THE IMPACT OF PILE DRIVING NOISE ON NORTH ATLANTIC RIGHT WHALE DETECTION USING COHERENTLY BEAMFORMED HYDROPHONE ARRAYS

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Abstract:
Measurements of radiated noise from offshore wind construction activity were collected on four bottom-mounted hydrophone arrays during May-August 2024 on the southern New England continental shelf. Calibrated source operations using a J-13 acoustic projector were conducted after completion of construction in September 2024 to quantify North Atlantic right whale (NARW) upcall detector-classifier performance and measure transmission loss at the site. Comparison of 32-channel array and omni-directional hydrophone detection performance reveals a nearly four-fold detection range advantage for the array in this 17logR TL environment. The calibrated source results were then used to validate the hypothesis that NARW upcall detection is a narrowband, rather than broadband, detection problem—the effective noise bandwidth (ENBW) employed in the sonar equation is linked to the mean instantaneous bandwidth of the upcall, empirically determined to be 12 Hz for a recognition differential of 5.5 dB. This finding has important implications for extrapolation of upcall detection performance models to new noise environments. Measurements of pile driving noise power spectra and array gain in third octave bands, as well as beam noise bearing dependence during pile driving, will be presented. These noise measurements, coupled with the narrowband ENBW definition, are then employed to predict upcall detection range for an array in the presence of pile driving.

Keywords: *Pile driving noise, offshore wind, hydrophone array, beamforming, passive sonar, performance metrics,*

INTRODUCTION

Analysis is presented of bottom-mounted hydrophone array measurements of pile driving radiated noise collected in May through August 2024 during Orsted's Revolution Wind construction project. The site and array laydown, located in US continental shelf waters off southeastern Massachusetts, is shown in Figure 1. This is an ecologically sensitive location and seasonal habitat for the endangered North Atlantic right whale. Acoustic data was collected on a ThayerMahan SeaPicket system[1] instrumented with a 32-channel hydrophone array and embedded digital signal processor. This paper decomposes radiated noise analysis of pile driving into "during strike" and "between strike" intervals and describes detection performance modelling for the NARW upcall that emphasizes the worst case "during strike" noise levels. It is well known that pile driving noise is quite loud. For example, even with bubble curtain noise mitigation,[2] median omni-directional hydrophone noise spectrum levels in the third octave band centered at 125 Hz measured more than 120 dB re 1μPa//Hz during the hammer strike at a range of 7 km from the noise source. The single hydrophone exposed to such a noise level is left completely masked and unable to detect all but the nearest vocalizing baleen whales. By comparison, median beam noise spectrum levels at the beamformer output for the same third octave band during the hammer strike were observed to be lower than 90 dB re 1μPa//Hz, illustrating that array gain, or spatial noise rejection, of more than 30 dB is achievable in such a highly anisotropic noise field. The analysis will show that coherent beamforming restores the desired upcall detection performance, i.e., detection ranges in excess of 10 km, for large angular sectors steered away from the line-of-sight (LOS) to the monopile in noise conditions that leave the hydrophone blanked. This is of particular importance to passive acoustic monitoring (PAM) during conditions of low visibility or at nighttime, when visual observation is typically impaired.

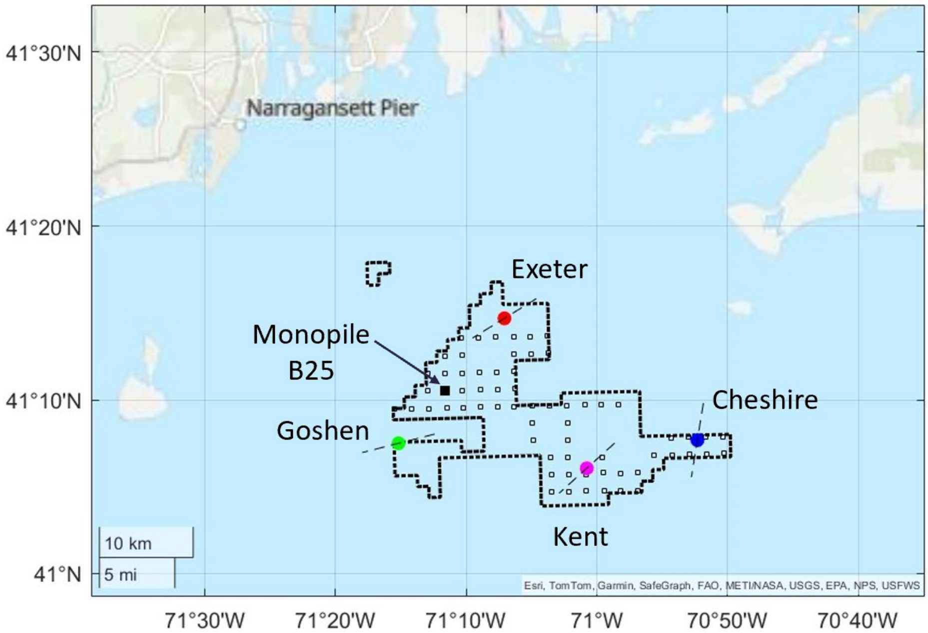

Figure 1 Revolution Wind lease area off southeastern Massachusetts. Lease area boundary denoted in black. Monopile locations denoted with black squares. Positions of the four bottom-mounted SeaPicket arrays deployed from May-August 2024 are indicated: Goshen (green), Exeter (red), Cheshire (blue), and Kent (magenta). For each array, orientation is denoted by dashed blue line.

METHOD

The passive acoustic sensing system used to support this work was the ThayerMahan SeaPicket system[1] comprised of a bottom-mounted hydrophone array tethered to a surface buoy instrumented with an embedded digital signal processor (DSP) and BGAN satellite communications modem. Figure 2(a) shows the SeaPicket surface expression after deployment. Fig. 2(b) depicts the sensor, a 32-channel, low-power, hydrophone array built by Raytheon Missiles and Defense (RMD) in Portsmouth, RI. Hydrophones are omni-directional and uniformly spaced at one half-wavelength for a design frequency of 625 Hz, or 1.2 m spacing, and 37.2 m total aperture length. Element data is digitized with 24-bit precision at a sample rate of 2.5 kHz.

Figure 2 SeaPicket system: (a) Surface buoy with satellite comms and solar panels, and (b) 32-channel hydrophone array

The real-time passive sonar processing architecture consists of a fast Fourier transform (FFT) followed by a frequency domain conventional beamformer.[3] Beam response is normalized to ensure distortionless response to an incident plane wave signal. Element data are Hanning shaded for reduced sidelobe response. All hydrophones are calibrated, and hydrophone sensitivity and preamp gain are used to support real-time reporting of ambient noise levels and received levels of signals of interest in absolute levels. Following the beamformer, detection and classification are performed using a "binarized" implementation of a spectrogram correlator that compares a candidate spectrogram feature to members of a "kernel library" to produce a confidence or similarity score.[4] The NARW upcall classifier operating point was programmed for a false alarm rate (FAR) of 1 per hour. The binarized spectrogram correlator runs in real-time, processing 32 beams concurrently at a frequency resolution of 3.9 Hz and an update rate of 64 milliseconds. For more detail on the sensor and processing, the reader is referred to [3].

RESULTS

To quantify the effect of pile driving noise on the performance of the North Atlantic right whale detector-classifier using a passive sonar equation reconciliation, it is best to process the array data through the lens of the real-time, spectrogram-correlator algorithm. This means using a FFT length, percentage overlap, and update rate that support a temporal granularity capable of resolving short duration (~100 ms) broadband transient signals. Thus, the DSP processing parameters used for this analysis are: df = 3.938 Hz (window corrected bin width of 5.89 Hz), OL = 75%, and dT = .0634 s. Representative noise power spectrum measurements for one of the arrays (Goshen) deployed at a range of 7 km to monopile B25 installed on 27 July 2024 are shown in Figure 3. The results are reported for the median frequency bin and median beam in each of 12 third-octave bands (although not in third octave band levels), partitioned into "during strike" and "between strike" intervals. To facilitate comparison to Wenz historical observations, the median noise levels are corrected to noise spectrum level (i.e., units of dB re 1μPa^2//Hz).

The data in Fig. 3 confirms what is already well known, radiated noise from the hammer strike is very loud. Even with the bubble curtain noise mitigation in place, at a range of 7 km—roughly 65 dB transmission loss (TL) in this 17logR environment—peak median noise spectrum levels approach 130 dB re 1μPa//Hz at 100 Hz, the bottom of the NARW upcall support band. Strike noise is also seen to exhibit a strong frequency dependence, with levels decaying rapidly above 100 Hz—this has important implications for PAM as much of the frequency support for the North Atlantic right whale upcall lies in the band 100-250 Hz.

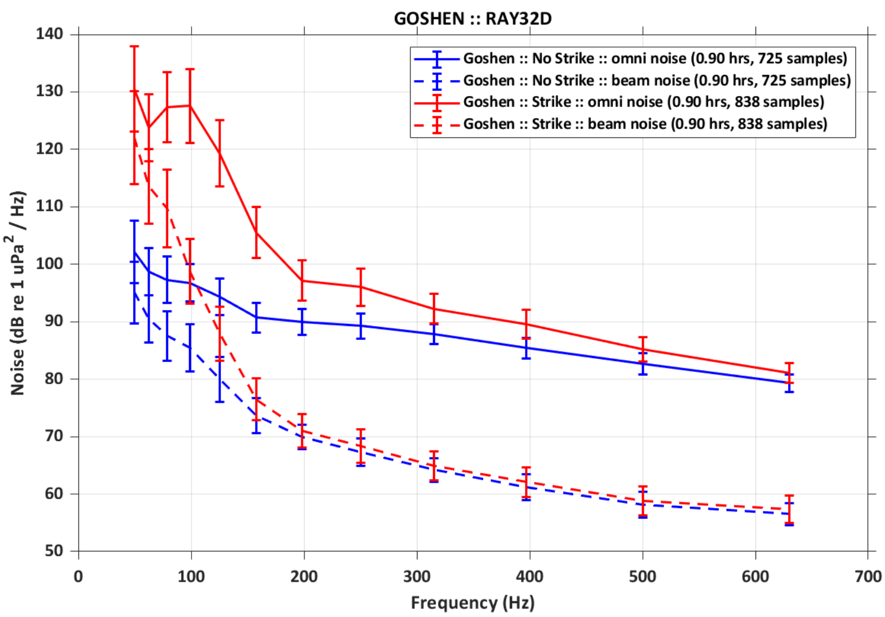

Figure 3 Noise power spectrum observed at array Goshen on 27 July 2024. Goshen is 7 km distance from the monopile, B25. Results are reported for the median frequency bin in third octave band, and median beam for the case of the beamformer output. Observations are partitioned into "strike" and "between strike" intervals. Sample size N ≅ 800.

At the center of the upcall support band, at a frequency of 150 Hz, the median omni noise spectrum level measures 105-115 dB re 1μPa//Hz, compared to a median beam noise spectrum level of 76-84 dB re 1μPa//Hz. It will be shown below that a beam noise spectrum level in the mid-80s dB//Hz, after the appropriate correction to in-band noise level, is enough to support a detection range more than 10 km in this 17logR TL environment.

Figure 4 shows the corresponding measured array gain (AG) on all four arrays during the same monopile event, B25, on 27 July 2024. Of particular note is the array gain during the hammer strike, which measures more than 25 dB over most of the array operating band at

Goshen, which is the closest of all four arrays to the monopile. In fact, measured array gain on all four arrays is observed to be well in excess of directivity index (gray line in Fig. 4), or $10\log(2L/\lambda)$ where L is the aperture length and λ is acoustic wavelength. This attests to the degree of anisotropy in this construction noise environment.

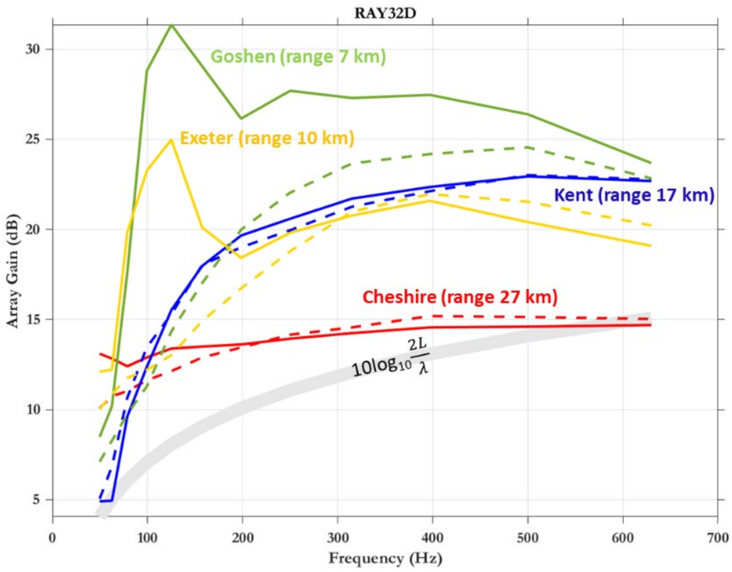

Figure 4 Measured array gain observed for monopile B25 on 27 July 2024 for all four arrays depicted in Fig. 1. Ranges of the pile to Goshen (green), Exeter (yellow), Kent (blue), and Cheshire (red), are 7 km, 10 km, 17 km, and 27 km, respectively.

To examine the detection performance impact of beamformer response to pile driving noise, it is necessary to first address the issue of in-band noise definition and the question of whether NARW upcall detection, and perhaps baleen whale detection generally, is a broadband or narrowband detection problem. On September 4, 2024, calibrated source operations using a J-13 acoustic projector were conducted at the Revolution Wind site after the completion of construction operations to quantify right whale upcall detector-classifier performance and measure *in-situ* transmission loss. Source operations were conducted at range offsets of 1, 2, 4, 6, and 8 NM at a source level of 160 dBrms re 1μPa @ 1 m.

Source testing revealed two important findings. First, comparison of the 32-channel array and omni-directional hydrophone detection performance revealed a 3.6x detection range advantage for the array, consistent with a roughly 10 dB of array gain observed in this 17logR TL environment. Second, the results showed that accurate interpretation of detector performance must occur at the instantaneous Fast Fourier Transform (FFT) frame level, recognizing that the effective noise bandwidth (ENBW) driving the detection decision is defined by the instantaneous upcall bandwidth.[5] Analysis of over 1500 upcall detection events conducted that day, as well as 4,090 exemplars from the DCLDE 2013 St. Andrews database,[6] showed that the instantaneous bandwidth of the upcall can vary from 8-30 Hz depending on SNR. The instantaneous bandwidth corresponding to a recognition differential of 5.5 dB (see discussion below) was determined to be approximately 12 Hz. Passive sonar equation analysis was used to show that the narrowband noise model based on an ENBW of 12 Hz accurately predicted the measured detection performance of the spectrogram correlator, while the broadband noise model (40-400 Hz) overestimated the applicable in-band noise level and thus severely underpredicted performance.[5] This finding has important implications for extrapolation of upcall detection performance models to new noise environments such as pile driving and is employed in the noise analysis that follows.

Measurements of in-band (12 Hz) beam noise during monopile installation were made on all four arrays throughout the 4-month construction period. Figure 5 shows one such example for monopile B39 which was installed on 1 July 2024—this monopile was chosen due to its central location. The lefthand panel depicts a representative snapshot of in-band beam noise contours for Goshen (green), Exeter (red), Kent (magenta), and Cheshire (blue) during a hammer strike. The noise level reticule dynamic range is 75-115 dB re μPa in 10 dB steps.

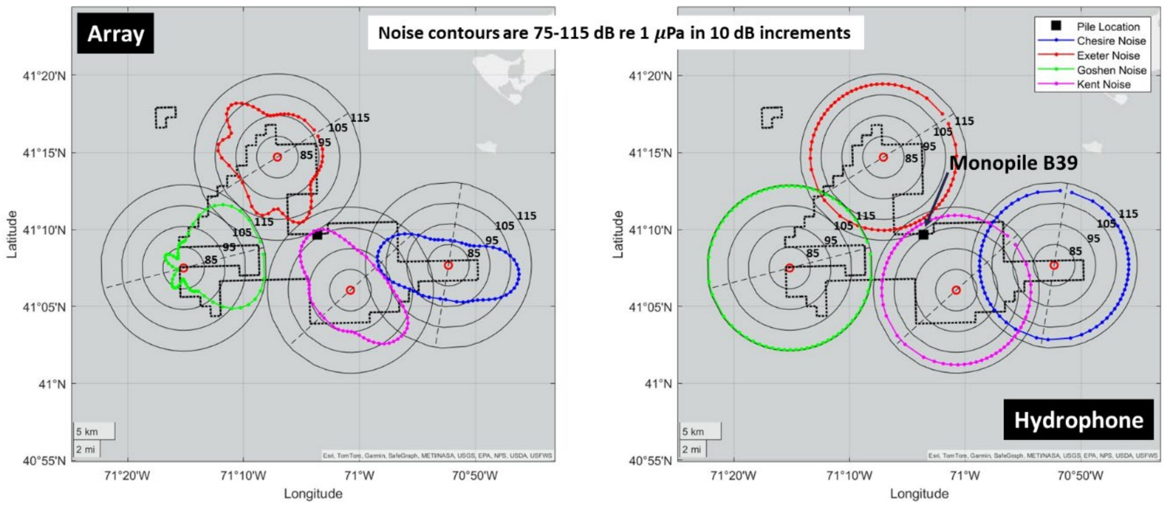

Figure 5 Measured in-band (12 Hz) beam and omni noise distributions during the hammer strike for monopile event B39 at 1500 GMT on 1 July 2024.

In-band noise level was calculated using an incoherent average of noise level in a 5.9 Hz window-corrected frequency bin over the support band 98-248 Hz. Empirical analysis has shown this to be the band for which the spectrogram correlator derives most of its positive performance. The incoherent average noise level in a 5.9 Hz band was then corrected for the 12 Hz ENBW of the spectrogram correlator detection decision. The righthand panel of Fig. 5 shows the corresponding omni-directional hydrophone noise contours taken from channel 16 of the array. Notice that the peak beam noise response for each array is equal to that of the omni-directional hydrophone and is closely aligned with the line-of-sight (LOS) to the monopile. For directions away from the monopile LOS however, the noise level is significantly reduced. This is the performance benefit of array gain. More precisely, array gain is the ratio of the area subtended by the hydrophone noise response to that of the beam noise response. The more anisotropic the noise distribution, the greater the benefit of the coherently beamformed array for acoustic detection.

Following Cox,[6] the passive sonar equation, given in (1), is typically expressed in terms of the figure of merit (FOM), which is defined as the maximum transmission loss that can be tolerated by a system and still maintain the desired receiver operating point:

$$FOM = TL = SL - (NL - AG) - NRD \quad (1)$$

where SL is the source level, NL is the in-band noise level at the hydrophone output, AG is the array gain, and NRD is the recognition differential, respectively. As reported previously,[3] the NRD of the ThayerMahan spectrogram correlator implementation has been empirically determined to be 5.5-6 dB for 50% Pd at a false alarm rate of 1 per hour.

Substituting the measured noise power spectrum results of Fig. 3 into eq. (1), it is straightforward to show that array gain against the hammer strike can yield a detection range of 10 km in this 17logR TL spreading loss environment. At an upcall source level of 170 dBrms re 1μPa @ 1 m, a coherently beamformed hydrophone array needs to deliver a beam noise spectrum level in the mid-80s dB re 1μPa//Hz, as shown in Fig. 3, or an in-band beam noise level of mid-90s re 1μPa in a 12 Hz band, in order to realize a detection range in excess of 10 km (e.g., 170 – 96 – 6 = 68 and $10^{68/17}$ = 10 km).

Further, used in conjunction with a transmission loss model, bearing-dependent measurements of beam noise can be substituted for the (*NL-AG*) term in (1) to extrapolate NARW upcall detection performance to the case of a realistic pile driving noise environment. Figure 6 depicts modelled detection performance contours for monopile B39 on 1 July 2024 for the four arrays corresponding to the measured beam noise contours shown in Fig. 5. This is not a uniformly worst-case hammer strike FFT frame, but a representative one. Here the reticule dynamic range is 0-10 km in 2.5 km steps.

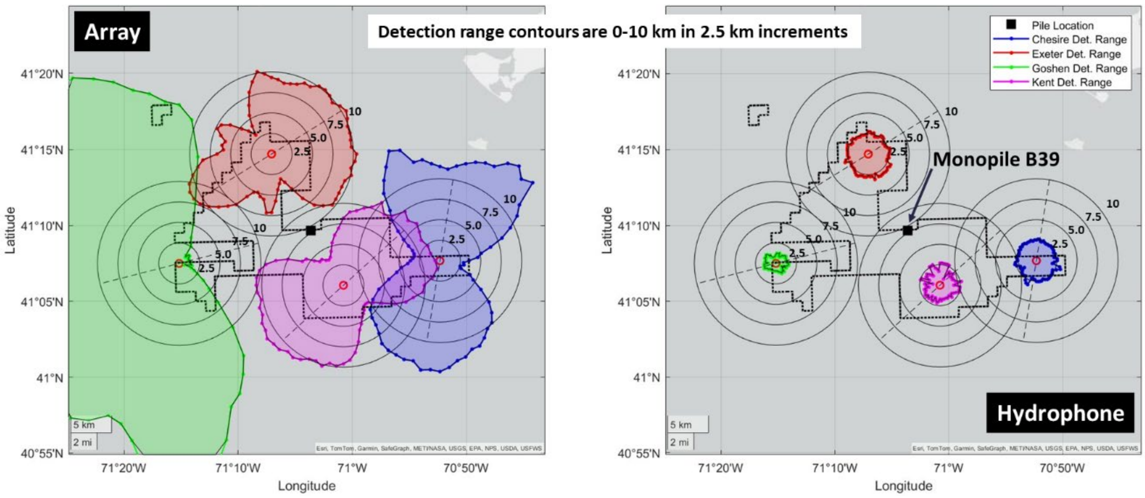

Figure 6 Modelled detection contours for a representative FFT frame corresponding to beam and omni-directional noise contours of Fig. 5 during the hammer strike for monopile B39 at 150000 GMT on 1 July 2024. Minor degree of bearing dependence in the hydrophone contours is due to bearing dependence of the modelled transmission loss.

Apart from the dramatic difference in total area coverage for the array relative to the single hydrophone, a couple of observations stand out. First, the nulls in the detection response at each array are aligned with the LOS to the monopile. The width of the null for the arrays at beam aspect (broadside) to the monopile, Kent, Exeter, and Cheshire, is much narrower than that of the array at endfire aspect, e.g., Goshen. This observation prompts the question as to the optimal orientation of the array relative to the pile driving—is it better to orient the monopile to endfire (as in the case of Goshen, green) to protect the most sensitive detection bearings at beam aspect, or to broadside (as in the case of Kent, magenta) to minimize the bearing extent of the impact. This question is still under consideration. Array orientation is primarily driven by wind conditions and currents at the time of deployment. Also, movement of the arrays as construction activity migrates from pile to pile incurs additional risk, so optimization on an individual monopile basis is challenging. Second, while the arrays closest to the monopile, in this case Exeter (red) and Kent (magenta) exhibit the most pronounced impact to performance, all four arrays show predicted detection coverage to 10 km or more for one-half to two-thirds of beamspace. The single hydrophone detection coverage during the strike is, of course, uniformly degraded at all bearings and struggles to reach 2.5 km range. In the case of Goshen at this time instant, where the in-band noise level approaches 115 dB re 1μPa, the detection range is projected to be less than 1 km.

CONCLUSION

This work reviewed analysis of pile driving radiated noise collected on four bottom-mounted hydrophone arrays during Orsted's Revolution Wind monopile installation from May-August 2024. The measurements show that median omni-directional hydrophone noise spectrum levels during the hammer strike can exceed 120 dB re 1μPa//Hz at a range of 7 km from the noise source. However, analysis of beam noise results demonstrated spatial noise rejection, or array gain, of up to 30 dB, during intervals corresponding to the hammer strike. The capacity of arrays to spatially filter such a strongly anisotropic noise distribution means that it is possible to deliver detection ranges more than 10 km *even during the hammer strike* for bearing sectors steered away from monopile LOS, while the single hydrophone is completely masked. Next steps are to conduct calibrated, ground truthed source operations during construction operations to validate the detection performance projections in the presence of pile driving presented herein.

ACKNOWLEDGEMENTS

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