Source levels of fin whale 20 Hz pulses measured in the Northeast Pacific Ocean

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Source levels of fin whale calls can be used to determine range to recorded vocalizations and to model maximum communication range between animals. In this study, source levels of fin whale calls were estimated using data collected on a network of eight ocean bottom seismometers in the Northeast Pacific Ocean. The acoustic pressure levels measured at the instruments were adjusted for the propagation path between the calling whales and the instruments using the call location and estimating losses along the acoustic travel path. A total of 1241 calls were used to estimate an average source level of 189 ± 5.8 dB re 1μPa at 1 m. This variability is largely attributed to uncertainties in the horizontal and vertical position of the fin whale at the time of each call and the effect of these uncertainties on subsequent calculations. Variability may also arise from station to station differences within the network. For call sequences produced by a single vocalizing whale, no consistent increase or decrease in source level was observed over the duration of a dive. Calls within these sequences that immediately followed gaps of 27 s or longer were classified as backbeat calls and were consistently lower in both frequency and amplitude.
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I. INTRODUCTION

Aggressive commercial whaling practices in the early-mid 20th century led to the near-extinction of fin whale (*Balaenoptera physalus*) populations throughout the world's oceans (Mizroch *et al.*, 2009). They were listed in the Endangered Species Act of 1973, and by 1976, the International Whaling Commission (IWC) gave them full protection from commercial whaling in the North Pacific. By the late 1980s, this protection had extended to include all oceans. Since that time, there has been interest in monitoring their recovery and assessing ongoing effects of anthropogenic influences (Croll *et al.*, 2002; Stafford *et al.*, 2009).

The distributions and movements of fin whales are poorly understood (Mizroch *et al.*, 2009). Several observational techniques have been employed to assess fin whale populations, including visual and aerial surveys (Forney and Barlow, 1998; Zerbini *et al.*, 2006), radio and satellite tagging (Watkins, 1981; Watkins *et al.*, 1984), genetic studies (Fujino, 1960; Bérubé *et al.*, 2002), and the compilation of historic whaling records (Gregr *et al.*, 2000). Passive acoustic monitoring provides an additional set of techniques, allowing for long-term, non-invasive observation of fin whale vocalizations.

Fin whales produce calls ranging from 18 to 300 Hz (Watkins, 1981; Watkins *et al.*, 1987; Thompson *et al.*, 1992). By far, the most common are the 20 Hz pulses, which are characterized by a chirp lasting approximately 1 s and sweeping down in frequency from about 25 to 15 Hz (Fig. 1). These high-amplitude, repetitive call sequences can be reliably detected using automated methods (Mellinger and Clark, 2000). A single acoustic recorder can be used to identify and count fin whale calls over time, and a fixed network of instruments can be used to locate a given call using relative arrival times at several instruments (Watkins and Schevill, 1972; McDonald *et al.*, 1995; Rebull *et al.*, 2006). The source level of a fin whale call can be used to help distinguish between multipath arrivals and constrain the range to a calling whale measured on a single instrument (McDonald and Fox, 1999). Once range is known, it can be used to calculate the proportion of calls detected within a specific region; this is one of the requirements for distance sampling estimates of call density (Buckland *et al.*, 2001). If the acoustic environment is well understood, and source levels of vocalizing whales are known, then it is possible to estimate the maximum communication range between animals; this can help assess the impact of anthropogenic noise (Croll *et al.*, 2001; Nowacek *et al.*, 2007).

Few studies estimating fin whale call source levels have been undertaken (Patterson and Hamilton, 1964; Northrup *et al.*, 1968; Watkins, 1981; Watkins *et al.*, 1987; Charif *et al.*, 2002; Širović *et al.*, 2007), due in large part to the difficulty in acquiring a set of calls where the positions of both the whale and the acoustic recorder are accurately known and the received level at the instrument can be measured in terms of absolute pressure level. Early measurements differed widely and were often based on very few measurements or did not report the number of measurements used. More recently, Charif *et al.* (2002) reported a mean source level of 37 fin whale calls recorded in the Northeast Pacific Ocean of 171 (159–184) dB re 1μPa at 1 m. Širović *et al.* (2007) took measurements in the Southern Ocean and found a mean source level of 189 (185–193) dB re 1μPa at 1 m based on 83 calls.

Globally distributed networks of ocean bottom seismometers (OBSs) are deployed to measure seismic activity

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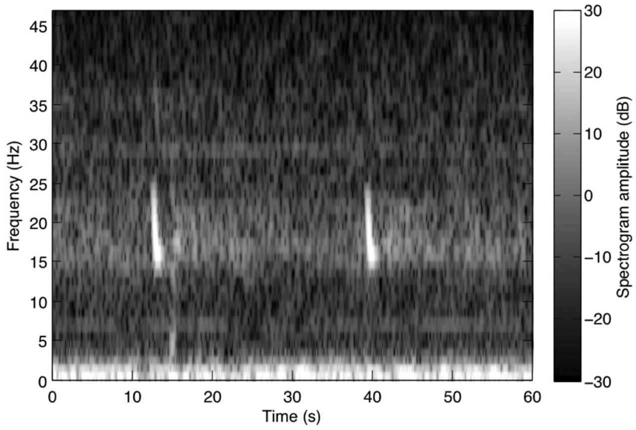

FIG. 1. Spectrogram showing two 20 Hz fin whale calls.

but are also sensitive to the low frequency sounds produced by both fin and blue whales. These instruments have been used to analyze calling patterns and to resolve tracks of fin and blue whales (McDonald *et al.*, 1995; Rebull *et al.*, 2006; Dunn and Hernandez, 2009). In this study, source levels of fin whale 20 Hz vocalizations are estimated using ocean bottom seismometer data recorded in the northeast Pacific Ocean between August 2003 and April 2004.

II. METHODS

A. Fin whale dataset

The experiment was located on the Endeavour segment of the Juan de Fuca Ridge (48.5°N, 129.0°W), where eight OBSs were deployed between 2003 and 2006. Data were collected continuously over the duration of the experiment. The network was centered on the axis of the mid ocean ridge, extending approximately 10 km in the along-axis direction, and 6 km across, with an average water depth of 2200 m (Fig. 2). Each OBS was positioned using an ROV equipped with an ultra-short baseline (USBL) beacon with an estimated absolute horizontal position error of ~10 m. Seven of the seismometers were short-period instruments sampled at 128 Hz with a flat frequency response between 1 and 90 Hz (Stakes *et al.*, 1998). One of the instruments was a broadband seismometer with a flat frequency response from less than 1 Hz to approximately 50 Hz, sampled at either 50 or 100 Hz (Romanowicz *et al.*, 2003).

In addition to seismic activity, the network also recorded more than 300 000 fin whale vocalizations during the 3 yr deployment with most calls appearing during the fall and winter months. A location algorithm was developed that utilized the relative arrival times and multipath structure of whale calls observed on the OBSs (Wilcock, 2012). For each station, up to five arrival times are determined by finding maxima in the instantaneous amplitude. These are then modeled using a grid search algorithm to search for the horizontal location and number of water column multiples for each arrival time that minimizes the RMS residual after erroneous arrival times are eliminated. The method does not have depth resolution for a shallow source, and so for simplicity, the method assumes that the calls are at the surface. Formal horizontal location uncertainties are estimated based on the

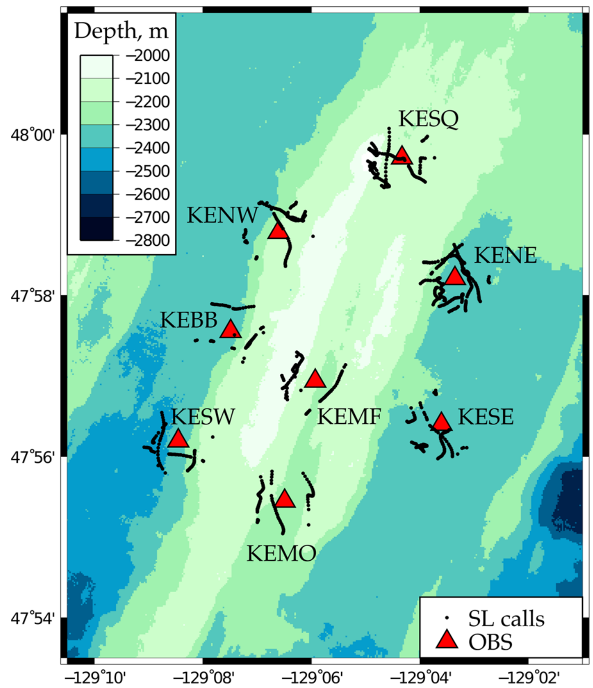

FIG. 2. (Color online) Bathymetric map of the experiment site on the Endeavour segment of the Juan de Fuca Ridge, in approximately 2200 m water depth. Seismometers are shown by triangles and the black circles show calls used in source level estimation. The seismic network extends approximately 10 km north-south, and 6 km east-west.

arrival time misfits using the F-statistic. Because the spacing of stations is only 2–3 km, the formal location uncertainties within the network are relatively uniform, ranging from 300 to 500 m. The uncertainties increase to several kilometers outside the network.

During the first year of deployment (2003–2004), over 150 individual tracks were resolved (Soule *et al.*, 2011). Tracks were analyzed for patterns in inter-pulse interval (IPI) and frequency, where IPI is defined as the space between the onset of one call and the one immediately before it. Four dominant IPI patterns are observed: 25-s simple IPI, 25/30-s dual IPI, 13/25-s dual IPI, and complex IPI. The 25-s simple IPI and the 25/30-s dual IPI are interpreted to represent single whales, while the 13/25-s dual IPI and the complex IPI are interpreted to represent two or more whales calling near the network (Soule *et al.*, 2011). Mean frequency for each call was weighted by call amplitude in decibels relative to a threshold of two standard deviations above the mean value of the spectrogram between 13 and 35 Hz. The most commonly measured call frequency was 19 Hz. Calls at distinctly higher frequencies were also observed with an average frequency of 24 Hz. Calls that are lower in both frequency and amplitude have been identified as backbeat calls (Watkins *et al.*, 1987; Hatch and Clark, 2004). Backbeat calls were observed to occur primarily after rests, which are pauses in calling that last more than 60 s and less than 20 min and also after 30-s IPIs.

The calculation of source level requires knowledge of the location of the OBS and the whale call, and the acoustic propagation path between the two. The tracking algorithm was optimized to find most but not every call in a track. For this study, the missed calls in the tracks were detected using an automatic detection algorithm based on a spectrogram detection method (Mellinger and Clark, 2000). The horizontal locations of the missing calls were interpolated based on time of call using a 300-s Gaussian smoothing operator.

B. Source level estimation

Source levels were estimated using the passive sonar equation (e.g., Kinsler *et al.*, 1999; Urick, 1983). Amplitudes of received signals are typically estimated using calibrated hydrophones but can also be estimated from OBS data. The difference is that an OBS measures ground velocity of the seafloor instead of pressure fluctuations in the water. The vertical component of the OBS is used for these measurements because coupling with the seafloor is more reliable in the vertical direction. The vertical particle velocity u_v is obtained by band-pass filtering the signal between 13 and 35 Hz. The root-mean-square (RMS) amplitude of the signal is calculated in a 1-s window centered on the detection time and is corrected for noise by subtracting the mean squared signal in a 1-s window preceding the call. The RMS amplitude is then converted to ground velocity in meters per second using the instrument response.

The Zoeppritz equations relate the particle velocity in the direction of the incoming acoustic wave to the seafloor particle velocity measured in the vertical direction. The acoustic pressure wave incident on the seafloor is converted to both pressure P and shear S wave energy. The amplitudes of the transmitted P and S waves at a fluid solid interface (T_{PP} and T_{PS}, respectively), relative to an incident pressure wave of unit amplitude, are given by

$$T_{PP} = \left(\frac{V_{P1}}{V_{P2}}\right)\frac{2B\rho_1 V_{P2}\cos(\theta_i)}{A_1\rho_2 V_{P2}\cos(\theta_i) + A_2\cos(\theta_i)\cos(\theta_t) + \rho_1 V_{P1}\cos(\theta_t)}, \tag{1}$$

$$T_{PS} = \left(\frac{V_{P1}}{V_{P2}}\right)\frac{2C\cos(\theta_i)\cos(\theta_t)}{A_1\rho_2 V_{P2}\cos(\theta_i) + A_2\cos(\theta_i)\cos(\theta_t) + \rho_1 V_{P1}\cos(\theta_t)}, \tag{2}$$

where

$$A_1 = B^2 = \cos^2(2\phi_t), \tag{3}$$

$$A_2 = 4\rho_2 V_{S2}\sin^2(\phi_t)\cos(\phi_t), \tag{4}$$

$$C = 2\rho_1 V_{S2}\sin(\phi_t), \tag{5}$$

and V_{P1} is the incoming P wave velocity, V_{P2} is the transmitted P wave velocity, V_{S2} is the transmitted S wave velocity, θ_i is the incidence angle of the incoming acoustic wave, θ_t is the transmitted P wave angle, ϕ_t is the transmitted S wave angle, and ρ_1 and ρ_2 are the densities in the fluid and solid layers, respectively (Ikelle and Amundsen, 2005). The incidence angle is estimated using the location of the whale relative to the OBS. The angles of the transmitted P and S waves are obtained from Snell's law. The measured vertical ground velocity, u_v, is scaled by the vertical projection of the Zoeppritz equations to obtain velocity in the direction of the incoming wave u:

$$u = u_v\left(\frac{1}{T_{PP}\cos\theta_t + T_{PS}\sin\phi_t}\right). \tag{6}$$

The received acoustic pressure level p_m of the incoming wave is then calculated according to

$$p_m = u\rho_1 V_{P1}. \tag{7}$$

This value is then expressed in decibels relative to 1 μPa, and the source level is obtained by subtraction of the transmission loss.

The sound speed and density of the water at the depth of the instrument were obtained using an average conductivity-temperature-depth profile from this location from the 2009 World Ocean Atlas using the formulation of del Grosso (1974). Most of the instruments in the network are directly coupled to the exposed volcanic basalt layer except for stations KEBB, KESE, and KESW, which are installed in areas having a thin sediment layer. Seafloor properties used in this analysis are based on average density and sound speed to a depth of one wavelength (~75 m). Because the sediment layer, where it exists, is no more than a few meters thick, the average properties of the underlying basalt are used. P wave velocities of mid-ocean ridge basalts near the seafloor estimated at this location using refraction (Cudrak and Clowes, 1993) and reflection data (Van Ark *et al.*, 2007) for sources near the sea surface and from the East Pacific Rise using refraction data for a source near the seafloor (Christeson *et al.*, 1994) range from 2.0 to 3.0 km/s with an average value of 2.5 km/s. Direct measurements for S wave velocities at the seafloor are not available for the Endeavour site, but the values of 0.4–0.6 km/s obtained from the East Pacific Rise (Christeson *et al.*, 1994) are consistent with indirect estimates from the Endeavour based on the arrival times of P to S wave and S to P wave phase conversions that occur at the base of the surface volcanic layer (Wilcock *et al.*, 2002). Measurement of the density of the shallow seafloor at this location range from 2190 to 2360 kg/m^3 (Gilbert and Johnson, 1999).

The Zoeppritz correction, which is the term in parentheses on the right hand side of Eq. (6), reaches a maximum at the critical angle [$\theta_c = \sin^{-1}(V_{P1}/V_{P2})$]. The parameter with the largest effect on the critical angle is the seafloor P wave velocity. Figure 3 shows the Zoeppritz correction for three P wave velocities: The lower and upper limits for typical mid-ocean ridge basalts and an average value, which is used in source level calculations. This indicates that errors from incorrect estimates of seafloor P wave velocity are less than 3 dB at incidence angles less than 20° but increase rapidly at larger incidence angles.

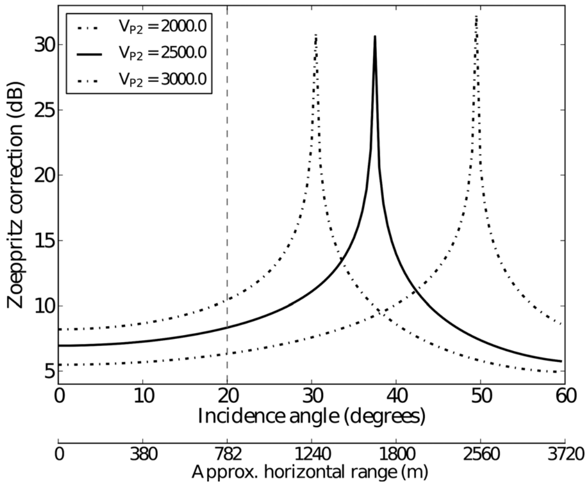

FIG. 3. Zoeppritz correction [term in parentheses on the right hand side of Eq. (6)] to convert vertical ground velocity to the velocity of the incoming acoustic wave, displayed in decibel units. This function shows the sum of the P and S waves projected onto the vertical direction, as a function of incoming P wave incidence angle. The results for upper and lower limits of likely seafloor P wave velocity are shown by dashed lines and are used to estimate the potential error resulting from an incorrect P wave velocity. The model is run using $V_{P1} = 1.5$ km/s, $V_{P2} = 2.5$ km/s, $V_{S2} = 200$ km/s, $\rho_1 = 1000$ kg/m^3, and $\rho_2 = 1700$ kg/m^3. Calls arriving at incidence angles greater than 20° were not included in the final source level calculations.

Both the transmission loss and the incidence angle were initially calculated using a depth varying sound speed profile in the BELLHOP acoustic propagation software from the Ocean Acoustics Toolbox (Porter and Bucker, 1987). The bias introduced by assuming an isospeed profile is only 0.2 dB with the whale directly above an instrument and increases to 0.4 dB at an incidence angle of 20°, which is small compared to other sources of error. Therefore to improve computational efficiency, a straight line travel path assumption was used for calculating incidence angle, and transmission loss was calculated assuming spherical spreading.

C. Variability in source level estimates

The amplitude of the Zoeppritz correction is a function of the incidence angle of the incoming P wave, which is dependent on the position of the whale relative to the instrument. An error in the whale's horizontal and vertical location would result in an incorrect incidence angle, which would give a biased estimate of the Zoeppritz correction. The uncertainty in the horizontal position of the whale in the vicinity of the OBS network is about 400 m. The location algorithm assumes that the whale is calling at the sea surface, so the vertical uncertainty is not resolved. Watkins *et al.* (1987) report a calling depth of 50 m but provide no details of the method or estimated uncertainties. The uncertainty in the Zoeppritz correction for a given uncertainty in the whale's position becomes larger as the incidence angle approaches the critical angle. For a water layer P wave velocity of 1.5 km/s, and a basement layer P wave velocity of 2.5 km/s, the peak in the Zoeppritz correction corresponds to a critical angle of ~37°.

Another effect that is highly dependent on the three dimensional position of the whale relative to the OBS is the interference between the direct path and surface reflected acoustic arrivals. The effect of interference is described in Urick (1983) and discussed with respect to fin whale call source levels in Charif *et al.* (2002). The time delay between the direct and surface reflected arrivals produces an interference pattern that is highly sensitive to changes in call depth and also varies with horizontal range and total water depth. For a tonal signal, the largest increase due to constructive interference will result in a doubling of signal amplitude, which is equivalent to a 6 dB increase in received level. Perfect destructive interference would result in complete cancellation. The fin whale call is not a tonal signal but a downswept chirp, so full constructive or destructive interference will not occur.

Interference between surface reflected and direct path arrival for the approximate geometry of this experiment was modeled for a series of different source depths and horizontal ranges. Based on inspection of recorded fin whale calls in the time and frequency domain, a simplified model of the call was developed, comprising a linear chirp with a 1-s duration, downswept from 25 to 15 Hz. The chirp amplitude was modulated over its duration using a 1-s Hann window. The model assumes a single layer of water with uniform sound speed and a depth of 2200 m. The ranges of the direct and surface reflected arrivals are calculated assuming straight line propagation. After accounting for a phase reversal for the surface reflected arrival, the time difference between the two paths can be used to calculate the effect of interference. The ranges are also used to calculate transmission loss, assuming simple spherical spreading for both the direct and surface reflected paths. The validity of the spherical spreading assumption was verified by comparing with transmission loss modeled using BELLHOP (Porter and Bucker, 1987). The comparison showed a bias of < 0.3 dB at $\theta_i < 20°$.

The model output for source depths between 5 and 60 m, for ranges between 0 and 3000 m, is summarized in Fig. 4. The RMS amplitude of the input source level was scaled to unit amplitude. For a source depth of 5 m, the travel time difference is small, but the surface reflected path is phase shifted by 180°, resulting in mostly destructive

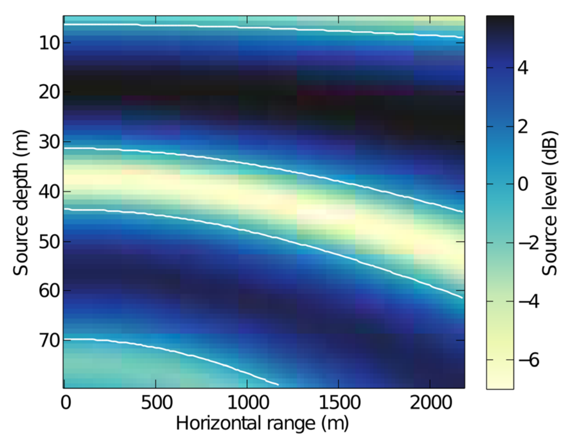

FIG. 4. (Color online) Result of interference between the direct path and surface reflected arrival for source depths between 5 and 80 m. Shading indicates the effect of the surface bounce on source level relative to the source level without a surface bounce. Propagation loss is estimated using spherical spreading over the distance of the propagation paths. White lines overlaid on the image indicate 0 dB contours where measured amplitude is equal to the input amplitude.

interference and a low amplitude for all ranges. A higher source level is predicted for a call depth of ~20 m because the surface reflection lags by approximately half a wavelength (where a full wavelength would be 75 m at 20 Hz and 1500 m/s), but with the 180° phase shift is nearly perfectly in phase with the direct path arrival. This results in almost complete constructive interference, and an increase of nearly 6 dB.

Due to the sensitivity of the calculations to incidence angle and range, the average position uncertainty of 400 m is expected to cause scatter in the resulting source level estimates. A model was developed to simulate the effect of depth and horizontal position uncertainty on the final source level, given the effects of both interference patterns and the Zoeppritz correction. A series of horizontal locations was randomly generated within 3000 m horizontal range of an instrument. Depths for each location were randomly generated assuming a Gaussian distribution with a mean of 50 m and standard deviation of 10 m. These were treated as the *true* call locations. The same amplitude modulated chirp used in the interference pattern model was used as input to this model. The RMS amplitude of the simulated source call was set to a pre-defined level. The *true* recieve level was calculated by combining the effect of both spherical spreading transmission loss and the interference between the direct path and surface reflected arrival for the *true* range and depth. From this, the *measured* vertical particle velocity was calculated using the Zoeppritz equations for the particular range and depth. A second set of horizontal locations was generated by adding Gaussian errors with a standard deviation of 400 m to the *true* horizontal positions to produce *measured* positions. These *measured* positions were used to calculate the Zoeppritz correction to convert back to the direction of the incoming signal. Finally, this value was corrected to represent a *measured* source level using spherical spreading transmission loss over the range between the instrument and the *measured* position of the calling whale. Because the source depth was unknown, no attempt was made to correct apparent measured source levels for interference from the surface reflected arrival. The output of the simulation is shown in Fig. 5(a). The combination of uncertainties results in scatter about the *true* source level. The upper limit of the simulated source level output at small incidence angles is limited to an increase of slightly less than 6 dB due to interference. The increase in this upper limit with increasing incidence angle, reaching a peak at the critical angle, is due to the Zoeppritz correction. There is increased scatter toward the smaller decibel values beginning near an incidence angle of 25°. This is a result of large errors in the Zoeppritz correction in the vicinity of the critical angle.

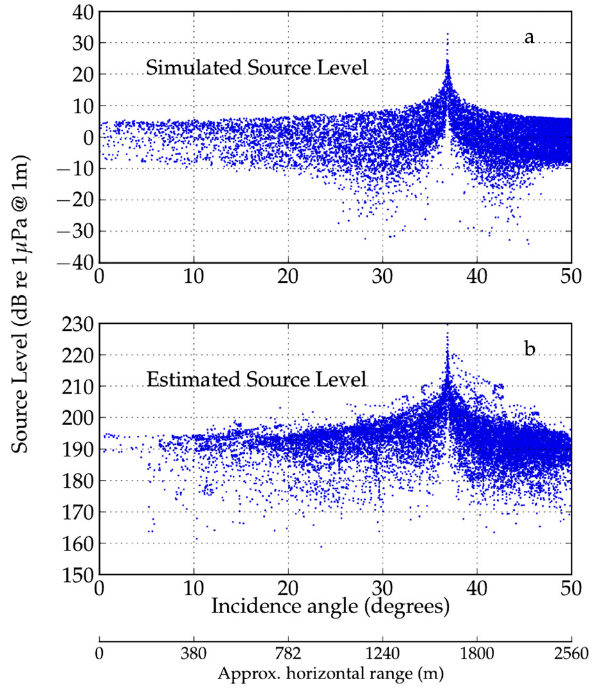

FIG. 5. (Color online) (a) Simulated source level output for an input source level of 0 dB and the same seafloor properties used in calculating the measured source levels. (b) Estimated source levels. Both are plotted versus incidence angle, but a second x axis shows approximate range for a call generated at a depth of 50 m and a water depth of 2200 m.

III. RESULTS

A. Source levels

Measured source levels from all instruments are shown in Fig. 5(b). There are fewer measurements at close ranges. Due to the increased uncertainty in the Zoeppritz correction and the increased errors that would arise from incorrect seafloor properties at large incidence angles (Fig. 3), calls used in source level estimates were restricted to those arriving at incidence angles < 20°. This reduces the dataset to a subset of 1241 calls from 32 individual whale tracks recorded between September 2003 and March 2004. Average source level within this subset is 189.9 ± 5.8 dB re 1 μPa at 1 m. Most of the calls used in the calculation occurred in November and December.

Interference effects were modeled for a variety of mean source depths and standard deviations of the depth. Only very shallow source depths (<10 m) resulted in variability greater than that in the observed data. At source depths greater than 10 m with standard deviations of source depth between 10 and 20 m, the standard deviation in the resulting modeled source levels is approximately 4–5 dB. This is 1–2 dB less than the measured standard deviation, suggesting that there may be some variability in the true source level. To test this, the model was repeated several times with Gaussian errors added to the input source level. A standard deviation of 4 dB added to the starting source level in the model resulted in a standard deviation of 5.7 dB within the first 20° of the model output (shown by dot-dashed lines in Fig. 6), which is close to the standard deviation of the data. The variability matches the model up until the cutoff frequency of 20°, where it begins to diverge, although there is a range dependent bias observed below 20°. The small standard deviation shown by the first error bar is likely the result of fewer tracks within this range bin.

Source levels were measured on all eight stations, and the mean and standard deviations of these are summarized in Table I. The lowest mean source level is measured by

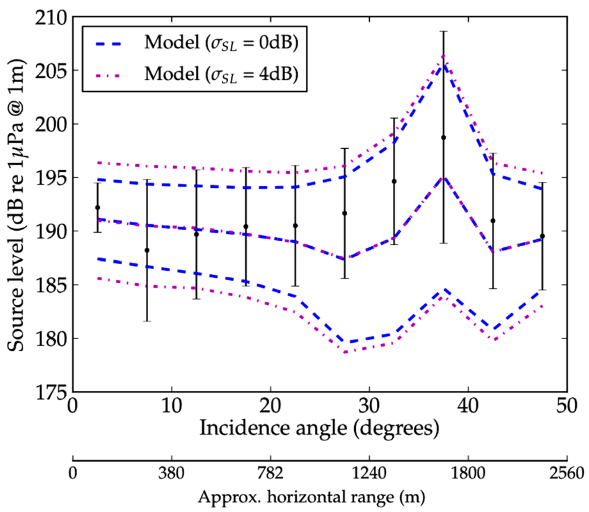

FIG. 6. (Color online) Comparison of the variability between simulated and estimated source levels. Variability in source levels is estimated by calculating the mean and standard deviation within 5-degree bins of incidence angle. The dots and error bars show the mean and standard deviation of the source level measurements [Fig. 5(b)], the dashed lines show the mean and standard deviation in the source levels calculated using the model [Fig. 5(a)], and the dot-dashed lines show the mean and standard deviation in the model where a 4 dB standard deviation has been added to the input source level.

KEBB, the one broadband instrument, at 183.3 dB. The highest mean source level, 194.2 dB, is measured at station KEMO. No significant seasonal trend was observed in the source level measurements.

B. Amplitude variation

A small number of track segments contained sufficient consecutive calls to investigate relationships between the inter-pulse interval, call frequency, and source level. The 25-s simple IPI and the 25/30-s dual IPI are interpreted to originate from a single vocalizing whale (Soule *et al.*, 2011). A total of two simple IPI and six dual IPI tracks were used in the analysis of amplitude variation. A typical single-whale track is shown in Fig. 7. Calls immediately following a gap longer than 27 s are consistently lower in amplitude and frequency and are believed to be backbeat calls. The backbeat calls for all tracks of this type are, on average, 2.7 dB lower in amplitude and 1.1 Hz lower in frequency. In Fig. 7, there is a negative trend in source level over time.

TABLE I. Summary of source level results for all stations. Decibel measurements are relative to 1 μPa at 1 m.

Station	μ_{SL} (dB)	σ_{SL} (dB)	n_{meas}	n_{tracks}
All	189.9	5.9	1241	36
KESQ	191.8	4.1	212	5
KEMF	186.4	7.8	110	5
KEMO	194.2	3.4	113	3
KESE	188.0	7.1	130	4
KENE	191.2	4.1	317	5
KENW	190.2	3.4	151	6
KESW	188.5	7.4	123	4
KEBB	183.3	4.5	85	4

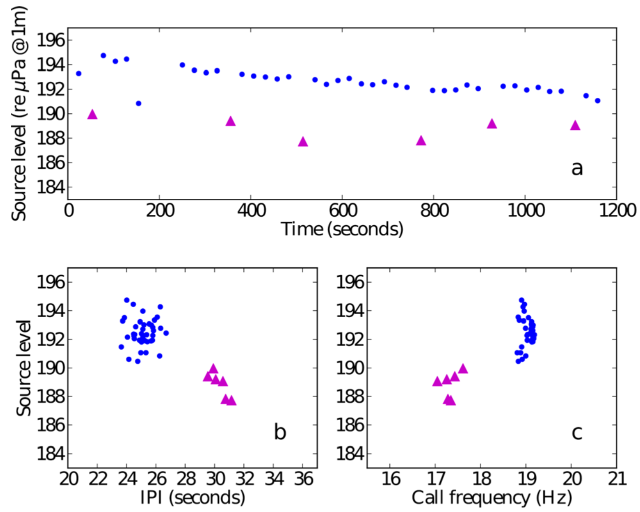

FIG. 7. (Color online) Example of a track with dominant IPIs near 25 and 30 seconds, interpreted as a single whale. (a) Source level measured over time, (b) source level versus IPI, and (c) source level versus call frequency. In all three panels, calls following an IPI less than 27 s are indicated by circles, and calls following IPIs longer than 27 s are indicated by triangles.

Complex IPI tracks have been interpreted to represent two or more whales calling together (Soule *et al.*, 2011). A total of four complex IPI tracks were resolved. Figure 8 shows an example of a complex IPI track with two dominant frequencies. The calls are divided into two groups based on frequency, where the mean of the lower frequency group is 19.7 Hz and the mean of the higher frequency group is 24.0 Hz. The calls alternate between the two frequencies over the duration of the track, possibly indicating communication. Mean source level is 192.7 dB for the lower frequency group and 191.8 for the higher frequency group, and there is a gradual increase in source level over time of approximately 5 dB.

Figure 9 shows an example of a complex IPI track with at least three different frequencies. The mean source levels for the frequency groupings shown in Fig. 9 are 184.1 dB for

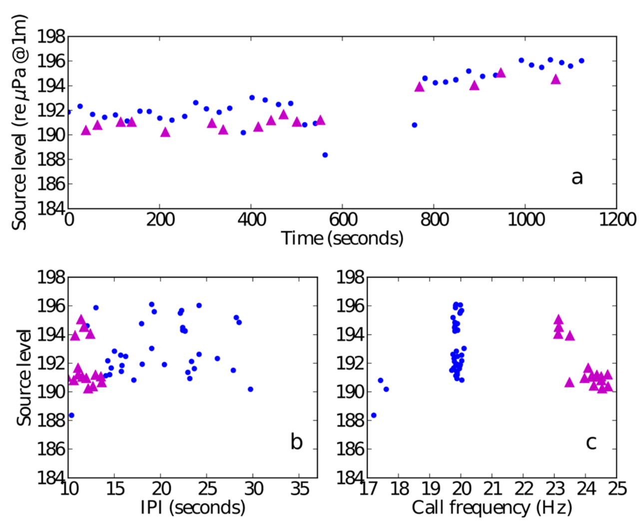

FIG. 8. (Color online) Example of a track with two whales calling (Complex IPI), plotted with the same conventions as Fig. 7, except symbols are assigned based on call frequency: Calls with center frequency <21 Hz and ≥21 Hz are indicated by circles and triangles, respectively.

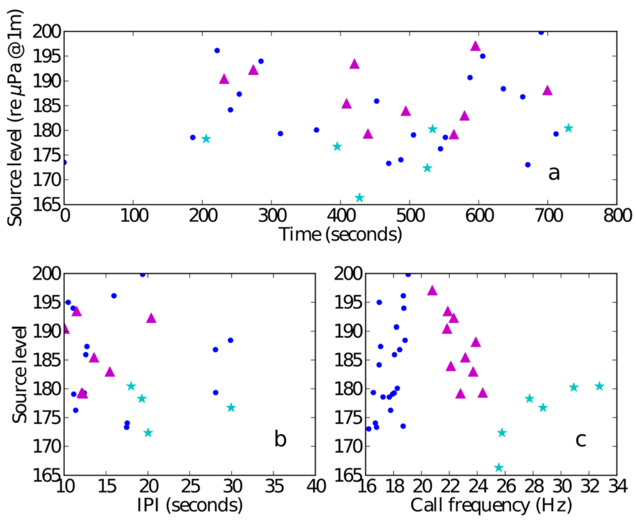

FIG. 9. (Color online) Example of a track with three or more whales calling together (complex IPI), plotted with the same conventions as Fig. 7, except symbols are assigned based on call frequency: Calls with center frequency <20 Hz, between 20 and 25 Hz, and ≥25 Hz are indicated by circles, triangles, and stars, respectively.

15–20 Hz, 186.2 dB for 20–25 Hz, and 175.7 dB for >25 Hz. This track shows a large spread in source levels for all three frequency groups. Because complex IPI tracks are interpreted to originate from multiple whales, the variability evident in this track may be indicative of variability between source levels from different individuals.

Call sequences for single-whale tracks were examined for either a positive or negative trend in source level over time following each pause of greater than 60 s. For both 25/30-s dual IPI tracks, and 25-s single IPI tracks, which are likely from a single calling whale, both positive and negative trends in source level are observed in about equal proportions.

IV. DISCUSSION

The average source level of 20 Hz fin whale calls measured in this study is 189 ± 5.8 dB re 1μPa at 1 m. This is generally consistent with other studies although it is at the higher end of the reported range. Charif *et al.* (2002) reported the only other measurements of source levels of fin whale calls in the northeast Pacific, and their mean, at 171 (159–184) dB re 1μPa at 1 m, is substantially lower. This may be due in part to differences in processing method. Charif *et al.* (2002) measure RMS amplitudes of individual calls over a 3-s window centered on the call. Because a fin whale call is approximately 1 s in length, the calculated amplitude will be reduced by a factor of 2/3, or ∼9.5 dB, compared to the 1-s measurement used in this study. Additionally, the amplitude for a given call described by Charif *et al.* (2002) is obtained from the loudest of four hydrophones. The loudest call is assumed to result from nearly complete constructive interference and is conservatively corrected using a reduction of 6 dB. For the geometry of the experiment, it is possible that the results could be biased by several decibels depending on the depth of the calling whale relative to the hydrophone array. Once these differences in methodology are taken into account, the results are closer to those described here, although average source level is still lower by about 5–10 dB. Source levels of fin whale calls are reported more recently by Širović *et al.* (2007) for the Southern Ocean. Source levels in this study were estimated using bottom-mounted hydrophones, where ranges to fin whale calls were estimated using the spacing between successive multipath arrivals recorded on single instruments. Their average source level of 189 ± 4 dB is similar to the results obtained in this study despite being measured in a different region.

Table I showed variability between stations, particularly station KEBB, which had a mean source level that was lower than the other stations. A *t*-test comparing the mean of KEBB to the rest of the dataset showed that it was likely part of a different population and therefore might not be appropriate for inclusion in the overall mean source level calculation. However, source levels estimated from different calls on the same track are unlikely to be independent because call amplitudes for a particular whale are likely to vary less than those for different whales, and the systematic portion of the location errors for calls on a track will be correlated. Conservatively, we might assume that each track, despite containing many calls, represents a single independent measure of source level. In that case, a single instrument might only measure a few whales, making it more difficult to draw the conclusion that the mean source level at KEBB belongs to a separate population. If these measurements do show a significant variability between stations, it may arise from errors in instrument calibration, different site characteristics, or different methods of deployment.

Figure 4 shows that for a whale calling very consistently at a depth of 25–35 m, the apparent amplitude of its call would increase gradually with increasing range. The same phenomenon would be observed at a consistent depth of between 65 and 70 m. If a fin whale was swimming consistently in one of these specific depth ranges, it could explain the divergence between the measured data and the model (Fig. 6). Alternatively the range dependent bias might arise because the model does not fully describe the physics of the interactions of acoustic waves with the seafloor and in particular, the generation of interface waves at larger incidence angles (Ewing *et al.*, 1957; Nolet and Dorman, 1996).

Uncertainty in the horizontal and vertical position of the fin whale was shown to introduce a large degree of scatter in the results as shown by the model [Fig. 5(a)]. However, the model does not describe all of the variability in the data. One explanation is that there is inherent variability in the sound levels produced by the whales. Some whales might vocalize more loudly than others or individuals might produce calls at different amplitudes. Another explanation would be site to site variability arising from differences in calibration between instruments or differences in acoustic environment at each site. Very little variation was observed within a single sequence, with the exception of backbeats. However, Fig. 9 showed greater than ±4 dB of variability from one frequency group to the next and also within calls from a single group. This may be indicative of differences in source level between individuals or it could be a result of different depths of vocalization. There is little evidence for a systematic change in source levels along tracks or within dives denoted by pauses. The trends observed are equally likley to be positive or negative and are most likely a result of systematic errors in the corrections to source levels arising from locations along a track.

Source level estimates depend on knowledge of the water and seafloor properties. The P wave velocity was shown to have the largest effect on the Zoeppritz correction in the vertical direction (Fig. 3). Error in the estimate of P wave velocity could reach up to 3 dB at an incidence angle of 20°. In addition to differences in overall scatter, the model results shown in Fig. 5(a) have a different distribution of source levels than the measured source levels shown in Fig. 5(b). The measured calls show larger overall spread in the range of source levels with a larger number of low amplitude calls relative to the mean, which may be a result of low amplitude backbeat calls.

Another source of uncertainty in this type of measurement may arise from sub-bottom arrivals that reach the instrument very close in time to the acoustic arrivals from the water column (Premus and Spiesberger, 1997). If the seafloor in the axial valley is modeled as a sheeted dike layer with a P wave velocity of 4.5 km/s overlaid by a 500 m thick extrusive volcanic layer with a P wave velocity of 2.5 km/s, the closest horizontal range at which this effect is likely to be observed is approximately 1.4 km ($\theta_i \sim 33°$). Because the source levels reported in this paper are limited to a maximum incidence angle of 20°, the effect should not be significant.

The observation that amplitudes are very consistent on a track, and show variations of only a few decibels between tracks has implications for the determination of range. Once the acoustic environment has been modeled, call amplitudes can be interpreted in terms of the range with relatively small variance. Improved range measurements would contribute to calculations of density estimation for population abundance. Knowledge of source levels and their distribution can also facilitate the calculation of acoustic communication space and the effect of anthropogenic noise sources.

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