Source level estimation of two blue whale subspecies in southwestern Indian Ocean

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Blue whales produce intense, stereotypic low frequency calls that are particularly well suited for transmission over long distances. Because these calls vary geographically, they can be used to gain insight into subspecies distribution. In the Southwestern Indian Ocean, acoustic data from a triad of calibrated hydrophones maintained by the International Monitoring System provided data on blue whale calls from two subspecies: Antarctic and pygmy blue whales. Using time difference of arrival and least-squares hyperbolic methods, the range and location of calling whales were determined. By using received level of calls and propagation modeling, call source levels of both subspecies were estimated. The average call source level was estimated to 179 ± 5 dB re 1 $\mu\text{Pa}_{\text{rms}}$ at 1 m over the 17–30 Hz band for Antarctic blue whale and 174 ± 1 dB re 1 $\mu\text{Pa}_{\text{rms}}$ at 1 m over the 17–50 Hz band for pygmy blue whale. According to previous estimates, slight variations in the source level could be due to inter-individual differences, inter-subspecies variations and the calculation method. These are the first reported source level estimations for blue whales in the Indian Ocean. Such data are critical to estimate detection ranges of calling blue whales. © *2010 Acoustical Society of America.* [DOI: 10.1121/1.3409479]

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I. INTRODUCTION

In the world's oceans, blue whales (*Balaenoptera musculus spp.*) are represented as at least three recognized subspecies based on morphologic distinctions and geographic distributions (Rice, 1998): *B. m. musculus* of the northern hemisphere, *B. m. intermedia* (the Antarctic or 'true' blue whale) of the Southern Ocean and *B. m. brevicauda* (the pygmy blue whale) of the Indian and South Pacific Oceans. The subspecies Antarctic and pygmy blue whales are both present in the southern hemisphere and differ somewhat morphologically (Ichihara, 1961), genetically (Conway, 2005; LeDuc *et al.*, 2007), acoustically (Ljungblad *et al.*, 1998; McDonald *et al.*, 2006) and they ostensibly inhabit different regions or latitudes at least during summer feeding period (Branch *et al.*, 2007).

Overexploitation during the 20th century by commercial whaling reduced blue whale populations to the brink of extinction (Clapham *et al.*, 1999). Despite gaining complete international legal protection several decades ago, blue whale populations remain at low levels and their recovery is uncertain. Nevertheless, populations of Antarctic blue whale seem to show signs of recovery (Branch *et al.*, 2004; Branch, 2008) while others, especially pygmy blue whale subspecies, have not been adequately monitored to determine their status. Today, the number of individuals, the seasonal occurrence, movements and distribution, the migratory routes, and the habitat preferences of many blue whale subspecies are still unknown (Branch *et al.*, 2007).

Monitoring blue whale subspecies to assess their distribution, movement, habitat preference and, finally the recovery of their populations remains difficult. This is especially true in high-latitude regions where standard visual surveys are costly and difficult. However, long-term deployment of passive acoustic recorders is a useful tool to monitor blue whale populations over ocean basins and long periods because blue whales emitted, almost year-round, redundant stereotyped low frequency calls (10–100 Hz) (e.g., Thompson *et al.*, 1996). Blue whale acoustic surveys help to identify areas of concentration, assess seasonal occurrence and distribution patterns, and potentially facilitate long-term monitoring of abundance through variations in call rates over years (Stafford *et al.*, 2001; Stafford, 2003; Širović *et al.*, 2004, 2009). Blue whale calls are geographically distinct in term of frequency, time and pattern that allows the distinction be-

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tween subspecies or subpopulations (reviewed in McDonald *et al.*, 2006). Finally, blue whale calls are among the most powerful sounds emitted by any animal (Cummings and Thompson, 1971). The source level measured from blue whale calls is very high (Richardson *et al.*, 1995) and can be detected for ranges of many hundreds of kilometers by other individuals or by passive acoustic monitoring systems (Cummings and Thompson, 1971; Clark, 1995; Stafford *et al.*, 1998, 2007; Širović *et al.*, 2007). The main characteristics of blue whale calls suggest that they are designed for long-range communication (Payne and Webb, 1971; Clark and Ellison, 2004) even if the hearing capacity of blue whales remains unknown (McDonald *et al.*, 2006). Currently, the behavioral context and functions of most blue whale calls are not well understood. Long patterned calling is believed to be a mal mating display (Oleson *et al.*, 2007a, 2007b).

There are surprisingly few source level estimates for blue whales and quantifying the range of source levels for different blue whale subspecies is necessary to improve the performance of passive acoustic monitoring programs, enhance our knowledge on the communication process of large baleen whales (Cato, 1998) and contribute to a better understanding of the potential impact of anthropogenic noise on critical habitats of these endangered species. Published estimates call source level of blue whale range from 180 to 189 dB re 1 μPa_{rms} at 1 m from different locations and by different methods (Cummings and Thompson, 1971; Cato, 1998; Thode *et al.*, 2000; McDonald *et al.*, 2001; McCauley *et al.*, 2001; Širović *et al.*, 2007). Propagation losses from source to receiver are subject to significant variability caused by many factors and given the variability of the source level estimating methods used, we propose to estimate source level of calls emitted by two blue whale subspecies using the same method in the same area with similar sound propagation conditions. In this paper, we report the estimated source levels of calls produced by the Antarctic and the pygmy blue whale, recorded at a hydroacoustic station of the International Monitoring System (IMS) moored in Southwestern Indian Ocean.

II. METHOD AND MATERIALS

A. Dataset

Acoustic data from May 2003 to April 2004 used for this study were recorded at a station of the IMS moored in the Southwestern Indian Ocean (Crozet Islands –46°51′S-51°53′E) in support of the Comprehensive Nuclear Test-Ban Treaty (CTBT) (Fig. 1). The station was composed of three instruments (S1, S2, S3) deployed in a triangular configuration (triad) with approximately 2 km spacing. Instruments were moored to the seafloor between 1100 and 1500 m depths and hydrophones were suspended near the sound channel axis (SOFAR) at a depth of approximately 300 m. Maximum error in the instruments positions was estimated to be less than 30 m, assuming currents in this area.

The hydrophones monitored sound continuously at a sampling rate of 250 Hz, coded by 24 bits (S/N: 126.5 dB) with a flat (±3 dB) frequency response from 1.2–102.5 Hz.

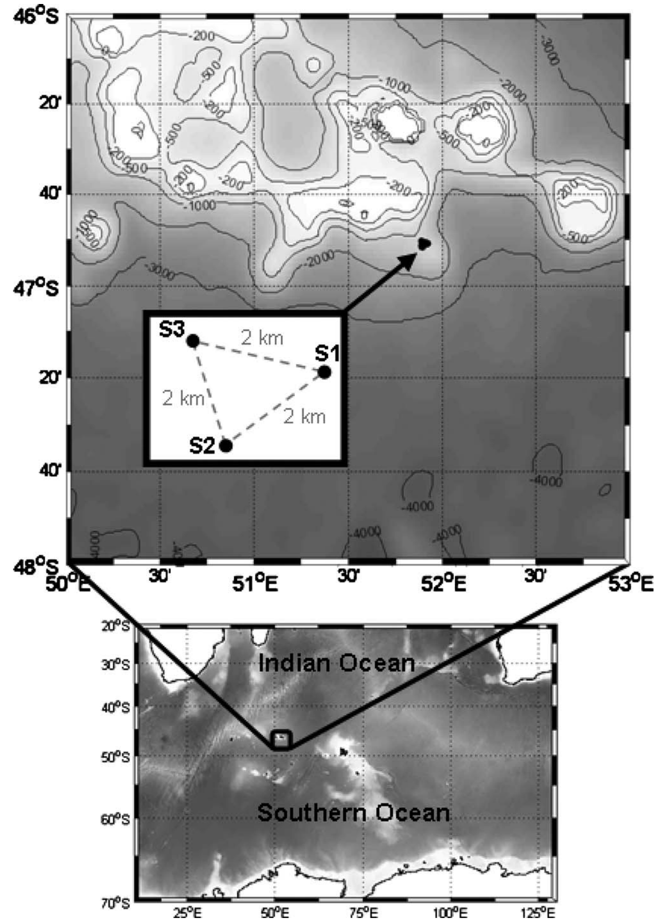

FIG. 1. Location of the hydroacoustic station of the IMS near Crozet Islands.

The hydrophones were calibrated with a calibration of −56.6 dB re: counts $2/\mu Pa^2$ in the 10–50 Hz band. The data were time stamped within 0.7 ms±0.1 ms with the use of a global positioning system clock. Acoustic data for H04S1 and H04S3 were available for the entire recording period; data for H04S2 were available only from May 2003 to December 2003.

Recordings from the hydrophones included a large variety of sounds including Antarctic blue and pygmy blue whale ‘Madagascar type’ calls. Antarctic blue whale calls (Fig. 2(a)) consist of three tonal units lasting approximately 26 s, and repeated in patterned sequences every 40–50 s over period extending from a few minutes to hours (Ljungblad *et al.*, 1998; Širović *et al.*, 2004; Stafford *et al.*, 2004; Rankin *et al.*, 2005; Samaran *et al.*, 2008). The first component is a constant frequency tone centered on 28 Hz followed by a short frequency-modulated (FM) down-sweep from 28 Hz to 20 Hz ending with the third component, a slightly modulated tone (20–18 Hz). Pygmy blue whale ‘Madagascar type’ calls (Fig. 2(b)) consist of two long units repeated in patterned sequences every 90–100 s over a period extending from a few minutes to hours (Ljungblad *et al.*, 1998; Samaran *et al.*, 2008). The first component is primarily a constant frequency tone at 35 Hz lasting 15–20 s. A silence (approximately 20 s) separates the two-part phrase. The second component starts

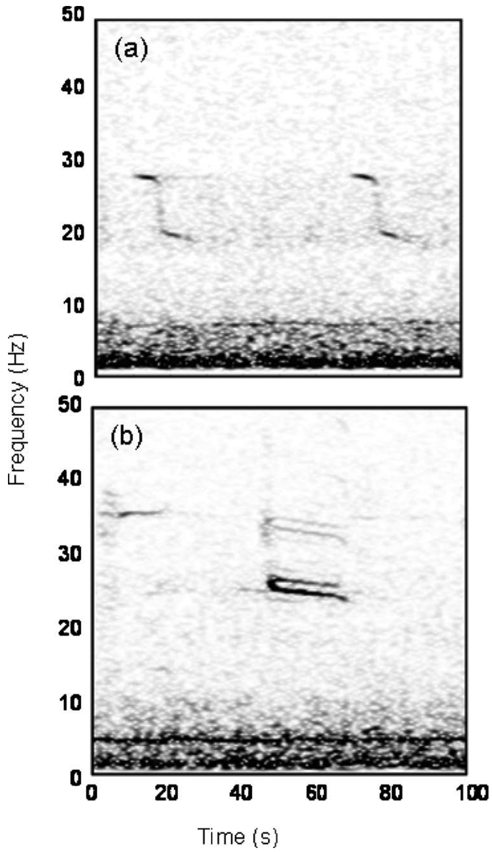

FIG. 2. Spectrograms of (a) two Antarctic blue whale calls and (b) one pygmy blue whale "Madagascar" type call, recorded on the hydroacoustic station of the International Monitoring System (spectrogram parameters: FFT 1024 points, 93.75% overlap, Hanning window).

with a 1–2 s 15–28 Hz FM down-sweep that ends with a long (20 s) slightly modulated tone. Each component has strong associated harmonics.

B. Detection of blue whale calls

To estimate Antarctic and pygmy blue whale source levels, the measured received level of calls on the hydrophones and the distance to the calling whale to each instrument of the triad are needed. To begin, the acoustic data from each instrument on both triads were analyzed to check the presence of calls typically associated with Antarctic and pygmy blue whales. An automatic detection method was employed to detect both call types using a matched filter process which cross-correlated the acoustic data with synthetic waveforms (templates) defined for both blue whales subspecies calls (based on the limited range of variability in the blue whale calls, see details in Samaran *et al.*, 2008). A detection threshold was chosen to provide a low false alarm rate. For each call detected, the arrival time corresponding to the peak correlation between the signal and the template was extracted. Received level (rms, in dB re 1 $\mu Pa^2/Hz$) was measured for each call detected as follows:

$$RL_{dB} = 10 \log_{10}\left[\frac{1}{T}\int_0^T x^2(t)dt\right],$$

where RL is the received level (in dB), T is the signal duration of the filtered signal.

Antarctic blue whale call received levels were measured over 17–30 Hz and pygmy blue whale call received levels were measured over 17–50 Hz. The signal-to-noise ratio (SNR) of the acoustic record was generally poor during the entire recording period. Therefore only a few calling blue whales were located near enough to the station that they were detected on all three instruments of the triad during the same time period. This limited the number of whale calls available for analysis.

C. Localization

A combination of time difference of arrival (TDOA) and least-squares hyperbolic approach was used to determine the range to and location of calling whales. This consisted of measuring the arrival time delay of the same call or sequence of calls recorded on multiple pairs of instruments to produce intersecting localization hyperbolas determining the precise position of the calling whale. This method has been used to locate and to track cetaceans, and blue whales in particular (Cato, 1998; Clark and Ellison, 2000; Stafford *et al.*, 1998; Širović *et al.*, 2007).

The method requires (1) a minimum of three, and ideally four or more, time-synchronized instruments, (2) spaced closely to allow the record of the same call on all of them but (3) widely-spaced enough to locate animals within a broad area (Spiesberger, 2001; Mellinger *et al.*, 2007). The hydroacoustic station of the IMS fit the first two first requirements. However by taking into account the maximum possible travel time delays of signals recorded on the instruments, only calling blue whales moving through or at close range of the triad could be tracked. For each blue whale subspecies, sequences of calls recorded on each instruments of the triad were identified by using intercall intervals. To reduce positioning errors, only those call sequences with more than 4 calls and a high SNR detected on all the hydrophones of the triad were used. Visual inspection of the spectral signatures of sequences of calls further ensured that the calls originated from a single individual. Under these circumstances, only one sequence of repeated calls for each blue whale subspecies was available.

1. Time difference of arrivals

TDOA were measured call-by-call for each pair of instruments that composed the triad. The detected call on one hydrophone was cross correlated with the other hydrophones within a ± 2 s window around the detection time. Peaks in the cross-correlation functions indicated the presence of the same call in the other hydrophone recordings. Lag time between the cross correlations peaks provided the TDOA data. TDOA were estimated by using both time domain waveform and spectrogram cross-correlations on the filtered signal. For the sequences of calls used in this study, both cross-correlation methods gave similar TDOA. However, spectrogram correlation was more consistent and provided a more stable measurement of TDOA, compared to time domain waveform correlation method. As TDOA were computed for relatively few blue whale calls in post-processing analysis,

TABLE I. Maximum theoretical TDOA of a signal between multiple pairs of instruments that compose the hydroacoustic stations (H04S1, H04S2, and H04S3)

	Distance between instrument (km)	Maximum theoretical TDOA (s)
S1–S2	2.0479	1.4262
S1–S3	2.0772	1.4460
S2–S3	2.0851	1.4513

computation time was not taken into account in the choice of the method and spectrogram cross-correlation was used in all further analysis.

A maximum theoretical TDOA allowed by the triad configuration was calculated for sources located in the same axis of the pair of hydrophones as:

$$\tau_{12} = \frac{d_{12}}{c_0},$$

where d_{12} is the distance between a pair of instruments H_1 and H_2, τ_{12} is the delay in arrival times of the calls received at the hydrophones from a same source and c_0 is the speed of sound, which was assumed to be constant and homogeneous because the hydrophones were close together. The sound speed (c_0) was deduced from the sound speed profile in the study area during austral winter as $c_0 = 1480$ m/s. Maximum theoretical time differences between multiple pairs of instruments that composed the station were calculated by taking into account the maximum error on the hydrophone positions and the precision of the time delay estimation (Table I).

2. Hyperbolic approach

The TDOA between pairs of instruments resulted in possible positions of a calling whale as a two dimensional hyperbola. Considering that the 2 hydrophones are on the y-axis, the first at $H_1[0,-(d_{12}/2)]$ and the second at $H_2[0,(d_{12}/2)]$; the x-axis is normal to the y-axis and intersects the y-axis at the middle of the $[H_1;H_2]$ segment. When the calling whale is at a $S(x_s.z_s)$ position, the hyperbolas equation for one pair of instruments is

$$\frac{z_s^2}{a_{12}^2} - \frac{x_s^2}{b_{12}^2} = 1, \quad (1)$$

where

$$a_{12}^2 = \left(\frac{c_0\tau_{12}}{2}\right)^2$$

and

$$b_{12}^2 = \frac{d_{12}^2 - (c_0\tau_{12})^2}{4}.$$

Note that $d_{12}^2 - (c_0\tau_{12})^2 > 0$, $d_{12} > |c_0\tau_{12}|$, $c_0 > 0$ and $d_{12} > 0$.

Equation (1) is the equation of the hyperbola, which center is the middle of the $[H_1;H_2]$ segment, which axis is the line given by the 2 hydrophones and which eccentricity e_{12} is defined by

$$e_{12} = \frac{d_{12}}{c_0|\tau_{12}|}. \quad (2)$$

The whale is located on the hyperbola closest to H_2 when $\tau_{12} < 0$ and closest to H_1 when $\tau_{12} > 0$.

With one pair of instruments, it is possible to deduce the bearing lines of the calling source with a left-right ambiguity relative to the line between the two instruments. The ambiguity was solved with the second calculated hyperbola of the other pair of instruments that composes the triad. Here, bearing lines of a calling source were obtained when two hyperbolas resulted in the same direction. Finally, a third hyperbola was calculated for the last pair of instruments that compose the triad. The intersection of the three hyperbolas defines the precise position of the calling source. This position was calculated using a least-squares optimization of the resulting intersection of the three hyperbolas. Range of the calling whale to each instrument was calculated with the resulting position. The location of successive calls along the same sequences defined the calling whale tracks around the array area. Minimum whale travel speeds were obtained using the time difference between consecutive positions, and assuming a straight-line travel between them.

D. Source level estimation

For each blue whale subspecies, the call source level (SL) was calculated as follows:

$$\mathrm{SL} = \mathrm{RL} + \mathrm{TL}, \quad (3)$$

where RL is the received level and TL the transmission loss.

TL can be described as a function of the range (R).

$$\mathrm{TL} = X \log_{10}(R/R_0), \quad (4)$$

where R_0 is the reference range (taken to be 1 m) and X is the transmission loss coefficient. This coefficient is environment-dependent and has the value of 20 when used under spherical spreading conditions ($R < 2$ km) and 10 in cylindrical spreading conditions ($R > 2$ km). Here, this value corresponds to the slope of the linear least-squares fit of call received levels and logarithmic of calculated ranges of calling whale estimated using hyperbolic localization. In our analysis, estimated values of X are close to 20, therefore the spherical spreading model was chosen due to the low distances between the instruments that are used for the tracking of calling blue whales moving close to the triad. The source level was estimated separately for each instrument, and the average of these three values was used to calculate source level for each call. Standard deviation for each estimate was calculated.

E. Location comparison with PMCC method

We tested our bearing results obtained with TDOA/hyperbolic approach by comparing it with a progressive multi-channel correlation (PMCC) method, previously used to detect seismic and infrasound events recorded on arrays similar to IMS hydroacoustic stations (Cansi, 1995). This method is based on a progressive study of the inter-instrument correlation functions, which leads to a consistent set of time-delays when a seismic phase going through a station (Cansi and Klinger, 1997; Le Pichon and Cansi, 2003). Detection is performed by testing the consistency of time-delays τ_{ij} using the following closure relation:

$$\tau_{ij} + \tau_{jk} + \tau_{ki} = 0. \quad (5)$$

In case of detection suggesting that a wave is then traveling through the array, velocity and bearing angle are deduced from this set of time-delays. For each call of a sequence, bearing of the calling source was estimated and the coherent variation of bearings of the calling source during time was compared to the bearings estimated by the TDOA method (correlation coefficient for angular variables, circular version of the Pearson's product moment correlation, Jammalamadaka and SenGupta 2001; performed in R 2.7.1).

III. RESULTS

A. Antarctic blue whale tracking and source level

In July 2003, five sequences of Antarctic blue whale calls, composed of 4 to 20 calls each, were selected, taking into account conditions described above. Using our automated detection method, we focused on the calls with the best SNR. These calls were detected during 4 consecutive hours (from 0700–1100) on 2 to 3 instruments of the station. Bearings of the calling source were estimated with TDOA/hyperbolic approach and PMCC method. Both methods revealed a progressive change in the direction of the calling source with time, with azimuth ranging from 235° to 80° (correlation coefficient for angular variables, $n=103$, corr $=0.97$, $p<0.01$). The changes in bearing were greater during hour 0900. During this period, interval intercalls were very regular suggesting a single Antarctic blue whale was producing all calls (Fig. 3(a)). The range of the calling whale to each instrument was calculated for 5 sequences (28 calls total). SNR was high and received levels on each instrument increased slightly with time, suggesting that the calling whale was getting closer to the station (Fig. 3(b)). The accurate position of the calling source given by the intersection of the three hyperbolas was computable for 7 calls. The 30 min tracking revealed the blue whale had moved close to the S2 hydrophone (Fig. 4(a)). The apparent travel speed was 15 ± 10 km/h. The transmission loss coefficient was -17 dB/m (Fig. 4(b)). Given these values, the average source level of these Antarctic blue whale calls was estimated to 179 ± 5 dB re 1 $\mu\text{Pa}_{\text{rms}}$ at 1 m over the 17–30 Hz band.

B. Pygmy blue whale tracking and source level

During the recording period few pygmy blue whale calls were detected at the station. However, in May 2003, pygmy blue whale calls were detected during 2 consecutive hours (51 calls total) on 2 to 3 instruments of the station. As explained above, the bearings of the calling source were estimated with TDOA/hyperbolic approach and PMCC method and both methods revealed a progressive variation in the direction of the calling source with, with azimuth ranging from 70° to 225° (correlation coefficient for angular variables, $n=35$, corr$=0.95$, $p<0.01$). Intercall intervals were regular, suggesting a single pygmy blue whale was recorded

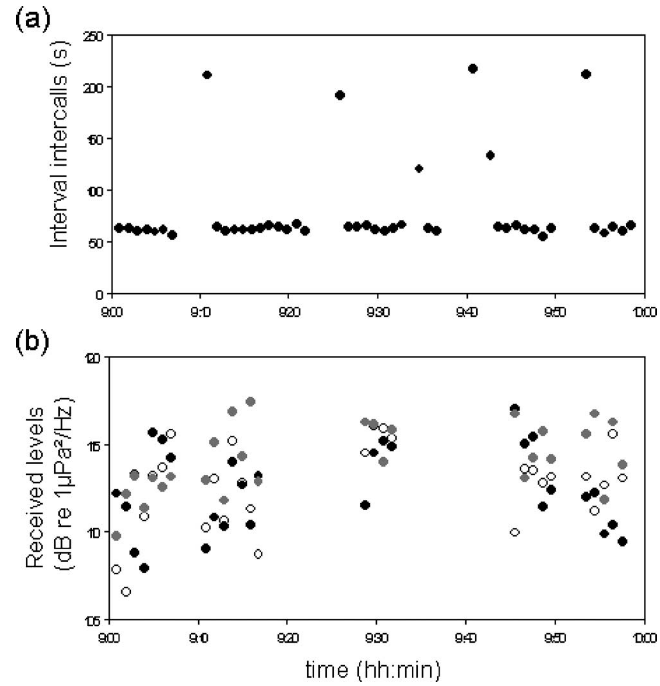

FIG. 3. Antarctic blue whale: (a) interval intercalls for the complete hour of record and (b) received levels (S1: dark, S2: white, and S3: gray) for the four sequences of calls retained for the tracking.

during this period of time (Fig. 5(a)). SNR was good and received levels were variable for the three instruments suggesting that the calling whale moved from the hydrophone S1 to the hydrophone S2 (Fig. 5(b)). The accurate position of the calling source given by the intersection of the three hyperbolas was computable for 23 calls. Representation of the track during one hour revealed that the calling whale moved through the array (Fig. 6(a)). The apparent speed was 5 ± 3 km/h. The transmission loss coefficient was -21 dB/m (Fig. 6(b)). The average source level of pygmy blue whale calls 'Madagascar' type was estimated to 174 ± 1 dB re 1 $\mu\text{Pa}_{\text{rms}}$ at 1 m over the 17–50 Hz band.

IV. DISCUSSION

Our study used two methods to deduce the bearings of the calling source, TDOA/hyperbolic approach and PMCC method. Using two different methods allow us to compare the results for validation for the little number of sample available for analysis. Results were significantly similar and it was the first time that we used PMCC method to detect biological events such as whale calls. This comparison illustrates that hydroacoustic methods used for seismic or infrasound studies can also provide valuable tools with regards to the tracking of vocal marine mammals.

Our study used TDOA and calling whale bearing to estimate source levels for two subspecies of blue whales. Source level estimates require high SNR and that the source be close to the hydrophone array for our study area. If these two requirements are not met, substantial errors in source level estimates may occur rendering these estimates highly inaccurate. Because of these stringent requirements, calling sequences from only one individual of each subspecies met these requirements. Nevertheless, given the paucity of data

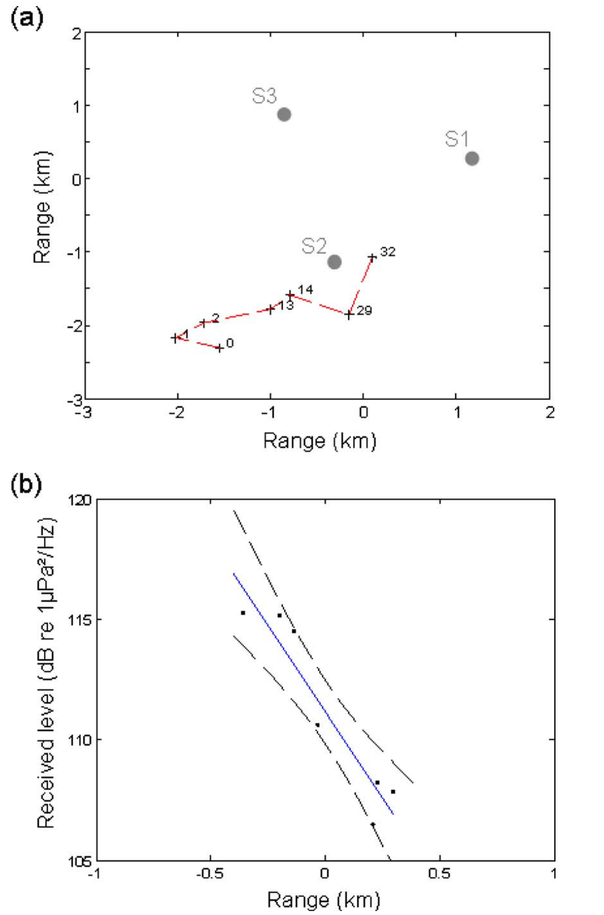

FIG. 4. (Color online) Antarctic blue whale: (a) track of a single blue whale moving through the study area. Whale calls were repeatedly located by time-of-arrival differences at the hydrophones (each point represent location of calling whale deduced from TDOA/hyperbolic methods). (b) Plot of Antarctic blue whale received levels versus calculated range (best fit and errors at 95%).

on blue whale source levels, we believe that our estimates represent a valuable contribution to the study of blue whale acoustics.

Estimates of the transmission loss coefficient for both tracks were comparable to the spherical spreading model (i.e., 20) because the calling whales were in close range to the hydrophone array. At these distances, spherical spreading conditions are applicable and the transmission loss coefficient used to determine source level could be directly chosen and not estimated. In this context, differences in source level estimation could be attributed to inter-subspecies variations.

The average call source levels of different blue whale subspecies have been previously estimated at several worldwide locations using several methods (Cato, 1998). In the Pacific Ocean, Northeast blue whale call source level (type B) was estimated in the 10–110 Hz band to be 186 dB re 1 μPa_{rms} at 1 m (McDonald *et al.*, 2001). Southeast Pacific blue whale call source level was slightly higher: 188 dB re 1 μPa_{rms} at 1 m (Cummings and Thompson, 1971) but this value was estimated in the 14–220 Hz band. Both estimates were obtained using a spherical spreading model and visual estimates of the distance to calling whales. It was also assumed that the whales in view were those producing sounds. By using a complex sound propagation modeling technique

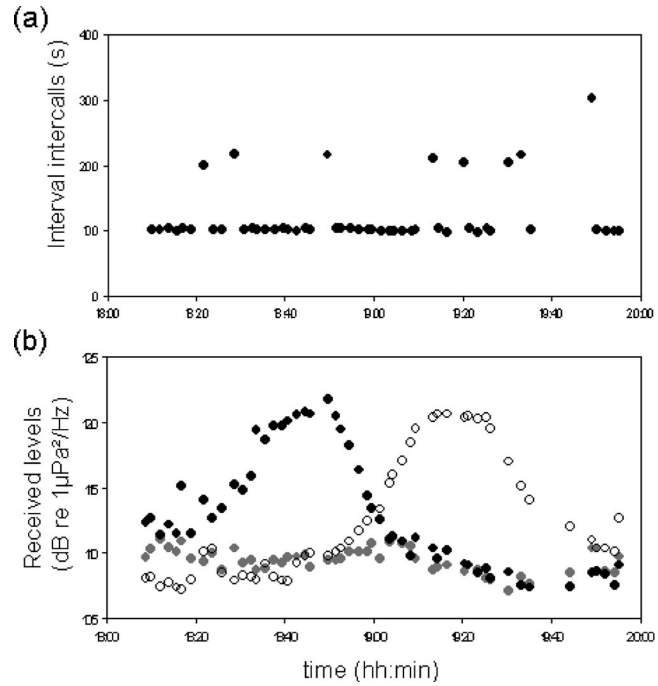

FIG. 5. Pygmy blue whale: (a) interval intercalls for the 2 consecutive h of record and (b) received levels (S1: dark, S2: white, and S3: gray) for the sequences of calls retained for the tracking.

to localize blue whale sources in a three-dimensional space using recordings from linear and vertical hydrophone arrays, Thode *et al.* (2000) estimated a lower blue whale source level in northeast Pacific Ocean (180 dB re 1 μPa_{rms} at 1 m). Two of these three estimates of blue whale source level were measured for call produced by the northern hemisphere blue whales (Thode *et al.*, 2000; McDonald *et al.*, 2001) while the third was from the southeast Pacific Ocean (Cummings and Thompson, 1971). These two populations have been considered as the more morphologically similar to the 'pygmy' type blue whales subspecies (Gilpatrick and Perryman, 2008). Source level estimation of Antarctic blue whale calls was estimated to be 189 ± 3dB re 1 μPa_{rms} at 1 m in the 25–29 Hz bandwidth in Western Antarctic Peninsula (Širović *et al.*, 2007) using measured received level on calibrated array of hydrophones and a transmission loss model adapted to the ranges of calling whale calculated with hyperbolic localization. The source level of the type II component of 'Australia' type calls produced by pygmy blue whales was estimated to be 183 dB re 1 μPa_{rms} at 1 m (McCauley *et al.*, 2001) in the Indian Ocean by using multipath signals to estimate the range and depth of calling whales from the relative arrival time and received level of the direct and surface reflected signals. No source levels for any other pygmy blue whale acoustic populations have been reported. The purpose of this work was to estimate source levels of calls produced by two different blue whale subspecies using the same array of hydrophones. Our results were within the lower range of published source levels. Even if differences in source level estimation could be attributed to inter-individual-subpopulation or -subspecies variations, it is clear that the choice of broadband, sound propagation modeling techniques and localization methods could explain the major part of these differences between studies.

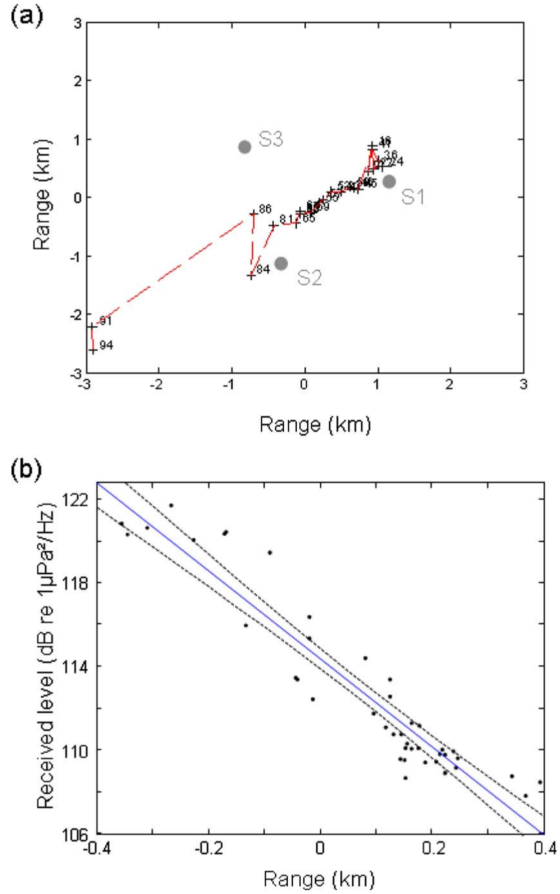

FIG. 6. (Color online) Pygmy blue whale: (a) track of a single blue whale moving through the study area. Whale calls were repeatedly located by time-of-arrival differences at the hydrophones (each point represent location of calling whale deduced from TDOA/hyperbolic methods). (b) Plot of pygmy blue whale received levels versus calculated range (best fit and errors at 95%).

Antarctic blue whale source levels reported here are 10 dB lower than the single Antarctic blue whale source level reported previously near Antarctica Peninsula (Širović *et al.*, 2007). This great difference could be attributed to the frequency range chosen. Širović *et al.* (2007) only estimated the source level of the first component of the call whereas we used the entire signal. Our whale was much closer to our receivers than those from the Antarctic Peninsula (Širović *et al.*, 2007) so this difference is not due to our overestimating transmission loss. It is possible that the difference could be due to inter-individual variation as we only have data from a single whale. Behavioral context, gender, breeding status could also affect source level values (Oleson *et al.*, 2007b). When a number of measurements have been made, significant variation in a source level has been observed for bowhead (Cummings and Holliday, 1987), finback (Watkins *et al.*, 1987), humpback (Thompson *et al.*, 1986) and blue whales (Širović *et al.*, 2007). Methods to estimate marine mammal source level don't allow to avoid the high probability of near field effects, it's the same for the propagation losses from source to receiver that are subject to significant variability caused by many factors. Finally, best estimates will always result from best assumptions of such losses combined with the largest number of samples over similar paths over time variations.

For a few decades now, passive acoustic approaches have been used to efficiently monitor calling whales over ocean basins (Mellinger *et al.*, 2007). Passive acoustic systems allow an assessment of the seasonal occurrence, movement, and distribution patterns of vocal whale populations (e.g., Stafford *et al.*, 1998), and could ultimately be used to estimate their density (Marques *et al.*, 2009). However, the capacity of passive acoustic monitoring systems strongly relies on the characteristics of the whale calls, the local ambient noise levels, and the propagation conditions (Stafford *et al.*, 2007). To estimate passive acoustic density, information like the probability of detecting calls is also needed. The detection probability is highly dependent on the distance of an animal from the receiving hydrophone. In this case, sound propagation and detection models for the call source level at the corresponding frequencies need to be used. In the same vein, to estimate maximum detection range of listening systems, sound propagation conditions and transmission loss of the whale calls in the monitored basin are also required. Acoustic propagation models are clearly necessary but their accuracy is highly dependent on the input parameters listed above (Stafford *et al.*, 2007). In this context, data on the precise source level for a specific blue whale subspecies (versus an estimate) will improve models that will ultimately determine the detectability and detection range of passive acoustic system for different species. Such information has the potential to improve our ability to move from inferences about the number of whales present to more realistic estimates; data that are needed to help in the recovery and conservation of difficult to study species such as blue whales.

V. CONCLUSIONS

Although we only provide source level estimates for on individual from each of two subspecies (Antarctic and pygmy 'Madagascar type' blue whales), given the paucity of data on blue whale source levels, we believe that our estimates represent a valuable contribution to the study of blue whale acoustics. Estimates of absolute levels of sounds produced and received by blue whale in their natural environment contribute to our understanding of the relative levels of biologic and anthropogenic sounds in relation to whale hearing, masking, and potential physiological damage. This work illustrates that hydroacoustic stations deployed for the IMS can also provide valuable data with regards to the monitoring and tracking of vocal marine mammals, allowing the study of their behavior without human disturbance. Future efforts to exploit the dual-use of this unique data set includes determination of the maximum acoustics detection range for each blue whale subspecies by using an acoustic propagation model configured with the precise characteristics of the source (frequency, source level) and the ambient noise levels received at the hydroacoustic station, as well as studying the seasonal variation of attenuation of low frequency sound present in the Crozet Islands.

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