Localization and tracking of phonating finless porpoises using towed stereo acoustic data-loggers

Songhai Li
Institute of Hydrobiology, The Chinese Academy of Sciences, Wuhan 430072, People's Republic of China

Tomonari Akamatsu
NRIFE, Fisheries Research Agency, Hasaki, Kamisu, Ibaraki 314-0408, Japan

Ding Wang[a] and Kexiong Wang
Institute of Hydrobiology, The Chinese Academy of Sciences, Wuhan 430072, People's Republic of China

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Cetaceans produce sound signals frequently. Usually, acoustic localization of cetaceans was made by cable hydrophone arrays and multichannel recording systems. In this study, a simple and relatively inexpensive towed acoustic system consisting of two miniature stereo acoustic data-loggers is described for localization and tracking of finless porpoises in a mobile survey. Among 204 porpoises detected acoustically, 34 individuals (~17%) were localized, and 4 of the 34 localized individuals were tracked. The accuracy of the localization is considered to be fairly high, as the upper bounds of relative distance errors were less than 41% within 173 m. With the location information, source levels of finless porpoise clicks were estimated to range from 180 to 209 dB re 1 μPa pp at 1 m with an average of 197 dB ($N=34$), which is over 20 dB higher than that estimated previously from animals in enclosed waters. For the four tracked porpoises, two-dimensional swimming trajectories relative to the moving survey boat, absolute swimming speed, and absolute heading direction are deduced by assuming the animal movements are straight and at constant speed in the segment between two consecutive locations.
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I. INTRODUCTION

Cetaceans are included as top trophic-level predators in food-chains of ecosystem (Baumgartner and Mate, 2003; Tynan, 2004). They occupy unique statuses in models of ecosystem dynamics. Researches on population status, ecology, behavior, and conservation of cetaceans in the wild are increasingly popular. Traditional visual observation methods for cetacean researches can only allow detection of a fraction of the animals present and observation of the surface behaviors, both due to the brief appearances of animals at the surface when breathing, and limited transparency of water. The weather condition, circadian pattern, and unintentional variation of efforts among observers cause additional biases in visual observation.

To aquatic life, cetaceans possess highly developed sound production and hearing capabilities (Herman, 1980). Furthermore, all investigated odontocetes possess a sophisticated echolocation system (Au, 1993). Small odontocetes, such as porpoises, frequently produce series of high-frequency echolocation clicks (i.e., click trains) for navigation, orientation, and prey capture (Au, 1993; Akamatsu *et al.*, 2005a, 2007). Therefore, it is not surprising that many researches of cetaceans focus on their acoustics, and passive acoustic methods are widely used for cetacean observation.

Passive acoustic methods in cetacean localization and observation can be distinguished to tagging acoustic systems, fixed acoustic systems, and mobile acoustic systems. Tagging acoustic systems with depth- and/or acceleration-meters have been widely used in the studies of humpback whales (Stimpert *et al.*, 2007), sperm whales (Johnson and Tyack, 2003; Zimmer *et al.*, 2003, 2005; Miller *et al.*, 2004a, 2004b), and even small odontocetes, such as porpoises (Akamatsu *et al.*, 2005a, 2005b, 2005c, 2007). The tagging acoustic systems do have enabled scientists to gain knowledge of underwater behaviors of cetaceans. However, the systems themselves can disrupt or alter the natural behaviors of the tagged animals, especially for the small odontocetes. Also the tagging procedures, in some of which the animals need to be captured (Akamatsu *et al.*, 2005b), are time consuming and difficult to implement.

Fixed acoustic systems, which may be left in stationary place for long time periods, are often used for monitoring of population status and ecological dynamics of cetaceans (Mellinger *et al.*, 2007). Recently, fixed acoustic systems with multiple hydrophone sensors, which compose arrays, are widely used for localization and behavior observation of cetaceans (Fox *et al.*, 2001; Au and Benoit-Bird, 2003; Wiggins, 2003; Kimura *et al.*, 2009). While these systems enable scientists to better understand the presence and seasonal occurrence patterns, as well as underwater acoustic activity, they are limited to be in small range. Furthermore, there are still many hurdles for the fixed systems to estimate abun-

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[a] Author to whom correspondence should be addressed. Electronic mail: wangd@ihb.ac.cn

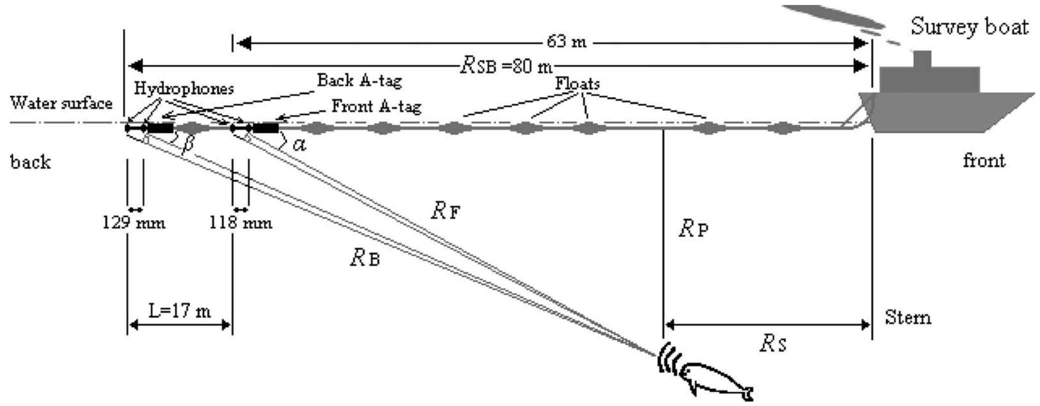

FIG. 1. A linear line array consists of two miniature stereo acoustic data-loggers (A-tags), which were towed 63 m (front A-tag) and 80 m (back A-tag) behind the survey boat, respectively. R_P, R_F, R_B, and R_S correspond to the distance of the phonating animal to the cruise line (i.e., perpendicular distance to the survey boat), the front A-tag, the back A-tag, and the stern of the survey boat along the cruise line, respectively.

dance of animals, which is the ultimate aim for ecological studies and management of the target animals (Mellinger *et al.*, 2007).

Mobile acoustic systems often consist of cabled hydrophones, which are towed behind a ship or affixed to a mobile platform to detect animals in a large area. The mobile systems are often used in joint visual and acoustic surveys, to detect animals with increased levels in accuracy. Experimentally, in joint visual-acoustic surveys, mobile acoustic systems can usually detect one to ten times as many cetacean groups as visual ones (Barlow and Taylor, 2005; Rankin *et al.*, 2007; Akamatsu *et al.*, 2008). However, for comparison between visual and acoustic observations to determine detection performance of each method, determination of number of animals traveling together, distance, and bearing angle to the animal/group are necessary. Previous attempts at acoustical location determination for cetaceans have generally used cabled hydrophone arrays and differences in time-of-arrival measurements (Miller and Tyack, 1998; Gillespie and Chappell, 2002). In the mobile acoustic systems, at least three hydrophones in a towed linear line array are necessary to determine the two-dimensional location of a phonating animal by evaluating the travel time differences of the input signal. These systems with long cables from the hydrophones to the recording devices on board are not easy to set up and handle on a moving platform. Multichannel recording and signal evaluation are also time consuming and difficult to implement because of the huge amount of data size.

This study describes a portable and operable acoustic system, which only requires two miniature acoustic data-loggers (A-tags; see below) detecting the high-frequency echolocation click events of odontocetes for localization and potential behavior observation of the animals in mobile survey. In each A-tag, there are two miniature acoustic sensors (i.e., hydrophones) with about 120 mm apart to record the travel time difference of each click. With the location information the source level of click signals is estimated. And also, the potential applications of this acoustic system are discussed.

II. MATERIALS AND METHODS

A. Subject and equipment

The subject is a freshwater subspecies of finless porpoises, living only in main stream and tributaries of the middle and lower reaches of Yangtze River and its conjoint large lakes, such as Poyang Lake and Dongting Lake. To document the population status of this subspecies, a joint visual-acoustic survey was performed between November and December 2006 in the main stream of the middle and lower reaches of Yangtze River (Akamatsu *et al.*, 2008; Zhao *et al.*, 2008).

In one of the survey boats, two miniature stereo acoustic data-loggers (A-tags; ML200-AS2, Marine Micro Technology, Saitama, Japan; Akamatsu *et al.*, 2008), which are 21 mm in diameter, less than 350 mm in length including the external hydrophones, and 72 g in weight, were towed 63 m (front A-tag) and 80 m (back A-tag) behind the boat, respectively, in a linear line array for localization and behavior observation of the porpoises (Fig. 1). Each A-tag contains a CPU (PIC18F6620, Microchip, USA) for system control and signal processing, a 128 Mbyte flash memory for data storage, a miniature high-frequency pulse event recorder, and a CR2 lithium battery cell, encased in a waterproof tube. The present A-tags are slightly modified from the previous model, but had identical signal processing (see Akamatsu *et al.*, 2005b). Each A-tag has two external hydrophones, apart each other with 118 and 129 mm for the front A-tag and back A-tag, respectively (Fig. 1). The hydrophone sensitivity is -201 dB re 1 V/μPa at 120 kHz (100–160 kHz within 5 dB), which is close to the dominant frequency of sonar signal of finless porpoises (Li *et al.*, 2005). An electronic band pass filter (55–235 kHz) is included to eliminate noise outside the frequency bands of porpoise sonar signals. Every 0.5 ms (i.e., using a 2 kHz sampling operation), the A-tags record and store the intensity of a received pulse and the travel time difference of each pulse to the two hydrophones with a resolution of 271 ns (one count in Fig. 2), which can be used to estimate the bearing angle to a sound source (Akamatsu *et al.*, 2008).

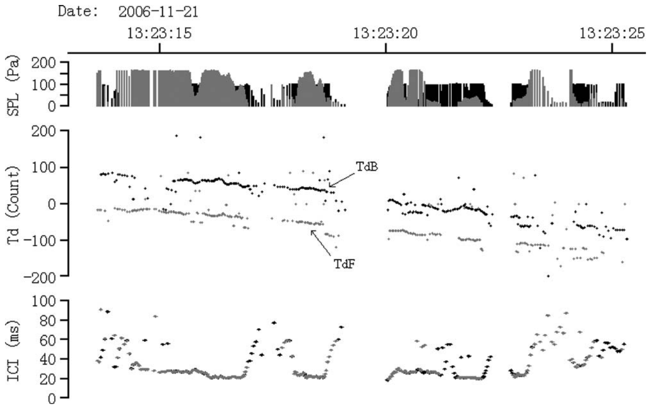

FIG. 2. Echolocation click trains from single porpoise passing by the two acoustic data-loggers (A-tags); the gray one corresponds to the front A-tag and the black one corresponds to the back A-tag. Top panel: The received SPL in pascals. Middle panel: The travel time difference of clicks (Td) in count (one count equals to travel time difference of 271 ns). Lower panel: ICI in milliseconds. Td_F and Td_B in the middle panel correspond to the travel time differences of clicks in the front A-tag and the back A-tag, respectively. Note that the trace of the travel time difference (Td) changes from positive to negative, corresponding to an individual passing from bow to stern relative to the data-loggers.

The A-tags were mounted on a towing cable, on which floats were placed at about 5 m interval to keep the cable to near the water surface (Fig. 1). To stabilize the position of data-loggers and to prevent them from swinging, a 5 m-length and 5 mm-diameter nylon rope was added behind the back A-tag.

B. Localization and tracking of phonating animals

Free ranging finless porpoises frequently produce series of high-frequency echolocation clicks (i.e., click trains), which usually contain over five to up to several hundreds of clicks. They produce click trains every 5 s in average (Akamatsu *et al.*, 2005a), with regular or gradual change in the sound intensity and interclick interval (ICI) changing typically between 20 and 70 ms (Akamatsu *et al.*, 1998). These characteristics can distinguish porpoises click trains from the noise of background, survey boat, and other cargo ships passing nearby, which have randomly changing ICIs and sound intensities. During the survey, the speed of the survey boat was kept to be approximately 15 km/h, much faster than the average swimming speed of finless porpoises (4.3 km/h; Akamatsu *et al.*, 2002). This means the porpoises will always pass the survey boat from bow to stern. When passing animals vocalize, the travel time differences of porpoise clicks to the two hydrophones in one A-tag that corresponded to the bearing angle will change from positive to negative (Fig. 2).

In theory, when one vocalizing animal passes by the A-tag, there would be one smooth gradual change trace of travel time differences, which changed from positive to negative (Fig. 2). And when the passing animals are two or more with both or all vocalizing, there would be two or more traces with gradual change in the travel time differences when two or more animals separated each other outside of the resolution of the acoustical location by A-tag. The number of independent traces could be used for counting of passing animals (see Akamatsu *et al.*, 2008).

When click trains of porpoises were received by both the front A-tag and back A-tag (Fig. 1), there would be two parallel traces of travel time differences recorded by front A-tag (Td_F) and back A-tag (Td_B), respectively (Fig. 2). The two parallel traces of travel time difference (Td), which correspond to two independent bearing angles to the phonating animal, could be used for localization and tracking of phonating animals. By measuring the travel time differences Td_F and Td_B, and taking advantage of the fact that the distance between phonating animal and the A-tags was significantly longer than the distances between two hydrophones of each A-tag and the opening angles from the animal to two hydrophones in each A-tag could be neglected, the two bearing angles α and β of phonating animals to the two A-tags could be determined by using the following equations (see Fig. 1):

$$\cos \alpha = \frac{Td_F}{Td_{F\,\max}}, \tag{1}$$

$$\cos \beta = \frac{Td_B}{Td_{B\,\max}}, \tag{2}$$

where Td_F is travel time difference of porpoise click to the two hydrophones of the front A-tag in count (one count equals to travel time difference of 271 ns), Td_B is the travel time difference recorded by the back A-tag in count, and $Td_{F\,\max}$ and $Td_{B\,\max}$ correspond to maximum time difference when the sound came from 0° for each A-tag. Since the distances between two hydrophones in front A-tag and back A-tag were 118 and 129 mm (Fig. 1), respectively, $Td_{F\,\max}$ and $Td_{B\,\max}$ in count can be calculated by $118 \times 10^{-3}/c/271 \times 10^{-9}$ and $129 \times 10^{-3}/c/271 \times 10^{-9}$, respectively, where c is the sound speed in water, which was calculated from the Medwin equation (Medwin, 1975) to be 1465 m s^{-1}, by setting the salinity (<1 ppt) and temperature (15 °C) measurements made in the survey season in the Yangtze River. Using triangulation and Eq. (3), the distances of the phonating animals to the cruise line R_P (i.e., perpendicular distance), the front A-tag R_F, the back A-tag R_B, and the stern of the survey boat along the cruise line R_S (see Fig. 1) are given by Eqs. (4)–(7), respectively,

$$\frac{R_P}{\tan(\pi - \alpha)} + \frac{R_P}{\tan \beta} = L, \tag{3}$$

$$R_P = \frac{L \times \sin \alpha \sin \beta}{\sin(\alpha - \beta)}, \tag{4}$$

$$R_F = \frac{L \times \sin \beta}{\sin(\alpha - \beta)}, \tag{5}$$

$$R_B = \frac{L \times \sin \alpha}{\sin(\alpha - \beta)}, \tag{6}$$

$$R_S = \frac{L \times \sin \alpha \times \cos \beta}{\sin(\alpha - \beta)} - R_{\mathrm{SB}}, \tag{7}$$

where L is the distance between the two A-tags, which is 17 m (Fig. 1); and R_{SB} is the distance of the back A-tag to the stern of the survey boat, which is 80 m (Fig. 1). R_P and R_S would determine the two-dimensional location of the phonating animals relative to the stern of the survey boat. R_F and R_B would be used for estimation of source levels of porpoise clicks.

In practice, while the traces of the time differences changed from positive to negative, the traces did not ideally change smoothly and gradually, but showed some fluctuation and bounce (Fig. 2). Both ambiguity at the trigger point in the waveform of porpoise clicks between two hydrophones in one A-tag and swing of A-tags due to water flow can have contributed the fluctuation of coordination. When the trigger points of two hydrophones are in different cycle of a click waveform, the ambiguity would be over 1 cycle, corresponding to over 8.5 μs in time (see Li *et al.*, 2005). This would reduce an increase of over 8.5 μs (corresponds to 31 counts in Fig. 2) in absolute value of travel time difference (Td). When the trigger points are in a same cycle, the ambiguity would be less than 1/4 cycle according to the characteristics of click waveforms, which corresponds to a less than 2.2 μs (8 counts in Fig. 2) increase of absolute value of Td. In localization of animals, to avoid the effect of the ambiguity and swing, only the click trains containing at least three consecutive clicks with Td change less than 1.4 μs (i.e., five counts in Fig. 2) in both the two A-tags were selected. The average of Td of the three consecutive clicks would be used for ultimate localization of the phonating animals. In addition, the over 1 cycle ambiguity at the trigger point between two hydrophones, which brought on an increase of over 31 counts in the absolute value of Td, could be kept away from the localization of phonating animals by selecting click cluster (over 3 clicks) with Td closer to 0 when there was a change of over 31 counts in Td among click clusters. For each animal identified by acoustics, if the localization could be determined for more than two times, the animal would be tracked acoustically.

C. Behavior observation

Once phonating animals were tracked, i.e., were localized for more than two times, the two-dimensional swimming trajectories of the animals relative to the survey boat were reconstructed by assuming the movements were straight and at constant speed in the segment between two consecutive locations. In the meantime, when the time duration of the given segment is longer than 0.5 s, the absolute speed and absolute heading direction in the segment were determined. If the authors assume a porpoise at a perpendicular distance to the survey boat R_{P1}, longitudinal distance to the stern of the survey boat along the cruise line R_{S1}, and instantaneous time t_1 heads straight to a perpendicular distance R_{P2}, longitudinal distance R_{S2}, and instantaneous time t_2, at a constant speed V, then the perpendicular and longitudinal speeds of the animal V_P and V_L could be given by the following equations:

$$V_P = (R_{P2} - R_{P1})/(t_2 - t_1), \qquad (8)$$

$$V_L = V_{\mathrm{SB}} - (R_{S2} - R_{S1})/(t_2 - t_1), \qquad (9)$$

where V_{SB} is the speed of the survey boat, which was monitored by hand-held GPS and could be considered constant in a short segment. Thus, the porpoise speed $V = \sqrt{V_P{}^2 + V_L{}^2}$ and heading direction could be estimated when crossing the given segment.

D. Source level measurement

The received intensity of porpoise click by the A-tags is termed sound pressure level (SPL). The source level (SL) defined as the SPL at 1 m from phonating porpoise on its acoustic axis could be estimated by Eq. (10) by assuming spherical spreading, which is typical of spreading observed in dolphin and porpoise sonar (Au, 1993) and using the above calculated distances between the phonating animals and A-tags.

$$\mathrm{SL} = \mathrm{SPL} + 20 \log R + \lambda R, \qquad (10)$$

where R is the distance between phonating animal and A-tags, and λ is the frequency-dependent absorption coefficient of water in dB/m. In this case, it was estimated to be ~0.004 dB/m in the freshwater at 15 °C and 125 kHz, the peak frequency of finless porpoise (Li *et al.*, 2005), with Fisher and Simmons' model (Fisher and Simmons, 1977).

Since dolphins and porpoises emit echolocation clicks directionally (Au, 1993) and it is very difficult, or almost impossible, to accurately determine whether the phonating animal points its acoustic axis at one of the A-tags with the present system, the received intensities of clicks (i.e., SPLs) were very likely acquired from both directly on and off the axis of porpoise sonar. In this paper, a term "apparent source levels" (ASLs) was introduced, which equals the sound intensity at 1 m from a directional source in an unknown direction (Villadsgaard *et al.*, 2007). Echolocation signals acquired from off the beam axis are lower in sound levels, relative to the source signals (Au, 1993). The directionality of porpoise sonar could have resulted in an underestimation of the on-axis source levels. The present ASLs should be regarded as conservative estimates of the true source levels.

In the determination of source levels, three policies were adopted: (1) only the click with maximum intensity in one click train was selected for level estimation; (2) source level was estimated by the front A-tag and back A-tag, respectively, and the higher one was selected as the final value; and (3) to maintain the independence of data, only one SL was estimated for each localized and/or tracked animal.

III. RESULTS

A. Localization and tracking of phonating animals

In the whole survey, the acoustic system with two towed A-tags, deploying about 120 h, detected 204 porpoises, in which 34 individuals (~17%) were localized acoustically, based on the selection criteria of travel time differences (Td). Figure 3(b) shows the two-dimensional locations of the 34 localized porpoises relative to the stern of the moving survey boat. Due to the symmetry of the linear line array consisting of A-tags, the animals can be on either side of the cruise line.

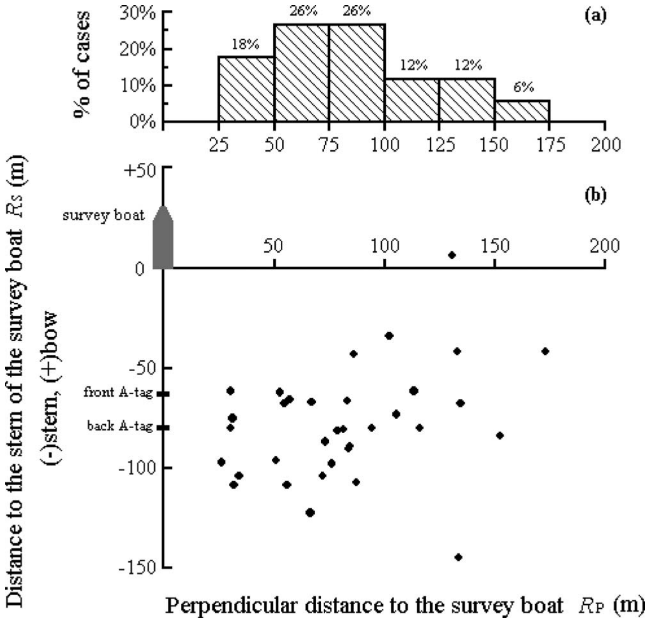

FIG. 3. Two-dimensional localization of phonating porpoises. (a) Histogram of distribution of perpendicular distance to the survey boat and (b) two-dimensional locations of 34 localized porpoises relative to the stern of the moving survey boat.

Most of the localizations distribute around the A-tag array within 150 m. The maximum detected perpendicular distance to the survey boat is 173 m, and 32 of 34 localizations have perpendicular distances (over 94%) distributing between 25 and 150 m [Fig. 3(a)]. No animals were detected within 25 m of the cruise line.

Among the localized individuals, four were tracked (i.e., localized acoustically for more than two times). The four tracked individuals had been localized for three, six, eight, and nine times with time spans of 10, 4, 10, and 9 s, respectively (Fig. 4). During these tracks the porpoises continuously emitted echolocation click trains detected by both the A-tags (see Fig. 2).

B. Swimming speeds and heading directions of animals

For the four tracked animals, the two-dimensional swimming trajectories of animals relative to the moving survey boat were reconstructed (Fig. 4). In Fig. 4, the absolute speed (and not relative) V, perpendicular-oriented speed V_P (x axis in Fig. 4), and longitudinal-oriented speed V_L (y axis in Fig. 4) of the animals in each segment between two consecutive localizations are presented along with the two-dimensional trajectories in format of $V\ (V_P, V_L)$, i.e., the numeral outside the parenthesis is the V, the former numeral inside the parenthesis is the V_P, and the latter numeral inside the parenthesis is the V_L. The marks "+" and "$-$" represent the directions of V_P and V_L along the x and y axes (see the upper right corner in Fig. 4). The absolute heading directions of the animals in each segment are sketched by arrowheads in Fig. 4. The

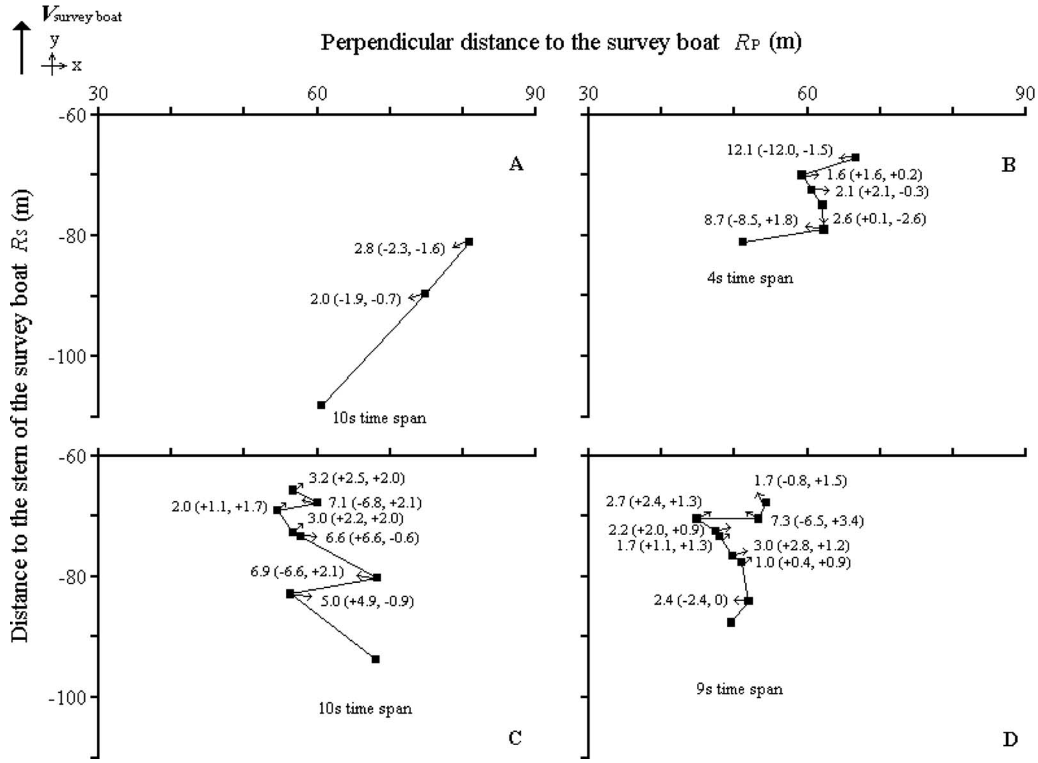

FIG. 4. Two-dimensional swimming trajectories of four animals relative to the moving survey boat. In each segment between two consecutive locations, the animal movements were assumed straight and at constant speed. Along with the two-dimensional trajectories, absolute speed (the numeral outside the parenthesis), perpendicular-oriented speed (the former numeral inside the parenthesis), and longitudinal-oriented speed (the latter numeral inside the parenthesis) are indicated. The marks "+" and "$-$" represent the directions of perpendicular-oriented speed and longitudinal-oriented speed along the x and y axes (see the up right corner). The absolute heading directions of the animals in each segment are sketched by arrowheads.

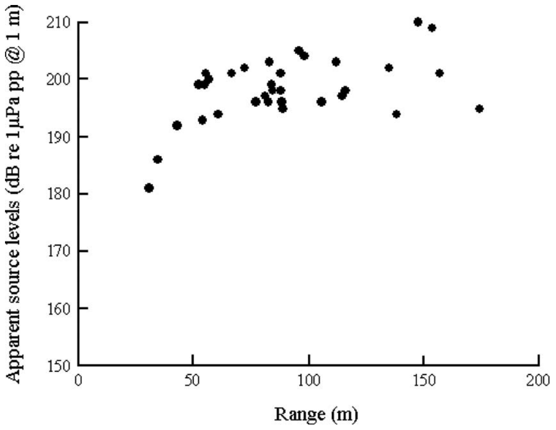

FIG. 5. The calculated ASL of porpoise clicks as a function of the distances between localized animals and A-tags.

fastest absolute speed V of the animals is 12.1 m s^{-1} [Fig. 4(b)], and most of the speed V (16 of 22, i.e., ~73%) are between 1.0 and 3.2 m s^{-1}.

C. Source levels of clicks

ASLs from 180 to 209 dB re 1 μPa pp at 1 m were estimated with an average of 197 dB (N=34). A scatter plot of ASLs as a function of the distances between localized animals and A-tags is presented in Fig. 5.

IV. DISCUSSION

A. Error estimation

Assuming the sound speed calculated from the Medwin equation (Medwin, 1975) is valid and constant, the accuracy of the localization in the present study mainly lies on errors of travel time differences (Td) of porpoise clicks to the two hydrophones of each A-tag. The errors of Td could be both from ambiguity at the trigger point between two hydrophones and swing of A-tags due to water flow. By selecting Td based on the criteria described above, and averaging Td of three consecutive clicks, the authors presume that the errors of Td have been well controlled less than five counts, corresponding to ~1.4 μs. Also, the measurement errors of distances between two A-tags could contribute minor effect to the accuracy of the localization. The accuracy of the present localization can be estimated with the total error differential of the distances, which is the sum of the partial derivatives of all variables multiplied by the error bounds of the variables [see Eqs. (11)–(13)]. The location errors were evaluated by using the relative distance errors of R_P, R_F, and R_B, which represent the distance of phonating animal to the cruise line (i.e., perpendicular distance to the survey boat), the front A-tag, and the back A-tag, respectively. The relative distance error was defined as the quotient of the total error differential of distance and the estimated distance as follows:

$$\frac{\Delta R_P}{R_P}=\frac{|\partial R_P/\partial Td_F|\cdot|\Delta Td_F|+|\partial R_P/\partial Td_B|\cdot|\Delta Td_B|+|\partial R_P/\partial L|\cdot|\Delta L|}{R_P}, \tag{11}$$

$$\frac{\Delta R_F}{R_F}=\frac{|\partial R_F/\partial Td_F|\cdot|\Delta Td_F|+|\partial R_F/\partial Td_B|\cdot|\Delta Td_B|+|\partial R_F/\partial L|\cdot|\Delta L|}{R_F}, \tag{12}$$

$$\frac{\Delta R_B}{R_B}=\frac{|\partial R_B/\partial Td_F|\cdot|\Delta Td_F|+|\partial R_B/\partial Td_B|\cdot|\Delta Td_B|+|\partial R_B/\partial L|\cdot|\Delta L|}{R_B}. \tag{13}$$

In the present error analysis, the error bounds of $|\Delta L|=0.1$ m and $|\Delta Td|=5$ count for travel time differences Td_F and Td_B are assumed. The error estimations of location are shown as scatter plots of $\Delta R_P/R_P$ to R_P, $\Delta R_F/R_F$ to R_F, and $\Delta R_B/R_B$ to R_B in Fig. 6. All the relative distance errors $\Delta R_P/R_P$, $\Delta R_F/R_F$, and $\Delta R_B/R_B$ depend on the relevant distances of the porpoise in a similar behavior and level, and tend to increase with increasing distances. The highest relative distance error is 41% for the present localization, and when the distances are within 100 m, the relative distance errors are even less than 30%.

The absorption coefficient λ is very low (only ~0.004 dB/m) in the present condition, and the uncertainty in its calculation does not contribute much to the source level measurement. By assuming spherical spread, the SL measurement error ΔSL can be expressed by

$$\Delta \mathrm{SL}=|20\log(1\pm\Delta R/R)|. \tag{14}$$

Considering a highest relative distance error of 41%, the upper bound of SL measurement error would be ~4.6 dB.

B. Application

The most important and powerful feature of this localization method is its potential application in *distance sampling* methodology, which was originally developed for visual survey to investigate population size of animals (Buckland *et al.*, 1993). In distance sampling, for reliable estimation of absolute density (i.e., number of animals in unit area), an accurate measurement of distance between the animal and the survey cruise line (i.e., perpendicular distance) is essential (Buckland *et al.*, 1993). The present localization using a towed linear line array consisting of two

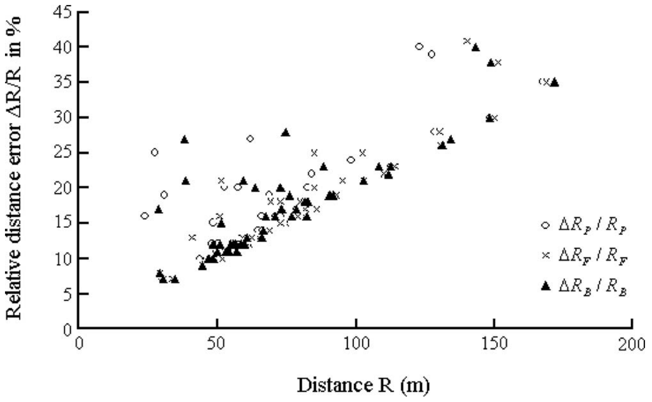

FIG. 6. Relative error in distance estimation of R_P, R_F, and R_B, which correspond to the distance of the phonating animal to the cruise line (i.e., perpendicular distance to the survey boat), the front A-tag, and the back A-tag, respectively.

A-tags is able to localize the phonating animals with a relative distance error less than 41% within 173 m, and when the distance is within 100 m, the relative error is even less than 30% (Fig. 6). The distance estimation by this acoustic localization method could be considered fairly accurate. The accurate distance estimation along with a high animal detection capability (see Akamatsu *et al.*, 2008) contributes the possibility for this localization method to apply in distance sampling methodology. A successful application of the towed acoustic system in distance sampling raises great perspectives for conduction of moving survey at regular intervals to monitor population status and estimate population size of selected species, such as finless porpoises, in long-term base. However, since the localization method can only localize animals in two dimensions, the methodology is not directly applicable to a deep water environment, where depth component cannot be neglected.

A second application of the present acoustic localization system is the acoustic tracking and behavior observation of animals in mobile survey and in large area. This is very useful for evaluation of habitat selection and ship or boat effect on behavior of the animals. Usually, acoustic tracking and behavior observation of marine mammals were done using fixed hydrophone arrays (Fox *et al.*, 2001; Au and Benoit-Bird, 2003; Wiggins, 2003), which were restricted in local area. In the present mobile survey, four finless porpoises were successfully tracked in their natural habitat. Two-dimensional swimming trajectories relative to the moving survey boat, absolute swimming speed V, and absolute heading direction of the tracked animals were deduced by assuming the animal movements were straight and at constant speed in the segment between two consecutive locations (Fig. 4). According to the distribution of the values of speed V (Fig. 4), they could be qualitatively divided into two subsets. One is between 1.0 and 3.2 $\mathrm{m\,s^{-1}}$ with an average of 2.1 $\mathrm{m\,s^{-1}}$, and the other one is between 5.0 and 12.1 $\mathrm{m\,s^{-1}}$ with an average of 9.0 $\mathrm{m\,s^{-1}}$. The former is slightly higher than the speed measured by Yang and Chen (1996) when animals were traveling, and Akamatsu *et al.* (2002). However, it should be noticed that the animals in Yang and Chen, 1996 and Akamatsu *et al.*, 2002 were living in a stagnant water environment, while the animals here are living in a running water environment. The latter speed is obviously higher than the one measured by Akamatsu *et al.* (2002), whereas, it is comparable to the speed measured by Yang and Chen (1996) when animals were in fright. Figures 4(b)–4(d) showed that the animals changed their heading direction frequently, and in most of the cases when there was an obvious change in heading direction between two conjoint segments, the speed V of the animals was changed to be very high, which was over 5 $\mathrm{m\,s^{-1}}$. One explanation is the higher speed implies that the animals were trying to move away from the survey boat. Alternatively, the higher speed could simply be artifact due to the errors in the location determination of the animals.

A third application of this localization system is the estimation of SLs of porpoise or dolphin clicks in the wild. This parameter is very important for studies of sonar and social behaviors of these animals. Previous researches on SLs of odontocete clicks were mainly for animals in captivity (Au, 1993) or in small enclosed waters (Li *et al.*, 2006), and might not substantially represent the SLs produced by animals in their natural habitat.

In this study, ASLs from 34 located finless porpoises in their natural habitat are estimated. The ASLs are over an order of magnitude higher than those reported for this species in an enclosed waters—Tongling Reserve, which is only 1600 m in length and 80–220 m in width (see Li *et al.*, 2006). The ASLs of 180–209 dB with an average of 197 dB re 1 μPa pp are also much higher than previous reports on other porpoise species, which were usually 160–170 dB re 1 μPa pp (Møhl and Andersen, 1973; Awbrey *et al.*, 1979). For other odontocete species, such as bottlenose dolphin (*Tursiops truncatus*) and beluga (*Delphinapterus leucas*), it was observed that the same individual in open bay was able to produce signals about 40 dB more intense than the signals produced when it was in captivity (Au, 1993). Recent field recordings of harbor porpoises (*Phocoena phocoena*) also indicated that the ASLs of harbor porpoise clicks could be up to 205 dB with an average of 191 dB re 1 μPa pp (Villadsgaard *et al.*, 2007). Probably, the flexibility in SLs of sonar signals depending on environments is not unique for dolphins, but also for porpoises.

V. CONCLUSIONS

The use of the present towed acoustic system consisting of two miniature stereo acoustic data-loggers (A-tags) provided a simple and relatively inexpensive way to acquire valuable information on odontocete location, two-dimensional moving trajectory, behavior, and sound SLs in moving survey. The localization method with the upper bound of relative distance error less than 41% within 170 m could be considered to be fairly accurate. This gives the towed acoustic system a potential in the application of distance sampling methodology, where accurate distance estimation is essential, to calculate absolute densities of selected animals in shallow water environment.

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