3. Sound source location by difference of phase, on a hydrophone array with small dimensions.

Abstract

A method for localizing calling animals was tested at the Research and Education Center "Dolphins Plus" in Key Largo, Florida, under realistic field conditions. Experiments were performed with bottlenose dolphins (*Tursiops truncatus*) using a special hydrophone arrangement. There were two groups of hydrophones, and the two hydrophones in each group were 15 cm apart. The groups were separated by a distance of 15m. Acoustic signals from the animals were recorded by use of a digital data acquisition system with a sampling rate of 1 MHz. All data were processed off-line. The time delay was measured by the phase difference in a single wavelength on whistles and clicks. The bearing of the signals was calculated with help of the time delay. This method has high precision and provides the possibility for analyzing overlapped signals.

Introduction

Until recently, the continuous observation of a large interacting dolphin group and the acoustic communication of an individual could not be carried out satisfactorily. One of the main problems is the assignment of the acoustic signals to the corresponding transmitters. Theoretically, it is possible to calculate the bearing from a sound source by the arrival time difference at different hydrophones.

In a study performed by Watkins in 1972, a ship platform with a four hydrophone array on a buoy system was used. This system needed to be calibrated absolutely. It was shown that the distance between the hydrophones must be about 30 meters to measure biological signals. The signal amplitudes were very strongly varied on all sensors, although identically constructed hydrophones were used. The precision of this system was also very limited (Watkins, 1972).

The first practicable system was used to investigate and estimate the population of Right Whales. This system measured the phase difference between the signals from a two-dimensional hydrophone array and calculates the bearing to the sound source. This system determined the direction with 12-degree resolution. By repeated determination of the direction from different positions, it was possible to locate the sound source (Clark, 1980, 1986). However, this system was not accurate enough to investigate the communication of dolphin groups in a small area. A similar system was used to estimate sperm whale populations (Leaper, 1992). Two hydrophones were used with a separation of 3 m. The sound source location was calculated by using bearings taken at different ship positions. Further experiments used a group of seven circularly positioned and tightly installed hydrophones. It was possible to locate the position of an acoustic source within this circle (Spiesberger, 1990). However, neither of the methods described above is suitable for the investigation of dolphins that are not widely separated with little spatial distribution.

Experiments in an aquarium and in a fenced ocean bay showed that the cross correlation of an entire whistle is possible (Friday, 1993). However, the cross correlation supplies exact results only if the signal on all hydrophones is undistorted and similar. Another solution is the use of a device attached to the animals. Small recorders and signaling lamps, which were fixed on the head of the animals, have been successfully used (Tyack, 1985). The caveat for this method is that it works only with captive and trained dolphins.

In the context of this study, it was possible to develop a disturbance insensitive method that provides a very accurate time delay measurement, which makes it possible to successfully locate the source of a sound. This method, used at the "Dolphins Plus Center", can easily be applied to the conditions in the open ocean.

Methods

The data recording was carried out at the "Marine Mammal Research and Education Center Dolphins Plus", Key Largo, Florida Keys. This center consists of two fenced pools, connected to an open ocean water channel between the Atlantic Ocean and the Gulf of Mexico. The recordings were made between 11/01/98 and 12/15/98. The observation pool (22m x 37m) contained four females and one young male.

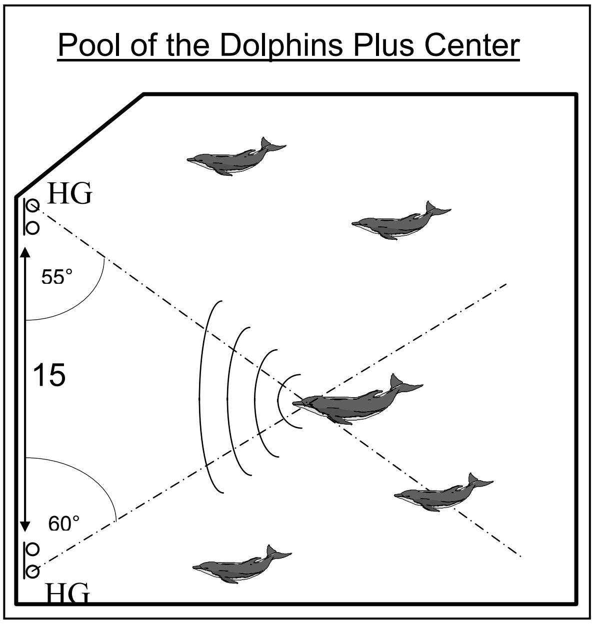

Figure 3.1: Schematic diagram of the pool at "Dolphins Plus Center". HG1 and HG2 are the two-hydrophone groups separated by 15 m. The distance between the two hydrophones in each group is 15 cm. The two dotted lines show the bearings with a dolphin at the intersection point. The figure is adapted to the video perspective by using an empirical formula complex.

The location of the sound source was determined as the intersection point of two bearings, measured by four hydrophones (C50a, Cetacean Research Technology, www.cetaceanresearch.com) in two groups (figure 3.1). Most of the problems described above, i.e., the large distance between and the fixed arrangement of the hydrophones, or the impact of devices on the dolphins, could be solved by reducing the distance between the hydrophones in each group to approximately 15 cm. This arrangement allows analyzing the time delay of single cycle waves. A specially designed transient recorder (GKSS Research Center Geestacht, Germany) with four channels and an accuracy of one microsecond was used. All four hydrophone channels were triggered simultaneously. The analog signals from every channel were digitized into an 8-bit digital data stream with a sampling rate 1 MHz. The resulting data stream of 4 MB per second was continuously saved for approximately 19 minutes on a 4500 MB SCSI hard drive for further analysis.

The two groups of hydrophones were attached to the wall of the pool with a separation distance of 15 meters (figure 3.1). The exact distance between all hydrophones was determined acoustically.

Every acoustic event in the pool produces a wave front, which passes through the hydrophone groups with a distinct time delay, which depends on the bearing. This time delay between the two channels in each group makes it possible to calculate the bearing and the intersection point of the bearings of the sound source, assuming a plane wave front.

The distance between the hydrophones in each group was approximately 15 cm. A sound wave in ocean water needs a maximum of about 100 µs to travel this distance. In the case that the sound source is in line with the hydrophones the time delay will be 100 µs. The opposite case is that the phase difference is zero, meaning that the sound source is in front of the hydrophone group and the waves arrives on both channels in the same moment without a time delay (figure 3.2 a/b). The high sampling rate of the system allows a description of a single cycle wave of 10 kHz in a 100 µs time frame with a resolution of 100 samples.

It is possible to determine the phase difference visually on a computer screen (figure 3.2) if they are less than four zero-crossings in a 100 µs time frame. Therefore, it is possible to analyze frequencies of up to 20 kHz. In relation to the system's sampling rate and the with the use of Pythagoras theorem, it is theoretical possible to determine the angle up to a maximum of 0.6 degree in front of the hydrophones. This precision decreased down to 8 degree on the sides (figure 3.3).

The sinusoidal form of the wave makes it impossible to recognize which hydrophone was passed by the wave first. This means, that two possible time delays and therefore two bearings belong to each cycle wave (Fig 2 c/d).

The position of the sound source lies on the intersection point of the bearings from the two-hydrophone groups (figure 3.1). In some circumstances, it is possible to get more than one intersection point. This depends on the possible second bearing of each hydrophone group. However, it is unlikely that there are dolphins at all intersection points. Therefore, an assignment is possible in most cases. The coordinates of the intersection were compared to the video recordings using the "RaPid" time code. It is not possible to correlate the intersection points directly to the video view. All photo and video sources have a distortion of perspective, depending on the angle of the camera. This distortion must be calculated in every case to obtain more exact positions. There are different methods to do so, having all considerable costs. In this study, an adequately exact formula complex was empirically developed.

The precision of these formulas was tested with a white PVC bar of 3.1 meters. This bar was moved around the pool. Since the length of the bar is constant, the bar must always be represented by the same numbers of pixels in any position. 130 measurements were carried out. The bar was represented by 3.09m ± 0.38m on average. This precision is acceptable and correlates with the quality of the data collected from the video screen. The corrected perspective of the positions of dolphins based on the calibration can be correlated to the exact position of the hydrophones and the corresponding intersection points.

Results and discussion

The main problem of time delay measurement is to recognize the starting point of biological signals. The beginning of a click impulse is easy to recognize by the shape of the waveform. The beginning of most biological signals, especially frequency-modulated tones, is not as obvious. To solve this problem and to get the average of the time delay, experiments with cross correlation over the whole whistles were performed (Friday 1993). However, this method is very sensitive to different influences. It is practically impossible to analyze a fast moving animal or overlapped signals in one time frame. In addition, this method requires a large distance between the hydrophones.

The first results from the data analysis found by using the method described in this publication, show clearly that this theoretical principal can be used in practice. The method was used successfully for the analysis of 50 whistles and 30 broadband impulses, meaning that it was possible to identify a dolphin. Figure 3.1 shows one of these cases as an example. The two possible time delays on hydrophone group 2 (HG_2) are 60µs, if the right hydrophone was passed first, and 81µs if the left hydrophone was passed first. This corresponds to an angle of 55° to the right and an angle of 38° to the left side. The angle of 38° was not a realistic option, due to a fenced- off area for sea lions. The calculation for hydrophone group 1 (HG_1) yields an angle of 60° to the left side. The bearing on the right side is outside the pool. It can be clearly shown that there is a dolphin in the intersection point of the two remaining lines. The precision of this method seems to be very high and comparable to Fig 3. Further analyses and statistical methods have to be employed to calculate an estimate of the precision.

The method makes it possible to analyze very small parts of signals. This way it is possible to analyze time delays independently from the speed of the animals. Another advantage is the possibility to analyze overlapped signals, if they are not completely overlapped. Early experiments show that it is also possible to filter overlapping signals by their frequency and subsequently to analyze the time delay for each filtered signal.

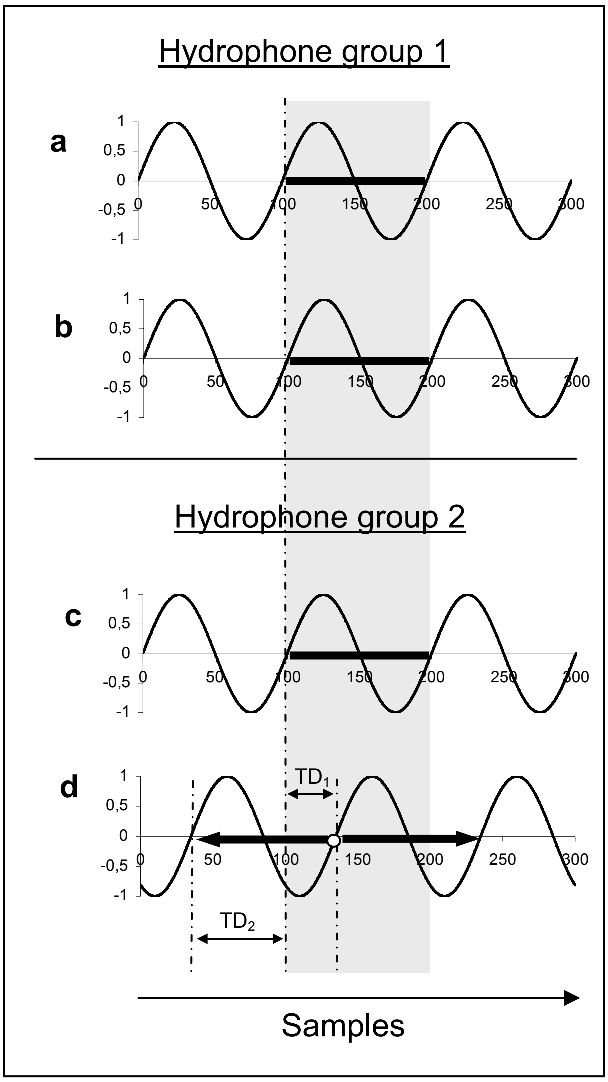

Figure 3.2: Waveform view of a 300 µs (300 samples) time frame of a whistle on four different channels. The time frame includes three complete waves, which corresponds to a frequency of 10kHz. The gray sector represents 100 µs (100 samples). This corresponds to the maximum time delay of a sound wave (sound velocity in ocean water 1500m/s), by hydrophones separation of 15 cm. The black bars on the x-axis show single cycles of a 10 kHz wave. There is no time delay in between a and b, meaning that the sound wave arrives on both hydrophones at the same moment or the delay is smaller than 1 µs. The phase shift between c and d is +35 samples or –65 samples, meaning that the sound wave has a time delay of +35 µs (TD_1) or -65 µs (TD_2) on channel d compared to channel c. This time delay between these hydrophones belongs to one cycle sinus wave, because the wave consist of less than four zero crossings and therefore less than two complete waves.

All analyzed sounds were undistorted signals of high intensity. Very low intensity signals with strong background noise are hard to analyze, because it not possible to see the signal in the amplitude directly. The reason for this is the low 8-bit data resolution. The resulting 256 values are not enough to adequately represent the dynamic range the environment. The amplification was increased in order to get a small dynamic range with a high resolution. The disadvantage of this solution is the loss of all loud sounds, which lie outside the range of the measurement. The ideal solution for this problem would be to increase the 8 bits to 16 bits. Another solution would be the dynamic preamplification. This means that a dynamic range with a high resolution is dynamically moved over the entire dynamic range caused by the special situation. For this reason a four channel dynamic preamplifier with a frequency range between 50 Hz and 500 kHz was developed in cooperation with GKSS. Recently some experiments with this preamplifier and the hydrophone array described in the Perspective below were performed satisfactorily.

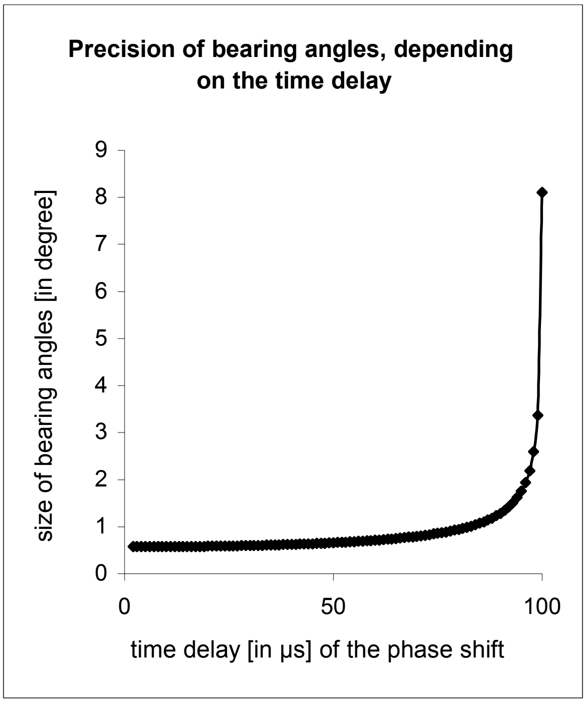

Figure 3.3: This figure shows the precision of bearing angles, depending on the time delay of the phase shift, calculated using the Pythagoras theorem. The size of bearing angles is the difference between two consecutive angles compared to the time delay in increments of one µs. It is possible to determine the angle with a maximum resolution of 0.6 degrees for a small time delay (in front of the hydrophones). For a time delay of 100µs and a sound source on the sides the resolution decreases to 8 degrees.

A further problem is that there are two time delays and two angles for a single sound wave. This makes it necessary to know which hydrophone was passed by the wave first. Earlier experiments show that it is possible to calculate these with a cross correlation of 10 to 100 wavelengths.

Perspective

The biggest advantage of the method described in this paper lies in the possibility to assemble the hydrophone groups closely together. An arrangement with two hydrophones side by side (for the horizontal angle) and two hydrophones above each other (for the vertical angle) provides the ability to measure 360° on the horizontal and the vertical angle, respectively. Therefore, this hydrophone cube is able to measure all bearings of sound sources surrounding the array. The dimension of the cube should not exceed 20X20X20 cm and can be easily attached to an underwater video system. If the aperture angle of the camera lens is known, it is easy to identify the corresponding signal transmitter in a group of animals.

This method allows for conducting experiments in the open ocean, which provides the opportunity to collect data with context specific behavior and the individual acoustic output of dolphins or other marine mammals.