

North Pacific right whale up-call source levels and propagation distance on the southeastern Bering Sea shelf

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Call source levels, transmission loss, and ambient noise levels were estimated for North Pacific right whale (*Eubalaena japonica*) up-calls recorded in the southeastern Bering Sea in autumn of 2000 and 2001. Distances to calling animals, needed to estimate source levels, were based on two independent techniques: (1) arrival-time differences on three or more hydrophones and (2) shallow-water dispersion of normal modes on a single receiver. Average root-mean-square (rms) call source levels estimated by the two techniques were 178 and 176 dB re 1 μ Pa at 1 m, respectively, over the up-call frequency band, which was determined per call and averaged 90 to 170 Hz. Peak-to-peak source levels were 14 to 22 dB greater than rms levels. Transmission loss was approximately $15 \cdot \log_{10}(\text{range})$, intermediate between cylindrical and spherical spreading. Ambient ocean noise within the up-call band varied from 72 to 91 dB re 1 μ Pa²/Hz. Under average noise conditions, call spectrograms were detectable for whales at distances up to 100 km, but propagation and detection distance may vary depending on environmental parameters and anthropogenic noise. Obtaining distances to animals and acoustic detection range is a step toward using long-term passive acoustic recordings to estimate abundance for this critically endangered whale population.

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I. INTRODUCTION

The eastern stock of North Pacific right whales (*Eubalaena japonica*) is among the most endangered large whale populations in the world (Clapham *et al.*, 1999; Brownell *et al.*, 2001). Prior to the mid-20th century, North Pacific right whales were encountered mainly in late spring through early fall, with highest concentrations in the Aleutian islands, Bering Sea, and western Gulf of Alaska (Shelden *et al.*, 2005). Since the 1960s, when the population was reduced to critically low abundance by illegal whaling, encounters with North Pacific right whales have been so rare that each one has merited publication. Most North Pacific right whale sightings since 1970 have been in the southeastern Bering Sea (SEBS), in the middle- and outer-shelf domains (Goddard and Rugh, 1998; Moore *et al.*, 2000, 2002; LeDuc *et al.*, 2001; McDonald and Moore, 2002; Barlow, 2005; Wade *et al.*, 2006). High rates of photographic and genetic resampling support a recent population estimate of fewer than 50 eastern North Pacific right whales (Wade *et al.*, 2010). One crucial research priority is to understand seasonal patterns in North Pacific right whale abundance within the SEBS and other known habitats. However, visual search effort for right whales in these habitats from vessel or aerial platforms is hampered by the relative remoteness of these areas, frequently poor survey conditions, and low right whale encounter rates.

In contrast to visual survey effort, passive acoustic recorders can collect data through nighttime and poor weather, and low-frequency sounds such as baleen whale calls are usually detectable at ranges several times greater than visual sighting ranges (e.g., Sirovic *et al.*, 2007; Wiggins *et al.*, 2004; McDonald and Fox, 1999; Stafford *et al.*, 2007; McDonald and Moore, 2002; Wade *et al.*, 2006). North Pacific right whale acoustic recording effort in the SEBS was initiated in 1999 during ship-based surveys and expanded in 2000 to include long-term moored recording packages for continuous, year-round monitoring (McDonald and Moore, 2002; Moore *et al.*, 2006; Munger *et al.*, 2008). The SEBS shelf is a particularly advantageous place for using acoustics to find and study right whales because it is shallow (<200 m) and relatively flat for hundreds of kilometers, acting as an acoustic waveguide bounded by the seafloor and air-sea interface that channels sound for long distances (Wiggins *et al.*, 2004). Right whale calls detected in real time during vessel-based surveys in the SEBS in 1999–2004 directed the ship to right whales from distances of 20–100 km (McDonald and Moore, 2002; LeDuc, 2004; Wade *et al.*, 2006), and a few right whale calls in seafloor hydrophone recordings from 2000 were localized to over 50 km (Wiggins *et al.*, 2004).

Acoustic detections on a fixed hydrophone may be suited to local abundance estimates using modified point transect methodology, which requires knowledge of the distance from the observer (or receiver) to the organism and probability of detection as a function of distance and other variables (Buckland *et al.*, 2001; Marques *et al.*, 2009). Additional information needs include individual call production rates and how these are influenced by covariates such as

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behavior and group size (Marques *et al.*, 2009). Determining distances and detection probability for autonomously recorded right whale calls requires knowledge of call source levels and the acoustic propagation environment, including transmission loss and ambient ocean noise levels within the study area (e.g., Sirovic *et al.*, 2007).

Source levels of North Pacific right whale calls have not been previously reported; however, they have been measured for two closely related species: southern right whales (*E. australis*) and North Atlantic right whales (*E. glacialis*). Source levels of southern and North Atlantic right whales vary depending on geographical location and call type. Southern right whale “belch-like utterance” source levels were reported at 172–187 dB re 1 μ Pa at 1 m (Cummings *et al.*, 1972); North Atlantic right whale tonal calls, including up-calls, were reported to be 137–162 dB re 1 μ Pa at 1 m and broadband “gunshot” sounds were 174–192 dB re 1 μ Pa at 1 m (Parks and Tyack, 2005). Bowhead whales (*Balaena mysticetus*), which are in same family as right whales (Balaenidae), produce tonal calls (“moans”) and songs with reported source levels of 129–178 dB and 158–189 dB re 1 μ Pa at 1 m, respectively (Cummings and Holliday, 1987). The loudest known mysticete sounds are produced by the largest two species, blue whales (*Balaenoptera musculus*) and fin whales (*B. physalus*) (both in family Balaenopteridae), with call source levels in some geographical regions estimated at over 180 dB re 1 μ Pa at 1 m (Sirovic *et al.*, 2007; Cummings and Thompson, 1971; Thode *et al.*, 2000; McDonald *et al.*, 2001; Watkins *et al.*, 1987; Charif *et al.*, 2002). Differences in source levels for a given species or population are in part due to individual variation (e.g., Sirovic *et al.*, 2007) as well as variation between animals.

This study presents estimates of North Pacific right whale call source levels and transmission loss based on calibrated hydrophone recordings in the SEBS in 2000–2001. Source levels are determined for up-calls, which are low-frequency (<500 Hz), frequency-modulated upsweeps slightly less than 1 s in duration; this call type is reportedly the most common call type in right whales when not engaged in reproductive behavior, and is made by both sexes, juveniles and adults (Clark, 1982, 1983; McDonald and Moore, 2002). Two techniques are demonstrated to estimate distances to calling animals: Localization using call arrival-time differences, which requires three or more hydrophones, and modeling dispersion of normal modes in a shallow-water waveguide, which is applicable to recordings from a single hydrophone. Average background noise levels over the right whale calling band are reported for the SEBS and are used to estimate the average range at which right whale calls would be detectable.

II. METHODS

Acoustic data were analyzed from four Acoustic Recording Packages (ARPs) (Wiggins, 2003) deployed in October 2000 and a single ARP (site “C”) deployed in August 2001 at approximately 70 m depth in the SEBS (Fig. 1). ARPs sampled continuously at 500 Hz and recorded for 3 to 11 months. The four ARPs in 2000 were spaced

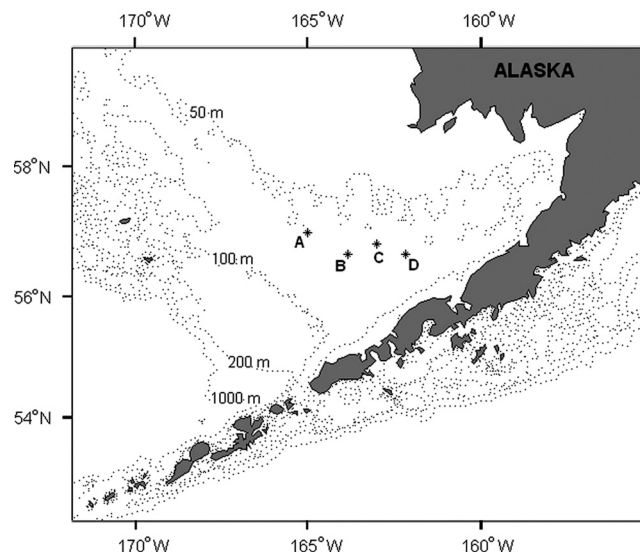


FIG. 1. ARP deployment locations (asterisks) in 2000–2002 and dotted bathymetric contours (from Smith and Sandwell, 1997) in the SEBS.

approximately 60 km from one another in the east-west direction, and 20–40 km in the north-south direction. This geometry was intended to bisect the middle-shelf right whale sighting area to maximize the chances of detecting right whales and not necessarily to function as an array for localizing calls. However, acoustic propagation distance of right whale calls on the SEBS shelf was sufficient for several calls to be detected on more than one ARP. Although right whale call maximum frequencies can exceed the 250 Hz effective bandwidth of ARP recordings, most up-calls previously recorded and described in the SEBS had maximum (“end”) frequencies below 220 Hz (McDonald and Moore, 2002), and all calls analyzed within this study were within the effective recording bandwidth of ARPs when examined visually in the spectrogram. Right whale calls were detected in long-term recordings using automated call detection software and by manually inspecting spectrogram data (Munger *et al.*, 2005, 2008).

Sections II A through II C describe methods used to measure call received levels and determine transmission loss in order to estimate source levels, using $SL = RL + TL$, where SL = source level, RL = received level, and TL = transmission loss, all expressed in decibels (dB), with source levels compared to a reference distance of 1 m. Whale call source levels are often reported as root-mean-squared (rms) values that are measured over a time interval or “window,” but the measurement of this window is not always reported. The rms sound pressure level (SPL) of a pure sinusoid signal is 9 dB below its peak-to-peak SPL, but for a transient, pulsed signal in which energy content varies with frequency, the rms SPL can be up to 20 dB or more below the peak-to-peak level (Madsen, 2005). The sound exposure level (SEL) accounts for the total energy within a sound by calculating cumulative sum-of-square pressure over the total duration of the sound. Right whale calls in the SEBS are brief, with variable energy content over the frequency sweep of the call, and become distorted with distance, arriving at the receiver as a series of modes with little

to no call energy between mode arrivals (McDonald and Moore, 2002; Wiggins *et al.*, 2004). In this study we measured peak-to-peak and root-mean-square SPL and SEL, to compare with each other and across other studies (e.g., Madssen, 2005; Au *et al.*, 2006).

A. Received levels

Received levels were estimated by first taking 5-s data segments that contained an up-call and then by band-pass filtering the data, with filter corner frequencies within 5–10 Hz of the start and end frequency of the call. Time series amplitudes were converted to absolute SPL based on laboratory calibration of ARP hydrophones, which had flat frequency response within ± 1 dB within the frequency band of 50–250 Hz (McDonald, 2006; Wiggins, 2003). Call received levels were calculated for bandpassed time series data using peak-to-peak (p-p) and rms SPL measurements. Time window boundaries for the rms measurement were determined by calculating call amplitudes of 10 dB down from the peak amplitude within the Hilbert-transformed call spectral envelope (Oppenheim and Schaffer, 1999). SEL was calculated using $SEL = \text{rms SPL (dB)} + 10\log_{10}(T)$, where T is the time window duration of the call in seconds, here taken to be the same window used for rms measurement.

B. Range to calls

Two different techniques were employed to estimate the range to calling animals. The first technique localized calls received during the first deployment period on three or more ARPs based on the difference in call arrival times. The second technique estimated range to calls received on one hydrophone, based on dispersion of normal modes within each call due to waveguide propagation on the SEBS shelf (Wiggins *et al.*, 2004).

1. Time-difference of arrivals (TDOA)

Right whale calls received on three or more ARPs deployed in October 2000 were localized using time-difference of arrivals (TDOA) between hydrophones. Arrivals of the same call(s) on multiple hydrophones (Fig. 2) were determined by visually analyzing spectrograms and matching call start and end frequencies, peak frequencies, and spectrogram contour shape. Right whale calls were infrequent and did not overlap in time, and also varied substantially in start and end

frequencies and sweep rates, allowing them to be distinguished by the analyst and matched across instruments. Calls within the same 1- to 2-min series were also distinguishable by having the same intervals between each call across ARPs. Call arrival times were picked in spectrograms to within 0.1 s, at the same frequency of the up-sweep ± 2 Hz across hydrophones. Error in call arrival times was a combination of spectrogram picking accuracy and instrument clock drift. All calls analyzed in this study were recorded within the first week of instrument deployments after synchronizing clocks to within 1 s, and ARP clock drifts are linear to approximately 0.5 s per day (Sirovic *et al.*, 2007); we therefore assumed clock accuracy of ± 0.5 s.

The TDOA localization routine (in MATLAB®, provided by David Mellinger) found an optimum 2-D sound source location by minimizing error between calculated and observed time-differences from the source to each possible hydrophone pair, using the Levenberg–Marquardt algorithm for nonlinear least-squares parameter estimation (Marquardt, 1963). Because the water depth is shallow (70 m) relative to horizontal distances (tens of kilometers), localizing in two dimensions was a good approximation. Sound speed was assumed to be vertically homogenous at 1470 m/s. The localization routine was repeated for all right whale calls received on at least three ARPs and distances were computed from the optimized source location to each receiver.

2. Normal mode dispersion model (NMDM)

Ranges to right whale calls recorded on a single hydrophone were estimated by modeling dispersion of normal modes in a shallow-water waveguide. The use of normal mode theory to characterize propagation is appropriate when propagation distance is several times greater than water depth, and when the ratio of water depth to wavelength is not large ($\sim 4:1$ or lower; Marsh and Schulkin, 1962). Both of these criteria are true for right whale calls in the SEBS study area, where calls propagate several tens of kilometers (McDonald and Moore, 2002; Wade *et al.* 2006; Wiggins *et al.* 2004), and where the ratio of water depth to call wavelength is approximately 4:1, assuming a call start frequency of 90 Hz (McDonald and Moore, 2002), sound speed of 1470 m/s, and water depth of 70 m.

The long-distance call propagation and numerous reflections off the seafloor and air–sea boundaries lead to constructive and destructive interference of groups of sound

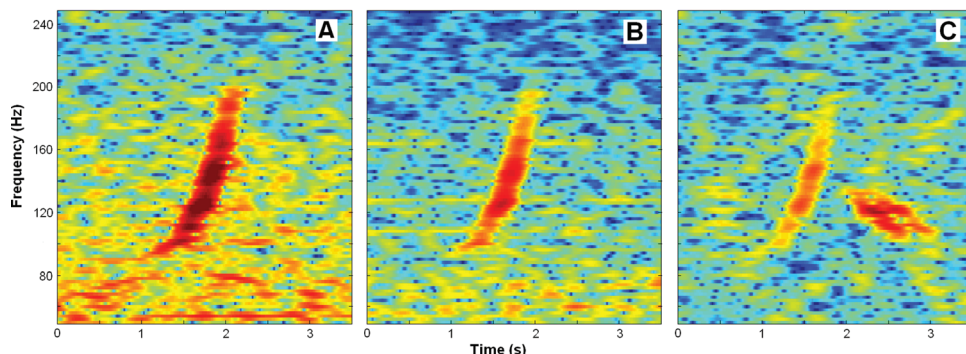


FIG. 2. (Color online) Right whale up-call recorded at ARP sites A, B, and C. A second call from an unidentified species was recorded on C. Sample frequency $F_s = 500$ Hz, FFT and Hanning window length = 250 points for 0.5 s window length, overlap = 98%. Same intensity of color-scale across spectrograms.

rays. This results in frequency-dependent dispersion of normal modes, apparent in the signal waveforms and call spectrograms (McDonald and Moore, 2002; Wiggins *et al.*, 2004). The normal modes are solutions to the cylindrical wave equation (Clay and Medwin, 1977). Group velocity of each mode is frequency-dependent within the SEBS right whale call band and effective recording bandwidth (<250 Hz), such that decreasing sound frequencies travel increasingly slowly until reaching a low-end cutoff frequency (the “Airy” frequency), below which group velocities rapidly approach the sediment sound velocity (Wiggins *et al.*, 2004). The time-differences between mode arrivals above the cutoff frequency provide information about the distance to the calling animal.

Mode arrivals were picked manually in the call spectrogram at the same frequency across the received call. Mode group velocities were calculated using equations described in Wiggins *et al.* (2004) for the same region of the SEBS, with the same input parameters: Sound speed in water = $c_1 = 1470$ m/s, water density = $\rho_1 = 1026 \text{ kg/m}^3$, sound speed in sediment = $c_2 = 1675$ m/s, sediment density = $\rho_2 = 1500 \text{ kg/m}^3$, and water depth = $h = 70$ m. Source depth was assumed to be 15 m and receiver depth was 60 m. Mode group velocities and difference in arrival times were used to determine the horizontal range (distance) to the caller, $\text{range} = r = (u_i u_j / |u_i - u_j|) |t_i - t_j|$, where u = group velocity and t = arrival times, respectively, for i th and j th modes (Wiggins *et al.*, 2004). A synthetic model of the initial call was created and distortion of the initial call contour was modeled using the distance obtained from mode arrival-time picks, and this modeled call was overlaid on the actual call spectrogram. Range and synthetic call contour parameters were adjusted manually through an iterative process to improve the model fit.

C. Transmission loss

Transmission loss was estimated empirically for right whale calls in the SEBS using ranges obtained from both TDOA and NMDM. Transmission loss can be expressed as a function of range as $TL = X \log_{10} \left(\frac{r}{R_0} \right)$, where r = horizontal range (m), R_0 = reference range (usually taken as 1 m), and X = transmission loss coefficient, between 10 for cylindrical spreading ($r \gg$ water depth) and 20 for spherical spreading ($r \leq$ water depth). Received pressure levels (RL) were plotted vs $\log_{10}(r)$ and a linear regression was fitted using

least-squares minimization to obtain the transmission loss coefficient, X , for range > water depth. We obtained X independently for peak-to-peak, rms, and SEL measurements, for right whale calls localized using TDOA on multiple ARPs (deployed in 2000), and for call ranges estimated from normal mode modeling on data from a single ARP (deployed in 2001).

D. Source level

Source levels (p-p, rms) as well as SEL of each call were estimated by adding the received level to transmission loss. At range within one water depth (70 m), transmission loss was assumed to be spherical and equal to $20 \log_{10}(r)$. Accounting for the initial spherical spreading loss within the first 70 m of propagation, call source levels were therefore equal to $SL = RL + X \log_{10}(r/70) + 20 \log_{10}(70)$. For calls recorded by more than one ARP, source level was averaged across instruments.

E. Background noise

Background noise within the right whale calling band was measured within a few seconds of each call. Time series data were bandpass filtered with corner frequencies within 10 Hz of the start and end frequency of the call, and rms amplitude was measured for background noise for 2–3 s immediately before or after the call and converted to SPL. Noise per Hz (dB re $\mu\text{Pa}^2/\text{Hz}$) was computed by subtracting $10 \cdot \log_{10}(\text{filter bandwidth})$. The right whale calls detected visually in spectrograms and analyzed in this study were at least 2 dB and on average 5 dB above background noise; these signal-to-noise ratios (SNR) were used to determine the range at which an analyst should be able to detect right whale up-calls in spectrograms recorded on the SEBS shelf.

III. RESULTS

A total of seven localizable right whale calls were detected in recordings on three or more hydrophones (only one of these calls was detected on all four hydrophones) from 2-Oct-2000 through 4-Oct-2000. Three of the calls were produced within a calling bout, less than 1 min apart, and the four singular calls were separated by at least 20 min.

An example of NMDM overlay plots is shown in Fig. 3 for a right whale call received on two ARPs (Wiggins *et al.*,

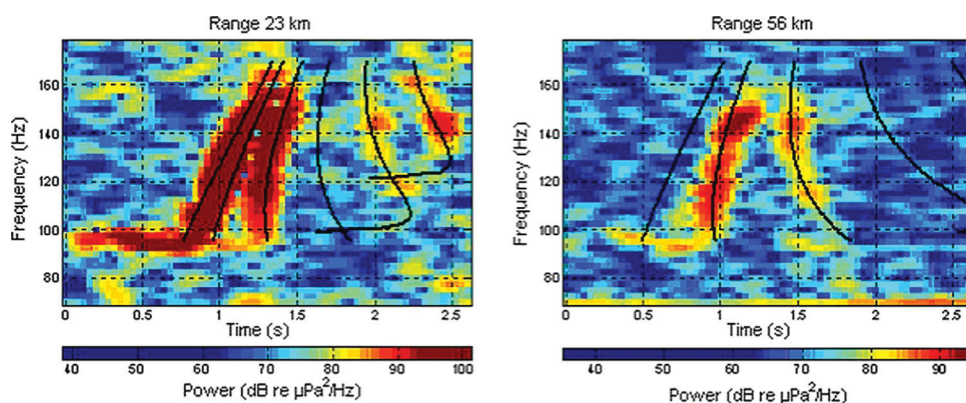


FIG. 3. (Color online) Spectrograms of a single right whale call received on two easternmost ARPs (site C and D), with overlaid normal mode arrivals of synthetic call based on range estimates, given above each call. Figure adapted with permission from Wiggins *et al.* (2004) in Canadian Acoustics.

TABLE I. Comparison of NMDM and TDOA range estimates for right whale calls received on multiple instruments (calls with visible mode arrivals only).

Call number	Receiver	NMDM range estimate (km)	TDOA range estimate (km)	(% error)	Average (% error)
2	A	38.6	38.8	0.5	
2	A	39.1	40.3	3.0	
2	A	44.8	40.2	11.4	
2	B	79.0	73.5	7.5	
2	B	69.0	75.1	8.1	
2	B	63.0	74.9	15.9	
4	A	36.9	39.6	6.8	12.3
4	B	80.0	97.9	18.3	
5	A	33.0	35.5	7.0	
11	A	39.0	29.4	32.7	
11	B	94.0	77.2	21.8	
12	A	38.9	31.2	24.7	
12	B	80.0	77.9	2.7	

2004). NMDM was applied to the seven calls recorded in October 2000 and used in TDOA distance estimates, as well as for 130 right whale calls recorded over a period of two days in September 2001 by a single ARP at site “C” (see Fig. 1). Of the 22 right whale call arrivals localized using TDOA, 13 ranges to calls recorded on two of the four ARPs were estimated using NMDM; the remaining calls did not display distinctive mode arrivals. The average percentage difference in distance estimates using NMDM compared to TDOA was 12% (Table I). The most reliable NMDM range estimates to calls were about between 20 and 50 km due to more distinctive mode arrivals at these ranges.

RMS received pressure levels of calls at distances determined by TDOA and NMDM are plotted vs the logarithm of range and fitted by a linear regression, the slope of which is

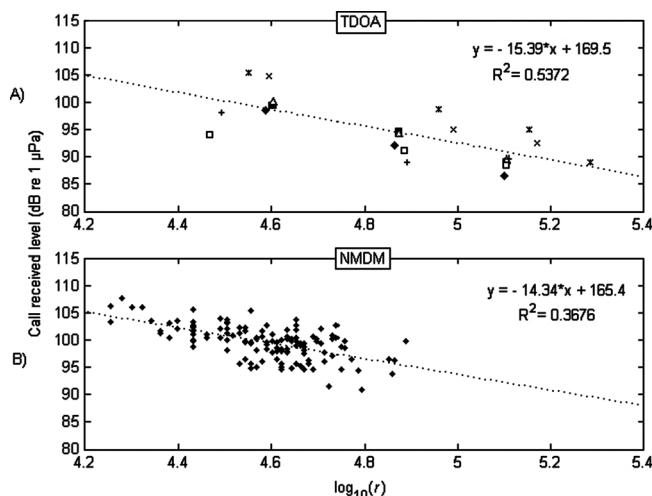


FIG. 4. Call rms received levels (dB re 1 μ Pa) plotted vs $\log_{10}(r)$, where r is the distance to the hydrophone. (A) Ranges calculated using TDOA localization; each call is represented by a unique symbol and distances are plotted on three or four receivers. (B) Ranges calculated using NMDM. Linear regression (dashed line) equations and R^2 values are displayed in upper right of each panel. Note that source level (Table I) does not equal the y-intercept of the linear regression, due to the additional term for spherical spreading loss over the first 70 m of propagation (one water depth).

equal to the transmission loss coefficient (Fig. 4). The linear regression was repeated for each data set and measurement type (peak-to-peak SL, rms SL, and SEL) to obtain independent transmission loss coefficients. Transmission loss coefficients, R^2 values, average source levels, and sample size are reported for the two ranging techniques and three measurement types in Table II. Most of the estimated transmission loss coefficients were approximately 14–15; however, the coefficient’s value was 18.1 for the TDOA-based SEL measurement, and 16.6 for the NMDM-based peak-to-peak measurement.

Source level was estimated for each call to determine the average and variation in source levels within the sample (Fig. 5). RMS source level estimates were fairly consistent between distance-estimation methods, ranging from 170 to 182 dB re 1 μ Pa at 1 m, and were on average 176 (NMDM) or 178 (TDOA) dB re 1 μ Pa at 1 m. Peak-to-peak source levels for individual calls were 13–24 dB above rms values. Average SEL was 178 dB re 1 μ Pa 2 -s at 1 m for NMDM calls.

Ambient noise levels in the right whale calling band (on average of 90–170 Hz) varied between 72 and 91 dB re 1 μ Pa 2 /Hz and were on average 80 dB re 1 μ Pa 2 /Hz (Fig. 6), with slightly greater average noise levels during the 2001 recording period than in 2000. The maximum observed range in our data, estimated using TDOA localization of calls recorded in October 2000, was 190 km, which corresponded to relatively low background noise of 73 dB re 1 μ Pa 2 /Hz over the call bandwidth at the time the call was received.

IV. DISCUSSION

Average source levels for North Pacific right whale “up” calls were 176–178 dB re 1 μ Pa at 1 m (depending on technique used to estimate source distance) and ranged from 170–184 dB. These values are within the range of values reported for southern right whale calls (172–187 dB re 1 μ Pa at 1 m) and bowhead whale calls (128–178, 152–185, and 158–189), both were summarized in Richardson *et al.* (1995). The source levels in this study are greater than the values of 137–162 dB re 1 μ Pa at 1 m, reported by Parks and Tyack (2005) for tonal calls of North Atlantic right whales. Peak-to-peak source levels were 13–24 dB greater than rms source levels, similar to the result reported by Au *et al.* (2006) for humpback whale song, for which peak-to-peak measurements were up to 17–20 dB greater than rms values. The rms measurements were the most consistent between distance estimation techniques, with average values differing by 2 dB. Average peak-to-peak source levels were about 5 dB greater for the NMDM sample than for the TDOA sample, whereas SEL was about 7 dB greater in the TDOA sample than in the NMDM sample. These discrepancies may be related to the small sample size of TDOA-localized calls, as well as the time window length for SEL estimates; for TDOA calls this time window averaged less than 1 s, resulting in a negative $10 \log_{10}(T)$ term in the calculation (see Sec. II A), whereas the average time window length for NMDM calls was slightly greater than 1 s.

It was not possible to determine the number of individuals for which source levels were estimated, as the ranging

TABLE II. Linear regression coefficients and R^2 value, average sound levels, and sample size (n) for peak-to-peak and rms source levels and SEL, using the two different ranging methods: TDOA and NMDM. Received level: $RL = SL - TL = -x \log_{10}(r) + b$.

Ranging technique	Measurement type	x	R^2	Sound level	Units	Sample size (n)
TDOA	peak-to-peak SL	15.15	0.52	192.1	dB re 1 μ Pa at 1 m	7
	rms SL	15.39	0.54	177.8	dB re 1 μ Pa at 1 m	
	SEL	18.06	0.64	184.8	dB re 1 μ Pa ² s	
NMDM	peak-to-peak SL	16.63	0.42	197.6	dB re 1 μ Pa at 1 m	131
	rms SL	14.34	0.37	175.8	dB re 1 μ Pa at 1 m	
	SEL	14.86	0.34	178.0	dB re 1 μ Pa ² s	

techniques were not precise enough to resolve group sizes if whales were within a few kilometers of each other. The source levels estimated using the TDOA method are based on a small sample size ($n = 7$) of right whale calls over a 3-day period that were suitable for localization. These calls may have been produced by a single individual. However, results obtained using the NMDM ranging technique ($n = 130$) corroborate these source level estimates. During the 2-day period analyzed, it is likely that multiple whales were producing calls within detection range of the hydrophone; this is supported by large variation in the distances obtained for NMDM calls [Fig. 4(B)] and relatively high calling rates that suggest larger group sizes (e.g., Matthews *et al.*, 2001). For an extremely small population such as North Pacific right whales, even a few animals may be a fairly good representative sample, particularly if individual source level variation is comparable to variation within the population.

In both ranging techniques, we assumed uniform sound velocity of 1470 m/s. In reality, the water column in the SEBS is temperature-stratified in summer; and in 2000 and 2001 through September and early October, surface temperatures were at least 5°C warmer than bottom temperatures, leading to a non-uniform sound velocity profile. However,

Wiggins *et al.* (2004) conducted a sensitivity analysis of the normal mode model and found that estimated group velocities for the first four modes were relatively insensitive (<1.5% change) to variation in the parameters such as water sound speed, sediment sound speed, water density, sediment density, and bottom depth, within a realistic range of values for the southeast Bering Sea study area. Small variations in bottom topography over the monitored area may have contributed to some error in our NMDM range estimates, but presumably not a systematic error that would bias the source level estimate.

The choice of mode numbers had the greatest effect on NMDM range estimates and was somewhat constrained by the fit of the normal mode model to the data (Fig. 3), but in some cases it was not clear. Mode excitation at a given frequency depends on depth of the source and the receiver (Wiggins *et al.*, 2004). Our estimates are based on a known receiver depth of 60 m and an assumed source depth of 15 m, but the actual depth at which the whale produced its call may have influenced which modes were visible above background noise and modeled by the analyst. Overall, multiple modes were most distinct in calls at modeled ranges of about 20–50 km, and resulted in the most confident range

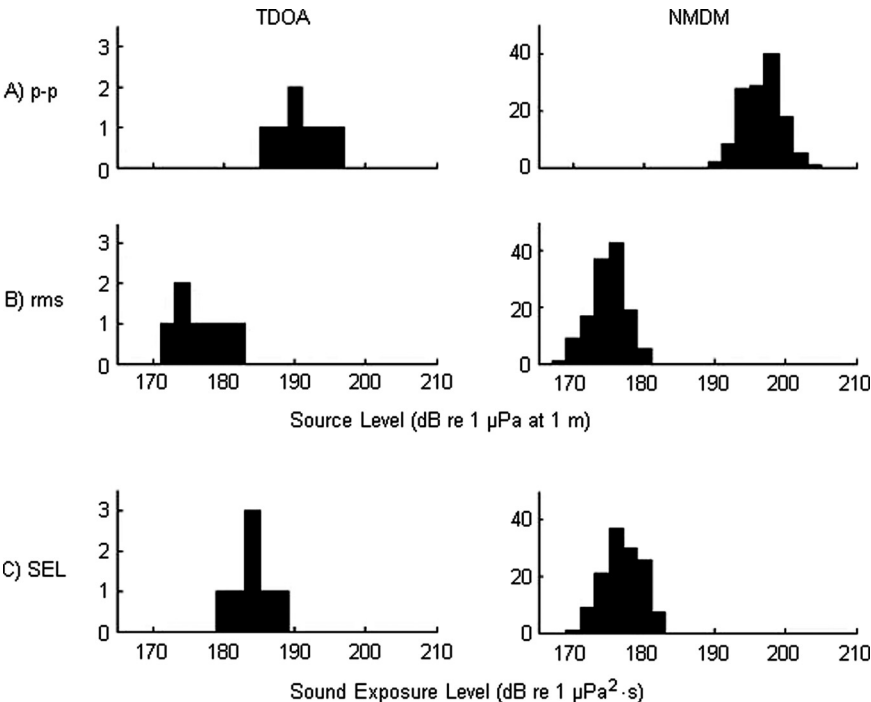


FIG. 5. Histograms of estimated call source levels, equal to received level plus transmission loss, using ranges based on TDOA (left) and NMDM (right), for (A) peak-to-peak and (B) root-mean-square measurements. (C) Estimated SEL for same data sets.

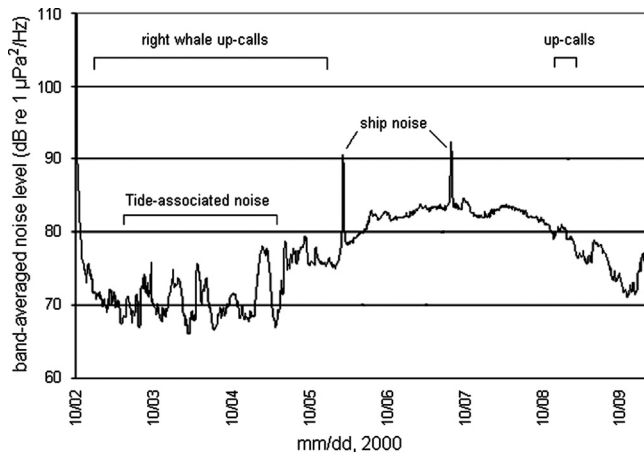


FIG. 6. Ambient noise average within 100–150 Hz band at site C, first week of recording, October 2000. Figure adapted with permission from Munger *et al.* (2005) in Canadian Acoustics.

estimates. At ranges <15–20 km, modes were so clustered together in time that it was difficult to distinguish and separate them, and at longer ranges often only one or two modes would be visible above background noise in the spectrogram, and it was not clear which modes were received.

Background noise (including flow noise, hydrophone cable strumming, and ship noise) was varied by instrument location, time of year, and on shorter time scales due to tidal cycles, storms and vessel traffic (Fig. 6). On average, background noise in the right whale calling band was 80 dB re 1 $\mu\text{Pa}^2/\text{Hz}$, and ranged from about 72 dB re 1 $\mu\text{Pa}^2/\text{Hz}$ to 110 dB re 1 $\mu\text{Pa}^2/\text{Hz}$ due to close passage of ships or increased hydrophone cable strumming resulting from tidal currents and/or storms. At these elevated noise levels, whales would have to be close (within a few km) to the hydrophone for calls to be detected. Under low noise conditions, an analyst able to detect a right whale call from 2 dB above background noise would theoretically be able to detect calls in the SEBS over 100 km from the source assuming a uniform seafloor, transmission loss of $14 \log_{10}(r)$, and source level of 178 dB re 1 μPa . However, the transmission loss may vary over time and space in the SEBS due to seasonal variation in the water column and spatial variation in bottom topography and sediment type, and small changes in the transmission loss result in large changes in detection range. The months with highest noise were January and February; months with lowest noise were July and August. This was probably due to greater wind speeds and more intense storms during winter months (Overland, 1981; Rodionov, 2007).

The detection ranges in this study of up to 100 km or more are considerable compared to other reports, due to the unique bathymetry on the SEBS shelf. The farthest localizations were based on arrival time differences of calls recorded on multiple hydrophones, and although the sample size was small (seven calls), the propagation of SEBS right whale calls over long distances is supported by the use of acoustic detection during real-time surveys to find whales at distances of several tens of km from the initial receiver (LeDuc, 2004; Wade *et al.*, 2006). Maximum detection ranges of 20–30 km have been reported for right whales in other shallow-water studies such as right whales in the Grand Manan Basin

region of the Bay of Fundy, where the seafloor slopes to a depth of 220 m in the center of a ~40–50 km wide channel (Laurinoli *et al.*, 2003). Detection ranges of 20–30 km have also been reported in regions over shelf breaks and slopes, as in a study of fin whale calls off Hawaii, where the hydrophone was located on the slope at 800 m and the bottom slopes from 400 to >3000 m in 20 km (McDonald and Fox, 1999). Propagation loss in deep water is greater due to spherical spreading and is also affected by bottom slope and topography, and therefore acoustic detection ranges on the southeast Bering slope (depth >1000 m), Aleutian Basin, and Gulf of Alaska are likely to have reduced detection ranges compared to the SEBS shelf.

The excellent propagation of right whale calls on the SEBS shelf may be an important attribute of this habitat, allowing whales to communicate at long distances, possibly to find mates or prey patches. However, anthropogenic noise from ships, drilling, and other activities would also propagate for long distances and the frequencies for many of these activities are within the same band used by North Pacific right whales and other marine mammals. Increases in anthropogenic noise (e.g., from increased vessel traffic or other industrial activities) may reduce the ranges at which whales can communicate and locate each other on the Bering Sea shelf.

V. CONCLUSIONS

This study demonstrates two independent techniques for estimating distances to calling right whales in the SEBS from fixed passive acoustic recorders. Distances were used to determine North Pacific right whale up-call source levels and transmission loss at the study site. Distances to calling animals and knowledge of acoustic characteristics, including detection distance, are some of the requirements for distance sampling methodology to estimate population abundance from passive acoustic recordings. Long-term passive acoustic monitoring, in conjunction with other efforts, provides important information on the occurrence and biology of critically endangered North Pacific right whales in the SEBS, with potential applications for population assessment.

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