Long-term Real-time Monitoring of Free-ranging Bottlenose Dolphins (*Tursiops truncatus*) in an Aquarium using 5-hydrophone Array System

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***Abstract*- Long-term real-time monitoring of free-ranging Bottlenose dolphins (*Tursiops truncatus*) in the pool of the aquarium "Izu Mito Sea paradise", i.e. in the enclosed observatory has been started from 22nd June 2008, and continuously conducted ever since then. The monitoring system consists of 1) a modified 5-hydrophone array system deployed in the pool, 2) a web camera placed overland for visual monitoring of the dolphins, and 3) the land base system to process and transmit the acoustic data from the hydrophones of the array and the video images from the web camera to the servers in real-time via internet. The echo-location characteristics of the Bottlenose dolphins in the pool and their behavioral changes in a long-term span have been initially observed and analyzed. Three echo-location phases (search, approach, terminal) have been observed. It is estimated that the dolphins are echo-locating the surrounding environment and targeting something else such as the array as a target. Solo burst-pulses emitted by one of two dolphins swimming side by side in the pool were also observed. For understanding the Bottlenose dolphins' behavioral changes during the long-term monitoring, the trend of the number of clicks recorded around the pool is applied for the analysis as an index of the dolphin's activities. The results show the trend and difference of the changes of the click number in each section of the pool depending on the time of day. Not only depending on the time, but also depending on natural phenomena, the dolphins' behavioral changes were observed. A definite trend of click number reduction is observed during the occurrence of an earthquake, even when they stayed underwater. Significant behavioral changes of the dolphins are also observed just after the earthquake. This indicates that the Bottlenose dolphins in the pool of the "Izu Mito Sea Paradise" did not actually "predict" the earthquake.**

I. INTRODUCTION

Dolphins belong to small Odontoceti species. The Bottlenose dolphins *(Tursiops truncatus)* inhabit the ocean, while the river dolphin's group, such as the Ganges river dolphin (*Platanista gangetica*), inhabit the river areas. Both species are found to inhabit areas that are also easily accessible to humans. Consequently, their numbers, especially those of the river dolphins have been reducing due to on-going human activities. It is said that Baiji, the Yangtze river dolphin (*Lipotes vexillifer*) has become extinct. On the other hand, only 2,000 of the Ganges river dolphins now inhabit the Ganges river system. In order to develop a strategy for their conservation, understanding of their ecology, especially of their underwater behavior in wild environment is essential. However, except for respiration, they stay underwater, where the water is sometimes too turbid to visually observe them. Therefore, not many studies on their underwater behavior in the wild environment have been conducted prior to our studies using passive acoustic observation method that utilizes the high frequency bio-sonar clicks that the dolphins emit for echo-location to understand the surrounding environment and to forage.

For the advanced observations aiming to develop a strategy for the conservation of the dolphins inhabiting both the river areas and oceans in Asian regions, the international collaborating project based on advanced acoustic and information technology between University of Tokyo, KDDI R&D Lab., WWF-India, Chilika Development Authority (CDA) and IIT Delhi has been in operation from January 2006.

For the project, the authors have been developing acoustic observation systems using array of hydrophones that can record the high frequency bio-sonar clicks which the dolphins emit for echo-location, and can estimate their 3-D location by calculating relative time delay of the clicks at the each hydrophone. The observation systems being absolutely passive, there is no adverse effect on the dolphins and the environment. The systems also include a RF network that distributes real time 2-D location data of the dolphins all over the world by internet.

From the operational experiments of these systems targeting captive Bottlenose dolphins in Japan and the Ganges river dolphins and Irrawaddy dolphins in wild environment in India and other countries as shown in table1, the characteristics of the echo-location clicks and the features of underwater behavior of these dolphins have been revealed [1] [2] [3]. Then, based on the operational experience of these observation systems, modifications have been made to make them rugged and operable for undertaking observations of each dolphin

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species in their corresponding environment. The long-term real-time monitoring at a fixed location for a few years would give us more detailed information of the dolphins' underwater behavior and the trend of the behavioral changes of the dolphins over the seasons and year after year. In addition, sharing real-time 2-D location data of the dolphins over internet, people all over the world can experience an affinity with the dolphins underwater. Considering these aspects for the observations, the international collaborating program for long-term real-time monitoring of the dolphins has been started since 2008. The program also includes monitoring of the dolphins in an aquarium, i.e. monitoring in an enclosed observatory, from where we could acquire useful experimental experience for the monitoring of the dolphins in wild environment.

Prior to the monitoring of dolphins in wild environment, the long-term real-time monitoring of Bottlenose dolphins in the pool of the aquarium "Izu Mito Sea Paradise" in Shizuoka, Japan has been started from 22nd June 2008. The monitoring has been continuously conducted for over one and half years since then. For the monitoring, we have modified a 5-hydrophone linear array system that was developed in 2005 and utilized for the Irrawaddy dolphins' observations and a Ganges river dolphin's observations in 2006 in India, as shown in Fig.1. The system can also monitor the dolphins by a networked camera set on the roof of the building next to the pool. From the data recorded by the array and the video images, the echo-location characteristics of the Bottlenose dolphins in the pool and their behavioral changes over a long-term span have been observed and analyzed. Initial results of the analysis will be shown in this paper.

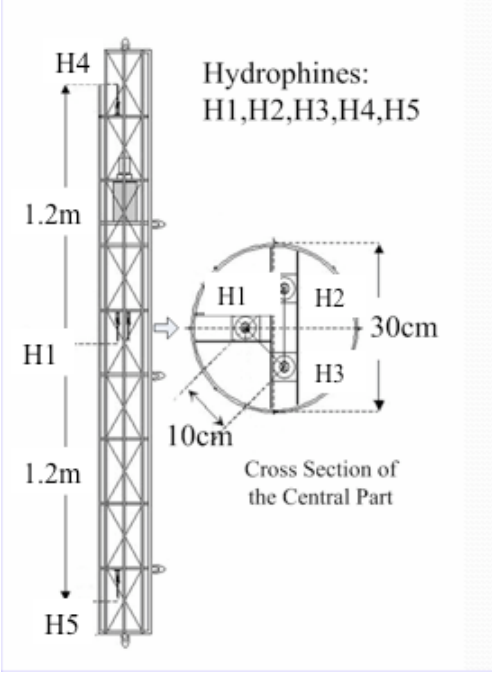


Fig.1 Structure of 5-hydrophone linear array modified for the monitoring

TABLE I
HISTORY OF THE PASSIVE ACOUSTIC OBSERVATION SYSTEMS

Year	Month	Target Species	Observation area	Observation system
2005	Jan.	Bottlenose dolphin	Izu-Mito Sea Paradise (Japan)	5-hydrophone linear array
2005	July	Finless Porpoise	Off Choshi (Japan)	5-hydrophone linear array
2005	Dec.	Irrawaddy dolphin	Oasis Sea World (Thai)	2- hydrophones
2006	Jan.	Irrawaddy dolphin	Chilika Lagoon (India)	5-hydrophone linear array
2006	April	Ganges River dolphin	Budhabalanga River (India)	5-hydrophone linear array
2007	Jan. - Feb.	Irrawaddy dolphin	Chilika Lagoon (India)	5-hydrophone cross array
2007	Feb.	Ganges River dolphin	Karnabas to Narora (India)	Single hydrophone
2007	Nov.	Irrawaddy dolphin	Chilika Lagoon (India)	5-hydrophone cross array
2008	Feb.	Ganges River dolphin	Karnabas to Narora (India)	6-hydrophone cross array
2008	Mar.	Irrawaddy dolphin	Irrawaddy river (Myanmar)	3-hydrophone mobile linear array
2008	July to up to now	Long-term real-time monitoring of Bottlenose dolphin	Izu-Mito Sea Paradise (Japan)	5-hydrophone linear array
2008 to 2009	Nov. to April	INCASTS: first long-term real-time monitoring of Ganges river dolphin	Karnabas to Narora (India)	6-hydrophone cross array and Compact 4-hydrophone arrays
2009	Nov. to up to now	Second phase of long-term real-time monitoring of Ganges river dolphin	Karnabas to Narora (India)	6-hydrophone cross array and Compact 4-hydrophone arrays
2009 to 2010	Nov. to Jan.	Initial trial for long-term real-time monitoring of Irrawaddy dolphin	Chilika Lagoon (India)	6-hydrophone cross array (modified from 5-hydrophone cross array)
2009	Dec.	Irrawaddy dolphin	Mahakam river in Borneo (Indonesia)	3-hydrophone mobile linear array and Compact 4-hydrophone array

II. METHOD

A. Monitoring System

In the aquarium "Izu Mito Sea Paradise", a part of shore of the Suruga bay is utilized for the dolphins' pool which is divided into 4 sections by nets, as shown in Fig.2 (a), (b). Thus, the semi-natural environment is created for the Bottlenose dolphins, where the average water depth of the pool is approximately 4 to 5 meters. Several Bottlenose dolphins are kept in each section of the pool. Sometimes, the dolphins are transferred to other areas. Every event such as the dolphins' transfer is recorded for the analysis. The dolphin's number in each section of the pool on 1st March 2010 is composed as follows; section 1: 4 dolphins (3 female, one male), section 2: two dolphins (female), section 3: two dolphins (one female and one male), section 4: no dolphin. The monitoring system consists of 1) a modified 5-hydrophone

array system deployed underwater at the corner of the section 1 of the pool, 2) a web camera set on the roof of the building next to the pool for visual monitoring the dolphins, 3) the land base system where the acoustic data from each hydrophone of the array and the video images from the web camera are processed and transmitted to the servers in real-time by internet, as shown in Fig.2(c).

The base line of the 5-hydrophone linear array system developed in 2005 was shortened from 1.6 meters to 1.2 meters for shallow water use and deployed underwater in vertical configuration as shown in Fig.1 and Fig.2(c). The array system is composed of three hydrophones (H1, H2, H3) forming an equi-spaced linear SBL (Short Base Line) array and another two hydrophones (H4, H5) in conjunction with the central hydrophone (H2) forming a small SSBL (Super Short Base Line) triangular array in a plane perpendicular to the array axis. The range (XY position) and depression angle (Z position) of the dolphin is calculated by the SBL system and direction of the dolphin is calculated by the SSBL system.

The clicks received on each hydrophone are amplified over a -3dB bandwidth of 10kHz to 180kHz and digitized at a sampling rate of 500kHz with 16bits resolution through an A/D converter and sent to a PC, where the dolphins' real-time 3-D location is calculated and transmitted to the data server by internet. The click data and dolphin's 3-D location data are also stored in a hard-disk for analysis. For reducing the amount of data volume during the long-tern monitoring in the pool, the system has four options of recording mode, i.e. 1) Full recording mode (click data, dolphin's 3-D location data are constantly recorded), 2) Intermittent recording mode (full recordings intermittently, for example, full recordings made of 30 seconds every 10 minutes), 3) Event mode (full recording only when clicks are detected) and 4) CSV mode (dolphin's 3-D location data is constantly recorded) suitable for variety of conditions. Intermittent recording mode of 30 seconds of every 10 minutes is usually selected for the recording mode for the monitoring.

The Bottlenose dolphins' real-time video images from the web camera are sent to the networked PC for encoding and transmitted to the video server by internet. The real-time low frequency sounds (10-20 kHz) recorded from two hydrophones of the array (H1, H2) are also sent to the PC, and transmitted to the video server with time stamp of the video images. The video images with low frequency sounds are stored in a hard-disk for the comprehensive analysis with the click data.

Data transmitted to the both servers consisting the dolphins' 2-D trajectories and video images in real-time is open to the public.
(cf.theURL:http://asianunderwater.jpn.org/dolphin/dolphinpool/index.html) for providing them the experience to develop affinity with the dolphins underwater.

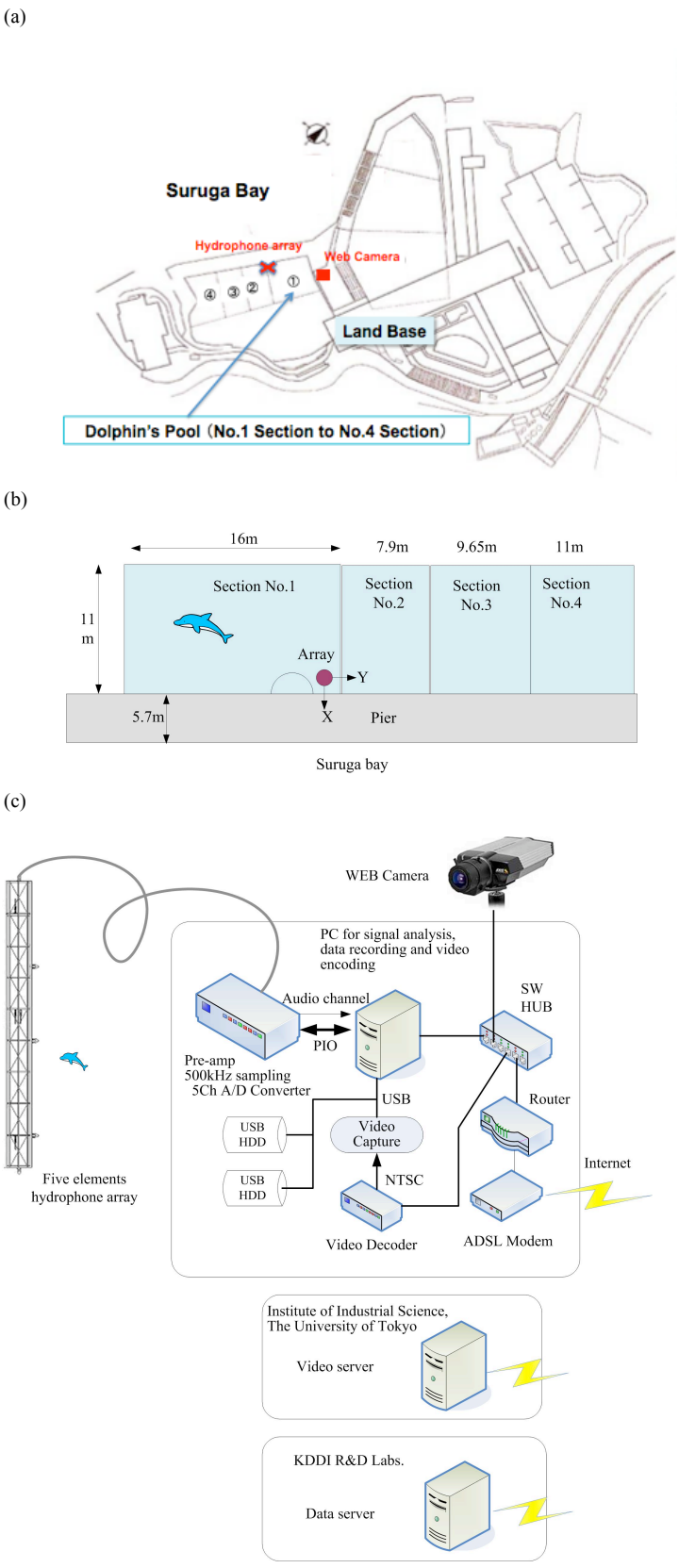


Fig.2 Schematic diagram of the monitoring system: (a) Aquarium "IZU MITO sea Paradise". (b) The dolphin's pool. (c) The monitoring system.

B. Range Error

Calibration of the original 5-hydrophone array of base line 1.6 meters for acoustic measurements of range was carried out in a freshwater tank using 70 kHz artificial dolphin clicks emitted by a pinger. The result of range calibration test in Fig. 3 shows that the acoustic range of the array is accurate to within 3% when actual range is less than 30 meters. The calibration result of range is in accordance with theoretical range error E of the array (for 500kHz sampling rate, 16bits resolution), which increases in proportion to the square of range, as shown in (1), where R is the range from the array, and a is the base line of the array.

$$E = \frac{0.003/a * R^2}{a} \quad (1)$$

Consequently, from equation (1), range error of the modified 5-hydrphone array with shortened base-line of 1.2 meters can be estimated as 1.875 meters at 30 meters range.

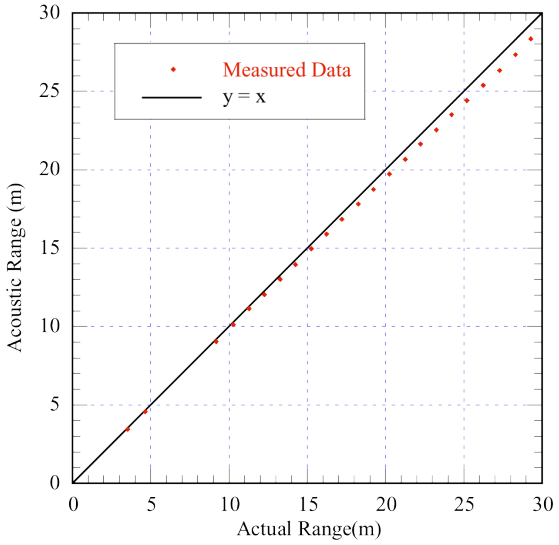


Fig.3 Range calibrations results of the original 5-hydrophone array of base line 1.6 meters

III. RESULTS

A. Echo-location Characteristics

Based on the data recorded by the on-going monitoring, the acoustic characteristics of the free-ranging Bottlenose dolphins have been initially analyzed. Here, we should note that the dolphins' clicks are only recorded when they are facing towards the array due to their narrow beam width [4].

Clicks, burst pulses and whistles are observed. An average click of the dolphin has a 30 μsec duration. ICI (Inter-click Interval) of the click train varies from 120msec to 1 to 3msec when the dolphin emits burst pulses. Peak frequency, centroid frequency and its standard deviation are seen to change with the dolphin's direction with respect to the array and its range from the array. Fig. 4 shows an example click of a dolphin in the enclosure section 1, when its range from the array is 17.9 meters. The click has a 35 μsec duration and centroid frequency 52kHz, standard deviation ±20kHz and peak frequency 49kHz. On the other hand, the frequency analysis results of near "on-axis" click of a dolphin recorded by the same array system during the target touch test made in the same aquarium [5], where the dolphin was approaching a spherical target suspended underwater, shows higher peak and centroid frequency and larger standard deviation than the former as shown in Fig.5.

From the analysis results of above target touch test prior to the long-term monitoring, three echo-location phases, i.e. search, approach and terminal phase were also observed. In the search phase, ICI and SPL (Sound Pressure Level) change frequently, i.e. the dolphin changes range to the target and the direction. In the approach phase, ICI and SPL reduce rapidly, i.e. the dolphin starts focusing on the target. In the terminal phase, ICI reduces to approximately 10 msec for few seconds (burst pulses). SPL also reduces. The dolphin almost reaches the target in the terminal phase.

In the data recorded by the monitoring, the above three ehco-location phases are observed as shown in Fig.6. It is estimated that the dolphins are echo-locating the surrounding environment and targeting something else such as the array as a target. However, we can also observe solo burst pulses as shown in Fig. 7, where one dolphin's burst pulses are recorded. Video images show that two dolphins swam towards the array direction side by side during the period. However, the dolphin's 2-D trajectory calculated by the recorded clicks indicates that only one dolphin emits burst pulses during the period as shown in Fig.8. SPL first changes every 4 pulses in the initial period, and then changes every 2 pulses in the following period, and finally reduces with every pulse in the later period during the burst pulses, where ICI is kept constant at 1.9 msec as shown as Fig.9. The pulse character also indicates that one dolphin emits burst pulses during the period.

Solo burst-pulses emitted by one of two dolphins swimming side by side in the pool were observed during the long-term monitoring. Estimated echo-location range of the dolphin when emitting the burst pulses with ICI of 1.9msec is approximately 1.4 meters without considering the processing time [3] [4]. On the other hand, the range to the array from the dolphin during emitting the burst pulses is over 5 meters as shown in Fig.9. Thus, the dolphin did not focus its attention on the array at least during the period. Some studies report that some dolphin's species utilize the burst-pulses for their social activities [6] [7]. Next, "what for does the dolphin emit burst-pulses?" should be considered in further analysis of the monitoring data.

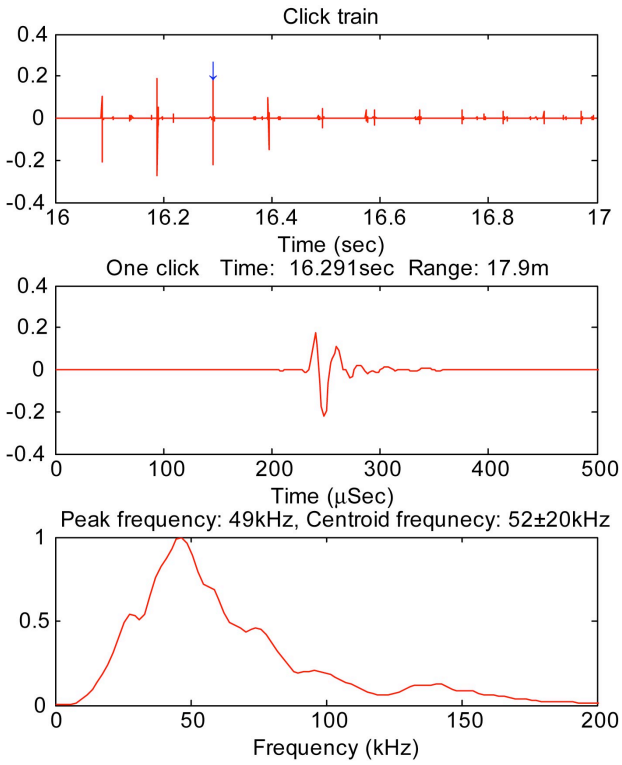


Fig. 4 Click train, Waveform and spectrum of an example click of a dolphin in the section 1 (recorded during the monitoring)

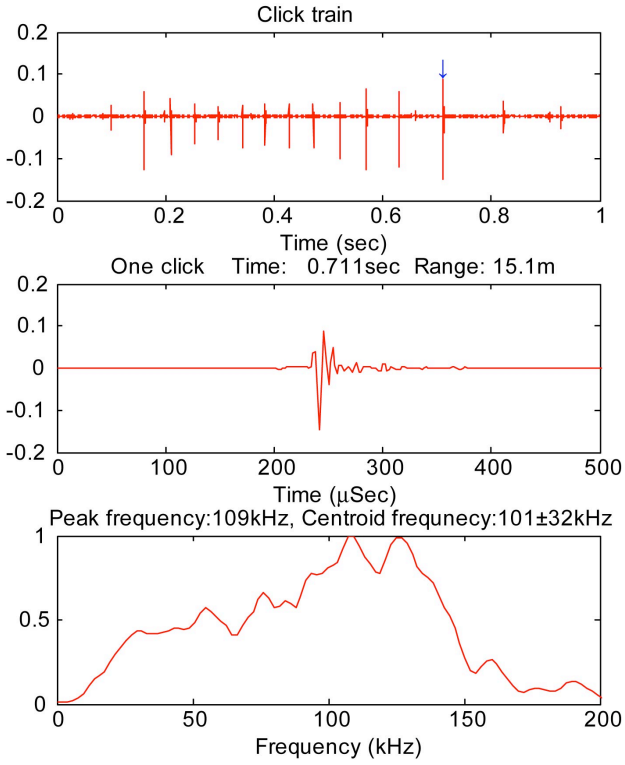


Fig.5 Click train, Waveform and spectrum of near on-axis click of a dolphin approaching to the target (recoded during the target touch test)

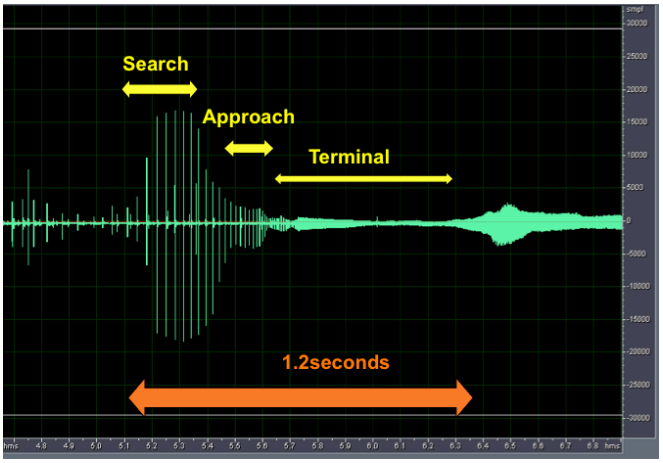


Fig.6 Three echo-location phases (search, approach and terminal) observed during the monitoring

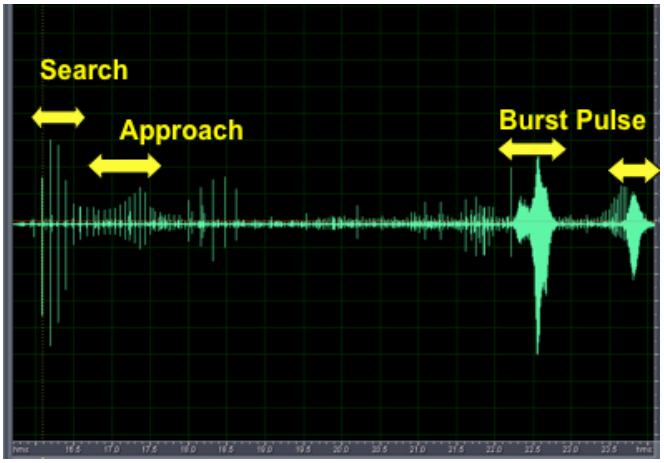


Fig.7 Solo burst pulses recorded during the monitoring

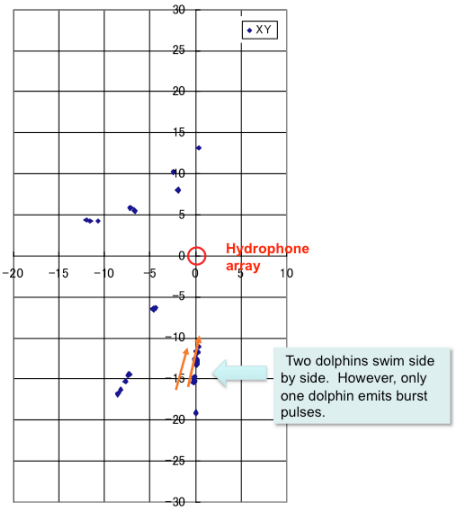


Fig.8 The dolphin's 2-D trajectory during solo-burst pulses

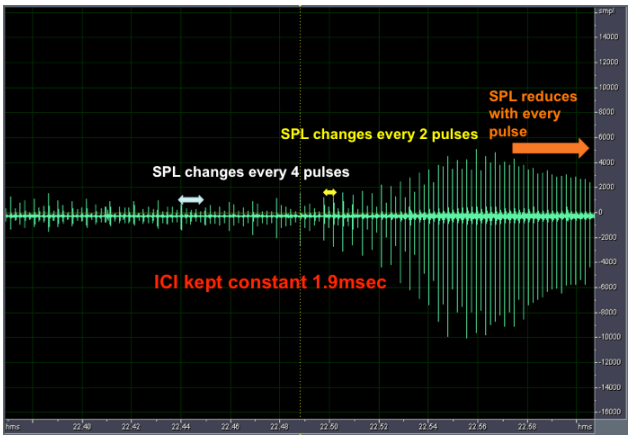


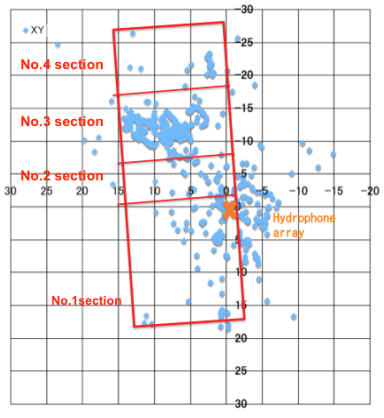
Fig. 9 Pulse character of solo burst pulses

B. Underwater Behavioral Changes

For understanding of the Bottlenose dolphins' underwater behavior and the trend of their behavioral changes over the seasons and year after year, the analysis has been started soon after the monitoring was started. Initially, the trend of the click number recorded around the pool is applied for the analysis as an index of the dolphin's activities. It is estimated that the dolphins are not active underwater or surfacing for resting or playing during the period when their click number reduced. Information from the video images would help to achieve an accurate assessment. Fig. 10 shows that the total click number and 2-D trajectories of the dolphins for the first 5 minutes in 3 hours from 12:36:46 26th June 2008 to 09:48:42 27th June 2008. The dolphin's number in each section of the pool during the period was as follows; section 1: 3 dolphins (3 female), section 2: no dolphin, section 3: four dolphins (3 female and one male), section 4: two dolphins (2 female). The trend and difference of the changes of the click number in each section depending on the time is clearly shown in Fig.10.

(a)

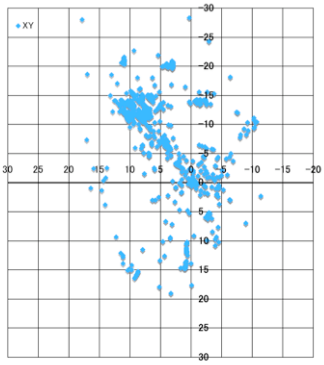
2008.06.26-12.36.46



• Available Clicks Number（5minutes）:1334

(b)

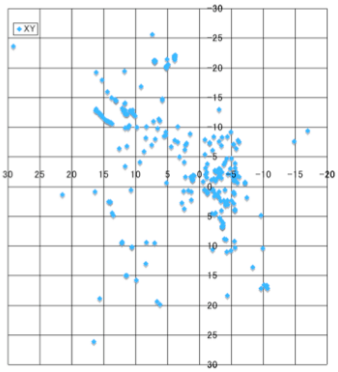
2008.06.26-15.27.02



• Available Click s Number （5minutes）：1717

(c)

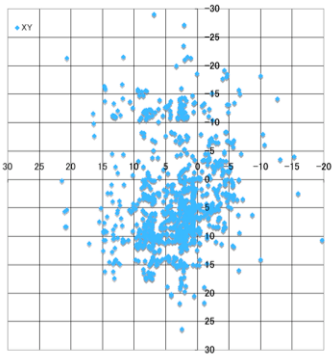
2008.06.26-18.29.16



• Available Click s Number （5minutes）：274

(d)

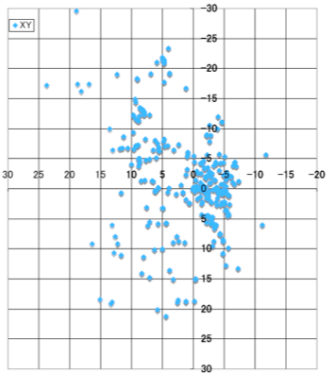
2008.06.26-21.29.33



• Available Click s Number （5minutes）：1218

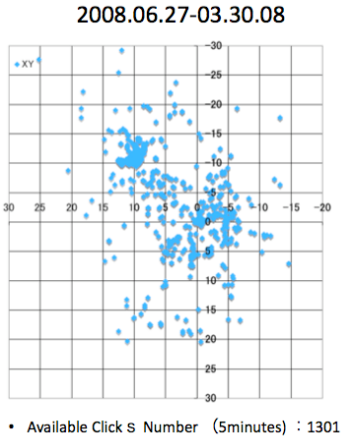
(e)

2008.06.27-00.29.50

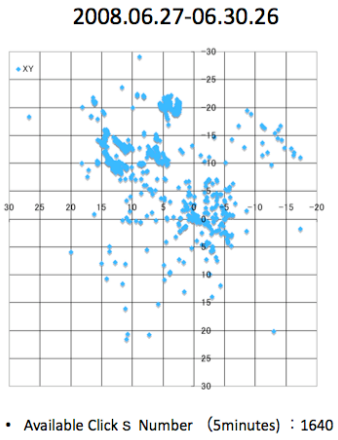


• Available Click s Number （5minutes）：410

(f)



(g)



(h)

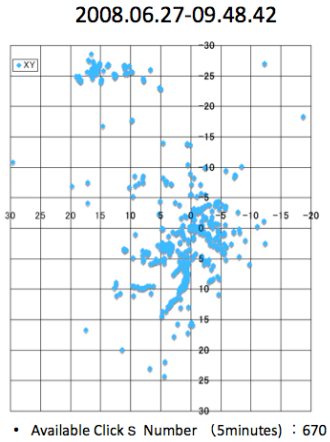


Fig.10 Trend of the click number and 2-D trajectories of the dolphins for the first 5 minutes in 3 hours from 12:36:46 26th June 2008 to 09:48:42 27th June 2008

C. Earthquake and Click Number Changes

The Bottlenose dolphins' behavioral changes were observed not only depending on the time, but also depending on natural phenomena. An earthquake of magnitude 6.5 recorded at Suruga bay (seismic center: N: 34.7862, E: 138.4993, depth of seismic center: 23.3 km) in Shizuoka Japan 05:07:05 on 11th August 2009. The Bottlenose dolphin's number in each section of the pool on 11th August 2009 was composed as follows; section 1: 4 dolphins (3 female, one male), section 2to section 4: no dolphin. Video images from the web camera shows that the dolphins' behavior never changed just before the earthquake occurred. Fig.11 (a) shows that a video image of the dolphins in the section 1 on 05:06:54 (just before the earthquake), where two dolphins played raising their tails up (relax mode). However, just after the earthquake occurred, the dolphins suddenly dived into the water as shown in Fig.11 (b). Its aftershocks were sequentially recorded during the day at Suruga bay. A large aftershock of magnitude 4.0 (seismic center: N: 34.8697, E: 138.4525, depth of seismic center: 23.6 km) was recorded at 06:27:08. The video images during that period show the trend that the dolphins stay mostly underwater.

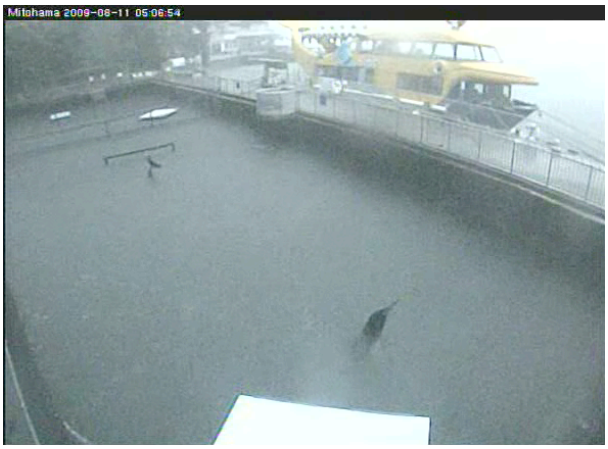
To know the dolphins' underwater activities before and after the earthquake, we calculated the 3 hours' click number (from 4 to 7 a.m.) of the day. The click number for the same 3 hours' recorded from 17th August 2009 to 19th August 2009 was also calculated for comparison with the former. The number of the dolphins in the pool during the period is fixed. Fig.12 shows the trend of the 3 hours' click number from 4 to 7 a.m. during that period. In comparison with other day's click number, the click number (16,992 clicks) decreased on 11th August 2009, when the earthquake occurred. However, the click number (16,923 clicks) also decreased on 30th July 2009, even though no earthquake or any other events are recorded during that day. Video images during the period on 30th July 2009 show that two to three dolphins were surfacing for rest (relax mode). This indicates that the duration of underwater stay is shorter than the other days. Consequently, we could say that the dolphins' click number reduction on 30th July 2009 is not related to the dolphins' underwater activities, but related to the dolphins' surfacing activities.

The behavioral changes of the dolphins in the pool after the earthquake are observed, as follows;

a. The dolphins dived into the water just after the earthquake occurred.
b. The dolphins stayed mostly underwater during the earthquake and its aftershocks.
c. 3 hours' click number from 4 to 7 a.m. of the day decreased in comparison with the same 3 hours click number of the other days for one month.

This is only one example data. Therefore, here, we could not conclude that the click number reduction on 11th August 2009 is clearly related to the earthquake at Sagami bay. Comprehensive analysis with video images of more examples acquired by the following monitoring is necessary. On the other hand, the dolphins' behavior never changed before the earthquake, but changed just after the earthquake occurred. This indicates that the Bottlenose dolphins in the pool of "Izu Mito Sea Paradise" did not predict the earthquake.

(a)



(b)

Fig. 11 Video images of the section of the pool before and after the earthquake: (a) Video image of the dolphins on 05:06:54 (just before the earthquake). (b) Video image of the dolphins on 05:07:23(just after the earthquake).

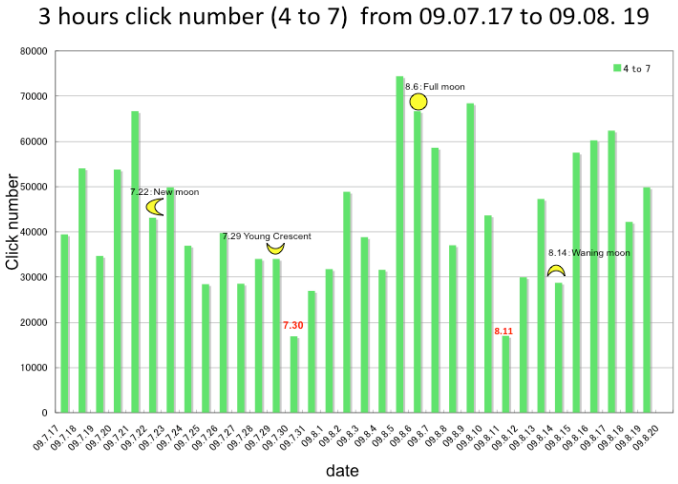


Fig.12 Trend of the 3 hours' click number from 4 to 7 a.m. from 17th August 2009 to 19th August 2009

IV. Conclusions

The long-term real-time monitoring of the Bottlenose dolphins in the pool of the aquarium, i.e. in the enclosed observatory was started from 22nd June 2008, and has been continuously conducted ever since then. The robustness of the system was well demonstrated to be applied for long-term real-time monitoring of the dolphins in the wild environment.

From the data recorded by the array and the video images, the echo-location characteristics of the Bottlenose dolphins in the pool and their behavioral changes in long-term span have been initially observed and analyzed as follows.

Three echo-location phases (search, approach, terminal) are observed. It is estimated that the dolphins are echo-locating the surrounding environment and targeting something else such as the array as a target. Solo burst-pulses emitted by one of two dolphins swimming side by side in the pool were also observed. What for solo burst-pulses are emitted will be considered in further analysis of the monitoring data.

For understanding the Bottlenose dolphins' behavioral changes during the long-term span monitoring, the trend of the click number recorded around the pool is applied for the analysis as an index of the dolphin's activities. The results show the trend and difference of the changes of the click number in each section of the pool depending on the time. Considering the aspects of their sex, age and birthplaces, the dolphins' activity difference as reported in each section depending on the time of a day will be analyzed in next step. For this, a detailed study with frequency analysis of the clicks recorded from each section of the pool will be made.

The dolphins' behavioral changes were observed not only depending on the time, but also depending on the natural phenomena. The trend of the click number reduction is observed during the earthquake, even when they stayed underwater. Significant behavioral changes of the dolphins are also observed just after the earthquake. It indicates that the Bottlenose dolphins in the pool of the "Izu Mito Sea Paradise" did not predict the earthquake.

As a follow-up step, the analysis using the data recorded by the continuing long-term real-time monitoring in the pool of the "Izu Mito Sea Paradise", it is expected to reveal more details of the bottlenose dolphin's echo-location characteristics and their behavioral changes depending on the time and the events. This would also help to understand the underwater behavioral studies of other dolphin species in wild environment so as to conserve them.

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