling[a] (km^2)	Density (#/km^2)	Corrected Density (#/km^2)[b]	Numbers Exposed	Population Size	Percentage of the Population Exposed
Offshore	123,669	15.03	0.0026	0.0122	0.2	-	-
NPZ I[c]	23,814	0.00	0.0664	0.3162	0.0	-	-
Northwest	4860	0.00	0.0109	0.0519	0.0	-	-
Northeast	2755	0.00	0.0092	0.0438	0.0	-	-
Central	2133	0.00	0.0493	0.2348	0.0	-	-
South	6614	0.00	0.1635	0.7786	0.0	-	-
Total	163,845	-	-	-	0.2	15,060	0.00

[a] Area exposed to received level at Site 2 = 15.03 km^2

[b] Corrected for availability bias by dividing by 0.21 (CV=0.09)

[c] Excluding the Heide-Jørgensen et al. (2010) survey blocks

Table H-3. Summary of values used to calculate the percentages of the narwhal population (and number of individuals) exposed to Check-Shot/VSP array received levels (RLs) of ≥150 dB re 1 μPa_{rms}.

Stratum	**Area (km²)**	**Overlap with RL Modeling[a] (km²)**	**Density (#/km²)**	**Corrected Density (#/km²)[b]**	**Numbers Exposed**	**Population Size**	**Percentage of the Population Exposed**
Offshore	123,669	102.76	0.0026	0.0122	1.3	-	-
NPZ I[c]	23,814	0.00	0.0664	0.3162	0.0	-	-
Northwest	4860	0.00	0.0109	0.0519	0.0	-	-
Northeast	2755	0.00	0.0092	0.0438	0.0	-	-
Central	2133	0.00	0.0493	0.2348	0.0	-	-
South	6614	0.00	0.1635	0.7786	0.0	-	-
Total	163,845	-	-	-	1.3	15,060	0.01

[a] Area exposed to received level at Site 2 = 102.76 km²
[b] Corrected for availability bias by dividing by 0.21 (CV=0.09)
[c] Excluding the Heide-Jørgensen et al. (2010) survey blocks

Table H-4. Summary of values used to calculate the percentages of the beluga whale population exposed to Check-Shot/VSP array received levels (RLs) of ≥198 dB re 1 μPa^2 · s M_{MFC}, ≥160 dB re 1 μPa_{rms}, and ≥150 dB re 1 μPa_{rms} during summer.

RL	Area (km^2)	Area Exposed to RL at Site 2 (km^2)	Percentage of the Population Available	Percentage of the Population Exposed[a]
≥198 dBSEL M_{MFC}	163,845	0.0006	1.0	0.00
≥160 dB_{rms}	163,845	15.03	1.0	0.00
≥150 dB_{rms}	163,845	102.76	1.0	0.00

[a] (Area exposed to RL at Site 2/Area) x percentage of the population available

Table H-5. Summary of values used to calculate the percentages of the ringed seal population (and number of individuals) exposed to Check-Shot/VSP array received levels (RLs) of ≥186 dB re 1 μPa^2 · s M_{PW} and ≥160 dB re 1 μPa_{rms}.

RL	Area (km^2)	Area Exposed to RL at Site 2 (km^2)	Density (#/km^2)	Numbers Exposed	Estimated Population Size	Percentage of the Population Exposed
≥186 dBSEL M_{PW}	163,845	0.0010	1.39	0.02	228,000	0.00
≥160 dB_{rms}	163,845	15.03	1.39	20.9	228,000	0.01

Table H-6. Summary of values used to calculate the percentages of the bowhead whale population exposed to Check-Shot/VSP array received levels (RLs) of ≥198 dB re 1 μPa$^2 \cdot$ s M_{LFC} and ≥160 dB re 1 μPa_{rms}.

RL	Area (km^2)	Area Exposed to RL at Site 2 (km^2)	Percentage of the Population Exposed
≥198 dB_{SEL} M_{LFC}	163,845	0.0010	0.00
≥160 dB_{rms}	163,845	15.03	0.01

Table H-7. Summary of values used to calculate the percentages of the walrus population exposed to Check-Shot/VSP array received levels (RLs) of ≥186 dB re 1 μPa$^2 \cdot$ s M_{PW} and ≥160 dB re 1 μPa_{rms}.

RL	Area (km^2)	Area Exposed to RL at Site 2 (km^2)	Percentage of the Population Exposed
≥186 dB_{SEL} M_{PW}	163,845	0.0010	0.00
≥160 dB_{rms}	163,845	15.03	0.01