Noise Measurements of an Oscillator System for Drilled Shafts

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ACRONYMS AND ABBREVIATIONS

cm	centimeter(s)
dB	decibel(s)
dB re 1 µPa	decibel referenced to 1 micropascal
FFT	fast Fourier transform
FHWA	Federal Highway Administration
FR	Federal Register
KABATA	Knik Arm Bridge and Toll Authority
KAC	Knik Arm Crossing
kHz	kilohertz
kg	kilogram(s)
km	kilometer(s)
LOA	Letter of Authorization
m	meter(s)
Mat-Su	Matanuska-Susitna Borough
MTR	Marine Terminal Redevelopment
NMFS	National Marine Fisheries Service
Pa	Pascal
POA	Port of Anchorage
rms	root mean square
SD	standard deviation
SL	source level
SPL	sound pressure level
TTS	temporary threshold shift

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EXECUTIVE SUMMARY

The goal of this study was to obtain baseline acoustic recordings of an oscillator system used to place large diameter (12-foot) steel casings, which is important in assessing potential environmental impacts where this technique is used. The study was conducted at the Gilmerton Bridge Replacement project in Chesapeake, Virginia. These noise recordings are the first documented to have been made during the operation of an oscillator. They are intended to be used to assess potential noise impacts to the Cook Inlet beluga whale if an oscillator is used to install large diameter piles for the proposed Knik Arm Crossing (KAC) project. The acoustic data will also be valuable as baseline data for other environmental impact assessments where the oscillator method for drilling shafts could be used.

Acoustic recordings were collected prior to oscillator activities to obtain ambient noise data at a distance of 30 meters (m) from the construction site (i.e., the pile installation site). Baseline environmental conditions that might affect sound propagation properties, such as salinity and water temperature, were collected to calculate the speed of sound. Acoustic recordings of the oscillator system (Leffer VRM 3800) during operation were collected during high tide at distances of 30 m and 300 m from the construction site—Site 1 and Site 2, respectively. A conservative approach was used in the analysis of the oscillator noise—all construction sounds associated with the oscillator were included during the analysis—therefore, although the obtained results might overestimate the actual noise produced by the oscillator, they also provide a more realistic approximation of the anthropogenic noise generated by such activities.

Ambient noise was measured at a distance of 30 m from the construction site (Site 1). The root mean square (rms) levels ranged from 114.9 to 116.9 decibels referenced to 1 micropascal (dB re 1 µPa), with a mean of 115.9 dB re 1 µPa (standard deviation [SD] = 0.4 decibels [dB]). Overall, 69.8 percent of the recorded oscillator sound pressure levels (SPLs) were lower than 120 dB re 1 µPa. The rms values of oscillator noise recorded from Site 1 ranged from 115.6 to 141.5 dB re 1 µPa, with a mean of 121.6 dB re 1 µPa (SD = 6.4 dB). The rms values of oscillator noise recorded at Site 2—a distance of 300 m from the construction site—ranged from 115.8 to 118.6 dB re 1 µPa, with a mean of 116.9 dB re 1 µPa (SD = 0.6 dB). As with measurements from Site 1, transient noises—those between 10 and 20 seconds in duration—are visible on the spectrogram for measurements made Site 2. The SPL distribution is centered at approximately 117 to 118 dB re 1 µPa rms and 96.7 percent of the SPLs were lower than 119 dB. It appears that most of the noise recorded at Site 1 dissipated rapidly over the distance to Site 2 and only the low-frequency component of the oscillator was visible on the spectrogram. Oscillator noise is below mean ambient noise levels for Knik Arm, the lowest at the proposed KAC site is 124 dB.

Acoustic recordings of the oscillator included loud, high-frequency construction noise (broadband and at 15 kilohertz [kHz], 30 and 45 kHz) separated by quieter periods of time. Based on the frequency spectrum, the most noticeable noises on the spectrogram—supposedly associated with the oscillator—are the short tones at 15 kHz and harmonics at 30 kHz and 45 kHz.

The beluga whale (*Delphinapterus leucas*) best hears sounds occurring between 11.2 and 90 kHz. The tones generated at 15 kHz with harmonics could be heard by beluga whales swimming in proximity (30 m) to an oscillator. The measured SPLs of the oscillator were below the levels estimated to cause hearing loss or behavioral disturbance in laboratory experiments and these high frequency sounds dissipated rapidly across distance and were not detectable at a distance of 300 m from the oscillator.

Although the Elizabeth River and Knik Arm have different environmental conditions, it is very likely that any measured sound levels from use of an oscillator in Knik Arm would still be much lower than those measured from the use of impact and vibratory pile-drivers in Knik Arm. This study confirms that use of an oscillator for pile-installation activities would introduce less noise to the existing environment of Knik Arm than impact and vibratory pile-drivers. Because most of the continuous oscillator noise measured during this study was below that measured for impact and vibratory pile drivers, and below the ambient noise measured at the proposed KAC project site, limited behavioral changes by belugas would be expected. It is recognized that the measured SPLs from the oscillator operating at the Gilmerton Bridge Replacement project in the Elizabeth River cannot be fully applied to the proposed KAC project in Cook Inlet and potential beluga impacts. A test-pile program using an oscillator at the proposed KAC site will be required to validate the preliminary data collected during this study of an oscillator in Virginia.

1 Introduction

The Alaska Division of the Federal Highway Administration (FHWA) and the Knik Arm Bridge and Toll Authority (KABATA) plan to construct the Knik Arm Crossing (KAC) project. This involves constructing a new bridge spanning Knik Arm (the Crossing) and approaches from the Matanuska-Susitna Borough (the Mat-Su) side of Knik Arm (the Mat-Su Approach) and the Municipality of Anchorage (Anchorage) side of the Arm (the Anchorage Approach).

The National Marine Fisheries Service (NMFS) has proposed designating critical habitat for the Cook Inlet beluga whale (*Delphinapterus leucas*), in portions of Cook Inlet, including Knik Arm and the site of the proposed KAC project. As the NMFS noted in its proposed critical habitat rule (74 Federal Register [FR] 63080–63095), anthropogenic noise above ambient levels may cause behavioral reactions in beluga whales (harassment) or mask communication between individuals. The NMFS also expressed concerns that the effects of harassment may include habitat abandonment by belugas.

In creating a foundation for a bridge, pile installation with hydraulic impact and vibratory hammers (pile driving) is used. Construction in and around water bodies has generated concerns about the types and level of impacts these activities have on aquatic organisms. The environmental impact of high sound pressure levels (SPL) from in-water pile-driving activities is an often-voiced issue of concern for marine mammals and is managed by NMFS as part of its marine mammal take permit program. In their application for a marine mammal take permit (Letter of Authorization; LOA), KABATA noted that it anticipates that an oscillator will be used to place the permanent, large-diameter drilled shafts (KABATA 2010).

The use of hydraulic oscillators to drive full-length casings for pile installation is gaining in popularity. Oscillators work by reciprocally oscillating a device that both grips and applies downward force. The noise generated by an oscillator is a continuous signal. There is no published literature or source data regarding the in-water noise levels produced by drilled shaft installation using oscillators. It is assumed that because physical impact is avoided, the noise level is likely to be lower in amplitude than that produced by vibratory and impact pile driving. Additionally, the drilled-shaft installation technique potentially has higher frequency components because of metal rubbing against metal. Higher frequencies attenuate more quickly than lower frequencies (Urick 1983).

The area over which anthropogenic noise may adversely impact marine species depends upon how well the sound propagates underwater, its frequency characteristics, and duration. Information on received levels and spectral content at different distances from the source can be compared with hearing thresholds of species of interest and local ambient noise levels. Together, these data can be used to determine the likelihood that the Cook Inlet beluga whale (and other marine mammal species found in Knik Arm) would be affected at different distances from the noise source.

To verify noise source data prior to construction of the proposed KAC project, in their application for an LOA, FHWA and KABATA committed to obtaining sound level and transmission-loss data for large-diameter, drilled-shaft construction methods involving oscillator activities (KABATA 2010). The goal of this study was to obtain baseline acoustic recordings of oscillator- related construction equipment and operations associated with placement of large diameter piles for the Gilmerton Bridge Replacement project in Chesapeake, Virginia. The sound recordings obtained by this study are the first documented to be made during operation of an oscillator for drilled shafts They are intended to be used to assess potential noise impacts to the Cook Inlet beluga whale if an oscillator is used to install large diameter piles for the proposed Knik Arm Crossing (KAC) project. The acoustic data will also be valuable as baseline data for other environmental impact assessments where the oscillator method for drilling shafts could be used.

2 METHODS

2.1 Study Location

The Elizabeth River is a short tidal tributary forming an arm of Hampton Roads at the southern end of the Chesapeake Bay in southeastern Virginia. It is located along the southern side of the mouth of the James River, between the cities of Portsmouth and Norfolk. The Southern Branch of the Elizabeth River is a gateway to the Atlantic Intracoastal Waterway. Dredging maintains a 40-foot bottom depth in the Elizabeth River. The bottom composition is a sandy clay substrate.

The City of Chesapeake, Virginia, owns and operates the existing Gilmerton Bridge, which is a double-leaf bascule (lift-type) bridge that was constructed in 1938 over the Southern Branch of the Elizabeth River. Acoustic sampling was conducted in conjunction with use of an oscillator during construction of the Gilmerton Bridge Replacement project on Military Highway in the City of Chesapeake, which will provide a new lift span bridge.

2.2 Sampling – Timing and Location

2.2.1 Data Collection

Acoustic recordings of baseline ambient noise conditions and oscillator noise were made between January 19 and 25, 2011. All recordings were collected at high slack tides (**Appendix A**) to minimize flow and self-noise generated by the equipment set-up. Baseline ambient noise recordings were made at a distance of 30 m (Site 1 in **Figure 1**) from the construction site (the pile installation site), while no pile-driving or construction activity associated with the bridge was taking place. Oscillator noise recordings were made at distances of 30 m and 300 m from the construction site (Site 1 and Site 2, respectively in **Figure 1**). Distance to the construction site was determined using a Nikon Laser range finder before every data collection period. The sites were selected based on the availability of places to secure the recording vessel, as well as for the lack of fixed objects that might have impeded the arrival path of sounds produced. Two sites were chosen to mitigate the possibility of site-specific propagation issues associated with low- and high-frequency sounds. Sites 1 and 2 were located at pier pilings to ensure that recordings were collected always at the same location.

The oscillator was a 72-ton Leffer VRM 3800 (specifications can be found in **Appendix B**). The Leffer hydraulic casing oscillator has over 11.6 million foot-pounds of torque and 750 tons of extraction force. This machine is capable of drilling over 200 feet deep with a 12-foot-diameter oscillator casing. The oscillator used during this study installed 12-foot-diameter steel casings.

In-water recordings were collected from a 5 m skiff with an outboard motor, and a small (~8 m) tug boat. For all recordings, the vessel engines were turned off. Once at the recording sites, the vessel was tied-off to a fixed structure (pylon). The scientific team included the vessel operator (PCL Civil Constructors, Inc.

employee), a person to deploy the hydrophone, a person to operate recording equipment, and an assistant to take notes. Noise-cancelling headphones were used by the person operating the recording equipment to monitor all recordings and provide information to the note taker about any transient noises and their source and time in the recording(s).

The hydrophone was lowered to a depth of 5 m (marked on the cable to ensure precise sampling depths) and recordings were made only during periods of slack tide (to preclude flow noise/vibration) and during clear weather (to ensure that ambient noise would not be increased by rain). A 5-ounce lead weight was tied to the hydrophone cable to ensure that the hydrophone was vertical in the water column.

2.2.2 Environmental Data

Temperature and salinity were measured before each acoustic recording session at every sampling site using a YSI 85 meter. These data were important for calculation of speed of sound through water. Temperature and salinity affect the density of water and therefore the speed at which sound travels through this media.

2.2.3 Recording Equipment

The noise measurements were made with a calibrated CR-3 hydrophone (Cetacean Research, Seattle, Washington) connected to a Reson PC100 pre-amplifier with a 0.1 hertz (Hz) high-pass filter. The CR-3 is an omnidirectional hydrophone that has a linear sensitivity to underwater sound in the frequency range from 60 Hz to 90 kHz. The noises were digitally recorded using a Microtrak II (M-Audio) recorder at a 96 kHz sampling rate, providing a 48 kHz bandwidth-recording of the noise. A 49 dB gain was used for each recording.

The recording files were stored as .wav files for further analysis. A total of 16 files of at least 1-minute duration were made. Each file was inspected visually to eliminate files with flow noise or saturated recordings. As much as possible, noise from boat traffic was excluded from the analysis of all measurements.

2.2.4 Analysis

The files were extracted using Adobe Audition 3.0 and analyzed in 1-second segments. A custom Matlab routine was used to analyze each 1 second segment individually. For each segment file, a 60 Hz high-pass filter was applied to eliminate self-noise generated by the system, which limited the frequency analysis to a band from 60 Hz to 48,000 Hz. Each 1-second file was Fast Fourier transformed (FFT) in combination with a Hanning window, which transforms the signal expressed in the time domain into the frequency domain where the composition of the signal is expressed in terms of frequency or pitch. Rms noise levels are reported in terms of the 1-second average continuous sound level expressed in dB re 1 µPa.

Preliminary analysis was performed on 3 files that were three to five minutes in duration. Sixty to ninety 1-second files were selected for analysis and used to assess both the ambient noise levels and the sound levels produced by the oscillator system. Additional construction noises were collected and will be analyzed and presented in later reports.

A conservative approach was selected to present the SPL associated with the oscillator system. All noise associated with the oscillator system, whether directly (i.e., noise generated by the oscillator itself) or indirectly (i.e., hammering), were grouped together. Although this method most likely provides overestimations of the SPL of the actual oscillator noise (due to the addition of other types of noise), these results encompass the entire range of SPL that can be expected with this pile-installation method.

3 RESULTS

3.1 Ambient Noise Measurements

Ambient noise was measured at a distance of 30 m from the construction site (Site 1). The rms levels ranged from 114.9 to 116.9 dB re 1 µPa, with a mean of 115.9 dB re 1 µPa (SD = 0.4 dB) (**Figure 2; Table 1**). Most of the noise was dominated by local boat traffic and industrial activity, with the highest SPLs between 60 and 500 Hz (**Figure 5**). Recordings with the least amount of transient boat traffic and industrial activity were selected for analysis (**Figures 2 and 3**), and therefore, represent the lower end of the ambient noise spectrum. The distribution of the ambient noise levels is shown in **Figure 6a**; 98.2 percent of the noise level was between 116 and 117 dB re 1 µPa.

3.2 Oscillator Noise Measurements

3.2.1 Distance of 30 m from construction site (Site 1)

The rms values of oscillator noise recorded at Site 1ranged from 115.6 to 141.5 dB re 1 µPa, with a mean of 121.6 dB re 1 µPa (SD = 6.4 dB) (**Table 1**). The spectrogram of the noise recorded at Site 1 is shown in **Figure 4a**. Hammering sounds could be identified and were matched to visual observations collected during the noise measurements. Overall, these sounds were short in duration (less than 1 second) and broadband (encompassing a wide band of frequencies). Other construction activities occurring during the noise measurements could not be isolated and eliminated from the measurements calculation, and were therefore, assumed to be associated with the oscillator system (**Figure 4a**). The most noticeable noises were transient, broadband, and occurred every 10 to 20 seconds, with occasional tones at 15 kHz, and harmonics at 30 kHz and 45 kHz.

One of the loudest measurements (SPL = 141.5 dB) was selected for discussion (see **Figure 5**). There are clear energy peaks at approximately 15 kHz (maximum SPL of 127.31 dB measured at 14.679 kHz), 30 kHz (maximum SPL of 119.3 dB measured at 29.358 kHz), and 45 kHz (maximum SPL of 111.1 dB measured at 44.034 kHz). It is difficult to assess whether the sounds were associated with the actual operating oscillator, or with on-going construction noise. It should be noted that these sounds were intermittent and were not recorded throughout the measurements. **Figure 5** shows the frequency distribution of one of the broadband noise measurements with the tones at 15 kHz, 30 kHz, and 45 kHz. Higher SPLs were observed at low- (300 Hz to 700 Hz) and mid- (800 Hz to 2,000 Hz) frequencies. The noise measurements were consistently above 8 kHz, with peaks at 15 kHz, 30 kHz and 45 kHz (with respective SPLs of 127.31, 119.3, and 111.1 dB re 1 µPa).

Figure 6b shows the distribution of the SPL measured at Site 1 (distance of 30 m from the construction site). While most of the noise is centered approximately at 118 to 120 dB, there were variations within the recordings at this location, presumably due to the proximity of Site 1 to the construction site, and the various types of noise producing construction activities occurring concurrently. Overall, 69.8 percent of the recorded oscillator SPLs were lower than 120 dB re 1 µPa.

3.2.2 Distance of 300 m from construction site (Site 2)

The rms values of oscillator noise recorded Site 2 ranged from 115.8 to 118.6 dB re 1 µPa, with a mean of 116.9 dB re 1 µPa (SD = 0.6 dB) (**Table 1**). The spectrogram of the noise measured at Site 2 is shown in **Figure 4b**. Similar to measurements made at Site 1 (see **Section 3.2.1**), transient noises (i.e., between 10 and 20 seconds in duration) are visible on the spectrogram (see **Figure 4b**). The SPL distribution is centered approximately at 117 to 118 dB re 1 µPa rms (see **Figure 6c**) and 96.7 percent of the SPLs were lower than 119 dB. It appears that most of the noise recorded at Site 1 (30 m from construction site) dissipated rapidly over the distance to Site 2 (300 m from construction site) and only the low-frequency component of the oscillator is visible on the spectrogram (see **Figure 4b**). This loss of noise over distance depends on several factors such as the actual frequency of the sound (i.e., the peaks at 15 kHz, 30 kHz, and 45 kHz are not visible on the spectrogram at a distance of 300 m from the construction site), the depth and type of bottom (i.e., more reverberation in rocky and shallow environments), as well as the sound profile of the area (e.g., salinity, water temperature) (Urick 1983).

4 DISCUSSION

The data collected during this study provide baseline information about the noise generated by installing piles using an oscillator system. A conservative approach was used in the analysis of the oscillator noise—all construction sounds associated with the oscillator were included during the analysis—therefore, although the obtained results might overestimate the actual noise produced by the oscillator, they also provide a more realistic approximation of the anthropogenic noise generated by such activities.

The Leffer VRM 3800 generated relatively little noise. At Site 1, the oscillator's mean SPL was calculated to be 121.6 dB re 1 µPa (SD = 6.4 dB). The mean SPL measured in the Elizabeth River for this oscillator is below the mean ambient noise levels of 124 dB to 136 dB re 1 µPa measured at the proposed KAC site in Upper Cook Inlet (KABATA 2011).

Acoustic recordings of the oscillator noise included loud, high-frequency construction noise (broadband and at 15 kHz, 30 kHz, and 45 kHz) separated by quieter periods of time. The sources of these sounds are not known at this time, and there was no information on equipment maintenance available. Hypothetically, the hydraulic rams which pushed the oscillator may have needed to be greased; therefore, they might have been the source of the oscillator noise that was recorded at ~141dB. Based on the frequency spectrum shown in **Figure 5**, it appears that the most noticeable noises on the spectrogram (**Figure 4a**)—supposedly associated with the oscillator—are the short tones at 15 kHz and harmonics at 30 kHz and 45 kHz. The frequencies of these tones are within the beluga whale's hearing range (the beluga's hearing range is best between 11.2 kH and 90 kHz, **Figure 7**) and are likely to be heard by animals in the vicinity of an operating oscillator system. Because the physical properties of the proposed KAC site and the Elizabeth River are different, it is difficult at this stage to calculate the distance at which the oscillator could be heard by beluga whales in Knik Arm. Hearing impairment, or temporary threshold shift (TTS), however, is unlikely to happen with oscillator sounds because the SPL is much lower than impulse sounds known to generate TTS (178dB to 193 dB). During TTS experiments, Schlundt et al. (2000) noted behavioral disruption when the 1-second fatiguing sounds were above 180 dB (frequencies between 400 Hz and 75 kHz). Because most of the continuous oscillator noise measured in this study was below these values, and below the ambient noise measured at the proposed KAC project site (KABATA 2011), limited behavioral changes by belugas would be expected.

In comparison to other pile-driving techniques, it appears that the oscillator system for drilled shafts produce lower SPLs than those measured for impact or vibratory pile-driving. The level of received sound at any distance from pile driving depends on the depth of the water in which the piles are driven, the density or resistance of the substrate, bottom topography and composition (e.g., mud, sand, rock), the physical properties and dimensions of the pipe being driven, and the type of pile driver that is used. Pile driving in Knik Arm was investigated in the following studies:

- Blackwell (2005) measured in-water sound produced from impact and vibratory pile driving during construction activities at the Port MacKenzie Dock in August 2004. Two 91-centimeter (cm) (36-inch) diameter steel pipes that were 46 m (150 feet) in length, were driven 12 m to 15 m (40 to 50 feet) into the seabed. These construction sounds were characterized in terms of their broadband and one-third octave band levels. Information on transmission loss was gathered by repeated measurements at different distances from the source. The source level (i.e., sound level at 1 m from the source; SL) of impact pile driving was 234 dB re 1 μPa rms, centered at about 400 Hz, with a −10 dB bandwidth of approximately 350 Hz to 1.5 kHz. The spectrum of the vibratory pile driving was higher than the impact pile driving, centered at 1 kHz, with a −10 dB bandwidth from 400 Hz to 3.5 kHz; SL of vibratory pile driving was not reported. Blackwell (2005) reported that most of the energy during vibratory activity was measured in the range of 400 Hz to 2.5 kHz and that beyond approximately 1,300 m (0.8 mile), background sounds contributed more to received levels than did the vibratory pile driving.

- During October 2007, in preparation for a proposed expansion of the Port of Anchorage (POA), a series of 36-cm (14-inch) H piles were driven using both impact and vibratory techniques (URS 2007). The SL for impact pile driving was 223 dB re 1 μPa rms. Most of the energy was reported as between 100 Hz and 1.5 kHz. The SL for the vibratory pile driving was estimated to be 194 dB re 1 μPa rms with the spectrum of 400 Hz to 2.5 kHz.

- During August through September 2009, a passive acoustic monitoring study of Cook Inlet beluga whales was conducted during the POA Marine Terminal Redevelopment (MTR) project (Širović and Saxon Kendall 2009). The average SPL in the vicinity of the MTR project during the survey was 129.4 ±5.4 dB re 1 μPa with construction activities, and 117.9 ±10.5 dB re 1 μPa without construction. The average SL of impact hammer pile driving during the survey was 196.9 ± 6.1 dB re 1 μPa rms at 1 m. Individual impact pile drives lasted an average of 0.0776 ±0.0110 seconds. The sound energy of impact hammer pile driving extended up to 20 kHz, although most of it was below 10 kHz. The average SL of vibratory hammer pile driving was 183.2 ±4.8 dB re 1 μPa rms at 1 m and the energy from vibratory pile driving was mostly contained at frequencies lower than 10 kHz. The peak SPL at 15 kHz and harmonics and the broadband sounds were not recorded 300 m from the oscillator system indicating that these sounds dissipated rapidly across distance.

Because noise interference was created by the recording system, a 60 Hz high pass filter was used throughout the analysis to avoid contaminating the recordings with electrical artifacts. This filtering removes noise below 60 Hz that contributes to the overall ambient noise and oscillator noise levels. Therefore, if the oscillator generated noise with frequencies below 60 Hz, the corresponding SPL could not be evaluated and presented in this report. These conditions, while not ideal, still provide valuable information about the type of noise generated by the oscillator in comparison to the ambient noise.

Although the Elizabeth River and Knik Arm have different environmental conditions, it is very likely that any measured sound levels from use of an oscillator in Knik Arm would still be much lower than those measured from the use of impact and vibratory pile-drivers in Knik Arm. This study confirms that use of an oscillator for pile-installation activities would introduce less noise to the existing environment. The level of received sound and the SPLs at any distance from pile driving are variable and depend on the depth of the water in which the piles are driven; the density or resistance of the substrate; bottom topography and composition (e.g., mud, sand, rock); the physical properties and dimensions of the pipe being driven; the type and model of pile driver that is used; and speed of sound (which as noted earlier, is dependent on salinity and temperature). As a result, the SPLs for use of an oscillator in the Gilmerton Bridge Replacement project in the Elizabeth River cannot be fully applied to the proposed KAC project in Cook Inlet and potential beluga impacts. A test-pile program using an oscillator at the proposed KAC site will be required to validate the preliminary data collected during this study of an oscillator in Virginia.

Table 1. Underwater monitoring results for oscillator noise measurements made during January 2011 at the Gilmerton Bridge Replacement Project in Chesapeake, Virginia.

Location; type of noise measurement	Distance to pile (m)	Mean SPL (dB re 1 μPa rms)	Standard deviation (dB)	SPL Range (dB re 1 μPa rms)
Site 1; ambient noise	30	115.9	0.4	114.9–116.9
Site 1; oscillator	30	121.6	6.4	115.6–141.5
Site 2; oscillator	300	116.9	0.6	115.8–118.6

Figure 1. Location of monitoring locations at the Gilmerton Bridge Replacement project in Chesapeake, Virginia.

Site 1 is 30 m from the oscillator system; Site 2 is 300 m from the oscillator system.

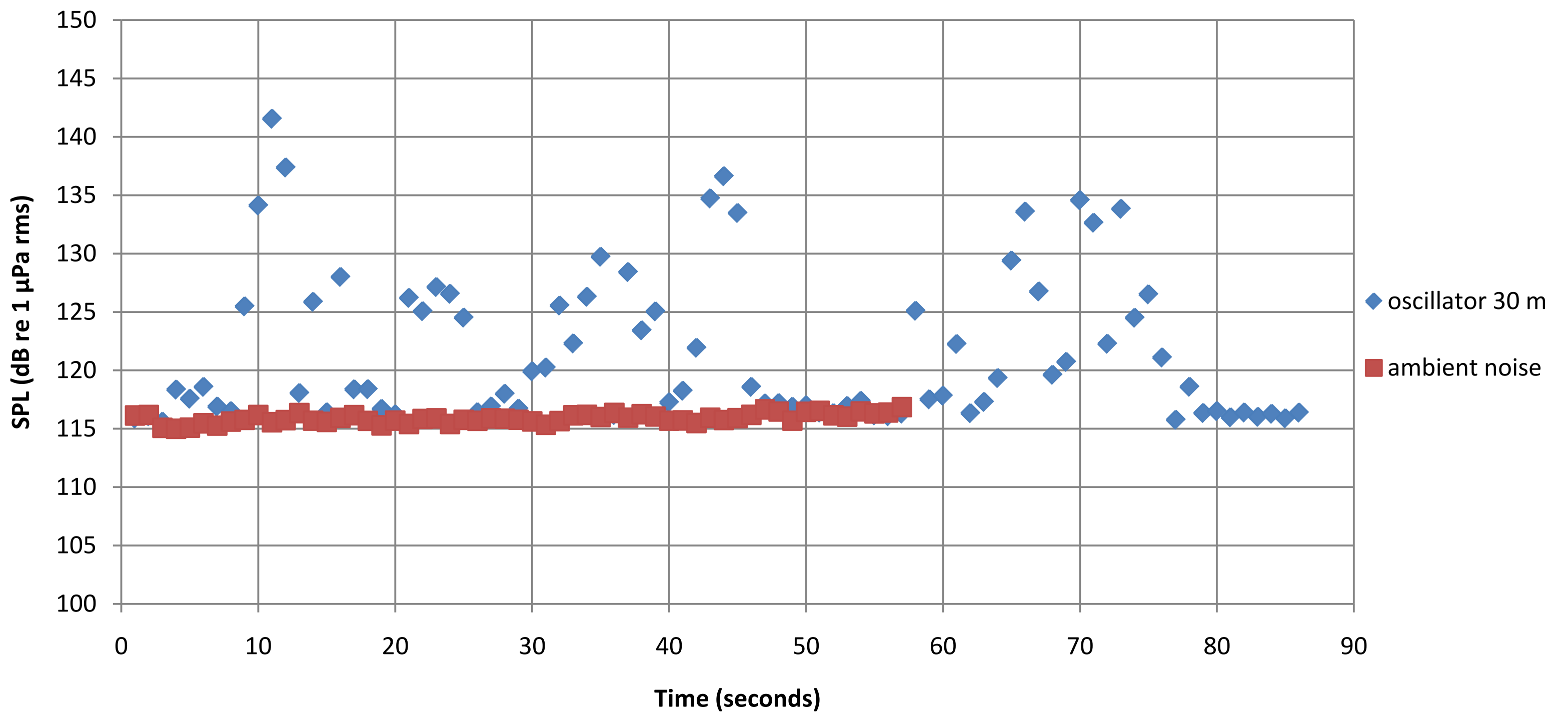

Figure 2. Temporal variation in SPLs for oscillator noise at a distance of 30 m from the construction site (Site 1) compared to ambient noise conditions.

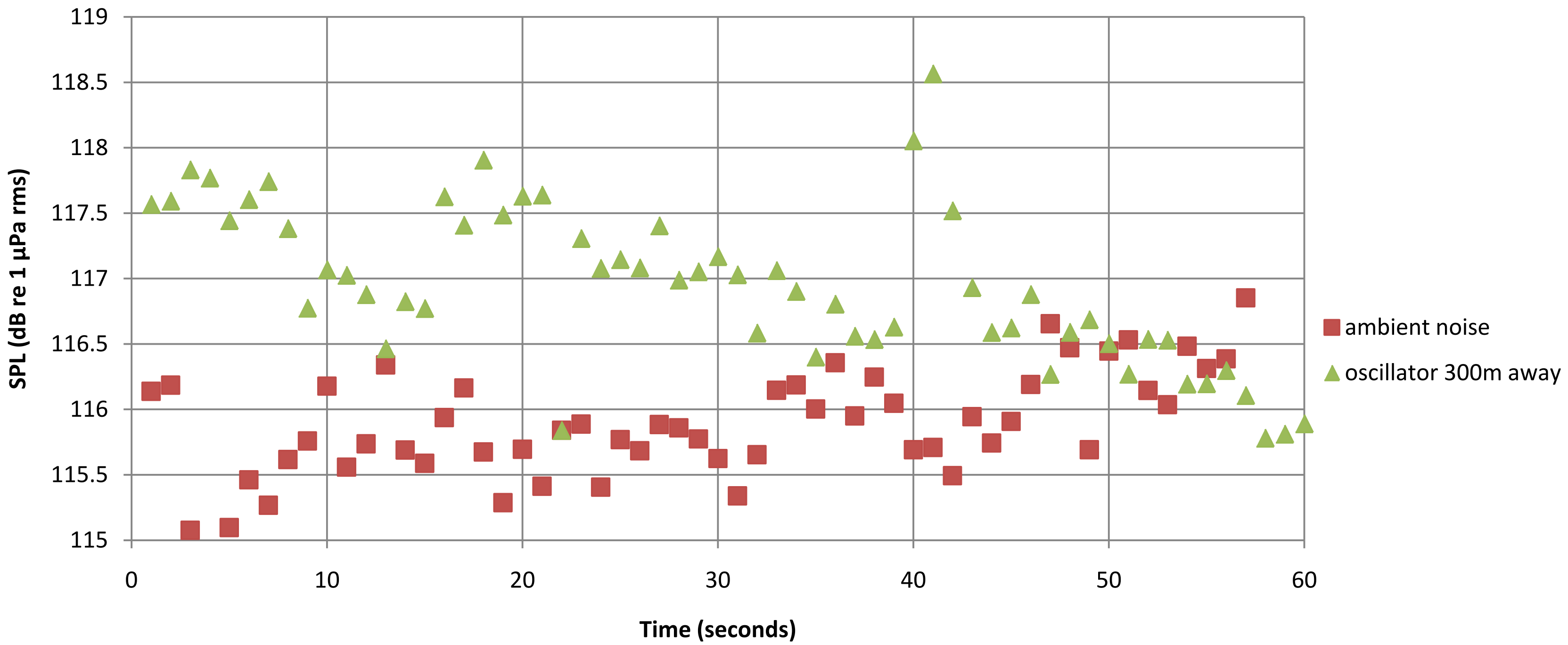

Figure 3. Temporal variation in SPLs for oscillator noise at a distance of 300 m from the construction site (Site 2) compared to ambient noise conditions.

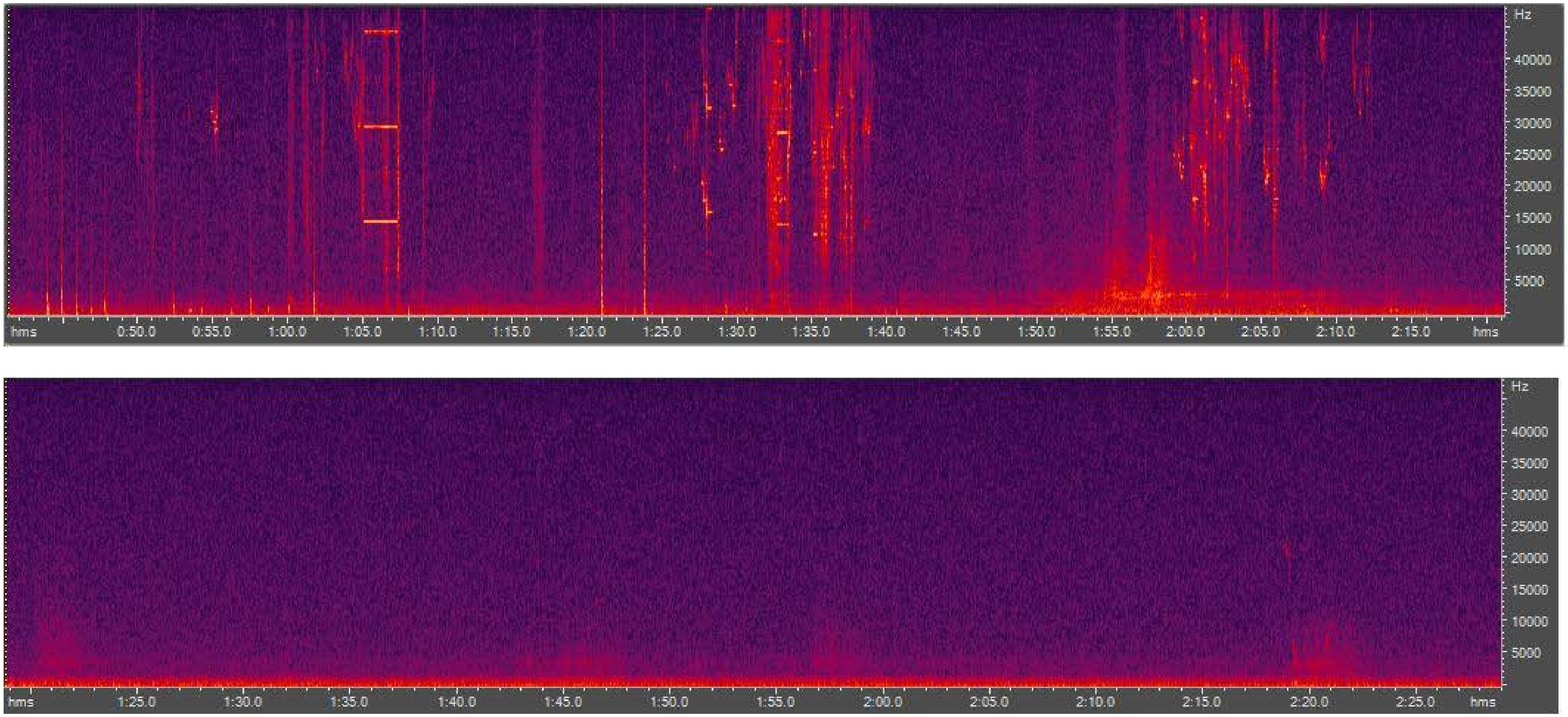

Figure 4. Spectrograms of the underwater noise recorded during oscillator operation.

Figure 4a, top, underwater noise recorded 30 m from the construction site (Site 1). Figure 4b, bottom, underwater noise recorded 300 m from the construction site (Site 2). Note on Figure 4a, that at 1:55:0 minutes the broadband noise corresponds to a nearby vessel; this recording segment was excluded from the analysis.

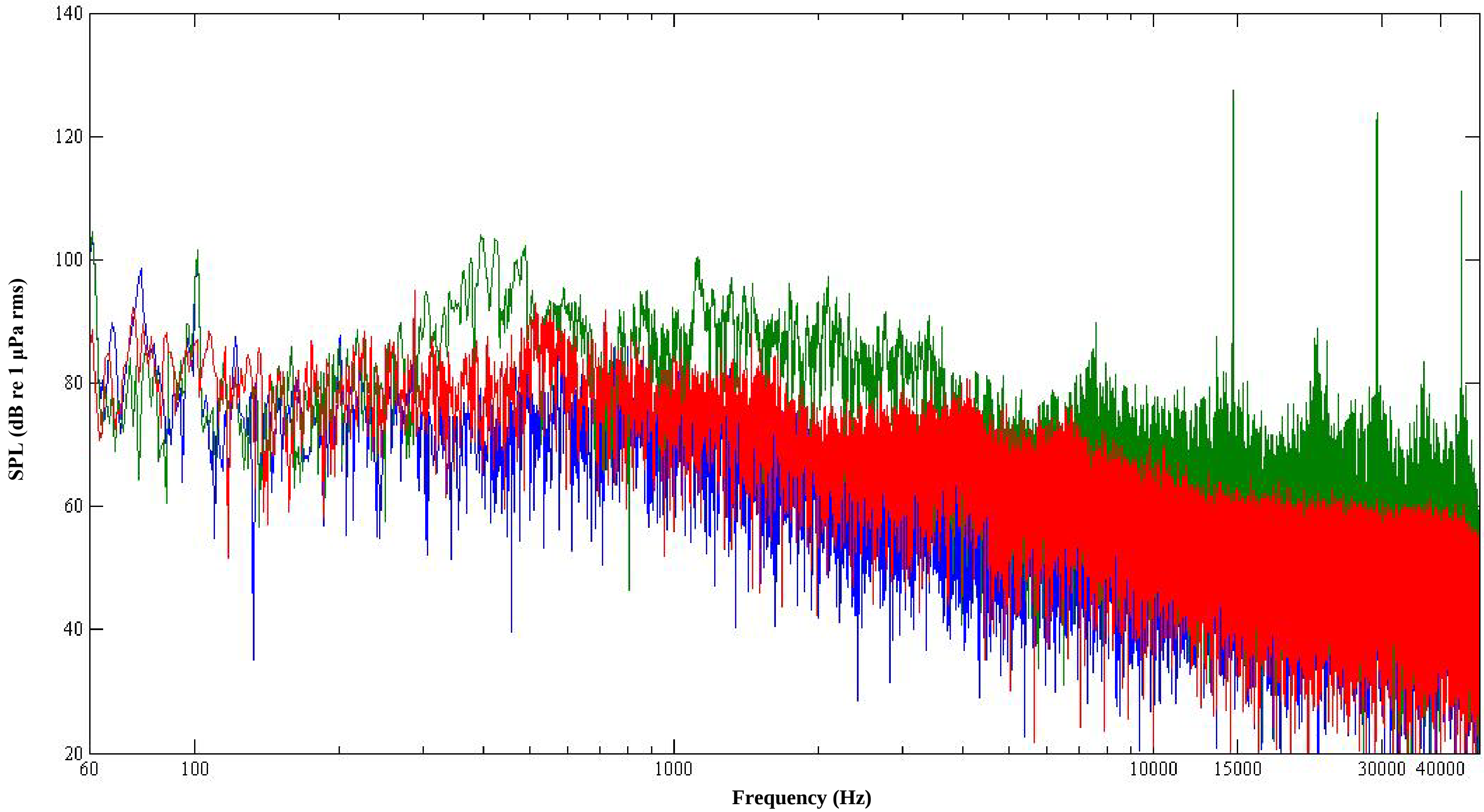

Figure 5. Combined sound spectra for ambient noise.

Ambient noise (blue) and oscillator noise at distances of 30 m (green) and 300 m (red) from the Leffar VRM 3800 oscillator at the Gilmerton Bridge Replacement Project in Chesapeake, Virginia.

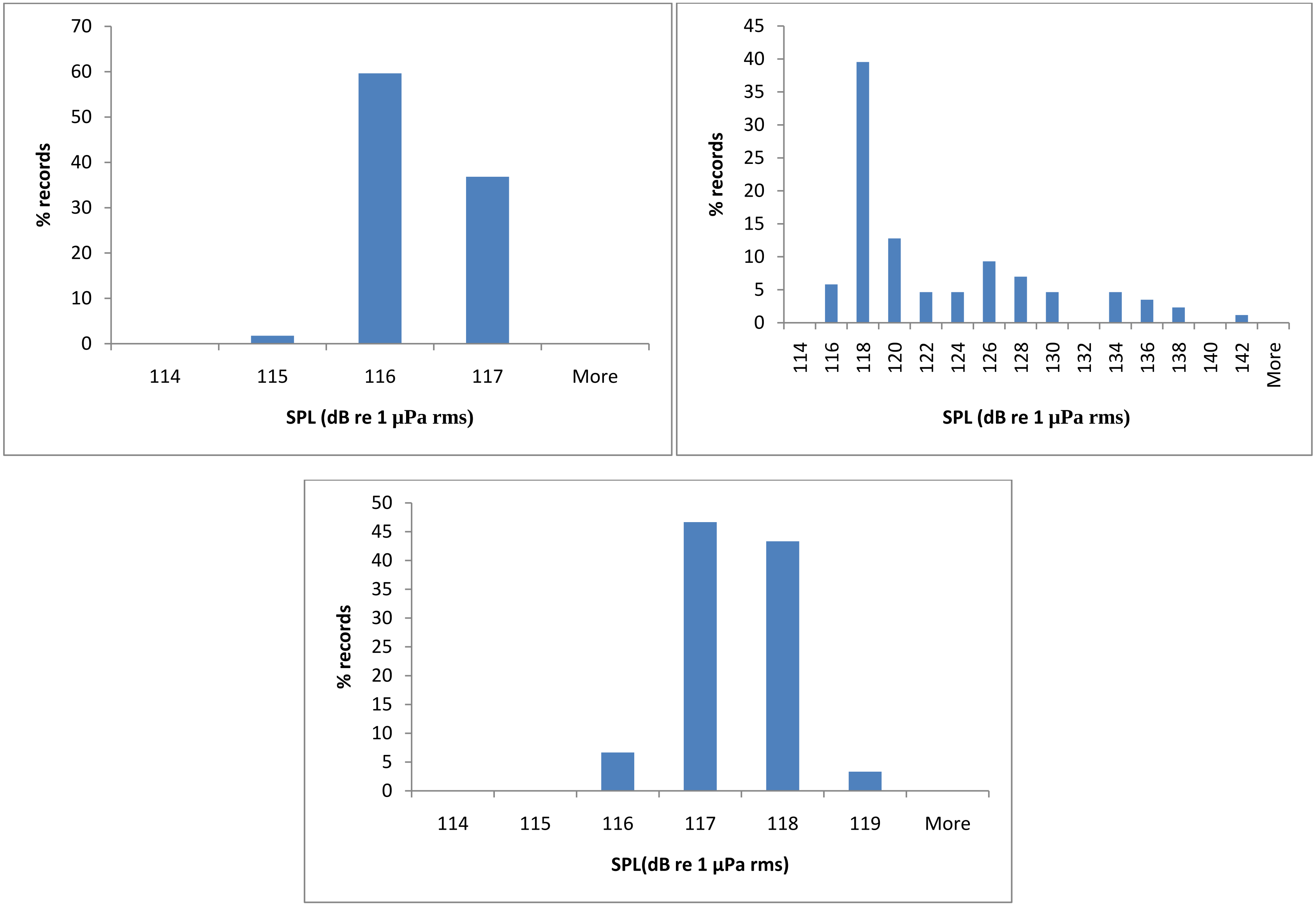

Figure 6. Sound pressure levels of underwater noise.

(a, b and c; left to right). Sound pressure levels (SPL [dB re 1 µPa rms]) of underwater noise at: (a) ambient noise at a distance of 30 m; (b) operating oscillator system at a distance of 30 m , and (c) operating oscillator at a distance of 300 m.

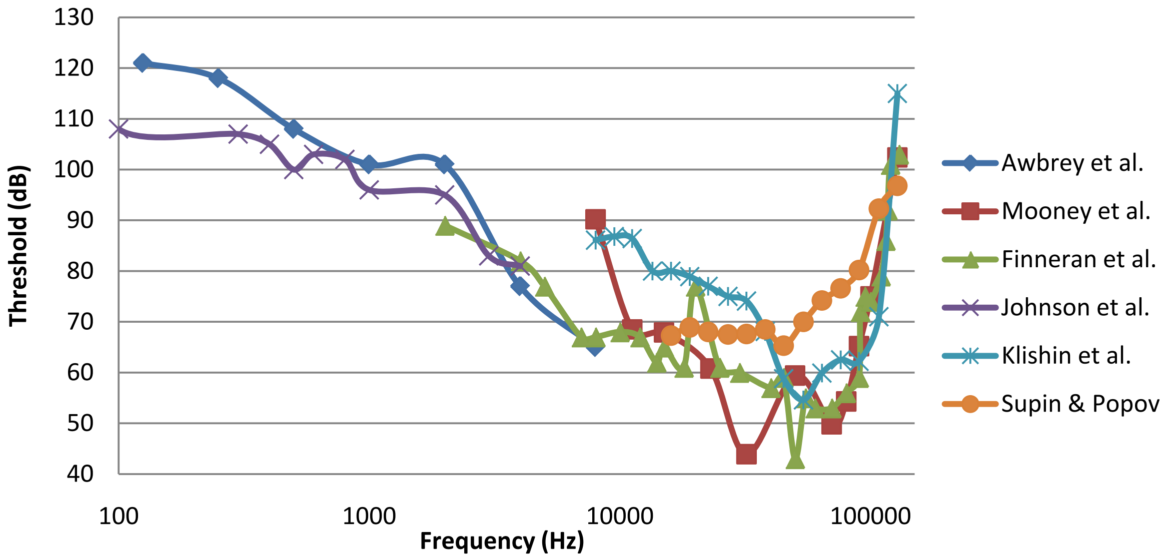

Figure 7. Beluga whale audiograms.

Sources: Johnson et al. (1989), Awbrey et al. (1988) (behavioral), Mooney et al. (2008) (auditory evoked potential), Klishin et al. (2000), Finneran et al. (2005), and Supin and Popov (2009).

5 ACKNOWLEDGEMENTS

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APPENDICES

APPPENDIX A

TIDAL CYCLES DURING JANUARY 19–25, 2011, IN THE ELIZABETH RIVER, VIRGINIA

Date	Low	High	Low	High	Low
1/19/2011	2:12 a.m.	8:34 a.m.	2:59 p.m.	8:57 p.m.	--
1/20/2011	3:03 a.m.	9:22 a.m.	3:44 p.m.	9:47 p.m.	--
1/21/2011	3:53 a.m.	10:10 a.m.	4:29 p.m.	10:37 p.m.	--
1/22/2011	4:44 a.m.	10:59 a.m.	5:14 p.m.	11:28 p.m.	--
1/23/2011	5:36 a.m.	11:47 a.m.	6:01 p.m.	--	--
1/24/2011	--	12:19 a.m.	6:33 p.m.	12:37 p.m.	6:53 p.m.
1/25/2011	--	1:11 a.m.	7:35 a.m.	1:29 p.m.	7:49 p.m.

Source: Go Fishing Forum. 2011. Accessed at: <http://gofishingforum.net/tide.pl?month=1&day=19&year=2011&days=4&location=Norfolk%2C+Elizabeth+River%2C+Virginia&lat=36.8517&lon=76.2983&submit=Update+Charts>.

APPENDIX B

OSCILLATOR SPECIFICATIONS

Leffer VRM 3800 Specifications

Collar height :	800 mm 31 1/2"
Lifting stroke :	650 mm 25 19/32"
Lifting force :	9000 kN 2023280 lbf.
Rotation angle :	24°
Clamping force :	5100 kN 1146526 lbf.
Retaining force :	1800 kN 404650 lbf.
Adjusting force fwd. :	500 kN 112404 lbf.
bwd. :	420 kN 94419 lbf.
Torque :	15800 kNm 11653000 ftlb.
Overall length :	10640 mm 34' 10 13/16"
Overall width :	5480 mm 18'
Overall height :	2730 mm 8' 4 9/64"
Total weight :	72 tons 158730 lbs.

APPENDIX C

CALCULATION OF THE SPEED OF SOUND

The speed of sound can be approximated by using Medwin's Equation (Medwin 1975):

$C \approx 1449.2 + 4.6T - 5.5 \times 10^{-2}T^2 + 2.9 \times 10^{-4}T^3 + (1.34\text{-}10^{-2}T) - (S\text{-}35) + 1.6x10^{-2}D$

Where C = speed of sound underwater, expressed in meters/second (m/s)
T = temperature of the water in degrees Celsius (°C)
S = salinity of the water in parts per thousand (ppt)
D = depth in meters (m)

Sixteen salinity and temperature measurements were made during collection of the acoustic recordings. The mean speed of sound was estimated to be approximately 1419.6 m/second (SD = 52.36).

Collection number	Salinity (ppt)	Depth (m)	Temperature (°C)	Speed of sound (m/s)
1	12.5	6	7.8	1261.47642
2	13.5	2	8.7	1394.308516
3	10.5	0	9.3	1456.904814
4	16.1	2	6.9	1390.394818
5	14	0	7.5	1454.163594
6	13.1	0	7.9	1454.634531
7	13.2	2	9	1395.10641
8	11.5	0	8.9	1456.589391
9	16.3	2	6.9	1390.649018
10	13.6	0	7.6	1454.060903
11	13.4	2	8.1	1391.811168
12	10.2	0	9.1	1455.748786
13	16.3	2	6.9	1390.649018
14	14.8	0	7.4	1454.772515
15	15.1	0	7.8	1456.75762
16	15.1	0	7.5	1455.555094
			MEAN	1419.598913
			SD	52.36469463

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