UNITED STATES DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NATIONAL MARINE FISHERIES SERVICE
Northwest Region
7600 Sand Point Way NE
Seattle, Washington 98115

Memorandum

To: Interested Parties

From: NMFS Northwest Region and Northwest Fisheries Science Center

Subject: Guidance Document: Data Collection Methods to Characterize Impact and Vibratory Pile Driving Source Levels Relevant to Marine Mammals

Date: January 31, 2012

Objectives: Provide guidance to characterize underwater pile driving source levels relevant to marine mammals.

Scope: This guidance is applicable to pile driving activities in the Northwest Region, specifically for use in marine mammal consultations and permit applications, pursuant to the Endangered Species Act (ESA) and the Marine Mammal Protection Act (MMPA). These measurements should take into account spectral, spatial, temporal and sample size considerations, as specified below. Equipment considerations and guidance on data processing are also provided.

Guidance:

Spectral considerations

For purposes of characterizing pile driving source levels relevant to marine mammals, analysis of collected data should eliminate frequencies below the range of functional hearing of marine mammals (described in Southall et al. 2007). The list below identifies common species that occur in inland waters of Washington State by functional hearing group.

Common marine mammal species that occur in inland waters of Washington State:

- Low-frequency cetaceans: humpback, gray and minke whales
- Mid-frequency cetaceans: killer whales (resident and transient)
- High-frequency cetaceans: harbor and Dall's porpoises
- Pinnipeds: Steller and California sea lions, harbor seals, and northern elephant seals

For pile driving, the majority of the acoustic energy is confined to frequencies below 2 kHz (Reinhall and Dahl 2011), whereas above 20 kHz there is very little acoustic energy from either impact or vibratory pile driving (as documented below in Appendix A), and between these two bounds there exists a small but largely negligible contribution. Therefore, 20 kHz provides a robust high-frequency limit (f-high) for measuring all pile driving source levels, whereas the low-frequency limit (f-low) should be defined by the estimated auditory bandwidth for each functional hearing group (Table 1).

There should be no attenuation in the band between f-low and f-high for the appropriate functional hearing groups listed in Table 1. The roll-off below f-low and above f-high should be as steep as possible and at a rate of at least -40 dB/decade (a decade is a factor of 10 in frequency) after f-low and f-high.

Table 1. F-low and f-high limits for characterizing underwater background sound relevant to marine mammals.

Functional hearing Group[1]	f-low[2]	f-high[3]
Low-frequency cetaceans	7 Hz	20 kHz
Mid-frequency cetaceans	150 Hz	20 kHz
High-frequency cetaceans	200 Hz	20 kHz
Pinnipeds	75 Hz	20 kHz

[1] See the above list of common species that occur in nearshore waters of Washington and Oregon, which identifies species to functional hearing groups. All genera represented in each functional hearing group are specified in Southall et al. 2007.
[2] F-low values of estimated auditory bandwidths in Southall et al. 2007.
[3] As documented in the Appendix A below.

Spatial considerations

A measurement range of 10 m from the pile driving activity is consistent with established practice, and there is certain value in continuing with this practice as results are readily comparable with past measurements. However, if the primary intent of this measurement is to serve as a close-range datum with which to estimate sound pressure at much longer ranges through use of propagation modeling, then the range for this close-range datum should be not less than 3 H, where H is water depth. This range will provide a more accurate estimate at longer ranges; physical reasons for this are discussed in Reinhall and Dahl (2011). The measurement depth should be 70-85% of H to provide the most consistent results (Appendix B).

Temporal considerations

Measurements should be collected during active pile driving. Measure the whole pile-driving event, but during data analysis only characterize the periods of maximum hammer energy. Maximum hammer energy is characterized by removing starts (ramp up of hammer energy) and stops (ramp down of hammer energy) from data being analyzed. Also, remove data collected during sound attenuation and transition periods associated with sound attenuation. For example, if a bubble curtain is used, remove data when bubbles are first turned on and after they become fully effective, as well as periods when bubbles are turned off and bubbles have not completely been removed from the water column. Bubbles can remain in the water column after the bubble curtain has been turned off at the source and therefore will interfere with source measurements up to ~one minute after the bubble curtain is turned off (Coleman 2011). Data collected during sound attenuation (i.e., when bubbles are fully effective) can be analyzed separately to determine the effectiveness of attenuation methods.

Sample size considerations

Characterize a representative number of pile driving events for each project. One whole pile driving event is characterized as one sample. Vibratory pile driving events should be considered separately from impact pile driving events. Where possible, it is beneficial to have repeat sampling for each of the following considerations: pile size (diameter) and type (e.g., wood, concrete, steel), which are likely to have greatest influence on source level (Carlson 2007). Other considerations also likely to affect source levels include bathymetry, substrate type, distance from shore, water depth, and hammer energy. Record and report these variables. Repeated sampling will help characterize variability.

Data processing

For each functional hearing group, measurements should be reported in overall SPL across the entire frequency band (referred to as “broad band SPL”, and defined as the decibel equivalent of the rms pressure within the frequency band, referenced to 1 μPa). Different data processing is required to characterize source levels for vibratory pile driving than for impact driving. For vibratory pile driving, characterize overall dBrms levels by taking 10 sec averages across the whole event and averaging all the 10 sec periods. Averaging 10 sec periods will likely capture the variation in sound levels over the pile-driving event. For impact pile driving, characterize overall dBrms levels by integrating sound for each waveform across 90% of the acoustic energy in each wave (using the 5-95 percentiles to establish the 90% criterion) and averaging across all waves in the pile-driving event (i.e., as demonstrated in Figure 1 of Madsen et al. 2006).

Equipment considerations

The recording system must be capable of recording the minimum bandwidth required per above frequency considerations (Table 1). Receiving sensitivities should be sufficient to measure very high acoustic pressures. This device will have different receiving sensitivity than the device used for background sound monitoring (NMFS 2011). For close-range (~10 m) measurements, it can be expected that peak pressures can reach as high as 10^5 Pa, which is equivalent to 220 dB re: 1 μPa. Therefore, document that hydrophone sensitivities and associated electronic recording networks (e.g., amplifier gains, digital recording ranges) are able to measure this large signal without distortion.

Applicability to other areas

Pile size and type are probably the most important factors affecting sound levels from pile driving, whereas wetted depth (a typical surrogate for water depth) is not very predictive of sound levels (Carlson 2007). Therefore, when data cannot be collected and you must instead estimate a source level for use in consultation or permit application, the best surrogate will have the following characteristics in common with the proposed project: pile size and type (most important), as well as bottom substrate, water depth and hammer energy.

References

Carlson, Thomas J. and Mark A. Weiland. 2007. Dynamic Pile Driving and Pile Driving Underwater Impulsive Sound. WA-RD 673.1. June 2007.

Coleman, James. 2011. Columbia River Crossing test pile project, hydroacoustic monitoring final report. David Evans and Associates, Inc.

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

NMFS. 2011. Guidance Document: Data Collection Methods to Characterize Underwater Background Sound Relevant to Marine Mammals in Coastal Nearshore Waters and Rivers of Washington and Oregon. Memorandum from NMFS Northwest Region and Northwest Fisheries Science Center to Interested Parties.

Reinhall, P.G., and P. H. Dahl. 2011. Underwater Mach wave radiation from impact pile driving: theory and observation. Journal of the Acoustical Society of America 130: 1209-1216.

Southall, B.L., A.E. Bowles, W.T. Ellison, J.J Finneran, R.L. Gentry, C.R. Greene, D. Kastak, D.R. Ketten, J.H. Miller, P.E. Nachtigall, W.J. Richardson, J.A. Thomas, and P.L Tyack. Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations. Aquatic Mammals 33(4): 411-521.

Acknowledgements
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Appendix A.

Dr. Peter H. Dahl, University of Washington

Fig. A1 shows the energy spectral density from both impact and vibratory pile driving, integrated over frequency in a cumulative manner and normalized to give a cumulative distribution function (CDF) over frequency. Such a CDF function asymptotes to 1 or 100%, and the plots indicate that the majority of the energy from both impact and vibratory pile driving is confined to frequencies less than about 2 kHz, as the CDF is approaching 1 at this frequency. The vibratory pile driving data are from the study conducted at the Port Townsend Ferry terminal in October 2010 (Stockham et al. 2011, Laughlin, 2010), and the impact pile driving data are from a re-evaluation of results from Reinhall and Dahl (2012); in this case a depth- averaged energy spectral density is used to compute the CDF. It is evident that for both impact and vibratory pile driving that an upper frequency of 20 kHz is entirely sufficient to adequately characterize the frequency distribution.

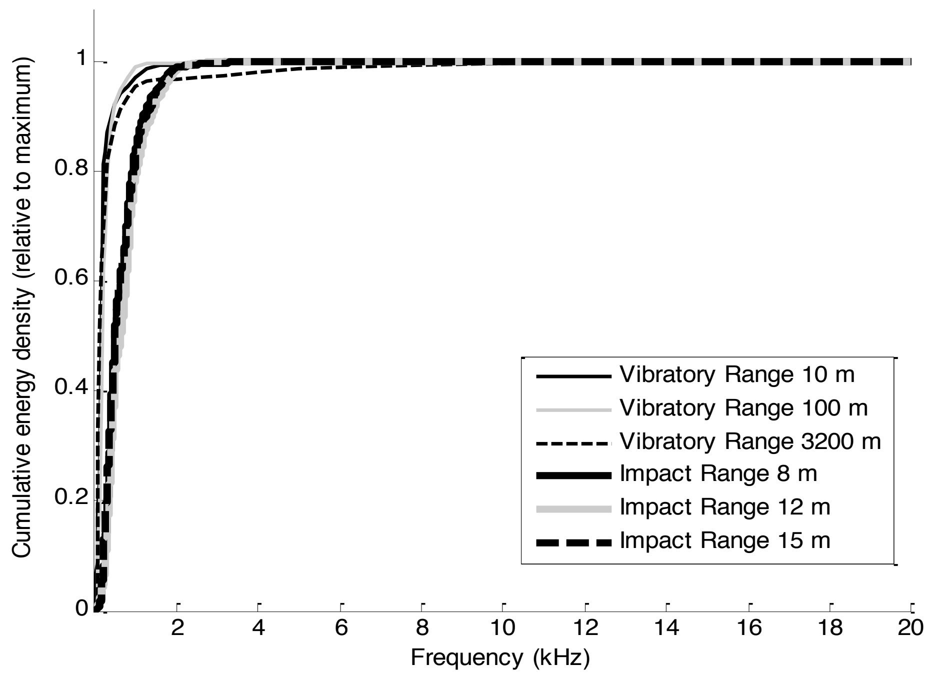

Fig. A1: Cumulative energy relative to maximum based on integration of a energy spectral density for vibratory pile driving from the Port Townsend experiment and impact pile driving from the Vashon Island experiment.

<u>References</u>

Reinhall, P.G., and P. H. Dahl. 2011. Underwater Mach wave radiation from impact pile driving: theory and observation. Journal of the Acoustical Society of America 130: 1209-1216.

Stockham, M.L., P.H. Dahl, and P.G. Reinhall. 2011 Underwater Sound Measurements During Vibratory Pile Driving at Port Townsend, WA.

Appendix B.

Dr. Peter H. Dahl, University of Washington

For purposes of obtaining a measure of pressure near the source of both impact and vibratory pile driving, deploy the hydrophone at a depth representing 0.70 H to 0.85 H, where H is the water depth. Close range measurements are typically made at nominal range of 10 m, however if the primary intent of this measurement is to estimate pressure at long range then the close-range measurement should be at ranges not less than 3 H.

Fig. B1 shows computed peak pressure from impact pile driving for several different combinations of hydrophone depth and hydrophone range. The actual values for peak pressure are consistent with measured results given in Reinhall and Dahl (2011). The combinations are scaled according to depth of hydrophone (D) divided by water depth (H), as shown in the legend, and by range of hydrophone from the pile divided by D as identified in the x-axis. Thus, for example, D/H = 1 represents a series of hypothetical measurements with the hydrophone on the bottom, and D/H = 0.5 represents similar set of measurements with hydrophone at mid-depth.

It is clear from the figure that pressures represented by D/H = 1 are always greater than D/H = 0.5, with this situation being in effect out to ranges of nearly 4 water depths. This is consistent with Reinhall and Dahl (2011) where it is shown that the maximum pressure occurs near the bottom for relatively close ranges on the scale of the water depth. Furthermore, a more representative average "peak pressure" is obtained by averaging from mid-water to the bottom. This is shown in Fig. B1 by the line consisting of symbols.

For the analyst who will make a measurement at just *one* depth, what is the depth that best represents this average? From Fig. B1, this depth is 0.85 times the water depth H. However, changing the water depth H will change this value to a small degree and simulations similar to that shown in Fig. B1 involving a range of expected pile driving water depths from 6 – 13 m suggest a guidance of 0.7 H to 0.85 H provides reasonably consistent values of peak pressure.

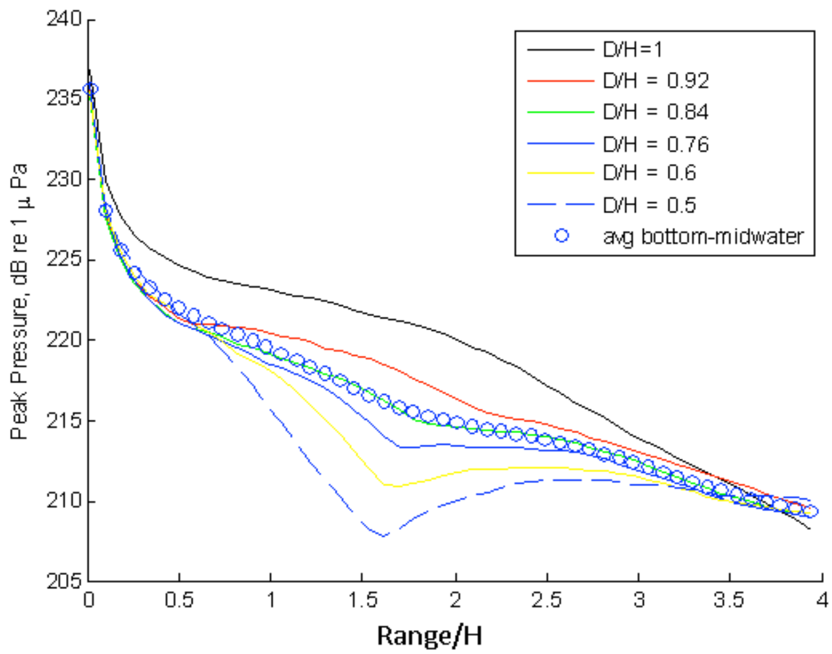

Fig. B1: Peak acoustic pressure as a function of range scaled by water depth (H), and as a function of measurement depth (D) scaled by H. The line of symbols represents an average from mid-water to bottom.

References

Reinhall, P.G., and P. H. Dahl. 2011. Underwater Mach wave radiation from impact pile driving: theory and observation. Journal of the Acoustical Society of America 130: 1209-1216.