Single-Hydrophone Method for Reconstructing Dynamic Behavior of Endangered Chinese River Dolphin*

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***Abstract*- Chinese River Dolphin (*Lipotes vexillifer*), usually called 'baiji', is one of the most endangered mammals in the world. The preservation of these mammals directly ensures the health of the ecosystem. However, not much behavioral information on baiji is available so far, that could effectively assist in undertaking their preservation. This research is an attempt to reveal baiji's hitherto unknown underwater dynamic behavior. For this work we have analyzed and extracted motion parameters from clicks of a free-swimming baiji recorded in 1996 at a single hydrophone. The absence of detailed bottom information made it difficult to localize baiji using the multiple reflections and forced us to rely completely on surface reflections only. From measurements of time delay between the direct path and the surface echo, not only large-scale behavior but also fine-scale behavior has been revealed, such as: periods of diving and surfacing, circling behavior underwater and a characteristic nodding motion. These studies have contributed towards a broad understanding of baiji's foraging exercises from the standpoint of formulating an acoustical survey for the search for this endangered marine mammal.**

I. INTRODUCTION

Baiji, the Chinese River Dolphin (*Lipotes vexillifer*), presently on the critical list [1] of endangered species, is said to be a "living fossil" since it is one of the oldest surviving cetaceans [2, 3]. It has been faced with a fight for survival with humans for fish, and more recently, accidental encounters with fishing gear and powered fishing and transportation boats have further raised its mortality. Industrialization in the cities along the Yangtze River causing water pollution, and water projects along the river and its branches have reduced and worsened the habitat of baiji. Urgent measures are thus needed to salvage a viable group of individuals that can sustain the continuity of this rare species. There is presently no baiji in captivity after the last one named QiQi (Fig. 1) died in July 2002 after almost 23 years at the Institute of Hydrobiology, the Chinese Academy of Sciences. Even worse, there is no specimen in any controlled environment that could be used to obtain information about its underwater behavior. Therefore, in order to make an efficient system to seek, to observe and possibly to capture baiji, it is essential to develop and use *in situ* methods.

Fig.1. Baiji, the Chinese River Dolphin.

Baiji has a long beak and tiny eyes. Maximum length and weight of mature baiji are around 2.5 m and 160 kg respectively. It feeds upon a variety of fish. Baiji, like other dolphins produces high frequency ultrasonic sounds called 'clicks' emerging from its forehead, also called melon, for purpose of echolocation [4]. While echolocation ability augments the visual ability of marine dolphins in understanding their environment and in search of prey, it becomes critical in situations where sight is of marginal use. The Yangtze River has poor transparency the year round, thus eyesight is rather ineffective for creatures living in this river. That would also explain why baiji's eyes are so tiny and have degenerated into near blindness that perhaps can only recognize ambient brightness. It is, therefore, not an exaggeration to say that baiji basically relies on its bio-sonar for survival.

* Funding and support for data collection was received from the Chinese Academy of Sciences (CAS) (No. KSCX2-SW-118), Institute of Hydrobiology, CAS (No. 220103), and Bio-oriented Technology Research Advancement Institution, Japan.

Methods have previously been proposed [5, 6, 7] for tracking and localizing free-swimming whales and dolphins based on passive observation of their vocalizations. These methods have usually relied on the deployment of several hydrophones or arrays that obtain independent "looks" at the same source. A single hydrophone method has also been proposed [8] for tracking dolphins, but strict conditions such as a flat sea bottom with known depth, and unambiguous identification of higher order reflections are required, which are very difficult to meet in practice. On the other hand, our work successfully makes intricate observations on baiji's diving behavior and its acoustic directionality without any constraining assumptions, while using a very simple set-up with a single hydrophone. This study has revealed the pattern of its dive and respiration, a characteristic nodding motion with its variation during the dive, and the variation in its bio-sonar range as it nears the bottom. Finally, its beam pattern is shown to have a unique multi-peak nature. The key feature of our analysis is that all these observations have been made by in-obtrusive acoustic monitoring of a free-ranging baiji.

Section II defines the click parameters and the basic data collected from the clicks over a period of about 24 minutes. Section III describes the dynamic behavior and the bio-sonar features derived from the observed click time series. Section IV summarizes the work and its utility for conducting an acoustical survey.

II. CLICK DATA EXTRACTION

A. Recording Method

The baiji was observed in Shishou Baiji Semi-Natural Reserve [9], a horse-hoof-shaped oxbow of the Yangtze River in January 1996. This reserve was established for conservation of baiji and Yangtze finless porpoise (*Neophocaena phocaenoides*) in 1992 by the Chinese government. One female baiji and fourteen finless porpoises had been living there at the time the recordings were made. The lake measures 21 km in length, 2 km in maximum width, and 20 m maximum depth [9,10], which is considered large enough for their natural sustenance. The baiji was 2.29 m in body length and 150 kg in weight. Unfortunately, she died in 1996 soon after the recording was done, so that those recordings are now considered very precious.

Recordings were done on a wooden boat drifting on the lake using a single hydrophone (B&K 8103) followed by a 1 kHz high-pass filter for removing low frequency background noise, and a SONY PCHB 244 data recorder with a sampling rate of 384 kHz. The frequency response of the recording system was within ±3 dB from DC to 147 kHz and was well suited for recording baiji's high frequency clicks that are centered at about 80 kHz. The digital data was archived in a PC hard-disk by re-sampling at 400 kHz. The hydrophone was kept at a depth of 2 m during the subject recording period. The calm state of the surface of the lake was ideal for recording, and consequently, the reflection loss at the surface was also expected to be small. Hence, not only the direct path click sound but also surface reflected sound was clearly recorded at the hydrophone (see Fig. 2).

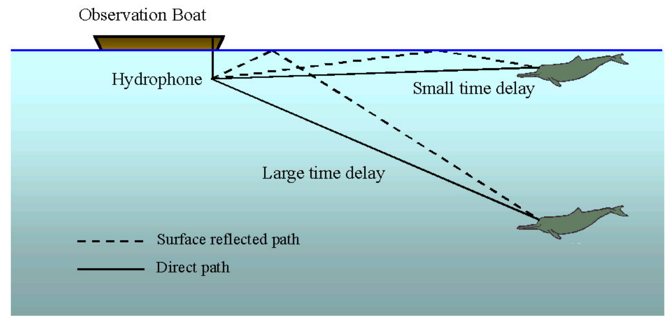

Fig. 2. Recording method.

The duration of one directly received click of baiji is typically about 50 microseconds at a dominant frequency of around 80 kHz, and the surface reflected echo has inverted phase (Fig. 3a) as would be expected at a pressure release boundary. Parameters used in signal analysis are the time delay between the direct and surface reflected clicks, and the Inter-Click-Interval (ICI). ICI is controlled by the dolphin and is defined as the interval between succeeding clicks (Fig. 3b). In addition, the signal energy of the direct click estimated in a 25 microsecond window around the peak has been used as a secondary parameter. The 8-bit digital recording permitted a maximum dynamic range of 42 dB over the quantization noise. However, the detection threshold was kept sufficiently above the noise floor so that the maximum possible range of signals above the threshold was about 30 dB. Clicks were intermittently captured in click trains (Fig. 3c) that were caused by the directionality of the sound beam.

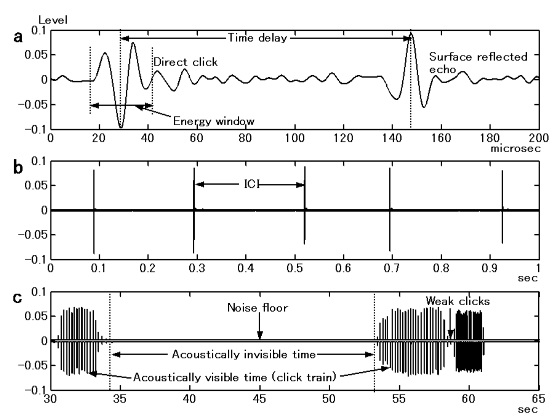

Fig. 3. Definition of click parameters.

Thus a click train was observed when the phonating animal was generally oriented toward the hydrophone and so becoming "acoustically visible" to the hydrophone. ICI longer than 1.2 seconds within a click train due to weak or missing clicks caused a break. The longer gaps between click trains are also called "acoustically invisible" time.

B. Click Events

Although the recording had originally been done intermittently over a longer period of time, one contiguous 24 minutes of data was found rich in baiji's clicks and has been scrutinized carefully for the purpose of this research. The extraction of clicks from the 24-minute record yielded the following basic data on baiji's vocalizations: the number of clicks detected is 1095, total acoustically visible time is 236.8 seconds, and the number of acoustically visible events (click trains) is 81.

The average click train or acoustically visible duration is estimated as 2.92 seconds, while the average acoustically dark or invisible duration is 15.9 seconds, resulting in an average click train periodicity of about 19 seconds.

III. DYNAMIC BEHAVIOR AND BIO-SONAR FEATURES

A. Large Scale Diving Behavior

Baiji's diving behavior is simply understood by observing the change in the time delay. Time delay depends on the geometrical location of the baiji, i.e. the depth and the range from the hydrophone. With the given deployment of the hydrophone, as the baiji comes nearer, and goes deeper, the time delay increases. Time delay variation over 24 minutes is shown in Fig. 4a. The corresponding average ICI in each acoustically visible time (click train) is shown in Fig. 4b. The very large ICI outliers arise due to the missed weak clicks that are below the detection threshold. In each dive cycle, lower ICI values are invariably seen near the peaks in the time delay pattern as indicated by the vertical dotted lines.

Visual observations of the respiring baiji (carried out in the foggy winter conditions) have indicated that the horizontal distance of the baiji roughly ranged from 150 to 200 meters over the observation period. We can also estimate the ratio of maximum-to-minimum distance of the clicking baiji by measuring the variation of energy of click signal assuming that the baiji was clicking at a constant source level. In order to eliminate the effect of transmission beam pattern of the baiji, we have taken the peak energy in each click train that would occur when the baiji's beam happened to be oriented directly towards the hydrophone (Fig. 4c).

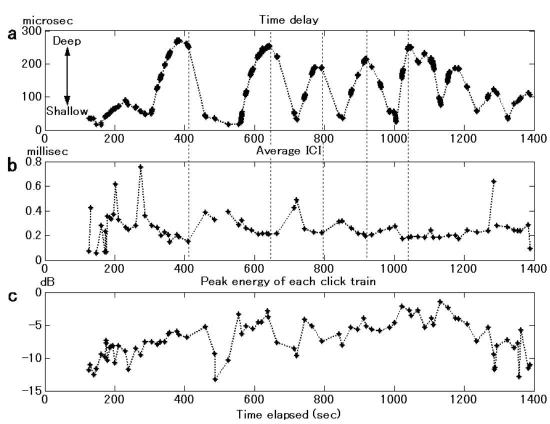

Fig. 4. Large scale behavior.

At 1131 seconds of the data record, the peak energy reaches the maximum value (-1.49 dB) so that we can conclude at this time the baiji was closest to the hydrophone. On the other hand, the baiji was farthest from the boat at 487 seconds (click energy of -13.28 dB). Assuming spherical spreading transmission loss model (20 log r), it is estimated that the ratio of the maximum-to-minimum range is 3.885. Given such a variation, if the nearest range during its underwater movement is taken, for example, as 75 m, then the farthest range is about 300 m.

In view of the visual and acoustical observations, we can say that in the present case, the baiji typically stayed about 150 meters from the boat, at which distance the time delay is about 30 times more sensitive to depth change than to distance change. Large-scale time delay variation is thus, dominated by the baiji's depth change. It is clearly seen from Fig. 4a that time delay variation is quite periodic, thus indicating that the baiji's depth changed periodically. The data shows 8 complete dive cycles (which also correlates with the field observations of its surfacing) indicating an average dive cycle of about 160 seconds. The maximum time delay observed in the 24 minutes data is 271.5 μs. Thus, the maximum depth the baiji probably reached is estimated to be around 15.3 meters at a nominal range of 150 meters from the boat, consistent with the lake's known depth.

The average ICI in each click train fluctuates between click trains largely between 50 to 400 milliseconds. It is known [4] that ICI of phonating dolphins increases with distance of the target object. Interestingly, ICI of baiji is also seen to vary periodically in each dive cycle; specifically, as time delay increases, ICI is seen to decrease, and vice versa. It can, therefore, be deduced from the ICI variation that as the baiji dives deeper towards the bottom, its target range grows shorter. This also suggested a search strategy that allowed it to concentrate on a potential target such as fish or crustacean as it approaches the lake bottom.

As noted from the observed data, the periodicity in the appearance of the click trains (average period of 19 seconds) due to its beam directionality also suggests a regular spiral-like movement of baiji's orientation relative to the hydrophone.

B. Horizontal Beam Sector

As explained above, click trains are those continuously received clicks that are detectable above the threshold. In our case, the maximum signal dynamic range that is detectable is about 30 dB. However, the permitted signal dynamic range is actually several dB's less than this in order to avoid saturation of the analog-digital converter. The click data has been collected when the baiji was not too far from the hydrophone (the peak click energy variation during the observation period being within 12 dB), so that all emitted clicks may be assumed to be within the capture range of the recording system. From the observed data, the probability of receiving a click train works out as 0.188. This is caused by the beam directionality and, therefore, depends on the orientation of baiji relative to the hydrophone. Considering that the free-swimming baiji has no preferable region to move to (such as migrating birds flying northwards or southwards) the horizontal orientation of the baiji relative to the hydrophone is equally probable over 360 degrees in the long observation period. Hence, baiji's horizontal beam sector is expected to be directly related to the statistics of the click trains, and has thus been estimated to be 67.5 degrees, or nominally 70 degrees. By definition, the beam sector is the angular region over which baiji's clicks are detectable, and which would obviously be significantly larger than the -3dB beam width. Previously known measurements of the beam pattern of a captive baiji reported in China in 1983 [11] in a cemented 4 meter deep pool have reported a -3 dB horizontal beam width of 13 degrees (which is less than the beam sector as discussed above), and a vertical beam width of 9.1 degrees. Due to the nature of *in situ* recordings we have been limited to determining the overall beam sector and it has not been feasible for us to determine the precise -3 dB beam width.

C. Fine Scale Behavior: Nodding Motion

While the large scale time delay variation appears quite smooth and continuous, a closer examination reveals fine scale fluctuations. Fig. 5a shows an example of periodic fine scale fluctuations of time delay within a click train that correspond to a few microseconds, with a period between 1-2 seconds. It may be noted that a fluctuation of 2 microseconds implies a depth change of about 15-20 cm depending on baiji's location relative to the hydrophone. Since dolphins thrust their bodies forward with their flukes swinging up and down, it causes a corresponding periodic 'nodding' motion of their heads. Thus, the small periodic time-delay fluctuations are, in fact, attributable to the depth change of baiji's melon. Our analysis successfully confirms and reveals baiji's nodding motion.

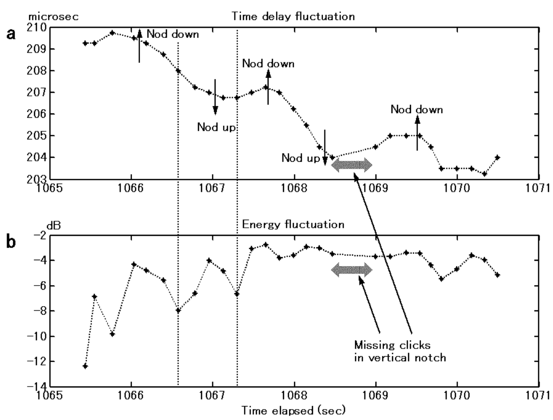

Fig. 5. Fine scale behavior.

A typical 5-second click-train is shown with a short break due to weak clicks that are missed below the detection threshold. The alternating peaks and troughs of the periodic time delay fluctuations (Fig. 5a) are marked as 'nod down' and 'nod up', respectively, and constitute a nod cycle. The vertical dotted lines indicate the valleys, or notches in the energy plot (Fig. 5b) and are seen to be midway between the nod extremes, thus there are two notches in each nod cycle. The region of missing clicks is indicated by the wide block arrows. It may also be noted that the click energy generally increases towards the middle of the click train and then reduces. This may be attributable to the beam pattern effect as the baiji's head swings across the field of view of the recording hydrophone.

D. Bio-Sonar Activity

As apparent above, the magnitude and frequency of nodding motion also relates to baiji's activity: for example, when baiji rapidly accelerates, its motion is expected to be accompanied by an increased nodding rate. We would also expect a reduction in its ICI when it approaches its prey. The data in Fig. 6 is shown for two consecutive dives as is apparent from the average time delay variation (Fig. 6a). The average ICI in the click trains (Fig. 6b) also varies periodically and in opposite phase with the time delay. The average nodding frequency (Fig. 6c) is also periodic and has larger values coinciding with the large time delay values and the lower ICI values, as shown by the vertical dotted lines.

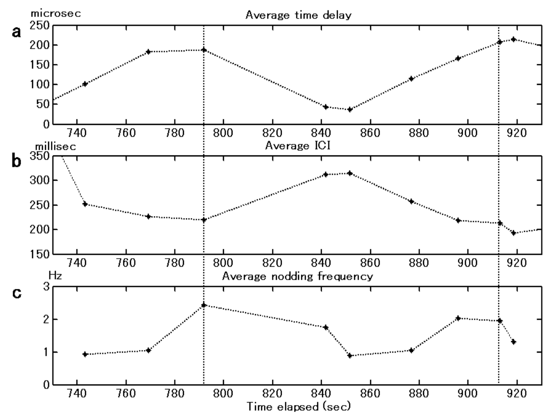

Fig. 6. Nodding and bio-sonar activity during dive cycles.

It is thus observed that when baiji is nearer to the lake bottom more frequent nodding occurs concurrently with a shorter ICI. This observation provides confirmation that baiji shows both enhanced physical and acoustical activity when it approaches the lake bottom in search of prey.

E. Multi-peak Beam Pattern

The energy fluctuation of several dB (Fig. 5b) within a click train is seen to be related to the time delay fluctuation. Thus, the periodic energy fluctuation is caused by the periodic nodding-induced change in the relative angle of the directional sound reaching the hydrophone in the vertical plane. Notably, it is observed that for every cycle of nod there are two cycles of energy variation. With the nodding motion of baiji's melon suggested above, this energy fluctuation is thought to be caused by a unique vertical beam pattern of baiji's vocalization, which is likely to have two peaks separated by a notch.

Fig. 7a schematically demonstrates that as the baiji nods up and down, the direct click sound path sequentially traverses through the lobes of baiji's vertical beam sector and the intervening notch. Assuming the rotation axis of baiji's nod is located at the region of the pectoral fins which are 35-40 cm from the melon, a 15-20 cm vertical nod would traverse a vertical sector of about 30 degrees. It can thus be deduced from the nature of energy fluctuation and time delay fluctuation that baiji's vertical beam sector covers more than 30 degrees and has two lobes separated by at least 15 degrees.

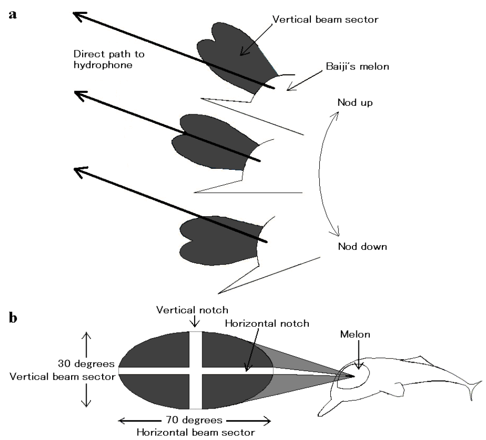

Fig. 7. Beam pattern notches revealed by baiji's motion.

Furthermore, a few consecutive clicks that are very weak (sometimes even missing, Figs. 3 and 5) are typically noticed within the click trains. While the large acoustically invisible periods with an average duration of 15.9 seconds are due to baiji's horizontal orientation facing away from the hydrophone, the few consecutive weak or missing clicks within a click train are attributable to a vertical notch in baiji's horizontal beam sector as it sweeps across the hydrophone, due to the turning of baiji's head. Just as in the vertical beam, this again leads us to a dual-lobe structure in the horizontal beam. The harbor porpoise (*Phocoena phocoena*) is the only one cetacean that is so far known to have such notches in its beam [12]. This is the first time that the presence of notches has been observed in baiji's beam, strongly indicating a unique multi-peak beam pattern. The composite beam sector with notches in both the horizontal and vertical directions is conceptually shown in Fig. 7b.

IV. DISCUSSION

The regular click trains and the time-delay pattern indicate the cyclic diving and respiration of the baiji during a continuous period of 24 minutes. The systematic variations of various parameters simultaneously correlate baiji's dive behavior with its instantaneous sonar range and its physical nodding activity *in situ* using a single hydrophone system. This has added significantly to the available knowledge on baiji's underwater behavior.

The multi-peak structure of baiji's beam pattern has also been strongly indicated. It is plausible that baiji uses the horizontal and vertical notches between the beam lobes, perhaps in combination with its head movement, to accurately position its prey relative to its beak, much like a cross-wire aiming system. The fact that baiji is virtually blind, makes it imperative for it to have a very advanced acoustic vision system with adequate beam sector coverage while achieving high target positioning accuracy.

Baiji's sonar seems to have evolved to ensure its survival in the shallow turbid environment, which it has done for well over 10 million years. However, we are currently faced with its extinction due to manmade hazards. Hopefully, this study of baiji's dive behavior and its vocalization characteristics, while providing new insights about its activity underwater and its bio-sonar characteristics, would help in formulating strategies for carrying out an acoustical survey for locating a viable pool of individual animals and thus save it from extinction.

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