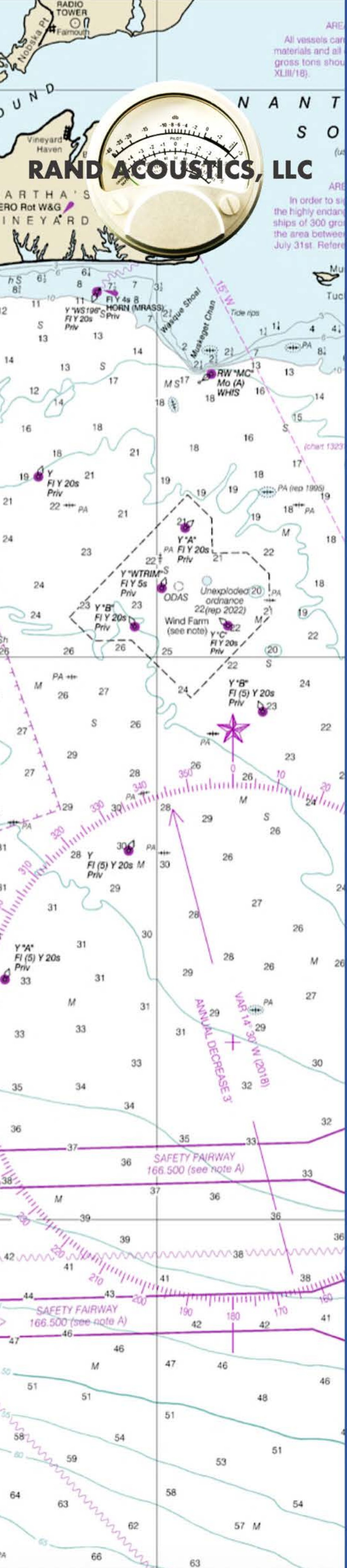

PILE DRIVING NOISE SURVEY
Technical Report

Survey Date:
November 2, 2023

Report Date:
March 28, 2024

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Abstract

This technical report presents the methodology, analysis, and results of an independent investigation of underwater noise levels from wind turbine pile driving operations, conducted southwest of Nantucket on November 2, 2023.

Keywords: noise, offshore, survey, vessel, hydrophone, pile driving, piling, hammer, threshold, transmission loss, peak, RMS, SEL, thermocline, bubble curtain

Foreword

This technical report serves as a comprehensive document intended to provide valuable insights, analysis, and information pertaining to wind turbine pile driving noise. It has been prepared to support understanding of pile driving noise levels versus distance for a diverse audience, including professionals, researchers, policymakers, and interested stakeholders. The primary purpose of this report is to facilitate informed decision-making, foster discussion, contribute to the advancement of knowledge in this field, and improve noise control protections for the critically endangered North Atlantic right whale and other ESA-listed mammals and marine species.

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EXECUTIVE SUMMARY

Recent whale and dolphin fatalities on the Eastern seaboard, coupled with concerns about the acoustic impact of offshore wind farm construction, prompted an independent investigation to measure and assess underwater noise emissions from pile driving activities. Specifically, this assessment focused on the operations of the pile driving vessel Orion within the Vineyard Wind project area, with recordings taken in the waters southeast of Nantucket Island.

Key Findings:

- Pile driving noise, even with advanced noise-mitigation techniques, rivals the loudness and frequency range of seismic air gun arrays, with impulsive peak noise levels measured up to 180 dB over 1 kilometer away and RMS levels over 160 dB at over 3.3 kilometers.
- The standard 90-percent RMS metric utilized by the National Marine Fisheries Service (NMFS) underestimates the sound level experienced by cetaceans by as much as 6 dB, potentially cutting the protective distances in half and reducing marine mammal safeguarding zones by up to 75%.
- The continuous noise generated by vessel propulsion and dynamic positioning (DP) thrusters significantly surpassed the federal threshold for behavioral harassment, with noise levels exceeding 120 dB out to over 6 kilometers. Given federal agencies' concerns over the compound effects of continuous and impulse noise, this frequently overlooked issue in regulatory assessments constitutes a definitive risk of behavioral harassment to marine mammals, underscoring the need to reevaluate current protective measures.

Conclusion:

This investigation discovered a substantial underestimation of both impulsive and continuous noise levels by current regulatory standards, suggesting that the actual exposure to harmful noise levels from pile driving for marine mammals like the critically endangered North Atlantic Right Whale is substantionally greater than NMFS acknowledges in its existing protective measures. This indicates an urgent need to review and possibly revise NMFS monitoring protocols and mitigation strategies for pile driving to ensure adequate protection for marine mammals against both impulse and continuous underwater noise pollution. The findings detailed in this report underscore the need for immediate action due to the substantial underestimations uncovered by this independent investigation.

Recommendations:

- Immediate reassessment of RMS computation methods to more accurately represent the potential risk of pile driving noise to marine mammal hearing.
- Inclusion of continuous noise assessment from vessel operations in regulatory reviews, with a focus on managing combined noise levels to remain below NMFS thresholds for behavioral harassment during impulsive activities such as pile driving.
- Enhancement of protective radii and mitigation distances to shield marine mammals from the risk of behavioral harassment and auditory injury.

1 Introduction

1.1 Background

Reports of recent whale and dolphin deaths along the Eastern seaboard, coupled with concerns of marine noise impacts from offshore wind development activities, prompted an independent investigation into pile driving noise levels in ocean areas leased by the Bureau of Ocean Energy Management (BOEM). The crane ship Orion (IMO: 9825453) has been utilized as a pile driving vessel in the Vineyard Wind BOEM Lease Area OCS-A 0501 southwest of Nantucket.

Figure 1. The Orion, drone view, in Vineyard Wind lease area. Photo by DEME [1], shows Orion (right) at stationary position with hammer on starboard side, monopile sections in laydown amidships. Bubble curtain support vessel at left.

The Orion is an offshore heavy lift vessel registered in Belgium [2]. The Orion is 216.5 m long, 49 m wide, with an operating draft of 11 m. It is equipped with a main crane with 5,000 ton capacity and an auxiliary crane with 1,500 ton capacity. Propulsion includes 4 x 4.500 kW Azimuth thrusters, 2 x 4,200 kW Retractable Thrusters, and 2 x 2,500 kW Tunnel thrusters. It is equipped with Dynamic Positioning (DP3, redundant hardware and control for assured positioning).

The Orion is equipped with an IHC IQIP S-4000 pile driving system rated for a 4,000 kiloJoule (kJ) maximum hammer blow energy, 397 kJ minimum hammer blow energy, hammer blow rate up to 36 bl/min, ram weight 200 tons, and hammer weight 430 tons.

1 https://www.deme-group.com/news/offshore-works-kick-vineyard-wind-farm-us-installation-first-foundation, publication date 06 JUN 2023.
2 DEME Orion, DP3 offshore installation vessel, https://www.deme-group.com/technologies/orion

Noise controls include a hydro sound damper and double bubble "Big Bubble" curtains [3,4,5,6] for pile driving noise reduction (HSD + DBBC). Appendix A provides details on the bubble curtain technology, which uses compressed air supplied by a nearby support vessel. Outer bubble curtain radius is roughly 150 to 200 meters. Hydro sound dampers are vertical nets with acoustic elements supported around the monopile and do not use compressed air. These noise reduction technologies may be considered "best available" for pile driving.

Figure 2. Drone view of he Orion showing double bubble curtains operating. Air compressor support vessel is out of frame at lower left edge of photo. The hydro sound damper is hung around the monopile from sea level to seabed. Photo by DEME [7].

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3 A hydro sound damper is a donut-shape cylindrical net vertically surrounding the monopile being driven. The damper net contains polyethylene foam or rubber material elements. Noise reduction is obtained with acoustic resonance, dissipation and damping, impedance shifts and sound speed reductions in the net elements.

4 https://www.researchgate.net/publication/293465032_Hydro_sound_emissions_during_impact_driving_of_monopiles_using_Hydro_Sound_Dampers_and_Big_Bubble_Curtain, accessed 1/1/24.

5 https://www.eenews.net/articles/blowing-bubbles-offshore-winds-new-strategy-to-save-whales/

6 https://www.hydrotechnik-luebeck.de/portfolio-items/compressed-air-hydro-sound-mitigation/

7 https://www.deme-group.com/technologies/orion#/media/5

1.2 Pre-Operational Noise Impact Assessments

In preparing this report, four project documents furnishing noise impact models and estimates were reviewed [8,9,10,11]. Underwater acoustics metrics are discussed in this report's Section 2.

- Vineyard Wind 1 Construction and Operations Plan Appendix III-M: Supplemental (Dec 2018)
- Offshore Wind Energy Project Biological Assessment (BOEM Mar 2019)
- IHA Application (Apr 2019)
- IHA Authorization (May 2021)

Key points are summarized below:

- PTS injury is estimated from weighted sound exposure accumulated over 24 hours (cSEL) or from very loud instantaneous sound pressure levels. TTS injury is estimated from weighted sound exposure accumulated over 24 hours (cSEL).

- Behavioral harassment is classified as a Level B harassment for received RMS sound levels above 120 dB and as the probability of 10%, 50% and 90% behavioral response using auditory weighting for received RMS sound levels respectively at 120, 140, and 160 dB re 1uPa.

- The NOAA (2005) behavioral threshold for all hearing groups is a Root Mean Square (RMS) sound pressure level (SPL, unweighted) of 160 dB re 1uPa. For this pile driving operation, NOAA has defined an estimated distance to 160 dB RMS re 1uPa of 2739 meters assuming a 12 dB noise attenuation utilized during pile driving.

- The Vineyard Wind noise model is completely redacted. Consequently, it is not possible to validate the noise model source level, propagation loss, or noise control insertion loss with the data acquired during this survey.

- For extent of Level B harassment zone verification, Vineyard Wind must report the measured or extrapolated distances where the received levels SPLrms decay to 160 dBrms, as well as integration time for such SPLrms.

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8 Appendix III-M, Revised Draft - Supplemental Information for the Assessment of Potential Impacts to Marine Mammals and Sea Turtles During Construction, Operation, and Decommissioning of the Vineyard Wind Project. Technical Report by JASCO Applied Sciences, November 20, 2018.

9 Vineyard Wind Offshore Wind Energy Project Biological Assessment December 2018 (Revised March 2019), Bureau of Ocean Energy Management.

10 Request for an Incidental Harassment Authorization, Vineyard Wind BOEM Lease Area OCS-A 0501, Vineyard Wind, April 2019. https://media.fisheries.noaa.gov/dam-migration/vineyardwind_2019iha_app_opr1.pdf

11 Incidental Harassment Authorization, issued to Vineyard Wind 1, LLC (Vineyard Wind), valid from May 1, 2023 through April 30, 2024. Digitally signed by Catherine Marzin, Acting Director, Office of Protected Resources, National Marine Fisheries Service, May 21, 2021. https://media.fisheries.noaa.gov/2021-05/VWconstr_FinalIHA_OPR1.pdf

- Cetaceans rely heavily on acoustics for communication, foraging, mating, avoiding predators, and navigation. North American Right Whales (NARW) frequent the Lease Area throughout the year and most often during winter and spring. Noise exposure associated with the proposed action can interfere with foraging, orientation, migration, predator detection, social interactions, or other activities, with the potential to cause a range of responses ranging from insignificant behavioral changes to ear injury, depending on the intensity and duration of the exposure.

2 Methodology

2.1 Instrumentation

Underwater sound pressure levels were acquired with a Cetacean Research (Golden, CO) C75 research-grade pre-amplified omnidirectional hydrophone. The C75 has an effective sensitivity of -180 dB re 1V/1uPA, an equivalent self-noise of 51 dB re 1uPA/√Hz, and a linear frequency response range of +/-1 dB from 25 Hz to 10 KHz and +/-3 dB from 20 Hz to 170 KHz (see Appendix B). The hydrophone preamp DC power supply was modified to provide 192 dB re 1 uPa full scale before clipping. The hydrophone output was input to a Tascam (Santa Fe Springs, CA) X8 digital audio recorder line-in at 192 KHz, 24-bit resolution. The Tascam X8 has a frequency response of 20 Hz – 40 kHz at 96 kHz: +0/-0.4 dB and 20 Hz – 60 kHz at 192 kHz: +0/-2.5 dB (JEITA).

The C75 hydrophone and Tascam recorder were calibrated end-to-end with a GRAS (Beaverton, OR) 42AG acoustic calibrator at a sound pressure level in air of 114 dB re 20 uPA at 251.2 Hz, an equivalent to the sound pressure in water at 251.2 Hz of 140 dB re 1 uPA, using a custom machined hydrophone calibrator adapter Model HADP42AG-C75 from BRC Engineering (Sonoma, CA) with calibration current and certified traceable to NIST (see Appendix C). Post-survey analysis was conducted with Spectraplus-SC software version 5.3.0.12C (Pioneer Hill Software, Sequim, WA). Custom Python scripts (The Python Software Foundation [12], V3.9.12) and Excel were utilized for data review, analysis, and plotting.

The acquired recordings had high signal to noise in the frequency ranges of interest and sufficient headroom to prevent digital signal clipping. Particle motion was not acquired during this survey.

2.2 Survey Locations

Underwater acoustic recordings were acquired on November 2, 2023 between 11:05 am and 2:45 pm, approximately 8 to 13 miles southwest of Nantucket Island (see Figure 3 below).

12 See www.python.org (Last viewed 25 March 2024).

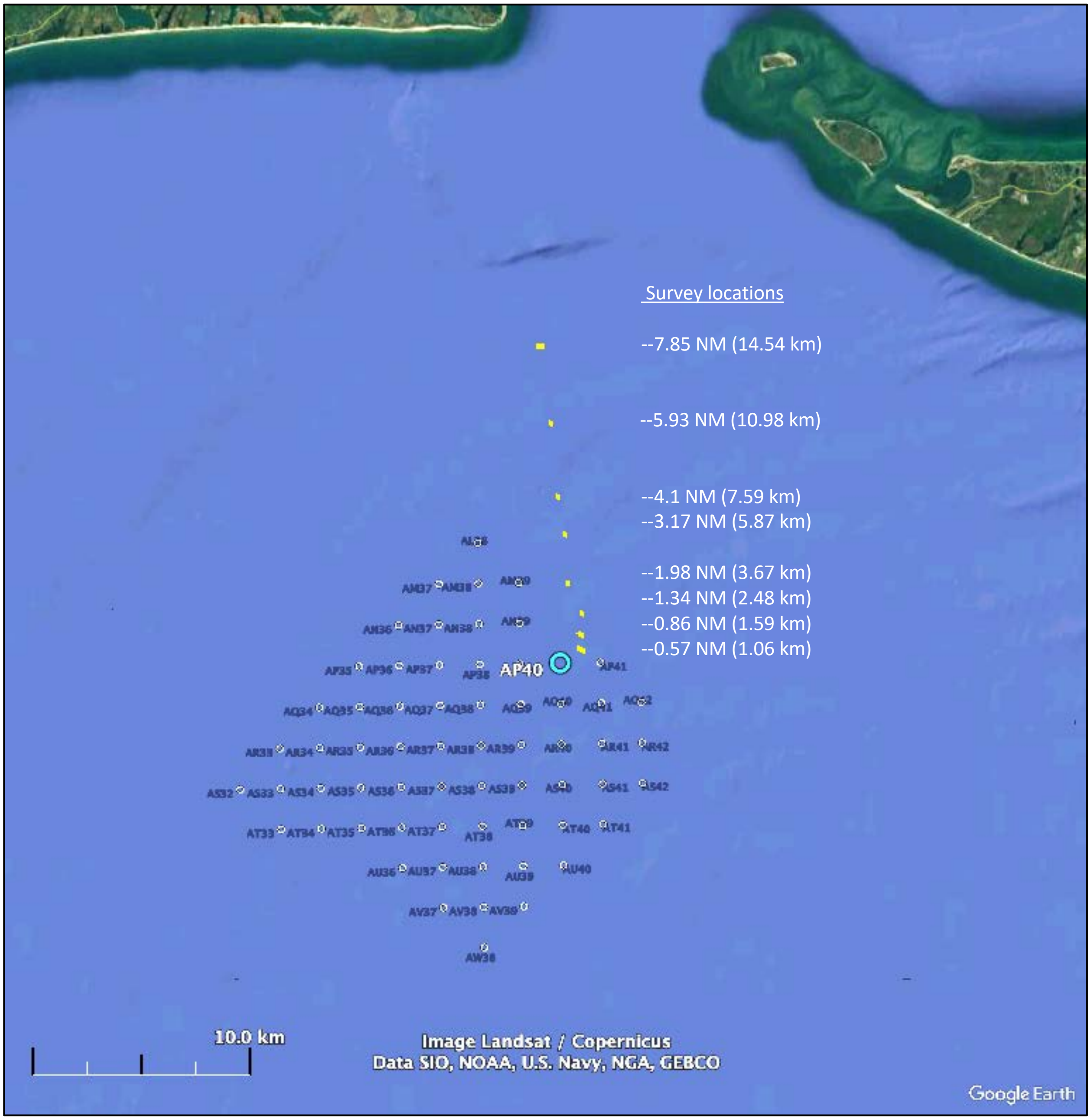

Figure 3. Survey locations marked withwhite dots and notations. Orion location at monopile AP40.

Passive acoustic monitoring (PAM) was conducted with a hydrophone dipped by hand to a 20 meter depth from the side of a 29-foot center-console sport-fishing boat ("investigator boat") at eight separate distances from the AP40 monopile [13]. These distances were 7.85, 5.93, 4.1, 3.17, 1.98, 1.34, 0.86, and 0.57 NM (14.54, 10.98, 7.59, 5.87, 3.67, 2.48, 1.59 and 1.06 km). Initial distance to the stationary Orion was estimated using the investigator boat's onboard marine radar prior to shutting off systems for acoustic recording. Distance to monopile was confirmed in post analysis with GPS tracking logged on cellular phone (iSailGPS, James Associates). A distance to

13 Recordings were made at all locations but pile-driving was not occurring while at 7.85 and 5.93 NM.

source uncertainty of ±60 m (worst case +/- 0.5 dB at 0.57 NM over 120 seconds) is assumed based on the measured investigator boat drift rate of 1.1 knots.

Weather conditions were sunny, with unlimited visibility, thin high clouds, air temperature 43 to 46 degrees F (6 to 8 C), light to moderate winds from the WNW, sea state Beaufort 2 to 3, 1 to 3 foot swells, light surface ripples, and occasional crest breaks. Water depth was 29 to 38 meters. Water temperature at the surface was 58 degrees F (14 C). Salinity was not measured. A shallow thermocline was visible on the onboard Simrad fishing sonar at 2 to 4 fathoms (roughly 4 to 7 meters). The investigator boat was seaworthy and stable with engine located amidships, and was allowed to drift downwind with engine off during hydrophone recording to minimize wave slap. Drift rate was calculated from GPS data at approximately 1.1 knot (~ 0.5 m/s).

The survey was conducted using methods consistent with NMFS guidelines [14] for hydrophone measurements including selection of a "far range" location of at least 20 times the water depth, and hydrophone depth at least 5 meters.

2.3 Acoustic Propagation

For purposes of regulatory management, marine mammalian hearing is based on sound pressure detection. Sound pressure in water is quantified as a sound pressure level using decibels referenced to 1 microPascal (µPa). Underwater sound pressure levels differ from those in air by 26 dB (the difference in the reference levels of 1 µPa in water versus 20 µPa in air), plus 36 dB (the difference in acoustic impedance between water and air). The differential is approximately 62 dB. For example, a sound pressure level of 160 dB re 1 µPa in water would equate roughly to 98 dB re 20 µPa in air. For humans in air, most acoustic energy bounces off the body due to the impedance contrast [15]. However, for marine mammals whose body acoustic impedance is similar to ocean water [16], sound pressure transients are expected to penetrate their bodies with little reduction in energy.

Acoustic waves in water have sound pressure and particle motion components. Water is compressible, like air (although denser), thus longitudinal pressure waves occur in the water fluid medium as they do in air: particles vibrate in the direction the sound is moving. The speed of sound in water is about 1500 m/s, nearly five times faster than in air (343 m/s). Underwater apparent sound "source level" (SL) is referenced at 1 meter and derived in practice from sound pressure measurements calculated back to 1 meter. Indeed, SL is a far-field property of the source and is not an actual sound pressure level at 1 meter [17].

14 NMFS Northwest Region and Northwest Fisheries Science Center, Guidance Document: Sound Propagation Modeling to Characterize Pile Driving Sounds Relevant to Marine Mammals, January 1, 2012.

15 Low frequencies of sufficient intensity may resonate organs. Acoustic energy below 20 Hz activates OHC efferent function as cochlear amplifier. Acoustic forces at very low frequencies may affect balance organs, per Schomer 2015 https://doi.org/10.1121/1.4913775.

16 Dong J, Song Z, Li S, Gong Z, Li K, Zhang P, Zhang Y, Zhang M. Acoustic properties of a short-finned pilot whale head with insight into temperature influence on tissues' sound velocity. J Acoust Soc Am. 2017 Oct;142(4):1901. doi: 10.1121/1.5005509. PMID: 29092562.

17 M. A. Ainslie, M. B. Halvorsen and S. P. Robinson, "A Terminology Standard for Underwater Acoustics and the Benefits of International Standardization," in IEEE Journal of Oceanic Engineering, vol. 47, no. 1, pp. 179-200, Jan. 2022, doi: 10.1109/JOE.2021.3085947.

Sound pressure level (SPL, dB re 1 µPa) at a distance beyond 1 meter is lower than the calculated SL due to attenuation with distance, referred to as propagation loss (PL) or "transmission loss" (TL) [18]. Propagation loss is influenced by underwater acoustic factors including sound speed gradients in winter versus summer, thermocline strength, and salinity. A first-order estimate of SPL using spherical spreading, ignoring absorption in the medium versus frequency, seabed topography, and other factors, is:

SPL, dB at r, meters = SL – 20log10(r), dB (spherical)

The drop in sound pressure level with distance using this equation is 20 dB per decade, or 6 dB per doubling of distance. NMFS applies spherical spreading for shallow water conditions. For near-shore conditions, NMFS recommends a "practical spreading" loss model to estimate the sound pressure level from a source level near shore. Using the practical spreading loss model, TL in dB units is defined by:

SPL, dB at r, meters = SL – 15log10(r), dB "practical spreading" (NMFS)

The drop in sound pressure level with distance using this equation is 15 dB per decade or roughly 4.5 dB per doubling of distance.

Acoustic propagation of pile driving hammer blows proceeds into the ocean water directly, via an angled pressure wave (line source) penetrating the water and via hammer shock entering the seabed from the monopole base. See Figure 4 below.

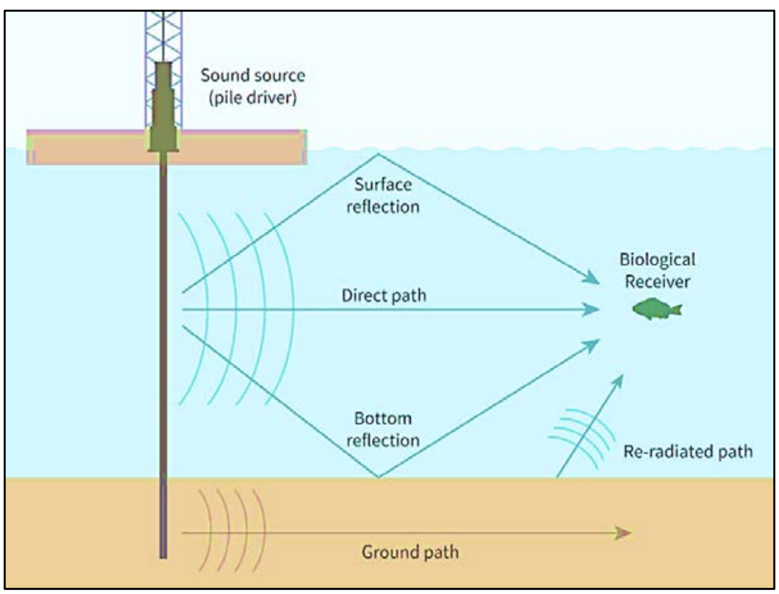

Figure 4. Sound propagation paths associated with pile driving (adapted from Buehler et al., 2015), from BOEM [8].

Since the seabed has a higher sound speed compared to ocean water, acoustic energy traveling through the seabed (the ground path) and re-emerging into the ocean water through refraction can

18 NMFS uses TL and PL interchangeably but they are technically distinct acoustical processes.

arrive at a distant location before the direct-path acoustic peak transmitted through the water. Additionally, acoustic energy that propagates through the seabed can circumvent noise mitigation technologies, such as bubble curtains. The interval between the arrivals of acoustic impulses through the ground path and the direct path widens with distance. This disparity can significantly and adversely affect the 90-percent root mean square (RMS) measurements utilized by NMFS.

2.4 Metrics

Table 1 lists those acoustic terms typically found in regulatory documents and acoustics-related ISO standards including ISO 18405 [19] which addresses underwater acoustics. All terms are unweighted unless weighting is noted.

Table 1. Summary of terminology.

ISO Symbol	Term used in this report	Description
p	P	Sound pressure, Pa
p_0	Pref	Reference sound pressure, Pa (1 uPa)
p_{peak}	Ppk	Peak sound pressure, Pa
$p_{pk\text{-}pk}$	Ppk-pk	Peak to peak sound pressure, Pa
$L_{p,0\text{-}pk}$	Peak, Lpk	Peak sound pressure level, dB re 1 uPa
-	Peak-to-peak, Lpk-pk	Peak to peak sound pressure level, dB re 1uPa
L_p	SPL	Sound pressure level, dB re 1 uPa
$L_{p,rms}$	RMS*	Root mean square SPL, dB re 1 uPa
L_E	SEL*	Sound exposure level, dB re 1 uPa^{2}s
$L_{E,w}$	SEL,w	Weighted SEL (e.g. LF, PW)
-	cSEL	Cumulative SEL, dB re 1 uPa^{2}s
L_S	SL	Source level, dB re 1 uPa
-	RL	Received level, dB re 1uPa
r	r	Distance from source, meters
ΔL_{TL}	TL	Transmission loss, dB
N_{PL}	PL	Propagation loss, dB

** Time durationg is required for RMS level and is referenced for cumulative SEL derived from RMS. RMS time durations include the 200-millisecond duration, and the variable time duration for the 5- to 95-percent "90pct" percentage energy signal duration.*

Terms used in this report include sound exposure level "SEL" and cumulative SEL "cSEL". NMFS evaluates the cumulative SEL for Level A harassment, e.g. the onset of permanent threshold shift (PTS, hearing loss). Level B harassment is defined as the sound level above which temporary threshold shift (TTS, temporary hearing loss) occurs. SEL is expressed in dB re 1 μPa^{2}s as a quantity of exposure over time.

$$SEL = 10 \cdot \log_{10}\left(\frac{1}{T}\sum_{i=1}^{N} p_i^2\right)$$

Where:

- T is the time duration over which the sound levels are integrated (in seconds).

19 Underwater Acoustics – Terminology, ISO 18405:2017, 2017. https:// www.iso.org/ standard/62406.html

- N is the total number of pressure samples in the given time interval.
- p is the sound pressure value at the i-th sample, usually given in Pascals.

SEL can also be expressed as RMS + 10log(T/1.0), with T equal to the RMS duration in seconds. The relationship of peak, peak-to-peak and RMS is illustrated in Figure 5 below.

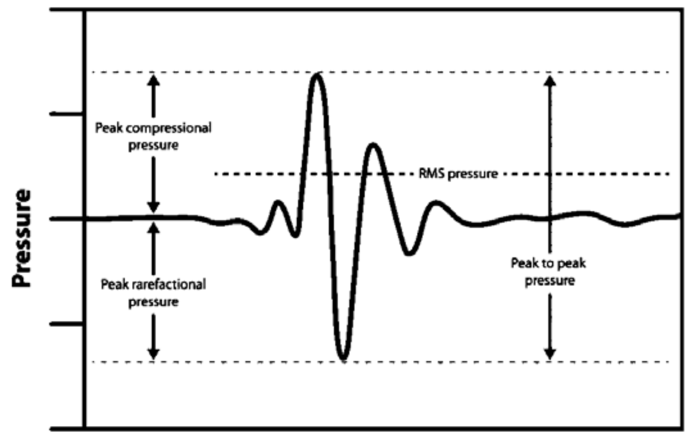

Figure 5. Sound pressure relationship of impulse waveform peak, peak-to-peak, and rms levels.

The peak sound pressure level is the highest sound pressure measured or "held" by the instrumentation depending on its circuitry. The "RMS pressure" is shown as the level integrated over the time period of the pulse, and is always lower than the peak pressure level. The "time period of the pulse" varies depending on waveform shape, complexity, and duration.

The sound pressure level (defined by ANSI as "rms" pressure) has no restrictions on the RMS integration time period. However, the RMS is *sensitive to time period* and the integration time period should always be provided with the sound pressure level when it is reported as RMS. The RMS amplitude value may adequately characterize slow-changing or continuous, non-impulsive noise per NRC 2003 and Madsen 2005 [20,21]. However, the RMS value of an impulsive sound does not reflect the peak energy in the signal. Peak and peak-to-peak sound pressure values are universally preferred over RMS for measuring, characterizing and evaluating impulse sounds.

Depending on the rapidity of the pressure change in impulsive sound, regulation of impulsive sound using RMS values may provide little protection from peak pressures. For reference, in-air impulsive sound limits for hearing damage are not assessed with RMS but rather with peak and peak-to-peak levels (Madsen 2005). When assessing the potential effect of impulsive sounds on the physiology of marine mammals and fishes, the peak sound pressure level Lpk and SEL with

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20 National Research Council (US) Committ.ee on Potential Impacts of Ambient Noise in the Ocean on Marine Mammals. Ocean Noise and Marine Mammals. Washington (DC): National Academies Press (US); 2003. Appendix E, Glossary of Terms. https://www.ncbi.nlm.nih.gov/books/NBK221261/ accessed 6/5/23.

21 Madsen PT (2005), Marine mammals and noise: Problems with root mean square sound pressure levels for transients. The Journal of the Acoustical Society of America (JASA), 117(6), 3952–3957. https://doi.org/10.1121/1.1921508, accessed 6/28/23.

frequency weighting are used [22]. The disparity between RMS and peak pressures underscores long-standing professional acoustic concerns about the suitability of using RMS levels for protection from impulsive noise sources. The RMS value does not track the impulsivity associated with startle and sudden hearing loss. As Madsen summarized in 2005,

> "*Current mitigation levels for noise transients impinging on marine mammals are specified by rms pressures. The rms measure critically relies upon choosing the size of averaging window for the squared pressures. Derivation of this window is not standardized, which can lead to 2–12 dB differences in rms sound pressure for the same wave forms. rms pressure does not represent the energy of the noise pulse and it does not prevent exposure to high peak pressures. Safety levels for transients should therefore be given by received peak–peak sound pressure and energy flux density instead of rms sound pressure levels.*"

Madsen 2005 noted further,

> "*Ears of terrestrial mammals generally integrate sound intensity over a time window of some 200 ms (Plomp and Bouman, 1959; Green, 1985), and the same appears to be the case for cetaceans at low frequencies (Johnson, 1968). It seems therefore reasonable to use 200 ms as the maximum integration time from a detector or sensation point of view (Madsen et al., 2002).*"

For impulsive sounds traveling in a highly reverberant environment, Madsen 2005 found that impulse waveforms were lengthened and densified due to reverberation and reflections, with RMS duration necessarily extended thus lowering the RMS value, concluding,

> "*long, fixed averaging times for calculation of rms sound pressures can yield very short safety radii around a noise source. Unless there is a specified protocol for determining the duration, it is possible to manipulate the rms level by varying the averaging window: the longer the averaging time, the lower the rms level. Measures for mitigation of sound exposure should not leave room for such analytical freedom.*"

Madsen 2005 recommended,

> "*apply a conservative approach and provide energy flux density integrated both over the entire pulse duration and with a 200 ms integration time if the actual duration is longer than that. Such measures should additionally be accompanied by a figure of the wave form, and information about the recording bandwidth and the duration used for integrating the pressure squared.*"

<u>RMS</u>: RMS time durations analyzed in this report include the 200-millisecond duration, and the variable time duration for the 5- to 95-percent "90pct" percentage energy signal duration while using a 1-second dataframe. The 0.125-second RMS value was also computed using a modified

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22 Southall, B. et al, Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects, Aquatic Mammals 2019, 45(2), 125-232, DOI 10.1578/AM.45.2.2019.125.

version of the approach from the 2019 Block Island Wind Farm study [23], and the data are included in Appendix D. The 90-percent effective signal duration was also computed for comparison to the 90-percent percentage energy signal duration, and the data are reviewed in Appendix D. The report conclusions rely on the 200-milliseond and 90-percent percentage energy signal duration RMS metrics outlined in Madsen 2005.

SEL: Energy flux density and sound exposure level metrics quantify the energy content of sound. The energy flux density quantifies the energy passing through a unit area, while SEL equals the total energy accumulated over a time period. The units are identical (uPa^{2}s). The SEL is calculated from the RMS level plus 10log(T). SEL values are listed in this report for 200-millisecond and 90-percent RMS.

Cumulative SEL: Sound exposures leading to PTS and TTS may be assessed with the cumulative sound exposure over time (cSEL). The cumulative operational sound exposure level cSEL was integrated over dozens of hammer blows during continuous pile driving for a time T at each location and adjusted using 10log(T/1.0) to an effective 1-second operational SEL integrating total pile driving impulse and vessel propulsion and thruster noise.

Weighted SEL: The unweighted and weighted (LF, MF, HF, PW) sound exposure level SEL was computed using the RMS,200 and RMS,90pct analysis timeframe for each hammer blow at the six measurement locations from 0.57 to 4.1 NM (1.06 to 7.59 km) when pile driving was occurring. MF and HF weightings filtered out the low-frequency hammer blow energy, resulting in data which could not be assessed for peaks and were not analyzed further in this report.

2.5 Underwater Thresholds for Noise Impact Assessment

NMFS is an office of the National Oceanic and Atmospheric Administration (NOAA) within the Department of Commerce. NMFS is charged with protecting marine species and their habitats in the United States. NMFS published guidance related to underwater noise and the potential impacts on marine mammals can be found in NMFS' "Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing." This document, often referred to as the "NOAA Technical Guidance," was published in 2016, 2018 v 2.0, and again in 2020 v 2.2.

NOAA defines impulsive and non-impulsive (continuous) noise as follows [24]:

> *Continuous sound: A sound whose sound pressure level remains above ambient sound during the observation period (ANSI 2005).*
>
> *Impulsive sound: Sound sources that produce sounds that are typically transient, brief (less*

23. S. Bruce Martin, David R. Barclay; Determining the dependence of marine pile driving sound levels on strike energy, pile penetration, and propagation effects using a linear mixed model based on damped cylindrical spreading. J. Acoust. Soc. Am. 1 July 2019; 146 (1): 109–121. https://doi.org/10.1121/1.5114797
24 National Marine Fisheries Service. 2018. 2018 Revisions to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0): Underwater Thresholds for Onset of Permanent and Temporary Threshold Shifts. U.S. Dept. of Commerce, NOAA. NOAA Technical Memorandum NMFS-OPR-59, 167 p. https://www.fisheries.noaa.gov/action/2018-revision-technical-guidance-assessing-effects-anthropogenic-sound-marine-mammal-hearing accessed 6/30/23.

than 1 second), broadband, and consist of high peak sound pressure with rapid rise time and rapid decay (ANSI 1986; NIOSH 1998; ANSI 2005). They can occur in repetition or as a single event. Examples of impulsive sound sources include: explosives, seismic air guns, and impact pile drivers.

Non-impulsive sound: Sound sources that produce sounds that can be broadband, narrowband or tonal, brief or prolonged, continuous or intermittent) and typically do not have a high peak sound pressure with rapid rise time that impulsive sounds do. Examples of non-impulsive sound sources include: marine vessels, machinery operations/ construction (e.g., drilling), certain active sonar (e.g. tactical), and vibratory pile drivers.

The NMFS Summary of Marine Mammal Acoustic Thresholds [25] states the following with respect to behavioral harassment,

"*Marine mammals are considered harassed when exposed to elevated sound levels that may lead to mortality, temporary or permanent hearing impairment (threshold shift), non-auditory physical or physiological effects, and behavioral disturbance. Using the best available science, NMFS has developed acoustic thresholds that identify the received level of underwater sound from explosive and non-explosive sources above which exposed marine mammals would be expected to:*
- *be behaviorally disturbed or incur a temporary threshold shift (TTS), both of which qualify as Level B harassment under the Marine Mammal Protection Act (MMPA), or*
- *incur a permanent threshold shift (PTS) of some degree or lung or gastrointestinal (g.i.) tract injury, both of which qualify as Level A harassment.*"

Level A harassment thresholds for marine mammal species are tabulated from the NMFS technical guidance document [26] in the Vineyard Wind IHA Table 6, shown in Figure 6 below.

25 NMFS Summary of Marine Mammal Acoustic Thresholds, https://www.fisheries.noaa.gov/s3/2023-02/MMAcousticThresholds_secureFEB2023_OPR1.pdf, 2/24/23, accessed 8/11/23.

26 National Marine Fisheries Service. 2018. 2018 Revisions to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0): Underwater Thresholds for Onset of Permanent and Temporary Threshold Shifts. U.S. Dept. of Commerce, NOAA. NOAA Technical Memorandum NMFS-OPR-59, 167 p. accessed 6/5/23.

Table 6. Summary of relevant PTS onset acoustic thresholds (NMFS 2018a).

Hearing group	PTS onset thresholds* (received level)	
	Impulsive	Non-impulsive
Low-frequency (LF) cetaceans	L_{pk}, flat: 219 dB $L_{E,LF}$, 24h: 183 dB	$L_{E,LF}$, 24h: 199 dB
Mid-frequency (MF) cetaceans	L_{pk}, flat: 230 dB $L_{E,MF}$, 24h: 185 dB	$L_{E,MF}$, 24h: 198 dB
High-frequency (HF) cetaceans	L_{pk}, flat: 202 dB $L_{E,HF}$, 24h: 155 dB	$L_{E,HF}$, 24h: 173 dB
Phocid seals in water (PW)	L_{pk}, flat: 218 dB $L_{E,PW}$, 24h: 185 dB	$L_{E,PW}$, 24h: 201 dB

* Dual metric acoustic thresholds for impulsive sounds: Use whichever results in the largest isopleth for calculating PTS onset. If a non-impulsive sound has the potential of exceeding the peak sound pressure level thresholds associated with impulsive sounds, these thresholds should also be considered.
L_{pk}, flat–peak sound pressure is flat weighted or unweighted and has a reference value of 1 μPa
L_E - denotes cumulative sound exposure over a 24-hour period and has a reference value of 1 μPa²s
The subscript associated with cumulative sound exposure level thresholds indicates the designated marine mammal auditory weighting.

Figure 6. IHA Application summary of relevant PTS onset acoustic thresholds (NMFS 2018a) for Vineyard Wind pile driving.

NMFS defines the threshold level for Level B Behavioral Harassment as follows:

> "*120 Decibel (dB) Root Mean Square (RMS) referenced to (re) 1 microPascal (μPa) for continuous noise and 160 dB RMS re 1 μPa for impulsive and non-continuous pulsed noise. The Zone of Influence (ZOI) is the area that is ensonified to those levels and constitutes the area in which take of marine mammals could occur*".

Behavioral harassment criteria are further detailed in project documents using the probability of behavioral response for auditory weighted sound pressure level (SPL, dB re 1 μPa), from Wood 2012 [27]. Project behavioral exposure exposure criteria are provided in the Biological Assessment Table 5.1-2 shown in Figure 7 below.

Table 5.1-2: Behavioral Exposure Criteria (based on Wood et al. 2012)

Marine Mammal Group	Probability of response to frequency-weighted SPL (dB re 1 μPa)				Unweighted (dB root mean square) [a]
	120	**140**	**160**	**180**	
Migrating mysticete whales	10%	50%	90%		160
All other species (and behaviors)		10%	50%	90%	160

Source: Adapted from Wood et al. 2012; Pyć et al. 2018

μPa = micropascal; dB = decibel; SPL = sound pressure level

Note: Probability of behavioral response frequency-weighted sound pressure level (SPL dB re 1 μPa); probabilities are not additive.

[a] Pyć et al. 2018

Figure 7. Biological Assessment Table 5.1-2, behavioral exposure criteria based on Wood et al. 2012.

Management of marine mammal impacts with the 120-dB threshold for Level B Behavioral Harassment is clearly presented in the 2016 incidental harassment authorization (IHA) to Ocean

27 Wood, J., Southall, B. L., & Tollit, D. J. (2012). PG&E offshore 3 D Seismic Survey Project EIR-Marine Mammal Technical Draft Report.

Wind, LLC (Ocean Wind), "*to incidentally harass, by Level B harassment only, marine mammals during high-resolution geophysical (HRG) and geotechnical survey investigations associated with marine site characterization activities off the coast of New Jersey in the area of the Commercial Lease of Submerged Lands for Renewable Energy Development on the Outer Continental Shelf (OCS–A 0498) (Lease Area)*" [28]. The Ocean Wind IHA recognizes behavioral harassment due to continuous noise for DP drill ship vessel noise, and prescribes protective radii. The scope of potential harassment and basis for take estimates are outlined in the IHA as follows (emphasis added):

> "*Project activities that have the potential to harass marine mammals, as defined by the MMPA, include underwater noise from operation of the HRG survey sub-bottom profilers and equipment positioning systems,* ***and noise propagation associated with the use of DP thrusters during geotechnical survey activities that require the use of a DP drill ship****. Harassment could take the form of temporary threshold shift, avoidance, or other changes in marine mammal behavior.* ***NMFS anticipates that impacts to marine mammals would be in the form of behavioral harassment*** *and no take by injury, serious injury, or mortality is proposed. ... The basis for the take estimate is the number of marine mammals that would be exposed to sound levels in excess of NMFS' Level B harassment criteria for impulsive noise (160 dB re 1 µPa (rms)* ***and continuous noise (120 dB re 1 µPa (rms.))****.*"

2.6 Auditory Weightings for Sound Exposure

Auditory weightings are considered important for assessing marine species *noise exposure* and susceptibility to noise-induced hearing loss [29]. NOAA Table A10 (shown in Figure 8 below) summaries species auditory weightings parameters and sound exposure level thresholds.

$W(f)=C+10\log_{10}\left\{\frac{(f/f_1)^{2a}}{\left[1+(f/f_1)^2\right]^a\left[1+(f\right.}\right.$						Non-impulsive		Impulse			
						TTS threshold	PTS threshold	TTS threshold		PTS threshold	
Group	a	b	f_1 (kHz)	f_2 (kHz)	C (dB)	SEL (weighted)	SEL (weighted)	SEL (weighted)	peak SPL (unweighted)	SEL (weighted)	peak SPL (unweighted)
LF	1	2	0.20	19	0.13	179	199	168	213	183	219
MF	1.6	2	8.8	110	1.20	178	198	170	224	185	230
HF	1.8	2	12	140	1.36	153	173	140	196	155	202
SI	1.8	2	4.3	25	2.62	186	206	175	220	190	226
OW	2	2	0.94	25	0.64	199	219	188	226	203	232
PW	1	2	1.9	30	0.75	181	201	170	212	185	218

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28 Incidental harassment authorization (IHA) to Ocean Wind, LLC (Ocean Wind), 6/8/2017, https://www.federalregister.gov/documents/2017/07/07/2017-14260/takes-of-marine-mammals-incidental-to-specified-activities-taking-marine-mammals-incidental-to-site#p-47

29 Jakob Tougaard, Michael Dähne; Why is auditory frequency weighting so important in regulation of underwater noise? J Acoust Soc Am 1 October 2017; 142 (4): EL415–EL420. https://doi.org/10.1121/1.5008901 accessed 6/29/23.

Figure 8. NMFS 2018a Summary of auditory weighting and exposure function parameters. Highlighting in the table denotes the species evaluated by "Hearing Group" listed in the IHA Application.

During this survey's post-survey analysis, NMFS 2018 auditory weightings were computed and applied to the unweighted audio recordings to evaluate weighted sound pressure levels. Hearing auditory weightings are shown below in Figure 9.

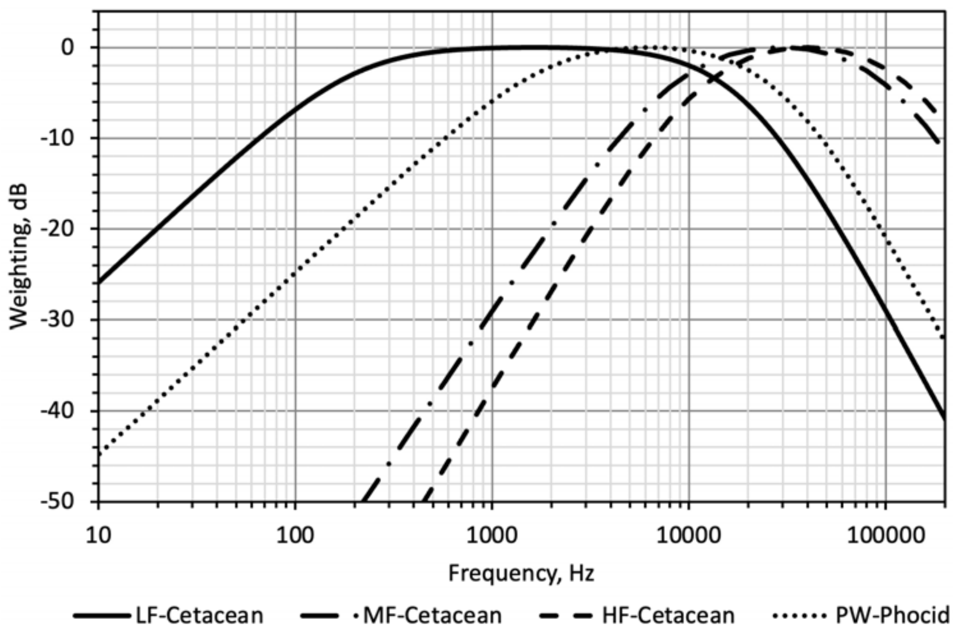

Figure 9. Bode diagram, marine species auditory weightings computed from NMFS 2018.

As noted earlier, MF and HF weightings filtered out the low-frequency hammer blow energy resulting in data which could not be assessed for peaks and were not analyzed further in this report. Species contained in the LF and PW classifications were defined by NMFS in 2016 [30],

> *"LOW-FREQUENCY (LF) CETACEANS: The LF cetacean group contains all of the mysticetes (baleen whales). Although there have been no direct measurements of hearing sensitivity in any mysticete, an audible frequency range of approximately 10 Hz to 30 kHz has been estimated from observed vocalization frequencies, observed reactions to playback of sounds, and anatomical analyses of the auditory system. A natural division may exist within the mysticetes, with some species (e.g., blue, fin) having better low-frequency sensitivity and others (e.g., humpback, minke) having better sensitivity to higher frequencies; however, at present there is insufficient knowledge to justify separating species into multiple groups. Therefore, a single species group is used for all mysticetes.*

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30 National Marine Fisheries Service. 2016. Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing: Underwater Acoustic Thresholds for Onset of Permanent and Temporary Threshold Shifts. U.S. Dept. of Commer., NOAA. NOAA Technical Memorandum NMFS-OPR-55, 178 p.

> *"PHOCIDS: This group contains all earless seals or "true seals," including all Arctic and Antarctic ice seals, harbor or common seals, gray seals and inland seals, elephant seals, and monk seals. Underwater hearing thresholds exist for some Northern Hemisphere species in this group."*

While this analysis utilized the 2018 NMFS auditory weightings, it should be noted that Southall et al. 2019 [31] published a set of modifications to the 2018 NMFS auditory weightings for consideration that are less flattened and closer to audiograms. It appears NMFS is still assessing the Southall 2019 weightings at the time of this writing.

2.7 Measurement Uncertainty

Uncertainties for the acoustic parameters presented in this report were considered in general accordance with United States and international standards [32,33]. Uncertainty considerations apply to the probability of replicating measured sound pressure levels at the same distances at the same location under the same conditions. Acoustic survey measurements can be affected by acoustic propagation and environmental conditions occurring during the survey. Utmost care was taken to minimize environmental effects by selecting a day with the calmest weather conditions available within the weather forecast, using a standardized depth of the dipped hydrophone, and minimizing handling noise of the dipped hydrophone.

System end-to-end calibration before and after the survey found calibration was constant within 0.5 dB. Class 1 digital sound meters have an intrinsic standard uncertainty of +/- 0.5 dB (ISO 1996-2). The remainder of the uncertainty was allocated to the drift distance from the source being measured at each measurement location, estimated at +/-0.5 dB. From ANSI 1996-2, the expanded uncertainty (2σ or coverage probability 95%) of effects on short-term measurements with Class 1 instrumentation (the type used during this survey) is +/-1.6 dB. No uncertainty was introduced by residual/ambient sound levels as they were well below measured pile-driving peak and RMS levels. All reported uncertainties are in the category of Type B evaluation or analysis other than a statistical analysis of repeated observations. While a precise total uncertainty for the offshore measurement survey is not known, the expanded uncertainty appears unlikely to exceed +/-3 dB.

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31 Southall et al., "Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects", Aquatic Mammals 2019, 45(2), 125-232, DOI 10.1578/AM.45.2.2019.125. accessed 6/26/23.

32 B.N. Taylor and C. E. Kuyatt, "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results," National Institute of Standards and Technology, Gaithersburg, MD, NIST Technical Note 1297, 1994. [Online]. Available http://www.nist.gov/pml/pubs/tn1297/ accessed 8/16/23.

33 ISO/FDIS 1996-2 "Acoustics — Description, measurement and assessment of environmental noise — Part 2: Determination of sound pressure levels", ISO/TC 43/SC 1-2017.

3 Results and discussion

3.1 Pile Driving Sound Pressure Data

Data are presented below for recording locations when the Orion was actively pile-driving. Survey recording for these locations is summarized in Table 2 below.

Table 2. Summary of recording locations and hammer counts.

Distance, NM	**4.10**	**3.17**	**1.98**	**1.34**	**0.86**	**0.57**
Distance, m	7.59	5.87	3.67	2.48	1.59	1.06
Start time	1:36 pm	1:45 pm	1:59 pm	2:09 pm	2:23 pm	2:34 pm
Recording time, mm:ss	3:53	5:30	4:10	5:15	5:50	2:30
Hammer count	126	146	117	143	160	51

Time-series sound pressure charts are shown below in Figures 10 through 15. These charts show the acoustic pressure occurring over time during the recording (x-axis) scaled in Pascals (y-axis). These pressures are unweighted and unaveraged. Each hammer blow has both positive-going and negative-going (compressive and rarefractive) peak pressures arriving at the hydrophone. The more-or-less solid blue section in the core of the chart is dominated by vessel propulsion and DP thruster noise.

Recording time at each location was between 3-1/2 and 5-1/2 minutes except for the last recording at 0.57 NM run which ran for 2-1/2 minutes during which pile driving ended within 2 minutes.

Tables listing summary data at each location are provided in Appendix D along with figures of the peak, RMS and spectrograms for the hammer blows with maximum RMS at each location.

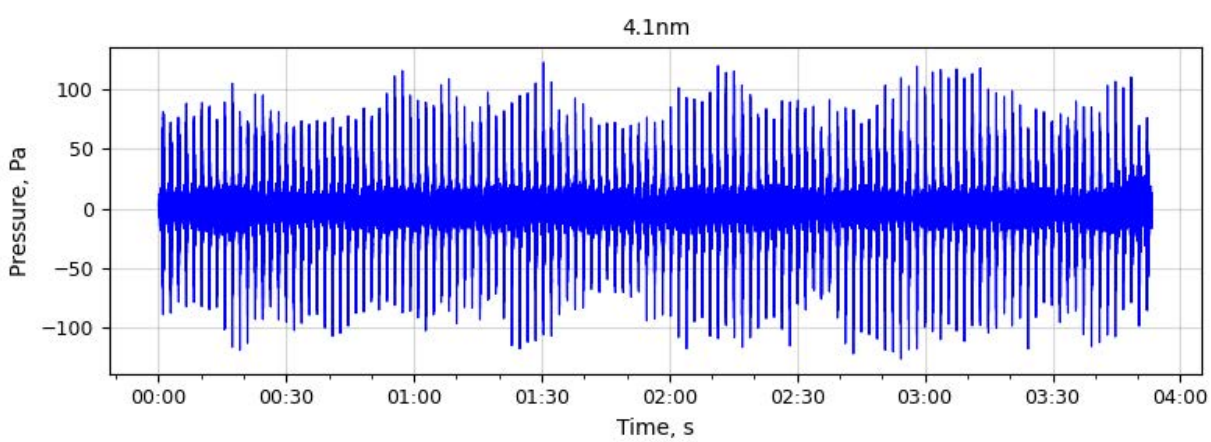

Figure 10. Time series sound pressure, Pa 1:36 pm, 4.1 NM (7.59 km). Pile driving dominant, 126 hammer blows recorded. Orion and support ship propulsion and thruster noise are highly audible (hydrophone through headphones).

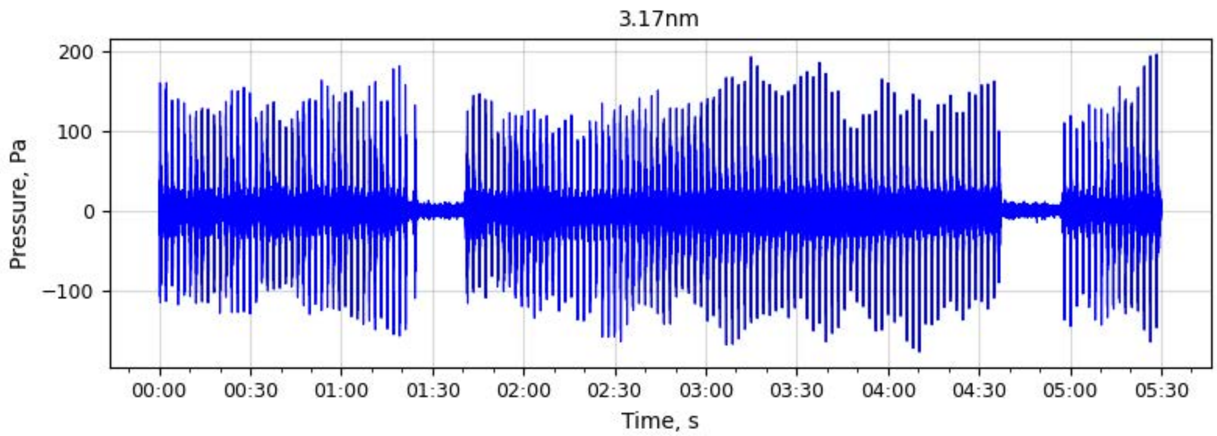

Figure 11. Time series sound pressure, Pa 1:45 pm, 3.17 NM (5.87 km). Pile driving dominant, 146 hammer blows recorded. Orion and support ship propulsion and thrusters are highly audible (hydrophone through headphones). The recording captured two stops with 20-second segments with no hammer blows. Ramp-up was not observed during the two pile driving startups.

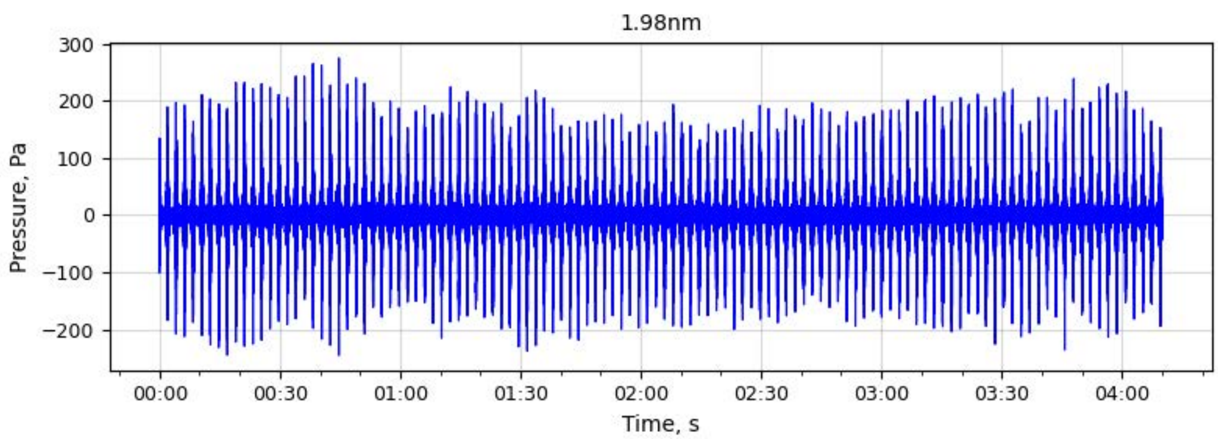

Figure 12. Time series sound pressure, Pa 1:59 pm, 1.98 NM (3.67 km). Pile driving dominant, 117 hammer blows recorded. Orion and support ship propulsion and thruster noise are highly audible (hydrophone through headphones).

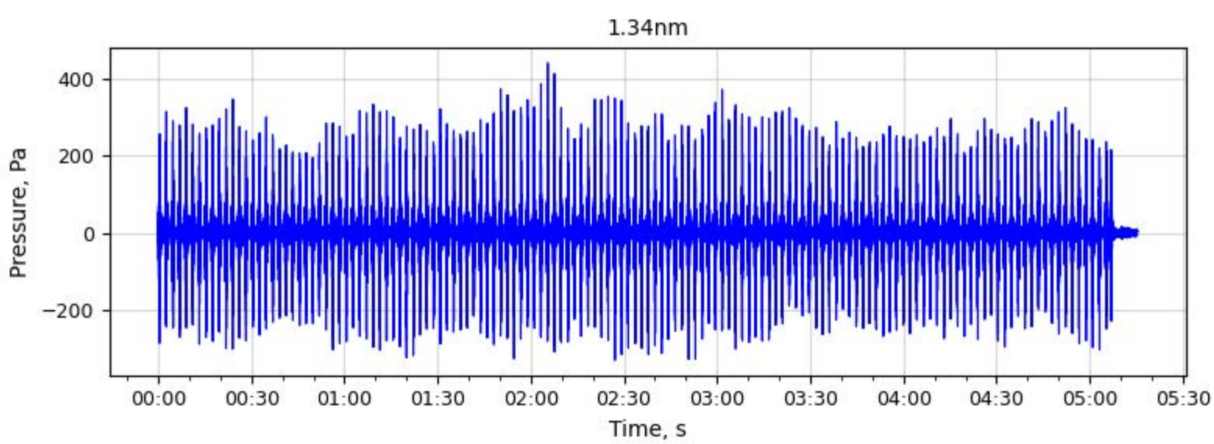

Figure 13. Time series sound pressure, Pa 2:09 pm, 1.34 NM (2.48 km). Pile driving dominant, 143 hammer blows recorded. Orion and support ship propulsion and thruster noise are highly audible (hydrophone through headphones).

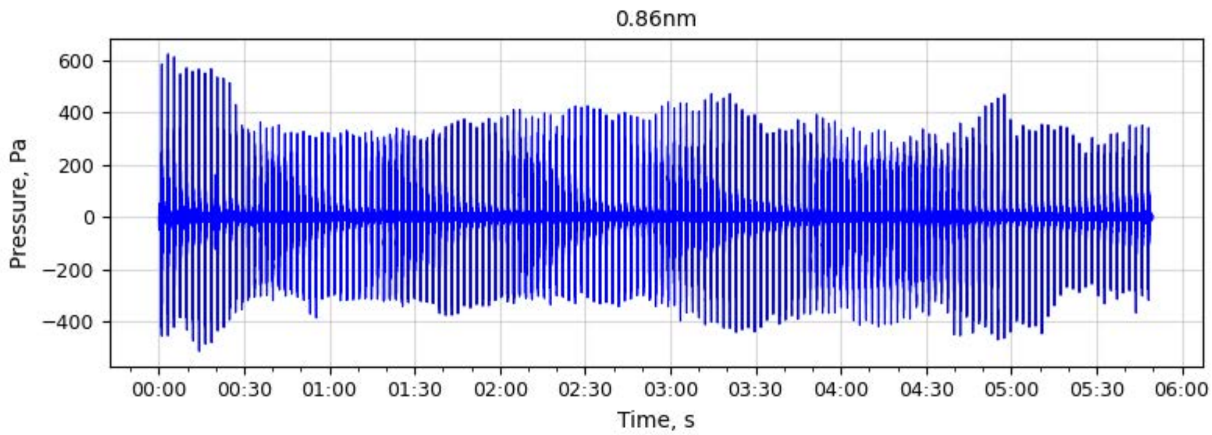

Figure 14. Time series sound pressure, Pa 2:09 pm, 0.86 NM (1.59 km). Pile driving dominant, 160 hammer blows recorded. Orion and support ship propulsion and thruster noise are highly audible (hydrophone through headphones).

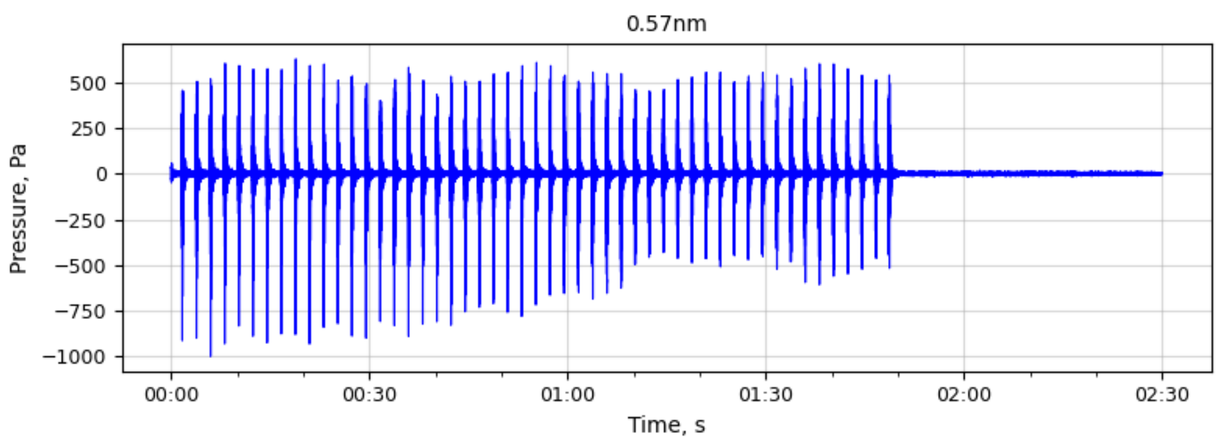

Figure 15. Time series sound pressure, Pa 2:34 pm, 0.57 NM (1.06 km). Pile driving dominant, 51 hammer blows recorded. Orion and support ship propulsion and thruster noise are highly audible (hydrophone through headphones).

Hammer interval is plotted below as a timeline in Figure 16 and with histograms in Figure 17. Interval width varied from 1.68 to 2.38 seconds. Hammer blow count varied from 24 to 34 per minute. Hammer ceased (pile driving completed) at approximately 2:36 PM.

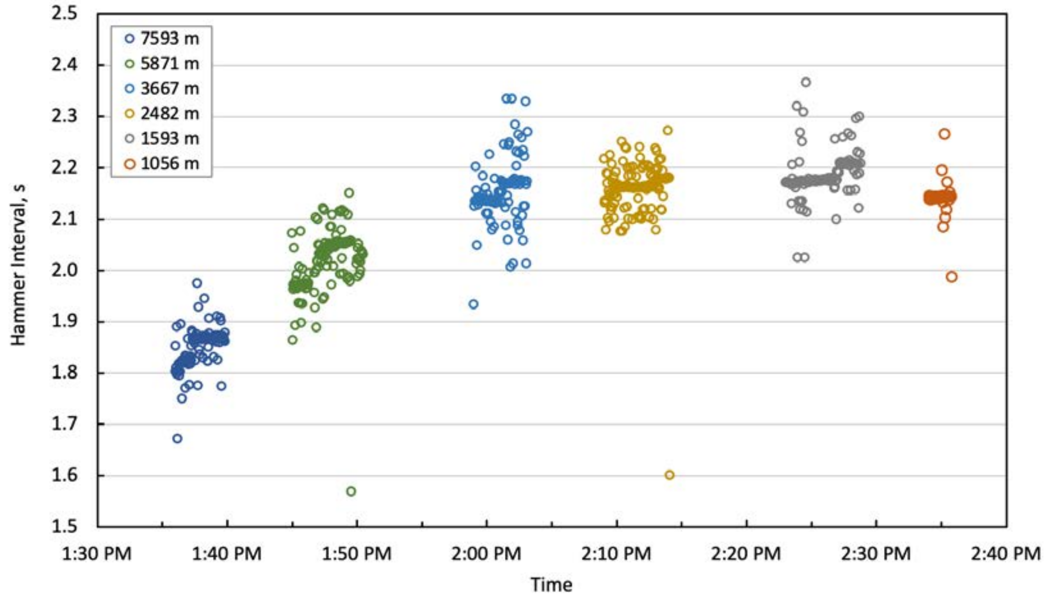

Figure 16. Hammer interval, seconds, for each measurement location. Locations shown by color.

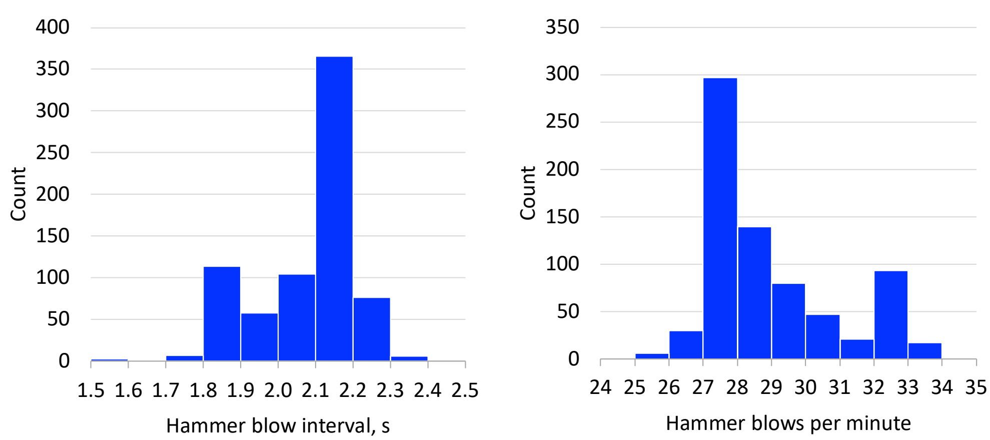

Figure 17. Histograms, hammer blow interval, seconds and blows per minute.

A hammer blow at 0.57 NM is plotted for illustration in Figure 18 below with the peak marked. Pile driving hammer blow pressures were observed generally to be comprised of a primary peak pulse with either positive (compressional) or negative (rarefractional) phase, within a group of pulses of various intensities and phases arriving *before and after* the peak pulse.

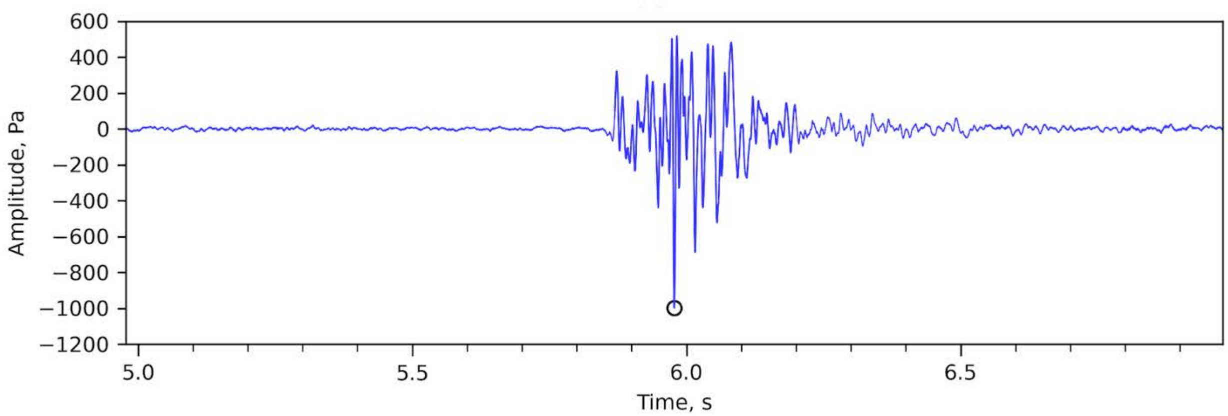

Figure 18. Time series sound pressure, Pa at the highest hammer blow peak at 0.57 NM (1.06 km). Hammer blow signal shows echo/reflection groups and multiple sound speed paths characteristic of reflections off bottom and surface and differing sound speed above and below thermocline.

Multiple pulse components with differing time arrivals are consistent with acoustic path time and strength modifiers:

- Direct path from sparker to hydrophone
- Primary reflections off the water surface and the ocean bottom
- Multiple sound speed paths, above and below thermocline
- Higher speed propagation through the sediment (seabed)
- Focusing, group velocities, and horizontal refraction
- Scattering

The waters in the survey area are shallow (about 35 to 38 meters) compared to open ocean and the distances to recordings (roughly 1 to 8 km). As a result, the water surface and sea bottom channel the acoustic energy horizontally, acting as containing surfaces with varying degrees of reflectivity and absorption from location to location between source and receiver. Hammer blow mach waves penetrate the seabed where the sound speed is faster than in water. If the sound speed also increases with depth in the seabed due to increased density, acoustic waves may bend back up into the water and arrive at the hydrophone before the waterborne acoustic peak.

The observed complex pulse shapes are consistent with Oliveira et al [34], "*Three-dimensional (3D) effects can profoundly influence underwater sound propagation and hence soundscape at different scales in the ocean ... In the particular case of coastal seas, a range of physical oceanographic and geological features can cause horizontal reflection, refraction, and diffraction of sound.*" The shallow 50-meter ocean depth evaluated by Oliveira et al resembles the 35- to 38-meter water depths during this survey.

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34 Oliveira, T., Lin Y.T., Porter, M., Underwater Sound Propagation Modeling in a Complex Shallow Water Environment, Front. Mar. Sci., 15 October 2021.

Data plotted in Figure 19 below illustrate the individual hammer blow sound pressure levels for peak-to-peak, peak, RMS,200 and RMS,90pct metrics.

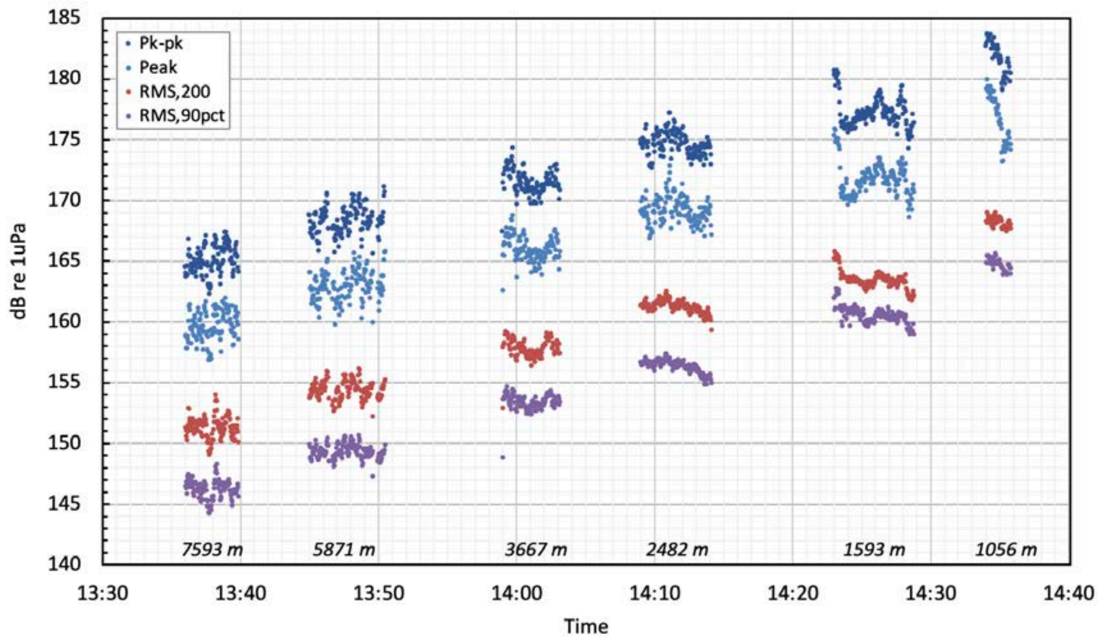

Figure 19. Computed metrics for hammer blows acquired during the survey (n=743).

These sound pressure levels are presented with trends in the following sections.

3.2 Peak Sound Pressure Levels

Peak sound pressure levels are plotted in Figure 20 below.

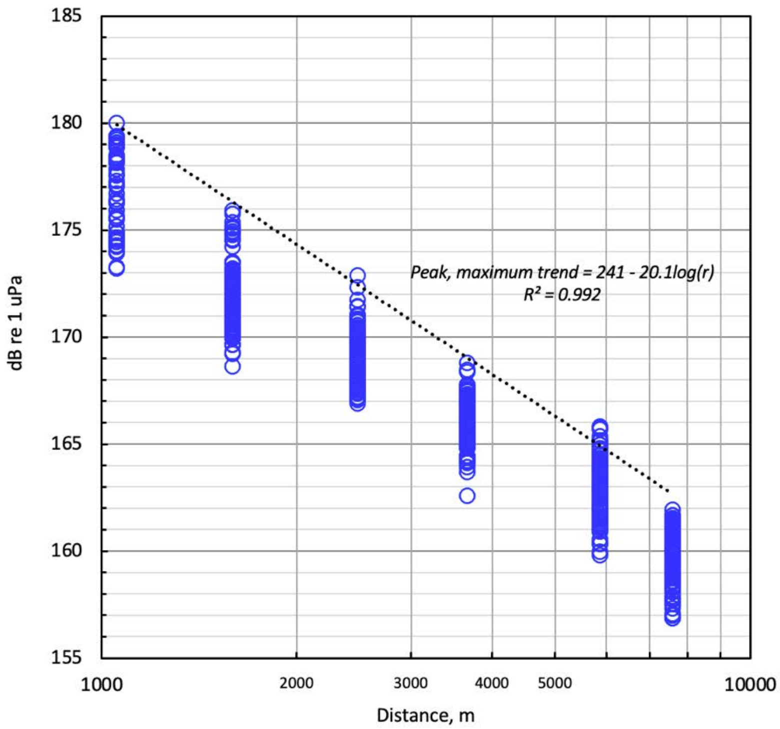

Figure 20. Peak values for all hammer blows during the survey. Lpk Source Level (SLpk) conservatively estimated with highest occurring peaks at each location/.

Peak levels measured up to 180 dB re 1uPa at 1.06 km, during pile driving operations with noise mitigations. The estimated effective source level SLpk is 241 dB re 1 uPa for maximum trend for the far-field range of roughly 1 to 8 km. Propagation loss was 20.1log(r) for the maximum trend, consistent with spherical spreading. Maximum peak values ran about 3 to 4 dB above median peak values. The peak level spread maximum to minimum at each location was 5 to 7 dB.

3.3 Pk-pk Sound Pressure Levels

Peak to peak (pk-pk) sound pressure levels are plotted in Figure 21 below to provide a picture of the total intensity in the hammer blow events.

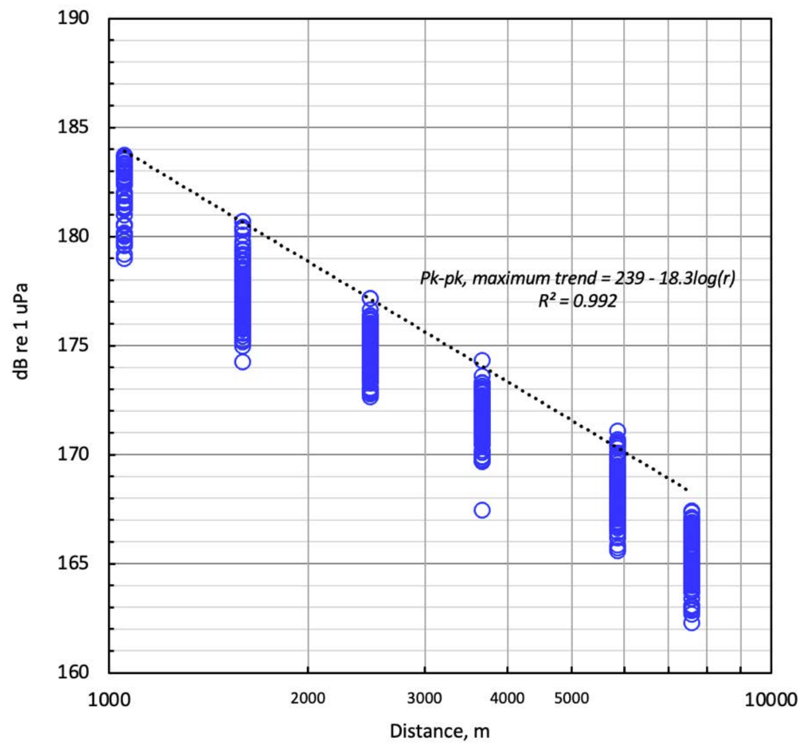

Figure 21. Peak to peak (pk-pk) values for all hammer blows during the survey. Lpk-pk Source Level (SLpk-pk) conservatively estimated with highest occurring peak-to-peak levels at each location.

Peak to peak levels measured up to 184 dB re 1uPa at 1.06 km, during pile driving operations with noise mitigations. The conservatively estimated apparent source level SLpk-pk is 239 dB re 1uPa for the far-field range of 1 to 8 km. Propagation loss was 18.3log(r) for the maximum trend, between spherical and practical spreading. Maximum peak-to-peak values ran about 2 to 3 dB above median values (see Appendix D). The peak-to-peak level spread maximum to minimum at each location was 5 to 7 dB.

3.4 RMS Levels

The RMS,200 is the RMS level computed using 200-millisecond exponential weighting, the recommended maximum fixed RMS time window in Madsen 2005 for mammalian hearing response. RMS,200 sound pressure levels are plotted in Figure 22 below. The NMFS 160 dB Level B harassment threshold is shown for visual comparison.

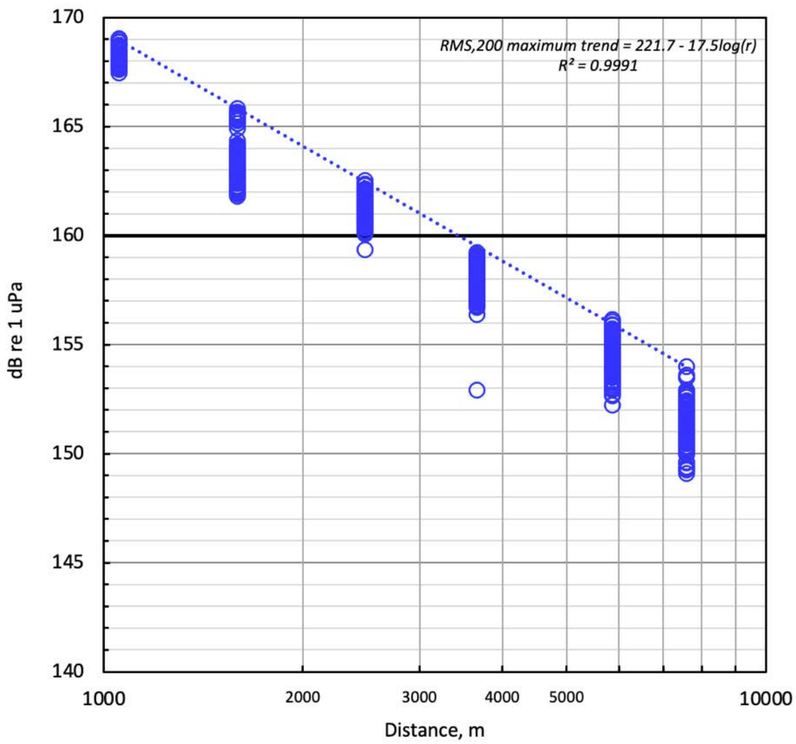

Figure 22. Scatter plot of RMS,200 values for all hammer blows during the survey, with trend of maximum levels for each location.

RMS,200ms levels measured up to 169 dB re 1uPa at 1.06 km, during pile driving operations with noise mitigations. The conservatively estimated apparent source level SL,RMS is 221.7 dB re 1uPa for the maximum trend for the far-field range of roughly 1 to 8 km. Propagation loss PL measured 17.5log(r) for the maximum trend, between practical and spherical spreading. Maximum RMS values ran 1 to 3 dB above median values (see Appendix D). The RMS level spread maximum to minimum at each location was 2 to 5 dB with two "outlier" lower-energy hammer blows. **Pile driving RMS, 200 sound level breach the NMFS 160 dB,RMS Level B harassment threshold out to 3355 meters.**

RMS,90pct sound pressure levels are plotted in Figure 23 below. These are determined with the percentage energy signal duration (between 5% and 95% cumulative energy points) referenced in Madsen 2005 and defined in ISO 18405:2017 (the ISO definition reference is Madsen 2005). The RMS analysis dataframe for each peak was selected at 1 second, previously used in industry pile driving reporting [35]. The 90 percent analysis returns unique 5-95 percent averaging time windows for each peak depending on a number of waveform lengthening and densifying factors including increased numbers of reflections with distance, group velocities, and early energy time arrivals via acoustic waves emitted from the monopile base and refracted out of the seabed. Compared to the RMS,200 mammalian hearing window analyzed in Madsen 2005 and shown in Section 3.4 in this report, the RMS,90pct averaging windows are longer and produce lower RMS levels. The NFMS 160 dB Level B harassment threshold is shown for visual comparison.

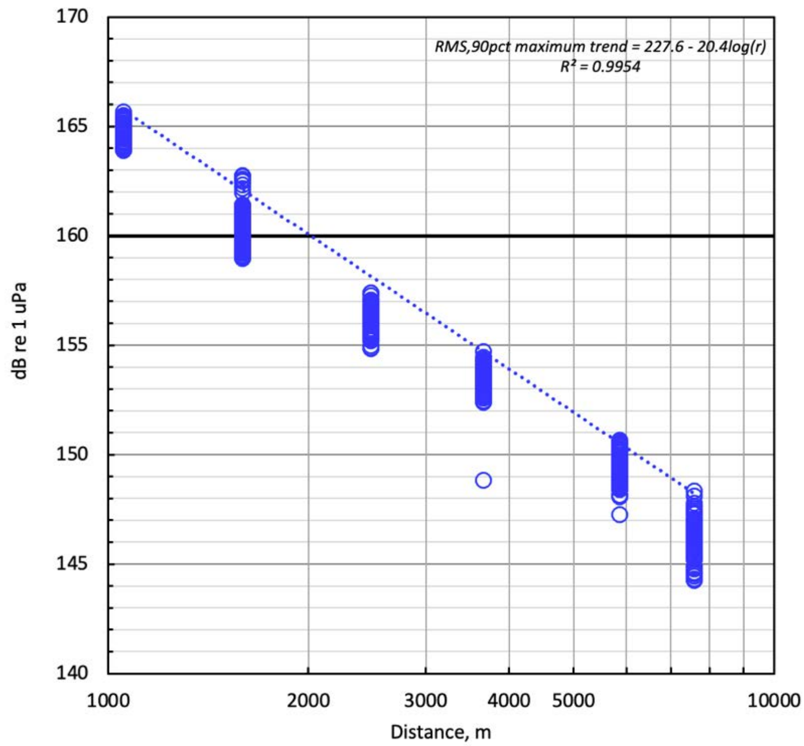

Figure 23. Scatter plot of RMS,90pct values for all hammer blows during the survey, with trend of maximum levels for each location.

RMS,90pct levels measured over 165 dB re 1 uPa at 1.06 km, during pile driving operations with noise mitigations. The estimated apparent source level SL,RMS is 227.6 dB for the maximum trend in the far-field range of roughly 1 to 8 km. Propagation loss PL measured 20.4log(r) for the maximum RMS trend, consistent with spherical spreading. Maximum RMS values ran about 2 to 3 dB above median values (see Appendix D). The RMS spread maximum to minimum at each location was 3 to 4 dB with two "outlier" lower-energy hammer blows. **Pile driving RMS,90pct sound levels breach the NMFS 160 dB,RMS Level B harassment threshold out to just over 2 kilometers.**

Due to the large difference in the computed protective radius to 160 dB, the two RMS metrics were compared. Figure 24 below provides decibel ratio plotting of the RMS,200 (maximum

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35 Dominion Energy CVOW Pilot Project – Revised Protected Species Observer (PSO) Monitoring Report and Pile Driving Noise Monitoring Report for WTG Construction and Observations, Document no.: JDN1823.REP.62.32, 28 November 2020.

recommended mammalian hearing window, Madsen 2005), and the RMS,90pct (RL_{90}, Madsen 2005) referenced in NFMS and BOEM documents reviewed for this report.

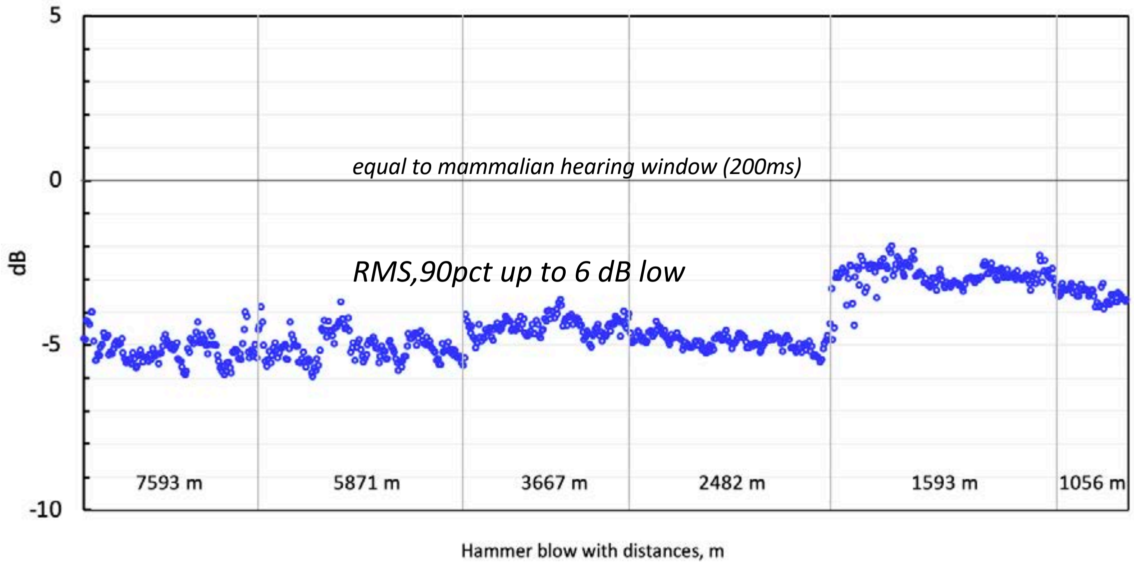

Figure 24. Computed difference of RMS,200 and RMS,90pct for all hammer blows during the survey (n=743). RMS,90pct underestimates the RMS computed for the mammalian hearing window by 2 to 6 dB.

The RMS,90pct is 2 to 6 dB below the 200-millisecond mammalian hearing window RMS. Underestimates were largest in the range of 2482 to 7593 meters from pile driving. The RMS,90pct reductions from mammalian hearing window appear related to the impulse waveforms lengthening and becoming more complex with reflections and group velocities in far-field distances, and increasing time differences between the waterborne peak and pre-peak acoustic waves arriving earlier having traveled faster through the seabed, resulting in larger averaging windows and lower RMS levels.

The results are not surprising and they are consistent with the cautions in Madsen 2005 and general acoustics practice. Longer RMS analysis windows produce lower RMS levels. The RMS,90pct necessarily using the 1-second analysis window to capture the full waveform ensemble underestimates the RMS levels associated with the energy occurring in the mammalian hearing window where detection and response would be expected to occur.

This leads to a professional caution. The 90-percent RMS should not be considered conservative for best practice acoustics planning to prevent adverse noise impacts on marine mammals. A protective setback radius based on the 90-percent RMS and spherical spreading results in a shortage of as much as a *halving* [36] of the regulatory radius required for protection based on the maximum recommended 200ms mammalian hearing window in Madsen 2005.

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36 For spherical spreading 20log(r), the change in distance for a drop of 6 dB can be determined using R1 = 10^(RMS/20) and R2 = 10^((RMS-6)/20). For any RMS, the distance R2 for RMS-6, dB will be one half the distance R1 associated with RMS, dB.

3.5 Pile Driving Sound Spectra

Piling one-third octave band sound spectra were analyzed in Spectraplus-SC. Spectrum acquisition on the 192KHz hydrophone recordings was decimated to obtain octave band analysis down to the 10 Hz ANSI one-third octave band, using a 16384 point FFT and Hanning weighting. ANSI S1.11 one-third octave band spectra were acquired using single-shot linear sampling triggered on the peak pile driving hammer blows arriving every 2 seconds. A 150-millisecond pre-delay was engaged to include portions of the hammer blow energy arriving prior to the peak time, traveling faster through the ocean seabed than the direct waterborne pulses and accompanying multiple reflections. Spectrum logs were imported into Excel and processed into box plots for each measurement location using macros from Peltier Tech [37].

One-third octave band analysis results show overall RMS pile driving levels ranged from 165 to 147 dB,RMS re 1uPa from 0.57 to 4.1 NM. The one-third octave pulse spectra contain a low-frequency acoustic signature. Pile driving spectra show acoustic energy principally below 160 Hz, and exhibit attenuation above 160 Hz resembling a 2nd-order 12dB per octave lowpass filter.

At 3.17 and 4.1 NM, one-third octave bands below 31.5 Hz exhibit larger amplitude scatter than at closer distances to the pile driving. This is judged to be due to increased reflections and variations in sound channeling and increased times between refracted pre-arrivals and the acoustic peaks at those distances from the Orion pile driving.

37 Peltier Tech. https://peltiertech.com/documentation/box-whisker-charts-box-plots/

One-third octave RMS spectra for 51 pile driving hammer blows are shown in Figure 25 below in box plot format per band for the 0.57 NM distance (1.06 km).

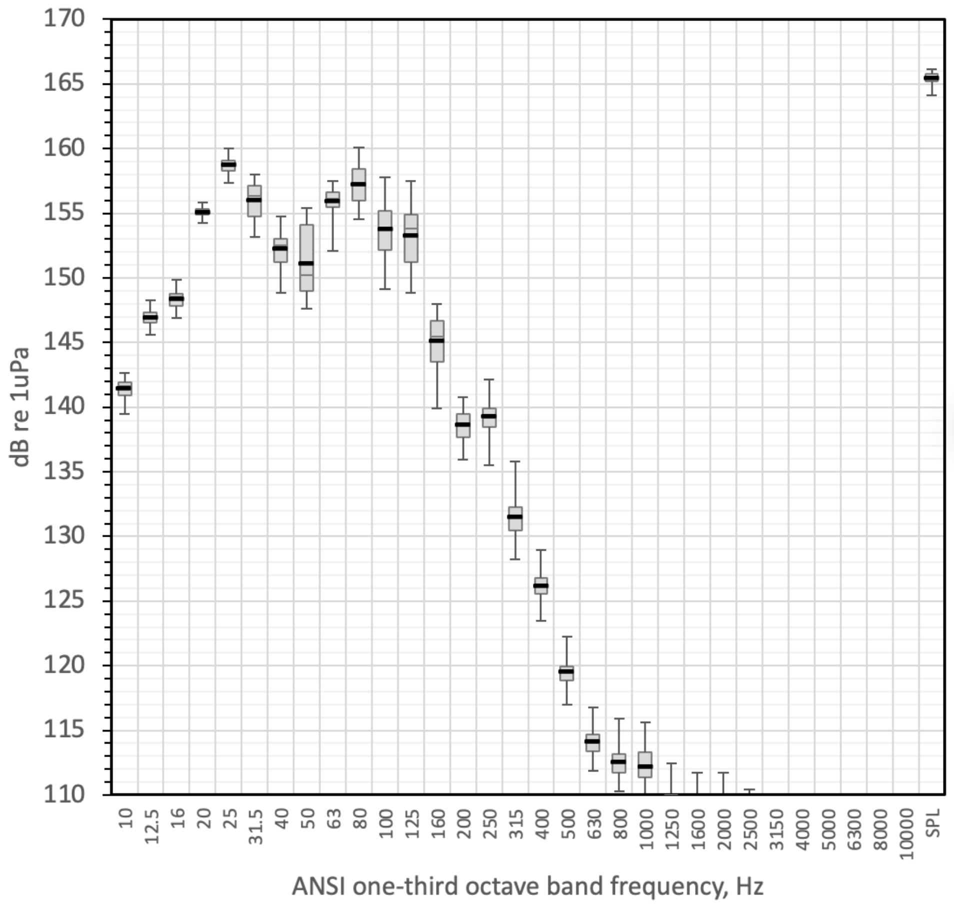

Figure 25. Box plot of one-third-octave band levels at 0.57NM (1.06 km).

One-third octave RMS spectra for 160 pile driving hammer blows are shown in Figure 26 below in box plot format per band for the 0.86 NM distance (1.59 km).

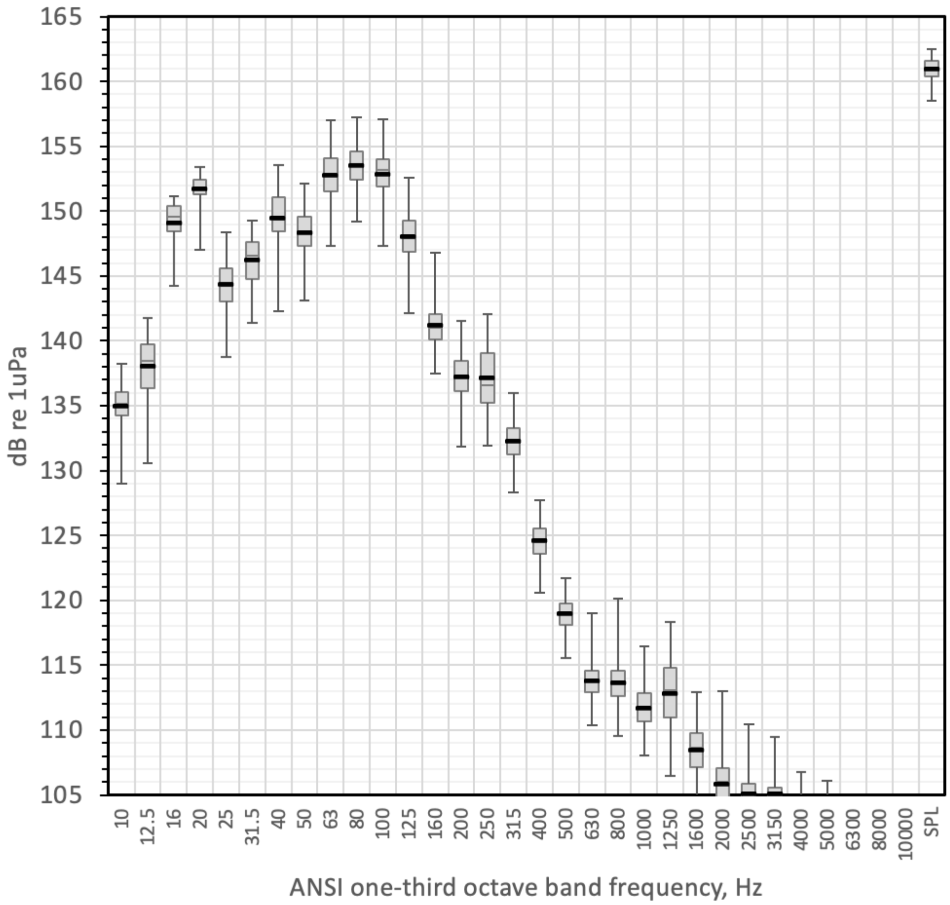

Figure 26. Box plot of one-third-octave band levels at 0.86NM (1.59 km).

One-third octave RMS spectra for 143 pile driving hammer blows are shown in Figure 27 below in box plot format per band for the 1.34 NM distance (2.48 km).

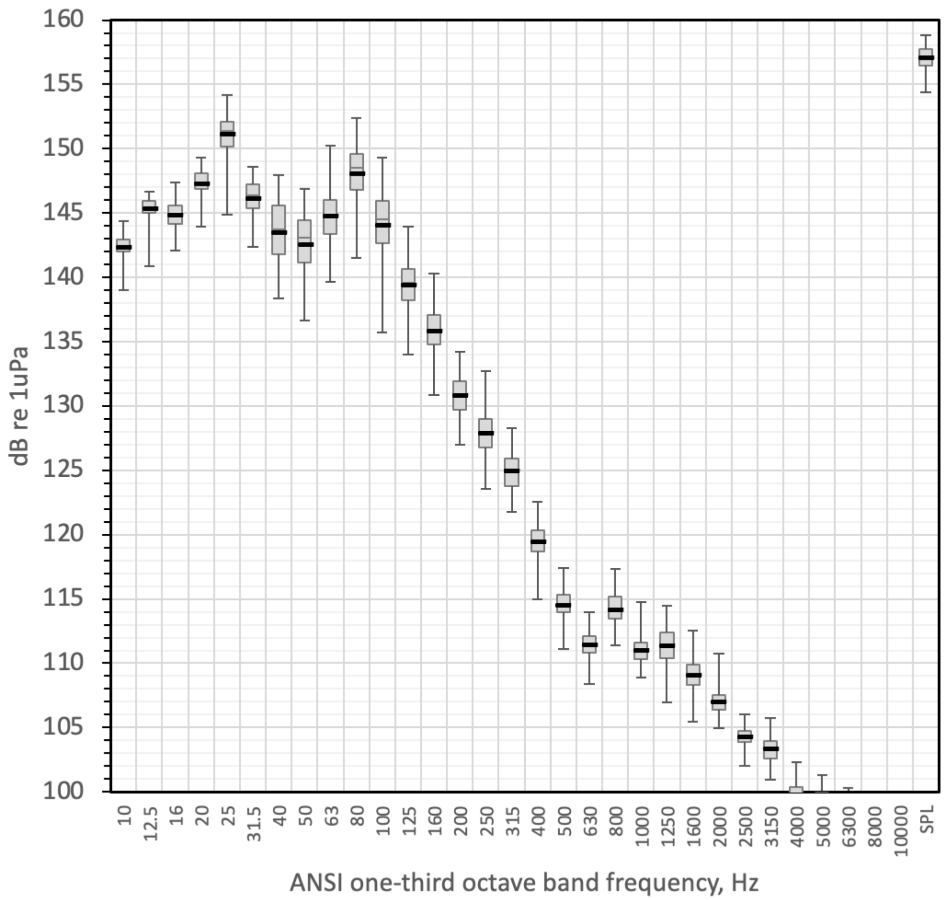

Figure 27. Box plot of one-third-octave band levels at 1.34NM (2.48 km).

One-third octave RMS spectra for 117 pile driving hammer blows are shown in Figure 28 below in box plot format per band for the 1.98 NM distance (3.67 km).

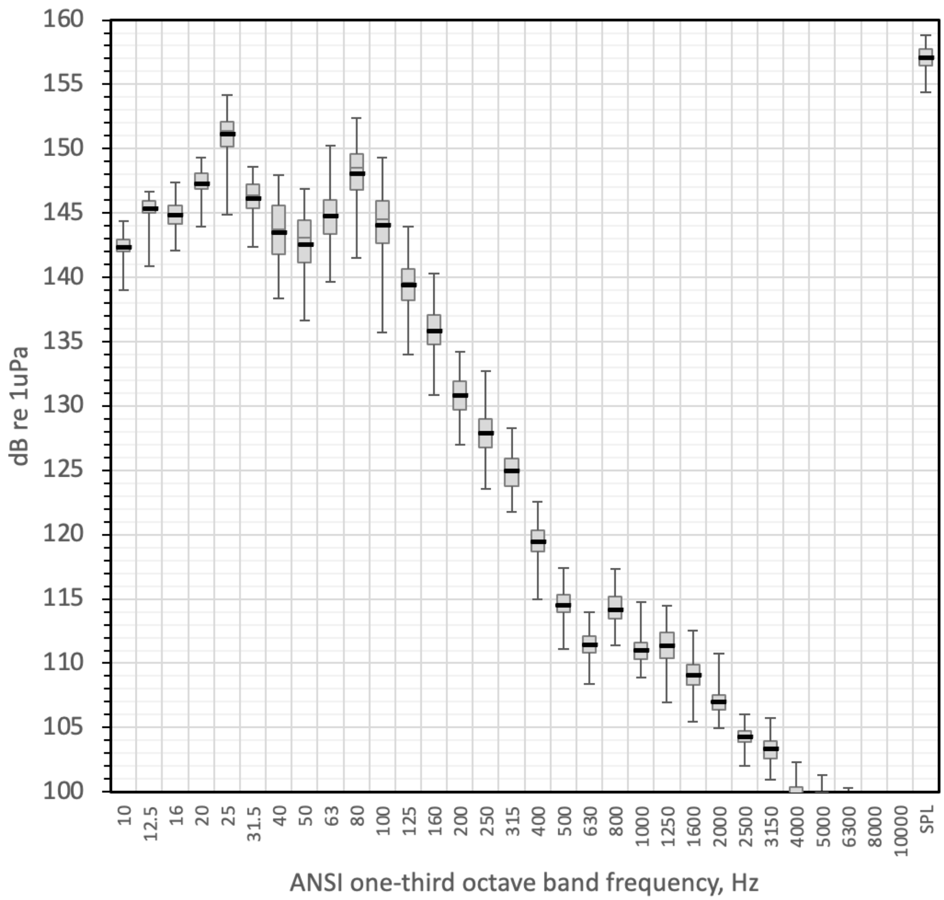

Figure 28. Box plot of one-third-octave band levels at 1.98NM (3.67 km).

One-third octave RMS spectra for 146 pile driving hammer blows are shown in Figure 29 below in box plot format per band for the 3.17 NM distance (5.87 km).

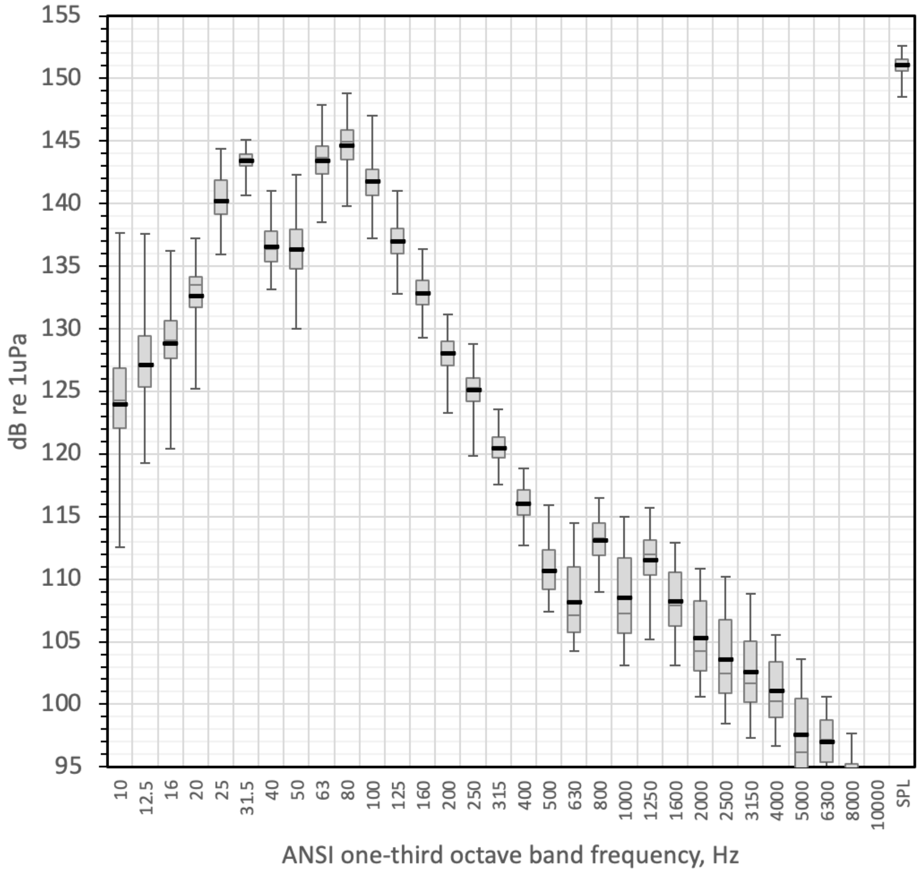

Figure 29. Box plot of one-third-octave band levels at 3.17NM (5.87 km).

One-third octave RMS spectra for 126 pile driving hammer blows are shown in Figure 30 below in box plot format per band for the 4.1 NM distance (7.59 km).

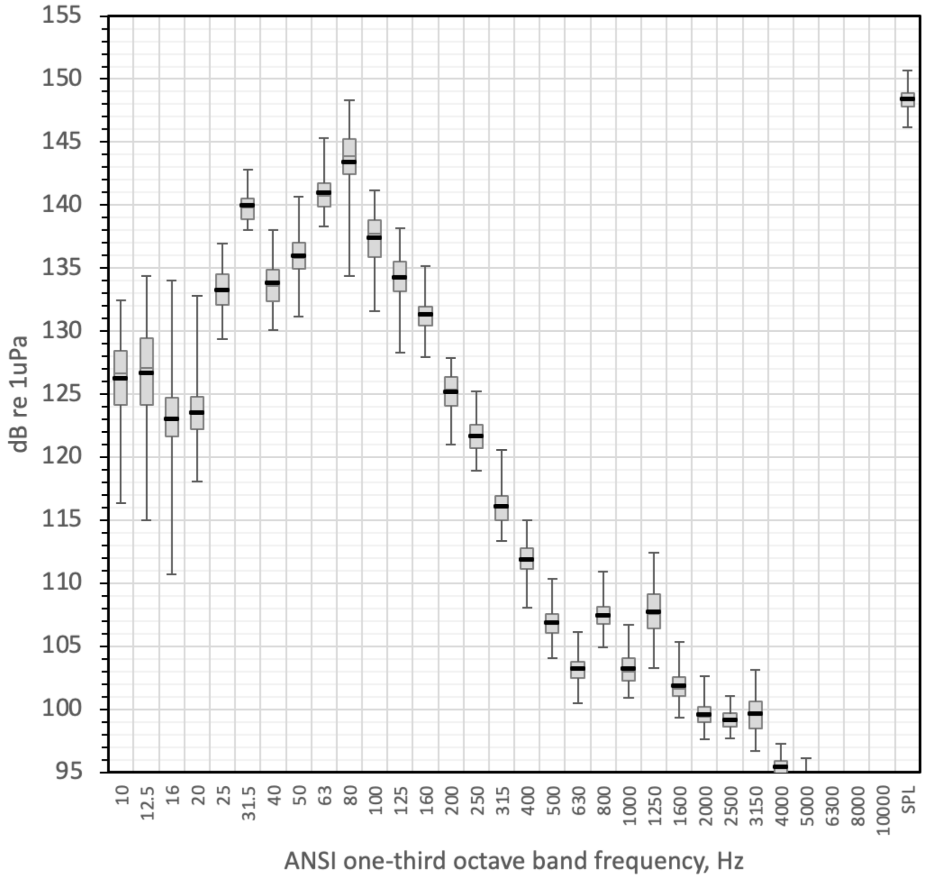

Figure 30. Box plot of one-third-octave band levels at 4.1NM (7.59 km).

3.6 SEL, Unweighted

Unweighted sound exposure level (SEL) was computed for each hammer blow using the measured RMS,200 and the 200-millisecond fixed window width for each hammer blow. The results are shown in Figure 31 below. SEL levels measured over 162 dB re 1uPa^{2}s at 1.06 km. Propagation loss PL measured 17.5log(r), falling between practical and spherical spreading.

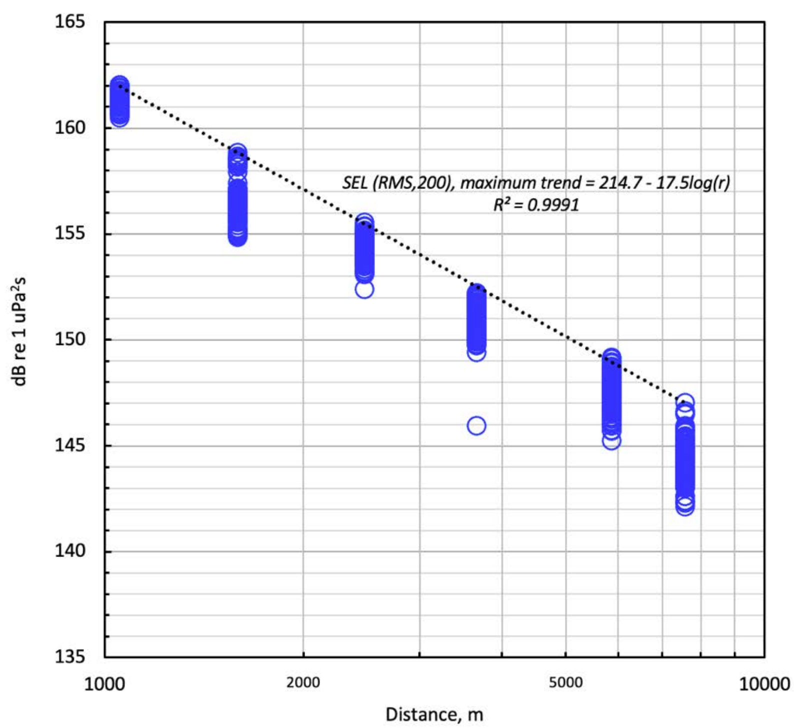

Figure 31. Sound exposure SEL values for all hammer blows acquired during the survey. The SEL values are calculated from the RMS,200 levels with fixed 0.2 second window width. SEL source level (SL) is conservatively estimated for maximum values at each location.

Unweighted sound exposure level (SEL) was computed for each hammer blow using RMS,90pct and the 90 percent window width for each hammer blow. The RMS 5-percent to 95-percent window width was computed within the selected RMS analysis dataframe of 1 second. The results are shown in Figure 32 below. SEL levels measured over 162 dB re 1uPa^{2}s at 1.06 km. Propagation loss PL measured 17.4log(r), falling between practical and spherical spreading. Each peak had a unique RMS time window in milliseconds based on the points where the 5- and 95-percent cumulative RMS sum was determined within the 1-second analysis window. Summary statistics for those values are provided in Appendix D.

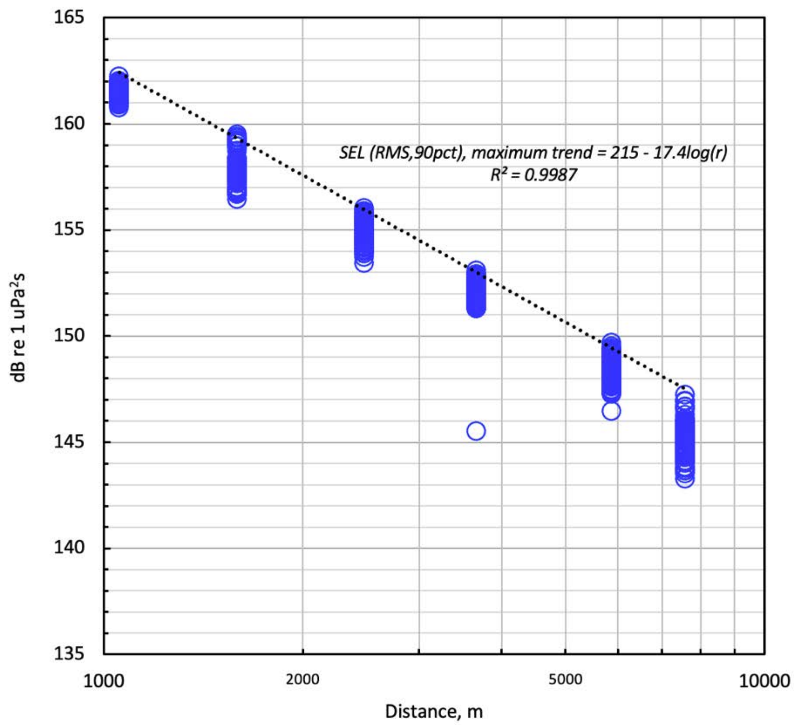

Figure 32. Sound exposure SEL values for all hammer blows acquired during the survey. The SEL values are calculated for the RMS,90pct levels and window width for each hammer blow. SEL source level (SL) is conservatively estimated for maximum values at each location.

3.7 Weighted (LF,Cetacean) RMS and Species Avoidance Response

LF-weighted RMS values are plotted in Figure 33 for each measurement location using the 200-millisecond mammalian hearing window (Madsen 2005). A severity scale of probabilistic behavioral responses to noise exposures between SPLs of 120-140, 140-160, and 160-180 decibels (dB) is shown corresponding to response thresholds listed in the BOEM Biological Assessment, March 2019, Table 5.1-2 for migrating mysticete whales (reference Wood 2012). These thresholds are listed in Wood 2012 Table 3.9 to define Level B behavioral responses. The thresholds reflect the behavioral response analysis method used by BOEM which "*applies frequency-weighted sound pressure levels for hearing groups (Wood et al. 2012) to estimate behavioral responses based on a gradual increase, or step function, that estimated a greater number of responses at higher SPLs and fewer adverse responses at lower SPLs farther from a sound source. This method applies a wider sound exposure range with different percentages of animals responding to noise exposure at each step between SPLs of 120-140, 140-160, and160-180 decibels (dBs) (Table 5.1-2).*"

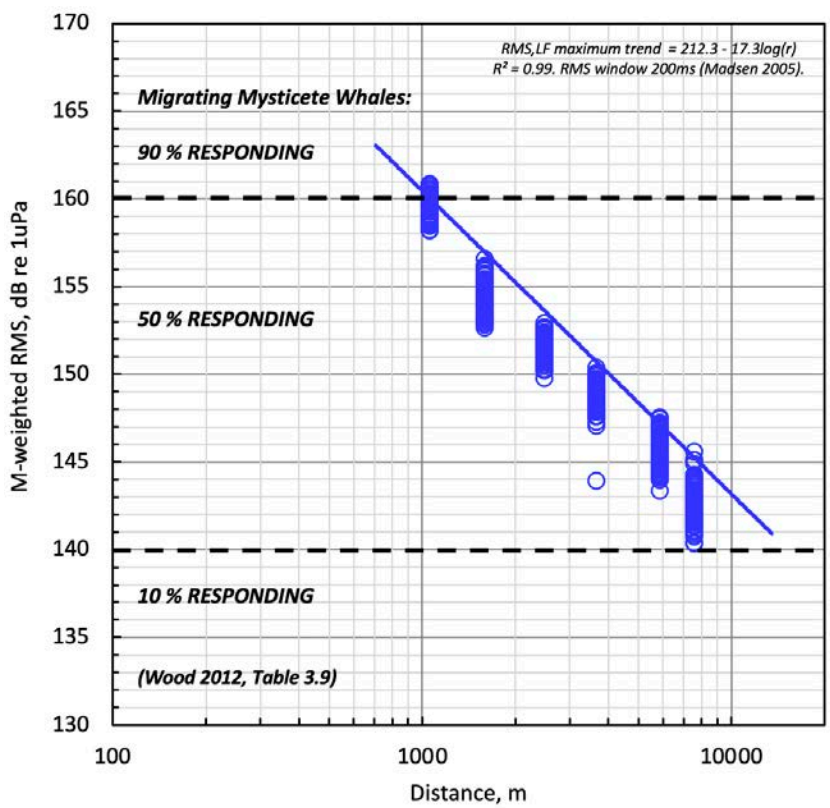

Figure 33. Scatter plot of RMS,LF values for all hammer blows during the survey. The trend for the highest RMS sound pressure levels over distance is shown with the propagation loss equation. BOEM 2019 thresholds for percentage mysticetes responding are shown for consideration.

RMS,LF levels computed from 200-millisecond fixed RMS windows measured up to 161 dB re 1uPa at 1.06 km. Ninety percent of mysticetes are expected to respond within 1 kilometer, with RMS sound levels exceeding 160 dB. Fifty percent of mysticetes are expected to respond behaviorally beyond 10 kilometers, with RMS sound levels exceeding 140 dB out to 14.5 km.

3.8 Weighted SEL for LF and PW Marine Species

The *effective far field* SEL during continuous pile driving was calculated for LF and PW marine species by computing total cumulative SEL sound levels over recording time T ranging from 111 to 248 seconds and 51 to 160 hammer blows per location, then normalizing those values to a 1-second SEL value by subtracting 10log(T/1.0) for each location. These normalized one-second SEL values enable the estimation of noise exposure over time by using using the sound expsoure factor 10log(T) during continuous pile driving. The extended dataset collected at 3.17 nautical miles offered a duration for analysis comparable to the other five sites, specifically between two operational cessation periods (refer to Figure 11).

Regarding the LF Cetacean Hearing Group, guidance from Southall (2019) [31] highlights the need for considerable caution due to the lack of direct hearing data for these species, which impacts the ability to predict their hearing capabilities and assess the vulnerability of their hearing to noise exposure. A prudent approach entails examining the unweighted linear SEL (SEL,Unweighted) to initiate an evaluation of potential hearing sensitivity to noise exposure.

SEL trends were established via logarithmic curve fit, with R^2 goodness of fit exceeding 0.98 with Unweighted, LF(Cetacean) and PW(Phocids) SEL data. MF and HF species weighting filtered hammer blow impulse data below useable range and were not evaluated further in this report. Figure 34 illustrates the effective SEL for unweighted SEL and LF and PW auditory weightings.

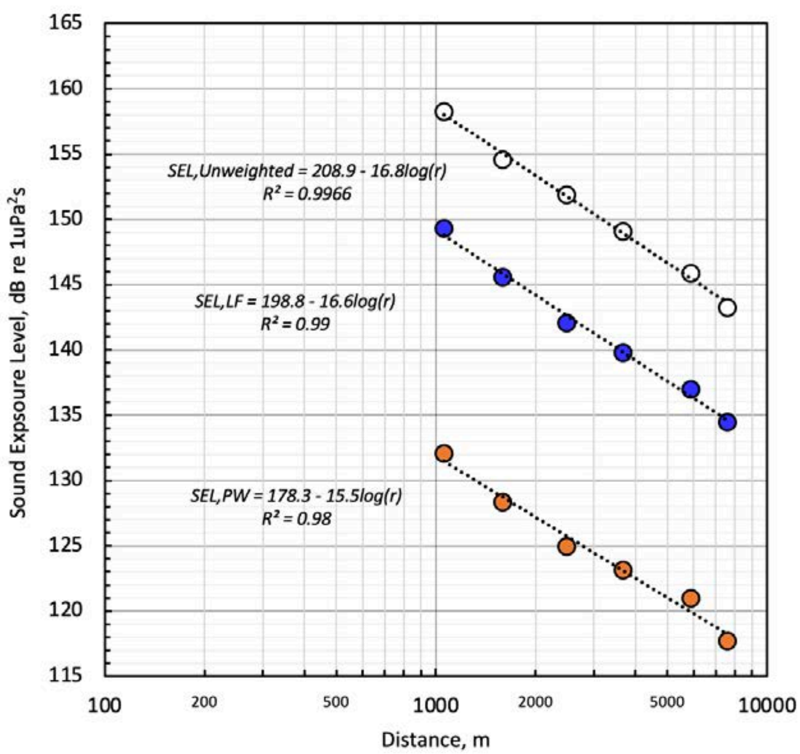

Figure 34. Sound exposure SEL values for unweighted, LF and PW weightings.

SEL,Unweighted measured 158.2 dB re 1uPa^{2}s at 1.06 km. The estimated source level is 208.9 dB re 1uPa^{2}s. Weighted SEL measured 149.3 and 132.1 dB re 1uPa^{2}s at 1.06 km for LF and PW species weighting, respectively. The estimated source level is 198.8 and 178.3 dB re 1uPa^{2}s for LF and PW species weighting, respectively.

Propagation loss PL for unweighted SEL was measured at 16.8log(r), close to practical spreading. Similarly, PL measured 16.6log(r) and 15.5log(r) for LF and PW species weighting, respectively, also close to practical spreading. Notably, assuming spherical spreading 20log(r) during sound exposure modeling would significantly underestimate SEL versus distance.

Notably, the LF weighting reduces the sound exposure level relative to unweighted SEL by approximately 9 dB at all locations from 1 to 8 km. With the absence of hearing data for mysticetes acknowledged by all parties and cautioned in Southall 2019, assuming SEL exposure for mysticetes as a function of LF weighting could significantly underestimate the actual, yet unknown noise impact on marine mammals.

3.9 Cumulative SEL and Level B and Level A Harassment Thresholds

The cumulative sound exposure level cSEL is computed by summing exposures to sound levels versus time. Higher sound levels and longer durations result in higher cSEL values. Drawing on extensive expertise in statistical audio noise dosimetry within power plant operations and acoustic evaluations of sonar survey vessels [38,39], questions emerged regarding the temporal durations necessary to exceed the NMFS Level B and Level A acoustic thresholds delineating the onset of temporary and permanent threshold shifts (TTS and PTS) in marine species.

The weighted cSEL was estimated for a range of distances and times assuming fixed source and receiver distances. Figure 35 below provides a log-log plot showing exposure times for the LF Cetacean marine species at Level A (PTS) and Level B (TTS) thresholds, 183 dB and 168 dB re 1 µPa^{2}s, respectively. The measured transmission loss of 16.6log(r) was employed. The results match calculations using the NMFS User Spreadsheet Version 2.2 (2020) Tab 'E' (Stationary).

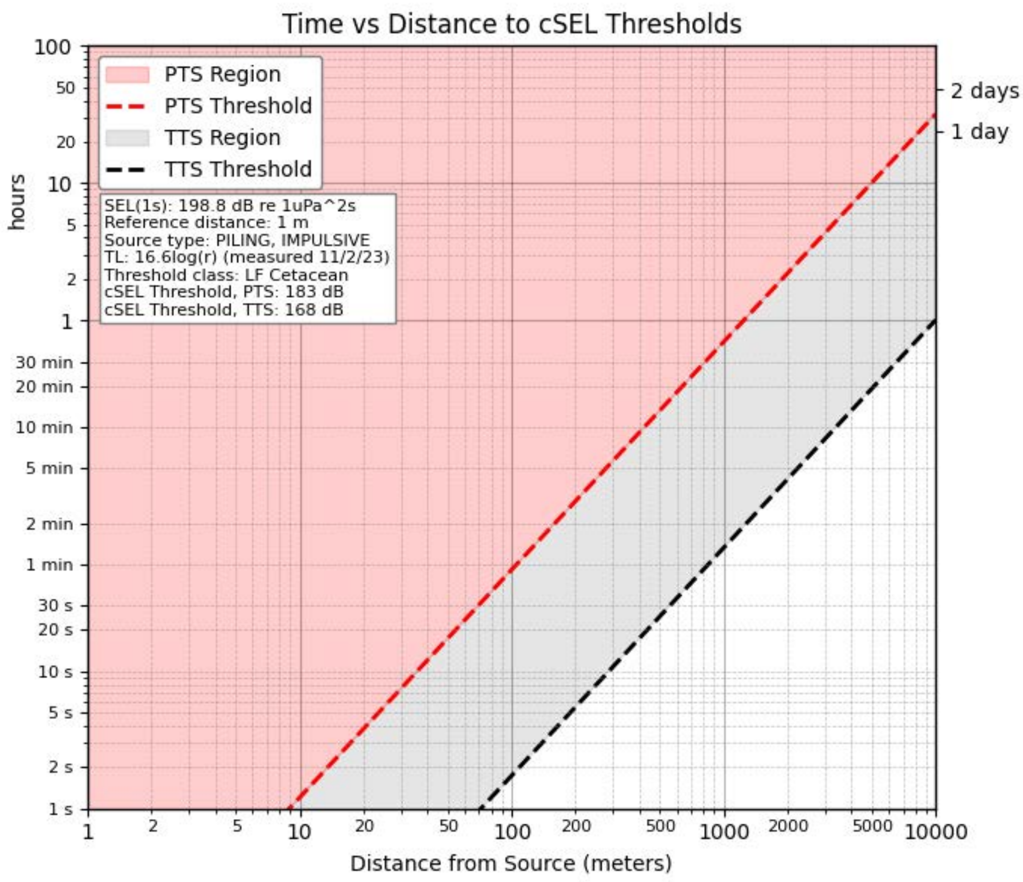

Figure 35. Log-log plot showing exposure times associated with Level B (TTS) and Level A (PTS) thresholds for the LF Cetacean marine species, 168 dB and 183 dB re 1uPa^2s, respectively, assuming exposure at a fixed position.

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38 Teplitsky, AM, Bradley, WE, Rand, RW and Suuronen, DE, "Statistical Audio Dosimetry Methodology", American Speech-Language-Hearing Association, November 1984. Research and work products were developed under contract with the New York Empire State Electric Energy Corporation (ESEERCO).

39 Rand, R.W., "Sonar Vessel Noise Survey", Rand Acoustics, LLC, 22 September 2023.

For LF Cetacean species (whales), a pile driving sound exposure of 13 minutes at 500 meters, 45 minutes at 1000 meters, or 2 hours at 1800 meters, yields a cumulative SEL exceeding the PTS threshold (onset of permanent hearing loss). A sound exposure of 2 minutes at 1200 meters, 5 minutes at 2200 meters, and 10 minutes at 3200 meters yields a cumulative SEL exceeding the TTS threshold (temporary threshold shift, hearing impaired).

Figure 36 below provides a log-log plot showing exposure times for the PW Phocid marine species at Level B (TTS) and Level A (PTS) thresholds, 170 dB and 185 dB re 1uPa^2s, respectively. The measured transmission loss of 15.5log(r) was employed. The results match test calculations using the NMFS User Spreadsheet Version 2.2 (2020) Tab 'E' (Stationary).

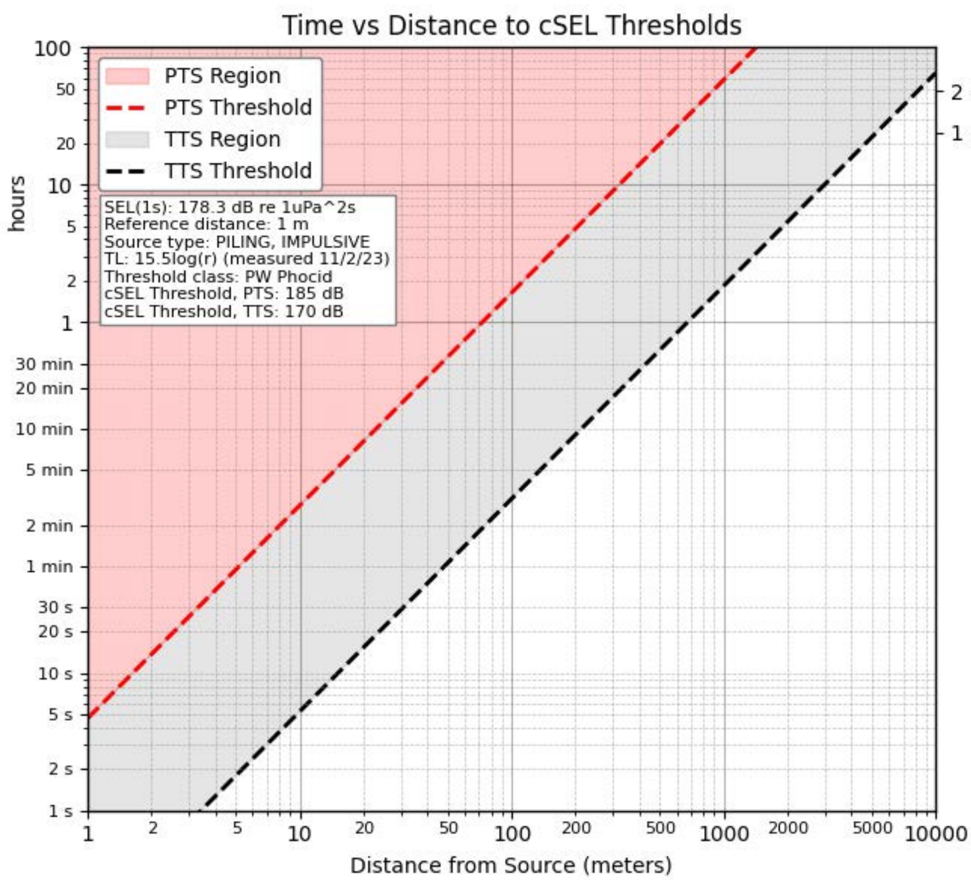

Figure 36. Log-log plot showing exposure times associated with Level B (TTS) and Level A (PTS) thresholds for the PW Phocid marine species, 170 dB and 185 dB re 1uPa^2s, respectively, assuming exposure at a fixed position.

For PW Phocid species (seals), a sound exposure of 1-3/4 hours at 100 meters yields a SELcum exceeding the Level A PTS threshold (onset of permanent hearing loss). A pile driving sound exposure of 40 minutes at 500 meters, or 2 hours at 1 kilometer, yields a SELcum exceeding the TTS threshold (temporary threshold shift, hearing impaired).

3.10 Reverberation

Reverberation time in the shallow littoral waters (depth 35-38 meters) was estimated with T20 decay estimation and Schroeder backward integration on selected portions of the audio recording at 0.57 NM, employing the Orion pile driving peak pulses as pulse source. Reverberation was estimated by averaging three RT60 tests, the highest peak at 5.98 seconds, the last peak, and a random peak at 21.1 seconds. The average RT60 measured 1.3 seconds at 40 Hz and 0.75 seconds at 250 Hz. Operational noise between hammer blows appeared elevated by several dB compared to the continuous noise observed from vessel-only noise emissions after hammer blows ceased at 1:49 elapsed time of recording. The elevated background between hammer blows is consistent with acoustic properties in a reverberant environment.

3.11 Vessel and ambient background sound levels

Vessel propulsion and DP thruster noise was highly audible on headphones out to 8 NM. Ambient sound levels were predominantly controlled by continuous vessel noise within 8 NM during the survey. Sounds heard included propulsion and DP thruster noise which were tonal. Continuous popping and rattling sounds were consistent with cavitation from DP thrusters and propulsion.

Vessel propulsion noise analyzed at 3.17 NM (5.87 km) with 10-second RMS averaging included prominent tones, as shown in Figure 38 below in the recording segment between pile driving at 1:26 to 1:36 mm:ss. Along with low-frequency noise from 50 to 100 Hz consistent with thrusters, tones were observed above 200 Hz, including 390, 780, and 1170 Hz, with higher harmonics. Total vessel noise from 40 to 10000 Hz measured 123 dB RMS.

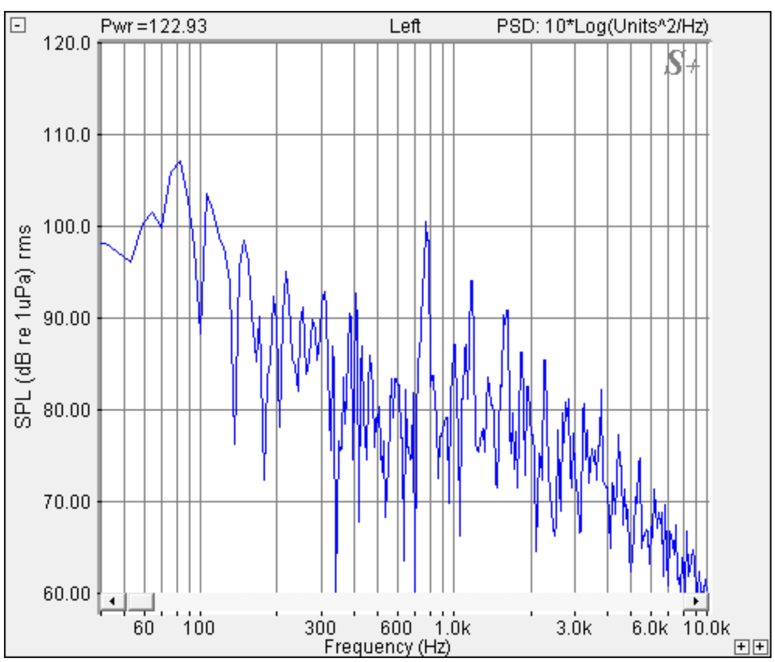

Figure 37. RMS spectrum plot, 3.17NM, between pile driving, recording segment at 1:26 to 1:36 mm:ss. Total RMS level measured 123 dB re 1 uPa from 40 to 10000 Hz.

Vessel propulsion noise analyzed at 0.57 NM (1056m) with 10-second RMS averaging included prominent tones as shown in Figure 39 below in the recording segment from 1:52 to 2:02 mm:ss. Along with low frequency emission in the 50 to 100 Hz consistent with thrusters, tones were observed at 200 Hz and above. Broadband noise included repetitive clattering sounds consistent with cavitation. Total vessel noise from 40 to 10000 Hz measured 127 dB (RMS,10-second).

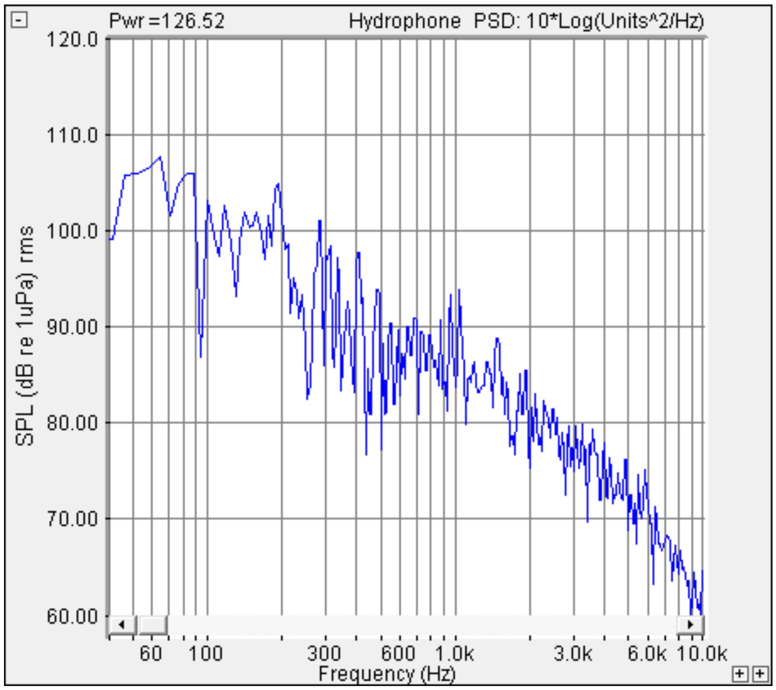

Figure 38. RMS spectrum plot, 0.5NM, between pile driving, recording segment at 1:52 to 2:02 mm:ss. Total RMS level measured 127 dB re 1 uPa from 40 to 10000 Hz.

The spectra at 0.57 and 3.17 NM were markedly different. At 3.17 NM, the outer support vessel was in line of sight and audible on headphones. At 0.57 NM, the outer bubble curtain was between the outer support vessel and the recording location, and likely acted as an acoustic barrier for that vessel's higher frequency noise.

Ambient RMS sound levels dominated by vessel noise and without pile driving were some 20 to 30 dB below pile driving RMS noise levels at all locations.

4 Discussion

4.1 Pile driving and seismic air guns

Pile driving and seismic air guns are impulsive sound sources with predominantly low frequency sound spectra. Seismic air gun source level data were reviewed from Ruppel et al 2022 [40] and compared to the pile driving sound data discussed in this report. The pile driving apparent source level was estimated from far-field sound levels from 1 to 8 kilometers during this survey at 241 dB re 1uPa @1m. This peak source level (SL) estimate is noted with a red arrow in Figure 40 below. Airgun peak SL levels within a 2 dB margin of the measured pile driving SL are outlined in the figure. Even with best available noise controls in place, the peak sound levels at the Vineyard Wind 1 project site are consistent with seismic airgun peak source levels for the highest output Tier 2, airgun arrays (2-36) and for Tier 1, airgun array surveys with total volume of 1500 in^3 or greater and/or 12 airguns or more.

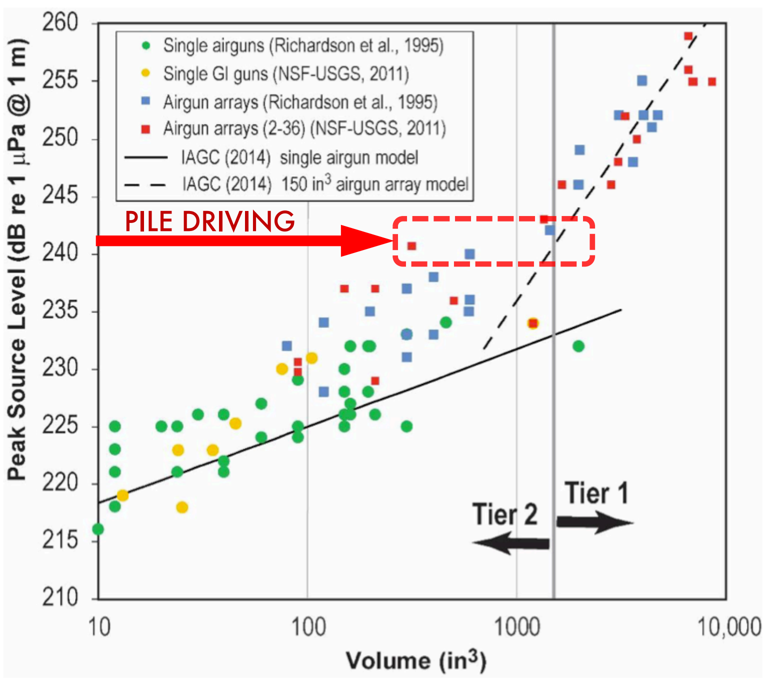

Figure 39. Comparison of 10.3-meter pile driving peak source level with compilation of source-level data on single airguns and airgun arrays from [40]: "The black solid and dashed lines correspond to modeled values for single airguns and an array of 150 in3 airguns, respectively. Tier 1 indicates airgun surveys with total volume of 1500 in^3 or greater and/or 12 airguns or more. All other airgun surveys are designated as Tier 2. Note that rms source level has no physical meaning for impulsive sources such as airguns, so the peak metric is used."

4.2 Caution on "90 percent" RMS for protecting endangered species

RMS is sensitive to the time window over which it is computed. The primary reference for RMS computation is Madsen 2005 which is cited for the 90-percent RMS computation in NMFS and

40 Ruppel, C.D.; Weber, T.C.; Staaterman, E.R.; Labak, S.J.; Hart, P.E. Categorizing Active Marine Acoustic Sources Based on Their Potential to Affect Marine Animals. J. Mar. Sci. Eng. 2022, 10, 1278. https://doi.org/10.3390/ jmse10091278.

BOEM documents. Madsen 2005 provides a comprehensive analysis of the sensitivity of the 90-percent RMS calculation to time window width, and cautions that "*it is possible to manipulate the rms level by varying the averaging window: the longer the averaging time, the lower the rms level. Measures for mitigation of sound exposure should not leave room for such analytical freedom.*"

Here is the basic problem for using the 90 percent window to evaluate pile driving at distance. In the 90 percent RMS algorithm, an analysis integration window must be selected that is wide enough in time to capture the waveform. The algorithm computes the cumulative sum from 5 to 95 percent of the energy within the integration window. The timespan between the 5- and 95-percent times forms the RMS window from which the RMS is determined.

For a 5-95 percent RMS measurement close in to a noise source such as a sparker or mammal click, the background is quiet, the impulse is brief, and the RMS measure is relatively insensitive to integration time. As Madsen found, "f*or short, well-defined transients such as odontocete clicks with good SNR, the rms measure is quite robust and not very sensitive to the criterion used to establish the integration window.*"

However, in the far-field from the pile-driving operation, the situation is different. Pile-driving is a complex noise source. On hammer impact, a shock wavefront travels down the monopile at the speed of sound in steel, acoustic mach waves radiate out the monopile into the water, the impact shock encounters the monopile base and radiates into the seabed, where acoustic energy propagates faster than in water, arriving at the hydrophone earlier than the direct water-borne peak. Meanwhile the shock wavefront is reflected back up the monopile and radiates more mach waves out into the water. Multiple reflections, path lengths, and group velocities and reverberation contribute to the now complex acoustic waveform measured in many tenths of seconds with distance. A 1-second dataframe may capture most of the signal and prevent including energy from the previous or following hammer blow (hammer blows averaged about 2 seconds between blows, with the minimum being 1.6 seconds).

Because the waveform is lengthened and complex due to the factors already discussed, the 90-percent RMS window is much longer than the maximum recommended time window of 200ms for mammalian hearing and reaction listed in Madsen 2005. This survey found the 90-percent RMS underestimates the RMS intensity in the mammalian response window by 2 to 6 dB. The 90-percent RMS is clearly unrepresentative of the intensity detected by mammalian hearing and cannot be considered a conservative metric.

Relying on the 90-percent RMS translates to smaller protective radii around pile driving operations by substantial distances. A 6-dB underestimate with spherical spreading is equivalent to *halving* the distance [36]. This results in a 50% reduction in the protective radius and a 75% reduction in protective area for the critically endangered North Atlantic Right Whale and other marine mammals.

5 Conclusions

This paper presents the methodology, analysis, and results of an independent investigation of underwater noise levels from pile driving by the crane ship Orion utilized as a pile driving vessel in the Vineyard Wind BOEM Lease Area OCS-A 0501 southwest of Nantucket Island, Massachusetts. The pile driving operations included double bubble curtains and hydro damper net for noise controls. Nonetheless, the survey results find pile driving impulsive sound levels are similar to seismic airgun arrays and raise concerns about heightened adverse noise impacts on marine mammals.

1. Peak levels measured up to 180 dB re 1uPa at 1.06 km. The calculated source level SL,pk is 241 dB with noise reduction mitigations employed. Despite double bubble curtains and hydro damper, *pile driving peak levels are comparable to seismic airgun arrays*. Propagation loss was 20.1log(r), consistent with spherical spreading.

2. NMFS relies on the RMS sound level for setting protective radii around impulsive pile driving. There are several different RMS computation methods. RMS was analyzed by applying two methods per Madsen 2005, with a 200ms window consistent with the limits of the mammalian hearing window, and a 90pct window using the 5- to 95-percent effective signal duration. The 90-percent RMS consistently *underestimated by 2 to 6 dB* the 200ms RMS for mammalian hearing response recommended in Madsen 2005. This disparity is consistent with the observations in Madsen 2005 and of the waveforms acquired in this survey that show lengthening with distance, increased numbers of reflections and pre-peak impulse arrivals of impulse energy through the sediment. It is concluded that at distances of 1 to 8 kilometers in waters of these depths the 90-percent RMS currently used by NMFS should not be considered a conservative metric for establishing protective radii for mammalian hearing and behavioral response.

3. The calculated sound exposure level weighted for LF Cetacean species is 198.8 dB re 1 $\mu Pa^2 s$. Pile driving sound exposures of 13 minutes at 500 meters, 45 minutes at 1000 meters, or 2 hours at 1800 meters, yields a cSEL exceeding the PTS threshold (onset of permanent hearing loss). A sound exposure of 2 minutes at 1200 meters, 5 minutes at 2200 meters, and 10 minutes at 3200 meters yields a cSEL exceeding the TTS threshold (temporary threshold shift, hearing impaired). It appears PTS exposure is possible for Cetaceans at significant distances.

4. The calculated sound exposure level weighted for PW Phocid species (seals) is 178.3 dB re 1 $\mu Pa^2 s$. Pile driving sound exposures of 1-3/4 hours at 100 meters yields a cSEL exceeding the Level A PTS threshold (onset of permanent hearing loss). A pile driving sound exposure of 40 minutes at 500 meters, or 2 hours at 1 kilometer, yields a cSEL exceeding the TTS threshold (temporary threshold shift, hearing impaired).

5. Propagation loss for Weighted SEL measured 16.5log(r) and 15.5log(r) for LF and PW weightings respectively. These propagation loss constants are consistent with practical spreading. Regulators assuming spherical spreading would underestimate sound exposure levels and resulting impacts including Level B and possibly Level A Harassment.

6. Level A Harassment appears feasible depending on time periods occupied at various distances to the pile driving. Further assessment using unweighted SELs (from cautions in Southall 2019) finds much larger setbacks are needed. It is unclear that the mitigation methods set in place are adequate to protect the NARW and other ESA-listed mammals and marine species.

7. The distance to the unweighted 160 dB,rms isopleth distance for Level B Harassment is 3355 meters, using the RMS,200ms time weighting for mammalian hearing (Madsen 2005). Whereas the IHA Authorization listed a distance of 2739 meters with 12 dB reduction.

8. The IHA Application and Authorization omit noise impact assessment for exposure at each step between SPLs of 120-140, 140-160, and 160-180 dB listed in the BOEM Offshore Wind Energy Project Biological Assessment Method 2 (Wood 2012). Whereas weighted (LF) RMS sound levels compared to the BOEM step table show ninety percent of mysticetes responding (avoidance response) within 1 kilometer, and fifty percent respomding out to 14.5 km.

9. The IHA Application and Authorization did not evaluate continuous vessel propulsion, DP thruster or combined noise levels by vessel operations in the lease area. The IHA documents including the Authorization treat the Orion and support vessels as silent. Ambient sound levels without pile driving were dominated by Orion and support vessel propulsion and thruster noise including cavitation, despite double bubble curtains surrounding the Orion. Orion and support vessel sound levels with pile driving off measured 127 dB RMS re 1uPa at 0.57 NM (1.06 km) and 123 dB RMS at 3.17 NM (5.87 km) from the Orion.

10. NMFS appears to have abandoned evaluation of its Level B behavioral harassment threshold at 120 dB,rms which leaves insufficient protections in place for marine species behavioral harassment. To meet the NMFS 120 dB,rms behavioral harassment threshold for the operation's continuous noise only, the distance required is estimated at over 6 km.

11. The data acquired during the survey and subsequent review of project and regulator documents raise concerns of sufficient NOAA review methods and mitigation distances to protect the critically endangered North Atlantic Right Whale (NARW) and other marine species from behavioral harassment and hearing loss impacts from pile driving.

Limitations

No information was available on hammer blow strike strengths (kJ) or specifics of noise controls used, including hydro sound damper materials and optimizations, bubble curtain air pressures, and bubble sizes produced during the survey. As a result, peak, RMS, SEL, and source level SL estimations from the far field measurements could under-estimate pile driving noise occurring during higher hammer strike strengths or reduced noise reduction performance.

Sound attenuation with distance underwater could differ from the results found during this survey depending on factors including absorption and scattering, winter versus summer sound speed gradients, thermocline strength, sea state, and sea bottom absorption and reflectivity.

Declaration of Conflicting Interests

The author declares no potential conflicts of interest with respect to the research, authorship, and/or publication of this report. INCE Members are required by professional ethics to ensure compliance with regulatory requirements and hold paramount the safety, health and welfare of the public. The author extends the same professional commitments to marine species.

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6 Appendices

Appendix A. Vineyard Wind Bubble Curtain Technology.

Source: https://maritime-executive.com/article/vineyard-wind-tries-bubble-curtain-system-to-cut-pile-driving-noise

Vineyard Wind Tries "Bubble Curtain" System to Cut Pile-Driving Noise

Twin curtains of bubbles surround this pile-driver during turbine foundation installation (Vineyard Wind)

PUBLISHED MAY 15, 2023 10:27 PM BY THE MARITIME EXECUTIVE

Vineyard Wind, the first wind farm to begin construction in U.S. federal waters, is beginning a trial of bubble curtain technology to reduce the subsea noise impact of pile-driving during installation of wind turbine foundations.

With $5 million in funding from Vineyard Wind's own Industry Accelerator Fund, run by the Massachusetts Clean Energy Center, survey contractor ThayerMahan will provide acoustic mitigation services using the Hydrotechnik-Luebeck "Big Bubble Curtain" technology. ThayerMahan will be moving its headquarters for this product line to the Foss Marine Terminal in New Bedford to support the project, and will be hiring and training locally to staff the operation. It will be the first bubble-curtain service in the U.S. offshore wind industry, according to Vineyard Wind.

The bubble curtain system consists of two concentric rings of perforated hoses laid on the bottom around the work area. Before piledriving begins, the hoses are inflated using special-purpose clean air compressors. The perforations leak a continuous stream of bubbles around the work site. The bubbles absorb and reflect sound energy, creating a barrier that reduces noise transmission from activity inside of the curtain. According to one European contractor which uses the technology, it can cut noise outside of the curtain by 90 percent.

Note: A "90 percent" noise reduction is approximately 10 dB. Noise reduction is frequency dependent. Bubble curtain noise reduction performance is better at higher frequencies.

Appendix A. Vineyard Wind Bubble Curtain Technology (continued)

Source: https://www.eenews.net/articles/blowing-bubbles-offshore-winds-new-strategy-to-save-whales/ (portions excerpted)

Blowing bubbles: Offshore wind's new strategy to save whales
By **Heather Richards** | 12/13/2023 01:24 PM EST

...
To create the bubble curtains, steel encased, perforated, rubber hoses are sunk to the seafloor in two concentric rings around a monopile. As sound waves pulse out during pile driving, that sound energy must travel through the two walls of air, greatly reducing their impact.
...
ThayerMahan vessels carry a suite of powerful air compressors to create the bubbles. At Vineyard, a crew of just under 30 — including union deck crews based in New England — ramp up about 30 minutes before pile driving begins. That's how long it takes to create suitable air barriers. Throughout the pile driving, the vessels are also monitoring the sound levels to gauge how much sound is getting thorough the curtain.
...
Pioneered in Germany to protect marine life in the North Sea, bubble curtains are most effective in shielding animals that rely on lower frequencies to communicate, like baleen whales. ... The bubble curtain technology is also somewhat effective for high frequency sound mitigation, helping mammals like porpoises and dolphins.
...
ThayerMahan is partnered with the world leader in bubble curtain technology, the Germany company Hydrotechnik Lübeck, to bring the industry to the U.S.
...
Big bubble curtains are not specifically required in the U.S., but they are an accepted option to meet federal sound control requirements set by the Bureau of Ocean Energy Management.
...
Vineyard said it has experimented with different sound-dampening options and found that a double bubble curtain like ThayerMahan's can be combined with a hydro sound damper — a related sound system that uses nets — to get the strongest result. That approach is being used on its 62 turbines off the coast of Martha's Vineyard.

Appendix A. Vineyard Wind Bubble Curtain Technology (continued)

Source: https://www.hydrotechnik-luebeck.de/portfolio-items/compressed-air-hydro-sound-mitigation/

How the compressed air hydro sound attenuation works

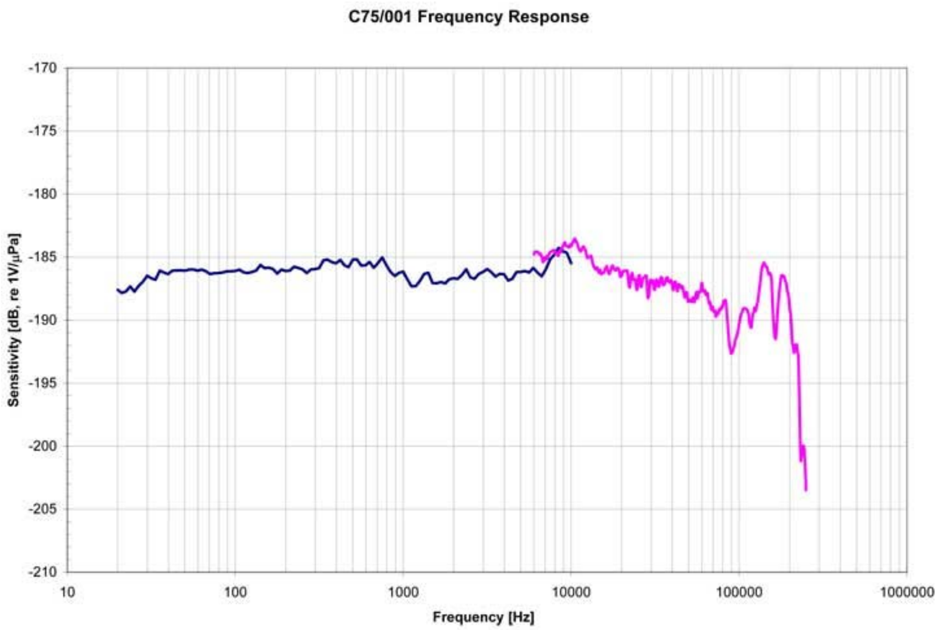
A flexible hose system with special nozzle openings is used. It is laid at a sufficient distance around the location of the sound generation on the seabed. Depending on the nature of the sea bed and the water current, up to two hose rings can be used. A ship equipped with special compressors is connected to the hose system and presses air into the hose system with up to 10 bar while the sound is generated. The compressed air escapes through the nozzles provided. The steadily rising air bubbles create a bubble veil. It changes the physical properties of the water. Sound waves are broken several times, reducing the volume by up to 95%.

The hose system is recovered after each use with the help of specially developed hose winches. The Big Bubble Curtain is independent of other trades and does not leave any traces on the water's bottom.

The maximum sound attenuation that has been achieved so far is 15 dB with one hose ring and 18 dB with two hose rings. The deployment and use of the Big Bubble Curtain depend in different ways on wind strength, wave height, water depth, current, and the environmental conditions of the respective construction site.

Note: A "95 percent" noise reduction is approximately 13 dB. Noise reduction is frequency dependent. Bubble curtain noise reduction performance is better at higher frequencies.

Appendix B Cetacean Research hydrophone frequency response (manufacturer test).



Appendix C. GRAS Model 42AG Acoustic Calibrator calibration certificate.

Calibration Chart

GRAS 42AG Multifunction Sound Calibrator, Class 1

Serial No.	281474
Calibration date	14. Feb. 2023
Operator	ZBA

Environmental calibration conditions

Temperature	23 °C
Relative humidity	44 %
Barometric pressure	1030 hPa

	Nominal Frequency [Hz]	Measured SPL [dB re. 20 uPa]	Measured Frequency [Hz]	Measured THD [%]	Measured THD + Noise [%]	Status
Tolerance		±0.20	±0.30	1.5	2.0	
Uncertainty		±0.08	±0.02	±0.1	±0.1	
94 dB	251.19	94.00	251.20	0.08	1.03	Pass
114 dB	251.19	114.02	251.20	0.13	0.23	Pass
94 dB	1000	94.02	1000.00	0.01	1.47	Pass
114 dB	1000	114.02	1000.00	0.02	0.13	Pass

Calibration

The performed tests refer to the sections 5.2, 5.3 and 5.5 in IEC 60942 (2003): Electroacoustics - Sound Calibrators. The calibrator has been tested ad described in Annex B of the IEC 60942 standard.

Approved by

Quality Manager

14. Feb. 2023

Date

GRAS Sound & Vibration

GRAS Sound & Vibration A/S
Skovlytoften 33, 2840 Holte, Denmark
Email support@gras.dk · gras.dk

Appendix C (continued). BRC hydrophone adapter calibration certificate.

BRC
Engineering

21870 Eighth St. E.
Unit # C-4
Sonoma, CA 95476

Tel: 707-226-3332
Fax: 707-236-8964
E-Mail: brcnorcal@aol.com

Specialists in Noise & Vibration Measurement & Analysis

CALIBRATION CHART for TYPE HADP42AG-C75 S/N: 65506

Hydrophone Adapter for Calibrator Type # 42AG used to

Calibrate CETACEAN Hydrophone Type # C75

Pressure Correction Factor: +0 dB +/- 0.5 dB at reference conditions

Nominal Frequency: 250 Hz

There is no pressure correction factor for the HADP42AG-C75. The sound pressure level inside the adapter is determined by the pressure level chosen on the G.R.A.S. 42AG, either:

1 Pa or 94 dB re 20 microPa or 120 dB re 1 microPa

or

10 Pa or 114 dB re 20 microPa or 140 dB re 1 microPa

Note: 250 Hz preferred for best accuracy.

Reference Conditions:

Ambient Temperature: 14.7 C
Ambient Static Pressure: 101.0 kPa
Relative Humidity: 64%

Reference Equipment:

Calibrator Type: G.R.A.S. # 42AG
Microphone Type: LD Type 377B02
Hydrophone Type: C-75

Approved by: Richard Craig

Signature Richard L. Craig

Date: May 3, 2023

Appendix D. Summary Data

This appendix delineates summary data for each measurement location, accompanied by visual representations of peak values, RMS levels, and spectrograms for hammer blows yielding maximal RMS at each site.

The RMS sound pressure level (defined by ANSI as "rms" pressure) contains no restrictions on the RMS integration time window. Nonetheless, the RMS is inherently *sensitive to the duration of its time window*. The integration time should always be provided with the sound pressure level when it is reported as RMS. In contrast, peak and peak-to-peak sound pressure values are universally preferred over RMS for measuring, characterizing and evaluating impulse sounds.

RMS assessments in this document include the 200-millisecond RMS, which Madsen 2005 recommends as the uppermost fixed interval for evaluating mammalian auditory responses. The 90-percent percentage energy signal duration, delineated as the interval between the 5-percent and 95-percent cumulative energy thresholds in Madsen 2005 and defined in ISO 18405:2017 [41], is also considered. This duration is contingent upon the overall analytical timeframe T, within which these cumulative levels are identified. The T dataframe spans 1 second, a duration established for this analysis to encompass the majority of the impulse at far-field measurements. The RMS window from 5 to 95 percent fluctuates with each impulse and escalates as the distance from the emission point to the measurement site increases, reflecting the influence of acoustic reflections and peak pre-arrivals refracted from the seabed. Consequently, the 90-percent RMS level differs for each peak, typically registering significantly lower than the RMS calculated using the fixed 200-millisecond window that Madsen 2005 advises as the conservative threshold for mammalian auditory analysis.

Figures 41 and 42 present triple plots illustrating data for the most intense hammer strike (centralized) at 0.57 NM (1056 meters or 1.06 km) and at 4.1 NM (7593 meters or 7.59 km), respectively.

In each instance, plot (a) exhibits the sound pressure in Pascals, with each pile driving hammer blow apex demarcated by an encircled highlight. The sound pressures are rendered in blue ink, and red ink illustrates the span wherein the RMS,90pct for the hammer blow is computed—ranging from 5 to 95 percent of cumulative energy as delineated by ISO 18405. The 1-second timeframe selected for the RMS computation is depicted by two dashed red lines flanking each peak.

Plot (b) delineates the continuous RMS level calculated with the 200ms exponential window (in black ink), as stipulated in Madsen 2005 for mammalian auditory response assessments. Additionally, plot (b) depicts the 90 percent RMS, derived from the 5 to 95 percent cumulative sum, as a 'boxcar' (in red ink). The lateral edges of this boxcar correspond to the 5 and 95 percentile points within the cumulative RMS sum, with the upper edges matching the RMS,90pct decibel value.

Plot (c) provides a spectrogram measured in dB re 1 uPa/√Hz, with time on the x-axis and frequency on the y-axis. The sound pressure level is computed via a 4096-point FFT employing

41 Underwater Acoustics – Terminology, ISO 18405:2017, 2017. https://www.iso.org/standard/62406.html

Hanning weighting and 99 percent overlap, standardized to 1 Hz, with color-coded intensity levels indicated in the accompanying colorbar. White dashed lines underscore the peak time location within the plot.

At the 0.57 NM measurement position (1.06 km northeast of the Orion), variations in the temporal signatures and intensities of hammer strikes were relatively subdued. Peaks presented a negative phase pressure characteristic. Energy from hammer blows was observed preceding the peaks and extending beyond them. The majority of this energy was concentrated below 200 Hz, with the peak hammer energy discernible on the spectrogram up to 400 Hz. Both 200-millisecond and 90-percent RMS metrics exceeded the NMFS Level B harassment threshold of 160 dB re 1uPa.

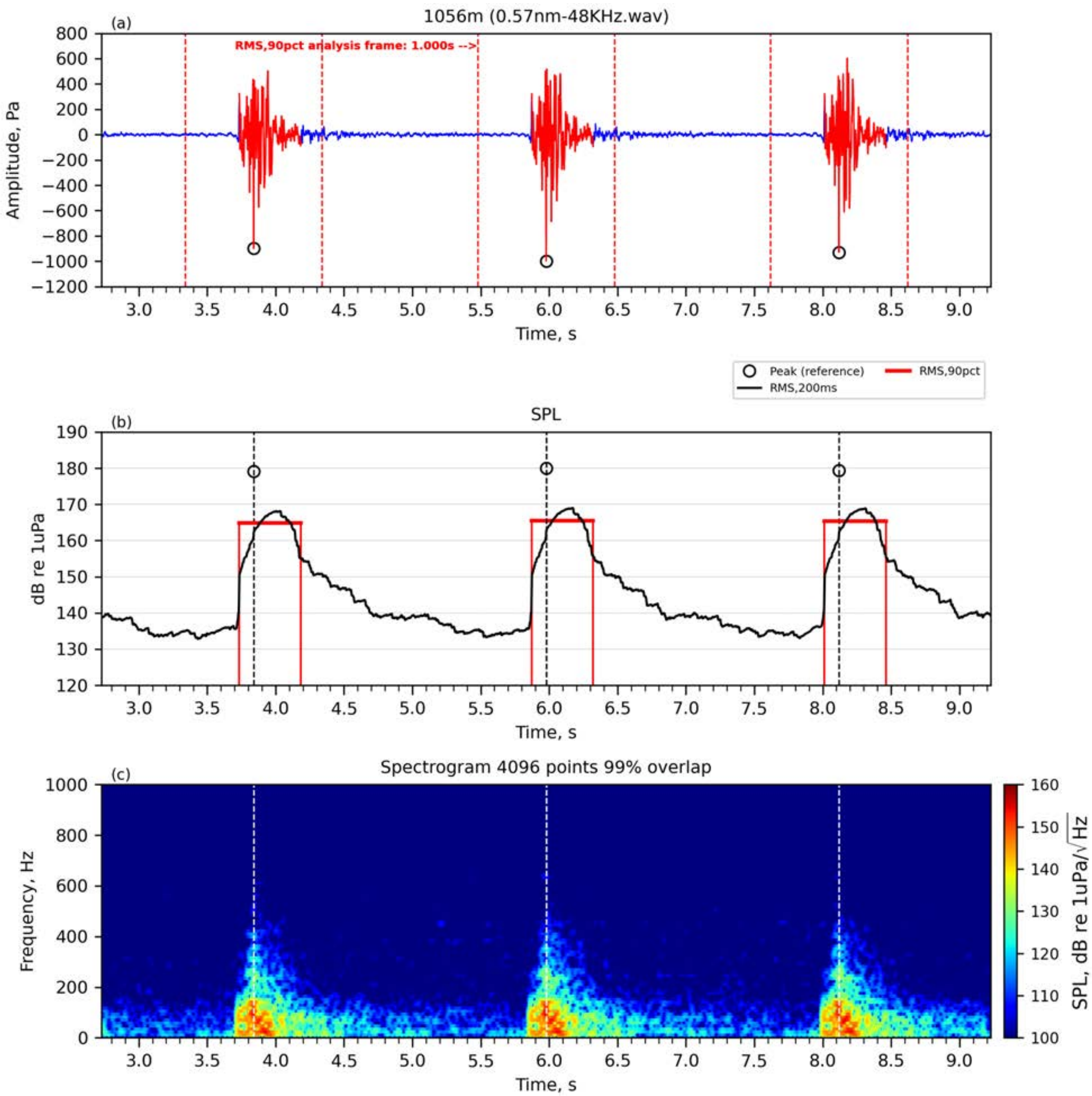


Figure 40. Unweighted sound pressure at 0.57 NM (1056 m), three peaks.

At the 4.1 NM measurement locale (7.59 km northeast of the Orion), hammer blow time signatures and intensities diverged significantly from those at 1.06 km. Hammer blow energy was observed arriving before peaks and lingering afterward. Oscillatory pressures in plot (a) were evident before peak arrival. Peaks displayed both positive and negative phase pressures. Energy from hammer blows primarily spanned below 100 Hz, with energy at the peak detectable on the spectrogram up to 300 Hz. The RMS_90pct's 1-second data frame, indicated by red lines in plot (a), largely contains the trailing energy signature post-peak but does not include pre-peak pressure oscillations appearing 0.5 to 0.9 seconds before the peak. The 200-millisecond and 90-percent RMS levels did not exceed the NMFS Level B harassment threshold of 160 dB re 1uPa.

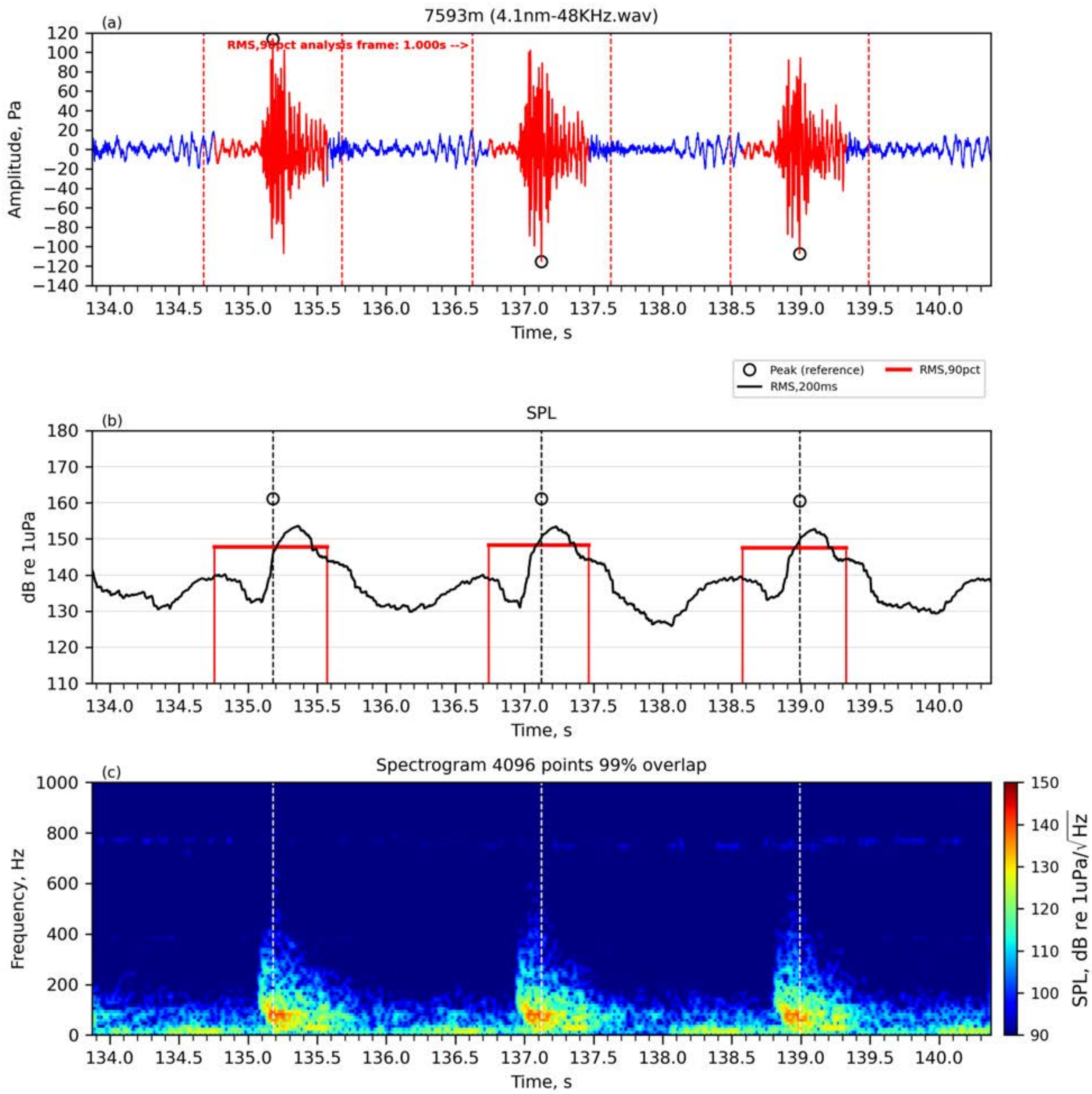


Figure 41. Unweighted sound pressure at 4.1 NM (7593 m), three peaks.

Appendix D (continued). Single Peak Waveform Plots

The nest six pages feature plots of the highest RMS_200 values at each measurement site, with waveforms and data pertinent to pile driving operations. The diagrams detail both the 90-percent duration RMS and the 200-millisecond RMS as per Madsen 2005. Spectrograms at increased distances reveal vessel noise at 390 and 780 Hz, implying acoustic shielding by bubble curtains at nearer distances. The 90-percent RMS consistently records significantly lower than the 200-millisecond RMS, while SEL findings remain consistent within 1 dB across both methodologies.

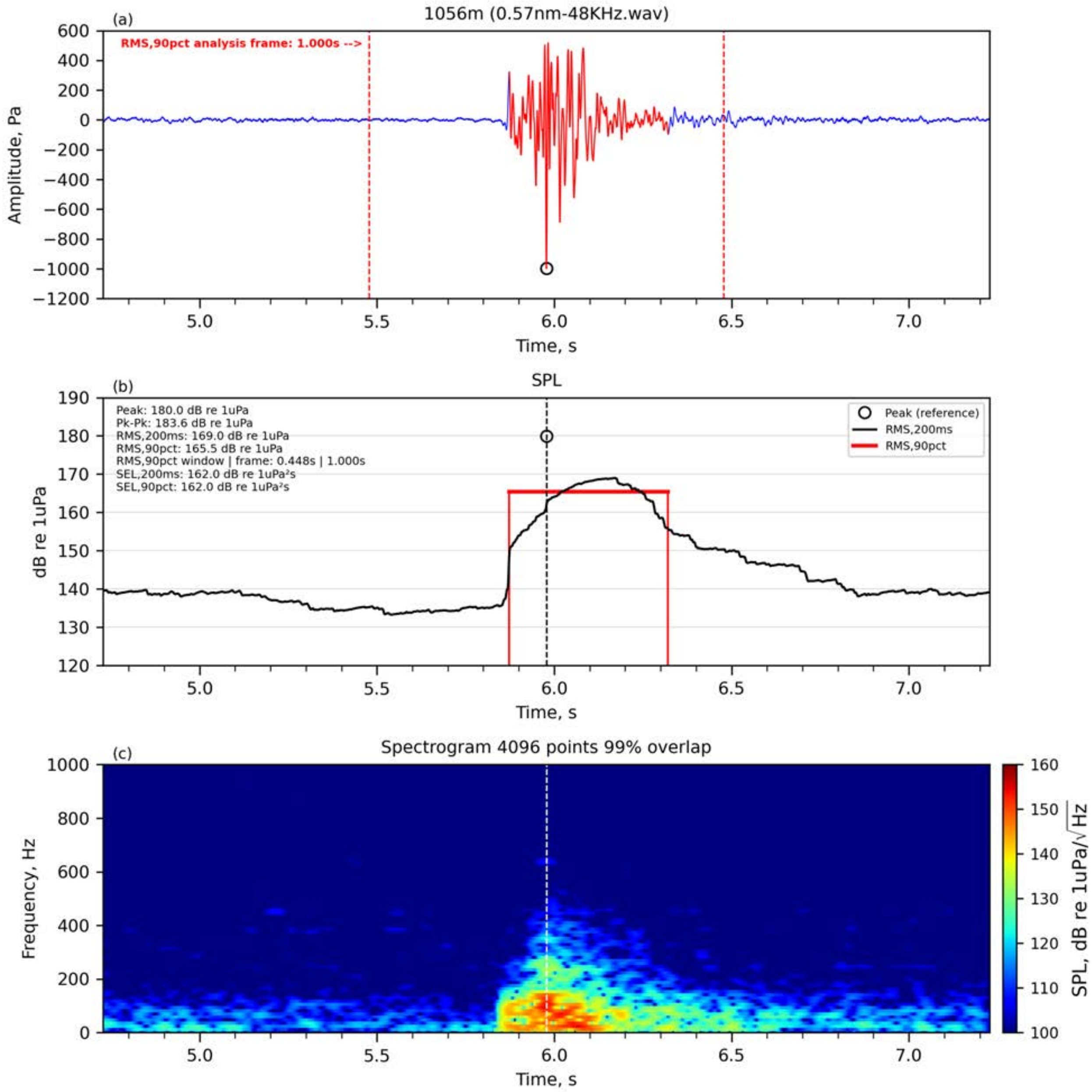


Figure 42. Unweighted sound pressure waveform, RMS levels, and spectrogram at 0.57 NM (1056 m).

Appendix D (continued). Single Peak Waveform Plots

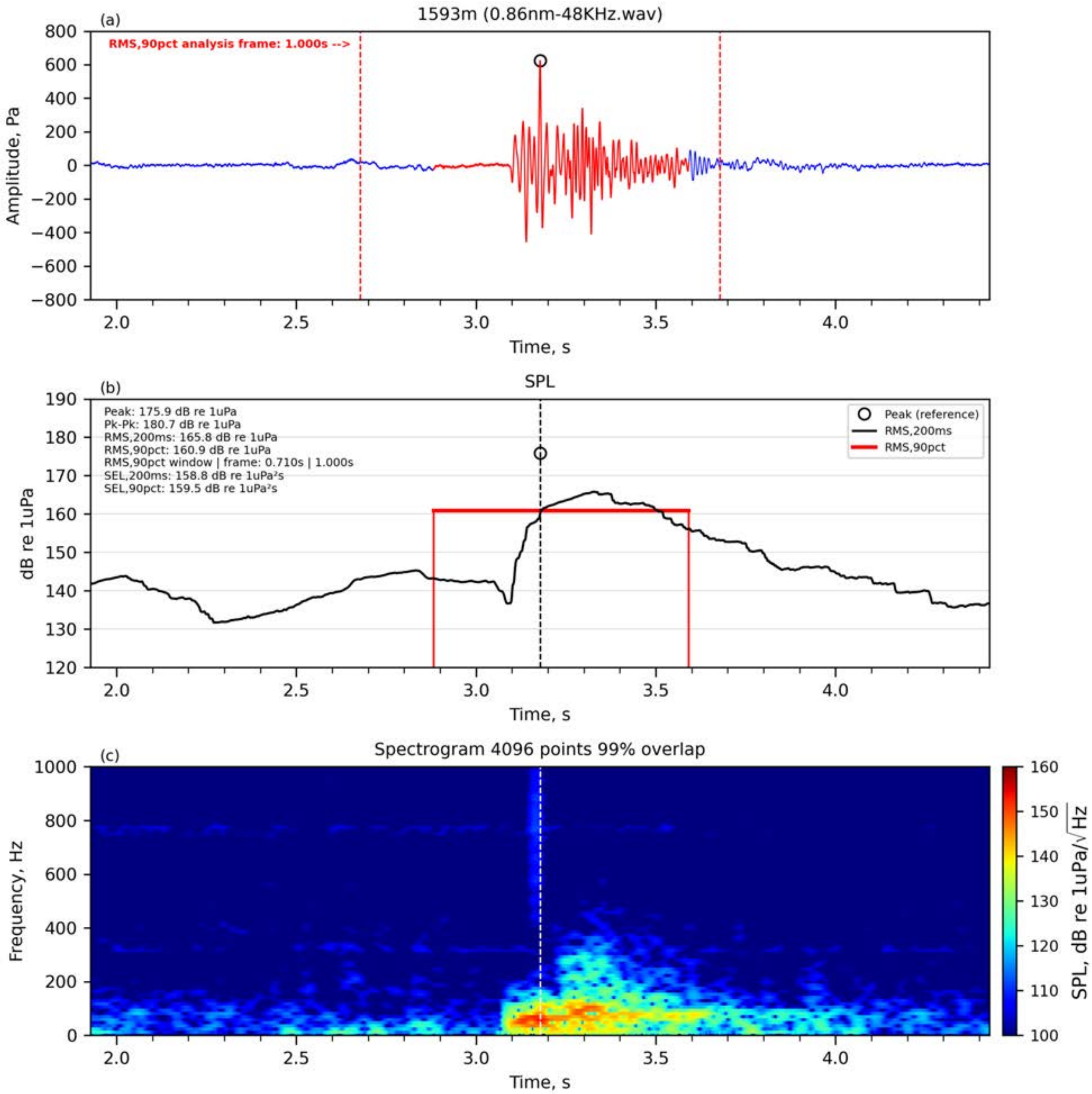


Figure 43. Unweighted sound pressure waveform, RMS levels, and spectrogram at 0.86 NM (1593 m).

Appendix D (continued). Single Peak Waveform Plots

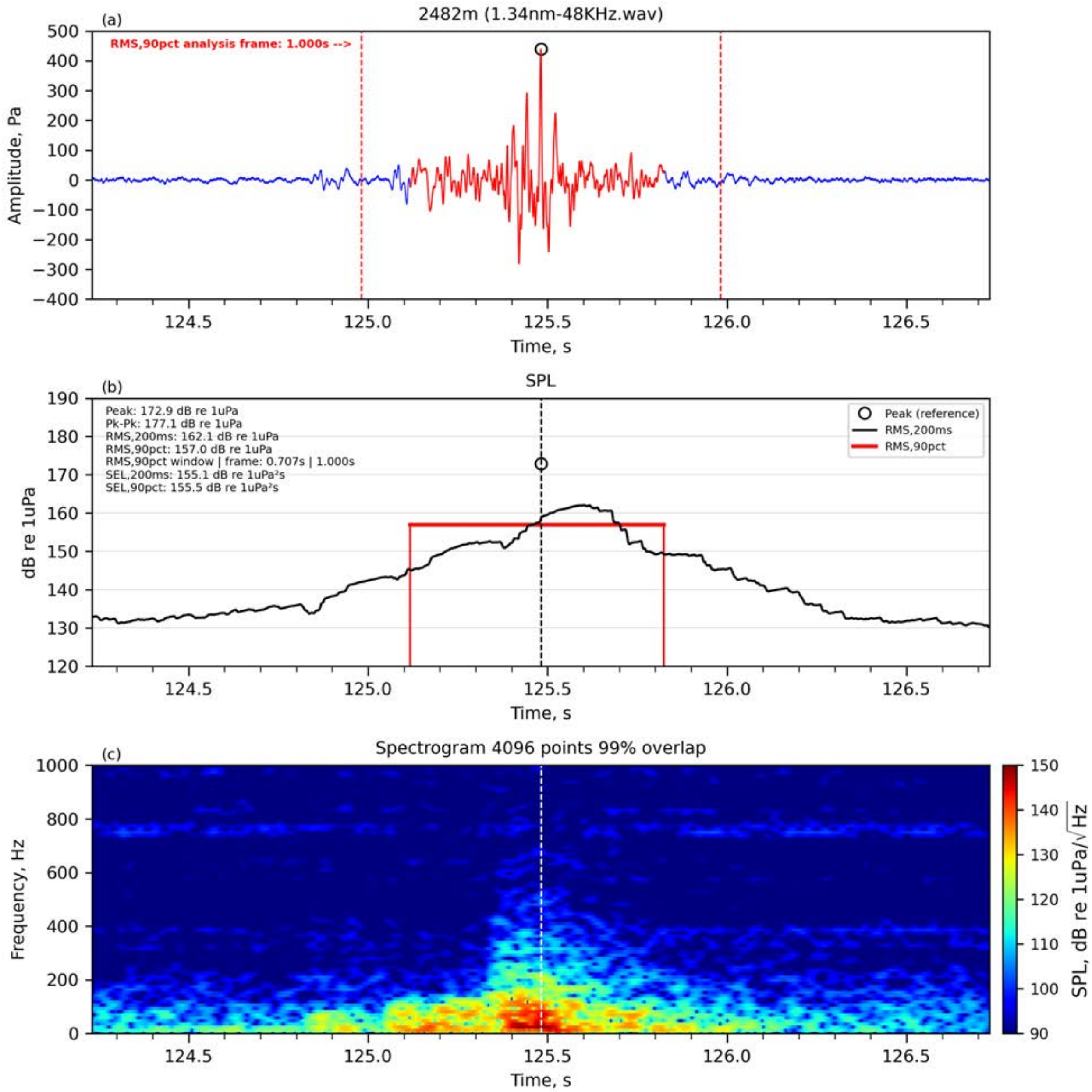


Figure 44. Unweighted sound pressure waveform, RMS levels, and spectrogram at 1.34 NM (2482 m).

Appendix D (continued). Single Peak Waveform Plots

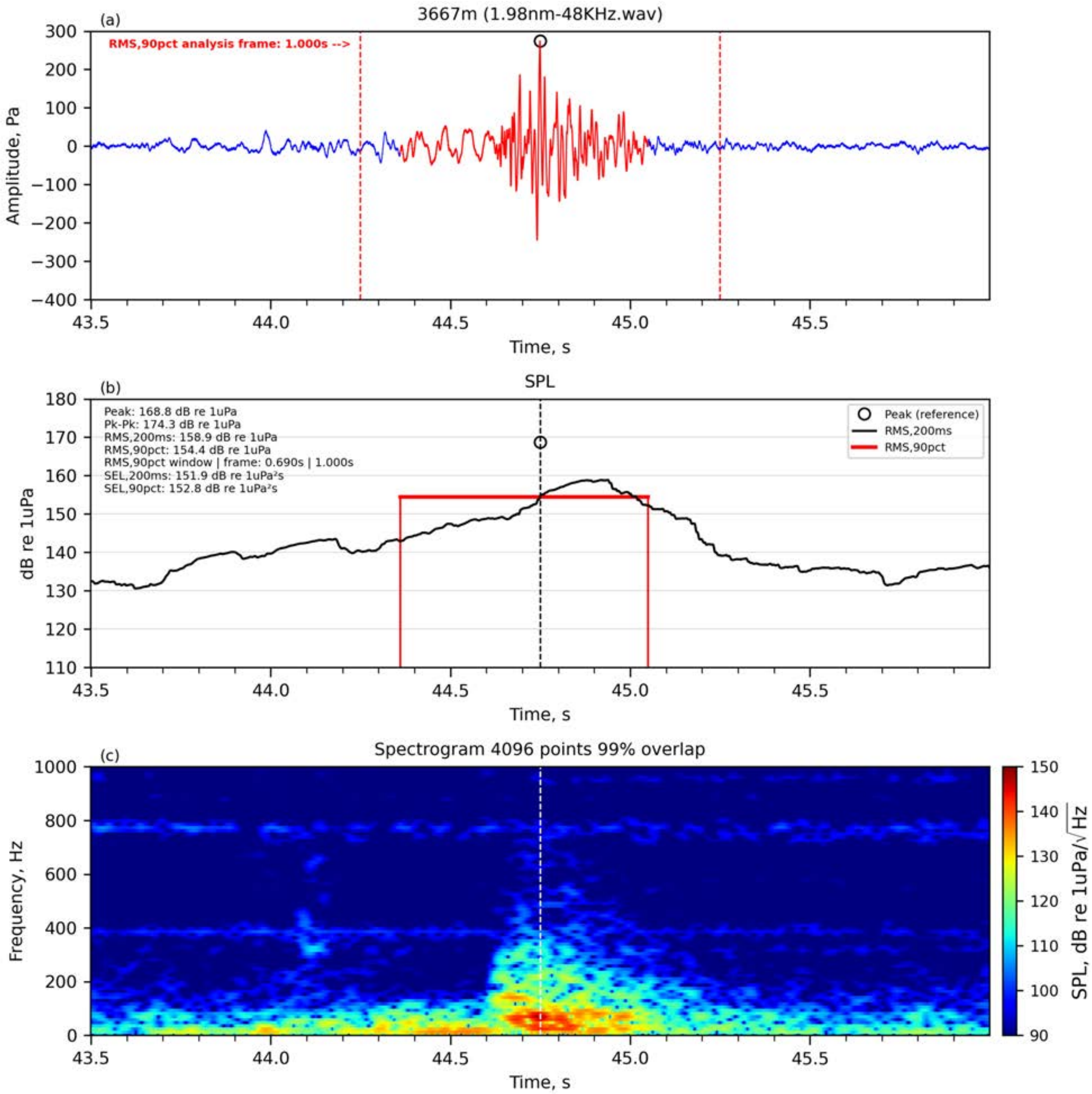


Figure 45. Unweighted sound pressure waveform, RMS levels, and spectrogram at 1.98 NM (3667 m).

Appendix D (continued). Single Peak Waveform Plots

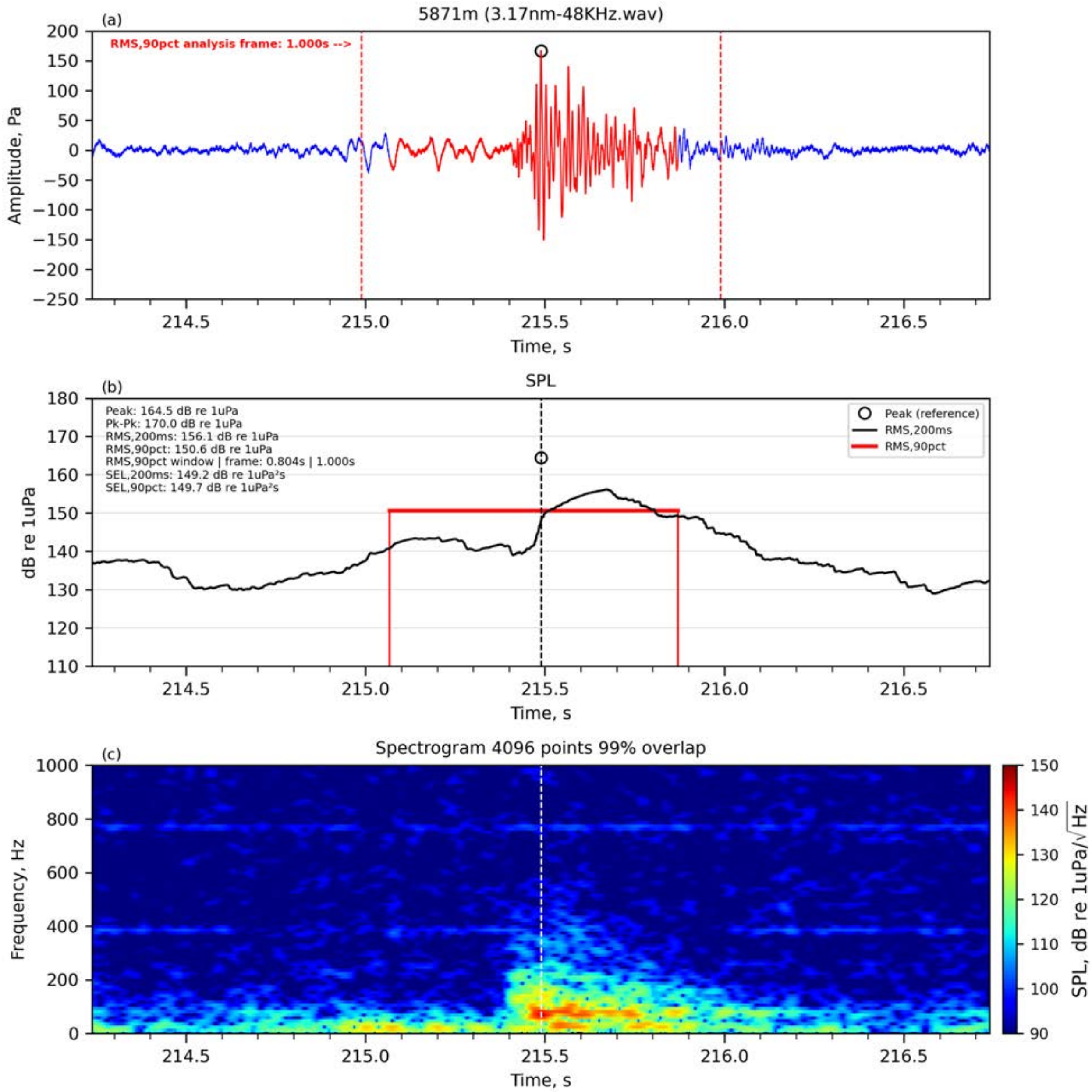


Figure 46. Unweighted sound pressure waveform, RMS levels, and spectrogram at 3.17 NM (5871 m).

Appendix D (continued). Single Peak Waveform Plots

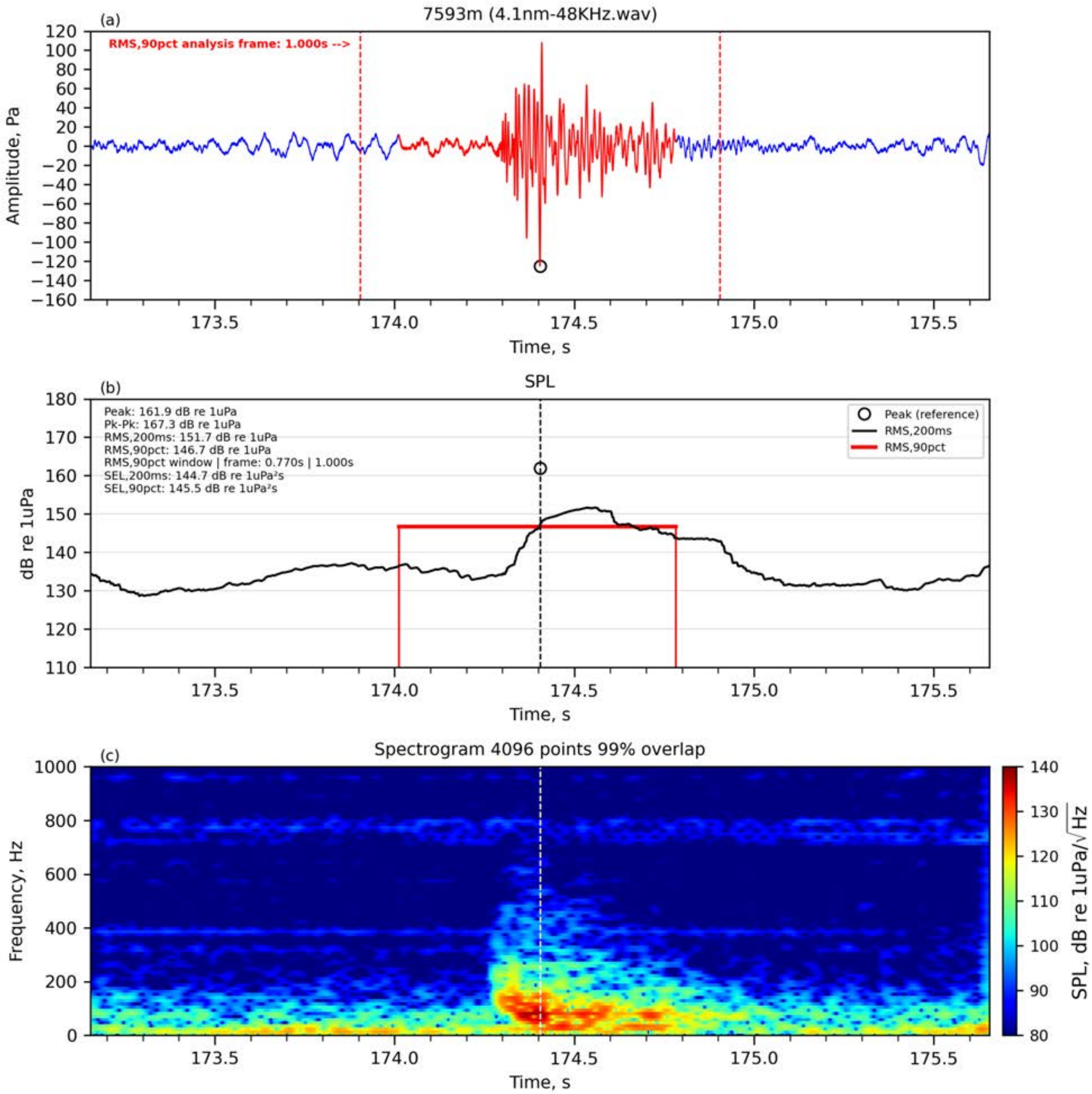


Figure 47. Unweighted sound pressure waveform, RMS levels, and spectrogram at 4.1 NM (7593 m).

Appendix D (continued).

Summary Tables

The subsequent tables encapsulate data procured from the six measurement locales during pile driving, delineated for both unweighted and weighted (LF, PW) datasets. Included metrics are "RMS_200" (200-millisecond RMS per Madsen 2005) and "RMS_90pct" (termed "RL_{90}" in Madsen 2005, and denoted as "effective signal duration" *Teff*, dB in ISO 18405 Section 3.5.1.3). Additionally, data encompass "RMS_125" (ANSI "Fast" 125-millisecond weighting) and "RMS_10dB" (-10dB 90-percent computation, termed "RL_{10dB}" in Madsen 2005, and designated as "threshold exceedance signal duration" *Ty*, dB in ISO 18405 Section 3.5.1.4).

Within these tables, "_CF" appended terms indicate the Crest Factor, defined as the ratio in decibels between peak and RMS levels. Terms suffixed with "_window_secs" refer to the RMS window duration in seconds. The "RMS_125" and "RMS_200" are computed using fixed windows of 125 and 200 milliseconds, respectively.

The "RMS_90pct" (reported as "RMS,90pct") utilizes a 1-second analysis frame, aligning with contemporary industry standards for pile driving noise monitoring [30]. The "RMS_10dB" is analyzed within a 1.5-second frame to encompass the broadest window without intersecting with adjacent peak waveforms, as the average interval between hammer blows was approximately 2 seconds and never less than 1.6 seconds. The "RMS_10dB" is calculated by identifying the furthest pre- and post-peak times at which the level in pascals is at 10 percent of the peak value (denoted as "10dB" level in Madsen 2005). The 90-percent RMS is derived by computing the RMS sum within these two time points.

Both "RMS_10dB" and "RMS_90pct" computations yield variable window lengths for each peak, contingent upon the specific impulse waveform and the acoustic conditions at the time of the peak—factors include reverberation, reflections, and pre-arrivals of early impulse energy.

At a range of 1.06 kilometers, the "RMS_10dB" computations rendered window sizes roughly equivalent to those of the "RMS_90pct". With increasing distance, the "RMS_10dB" windows expanded, occasionally reaching the 1.5-second frame limit beyond 5 kilometers.

A parallel analysis evaluated the "RMS_90pct" ("effective signal duration") within a 1.5-second frame, as used for the "RMS_10dB" ("threshold exceedance signal duration"). The deduced "RMS_90pct" levels were marginally lower (~1 dB) than those computed with a 1-second frame. Notably, the "RMS_90pct" window widths extended significantly with distance when analyzed with a 1.5-second frame, which in turn, drew down the RMS levels and steepened the propagation loss above the spherical spreading rate. These findings affirm the sensitivity of the 90-percent computation to window width selection, a central point of caution in Madsen 2005. This underscores the critical need for meticulous selection of averaging window sizes and thorough review of the resultant data to ensure the validity of acoustic impact assessments on mammalian hearing over extensive distances.

Appendix D (continued).

Table 3. Unweighted sound pressure.

NM	meters	Metric	Count	Maximum	Mean	Median	Minimum
0.57	1056	peak_dB	51	180.0	176.8	177.0	173.2
0.57	1056	peak_to_peak_dB	51	183.7	181.7	181.9	179.0
0.57	1056	RMS_125	51	170.3	169.4	169.4	168.5
0.57	1056	RMS_125_CF	51	9.7	7.4	7.6	4.5
0.57	1056	RMS_200	51	169.0	168.2	168.2	167.4
0.57	1056	RMS_200_CF	51	11.0	8.6	8.8	5.5
0.57	1056	RMS_10dB	51	166.8	164.6	164.7	162.3
0.57	1056	RMS_10dB_CF	51	14.0	12.1	12.2	10.2
0.57	1056	RMS_10dB_window_secs	51	0.741	0.494	0.477	0.315
0.57	1056	RMS_90pct	51	165.6	164.7	164.7	163.9
0.57	1056	RMS_90pct_CF	51	14.5	12.0	12.1	8.7
0.57	1056	RMS_90pct_window_secs	51	0.521	0.470	0.462	0.436
0.57	1056	SEL_125	51	161.3	160.3	160.4	159.5
0.57	1056	SEL_200	51	162.0	161.2	161.2	160.4
0.57	1056	SEL_10dB	51	162.3	161.5	161.5	160.8
0.57	1056	SEL_90pct	51	162.2	161.4	161.5	160.7

NM	meter	Metric	Pile Count	Maximum	Mean	Median	Minimum
0.86	1593	peak_dB	160	175.9	171.7	171.7	168.6
0.86	1593	peak_to_peak_dB	160	180.7	177.2	177.0	174.2
0.86	1593	RMS_125	160	166.4	164.0	164.0	162.2
0.86	1593	RMS_125_CF	160	9.6	7.7	7.8	5.9
0.86	1593	RMS_200	160	165.8	163.5	163.4	161.8
0.86	1593	RMS_200_CF	160	10.1	8.3	8.4	6.4
0.86	1593	RMS_10dB	160	162.7	159.8	159.7	157.6
0.86	1593	RMS_10dB_CF	160	16.0	12.0	12.0	9.6
0.86	1593	RMS_10dB_window_secs	160	1.178	0.651	0.655	0.454
0.86	1593	RMS_90pct	160	162.7	160.5	160.5	159.0
0.86	1593	RMS_90pct_CF	160	15.0	11.2	11.3	8.5
0.86	1593	RMS_90pct_window_secs	160	0.710	0.531	0.537	0.443
0.86	1593	SEL_125	160	157.4	155.0	155.0	153.2
0.86	1593	SEL_200	160	158.8	156.5	156.4	154.8
0.86	1593	SEL_10dB	160	159.5	157.9	157.9	156.5
0.86	1593	SEL_90pct	160	159.5	157.8	157.8	156.4

Appendix D (continued).

Table 3. Unweighted sound pressure.

NM	meter	Metric	Pile Count	Maximum	Mean	Median	Minimum
1.34	2482	peak_dB	143	172.9	169.1	169.1	166.9
1.34	2482	peak_to_peak_dB	143	177.2	174.6	174.6	172.7
1.34	2482	RMS_125	143	163.4	162.2	162.2	160.1
1.34	2482	RMS_125_CF	143	9.6	7.0	7.0	5.0
1.34	2482	RMS_200	143	162.5	161.3	161.3	159.3
1.34	2482	RMS_200_CF	143	10.8	7.9	8.0	5.9
1.34	2482	RMS_10dB	143	156.9	155.0	155.0	153.4
1.34	2482	RMS_10dB_CF	143	16.2	14.2	14.2	12.1
1.34	2482	RMS_10dB_window_secs	143	1.220	1.032	1.025	0.735
1.34	2482	RMS_90pct	143	157.4	156.3	156.4	154.8
1.34	2482	RMS_90pct_CF	143	15.9	12.8	12.8	10.2
1.34	2482	RMS_90pct_window_secs	143	0.797	0.730	0.726	0.694
1.34	2482	SEL_125	143	154.4	153.2	153.2	151.0
1.34	2482	SEL_200	143	155.5	154.3	154.3	152.4
1.34	2482	SEL_10dB	143	156.1	155.1	155.2	153.6
1.34	2482	SEL_90pct	143	156.0	155.0	155.0	153.4

NM	meter	Metric	Pile Count	Maximum	Mean	Median	Minimum
1.98	3667	peak_dB	117	168.8	166.0	165.9	162.6
1.98	3667	peak_to_peak_dB	117	174.3	171.5	171.4	167.4
1.98	3667	peak_pos_pa	117	274.379	189.758	186.886	131.485
1.98	3667	peak_neg_pa	117	-100.974	-187.547	-187.259	-244.707
1.98	3667	RMS_125	117	160.2	158.5	158.4	154.0
1.98	3667	RMS_125_CF	117	9.8	7.5	7.4	6.0
1.98	3667	RMS_200	117	159.2	157.8	157.8	152.9
1.98	3667	RMS_200_CF	117	10.4	8.2	8.1	6.9
1.98	3667	RMS_10dB	117	153.6	151.9	152.0	147.6
1.98	3667	RMS_10dB_CF	117	16.3	14.1	14.0	12.7
1.98	3667	RMS_10dB_window_secs	117	1.363	1.081	1.074	0.694
1.98	3667	RMS_90pct	117	154.7	153.4	153.4	148.8
1.98	3667	RMS_90pct_CF	117	15.0	12.6	12.5	11.1
1.98	3667	RMS_90pct_window_secs	117	0.793	0.742	0.743	0.464
1.98	3667	SEL_125	117	151.2	149.5	149.4	144.9
1.98	3667	SEL_200	117	152.2	150.8	150.9	145.9
1.98	3667	SEL_10dB	117	153.2	152.3	152.3	146.0
1.98	3667	SEL_90pct	117	153.1	152.1	152.1	145.5

Appendix D (continued).

Table 3. Unweighted sound pressure.

NM	meter	Metric	Pile Count	Maximum	Mean	Median	Minimum
3.17	5871	peak_dB	146	165.8	163.0	162.9	159.8
3.17	5871	peak_to_peak_dB	146	171.1	168.3	168.3	165.6
3.17	5871	RMS_125	146	157.2	155.4	155.5	153.3
3.17	5871	RMS_125_CF	146	9.9	7.6	7.6	5.7
3.17	5871	RMS_200	146	156.1	154.4	154.5	152.2
3.17	5871	RMS_200_CF	146	10.7	8.6	8.6	6.5
3.17	5871	RMS_10dB	146	149.4	147.6	147.6	145.6
3.17	5871	RMS_10dB_CF	146	17.8	15.4	15.5	13.5
3.17	5871	RMS_10dB_window_secs	146	1.499	1.286	1.288	0.949
3.17	5871	RMS_90pct	146	150.6	149.3	149.3	147.3
3.17	5871	RMS_90pct_CF	146	16.3	13.6	13.8	11.1
3.17	5871	RMS_90pct_window_secs	146	0.854	0.802	0.811	0.629
3.17	5871	SEL_125	146	148.2	146.4	146.5	144.3
3.17	5871	SEL_200	146	149.2	147.4	147.5	145.2
3.17	5871	SEL_10dB	146	149.9	148.7	148.6	146.8
3.17	5871	SEL_90pct	146	149.7	148.4	148.3	146.4

NM	meter	Metric	Pile Count	Maximum	Mean	Median	Minimum
4.1	7593	peak_dB	126	161.9	159.7	159.6	156.9
4.1	7593	peak_to_peak_dB	126	167.4	165.1	165.0	162.3
4.1	7593	RMS_125	126	155.0	152.3	152.3	150.0
4.1	7593	RMS_125_CF	126	9.9	7.4	7.3	5.5
4.1	7593	RMS_200	126	154.0	151.3	151.4	149.1
4.1	7593	RMS_200_CF	126	11.1	8.4	8.3	6.3
4.1	7593	RMS_10dB	126	146.3	144.4	144.4	142.3
4.1	7593	RMS_10dB_CF	126	18.2	15.3	15.3	13.3
4.1	7593	RMS_10dB_window_secs	126	1.499	1.352	1.384	1.093
4.1	7593	RMS_90pct	126	148.3	146.2	146.3	144.3
4.1	7593	RMS_90pct_CF	126	16.5	13.5	13.5	11.0
4.1	7593	RMS_90pct_window_secs	126	0.875	0.807	0.815	0.667
4.1	7593	SEL_125	126	146.0	143.2	143.3	140.9
4.1	7593	SEL_200	126	147.0	144.3	144.4	142.1
4.1	7593	SEL_10dB	126	147.5	145.7	145.7	143.8
4.1	7593	SEL_90pct	126	147.2	145.3	145.3	143.3

Appendix D (continued).

Table 4. Weighted sound pressure, LF (Cetacean).

NM	meter	Metric	Pile Count	Maximum	Mean	Median	Minimum
0.57	1056	peak_dB	51	172.7	169.1	170.2	165.0
0.57	1056	peak_to_peak_dB	51	177.3	174.0	174.5	170.8
0.57	1056	RMS_125	51	162.0	160.7	160.8	159.3
0.57	1056	RMS_125_CF	51	11.1	8.4	9.3	5.5
0.57	1056	RMS_200	51	160.9	159.5	159.6	158.2
0.57	1056	RMS_200_CF	51	12.2	9.6	10.5	6.5
0.57	1056	RMS_10dB	51	158.2	156.1	156.2	153.3
0.57	1056	RMS_10dB_CF	51	15.2	13.1	13.5	10.3
0.57	1056	RMS_10dB_window_secs	51	0.696	0.453	0.450	0.314
0.57	1056	RMS_90pct	51	157.3	156.0	156.1	154.4
0.57	1056	RMS_90pct_CF	51	15.9	13.2	14.1	10.2
0.57	1056	RMS_90pct_window_secs	51	0.498	0.454	0.451	0.421
0.57	1056	SEL_125	51	153.0	151.6	151.7	150.2
0.57	1056	SEL_200	51	153.9	152.5	152.6	151.2
0.57	1056	SEL_10dB	51	153.8	152.6	152.6	151.3
0.57	1056	SEL_90pct	51	153.7	152.5	152.6	151.3

NM	meter	Metric	Pile Count	Maximum	Mean	Median	Minimum
0.86	1593	peak_dB	160	166.6	163.6	163.7	160.3
0.86	1593	peak_to_peak_dB	160	172.0	169.1	169.0	166.0
0.86	1593	RMS_125	160	156.8	155.2	155.1	153.6
0.86	1593	RMS_125_CF	160	10.7	8.4	8.6	6.4
0.86	1593	RMS_200	160	156.6	154.5	154.4	152.6
0.86	1593	RMS_200_CF	160	11.4	9.2	9.4	6.9
0.86	1593	RMS_10dB	160	153.2	150.8	150.8	148.8
0.86	1593	RMS_10dB_CF	160	15.8	12.8	12.9	10.5
0.86	1593	RMS_10dB_window_secs	160	1.234	0.637	0.636	0.453
0.86	1593	RMS_90pct	160	153.6	151.5	151.5	149.6
0.86	1593	RMS_90pct_CF	160	14.5	12.1	12.3	9.2
0.86	1593	RMS_90pct_window_secs	160	0.651	0.531	0.533	0.448
0.86	1593	SEL_125	160	147.8	146.2	146.1	144.6
0.86	1593	SEL_200	160	149.6	147.5	147.4	145.6
0.86	1593	SEL_10dB	160	150.6	148.8	148.8	147.3
0.86	1593	SEL_90pct	160	150.5	148.7	148.7	147.2

Appendix D (continued).

Table 4. Weighted sound pressure, LF (Cetacean).

NM	meter	Metric	Pile Count	Maximum	Mean	Median	Minimum
1.34	2482	peak_dB	143	163.5	160.0	160.0	157.5
1.34	2482	peak_to_peak_dB	143	167.9	165.4	165.5	163.2
1.34	2482	RMS_125	143	153.8	152.3	152.3	150.4
1.34	2482	RMS_125_CF	143	10.2	7.7	7.7	5.9
1.34	2482	RMS_200	143	152.9	151.4	151.3	149.7
1.34	2482	RMS_200_CF	143	11.4	8.6	8.7	6.7
1.34	2482	RMS_10dB	143	147.0	145.1	145.1	143.3
1.34	2482	RMS_10dB_CF	143	16.5	14.9	14.9	13.1
1.34	2482	RMS_10dB_window_secs	143	1.308	1.045	1.026	0.730
1.34	2482	RMS_90pct	143	147.9	146.6	146.6	145.2
1.34	2482	RMS_90pct_CF	143	16.4	13.4	13.5	11.0
1.34	2482	RMS_90pct_window_secs	143	0.773	0.719	0.718	0.686
1.34	2482	SEL_125	143	144.8	143.2	143.2	141.4
1.34	2482	SEL_200	143	145.9	144.4	144.4	142.8
1.34	2482	SEL_10dB	143	146.5	145.3	145.3	144.0
1.34	2482	SEL_90pct	143	146.4	145.1	145.2	143.8

NM	meter	Metric	Pile Count	Maximum	Mean	Median	Minimum
1.98	3667	peak_dB	117	160.7	157.5	157.7	154.1
1.98	3667	peak_to_peak_dB	117	165.6	162.9	163.0	158.6
1.98	3667	RMS_125	117	151.2	149.4	149.3	145.1
1.98	3667	RMS_125_CF	117	10.6	8.1	8.1	6.4
1.98	3667	RMS_200	117	150.4	148.8	148.8	143.9
1.98	3667	RMS_200_CF	117	11.5	8.8	8.7	6.7
1.98	3667	RMS_10dB	117	144.2	142.5	142.6	137.9
1.98	3667	RMS_10dB_CF	117	17.2	15.0	15.0	13.2
1.98	3667	RMS_10dB_window_secs	117	1.364	1.119	1.107	0.790
1.98	3667	RMS_90pct	117	145.5	144.2	144.2	139.6
1.98	3667	RMS_90pct_CF	117	16.4	13.4	13.3	11.0
1.98	3667	RMS_90pct_window_secs	117	0.770	0.734	0.738	0.466
1.98	3667	SEL_125	117	142.2	140.4	140.3	136.1
1.98	3667	SEL_200	117	143.4	141.8	141.8	136.9
1.98	3667	SEL_10dB	117	143.9	143.0	143.1	136.9
1.98	3667	SEL_90pct	117	143.8	142.8	142.9	136.3

Appendix D (continued).

Table 4. Weighted sound pressure, LF (Cetacean).

NM	meter	Metric	Pile Count	Maximum	Mean	Median	Minimum
3.17	5871	peak_dB	146	158.0	154.7	154.7	150.8
3.17	5871	peak_to_peak_dB	146	163.2	160.1	160.0	156.6
3.17	5871	RMS_125	146	148.7	146.6	146.6	144.5
3.17	5871	RMS_125_CF	146	10.7	8.1	8.0	6.0
3.17	5871	RMS_200	146	147.5	145.7	145.7	143.3
3.17	5871	RMS_200_CF	146	11.7	9.0	9.0	6.9
3.17	5871	RMS_10dB	146	141.3	138.7	138.6	136.2
3.17	5871	RMS_10dB_CF	146	18.3	16.0	16.0	13.9
3.17	5871	RMS_10dB_window_secs	146	1.498	1.317	1.349	0.864
3.17	5871	RMS_90pct	146	142.1	140.6	140.5	138.3
3.17	5871	RMS_90pct_CF	146	17.4	14.1	14.1	11.6
3.17	5871	RMS_90pct_window_secs	146	0.840	0.791	0.802	0.615
3.17	5871	SEL_125	146	139.6	137.6	137.6	135.4
3.17	5871	SEL_200	146	140.5	138.7	138.7	136.3
3.17	5871	SEL_10dB	146	141.1	139.8	139.8	137.6
3.17	5871	SEL_90pct	146	140.9	139.6	139.6	137.4

NM	meter	Metric	Pile Count	Maximum	Mean	Median	Minimum
4.1	7593	peak_dB	126	154.0	151.6	151.5	148.6
4.1	7593	peak_to_peak_dB	126	159.8	157.0	156.8	154.3
4.1	7593	RMS_125	126	146.7	143.7	143.7	141.0
4.1	7593	RMS_125_CF	126	10.6	7.9	7.9	6.1
4.1	7593	RMS_200	126	145.6	142.8	142.8	140.4
4.1	7593	RMS_200_CF	126	11.8	8.8	8.8	6.9
4.1	7593	RMS_10dB	126	137.7	135.7	135.7	133.3
4.1	7593	RMS_10dB_CF	126	19.1	15.9	15.9	13.9
4.1	7593	RMS_10dB_window_secs	126	1.497	1.333	1.348	1.043
4.1	7593	RMS_90pct	126	139.9	137.7	137.8	135.4
4.1	7593	RMS_90pct_CF	126	17.1	13.8	14.0	11.6
4.1	7593	RMS_90pct_window_secs	126	0.849	0.779	0.784	0.636
4.1	7593	SEL_125	126	137.6	134.7	134.6	132.0
4.1	7593	SEL_200	126	138.6	135.8	135.8	133.4
4.1	7593	SEL_10dB	126	138.9	136.9	137.0	134.9
4.1	7593	SEL_90pct	126	138.7	136.6	136.7	134.6

Appendix D (continued).

Table 5. Weighted sound pressure, PW (Phocids).

NM	meters	Metric	Pile Count	Maximum	Mean	Median	Minimum
0.57	1056	peak_dB	51	155.8	152.5	153.5	148.2
0.57	1056	peak_to_peak_dB	51	160.8	157.4	157.9	154.1
0.57	1056	RMS_125	51	145.0	143.5	143.5	141.9
0.57	1056	RMS_125_CF	51	11.7	9.0	9.8	6.2
0.57	1056	RMS_200	51	143.8	142.3	142.4	140.8
0.57	1056	RMS_200_CF	51	12.8	10.2	10.9	7.3
0.57	1056	RMS_10dB	51	140.9	138.3	138.9	133.4
0.57	1056	RMS_10dB_CF	51	16.8	14.2	14.5	11.8
0.57	1056	RMS_10dB_window_secs	51	1.248	0.516	0.461	0.313
0.57	1056	RMS_90pct	51	139.6	138.0	138.0	135.9
0.57	1056	RMS_90pct_CF	51	17.5	14.5	15.3	11.3
0.57	1056	RMS_90pct_window_secs	51	0.646	0.540	0.529	0.450
0.57	1056	SEL_125	51	136.0	134.5	134.5	132.9
0.57	1056	SEL_200	51	136.8	135.3	135.4	133.8
0.57	1056	SEL_10dB	51	136.6	135.3	135.3	134.0
0.57	1056	SEL_90pct	51	136.6	135.3	135.4	134.0

NM	meters	Metric	Pile Count	Maximum	Mean	Median	Minimum
0.86	1593	peak_dB	160	149.4	147.0	147.2	144.0
0.86	1593	peak_to_peak_dB	160	155.4	152.5	152.5	149.8
0.86	1593	RMS_125	160	139.5	138.0	137.9	136.5
0.86	1593	RMS_125_CF	160	11.4	9.0	9.1	7.1
0.86	1593	RMS_200	160	139.1	137.2	137.0	135.5
0.86	1593	RMS_200_CF	160	12.2	9.8	10.0	7.7
0.86	1593	RMS_10dB	160	134.6	131.6	131.5	129.0
0.86	1593	RMS_10dB_CF	160	18.8	15.4	15.2	12.6
0.86	1593	RMS_10dB_window_secs	160	1.495	1.045	0.989	0.544
0.86	1593	RMS_90pct	160	135.1	133.4	133.4	132.0
0.86	1593	RMS_90pct_CF	160	16.2	13.6	13.8	11.5
0.86	1593	RMS_90pct_window_secs	160	0.753	0.652	0.660	0.554
0.86	1593	SEL_125	160	130.5	129.0	128.9	127.5
0.86	1593	SEL_200	160	132.2	130.2	130.1	128.5
0.86	1593	SEL_10dB	160	133.3	131.6	131.6	130.1
0.86	1593	SEL_90pct	160	133.2	131.5	131.5	130.0

Appendix D (continued).

Table 5. Weighted sound pressure, PW (Phocids).

NM	meters	Metric	Pile Count	Maximum	Mean	Median	Minimum
1.34	2482	peak_dB	143	146.3	143.1	143.1	140.9
1.34	2482	peak_to_peak_dB	143	150.8	148.6	148.6	146.6
1.34	2482	RMS_125	143	136.3	134.7	134.7	133.0
1.34	2482	RMS_125_CF	143	10.9	8.4	8.4	6.7
1.34	2482	RMS_200	143	135.3	133.9	133.8	132.4
1.34	2482	RMS_200_CF	143	11.8	9.3	9.3	7.5
1.34	2482	RMS_10dB	143	127.7	126.3	126.3	125.1
1.34	2482	RMS_10dB_CF	143	19.0	16.8	16.9	14.8
1.34	2482	RMS_10dB_window_secs	143	1.500	1.472	1.489	1.179
1.34	2482	RMS_90pct	143	130.2	128.9	129.0	127.6
1.34	2482	RMS_90pct_CF	143	17.0	14.2	14.2	12.1
1.34	2482	RMS_90pct_window_secs	143	0.812	0.766	0.765	0.721
1.34	2482	SEL_125	143	127.2	125.7	125.7	124.0
1.34	2482	SEL_200	143	128.4	126.9	126.8	125.4
1.34	2482	SEL_10dB	143	129.1	128.0	128.0	126.9
1.34	2482	SEL_90pct	143	128.9	127.8	127.8	126.6

NM	meters	Metric	Pile Count	Maximum	Mean	Median	Minimum
1.98	3667	peak_dB	117	144.1	141.1	141.1	138.3
1.98	3667	peak_to_peak_dB	117	149.0	146.5	146.5	144.0
1.98	3667	RMS_125	117	134.0	132.1	132.1	128.3
1.98	3667	RMS_125_CF	117	15.3	9.0	8.9	7.3
1.98	3667	RMS_200	117	133.1	131.6	131.6	127.1
1.98	3667	RMS_200_CF	117	16.4	9.5	9.5	7.8
1.98	3667	RMS_10dB	117	125.3	124.4	124.5	122.1
1.98	3667	RMS_10dB_CF	117	21.5	16.7	16.5	14.6
1.98	3667	RMS_10dB_window_secs	117	1.500	1.487	1.498	0.741
1.98	3667	RMS_90pct	117	127.9	126.8	126.8	123.2
1.98	3667	RMS_90pct_CF	117	20.3	14.3	14.2	12.3
1.98	3667	RMS_90pct_window_secs	117	0.821	0.792	0.796	0.446
1.98	3667	SEL_125	117	124.9	123.1	123.1	119.2
1.98	3667	SEL_200	117	126.2	124.6	124.6	120.1
1.98	3667	SEL_10dB	117	127.1	126.2	126.2	120.8
1.98	3667	SEL_90pct	117	126.7	125.8	125.9	119.7

Appendix D (continued).

Table 5. Weighted sound pressure, PW (Phocids).

NM	meters	Metric	Pile Count	Maximum	Mean	Median	Minimum
3.17	5871	peak_dB	146	141.2	138.4	138.2	136.1
3.17	5871	peak_to_peak_dB	146	146.5	143.8	143.7	141.4
3.17	5871	RMS_125	146	131.4	129.5	129.4	127.8
3.17	5871	RMS_125_CF	146	11.6	8.9	8.9	6.9
3.17	5871	RMS_200	146	130.3	128.6	128.5	127.1
3.17	5871	RMS_200_CF	146	12.2	9.8	9.8	7.8
3.17	5871	RMS_10dB	146	123.0	121.6	121.6	120.4
3.17	5871	RMS_10dB_CF	146	19.8	16.8	16.8	14.9
3.17	5871	RMS_10dB_window_secs	146	1.500	1.494	1.499	1.062
3.17	5871	RMS_90pct	146	125.0	123.6	123.6	122.6
3.17	5871	RMS_90pct_CF	146	17.6	14.7	14.8	13.1
3.17	5871	RMS_90pct_window_secs	146	0.862	0.831	0.833	0.655
3.17	5871	SEL_125	146	122.4	120.4	120.4	118.8
3.17	5871	SEL_200	146	123.4	121.6	121.5	120.1
3.17	5871	SEL_10dB	146	124.7	123.3	123.3	122.2
3.17	5871	SEL_90pct	146	124.2	122.8	122.8	121.7

NM	meters	Metric	Pile Count	Maximum	Mean	Median	Minimum
4.1	7593	peak_dB	126	137.3	135.1	135.1	132.2
4.1	7593	peak_to_peak_dB	126	143.1	140.5	140.5	138.0
4.1	7593	RMS_125	126	129.4	126.5	126.4	123.8
4.1	7593	RMS_125_CF	126	11.2	8.6	8.5	6.7
4.1	7593	RMS_200	126	128.3	125.6	125.6	123.2
4.1	7593	RMS_200_CF	126	12.4	9.5	9.4	7.8
4.1	7593	RMS_10dB	126	120.2	118.4	118.4	116.6
4.1	7593	RMS_10dB_CF	126	19.6	16.7	16.8	14.8
4.1	7593	RMS_10dB_window_secs	126	1.500	1.497	1.498	1.476
4.1	7593	RMS_90pct	126	122.6	120.6	120.6	118.5
4.1	7593	RMS_90pct_CF	126	17.5	14.5	14.5	12.6
4.1	7593	RMS_90pct_window_secs	126	0.853	0.816	0.817	0.764
4.1	7593	SEL_125	126	120.3	117.5	117.4	114.8
4.1	7593	SEL_200	126	121.3	118.6	118.6	116.2
4.1	7593	SEL_10dB	126	121.9	120.1	120.2	118.3
4.1	7593	SEL_90pct	126	121.6	119.7	119.7	117.8