Tracking of Pacific walruses in the Chukchi Sea using a single hydrophone

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The vocal repertoire of Pacific walruses includes underwater sound pulses referred to as knocks and bell-like calls. An extended acoustic monitoring program was performed in summer 2007 over a large region of the eastern Chukchi Sea using autonomous seabed-mounted acoustic recorders. Walrus knocks were identified in many of the recordings and most of these sounds included multiple bottom and surface reflected signals. This paper investigates the use of a localization technique based on relative multipath arrival times (RMATs) for potential behavior studies. First, knocks are detected using a semi-automated kurtosis-based algorithm. Then RMATs are matched to values predicted by a ray-tracing model. Walrus tracks with vertical and horizontal movements were obtained. The tracks included repeated dives between 4.0 m and 15.5 m depth and a deep dive to the sea bottom (53 m). Depths at which bell-like sounds are produced, average knock production rate and source levels estimates of the knocks were determined. Bell sounds were produced at all depths throughout the dives. Average knock production rates varied from 59 to 75 knocks/min. Average source level of the knocks was estimated to 177.6 ± 7.5 dB re 1 μPa peak @ 1 m. © *2012 Acoustical Society of America*. [DOI: 10.1121/1.3675008]

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I. INTRODUCTION

Pacific Walruses (*Odobenus rosmarus divergens*) are segregated by gender for much of the year (Fay, 1982). Adult females and young follow the ice edge as it recedes through the Chukchi Sea in summer and return to the Bering Sea in winter, while most males stay in the Bering Sea year round (Fay, 1982; Fay *et al.*, 1984; Jay *et al.*, 2008). Recent trends of decreasing sea ice coverage (Stroeve *et al.*, 2007) and recent increase in anthropogenic activities in the Arctic could affect walruses and their habitat (CBD, 2008). The potential effects are presently uncertain, but reduced sea ice or increased anthropogenic activity near feeding habitat could be detrimental to walruses (Learmonth *et al.*, 2006; CBD, 2008). In view of those potential uncertainties, new monitoring methods are desired to study walruses in their natural habitat.

Studying walruses in the wild is often difficult due to the harshness of their habitat (i.e., remote locations, cold weather, unstable ice). Monitoring methods such as aerial visual surveys (Estes and Gol'tsev, 1984; Gilbert, 1989) and aerial infrared imagery (Udevitz *et al.*, 2008; Burn *et al.*, 2009) are the most common approaches, but these methods are often constrained by bad weather and they require animals to be at the surface or hauled out on ice. Electronic tags equipped with depth and location recorders can be attached to a tusk or anchored subdermally into the animal's blubber. These tags provide highly valuable information about walrus movements underwater but they are difficult to deploy. Tags are also intrusive and often involve chemical immobilization of the animals (Wiig *et al.*, 1993; Gjertz *et al.*, 2001; Jay *et al.*, 2001, 2006). Stirling *et al.* (1983) showed that passive acoustic monitoring was a valuable tool for the study of pinnipeds in the Arctic at large scale. Although the deployment of multiple acoustic recorders can be expensive, this type of monitoring is entirely non-intrusive and can capture presence information for relatively long periods of time. Acoustic monitoring also has some ability to provide local behavioral information; we describe here a method analyzing acoustic data to track the depth and distance of free-ranging walruses near passive acoustic recorders.

Walruses are loquacious animals able to produce sounds both airborne and underwater. Their underwater repertoire includes a great variety of grunting sounds, knocks and bell-like sounds. Grunts have not been well described in the literature. They are short (~0.2 s) low frequency vocalizations with most of the energy below 1 kHz and usually containing harmonics (Fig. 1, Stirling *et al.*, 1983; JASCO unpublished data). Figure 1(a) shows a succession of chimp sounds which are the most distinctive type of walrus grunts found in the eastern Chukchi Sea during the summer. Knocks are low frequency pulses (most of the energy between 500 and 2000 Hz) usually repeated in long sequences [Fig. 1(b), 2, Stirling *et al.*, 1983, 1987; Fay *et al.*, 1984; Sjare *et al.*, 2003]. Stirling *et al.* (1987) and Sjare *et al.* (2003) showed that during the breeding season, mature males produce series of highly stereotypical knock sequences (songs). Bell-like sounds, first reported by Schevill *et al.* (1966), are the most distinctive walrus calls [Fig. 1(b)]. It may be given singly, in short series or, most often, at the end of a series of knocks (Stirling *et al.*, 1983, Sjare *et al.*, 2003). Although never reported in

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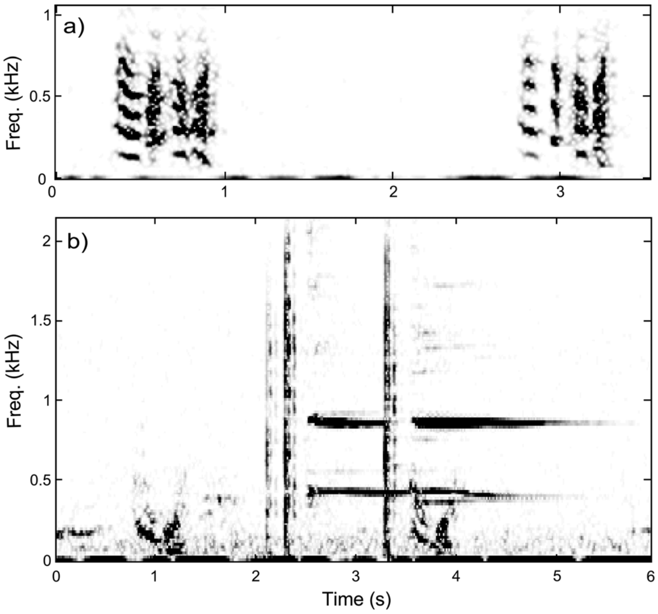

FIG. 1. Underwater vocalizations of the Pacific Walrus. Spectrograms representing (a) a succession of two pairs of walrus grunts (*chimp sounds*); (b) two grunts below 500 Hz, three knocks and two bell sounds (i.e., spectral rays at 500 and 1000 Hz following the knocks).

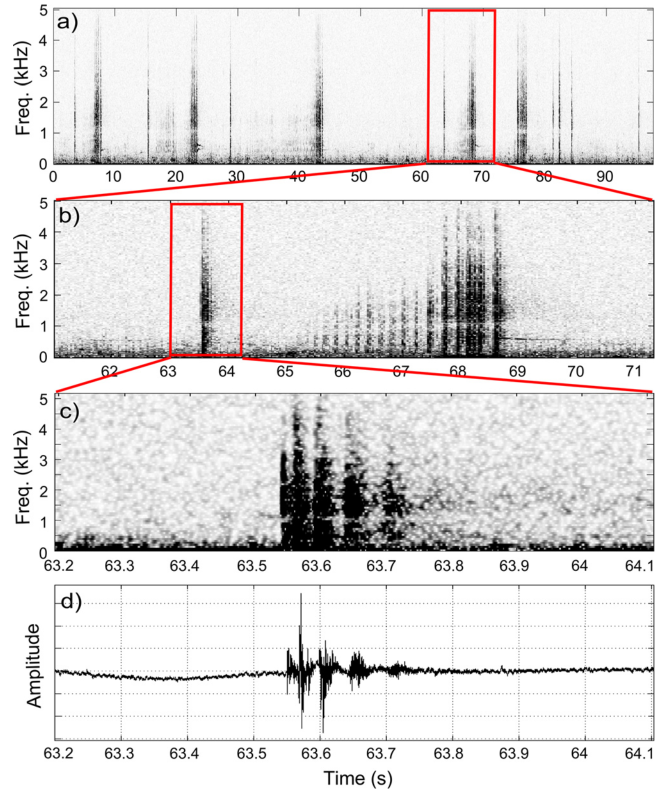

FIG. 2. (Color online) Walrus knocks. (a) Spectrograms of a sequence of walrus knocks, (b) zoom of this sequence between seconds 62 and 71, (c) spectrogram, and (d) pressure oscillogram of a single knock of the sequence showing several multipaths due to surface and bottom reflections.

the wild, Schusterman and Reichmut (2008) observed a female in captivity producing knock and bell-like sounds.

Walrus sounds are suspected to be detectable for only a few kilometers underwater (Stirling *et al.*, 1983, JASCO, unpublished data). Localization techniques such as hyperbolic fixing (Mitchell and Bower, 1995; Laurinolli *et al.*, 2003; Simard *et al.*, 2004) and isodiachrons (Spiesberger and Wahlberg, 2002; Spiesberger, 2004) use time difference of arrival of a vocalization recorded on several spatially-separated hydrophones. Localization of walruses is not possible using such techniques if the acoustic recorders are too far apart because the received signal levels will be too weak to detect. The eastern Chukchi Sea is a shallow environment with relatively constant water depth which supports multipath propagation. Walrus knock signals recorded in the Chukchi Sea contain several multipaths from the surface and bottom boundaries following the direct (i.e., first) arrival [Figs. 2(c)–2(d)]. Typical measurements contained between six and ten discernible multipath arrivals for a single knock. The relative times of these multipaths can be used for locating the vocalizing animal. Aubauer *et al*. (2000) were able to define range and depth of clicking dolphins by measuring the time delays of the signals traveling via the surface and bottom reflection path to a hydrophone relative to the direct signal. Thode *et al*. (2002) calculated depth, range and also azimuth of diving sperm whales by analyzing surface and bottom reflections received by two hydrophones of a towed array deployed at unknown depth and orientation. Laplanche *et al*. (2005) developed another technique based on the history of range estimates from a single hydrophone to make a three dimensional track of sperm whale motion relative to the hydrophone. All these techniques required manual identification of the received multipath (direct-path, surface-reflected, etc.), which is difficult and time consuming. Tiemann *et al.* (2006) and Tiemann (2008) introduced a model-based method that does not require multipath identification and allows localizing sperm whales in three-dimensions using a single hydrophone.

This paper investigates (1) a localization technique for estimating the range and depth of vocalizing walruses using the relative multipath arrival times of knocks received on a single hydrophone and (2) shows the potential of such method for studying the behavior of walruses in their natural habitat. Section II describes the equipment used and methods for acoustic monitoring in the 2007 Chukchi Sea program. It also describes the localization algorithm. Section III presents three examples of walrus tracks identified using this method and Sec. IV discusses the method, the information that can be retrieved from these tracks and how it can be used in behavioral studies.

II. EQUIPMENT AND METHODS

A. Data collection

Thirty seven AURAL M2 autonomous recorders (Multi-Electronique, Inc., Rimouski, QC, Canada) were deployed in the eastern Chukchi Sea between July 17 and October 26, 2007, in order to monitor marine mammals summering in this part of the Arctic (Fig. 3). They were anchored to the bottom and kept in an upright position with four surrounding floats. The hydrophone sensor (HTI-96-MIN from High Tech, Inc., Gulfport, Mississippi), located at the top of the recorder, was tethered at approximately 2 m above the seafloor. AURALs were configured to record continuously with

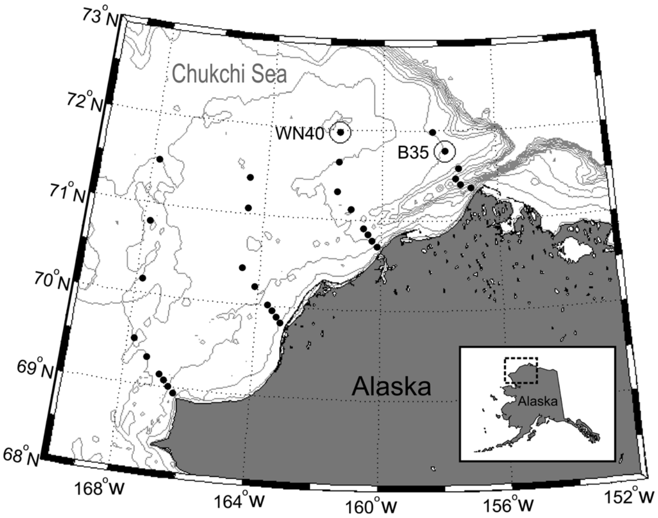

FIG. 3. Map of the study area and locations of the recorders deployed in 2007 (black dots). Circled stations (WN40 and B35) indicate recorders from which data discussed in this paper were acquired.

a sampling frequency of 16 384 Hz to capture acoustic signals to 8192 Hz with a resolution of 16 bits. Even though walrus sounds were identified at nearly all of the stations only recordings collected at stations B35 and WN40 are shown here as they illustrate best the possible applications of the presented method (Fig. 3). Sea bottom depths at recorder locations were measured when deploying and retrieving the instruments with the navigation echo-sounder mounted on the *R/V* Norseman II (Table I).

B. Semi-automatic detection of walrus knocks

Considering the large amount of data collected (∼5 Tb), the manual labeling and time-stamping of walrus knocks on recordings would have been too time consuming. Therefore, a semi-automated detection algorithm was developed to identify and log precise arrival time of the first arrival (direct-path) of each knock. The detection method is based on the measure of kurtosis of the amplitude of the acoustic signal. Kurtosis is a fourth order statistical moment that describes the *peakedness* of a distribution (Balanda and MacGillivray, 1988). For a set x of N data points $x[n]$, the kurtosis K is defined by

$$K(x) = \frac{\sum_{n=1}^{N} (x[n] - \mu)^4}{(N-1)\sigma^4}, \qquad (1)$$

where μ and σ are the mean and the standard deviation of x, respectively. A higher kurtosis means more of the variance is due to infrequent extreme deviations. Kurtosis of amplitude values was calculated for overlapping frames of the acoustic signal. Because of their impulsive nature, knock events were indicated on recordings by high kurtosis peaks and were automatically extracted using an empirically defined threshold of 10 (Fig. 4). The kurtosis detector was chosen over other Teager–Kaiser energy-based methods mainly because its execution speed is significantly faster. Detection times were automatically adjusted within the analysis frame to the first upward amplitude peak. To avoid multiple detections of single knocks due to multipaths, detections were constrained to be at least 50 ms apart. If multiple detections occurred in that time-frame then only the detection with the highest amplitude peak was selected [dots in Figs. 4(b)–4(c)].

Detection was performed in two stages: the kurtosis detector was initially applied to all data using a low time resolution (18 ms frames overlapped at 17%). This allowed identification of recordings containing walrus knocks with a low computing time. A second pass of the kurtosis detector was made over the sections of data where knocks were identified. The second pass used a finer resolution (12 ms frames overlapped at 96%) to provide more accurate detection times for knocks. To ensure accuracy, the automatic detections were checked manually: false alarms were removed and knock start times were adjusted when needed. Knocks with overlapping multipaths and fainter knocks with non-obvious multipaths were discarded from the analysis.

TABLE I. Recorders depth and location.

Recorder location ID	Sea floor depth (m)	Hydrophone depth (m)	Latitude (°N)	Longitude (°W)
B35	60.4	58.4	71.7742	157.7964
WN40	31.1	29.1	71.9726	161.5384

C. Localization

The localization was performed in three stages. First, a ray-tracing model was used to simulate the multipath arrival times in the area of interest. Second, weak multipaths of the knock signals were enhanced by calculating the Teager–Kaiser energy. Finally, measured and modeled relative multipaths arrival times were matched for all possible animal positions, and the location providing the best match was used as the walrus's range and depth localization estimate.

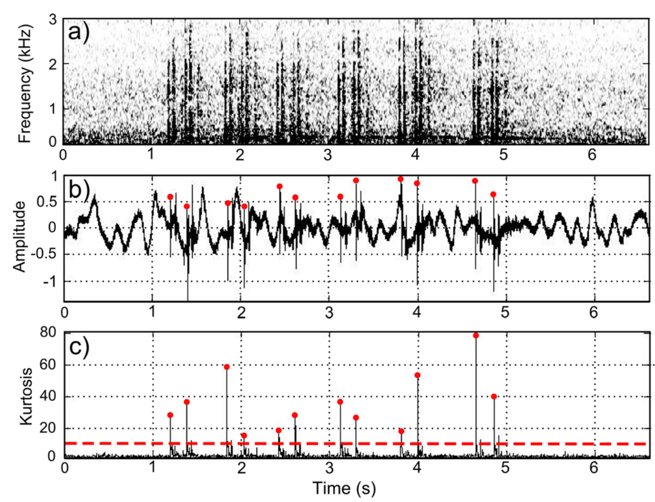

FIG. 4. (Color online) Detection of knocks in recordings. (a) Spectrogram and (b) pressure oscillogram of an acoustic recording containing 12 walrus knocks; (c) kurtosis of the amplitude of the acoustic signal calculated on 12 ms frames overlapped at 96%. The dashed line and the dots indicate the detection threshold and the detection times, respectively.

1. Ray-tracing modeling

The Gaussian beam acoustic propagation model BELLHOP was used to simulate the relative multipath arrival times (RMATs) received by a hydrophone for hypothetic acoustic sources located at different range and depth positions (Porter and Bucker, 1987). The bottom and hydrophone depths used are referenced in Table I. Only locations with constant depth were chosen for analysis. Water column sound speed profiles were extracted from the Generalized Digital Environmental Model—GDEM (Davis *et al.*, 1986; Teague *et al.*, 1990). GDEM provides monthly average profiles of temperature and salinity for the world's oceans with 0.25° resolution, based on historical observations of global temperature and salinity from the U.S. Navy's Master Oceanographic Observational Data Set (MOODS). Temperature-salinity profiles were converted into sound-speed profiles using the equations defined by Coppens (1981). Figure 5(b) shows a typical sound speed profile used in the model. The RMATs were modeled for source ranges from 1 to 1000 m by 1 m increments and with a depth resolution of 0.5 m. The models assumed flat bathymetry, a nominal source frequency of 1 kHz and a single range-independent sound speed profile per monitoring station. Since the amplitude of the received multipath is not needed in the present localization process, the surface and bottom interfaces were modeled using reflection coefficients of 1. One model with site-specific depths and sound speed profiles was used for each monitoring station. Figure 5(c) shows an example of modeled RMATs at station B35 (Fig. 3) for a source located at 15 m depth and 200 m from the hydrophone. Notice that the proposed method uses a frequency independent sound speed profile and does not take into account the amplitude of the signal, therefore the choice of the signal frequency in the model does not affect localization results.

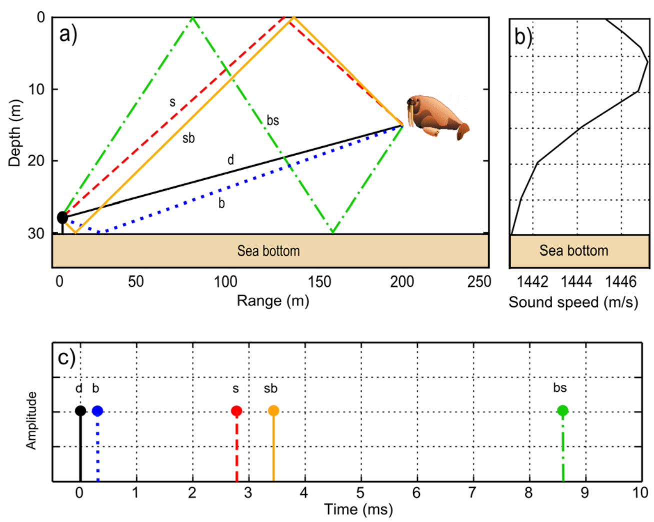

FIG. 5. (Color online) Modeling of surface and bottom reflections. (a) Illustration of the direct and reflected paths of the sound for a source located at 200 m from the hydrophone at a depth of 15 m, assuming flat boundaries and the average sound speed profile plotted in (b); (c) modeled time of arrival of the reflections received by the hydrophone relative to the direct arrival. Annotations **d**, **b**, **s**, **sb**, and **bs** indicate the direct path and the bottom, surface, surface-bottom, and bottom-surface reflections, respectively.

2. Enhancement of measured multipath

To enhance weak multipaths of the knock signals, the Teager–Kaiser (TK) energy operator of the acoustic signal was calculated (Kaiser, 1990). This operator emphasizes impulsive parts of a signal. It is defined in the discrete domain by

$$TK[n] = x[n]^2 - x[n+1]x[n-1], \qquad (2)$$

where x is the signal and n denotes the sample number. This approach is effective for automatic detection of marine mammal clicks and accurate measurement of time difference of arrivals for passive acoustic localization (Kandia and Stylianou, 2006; Kandia *et al.*, 2008). The absolute value of the TK operator was calculated for each recorded knock and the maximum amplitude was normalized to 1 [Fig. 6(b)]. The start time of knocks was determined as the time of the first amplitude peak of the signal x. Duration was first selected at 0.0625 s (1024 points) and then automatically adjusted so the stop time corresponded to the time when the accumulated amplitude of the normalized TK operator function reached 99% of the total amplitude [Fig. 6(c)]. The accumulated amplitude function $C[n]$ is defined as

$$C[n] = \sum_{i=1}^{n} |TK[i]|. \qquad (3)$$

The stop time of the signal is defined when $C[n] = 0.99\max(C)$.

3. Matching model and measurements

Relative multipath arrival times (RMATs) at the hydrophone are unique to each range and depth of the sound source (Tiemann *et al.*, 2006; Tiemann, 2008). Consequently, knowing the RMATs of the measured signal allows determination of the depth and range of the source. The RMATs of the measured signal are compared to the RMATs modeled for every position of the model grid. The position

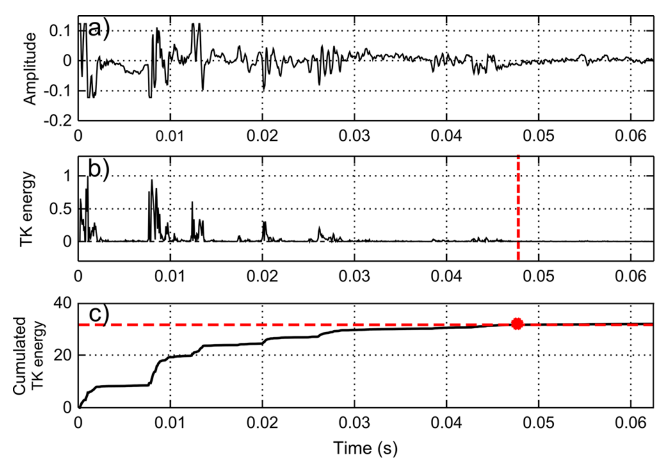

FIG. 6. (Color online) Enhancement of multipaths in the signal. (a) Pressure oscillogram of a knock signal with multipaths and (b) its absolute Teager–Kaiser (TK) energy normalized in amplitude; (c) cumulated Teager–Kaiser energy, C. The end of the signal is defined when C reaches 99% of $\max(C)$ (dot and dashed lines).

of the model for which the best match between measured and modeled RMATs is achieved is assumed to define the real source location. Because the water depth was constant, RMATs were not azimuth-dependent and only the walrus's range and depth can be determined. However, if bathymetry was azimuth-dependent then the walrus's azimuth might also be determined (e.g., Tiemann *et al.*, 2006).

The matching process is performed as follows. First, the measured signal (i.e., absolute value of the normalized Teager–Kaiser energy) is represented by a vector m [solid line in Fig. 7(a)]. Second, a binary vector s, representing the presence of modeled multipaths is created. Presence of a multipath at each relative time sample in s is represented by a value of 1. To compensate for uncertainties in environmental parameters (i.e., sound speed profile and bathymetry) that would introduce time errors in the modeled RMATs, each arrival in s is represented with a box function of width +/−1 ms [dashed line in Fig. 7(a)]. Finally, the score I, of the match between a measured knock and a modeled set of RMATs at a range r, and depth z, is defined by

$$I_{(r,z)} = \frac{ms'_{(r,z)}}{m\overline{s'_{(r,z)}}}\frac{1}{M}, \tag{4}$$

where M is the number of modeled multipath in s, s' is the transpose of vector s, and the horizontal bar denotes the logical complement. Therefore elements of $\bar{s}$ equal 1 if the corresponding elements of s equal 0, and vice versa. In Eq. (4), the denominator $m\overline{s'_{(r,z)}}$ acts as a mismatch penalty and increases when s and m do not match well. High values of the score I indicate high coincidence between both vectors.

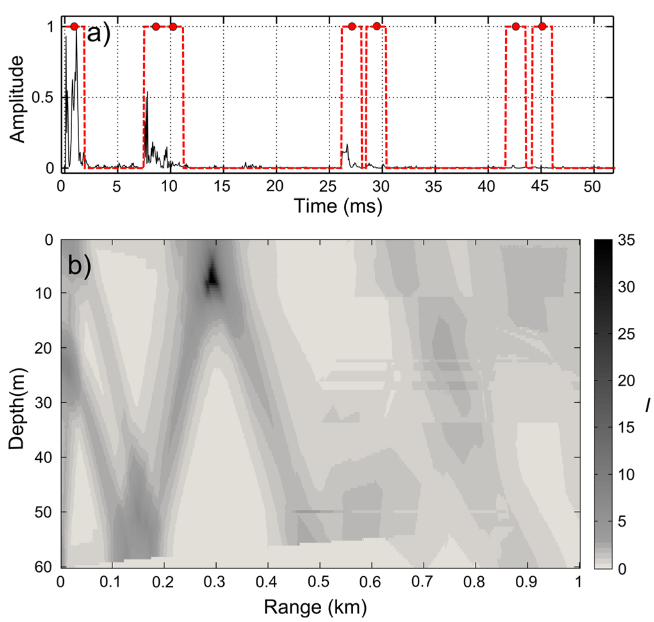

FIG. 7. (Color online) Matching of the modeled and measured RMATs. (a) Measured multipaths m (solid line), and modeled RMATs (thick dots) with ±1 ms uncertainty envelope s (dashed line). Notice the second and third arrivals in s are separated by less than 2 ms and are merged. (b) Ambiguity surface representing the matching score I for every point of the model. The maximum matching score indicates the location of the acoustic source (i.e., range = 300 m, depth = 5 m).

This scoring process is repeated for all source position candidates. Figure 7(b) shows an ambiguity surface representing the matching score for all depths and ranges of the model. The position for which I is maximum defines the best estimate of the animal location. In a few cases the maximum score was obtained at several contiguous positions. In those cases, the final position estimate was the average of all positions.

D. Swimming speed

In many cases the extracted range profiles suggested that the animal was moving on a straight line (i.e., constant speed, symmetrical V-shaped range profile). For such cases, the range r separating the walrus from the hydrophone at a time t could be represented by

$$r(t) = \sqrt{r_{cpa}^2 + v_h^2\left(t - t_{cpa}\right)^2} \tag{5}$$

where, v_h is the horizontal speed of the animal (i.e., in the latitude-longitude plan), and r_{cpa} and t_{cpa} are the range and time of the closest point of approach, respectively. A least-square fit of the Eq. (5) to the measured range values lead to an estimation of v_h, r_{cpa}, and t_{cpa}. When applicable, the vertical speed v_z (i.e., descent speed) of the animal was estimated using a linear interpolation of depth values

$$z(t) = v_z t + \alpha, \tag{6}$$

where $z(t)$ is the depth value at the time t, v_z is the vertical speed, and α is a constant.

E. Estimation of acoustic source levels

The acoustic source levels were calculated on the first arrival of the localized walrus knocks by applying estimated transmission loss values to the received levels using (Urick, 1983),

$$SL = RL + TL, \tag{7}$$

where SL is source level, RL is received level, and TL is transmission loss. Received peak levels were calculated for each knock after converting the amplitude of the digitalized signal $x(t)$ into pressure values using

$$P(t) = 10^{-(S+G+D)/20}\, x(t), \tag{8}$$

where, $P(t)$ is the pressure signal in μPa, S is the sensitivity of the hydrophone, G the amplifier gain, D the digitalization gain of the acquisition board, and where $x(t)$ is normalized by the full digitalization scale, FS (i.e., amplitudes values between −1 and 1). For this study $S = -164\,\mathrm{dBre1V}/\mu\mathrm{Pa}$, $G = 22\,\mathrm{dB}$, and $D = -6\,\mathrm{dBreFS/V}$ (i.e., acquisition range of +/− 2 V). Received peak sound pressure level of the first arrival, RL_{pk} is defined (in dB re 1 μPa) as

$$RL_{pk} = 20\log_{10}(\max(|P(t)|)). \tag{9}$$

Source levels were calculated by assuming a spherical spreading of the acoustic wave. The transmission loss in Eq. (7), is then defined by

$$TL = 20\log_{10}(R), \quad (10)$$

where R is the distance in meters between the source (walrus) and the receiver (hydrophone).

F. Average knock production rate

Average knock production rate was calculated for tracks with single animals. It was defined as the ratio of the number of knocks produced from the beginning to the end of the track to the duration of the track (in minutes).

III. RESULTS

Several walrus tracks were extracted from the data collected in the eastern Chukchi Sea in 2007. This section shows three relevant tracks showing the potential of the localization method presented in this paper.

A. Walrus tracks

Figure 8 shows a 12-min walrus track extracted from a recording collected on August 10, 2007 at location B35 (Fig. 3). The range profile [Fig. 8(a)] shows the path of a single walrus first swimming toward the recorder and then moving away. This V-shaped range profile suggests that the walrus is traveling uniformly and we assume its path is a straight line. Interpolation of range values using Eq. (5) indicates that the walrus would move from the range $r_1 = 526$ m to the range $r_2 = 622$ m at speed $v_h = 0.98$ m/s and passing at $t_{cpa} = 267$ s at the closest point of approach $r_{cpa} = 457$ m. Depth profile [Fig. 8(b)] shows that the walrus is producing knocks at constant depths ($z = 8.3 \pm 1.7$ m). Average knock production rate for this track is 59.8 knocks/min.

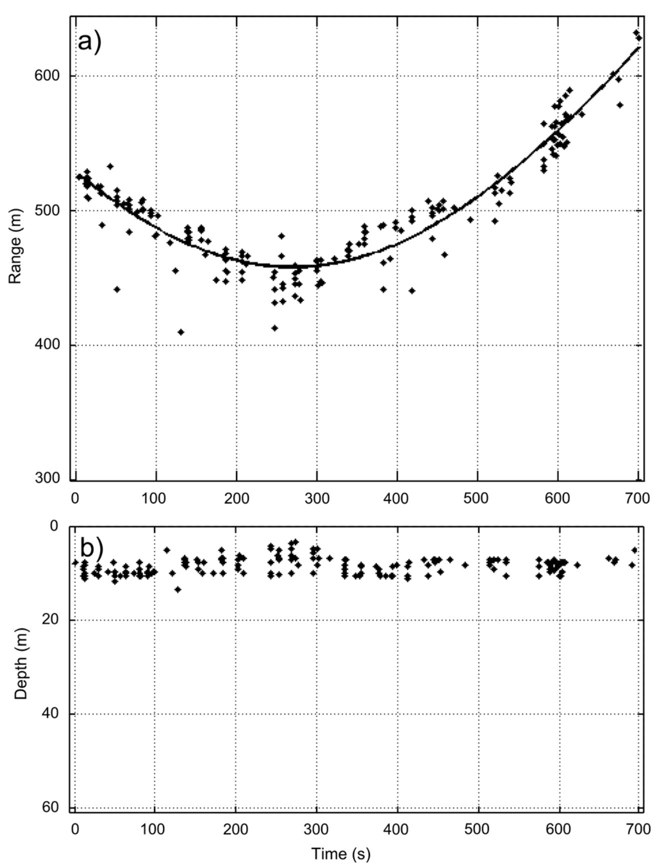

FIG. 8. Walrus track extracted at location B35 (August 10, 2007). (a) Walrus range and (b) depth (dots). The solid line in (a) represents the interpolation of range values based on Eq. (5). The walrus horizontal speed is $v_h = 0.98$ m/s and the average knock production rate is 59.8 knocks/min.

Figure 9 shows an 18-min walrus track extracted from a recording collected on August 8, 2007 at location WN40 (Fig. 3). Variation of range values suggest a single walrus moving at constant speed in a straight line. Interpolation of range values using Eq. (5) indicates that the walrus would move from the range $r_1 = 365$ m to the range $r_2 = 318$ m at constant speed $v_h = 0.62$ m/s passing at $t_{cpa} = 577$ s at the closest point of approach $r_{cpa} = 59$ m. The depth profile [Fig. 9(b)] shows that the walrus was making consecutive short dives at depth $z \approx 10$ m. Dive durations are shorter than 3 min. Descent speed was estimated for the second ($t_1 = 96$ s, $t_2 = 114$ s), the third ($t_1 = 237$ s, $t_2 = 258$ s) and the fourth dive ($t_1 = 385$ s, $t_2 = 413$ s). Linear regressions indicated descent speeds v_z of 0.35, 0.28, and 0.22 m/s, respectively. Bell sounds associated with knocks were manually time stamped and the depth at which they were produced was defined as the depth of the previous closest knock [red triangles in Fig. 9(b)]. Bell sounds were produced at all depths throughout the dive ($z_{\min} = 4$ m, $z_{\max} = 15.5$ m). Average knock production rate for this track is 75.4 knocks/min.

Figure 10 shows a 21-min walrus track extracted from a recording collected on August 10, 2007 at location B35 (Fig. 3). Closest and farthest estimated locations are respectively 35 and 650 m. The distance separating walrus locations at $t_1 = 416$ s and $t_2 = 429$ s and at $t_1 = 840$ s and $t_2 = 870$ s ($\approx$125 m), suggest the presence of at least two animals. The depth profile [Fig. 10(b)] shows a walrus performing a deep dive at $z = 53$ m between times $t_1 = 150$ s and $t_2 = 196$ s. Linear regression indicates a descent speed $v_z = 1$ m/s.

B. Estimated source levels of knocks

Acoustic source levels of knocks were calculated for the animal localized at station WN40 (track shown in Fig. 9). Careful inspection of the ray-tracing model at this station confirmed that a direct path exists and is the first arrival at all depths for ranges less than 700 m. On 794 localized knocks, 144 were clipped (i.e., received level > 148 dB re 1 μPa peak) and were removed from the analysis. Also, to ensure that bottom and surface reflections did not interfere with the direct arrival (i.e., good enough separation in time between the first and second arrivals), source levels were only calculated for ranges less than 200 m. Source levels were calculated with the 408 remaining knocks using Eq. (7). Figure 11 shows a histogram of the estimated source levels. Mean source levels is 177.6 dB re 1 μPa peak @ 1 m. Table II shows the mean, standard deviation, and extremes of the estimated source levels. Most of the time, source levels increased gradually within a knock sequence [e.g., Fig. 2(b)]. The difference of source levels between the first and last knock of a sequence was typically $\sim$20 dB re 1 μPa peak. The largest distance to the source at which the recorder

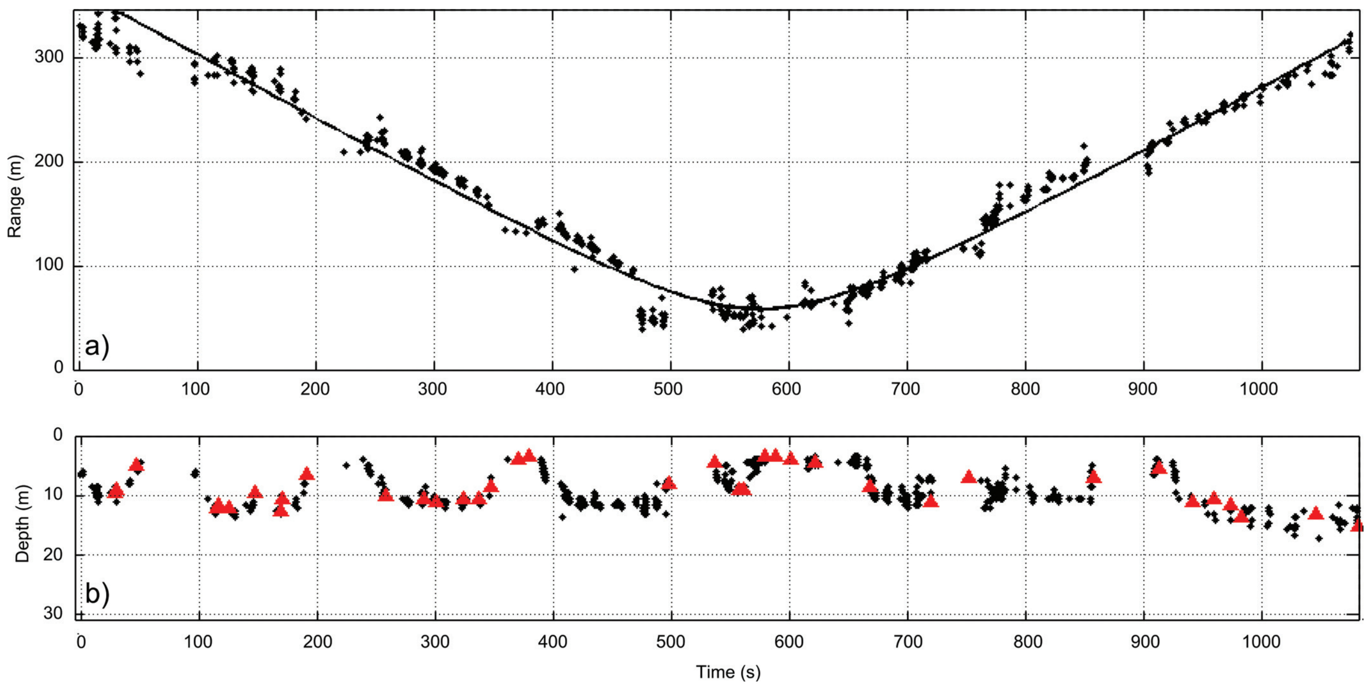

FIG. 9. Walrus track extracted at location WN40 (August 8, 2007). (a) Range of the walrus (dots) and interpolation based on Eq. (5) (solid line). (b) Depths of knocks (dots) and bell sounds (red triangles). The walrus travels with a horizontal speed $v_h = 0.62$ m/s. The average knock production rate is 75.4 knocks/min.

was saturated was 290 m. The smallest distance at which the recorder was not saturated was 42 m.

IV. DISCUSSION AND CONCLUSIONS

Examination of depth and range profiles provides valuable information on walrus behavior. Jay *et al.* (2001) and Gjertz *et al.* (2001) defined several types of dives from time-depth-recorder data collected from Pacific and Atlantic walruses. Dives observed in Fig. 9 are similar to type-I dives described in Jay *et al.* (2001). They are characterized by short durations and shallow depths. This dive type was mostly associated with traveling behavior. Such dives were also attributed to traveling behavior in other pinnipeds (Bengtson and Stewart, 1992; Burns *et al.*, 1997). The deep dive in Fig. 10 could correspond to the type-IV dive described by Jay *et al.* (2001). This type of dive was associated in previous studies with navigation, and exploration of the sea floor for prey and suitable foraging habitat (Bengtson and Stewart, 1992; Schreer and Testa, 1996; Jay *et al.*, 2001). However, since the walrus was only producing knocks in the descent phase of the dive, no strict conclusions about this dive can be drawn. The walrus track in Fig. 8 does not show any clear depth profile. However the constant speed and the linearity of the track strongly suggest a traveling behavior. The proposed method also allows estimation

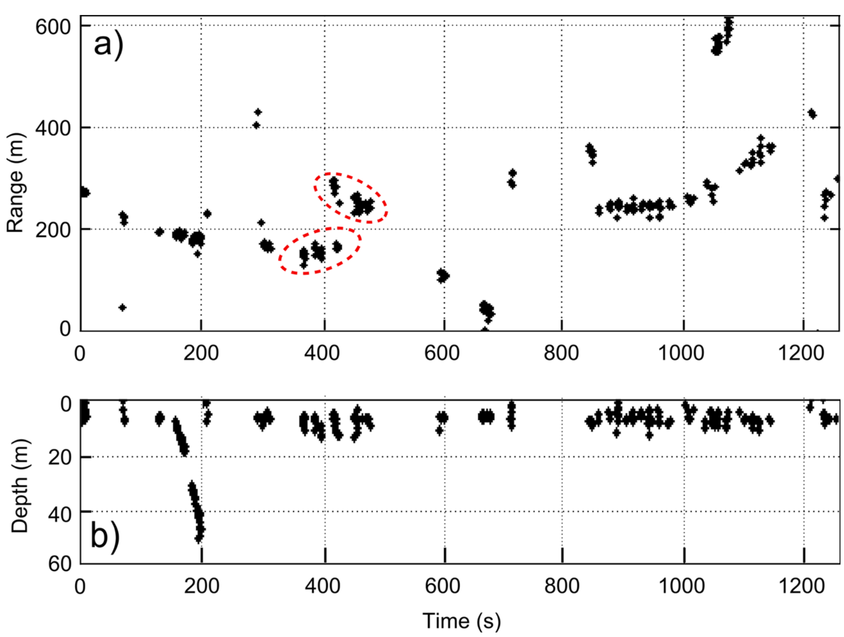

FIG. 10. (Color online) Walrus track extracted at location B35 (August 10, 2007). (a) Walruses ranges and (b) depths. Non-continuous variations of range estimates (circled) suggest the presence of several walruses. The descent speed of the deep dive observed between times $t_1 = 150$ s and $t_2 = 196$ s is $v_z = 1$ m/s.

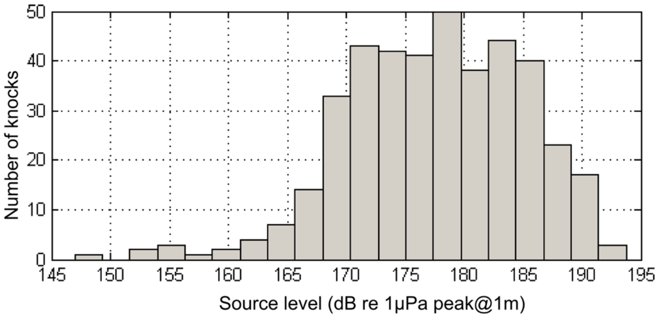

FIG. 11. (Color online) Histogram of estimated knock source levels for the animal localized at station WN40 (track shown in Fig. 9).

of the depths at which bell-like sounds are produced [Fig. 9(b)]. Bell sounds were produced at all depths throughout the dive. This represents new information which can be valuable for vocal behavior studies. Note that no conclusion regarding bell depth patterns can be made from this single walrus track. Extraction of more dive profiles should allow looking for evidence of patterns in depth of bell sound production. Isolating single vocalizing walruses allows determining the average knock rate which is required information for density estimation studies (Marques *et al,* 2009).

Source levels of knocks estimated from the walrus track in Fig. 9 are generally higher than the ones reported by Reichmuth *et al.* (2009) with captive walruses (i.e., maximum source level of 179 dB re 1 μPa peak @ 1 m). In our study, fainter knocks may not have been localized and this could produce a bias favoring higher knock source levels. From these measurements, it is clear that walruses produce knocks with a large spread of source levels. Source levels represent valuable information that can be used for determining detectability range of walrus vocalizations in density estimation studies. Such information also could allow calculating the animal's communication space when estimating the impact of anthropogenic noise on animal communication (Clark *et al.,* 2010). Several factors can influence the quality of the source level estimates. First, inaccuracy in the localization could lead to selecting an incorrect value of the transmission loss, which can result in either underestimation or overestimation of the source level. Second, spherical spreading may not be the best assumption for the acoustical environment, parabolic equation based models such as the range-dependant acoustic model would provide more accurate transmission loss values (Collins, 1993).

The semi-automated detection of the knocks in the recordings presented in this paper decreases the time of the manual analysis which allow this method to be applicable on large sets of data. The ray tracing modeling used is basic and requires only few parameters describing the propagation medium: the depth of the bottom, the depth of the hydrophone and the average sound speed profile. Since the amplitude of the received sound is not taken into account, geo-acoustic properties of the sea bottom are not required. Measurements made using this technique can be used for behavior studies and can bring new information about walrus ecology in a non-intrusive manner. In some cases, this method can also allow to estimate at least a minimum number of animals vocalizing at short range.

The method presented here has some limitations. First, localization in very shallow water (<20 m) is difficult; multipaths are too closely separated in time to be distinguished. Second, presence of background noise in recordings decreases the call detectability and accuracy of multipath arrival time measurements, leading to inaccurate localization results. Overlapping of multipath from consecutive knocks also leads to inaccuracies in the matching stage of the localization process. In this paper, these overlapping multipaths were discarded manually by the operator during the knock labeling process. Third, the tracks extracted and examined here showed that the maximum localization range was approximately 650 m. This limitation is mainly due to low signal to noise ratios obtained at farther ranges and also because the arrival time differences decrease with range, making arrivals less distinguishable. Finally, this method uses knock sounds to localize the animals. Determining multipath arrival times for longer-duration call types such as grunts is more difficult and different methods would have to be developed to apply this method to those call types.

In conclusion, the method presented in this paper is a valuable tool that augments the set of methods already available for studying free-ranging walruses. It allows retrieval of information similar to that provided by Time-Depth-Recorders or acoustic tags but is generally easier to implement and it is non-intrusive. The method allows the study of movement and calling behavior of several walruses over relatively short distances. It can determine dive profiles and timing and can help to identify walrus feeding grounds. We suggest that surface and bottom reflections of knocks may be used by walruses to retrieve information about their environment such as defining bottom depth in murky water or identifying sea bottom type associated with benthic preys.

Further anticipated work will include improvement of the detection and timing algorithms as well as analysis of more walrus tracks. Full automation of the knock detection process should decrease the time required for applying this method. Additional steps could be added to the kurtosis detector. For instance, classification of detections using energy ratios in different spectral bands (Klinck and Mellinger, 2011) or more advanced algorithms such as Support Vector Machine or Gaussian Mixture Models could largely decrease the false alarm rate (Roch *et al.*, 2007; Roch *et al.*, 2008). Denoising algorithms applied to the acoustic signal could contribute to more accurate localization and likely allow localizing at further ranges. Denoising techniques such as wavelet shrinkage (Donobo, 1995) would be well suited and are currently being investigated. JASCO deployed similar hydrophone arrays in the eastern Chukchi Sea in 2009, 2010, and 2011 so a wealth of acoustic data is available.

TABLE II. Estimated source levels of knocks.

	Mean	Standard deviation	Minimum	Maximum
Peak levels (dB re 1 μPa peak @ 1 m)	177.6	7.5	147	193.7

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