9-1-2009

47-Channel Burst-Mode Recording Hydrophone System Enabling Measurements of the Dynamic Echolocation Behavior of Free-Swimming Dolphins

Josefin Starkhammar
Lund University, josefin.starkhammar@elmat.lth.se

Mats Amundin
Linkoping University

Johan Nilsson
Lund University

Stan A. Kuczaj
University of Southern Mississippi, S.Kuczaj@usm.edu

Monica Almqvist
Lund University

See next page for additional authors

Authors
Josefin Starkhammar, Mats Amundin, Johan Nilsson, Stan A. Kuczaj, Monica Almqvist, and Hans W. Persson

47-channel burst-mode recording hydrophone system enabling measurements of the dynamic echolocation behavior of free-swimming dolphins (L)

Josefin Starkhammar[a)]
Electrical Measurements, Faculty of Engineering LTH, Lund University, P.O. Box 118, SE-221 00 Lund, Sweden

Mats Amundin
Kolmarden Wildlife Park, SE-618 92 Kolmarden, Sweden and Department for Physics, Chemistry and Biology (IFM), Linkoping University, SE-581 83 Linkoping, Sweden

Johan Nilsson and Tomas Jansson
Electrical Measurements, Faculty of Engineering LTH, Lund University, P.O. Box 118, SE-221 00 Lund, Sweden

Stan A. Kuczaj
Department of Psychology, The University of Southern Mississippi, P.O. Box 5025, Hattiesburg, Mississippi 39406-5025

Monica Almqvist and Hans W. Persson
Electrical Measurements, Faculty of Engineering LTH, Lund University, P.O. Box 118, SE-221 00 Lund, Sweden

(Received 9 February 2009; revised 30 June 2009; accepted 30 June 2009)

Detailed echolocation behavior studies on free-swimming dolphins require a measurement system that incorporates multiple hydrophones (often >16). However, the high data flow rate of previous systems has limited their usefulness since only minute long recordings have been manageable. To address this problem, this report describes a 47-channel burst-mode recording hydrophone system that enables highly resolved full beamwidth measurements on multiple free-swimming dolphins during prolonged recording periods. The system facilitates a wide range of biosonar studies since it eliminates the need to restrict the movement of animals in order to study the fine details of their sonar beams. © *2009 Acoustical Society of America.* [DOI: 10.1121/1.3184536]

PACS number(s): 43.80.Ev, 43.80.Ka, 43.60.Qv [WWA] Pages: 959–962

I. INTRODUCTION

The echolocation of dolphins and other odontocetes has been extensively studied, a primary focus being the beam axis (Nachtigall and Moore, 1988; Thomas and Kastelein, 1990; Au, 1993; Villadsgaard *et al.*, 2007; Kyhn *et al.*, 2009). Recording scenarios that focus on the beam axis typically provide accurate and effective measurements. However, since these situations often require that the echolocating animal be kept stationary, it is likely that the full dynamics of the sonar beam has not yet been described. In addition, these static test conditions are by definition impossible to use in other important contexts, such as in studies of the spontaneous use of echolocation by free-swimming dolphins, object investigation behavior in groups of dolphins, and calf mimicry of their mother's echolocation clicks. Although detailed sonar studies have been conducted with free-swimming dolphins (Sigurdson, 1996; Martin *et al.*, 2005, among others), these studies used relatively few hydrophones and consequently had limited sonar beam coverage. As a result, much is known about the beam axis, and little is known about the rest of the beam.

Recording dolphin sonar in dynamic test conditions requires a system able to deal with varying measurement parameters, including the animal's relative distance to the receivers, the number of animals present, the orientation of the beam relative to the receivers, and the required time for the animal to respond to an echolocation task. Consequently, a measurement system capable of long recording periods, large beamwidth coverage, and high spatial and temporal resolutions is needed in order to localize the beam axis and to measure the rest of the beam with high accuracy from free-swimming dolphins.

Multi-channel sonar recording systems have previously been reported by Miller and Tyack (1998), Ball and Buck (2005), Starkhammar *et al.* (2007), Amundin *et al.* (2008), and Moore *et al.* (2008), among others. The most extensive system developed thus far was created by Moore *et al.* (2008), who employed 24 hydrophones in an array. It was designed for high spatial resolution across the array area since it was used in a study of beamwidth control in a bottlenose dolphin (*Tursiops truncatus*) and so required measure-

[a)]Author to whom correspondence should be addressed. Electronic mail: josefin.starkhammar@elmat.lth.se

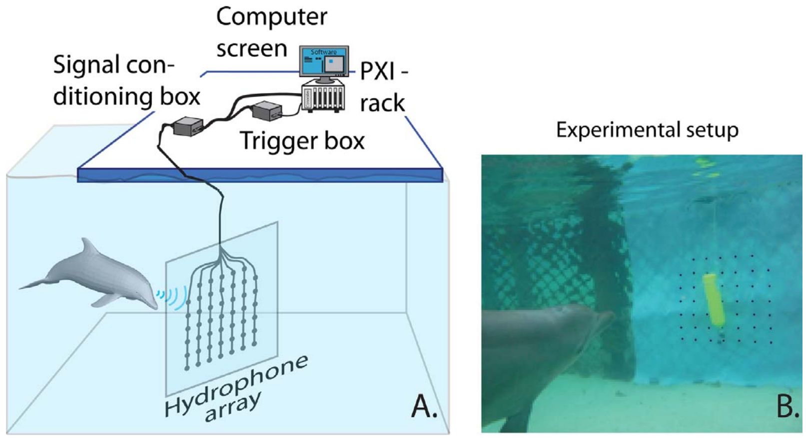

FIG. 1. (Color online) (A) A schematic drawing of the system setup in the field test. (B) An underwater photograph of the experimental setup.

ments of small spatial alterations of the amplitude distribution across the whole beam cross-section. The system recorded data during 5 s intervals with a sample rate of 312.5 kS/s, resulting in a data flow rate of 16 Mbytes/s. Although this system worked well for its purpose, the extremely high data flow rate makes it unsuitable for measuring echolocation behavior in free-swimming dolphins. Using this system, a single minute of recordings would result in a 1 Gbyte large file.

A measurement system optimized for dynamic test conditions requires large beamwidth coverage and higher spatial and temporal resolutions. The system must also be able to record for longer time periods in order to be useful in the field. This requires an increase in the number of array elements, the physical size of the array, and, preferably, also the sample rate. In addition, the problems associated with extremely high data flow rates must be solved.

This report describes a system with a measurement approach optimized for studies of dolphin sonar under dynamic test conditions. The system uses a larger number of hydrophones (47 channels), allows an increased sample rate (1 MHz), and acquires data with lower data flow rates than previously reported multi-hydrophone systems. This facilitates full waveform recordings of the echolocation activity of dolphins during prolonged time periods and comprehensive beamwidth coverage, provided that the dolphins are within reasonable distance from the screen. In addition, the approach enables real-time analysis and real-time visualization of data during recordings. This measurement approach and recording system enables researchers to investigate dolphin sonar use in a wider range of contexts than has previously been made possible. In the following sections, the authors describe this system and provide examples of its potential uses with free-swimming dolphins.

II. MATERIALS AND METHODS

A new 47-channel dolphin echolocation measurement system was developed and tested with a group of 19 Atlantic bottlenose dolphins, housed together in a large open sea pen at Roatán Institute of Marine Science, Roatán, Honduras. All dolphins were allowed to swim freely and to explore at will objects suspended in front of or behind the recording hydrophone array. The size of array was 0.75×0.75 m^2. Figure 1(A) shows a schematic representation of the experimental setup, and Fig. 1(B) shows a photograph of the setup during one trial.

Typically, multi-hydrophone arrays used in biosonar applications produce a considerable amount of data due to the relatively high sample rate required to reconstruct the full waveform accurately in post-analysis [approximately ten times the maximum frequency for accurate visualization (Buchla and McLachlan, 1992)]. The long recording times required in test conditions with spontaneously echolocating dolphins using a 47-element array system would result in unmanageably large data files after only a few seconds, using the data acquisition approaches in previous systems. Therefore, an alternative approach to continuous sampling of all parallel channels was needed for the 47-element hydrophone array system.

In order to facilitate longer recordings and to keep the data flow rate manageable with a high sample rate, the system was designed to be triggered by one echolocation click at a time and to not sample data during the silent periods that occur between clicks in click trains. Figure 2 describes the basic data acquisition method. Basically, the system only acquires a small pre-set number of samples, containing only the actual click, when a hydrophone output exceeds the chosen trig level. This is referred to here as burst-mode sampling (as opposed to continuous sampling). The time stamps (T1 and T2 in Fig. 2) correspond to the start time of each sample burst and are stored in association with each click.

Successful burst-mode sampling required data acquisition hardware capable of extremely fast re-triggering of measurements even after the particularly short inter-click intervals (<1 ms) that may occur in click train "buzzes" (see

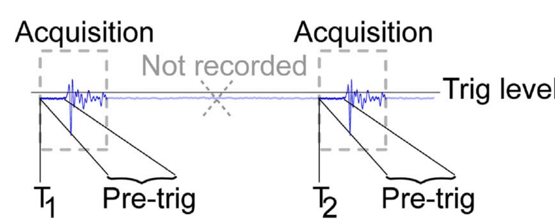

FIG. 2. (Color online) Basic data acquisition method.

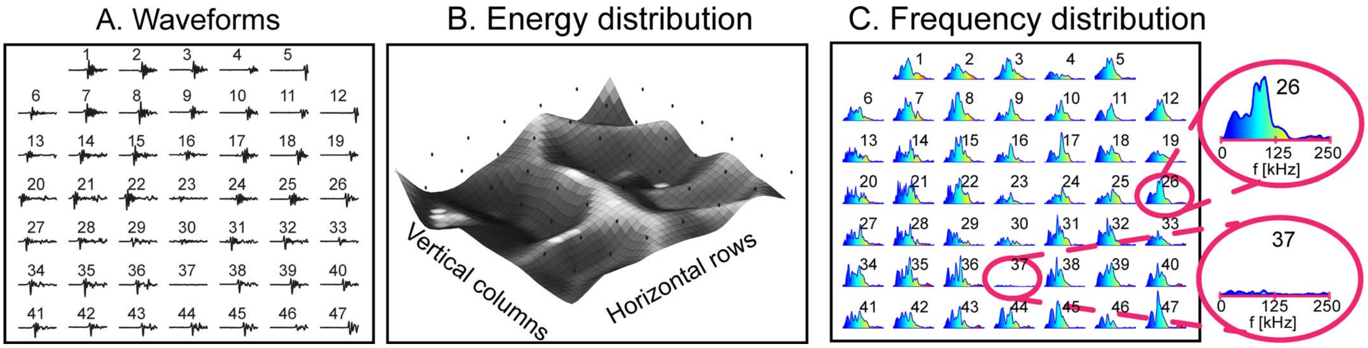

FIG. 3. (Color online) Visualization of one echolocation click acquired at the 47 hydrophone positions in the experimental setup. This click can be visualized by plotting (A) the waveforms, (B) the relative energy distribution within the beam, or (C) the color coded frequency distribution within the beam. High click energy in (B) is illustrated by letting it push the interpolated 3D surface downward, away from the echolocating dolphin.

Herzing, 1996; Herzing and dos Santos, 2004) or when multiple dolphins echolocate concurrently. The total time required to finish one burst-mode acquisition, re-trig, and start a new one is referred to here as the system's rearm time.

In order to capture the echolocation data across the entire array, the system was designed to simultaneously trigger all channels, regardless of which hydrophone was hit first by the sonar beam. Signals were acquired from 6×8 parallel and synchronized channels using six PXI-digitizer cards (NI PXI-5105, National Instruments, USA), each with eight simultaneously sampling analog-to-digital-channels and 12 bit voltage resolution. One of the digitizer channels was used as a trig-channel. The 47 remaining channels were wired to the 47 individually pre-amplified hydrophones, all amplified with either 35 or 50 dB, depending on the measurement situation. The sum of all the 47 pre-amplified hydrophone signals was wired to the pre-designated trig-channel using a separate signal summarizing hardware circuitry.

The software was optimized to ensure fast rearm time and real-time visualization and analysis of data, aspects that were typically the most time-consuming as well as important determinants of the overall system performance. This improvement was accomplished with software created in LABVIEW 8.6™ (National Instruments, USA) enabling dual-core operation of the CPU.

III. RESULTS AND DISCUSSION

The echolocation measurements of the free-swimming dolphins in the group of 19 individuals demonstrated that the system is capable of measuring the full waveforms of the spontaneous sonar activity in the group. Measurements were obtained with all 47 simultaneously sampling hydrophones at a sample rate of 1 MHz during measurement sessions of various lengths (often >15 min). Each acquisition in these tests was set to record during a time window of 150 μs around each click event with a pre-trig time period of 40 μs (see Fig. 2). The total duration of the measurement sessions was determined by the tourist activity at the facility. Sessions were never aborted due to system failure.

Figure 3(A) shows the corresponding waveforms of one single click acquired simultaneously by all 47 hydrophones. Each position of the numbered elements corresponds spatially to the hydrophones shown in Fig. 1. The level of spatial resolution and comprehensive beamwidth coverage provides new information concerning the entire cross-section of the beam during one single click. As an example, Fig. 3(B) shows the relative energy distribution of the cross-section in the beam. The energy in the click is coded as an indentation of the interpolated three dimensional (3D) surface where high energies "push" the surface downward, away from the echolocating dolphin.

A suspended scuba tank provided a way to further demonstrate the functionality of the system by shadowing the hydrophones in the center of the screen when a dolphin echolocated toward the tank from small bearing angles (i.e., close to the perpendicular to the screen). This shadowing effect is clearly seen as a ridge in the middle of the beam energy plot in Fig. 3(B).

The presented level of spatial resolution and comprehensive beamwidth coverage give an unprecedented detailed measure of the spectral content within the cross-section of the beam [Fig. 3(C)]. The minimized data flow rates make it possible to view the spectral content even in real-time. The system also allows researchers to study entire echolocation scan sequences in detail by processing all successive clicks and then re-playing them at variable frame rates. The resolution of the measurements enables detailed re-plays of the propagation of every single click across the array, further facilitating quantified detailed studies of the dynamic variations in the echolocation behavior of dolphins during prolonged periods of time.

Benchmark tests of the system performance showed that the low data flow makes possible recordings during 20 min of constantly echolocating animals with inter-click intervals of 20 ms before the data file size reaches 1 Gbyte and becomes unreasonably large for commonly used post-processing tools (such as MATLAB®, The MathWorks™ Inc., USA). This is a considerable improvement compared to previously published systems. The low data flow rate of the present system (0.83 Mbyte/s under the conditions in the benchmark tests) is even more advantageous in more realistic measurement scenarios, where free-swimming dolphins echolocate spontaneously and when minute long silent periods in the recordings are likely to occur.

In conclusion, the presented 47-element hydrophone system enables recordings with improved spatial and temporal resolutions of the cross-section of the echolocation beam of free-swimming dolphins. Moreover, the system makes possible extended recording periods due to the minimized data flow rate. These features facilitate the reconstruction, visualization, and re-play of significant aspects of the clicks during extended echolocation sequences. The system's ability to process information from free-swimming dolphins in groups opens the door to a completely new range of studies, which will help us to better understand the functions of dolphin sonar since it eliminates the need to restrict the movement of animals in order to study the fine details in their sonar beams.

Amundin, M., Starkhammar, J., Evander, M., Almqvist, M., Lindstrom, K., and Persson, H. W. (**2008**). "An echolocation visualization and interface system for dolphin research," J. Acoust. Soc. Am. **123**, 1188–1194.

Au, W. L. (**1993**). *The Sonar of Dolphins* (Springer, New York).

Ball, K. R., and Buck, J. R. (**2005**). "A beamforming video recorder for integrated observations of dolphin behavior and vocalizations," J. Acoust. Soc. Am. **117**, 1005–1008.

Buchla, D., and McLachlan, W. (**1992**). *Applied Electronic Instrumentation and Measurement* (Macmillan, New York), pp. 384–388.

Herzing, D. L. (**1996**). "Vocalizations and associated underwater behavior of free-ranging Atlantic spotted dolphins, *Stenella frontalis* and Bottlenose dolphins, *Tursiops truncatus*," Aquat. Mamm. **22**, 61–79.

Herzing, D. L., and dos Santos, M. E. (**2004**). "Functional aspects of echolocation in dolphins," in *Echolocation in Bats and Dolphins*, edited by J. A. Thomas, C. F. Moss, and M. Vater (University of Chicago Press, Chicago), pp. 386–393.

Kyhn, L. A., Tougaard, J., Jensen, J. F., Wahlberg, M., Stone, G., Yoshinaga, A., Beedholm, K., and Madsen, P. T. (**2009**). "Feeding at a high pitch: Source parameters of narrow band, high-frequency clicks from echolocating off-shore hourglass dolphins and coastal Hector's dolphins," J. Acoust. Soc. Am. **125**, 1783–1791.

Martin, S. W., Phillips, M., Bauer, E. J., Moore, P. W., and Houser, D. S. (**2005**). "Instrumenting free-swimming dolphins echolocating in open water," J. Acoust. Soc. Am. **117**, 2301–2307.

Miller, P. J., and Tyack, P. L. (**1998**). "A small towed beamforming array to identify vocalizing *resident* killer whales (Orcinus orca) concurrent with focal behavioral observations," Deep-Sea Res., Part II **45**, 1389–1405.

Moore, P. W., Dankiewicz, L. A., and Houser, D. S. (**2008**). "Beamwidth control and angular target detection in an echolocating bottlenose dolphin (Tursiops truncatus)," J. Acoust. Soc. Am. **124**, 3324–3332.

Nachtigall, P. E., and Moore, P. W. B. (**1988**). *Animal Sonar, Process and Performance* (Plenum, New York).

Sigurdson, J. E. (**1996**). "Open-water echolocation of bottom objects by dolphins (*Tursiops Truncatus*)," J. Acoust. Soc. Am. **100**, 2610.

Starkhammar, J., Amundin, M., Olsén, H., Ahlmqvist, M., Lindstrom, K., and Persson, H. W. (**2007**). "Acoustic touch screen for dolphins," in *Proceedings of Fourth International Conference of Bio-Acoustics*, Institute of Acoustics, Loughborough University, edited by S. Dimble, P. Dobbins, J. Flint, E. Harland, and P. Lepper, pp. 55–60.

Thomas, J. A., and Kastelein, R. (**1990**). *Sensory Abilities of Cetaceans* (Plenum, New York).

Villadsgaard, A., Wahlberg, M., and Tougaard, J. (**2007**). "Echolocation signals of wild harbour porpoises, *Phocoena phocoena*," J. Exp. Biol. **210**, 56–64.