Widespread passive acoustic detection of Yangtze finless porpoise using miniature stereo acoustic data-loggers: A review[a)]

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(Received 13 January 2010; revised 21 May 2010; accepted 25 May 2010)

Data on distribution, abundance, ecology, and behavior are essential for conservation and management of endangered animals in the wild. Yangtze finless porpoise (*Neophocaena phocaenoides asiaeorientalis*) is an endangered small odontocete species, living exclusively in the Yangtze River and its connecting Poyang and Dongting Lakes. Frequent production of high-frequency bio-sonar signals allows the animal to be detectable using passive acoustic methods. Recently, a stereo acoustic event data-logger (A-tag) has been used extensively to detect the animal by using both fixed and mobile platforms. The passive acoustic monitoring methods were not only successful in detecting the presence of animals, but also in counting, localizing, and tracking phonating individuals. Underwater behavior observed acoustically helped to assess possible effects of vessels on the animals during acoustic surveys.
 [DOI: 10.1121/1.3455829]

PACS number(s): 43.80.Ka, 43.80.Ev, 43.80.Nd [WWA] Pages: 1476–1482

I. INTRODUCTION

The Yangtze River used to be one of only two river systems in the world, which were home to two odontocete species. However, with the likely extinction of the Yangtze River dolphin (locally called Baiji, *Lipotes vexillifer*) (Turvey *et al.*, 2007), the Yangtze finless porpoise (*Neophocaena phocaenoides asiaeorientalis*) is becoming the only aquatic mammal residing in the middle and lower reaches of the Yangtze River from Yichang to Shanghai and its connecting Poyang and Dongting Lakes (Fig. 1). The Yangtze finless porpoise is also the only freshwater subspecies of finless porpoise (*Neophocaena phocaenoides*) (Wang, 1992; Gao and Zhou, 1993, 1995), which might have been separated genetically from the oceanic subspecies for over two-hundred thousand years (Zheng, 2005).

Large rivers are extensively exploited by humans, especially in developing countries. The Yangtze River system is the so-called "golden channel" of China, and is an integral resource for the economic development of the country. Many human activities including fishing, transportation, pollution, dam construction and other developments have been expanding rapidly over the last several decades. These activities created a serious threat and raised concern for the region's bio-diversity and conservation efforts. Both the Baiji and Yangtze finless porpoise populations suffered and the species were designated as endangered by IUCN (Reeves *et al.*, 2003). After a six-week intensive visual-acoustic joint survey in November and December 2006 (Yangtze Freshwater Dolphin Expedition 2006, YFDE 2006), no Baiji was sighted (Turvey *et al.*, 2007). This survey covered the entire historical distribution range (Fig. 1) of Baiji and Yangtze finless porpoise in the main stem of the Yangtze River and part area of the Poyang Lake. As the outcome of this survey, Baiji was declared to be likely extinct (Turvey *et al.*, 2007). The population of the porpoise in the main channels of the Yangtze River was estimated as only approximately 1000–1200 (Zhao *et al.* 2008). This population size is less than half the estimate from visual surveys conducted between 1984 and 1991 (Zhang *et al.*, 1993), and it implies an annual rate of decline at least 5% for the population in the main stem of the river (Zhao *et al.*, 2008). Zhao *et al.* (2008) estimated that the total population size of porpoise in the Yangtze River System is only about 1800, with approximately 400 individuals living in the Poyang Lake and 200 individuals in the Dongting Lake.

[a)]This work was presented at the 5th Animal Sonar Symposium, Kyoto, Japan, 14–18 September 2009.
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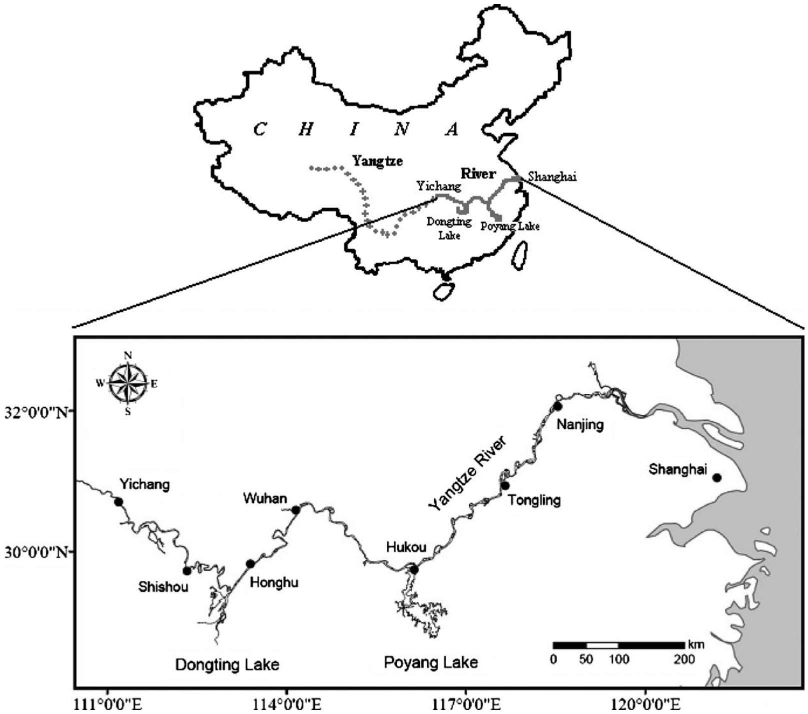

FIG. 1. Distribution range (gray solid line in the upper panel) of the Yangtze finless porpoise (*Neophocaena phocaenoides asiaeorientalis*) in the Yangtze River System (both gray dotted and solid lines in the upper panel), including the main stem and tributaries of the middle and lower reaches (Yichang to Shanghai) of the Yangtze River and its connecting Poyang and Dongting Lakes.

Regular surveys of the population's status, ecology, and behavior are essential for conservation, evaluation of conservation outcomes, and management of Yangtze finless porpoise. Traditional visual survey for cetacean can only allow detection of a fraction of the animals both due to the brief surfacing of animals when breathing, and reduced clarity of the water. Finless porpoise, due to its small body size (approximately 1.5 m length), no dorsal fin, and short (1–2 s) surfacing durations, are even more difficult to detect and count visually. Additionally, weather conditions and variation of experience between observers cause additional biases and confound detection probabilities. However, cetaceans possess highly developed sound production systems (Au, 1993; Richardson *et al.*, 1995). Acoustic signaling functions to aid in foraging, communication, navigation and orientation (Au, 1993; Richardson *et al.*, 1995). All investigated odontocetes demonstrate a sophisticated echolocation system for navigation, orientation, and prey capture (Au, 1993). Given this, passive acoustic surveys have become increasingly widespread for cetacean monitoring and detections. Passive acoustic surveys were often conducted during concurrent visual surveys. In joint visual-acoustic surveys, mobile towed acoustic systems usually detect several times more cetacean groups than visual techniques (Barlow and Taylor, 2005; Rankin *et al.*, 2007).

For the Yangtze finless porpoises that spend much of their time in the dark and turbid riverine water, sound are likely the primary means of acquiring environmental information. Acoustic behavior research based on both cabled hydrophone and tagging data loggers indicate that the porpoise, even in neonate individuals, produce high-frequency clicks frequently (Akamatsu *et al.*, 1998, 2005c, 2007; Li *et al.*, 2005, 2007, 2008b). The peak frequency of a click is approximately 125 kHz (Li *et al.*, 2005), which is prominent from background noise and most anthropogenic sources. By monitoring the underwater high-frequency click production of porpoises using B&K 8103 hydrophones with concurrent visual observations, Akamatsu *et al.* (2001) concluded that animals could be detected reliably within 300 m of the hydrophones, and suggested that passive acoustic detections would be an effective method for field surveys of the species in the Yangtze habitat. However, surveys with cabled hydrophones and high-frequency recording devices on board vessels are not easy to set up nor are feasible on many of the vessel research platforms. In addition, high sampling-rate recordings and subsequent signal processing and analysis are also time consuming and difficult to implement because of the voluminous amount of data. The practical application of the cabled hydrophones for long-term and wide range of passive acoustic surveys was therefore limited. In recent years, a miniature stereo acoustic event data-logger (A-tag) was developed and extensively used to detect and count the number of the porpoises from both mobile and fixed platforms.

In this paper, we review the published work of mobile and fixed passive acoustic detections of the Yangtze finless porpoise using the A-tag. We examine the feasibility of using the A-tag on moving vessels for acoustic surveys and fixed platforms for acoustic monitoring of the animal. Significance, practicability, and advantages of the passive acoustic methods are discussed. Improvements and future works are suggested.

II. INSTRUMENTATION

The stereo miniature acoustic event data-logger (A-tag) used for the widespread passive acoustic detections of the Yangtze finless porpoise, including mobile acoustic survey and fixed acoustic monitoring, was originally developed for tagging experiments (Akamatsu *et al.*, 2000, 2002, 2005a, 2005b). After a pilot experiment in an enclosed reserve with

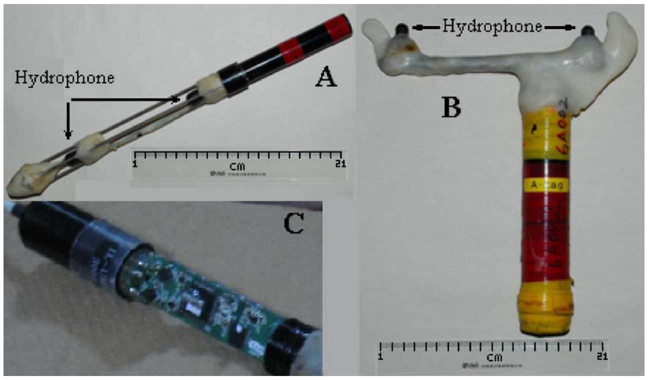

FIG. 2. (Color online) External and internal appearance of the miniature stereo acoustic event data-logger (A-tag). (a) External appearance of a linear type A-tag with one CR2 lithium battery inside used for relatively short-term acoustic survey; (b) external appearance of T-type A-tag with two alkaline UM-1 batteries inside used for long-term acoustic survey up to one month; (c) internal appearance of a A-tag with electronics module containing.

over 20 porpoises, the A-tag successfully detected the presence of phonating porpoises and demonstrated the potential to estimate group sizes of passing porpoises (Wang *et al.*, 2005). It was determined to be an ideal passive acoustic detection system for surveys in the Yangtze River system.

Each A-tag consists of two external hydrophones, approximately 128 mm [for linear type A-tag, Fig. 2(a)] or 170 mm [for T-type A-tag, Fig. 2(b)] apart to identify the sound source direction, a preamplifier with passive band-pass filter between 55–235 kHz to eliminate noise outside the frequency bands, a PIC18F6620 CPU, 128 MB flash memory, and a waterproof tube to encase batteries (one CR2 lithium for the linear type A-tag used for relatively short-term detections, or two alkaline UM-1 battery cells for the T-type tag used for long-term detections). The hydrophone sensitivity is −201 dB *re* 1 V/μPa at around 120 kHz (100–160 kHz within 5 dB), which is in the range of the dominant frequency of click signal of finless porpoises (Li *et al.*, 2005). For comparability of data among A-tags, hydrophone sensitivity of each A-tag was calibrated in a same way. Each A-tag records peak pressures and travel time differences (Td) of signals between the two hydrophones every 0.5 ms (2 kHz event sampling frequency). It does not record the waveforms of the received sound. Because of small memory consumption due to the event sampling, the operational life time of the A-tag largely depends on the batteries. The operational life time of an A-tag with one CR2 lithium battery (linear type A-tag) is approximately 40 h, and the operational life time with two alkaline UM-1 batteries (T-type A-tag) is about one month. The active range of the A-tags for porpoise detection is approximately 300 m (Wang *et al.*, 2005; Akamatsu *et al.*, 2008), depending on level of background noise, trigger level of the instrumentation, and source levels of porpoise clicks.

High-frequency clicks produced by finless porpoises always come in series (i.e., click trains), which usually contain over 5 and up to several hundreds of clicks (Akamatsu *et al.*, 2005c), with regular or gradual change of received sound intensity and interclick interval (ICI) varying typically between 10–80 ms (Akamatsu *et al.*, 1998, 2005c, 2007).

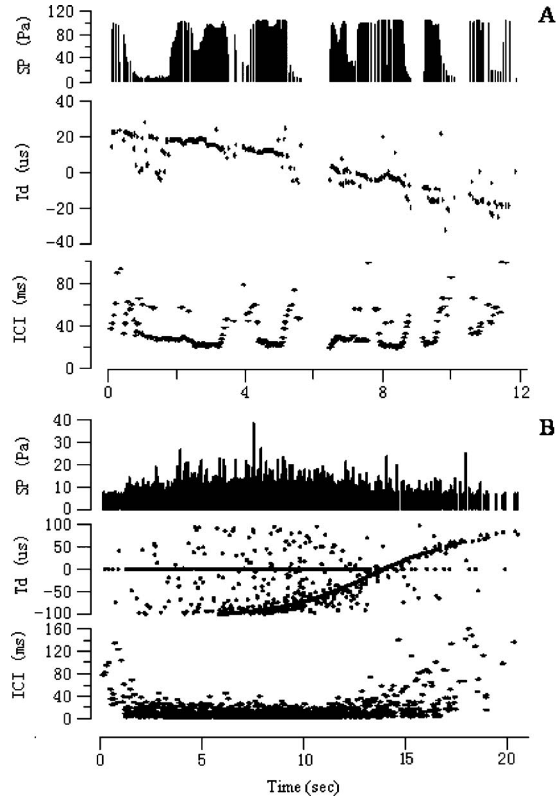

FIG. 3. Sound pressure (SP), travel time difference (Td) between two hydrophones of an A-tag, and interclick interval (ICI) of typical porpoise click trains (a) and ship noise (b) recorded by the miniature stereo acoustic data logger (A-tag). Note that the sound pressures and ICIs of porpoise click trains are changing smoothly, while those of ship noise are changing randomly. The travel time difference (Td) of porpoise clicks are changing smoothly and gradually from positive to negative.

These characteristics can distinguish porpoises click trains from background noise, noise from survey vessels and other cargo ships passing nearby (Fig. 3).

III. APPLICATION

A. Mobile acoustic survey

Mobile acoustic surveys with the A-tags were introduced to a large-scale joint visual-acoustic effort to best document the population status of the Yangtze finless porpoise during the Yangtze freshwater dolphin expedition (YFDE 2006) in November and December 2006 (Zhao *et al.*, 2008; Akamatsu *et al.*, 2008; Li *et al.*, 2008a, 2009). The survey covered the entire historical distribution range of porpoise in the main stem of the Yangtze River from Yichang to Shanghai and part area of the Poyang Lake (Fig. 1) (Zhao *et al.*, 2008). Beginning in 2007, a small-scale joint visual-acoustic survey using fishing boats was carried out once a season in the mouth area of Poyang Lake (Hukou, Fig. 1) ranging approximately 20 km around, to monitor the population status and movement patterns of porpoises in this confluence area (Kimura *et al.*, 2009a).

In these joint visual-acoustic porpoise surveys, two linear type A-tags were mounted on a towed cable, on which floats were placed at 5 m intervals to keep the cable near water surface [Fig. 4(b)]. During surveys, the speed of the survey boat was always kept to be 7–15 km/h, faster than the

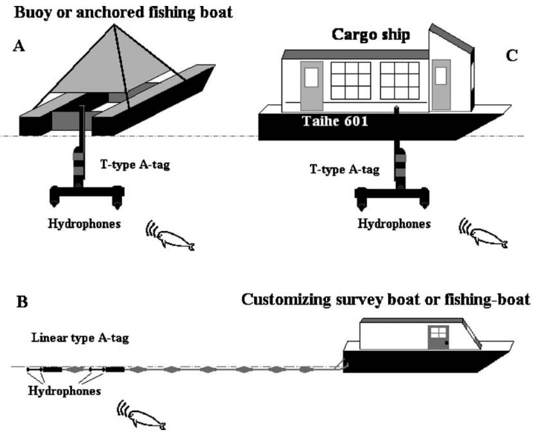

FIG. 4. Diagrams of the passive acoustic monitoring and detection platforms. (a) A buoy or anchored fishing boat for fixed passive acoustic monitoring deploying a T-type A-tag; (b) a customizing survey boat or fishing boat towing two linear type A-tags for passive acoustic surveys in joint visual-acoustic surveys or regular fishing boat based long-term passive acoustic surveys; (c) cargo ship based survey platform deploying a T-type A-tag.

average swimming speed of finless porpoises (4.3 km/h; Akamatsu *et al.*, 2002). This aims to have the porpoises passing the survey boat from bow to stern. When passing animals vocalize, the travel time differences of porpoise clicks to the two hydrophones on the A-tag should correspond to a bearing angle that changes from positive to negative, representing a smooth gradual trace of travel time differences [Td, Fig. 5(b)]. The number of independent traces of Td represents the number of animals detected within each group passing the towed A-Tag [Td, Fig. 5(b)] (Akamatsu *et al.*, 2008; Li *et al.*, 2009).

Applying the strip transect model (Buckland *et al.*, 1993), Akamatsu *et al.* (2008) and Kimura *et al.* (2009a) calculated and compared the detection performance of visual and acoustic detections in the large-scale joint visual-acoustic survey from relatively higher viewing platforms (YFDE 2006, 4 m high viewing platform) and the small-scale one with lower viewing platform (~0.5 m high), respectively. Despite the different heights of the visual platforms, the detection probabilities using acoustic methods by the A-tags were approximately twice that for visual detection (Akamatsu *et al.*, 2008; Kimura *et al.*, 2009a). These suggested that passive acoustic detection using the A-tags is an effective way to detect and count phonating porpoises.

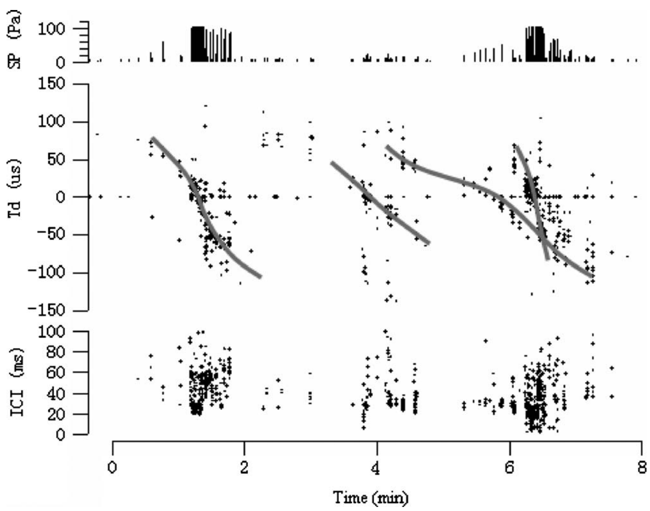

FIG. 5. An example for counting the number of detected animals. SP, Td, and ICI are sound pressure in Pa, travel time difference between two hydrophones of an A-tag in μs, and interclick interval in ms of porpoise click trains recorded by the miniature stereo acoustic data logger (A-tag). In this case, four smoothly and gradually changing travel time difference traces (gray solid lines in the middle panel) were identified, representing four animals were detected.

With two A-tags in a linear array, it was also demonstrated that the towed acoustic detection system cannot only detect and count the echolocating porpoises, but also localize and track the animals in a two-dimension space (Li *et al.*, 2009), and evaluate the effects of boats on animal behavior (Li *et al.*, 2008a). With a distance of 17 m apart between the two A-tags, Li *et al.* (2009) localized approximately 17% of the detected animals. Based on estimation of total error differential, the localization was considered fairly accurate, as the upper bounds of relative distance errors were less than 41% within 173 m (Li *et al.*, 2009). The two-A-tag acoustic detection method was suggested to be a simple and relatively inexpensive way to acquire valuable information on odontocete localization, two-dimensional movement trajectories, speculation of underwater behavior, and sound source levels in mobile vessel surveys (Li *et al.*, 2009). It can be potentially applied in *distance sampling* methodology (Buckland *et al.*, 1993) to calculate absolute densities (i.e., number of animal in unit area) of selected species (Li *et al.*, 2009), since in *distance sampling*, for reliable estimation of absolute density, an accurate measurement of distance between the animal and the survey cruise line (i.e., perpendicular distance) is essential (Buckland *et al.*, 1993).

B. Fixed acoustic monitoring

The fixed acoustic monitoring of Yangtze finless porpoise were performed mainly in the mouth area of the Poyang Lake (Hukou, Fig. 1) (Kimura *et al.*, 2009b; Li *et al.*, 2010), where the lake is confluent to the Yangtze River. The mouth area of the Poyang Lake is a traditional "hot spot" area for porpoises. Historically, large groups of porpoises could be frequently observed in this area moving back and forth between the Yangtze River and Poyang Lake (Zhang *et al.*, 1993; Wei *et al.*, 2002). However, in the last two decades, increased human activities, such as fishing, transportation, and bridge construction, have caused serious threats to the survival of the porpoises at the mouth of the lake. Since the animals in this area probably maintain a gene flow between groups in the Yangtze River and Poyang Lake, where approximately 1/4 of the whole population of the Yangtze finless porpoise are living, conservation measures and management actions of the porpoise population in the mouth of the Poyang Lake are vital to prevent genetic isolation due to loss of gene flow between the two habitats. To evaluate the status of porpoises in this area, fixed passive acoustic monitoring was initiated in November, 2005, by deploying A-tags on anchored fishing boats or buoys [Fig. 4(a)].

Data from a short-term visual-acoustic observations from the anchored fishing boats indicated there were still some porpoises aggregating around this critical area, however, the animal density was gradually diminishing spatially between the river and the lake (Kimura *et al.*, 2009b; Li *et al.*, 2010). Even few porpoises were visually observed, a buoy-based acoustic monitoring lasting approximately 3 months suggested there were still porpoises swimming both upstream to the Poyang Lake and downstream to the Yangtze River. However, the "back and forth" movement, and gene flow might become limited since the animal densities are relatively low in this area (Li *et al.*, 2010). Additionally, Li *et al.* (2010) found that the presence pattern of porpoises in the acoustic monitoring area indicated regular diurnal and monthly change. Again, the fixed passive acoustic detections by using the A-tags were demonstrated to be effective ways to monitor the porpoises in the low density area.

Kimura *et al.* (2009b) compared porpoise detection rate between acoustic detections and visual observations from the anchored fishing boats. The results showed that porpoise detection rate by acoustic detections were about seven times higher than that by visual observations and clearly demonstrated that the acoustic detections were more effective at detecting the presence of the porpoises, especially for the single animal. The stereo A-tag deployed on the anchored fishing boat also demonstrated the ability to detect directional movement of the animals (Kimura *et al.*, 2009b).

IV. DISCUSSION, PROSPECTS AND FUTURE WORKS

A. General discussion

In recent years, passive acoustic monitoring methods have become increasingly widespread for cetacean detections (Mellinger *et al.*, 1997), including both mobile surveys and fixed monitoring. The instruments designed for the acoustic surveys and monitoring are varied, depending on a specific purpose and species of interest. Systems for mobile acoustic surveys often consist of cabled hydrophones and onboard multi-channel recording devices (Miller and Tyack, 1998; Gillespie and Chappell, 2002; Barlow and Taylor, 2005; Rankin *et al.*, 2007), which are usually expensive and complicated to operate. Instruments designed for fixed acoustic monitoring often consists of one or two hydrophones and a battery-powered data-recording system that can provide continuous recordings of signals with a sampling rate up to 100 kHz (Scripps HARP, Wiggins and Hildebrand, 2007; HIMB/PIFSC EAR, Lammers *et al.*, 2008; Cornell Pop-Ups, Au and Hastings, 2008). Since they record the waveforms of the signals with a high sampling rate, these instruments usually need larger battery systems and data storage capacity. Their sizes are also variable and can weigh in excess of over 100 kg (Au and Hastings, 2008). Other instruments (such as T-PODs, Thomsen *et al.*, 2005) developed for fixed acoustic monitoring of porpoises and dolphins do only log the times and duration of clicks resembling to the echolocation clicks of target species without flooding the memory, they have only one hydrophone and therefore are unable to track individual animals and tell their swimming direction. The stereo event recording package (A-tag) used for the finless porpoise monitoring and detection consists of two hydrophones, and only records peak pressures and travel time differences (Td) between the two hydrophones with a sampling rate of 2 kHz. It is much smaller in comparison (Fig. 2), and requires fewer batteries and data storage in general.

Recent widespread mobile acoustic surveys and local fixed acoustic monitoring using the A-tag were successful and valuable in detecting the presence of phonating Yangtze finless porpoise (Akamatsu *et al.*, 2008; Kimura *et al.*, 2009a, 2009b; Li *et al.*, 2010), counting (Akamatsu *et al.*, 2008; Kimura *et al.*, 2009a), localizing, tracking (Li *et al.*, 2009) individuals, and evaluating the effect of boats on animal behavior (Li *et al.*, 2008a).

Compared to traditional visual methods, passive acoustic methods using the A-tag for Yangtze finless porpoise monitoring and detection have a variety of advantages:

(1) The passive acoustic methods can be undertaken by deploying the A-tag without consideration of daylight and weather conditions. On the contrary, visual methods can be only undertaken during daylight hours and in relatively good weather (Zhao *et al.*, 2008).
(2) Passive acoustic monitoring can detect porpoises with a much higher detection rate (Kimura *et al.*, 2009b), resulting in a higher detection probability (Akamatsu *et al.*, 2008). The higher detection probability in acoustic methods was mainly caused by the large number of single individuals that could be missed by visual observers (Akamatsu *et al.*, 2008). This is ideal for the Yangtze finless porpoises since their group sizes are generally relatively small and the overall densities have declined (Kimura *et al.*, 2009b). Acoustic detections were suggested to be a desirable independent observation method for population surveys of Yangtze finless porpoise (Akamatsu *et al.*, 2008). This would improve the precision of estimates for the total population size of the porpoises by using the standard line transects method (Buckland *et al.*, 1993) with acoustic surveys (Akamatsu *et al.*, 2008).
(3) The overall length of the A-Tag used for the passive acoustic monitoring and detections of the Yangtze finless porpoise is only approximately 30 cm (Fig. 2) and weighs less than 500 g (only 72 g for the linear type), and therefore portable. Due to the portability and automated underwater high-frequency acoustic event detection, the A-tag can be used for passive acoustic detections for long-term deployments on fixed or mobile platforms, economizing survey efforts and financial resources. Visual surveys are still preferred for many studies and are beneficial for collecting ancillary data especially species and big group size identification, but these can be easily augmented with the improvement of passive acoustic methods with autonomous recording and individual track capabilities.
(4) Results from acoustic monitoring methods can be replicated with the use of the equipments calibrated in same way and adjusted to have the comparable sensitivity/trigger level in all surveys. Whereas, visual survey re-

sults can be highly variable as they are dependent on experience of observers, weather condition, survey platforms, and many other parameters.

B. Improvements

Passive acoustic detections with the A-tag have been successfully employed to survey and monitor the population status and distribution of Yangtze finless porpoise in its main distribution range in recent years. Their utility has become clear and it has demonstrated a range of advantages including their useful application to supplement visual surveys in the turbid riverine waters. However, despite their values to the monitoring and survey, there are improvements that can be made before the methods can reliably be used to evaluate the population status, distribution and potential migration patterns, as well as abundance estimates of the Yangtze finless porpoise across the entire distribution range, which is the ultimate goal for both conservation and management purposes.

For example, mobile vessel acoustic surveys have to accommodate noisy environments from running engines and water current. These noise sources can create false alarms for animal detections leading to an overestimation of populations that may be subject to conservation measures and protected management status. Reduction of false alarm is essential for acoustic studies in noisy environments. To minimize the false alarm rates, development of adequate filters are necessary. Matched filters comparing incoming signals with a template signal, or wavelet analysis, are examples to mitigate false detections (Thomsen *et al.*, 2005). Sound source location, source levels, pulse interval sequences, and power spectral shapes are other ways to discriminate biosonar signals out of ambient noise sources (Au, 1993).

In addition, quantitative model for the acoustic detection still needs to be developed and improved. While the mobile acoustic surveys with two A-tags in a linear line array can localize the phonating animals, and thus is potentially able to estimate absolute density abundance of animals (Li *et al.*, 2009), only a fraction (approximately 17%) of the detected animals can be localized (Li *et al.*, 2009). In most of the cases, high-frequency signal events of the detected animals were only recorded by one of the two A-tags. This resulted in a low percentage of the localized animals. Several improvements of the mobile acoustic survey system might be necessary for increasing the percentage of the localized animals: (1) decreasing the distance between two A-tags to account for the narrow sonar beam of porpoises; (2) adjust sensitivity of hydrophones to be a same level between two A-tags; (3) mount two A-tags in a more rigid linear line array preventing movement between them. By combining visual data in a joint visual-acoustic survey, Akamatsu *et al.* (2008) obtained a detection probability of the acoustic A-tag system within a 300 m strip transect. The authors suggested animal abundance can be deduced by the detection probability (Akamatsu *et al.*, 2008). Kimura *et al.* (2010) also tried to estimate animal density in a fixed acoustic survey by using acoustic "cues" of the animal, such as average signal production rate and source levels of signals produced. However, all of the proposals for density estimation mentioned above would be strongly influenced by the animal's observed and contextual behaviors. Detailed behavioral information, such as the rate of sound production, source levels of sounds, and ship avoidance behavior, are required. For Yangtze finless porpoise in its natural habitat, little information is available. Future work to investigate the behavioral information of the porpoise in its natural habitat is essential to standardize a method of density estimation in the natural habitat for the species.

C. Future survey efforts

Once adequate filters would be developed, comparisons between visual and acoustical detection performance would be completed, and detection probabilities would be estimated, the automation of animal detection will be possible. A cargo ship would be an ideal platform [Fig. 4(c)] to regularly deploy the A-tags for the survey of Yangtze finless porpoise in the main stem of the Yangtze River. Fishing boats can be employed for the mobile acoustic survey in the main channel of the Poyang Lake (Fig. 1). These automated acoustic methods by using the A-tags will provide distribution information of the Yangtze finless porpoise in its main distribution range, which can be compared to visual detection data previously collected. Since the acoustic methods need relatively less human effort for consideration of future survey endeavors, it could be performed more often with small number of researchers as long as appropriate platforms are available. Seasonal and annual changes in distribution patterns and monitoring of the population size will be desirable aims to aid in conservation and management efforts.

ACKNOWLEDGMENTS

We thank Mr. S. Dong, Mr. J. Cheng, and many other persons, who made good effort for the field survey. We would also like to express our appreciation to Mr. M. F. Richlen of HIMB, University of Hawaii, two anonymous reviewers for their valuable comments and detailed English edits. This research was supported by the National Basic Research Program of China (Grant No. 2007CB411600), the Chinese National Natural Science Foundation (Grant No. 30730018), the Ocean Park Conservation Foundation of Hong Kong (OPCFHK), Special Funds for Presidential Scholarships of the Chinese Academy of Sciences (Grant No. 082Z01), and Research and Development Program for New Bio-industry Initiatives, Japan.

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