

Density estimation of Yangtze finless porpoises using passive acoustic sensors and automated click train detection^{a)}

Satoko Kimura

Graduate School of Informatics, Kyoto University, Kyoto 606-8501, Japan

Tomonari Akamatsu

National Research Institute of Fisheries Engineering, Hasaki, Kamisu, Ibaraki 314-0408, Japan

Songhai Li, Shouyue Dong, Lijun Dong, Kexiong Wang,^{b)} and Ding Wang

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

Nobuaki Arai

Graduate School of Informatics, Kyoto University, Kyoto 606-8501, Japan

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A method is presented to estimate the density of finless porpoises using stationed passive acoustic monitoring. The number of click trains detected by stereo acoustic data loggers (A-tag) was converted to an estimate of the density of porpoises. First, an automated off-line filter was developed to detect a click train among noise, and the detection and false-alarm rates were calculated. Second, a density estimation model was proposed. The cue-production rate was measured by biologging experiments. The probability of detecting a cue and the area size were calculated from the source level, beam patterns, and a sound-propagation model. The effect of group size on the cue-detection rate was examined. Third, the proposed model was applied to estimate the density of finless porpoises at four locations from the Yangtze River to the inside of Poyang Lake. The estimated mean density of porpoises in a day decreased from the main stream to the lake. Long-term monitoring during 466 days from June 2007 to May 2009 showed variation in the density 0–4.79. However, the density was fewer than 1 porpoise/km² during 94% of the period. These results suggest a potential gap and seasonal migration of the population in the bottleneck of Poyang Lake. © 2010 Acoustical Society of America. [DOI: 10.1121/1.3442574]

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I. INTRODUCTION

The vocalizations of aquatic mammals have been used for passive acoustic monitoring (PAM) to observe the occurrence, movement, and behavior of target species (reviewed by Mellinger *et al.*, 2007). PAM methods can be divided roughly into two categories, towed and stationary methods. Towed passive acoustic platforms were developed as simultaneous or alternative methods for monitoring visual transects during vessel-based surveys (e.g., Barlow and Taylor, 2005). Acoustic transect methods for monitoring finless porpoises, *Neophocaena phocaenoides*, had higher detection probabilities than visual methods, especially for isolated individuals (Akamatsu *et al.*, 2008a), and the data can be used to estimate perpendicular distance between the animal and survey ship for use in line transect abundance estimation (Li *et al.*, 2009).

Stationary acoustic monitoring methods have been applied to several marine mammals in various aquatic systems (e.g., Van Parijs *et al.*, 2002; Au and Benoit-Bird, 2003; Širovic *et al.*, 2004; Carstensen *et al.*, 2006; Ichikawa *et al.*,

2006; Soldevilla *et al.*, 2010). These methods enable the observation of trends in relative abundance and the behaviors of target animals within a focal area (Carlstrom 2005; Hastie *et al.*, 2006; Verfuß *et al.*, 2007). One disadvantage of stationary acoustic monitoring is that double counting cannot be avoided, which makes estimating the absolute abundance or the density of the target species difficult. To estimate the detection performance of this method, one needs to know the sound production rate and the beam pattern of the target animals in detail beforehand.

Marques *et al.* (2009) presented a framework for estimating the size or density of a cetacean population through a combination of stationary acoustic platforms and biologging experiments. Although the proposed model using acoustic cues was very useful, the method was to estimate the density of Blainville's beaked whale, *Mesoplodon densirostris*, which uses individual clicks only when foraging in deep waters (Johnson *et al.*, 2004; Johnson *et al.*, 2006; Tyack *et al.*, 2006). In contrast, dolphins and porpoises frequently emit sequences of ultrasonic clicks (a click train) to orient in their environment and capture prey, regardless of water depth (Au, 1993). Especially for porpoises, click trains are easier to identify and detect among background noise given their high frequency and narrow band sonar signals (Au 1993). Here, we compared sound production and sound detection of por-

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^{b)}Author to whom correspondence should be received. Electronic mail: wangk@ihb.ac.cn

poise biosonar sounds observed by biologging and PAM systems, respectively. A model for estimating the density of odontocetes using click trains was applied to estimate the density of the Yangtze finless porpoise, *Neophocaena phocaenoides asiaorientalis*.

The Yangtze finless porpoise is a freshwater subspecies that is unique to the Yangtze River, China. The population size has been declining, and the distribution ranges have been reduced sharply in the past thirty years (Wang *et al.*, 2006). The Yangtze finless porpoise has been listed as endangered by the IUCN since 1996 (Baillie and Groombridge, 1996). The population size in 2006 was estimated at 1800 in its entire distribution range (Zhao *et al.*, 2008). Zhao *et al.* (2008) documented that the population has continued to decline and that its distribution is becoming more fragmented. Countermeasures require more ecological information on finless porpoises. Estimations of population size or density within a focal area greatly facilitate conservation or management strategies. The long-term monitoring of the animal's density is essential in the critical fragmentation area to save this species. It has been reported that the stationary passive acoustic monitoring method is effective for this subspecies, especially in low-density areas (Kimura *et al.*, 2009). In the present study, we applied the proposed model to estimate the trends of density in an area of possible growing fragmentation of the population (Li *et al.*, 2010).

II. MATERIALS AND METHODS

For density estimation using stationary passive acoustic monitoring, a three-step procedure including filtering, modeling, and validating was conducted. First, we developed the automated off-line filter to extract click trains from background noise. Second, a model was proposed for estimating density. Third, the model was applied for the long-term observation of wild finless porpoises.

We used an acoustic data logger, A-tags (Marine Micro Technology, Saitama, Japan), for all experiments and monitoring. The A-tag is a pulse event data logger that records the sound pressure level (SPL) and the time difference in sound arrival between two hydrophones (Akamatsu *et al.*, 2005a). The waveform and frequency of received sound are not recorded. The loggers were equipped with specially designed hydrophones (-201 dB/V sensitivity) having a resonant frequency of 120 kHz (100–160 kHz, 5-dB bandwidth), which is similar to the dominant frequency of finless porpoise sonar signals. Each data logger had two hydrophones to allow the identification of sound-source direction. The two hydrophones were stationed horizontally approximately 105 mm apart for tagging experiments, and 170 and 600 mm apart for fixed monitoring before and after May 2008, respectively. The longer hydrophone spacing enhances the resolution of sound-source direction. However, we did not use the sound-source direction to extract click trains for stationary monitoring (see below).

A band-pass filter of 55–235 kHz was used to eliminate low-frequency background noise. This filter enabled us to receive the frequency band of Yangtze finless porpoise sonar signals, which is in the range of 87–145 kHz, with an aver-

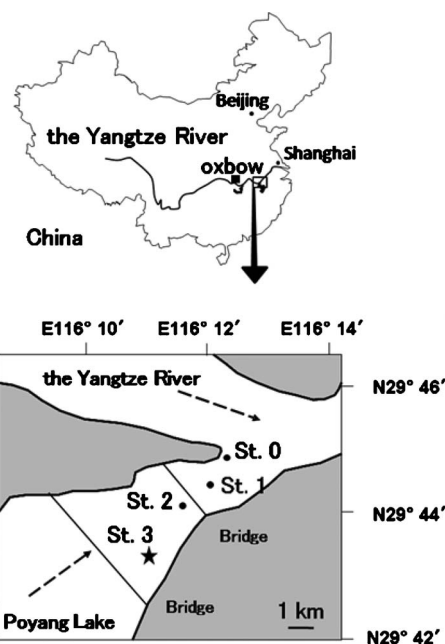


FIG. 1. Map of the study area. The black square on the map of China indicates the oxbow lake where biologging experiments were conducted. This lake is part of the Tian-e-Zhou Baiji National Natural Reserve of the Yangtze River, Shishou, Hubei Province. The acoustic monitoring station was located near the confluence of the Yangtze River and Poyang Lake, which is located in the middle reaches of the Yangtze River. The densities were estimated at Station 0–3. The dash lines of the lower map indicated the water direction.

age of 125 ± 6.92 kHz (Li *et al.*, 2005a). Akamatsu *et al.* (2005a) and Kimura *et al.* (2009) provide further details regarding signal processing, data structure, and calibration.

The A-tag was attached to a navigation buoy using an iron bar at a depth of approximately 1 m at Station 3, and it was fixed by a bamboo rod at 1 m depth from the side of each anchored boat at Stations 0–2 (Fig. 1). We used acoustic data obtained between 9:05 on 10 May and 14:35 on 11 May 2007 (7–8 m depth), including nighttime, as a training data set for the calculation of correct-detection and false-alarm ratios. We did not use this data set to estimate the density. For the application of the density estimation model, we used a data obtained during 9–10 May 2007 at Station 0, 27–29 April 2006 at Station 1, 27–28 April 2006 at Station 2, and from the end of June 2007 to the middle of May 2009 at Station 3. The water depth was approximately 3 m at Station 0–2 during the acoustical observation and varied seasonally between 2 and 20 m at Station 3.

A. Automated off-line filter to detect click trains for PAM

An automated off-line acoustic filter was developed to extract click trains from background noise using Igor Pro 6.03 (WaveMetrics, Lake Oswego, OR, USA). For the extraction of biosonar clicks, pulse intervals in a click train were used as a key for identifying porpoise signals, as shown in Fig. 2. The echolocation signals of finless porpoises are characterized by smoothly changing patterns of inter-click intervals and received sound pressure (Akamatsu *et al.*, 2005b, 2007), whereas background noise causes randomly

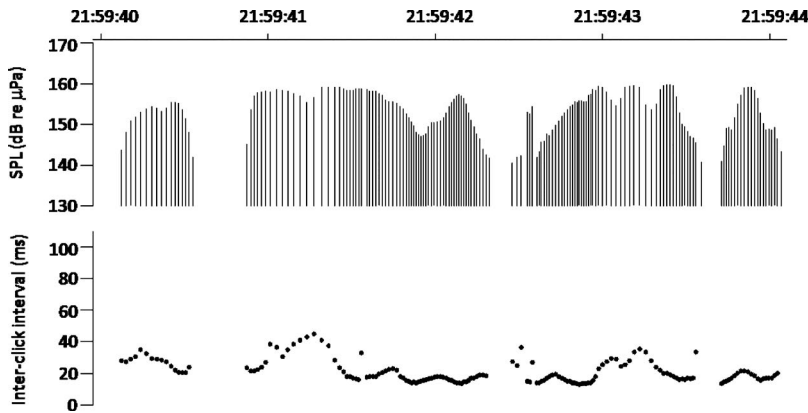


FIG. 2. Example of four click trains of Yangtze finless porpoise recorded with a stereo acoustic data logger, A-tag. The vertical axes show the received SPL (dB, upper) and inter-click interval (ms, lower).

changing patterns in inter-click interval and sound pressure (Akamatsu *et al.*, 2008b). This predictable structure enables porpoise click trains to be distinguished from background noise (Kimura *et al.*, 2009; Li *et al.*, 2009). No other cetacean species is thought to be in the Yangtze River, although there is a slight possibility that very few Yangtze River dolphins or baiji, *Lipotes vexillifer*, may live there (Turvey *et al.*, 2007). Therefore, species identification was not required in our study area.

Multipath sound propagation in the Yangtze River could cause echolocation signals to have a multi-pulse structure (Li *et al.*, 2005b). In this shallow freshwater system, reflected signals came just after the direct path signal. The surface and bottom reflection had an angle similar to the direct path signal; this resulted in the echo's very short delay time (Li *et al.*, 2005b). Here, the maximum delay time of reflected signals was estimated at 1.5 ms because the depth of the hydrophone at the stationary monitoring site was 1 m when the sound incident angle was perpendicular to the surface. Otherwise, the delay time should be shorter than 1.5 ms.

To maximize correct detection with small false-alarm ratio by filtering, nine parameters were examined (Table I). To validate the parameters, we changed each parameter from the values of 'Start' to 'End' by 'Step' as shown in Table I, and calculated the correct-detection and false-alarm ratios. Ground truth data were used to manually identify click trains, which were used as training data. These data were compared with the detected click trains using proposed filters

including the parameters in Table I. The appropriate parameters were identified at a high detection and low false-alarm ratio.

B. Density estimation

1. Proposed estimators and model

Density, D , is the number of animals per unit area. When an observer or any observation systems misses the target animals, density can be calculated as the observed number of animals divided by the detection probability and the observable area (Buckland *et al.*, 2001). Acoustical detection probability is affected by the sound-production rate of each individual. Acoustical observable area can be calculated by the source level and beam pattern using the sound-propagation model.

Using the equation proposed by Marques *et al.* (2009), an estimator of density \hat{D} can be calculated by

$$\hat{D} = \frac{n_{ct}(1-\hat{F})\alpha}{\hat{R}\pi\hat{w}^2\hat{P}\hat{C}}, \quad (1)$$

where n_{ct} is the number of detected click trains in a day, \hat{R} is the cue-production rate, which is equal to the calculated number of click trains produced by a porpoise in a day, \hat{P} is the estimated probability of detecting cues (which is dependent on the detection distance calculated from the source level, SL) within distance \hat{w} (beyond which cues are as-

TABLE I. Parameters used in the detection filters for sonar signals. The ROC curve for each parameter was examined. Appropriate values for each parameter were chosen according to the highest correct-detection and lowest false-alarm rates. ICI and CT were abbreviations of inter-click interval and click train, respectively.

No.	Parameter	Aim	Start	End	Step	Result
1	The detection threshold of passive SPL (Pa)	To extract noises or reflections	9.0	12.0	0.5	10.5
2	The min. duration of ICI (ms)	To remove reflections	0.5	5.0	0.5	2.0
3	The isolation from the next pulse (ms)	To remove isolated background noise	10^2	10^6	$\times 10^1$	-
4	The differences of ICI between two pulses	To check the smoothness of ICI	1.5	5	0.5	-
5	The differences of SPL between two pulses	To check the smoothness of passive SPL	1.5	5	0.5	-
6	The max. duration of ICI (ms)	To extract as one click train	100	300	10	100
7	The min. number of pulse in one CT	To avoid false detection of noise	4	10	1	6
8	The coefficient variance of ICI in one CT	To check the smoothness of ICI	0.1	1	0.1	0.40
9	The coefficient variance of SPL in one CT	To check the smoothness of passive SPL	0.1	1	0.1	-
	The detailed coefficient variance of ICI in one CT	To decide coefficient variance of ICI	0.40	0.80	0.05	0.40

sumed not to be detected), \hat{C} and \hat{F} are the correct-detection and false-alarm ratios calculated from automated off-line signal processing as described above, and α is the coefficient of group size and the number of click trains produced in a unit time ($\alpha=1$ when they have linear correlation). These parameters were obtained from a biologging experiment and during stationary acoustic monitoring. Note that n_{ct} and \hat{R} are the detected and produced number of acoustic cues, respectively, in the same unit time. This means that the density \hat{D} is independent of the observation duration of n_{ct} and \hat{R} . The estimated density in the present study provides the number of porpoises/km².

We used the data from one stationary sensor for the density estimation at each location. The number of sensors used was not considered. We estimated the detection probability \hat{P} and observable area size $\pi\hat{w}^2$ from the sound propagation model. Values of \hat{R} were determined by attaching acoustic tags to animals. The values of α and n_{ct} were obtained using the stationary passive acoustic monitoring method. The time period to estimate the density was set as 1 day. If the time period is set very short, such as 1 min or hour, the estimated density fluctuates greatly with over time. Conversely, if the period is too long, such as 1 month or year, we cannot monitor the possible effects of daily or seasonal changes on the density. The time period can be chosen to fit the purpose of the study.

Differences among local populations, habitat areas, and geographic locations were not considered in this study because environmental parameters such as bottom sediment, depth, and water current do not differ much within the habitat of this species. A few required assumptions were that acoustic cue production observed using the biologging technique is the same as that within the area in which we deployed stationary acoustic monitoring systems.

2. Cue-production rate (the number of click trains produced by a porpoise in a day)

Biologging experiments were conducted to examine the click-train production rate, \hat{R} . Fifteen finless porpoises were successfully tagged for periods greater than 7-h under free-ranging conditions in an oxbow of the Yangtze River (29.47'–29.51'N, 112.32'–112.37'E; Fig. 1) on 14 Oct. 2004, 21 Apr. 2006, and 3 Apr. 2008. This oxbow lake, part of the Tian-e-Zhou Baiji National Natural Reserve of the Yangtze River, Shishou, Hubei province, China, is about 21 km long and 1–2 km wide and has a maximum depth of 20 m, which is approximately the same width and depth as the wild habitat. The porpoises were fitted with two tags, an A-tag and a behavioral data logger (PD2GT; Little Leonardo, Tokyo, Japan). Depth, swimming speed relative to the water, and pitch and roll acceleration were recorded with the behavioral data logger. The sampling intervals for depth, speed, and acceleration were 1, 0.125, and 0.0625 s, respectively. The tags were attached using a suction cup to the side of the body above the pectoral fin, about 30 cm from the head. Acoustic tags were always attached to the right side, and behavior tags to the left side. The hydrophone of the acoustic

tag was positioned about 30 cm behind the animal's blow-hole. Upon spontaneous release of the suction cup, a tag was retrieved using a VHF radio transmitter (MM110; Advanced Telemetry Systems, Isanti, MN, USA). The data from October 2004 were reported in Akamatsu *et al.* (2007), and the present study shows results from all three survey periods.

The definition of a click train was the same as that established for an automated off-line filter to detect click trains, except for the detection threshold level, which was set to 134 dB, 5 Pa. Although the automated filter for detecting click trains from stationary monitoring data had a higher threshold, the detection and false-alarm ratios to detect click trains from the PAM data were included in the density estimation model.

During signal processing, we extracted click trains from recordings for which the dive duration was more than 0.1 s because this was the maximum inter-click interval within one click train. To exclude splash noises, we did not use acoustic data recorded when the animal's depth was shallower than 0.3 m and when its swimming speed pulse at minus 2 s from the beginning of respiration was slower than 0.2 m/s. Because we attached the tags to the side of the body about 30 cm from the blow whole, depth less than 0.3 m shown by the behavioral data logger indicated respiration by the porpoise. During respiration, porpoises tend to produce a splash, which creates broadband noise. At this moment, the propeller sensor is stopped in the air. Although clicking occurs at the surface, we cannot extract these click trains due to the splash noise. To exclude splash noise contamination, we used Ethographer ver. 1.42 under an Igor Pro platform (made by Kentaro Q. Sakamoto, available at no charge for academic use; <http://bre.soc.i.kyoto-u.ac.jp/bls/index.php?Ethographer>).

Clicks produced by a tagged animal were identified using the time difference between the two hydrophones of the acoustic tag (Akamatsu *et al.*, 2010). Clicks from the tagged animal would come from a specific angle range, as the relative direction from the acoustic tag to the sound source below the blowhole was constant. Only clicks coming from an angle of $\pm 34^\circ$ were considered to have been produced by the tagged animal; this angle range corresponded to a 12-cm shift in the position of the head relative to the body (Akamatsu *et al.*, 2010). If another porpoise phonated from a location ahead of the tagged animal and it exceeded the threshold and passed other filters, we were not able to distinguish its signal from the signals of tagged one.

3. Observable area and detection probability

Detection distance depends on the source level, sound propagation, and beam pattern. The A-tag detects the bearing angles and received sound pressure. However, it does not record the distance to the target as long as a single system is being used. We referred to the SL reported by Li *et al.* (2009), which is the only SL recorded in the wild habitat of the Yangtze finless porpoise, ranging from 180 to 209 dB re 1 μ Pa pp at 1 m, with an average of 197 dB ($N=34$). The distribution of the SL recorded by the A-tags of the tagged porpoises was not appropriate for this model because it recorded the off-axis SPL. Although the SL reported in Li *et al.*

(2009) was equal to the intensity at 1 m from a directional source in an unknown direction (Villadsgaard *et al.*, 2007), almost all sound was considered to be on-axis signals because SPLs were only calculated when two A-tags, separated by 17 m, both recorded signals and positions of porpoises. Values were estimated from a few dozen animals that were far from the A-tags.

Li *et al.* (2009) selected the click with the maximum intensity in a click train for SL estimation, whereas we used click trains containing 6–500 pulses (see the results of the automated off line filter). This means that the received sound pressure level of six successive clicks in a train should be larger than the detection threshold level of the A-tag. We compared the maximum and sixth greatest sound pressure level in one click train received by the stationed A-tag. For this evaluation, we used 51 sample click trains detected correctly by the automated filter. The data set was the same as those used to calculate the detection and false-alarm rates. The difference in the maximum and sixth sound pressure level was 2.6 dB on average (S.D.=2.4). We used the source level distribution, which was 2.6 dB lower than that reported by Li *et al.* (2009), to calculate the detection probability and area size.

The detection threshold of the sound pressure level of the stationary A-tags was set to 140.4 dB. Assuming a simple spherical propagation model, when a source level was bigger than a received level, the maximum detection range of a click train, d , was calculated using the formula for transmission loss:

$$\text{Source Level} - \text{Received Level} = 20 \log_{10}(d) + Ad, \quad (2)$$

where received level is 140.4 dB (10.5 Pa), and A is the frequency-dependent absorption coefficient of water in dB/m, which was estimated to be 0.004 dB/m at 125 kHz (the peak frequency of finless porpoises; Li *et al.*, 2005a) in fresh water using the model of Fisher and Simmons (1977).

Clicks exhibiting a sound pressure level larger than the detection threshold level can be detected by an A-tag or is not recorded. In this case, the probability of detecting a click train is 1 or 0. The source levels of click trains are not constant and exhibit variations (Li *et al.*, 2009). Therefore, even at the same distance, the detection probability depends on the source level distribution. $g(r)$ is defined as the probability of a sound source having a statistically significant distribution of SL at distance r and a threshold level at the receiver. The detection probability \hat{P} can be obtained by integrating the multiplication $g(r)$ by the expected proportion of the annulus at each distance r to the observable area (Buckland *et al.*, 2001).

Detections of the off-axis beam were also considered. Akamatsu *et al.* (2005c) reported that the beam intensity of the off-axis signals in this species was nearly constant between 45° and 115°, where 0° corresponds to the on-axis direction, and that it reached 162 dBp-p re 1 μ Pa maximum. Consequently, we simplified beam patterns such as the on- and off-axes. The off-axis beam is assumed to be 47 dB smaller than the on-axis beam based on the difference of the maximum SPLs. The on-axis beam pattern (a 3-dB beam

width in the horizontal planes) is referred to as the 16° pattern by Au *et al.* (1999), who reported the pattern of harbor porpoises, *Phocoena phocoena*. The other 344° were considered to have the same SPL value as the off-axis signals. This means the A-tags detected on- and off-axis porpoise signals approximately 4.4% and 95.6% of the time, respectively.

The probability of detecting click trains depends on the beam pattern. This is the probability that an A-tag detected either on-axis or off-axis porpoise signals. The body axis angle relative to a hydrophone depends on the orientation of the porpoise. Porpoises were assumed to orient in all directions randomly during this study. The porpoises were considered to swim nearly horizontally most of the time (Akamatsu *et al.*, 2010), and thus, we used only two dimensions, as the water depth in the study area was shallow (less than 30 m) compared with the maximum estimated detection range (see Sec. III).

4. Effect of group size on the cue-production rate

Group size and the number of click trains were compared. Group size was defined as the number of porpoises in a 1-min time bin. We used 36.4-h daytime data from Stations 0–2 and 44 days worth of data including nighttime data from Station 3, which were randomly selected from 28 June to 14 December 2007 (Fig. 1).

The counting methods of the group size were the same as those of Kimura *et al.* (2009). The stereo hydrophone enabled the discrimination of sound-source bearing angles among individuals. We considered a sequence of click trains that came from a similar bearing angle as one individual located near the stereo acoustic data logger. See more details in Kimura *et al.* (2009).

The acoustically determined number of porpoises within 1 min varied from 0 to 5 at Stations 0–2 (Kimura *et al.*, 2009) and from 0 to 4 at Station 3. The number of porpoises was averaged per day at Station 3 and per hour at Stations 0–2 because observations were only conducted during the daytime at Stations 0–2.

5. Variance

The variance in porpoise density was approximated using the delta method (Seber, 1982, pp. 7–9; reviewed in Buckland *et al.*, 2001, p. 52). Except for the detection and false-alarm probabilities of click trains among noise, we assumed that the various random components were independent (Marques *et al.*, 2009). The variance in porpoise density was estimated by

$$\text{Var}(\hat{D}) \approx D^2\{CV(n_{ct})^2 + CV(\hat{R})^2 + CV(\hat{P})^2\}, \quad (3)$$

where CV is the coefficient of variance of each component.

III. RESULTS

A. Automated off-line filter to detect click trains for PAM

We manually detected 71 click trains from the training data set. According to the criterion established to fix the appropriate value of each parameter, described in the Materials

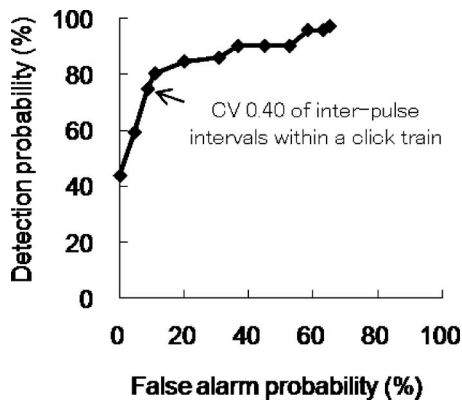


FIG. 3. ROC curve for the present acoustic filter for detecting click trains of finless porpoises ($N=71$) with optimum CV value. We adopted a value of 0.40 for the CV.

and methods, the threshold sound pressure level (No. 1 in Table I) was chosen as 10.5 Pa or 140.4 dB re $1 \mu\text{Pa}$ pp. The pulse within 2 ms after the direct path pulse was chosen to eliminate reflections effectively (No. 2). The parameters of removing isolated pulse (No. 3), smoothing pulse sequence (No. 4), and sound pressure (No. 5) did not affect the correct-detection and false-alarm ratios. The maximum duration of the inter-click interval within one click train (100 ms, No. 6) was adopted conservatively because the detection rate and false-alarm rate were almost identical when it was altered from 100 to 150 ms in 10-ms steps. Correct detection was high, and the rate of false alarms by noise contamination was low when the click train contained six pulses (No. 7) with inter-click intervals from 2 (No. 2) to 100 ms (No. 6). Employing this criterion, a maximum of 50 pulses was detected in 100 ms, which means all pulses exhibited 2 ms intervals within a train. When the CV of inter-click intervals within a click train was between 0.4 and 0.8, the click-train detection rate was high ($>70\%$). Given that correct detections were highly sensitive to CV (Fig. 3), fine-scale examination from

0.35 to 0.85 in 0.05 steps was conducted. A value of 0.35 produced the highest true-detection to false-alarm ratio, and 0.45 was the inflection point of the receiver operating characteristic (ROC) curve (Fig. 3). We adopted a value of 0.40 for the coefficient of variance (No. 8). The false alarm, \hat{F} , and correct detection, \hat{C} , probabilities were 8.62×10^{-2} and 7.47×10^{-1} , respectively. The other parameters (Nos. 3, 4, 5, and 9) did not affect both the correct-detection and false-alarm rates, so they were not included in the automated filter for detecting click trains.

B. Density estimation

1. Cue-production rate (the number of click trains produced by a porpoise in a day)

Porpoises were tagged for a minimum of 7 h and a maximum of 35 h, depending on when the spontaneous separation of the suction cup from the animal occurred. Table II shows the time of deployment, sex, body length, bodyweight, the number of dives, click detection of tagged animals, and percentage of the time that was excluded as splash noise. Within the signal processing, 4.5% of the data were completely eliminated from the effective data as splash noise. We obtained more than 279 h of acoustical data and analyzed 270 816 click trains. Figure 4 shows the distribution of the inter-click-train intervals produced by 15 porpoises ($N=270\ 801$). The average inter-train interval was 3.01 ± 16.13 s. The minimum inter-train interval was 0.1 s, according to the definition in Table I, and the maximum was 2748.68 s (45.8 min). Intervals shorter than 3 s accounted for 84.2% of the total number of click trains. The calculated number of click trains produced by a porpoise in a day, \hat{R} , was estimated at 2.87×10^4 (CV=0.943).

TABLE II. Detailed information of tagged porpoises. Both data logger worked during the time of effective data. The data were excluded when the animal's depth was shallower than 0.3 m and its swimming speed ± 2 s from the beginning of respiration was slower than 0.2 m/s; these data are shown as % of the data excluded.

ID	Sex	Body length (m)	Body weight (kg)	Day of attachment	Start time	End time	Effective data	Number of dives (deeper than 0.3 m)	Number of click trains	% of the data excluded
28	M	1.23	34.0	14 Oct. 2004	10:24	17:44	7:20:25	1338	11 231	1.5
29	M	1.48	48.7	14 Oct. 2004	10:29	3:39	17:49:45	3036	26 553	12.1
30	M	1.59	59.4	14 Oct. 2004	10:33	12:23	25:49:30	3071	37 997	1.9
31	M	1.46	48.5	14 Oct. 2004	10:37	11:29	24:52:11	3517	91 948	2.2
35	M	1.34	42.0	21 Apr. 2006	9:30	8:35	23:05:03	2602	8674	2.7
37	F	1.25	37.0	21 Apr. 2006	9:37	19:49	10:11:42	1024	1106	2.2
38	M	1.48	65.8	21 Apr. 2006	9:48	23:50	14:01:54	1942	7062	0.4
42	M	1.56	55.5	21 Apr. 2006	10:13	3:09	16:56:03	2238	14 562	1.5
50	M	1.33	38.6	3 Apr. 2008	12:55	20:29	7:33:29	631	7797	4.7
51	F	1.37	47.7	3 Apr. 2008	13:02	1:32	12:30:41	1201	8356	0.6
52	M	1.61	70.5	3 Apr. 2008	15:13	5:40	14:27:30	1451	8644	0.2
53	M	1.61	68.7	3 Apr. 2008	15:28	1:03	33:35:28	2678	23 227	21.3
54	M	1.33	39.5	3 Apr. 2008	15:36	20:16	28:39:55	5103	12 420	0.4
55	F	1.46	51.9	4 Apr. 2008	10:00	21:02	35:02:27	3844	8123	1.3
60	M	1.42	53.0	5 Apr. 2008	13:40	21:01	7:21:50	1256	3115	0.4

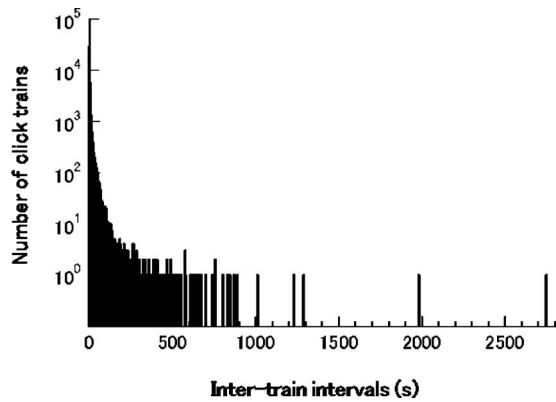


FIG. 4. Histogram of inter train intervals obtained from 15 tagged porpoises.

2. Observable area and detection probability

The estimated detection probability and maximum detection range of on- and off-axis click trains, d , was calculated using the Newton–Raphson method (Fig. 5(a) and 5(b)). The total area, πd^2 , was 4.96 km², whereas the area for only off-axis signals was 7.85×10^{-5} km². $g(r)$ was calculated as a fitted curve of Fig. 5(a) and 5(b). $g(0)$ of on- and off-axis signals was estimated to be 1 and 0.91, respectively, as the three off-axis SL calculated were lower than the threshold level (140.4 dB), whereas all on-axis SL could de-

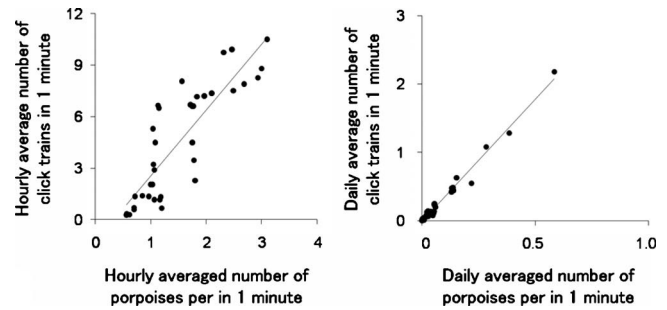


FIG. 6. Correlation between the average number of porpoises and the number of click trains detected in 1 min at Stations 0–2 (left) and during 1 day at Station 3 (right). The number of porpoises was averaged over either every hour (left) or day (right).

tect at 0 m from the A-tag. As indicated previously in this paper, the ratio of area of on- and off-axis beam widths were 4.4% and 95.6%, respectively, the detection probability of click trains \hat{P} was estimated at 7.96×10^{-3} (CV=0.640), and $g(0)$ was determined to be 0.92 (Fig. 5(c)).

3. Effect of group size on the cue-production rate

The average number of porpoises within an hour and a day, counted over every 1-min time bin, was correlated with the number of click trains detected using the filter (Fig. 6). A stronger correlation was found at Station 3, where lower

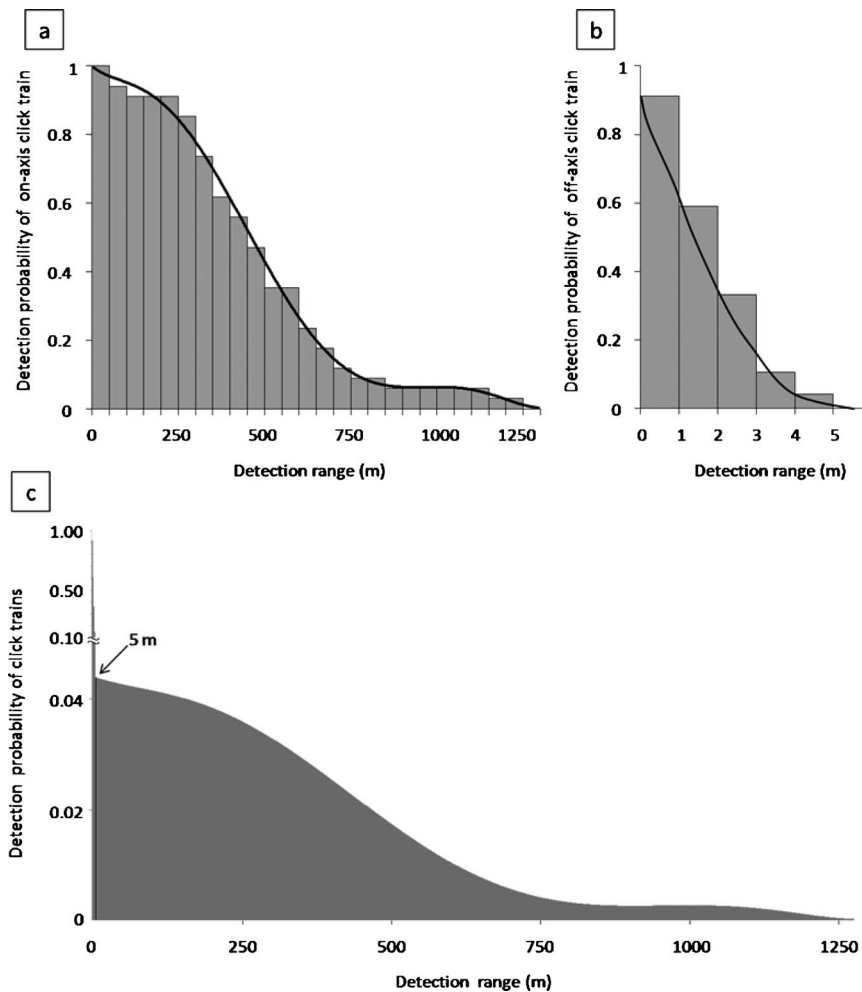


FIG. 5. Estimated detection probability of click trains by distance. Probabilities were calculated from source level ($N=34$) values recorded from porpoises in a wild habitat (Li *et al.*, 2009). (c) was obtained by (a) with a weight of 4.4% of on-axis beam and (b) with weight of 95.6% of on-axis beam. The solid line of (a) and (b) shows $g(r)$, which was calculated as a fitted curve (a: $g(0)=1$, $R^2>0.99$, $p<0.01$, b: $g(0)=0.92$, $R^2>0.99$, $p<0.01$).

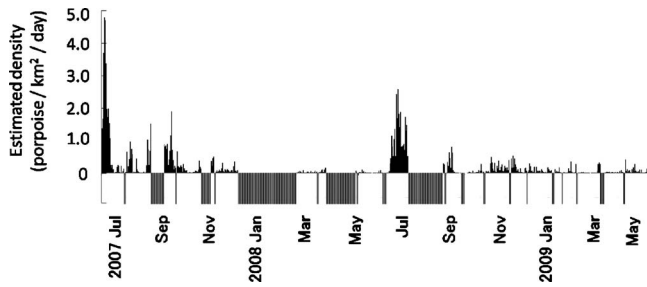


FIG. 7. Changes in the estimated density of finless porpoises (individual/km²/day). Gray bars indicate periods that were not monitored.

numbers of porpoises were observed ($N=44$, lower: $R^2=0.98$, $p<0.01$), compared with the other areas ($N=37$, $R^2=0.726$, $p<0.01$). Both results showed positive linear correlations between the cue-production rate and group size for periods of either 1 h or 1 day. Therefore, the coefficient between group size and cue production rate $\alpha=1$, and this effect was not considered further in this study.

4. Field application

Click trains were detected using the filter that was used for determining the detection and false-alarm probabilities above. The numbers of click trains detected per day were 585 and 1690 at Station 0 ($N=2$), 512–3376 at Station 1 ($N=3$), 134 and 1240 at Station 2 ($N=2$) and 0–4450 (average 218.15, $CV=2.26$, $N=466$) at Station 3. Note that the data were obtained on different days, except that those from Station 2 overlapped those from Station 1.

Using Eq. (1), the density of finless porpoises per day was estimated to be 7.54, 6.20, 3.20, and 0.24 (porpoise/km²/day) on average at Stations 0–3, respectively. The estimated densities at Stations 0–2 were converted to 1-day unit time because we were unable to obtain data for the whole. Figure 7 shows the change in the estimated density of finless porpoises at Station 3. The contributed values of $\pi\hat{v}^2$, \hat{P} , \hat{R} , \hat{C} , \hat{F} , and α were 4.96, 7.96×10^{-3} , 2.87×10^4 , 7.47×10^{-1} , 8.62×10^{-2} , and 1, respectively.

The CVs for n_{ct} , \hat{R} , and \hat{P} were 2.26, 5.36, and 0.640, respectively. Thus, the variance of porpoise density, $\text{var}(D)$, was estimated to be $0 \sim 147.2$, 2.15 on average.

IV. DISCUSSION

A. Automated off-line filter

The definition of inter-click-train interval, 100 ms, was supported by previous work in which nearly 90% of clicks during a click train were produced within 100 ms (Akamatsu *et al.*, 2005b). The smoothness of the inter-click intervals was characterized by the coefficient of variance of the inter-click interval within a click train (No. 6). The coefficient of variance of the inter-click interval was mostly affected by the detection and false-alarm probabilities. Although the effect of the order of the filter parameters was not examined in the present study, the filtering was conducted from physical parameters to behavioral parameters. The detection performance and false-alarm level of the present system were simi-

lar to the values reported in previous work, in which the correct detection rate was 77.6%, and the false-alarm probability was 5.8% using a stationary acoustic data logger array (Wang *et al.*, 2005). That work was conducted in an old course of the Yangtze River, unlike the present habitat of the finless porpoise in the wild. The similarity in the correct-detection performance suggests that the selection of the other parameters was effective both in the wild and in a semi-closed water system.

B. Density estimation

1. Cue-production rate (the number of click trains produced by a porpoise in a day)

Acoustic data from more than 279 h of recording, including both day and night recordings of 15 porpoises, were obtained and used to estimate the click-train production rate and SPL level of finless porpoises.

We assumed that the acoustic cue production rate was constant and that it did not change by season or location. The click-train production rate of sperm whales, *Physeter macrocephalus*, has been reported to change from year to year (Whitehead and Weilgart, 1990) and to be dependent on the population (Douglas *et al.*, 2005). Biologging experiments were conducted over multiple years in different seasons, and we could not detect notable differences between years.

Finless porpoises produced sonar click trains every 3 s on average. Akamatsu *et al.* (2007) reported that porpoises emitted signals every 6 s on average. This difference results from the definition of a click train. Akamatsu *et al.* (2007) defined the maximum inter-click interval of a click train as 200 ms, which is double the maximum value used in the present study. In other words, porpoises produced sonar signals with the same frequency. Note that the results of Akamatsu *et al.* (2007) were included in this study and comprised approximately 30% of our data.

The 134.0-dB threshold level employed by the biologging experiment could result in low-level click trains being missed, although detection distance of low-intensity sounds is short and does not increase the number of detections. We determined that clicks within one click train exhibited intervals between 2 and 100 ms. Therefore, if porpoises emitted one or more clicks at intervals of less than 2 ms or more than 100 ms, they would not be identified as belonging to the same click train. Additionally, when an animal's depth was less than 0.3 m or its swimming speed was slower than 0.2 m/s within 2 s after respiration, we omitted the acoustic data to exclude splash noises. Our results provide conservative estimates of sound production, although splash noise comprised only 4.5% of the effective data.

Inter-train intervals greater than 900 s (15 min) were observed only five times (0.002% of all click trains and 0.8% of total observation time) from two individuals. These porpoises continued to dive and respire silently over periods that lasted up to 45 min. Several possible explanations exist for these observations, such as the failure to record low-level click trains or behaviors such as sleeping.

2. Observable area and detection probability

We used the conventional distance sampling approach as described by Buckland *et al.* (2001) to estimate the detection probability. Detection distances were calculated from the SL following the methods employed by Zimmer *et al.* (2008) or Stafford *et al.* (2007).

We used a simple spherical propagation model to estimate the detection probability and estimated area size. If a cylindrical propagation model were used instead, 50% detection distance could be calculated up to 4 km for on-axis sonar sound. This is not consistent with the previous studies using different platforms and our experience in the focal research field. Akamatsu *et al.* (2008a) calculated that the acoustical detection distance was up to 300 m using towed A-tags, which was confirmed by matching with visual observations and is in accordance with results of the present study. Li *et al.* (2009) also measured the distance to the sound source acoustically up to 175 m by two-dimensional acoustic tracking using towed A-tags. DeRuiter *et al.* (2010) reported that the clicks of harbor porpoises have spread spherically at least up to 200 m in shallow waters (~15 m deep). Hamilton (1972) showed that the attenuation of the marine sediment is approximately dependent on the first power of frequency. This means that ultrasonic sounds such as porpoise clicks (125 kHz) lose the most energy at the sediment. Instead of a propagation model, Marques *et al.* (2009) used a generalized additive model to estimate the detection function because the sample size of their tag data was small. Although this provides an alternative method, it is an indirect method. The large sample size in our data set allowed for a simple and direct estimation of the detection probability.

We used a SL value that was recorded from porpoises ($N=34$) in a wild habitat (Li *et al.*, 2009) and assumed that the source level distribution was 2.6 dB lower than that reported by Li *et al.* (2009) to detect at least six successive clicks. For other odontocete species, such as the bottlenose dolphin, *Tursiops truncatus*, and the beluga whale, *Delphinapterus leucas*, the same individual in an open bay was found to be able to produce sonar signals that were approximately 40 dB more intense than the signals produced while in captivity (Au, 1993). Therefore, the SPL should be recorded in wild habitats. It was assumed that RL was TL + SL and that the simple proportion of the SPL of a detected click train could be used to directly estimate the detection probability (Fig. 5). Although our small sample size for SL ($N=34$) resulted in a rough estimate of the probability, these SL values are the only results obtained for porpoises in natural habitats.

Additionally, we converted on-axis SL into off-axis SPL based on the previous off-axis signal study (Akamatsu *et al.* 2005c). The estimated value, 47 dB between on- and off-axis beams, was almost the same as off-axis dependent attenuation of the echolocation signal of Cuvier's beaked whale, *Ziphius cavirostris* (Zimmer *et al.*, 2008). However, the true beam pattern of echolocation signals is not simply two patterns (Au 1993). Further SL recordings and studies of beam pattern from porpoises are necessary to improve the accuracy of the detection function.

3. Effect of group size on the cue-production rate

Group size did not affect the sound-production rate (Fig. 6), which is consistent with the reported click rate of sperm whales (Whitehead and Weilgart, 1990). Eavesdropping of echolocation clicks was indicated during synchronous swimming by rough-toothed dolphins, *Steno bredanensis* (Götz *et al.*, 2006), during a study that involved comparing 10-s recording sequences. In the present study, synchronous behaviors by animals were not examined. However, two or three porpoises swimming close together could be identified through the doubling or tripling of different cyclic characteristics of the sound pressure and/or inter-click interval within a single trace (Kimura *et al.*, 2009). Group size would be underestimated if porpoises produced click trains alternately while swimming very close to each other (Kimura *et al.*, 2009). Our results, however, support previous studies in that the use of biosonar in finless porpoises occurred on a regular basis and was affected on a fine scale by changes in behavior such as foraging trials (Akamatsu *et al.* 2010). Additionally, acoustic estimates of group size for this species are reported to be more accurate than those produced by visual observation (Kimura *et al.*, 2009).

C. Field application

The average estimated density of finless porpoises declined from the junction area to the lake. This is consistent with Kimura *et al.* (2009) and Li *et al.* (2010), who reported that porpoises were rarely seen between the two bridges shown in Fig. 1. We detected click trains at different sites and periods, except that observation periods overlapped at Stations 1 and 2. We focused on the population densities within an area on a certain day. Note that this does not reflect the population size or abundance of the animals in the focal area.

Underwater sounds were recorded over approximately 2 years at Station 3. Animal density might increase during low water seasons in a shallow water system, as has been found with other riverine dolphins (Smith *et al.*, 2009). High and low water seasons occur in the summer and winter, respectively, around the study area. However, porpoise density seems to be high during June and July at Station 3, which is the transition period from the dry to the rainy season. Seasonal changes in distribution or habitat use have been reported for other porpoises (e.g., Verfuß *et al.*, 2007) and riverine dolphins (Martin and da Silva, 2004). Note that 2 years of monitoring were not sufficient to reveal the ecology of the target animal, but that a longer period of acoustic monitoring would allow such a determination.

V. CONCLUSIONS

The density of finless porpoises in the Yangtze River was estimated using a passive acoustic device. Required parameters were the detection and false-alarm probabilities of click trains, the acoustical cue-production rate, source-level distribution, and the effect of group size on cue production. Combining biologic methods with PAM, quantitative

acoustical observation of density of phonating animals was possible. To establish a more precise model, we should note the possible variance of parameters.

Recordings of target animal cues and background noise in the focal area were necessary. The probability of correct detection and the false-alarm rate were required for the automatic filter to detect the click train among noise. Parameter choice was essential for the design of the automated filter. Reliable ground truth data for a training set was important for the evaluation of the receiver operating characteristics curve. Creating a filter for detecting the target cue facilitated analysis of very large amounts of data.

Tagging or biologging methods are useful for measuring the rate of cue production and the SPL of animals. Frequent sonar production is considered suitable for estimating the density of odontocetes compared with other species that make periodic sounds such as whistles or mating songs. Large data sets should be obtained under as many different conditions as possible because the cue rate and SL may be affected by factors such as the time of day, season, area, or sex. In some cases, for example, when target animals phonate very rarely in the focal area, playback experiments are better for calibrating detection probabilities, as was demonstrated by Ichikawa *et al.* (2009).

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