Is Synthetic Aperture an Essential Tool for Echoic Shape Recognition in Dolphins?

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***Abstract*—A dolphin had previously been trained to perform a cross-modal matching-to-sample task. In one version of this task the animal had to investigate a sample object that was concealed in a box through its echolocation sense alone, then select the correct match among up to three alternative objects visually in air. Given the frequency range of a dolphin click and the limited number of sensors that the dolphin receives the sonar returns with, the dolphin should have difficulties resolving the details of the object. We suggested earlier that the dolphin might be using synthetic aperture to gain a higher resolution of the stimulus. To test this hypothesis we proposed to restrict the movement of the dolphin by stationing him on a bite-plate that was fixed in front of the box that contained the sample object. We trained the dolphin to station on the bite-plate while performing the cross-modal task (echolocation to vision) while recording the sound field around the dolphin through a 16-hydrophone array that was placed in a variety of positions and configurations between the object and the dolphin stationed on the bite-plate. The acoustic data were recorded at 500 kHz and later analyzed. To our surprise the dolphin was still able to perform the discrimination task. In this paper, we present the analysis of the data collected and show that the dolphin employs techniques such as beam steering and beam shaping while acoustically interrogating the object. This suggests that while the dolphin might still employ a synthetic aperture when possible, he might not need it to resolve the details of the object. We are planning to extend the range of objects to new and unfamiliar objects to explore whether the dolphin is indeed able to resolve details of the object acoustically without the need for synthetic aperture.**

I. Introduction

What exactly does the dolphin perceive when he echolocates on an object? Is it a collection of features and highlights or does he perceive the object holistically? One way of investigating this question is to test the animal in a cross-modal matching-to-sample experiment where the dolphin has to match shapes across the senses from echolocation to vision or visa versa. Because the sample object is exposed to the echolocation sense *alone* and the alternatives from which the dolphin must choose the correct match are presented to vision *alone*, the only feature of a stimulus that is accessible to both senses is its shape. But what parts or features of the objects shape are essential for its recognition in the other sense? If the dolphin perceives the complete object holistically through echolocation then he must have access to *all* of its features and in order to achieve that the animal might have to interrogate the object from different aspects as not all features might reflect the dolphin's echolocation click from a single position. Previously we suggested that the dolphin might be using synthetic aperture to gain both a higher resolution of the stimulus and different aspects [1]–[4]. Some of our simulation results showed that this would indeed increase the dolphin's ability to resolve fine differences as well as allow the dolphin to perceive features of the object that he would not have access to if he did not move around the object [5]. These simulation results fit with the acoustic and video data collected in our experiment where we observed the animal changing its relative position in reference to the object by about 65 degrees along the vertical axis, thus gaining a larger synthetic aperture. In the visual sense the eye acts as a *fully* populated sensor array which allows for the creation of an image as a representation of the real world, this though seems to be unlikely the case in the dolphins echolocation sense. At best it might be a sparsely populated array as suggested in [6] and [7]. With such an array the dolphin would end up with a click association problem on the various sensors [4]. The dolphin may get around this problem by using an incoherent synthetic aperture approach in which the animal would move around the object to exclude the ghost reflections caused by the reduced number of sensors.

In this paper, we present results from an experiment to explore whether the dolphin needs a synthetic aperture by restricting the movement of the dolphin by stationing him on a bite-plate that was fixed in front of the box that contained the sample object. Therefore the animal would have access to only *one* aspect of the stimulus and would not be able to integrate successive positions over time as he moved in front of the sample box. This bite-plate also controlled the dolphin's ability to echolocate on the object through a bubble screen that was turned off when the dolphin bit on the plate. The dolphin was trained to station on a fixed bite-plate while performing the cross-modal task (echolocation to vision). We predicted that the performance of the dolphin should decrease if we restricted the movement. To our surprise despite the change in setup the dolphin was still able to perform the task. This would lead to the conclusion that the dolphin might not

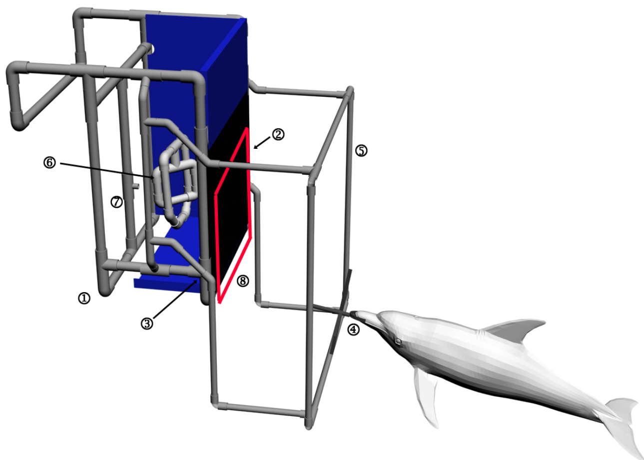


Fig. 1: Computer rendering of the setup with the box (1), plexiglas (2), bubble screen (3), bite-plate (4), frame (5), stimulus (6), object holder (7) and position of the hydrophone array frame in red (8). One side panel is removed to see the placement of the object.

necessarily need the synthetic aperture – although he might use it when available. To investigate how else the dolphin might solve the task we placed a 16-hydrophone array between the dolphin stationed on the bite-plate and the object that he was echolocating on, and analyzed the acoustic signals recorded on the hydrophones.

If the dolphin was moving, then any possible beam steering would be occluded by the movement because the array would be exposed to different parts of the echolocation beam. Previously researchers have shown that dolphins are able to steer the center of their echolocation beam by 18 degrees in a target detection test even when stationed on a bite-plate [8], [9]. Our current experiment builds on that by demonstrating that the dolphin is not just able to detect the presence or absence of a target through beam steering but that dolphins can also perform a more difficult shape recognition task through their ability to steer their echolocation beam.

II. Material and Methods

A. Subject

The subject of this study was a 6-year old bottlenose dolphin (*Tursiops aduncus*) named Ginsan that was housed with several other dolphins at a facility at Ocean Park Hong Kong. Ginsan had been the subject of previous studies on cross-modal shape recognition of objects and was very familiar with the task [1]. Over the course of one year he had been trained in the use of the bite-plate while still maintaining his ability to perform the original cross-modal matching task. On a regular day Ginsan was participating in the research three times per day with each session lasting about 35-40 minutes.

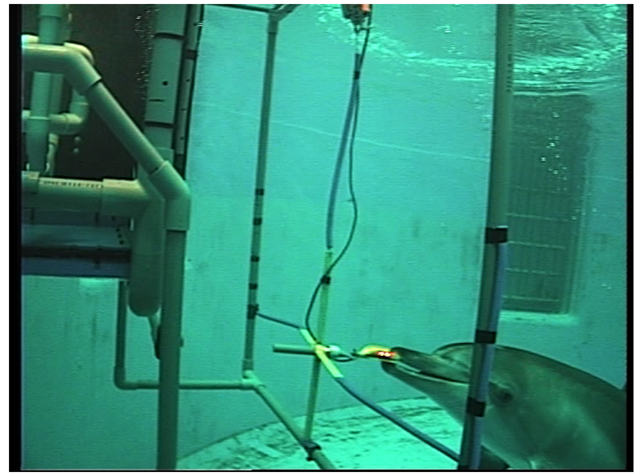


Fig. 2: Video capture of Ginsan stationed on the bite-plate (side view).

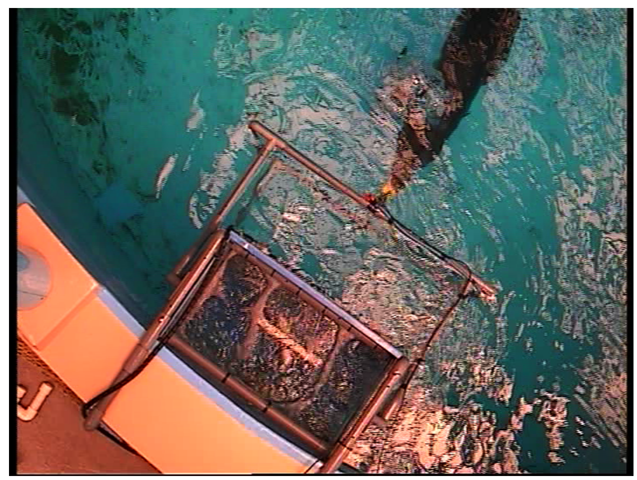


Fig. 3: Video capture of Ginsan stationed on the bite-plate (top view).

B. Experimental Setup

In order to present stimuli to one sense only, a custom anechoic box (see Fig. 1) was built from PVC Schedule 80 pipe and fittings. The box consisted of a 40 mm diameter PVC frame, opaque side and bottom panels and a front plexiglas of 3 mm that allowed the dolphin to interrogate any object placed inside the box through his echolocation sense but not to visually explore the object. Attached to the side panels were 6 mm thick neoprene sheets that blocked echolocation transmission from the side. Acoustic exposure of the object inside the box was controlled by a bubble screen that was generated by two airstrips that were mounted directly behind the front plexiglas on the bottom panel. Airflow to these strips was generated through a scuba tank that was connected via a pressurized hose system. The flow of air and thus the ability of the dolphin to echolocate on the object inside the box could either be controlled manually or via a magnetic switch that

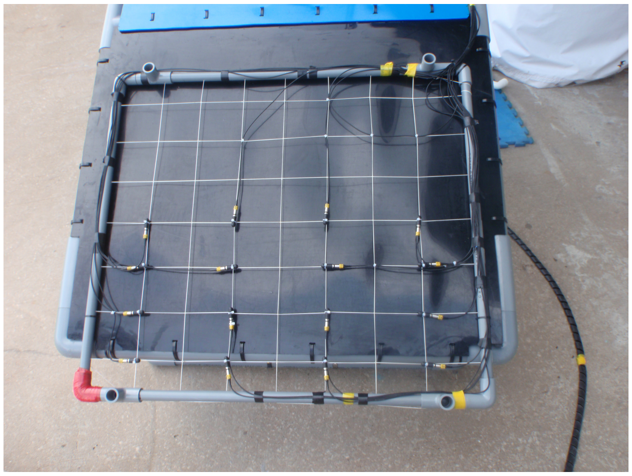


Fig. 4: Photograph of the hydrophone array mounted in front of the anechoic box.

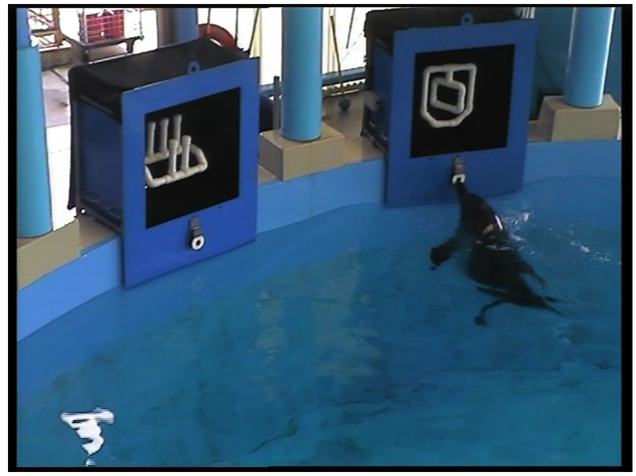


Fig. 5: Ginsan selecting the correct alternative.

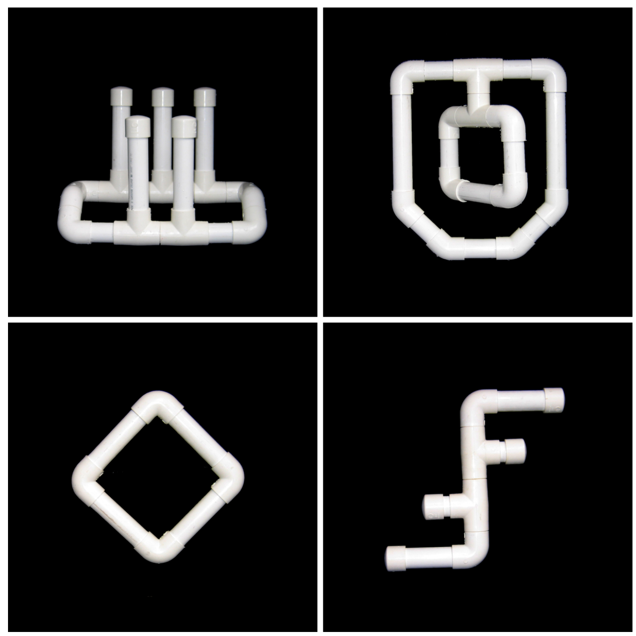


Fig. 6: Photographs of the four objects used for this experiment. Paired objects are in rows.

was embedded in a custom designed bite-plate. The bite-plate was mounted on a frame that was clipped onto the box that contained the stimulus and extended to a distance of 50 cm in front of the box and a depth of 1.3 m. This frame did not obstruct the dolphin's ability to echolocate on the object. It also guaranteed that the dolphin could only interrogate the stimulus from directly in front of the object and not from any other angle. Furthermore, the dolphin had now control over how long he would echolocate on the object in question. When the bite-plate was released the the bubble stream came back on and thus blocked the dolphins echolocation signal.

Fig. 2 shows a video capture from an underwater camera that was mounted on the tank wall to the left of the dolphin. For the purpose of better illustration we removed the opaque PVC side panel of the box and replaced it with a 5 mm plexiglas. This allowed us to see the object that was placed inside the box as well as the cut-off of the bubble screen and made it easier to synchronize video and acoustic data. The frame that held the bite-plate and other equipment mounted on this side of the pool prevented the dolphin from looking into the box from this side to visually identify the object.

To monitor the dolphin's approach to the bite-plate as well as his final position when he stationed on the plate, a camera was mounted in the ceiling of facility and placed directly over the front of the box. Fig. 3 shows a video capture from this camera. Through this setup we were able to determine if Ginsan was moving while he stationed on the plate and echolocated on the stimulus inside the box.

C. Hydrophone Array Setup

An array of 16 hydrophones (Reson TC4013 miniature reference hydrophones) was built by constructing a frame (87 $\times$ 78 cm) from 16 mm Schedule 80 PVC pipe and fittings. 1 mm fishing line was arranged in the frame in a 10 $\times$10 cm grid that allowed for the exact placement of hydrophones on the grid points. This array frame could then be placed in various desired location for different tests. For the data presented here, the array was placed vertically centered outside the plexiglas and with the frame extending about 8 cm below the box (see Fig. 4). The signals from the array were then fed into two custom made 8-channel amplifiers and then acquired through a National Instruments data acquisition system consisting of a PXIe-1062Q 8-Slot 3U PXI Chassis, a PXIe-8108 Core 2 Dual 2.53 GHz Controller and two NI PXI-6133 32 MS Memory Series Multifunction DAQ Devices. Data was acquired at 500 kSamples per second per channel with a custom written LabView software interface. Recordings lasted normally 20 seconds during a trial and data acquisition was started when the dolphin was about 2 m away from the bite-plate. Thus, each recording started with bubble noise first, then the actual echolocation clicks when the dolphin bit on the

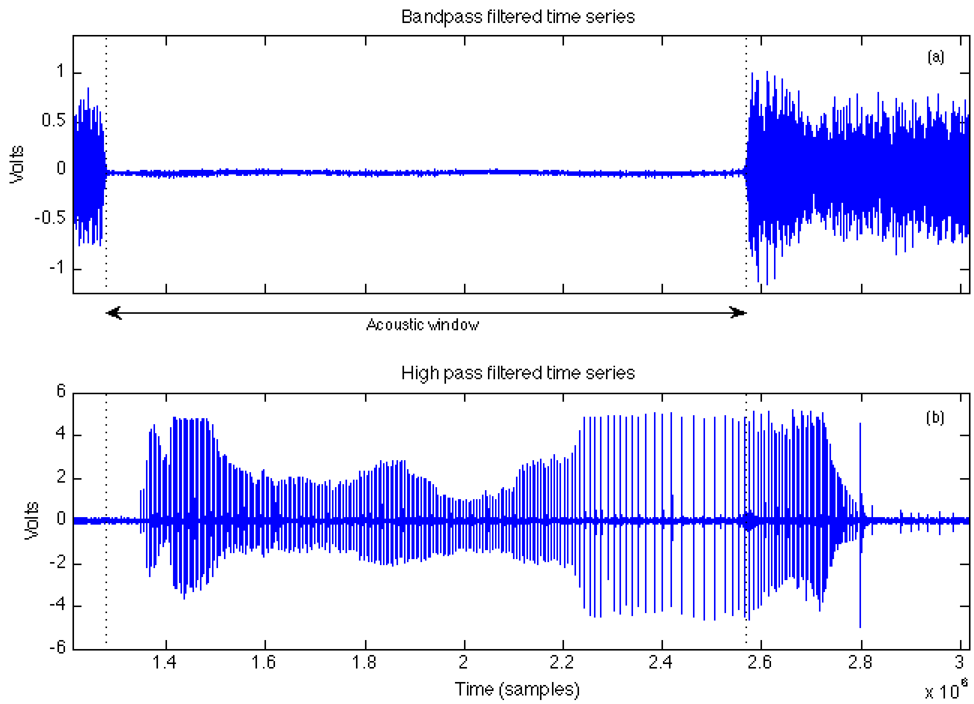


Fig. 7: Panel (a) shows the bandpass filtered bubble noise recorded on a selected hydrophone. The dotted lines de-mark the acoustic window during which the bubbles are turned by the dolphin at the bite-plate. Panel (b) shows the highpass filtered timeseries from the same hydrophone over the same time. The dolphin clicks can clearly be seen as the dolphin interrogates the target.

plate, and then bubble noise again when he released the bite-plate to swim to the other side of the pool to make his choice.

D. Experimental Method

A delayed matching-to-sample procedure was used where the dolphin was exposed to a sample stimulus inside the anechoic box. After the dolphin had interrogated the object acoustically he would then swim to the other side of the pool where two alternatives were presented in air to his visual sense in two separate display boxes (Fig. 5). Ginsan then indicated his choice by pressing a response paddle that mounted on each box. On correct trials he was rewarded with a whistle and fish by his trainer and returned to his station. After a brief interval of about 2-3 minutes in which the stimuli were exchanged the next trial ensued. During this interval the dolphin was in the adjacent pool and the bubble screen was switched on, thus preventing the animal from seeing the objects placed inside the box or prematurely echolocating on the next stimulus.

E. Stimuli

All stimuli (see Fig. 1) were constructed from 32 mm diameter white Schedule 40 PVC pipe and fittings and were equated for reflective surface area within each pair of objects. The objects were air-filled and suspended inside the box through a PVC holder that could be lowered and attached to the rear side of the box. This setup ensured that the objects were always placed in the same location during the experiments. Fig. 6 shows all four PVC objects used in this experiment as they would appear to the visual sense of the dolphin.

III. Acoustic Data Processing

A. Automated Acoustic Window Identification

The acoustic data from the 16 hydrophone channels was synchronously recorded and later analyzed. To automate the processing needed for the analysis, we first had to identify sections of the data when the acoustic window for the dolphin to echolocate on the objects was open. Since the acoustic window is formed by a bubble screen, the noise from the bubbles can clearly be heard on the hydrophones when the window is closed. The bubble noise disappears when the dolphin bites on the bite-plate and the window opens, and then reappears when he releases the bite-plate and the window closes. We identified one of the hydrophones that is close to the source of the bubbles and used the recording from this hydrophone to identify the sections of interest as described next. First, we digitally bandpass filtered the signal to retain the bubble noise that dominates the frequency band from 1–2 kHz using a 512 tap finite impulse response (FIR) filter. We then applied a Hilbert transform to extract the envelope of the filtered signal. Next we convolved the Hilbert transformed signal with a rectangular window of 20 ms as a smoothing filter on the extracted envelope. We then compared the resulting signal with a predetermined threshold to identify sections of the data where the bubble noise is absent. These data for the identified

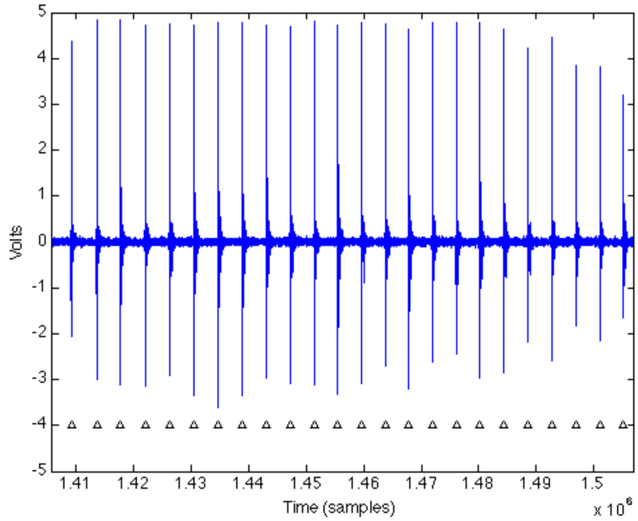


Fig. 8: The output of the click detection algorithm on a sample section of the recorded echolocation clicks while the dolphin interrogates the object.

time sections were extracted for all hydrophones and used in the rest of the analysis. An example of the process is shown in Fig. 7.

B. Filtering and Calibration

The environment presented significant pump and machinery noise at low frequencies. Since the dolphin clicks do not have substantial energy at low frequencies, we digitally highpass filtered all identified data sections before further analysis. A 512 tap FIR filter with a cut-off frequency of 5 kHz was applied to each hydrophone data.

In order to localize the acoustic beam projected by the dolphin, we needed to compare the acoustic power received on different hydrophones. This comparison required that the effective sensitivity of each recorded channel to the dolphin's click is the same. Since there may be small variations in the sensitivity of the hydrophones and the gains of the preamplifiers used, we performed a calibration of the channels by recording the same ambient acoustic noise and measuring the power recorded on all channels. The calibration was repeated four times with small changes in position to check the consistency of the calibration. We were satisfied that the calibration estimates from all the calibration recordings were within 1 dB, and the average calibration was saved for later use. The saved calibration correction was applied to the highpass filtered data from each channel during the analysis.

C. Automated Click Identification

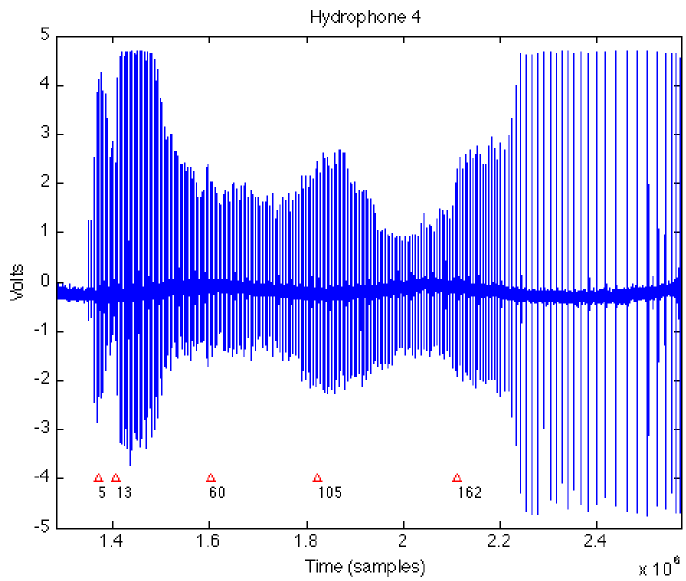
After the acoustic window was identified, the relevant signals were extracted, filtered and calibrated. A click detection algorithm then identified all clicks on a selected reference hydrophone near the center of the array. The clicks were identified by applying a Hilbert transform to the calibrated signal and comparing the output with a threshold. Once a click was detected, a blanking interval of 2 ms ensured that subsequent oscillation or reflections did not cause false alarms. The clicks identified by the detection algorithm on a sample data section are shown in Fig. 8. For each detected click, the search for maximum amplitude was performed within a 1 ms window on each hydrophone. Based on the occurrence of the maximum amplitude, the click time and the click peak-to-peak amplitude was recorded in a database for each hydrophone. The end result of this processing was a database of all clicks with the time of arrival of the click and the peak-to-peak click amplitude at each hydrophone.

D. Beam Estimation

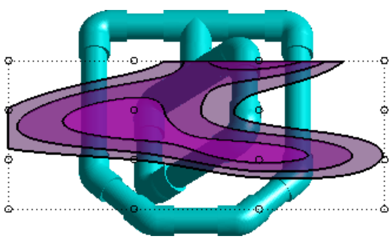
For each click, we have received acoustic intensity estimates at 16 hydrophone locations. Since we know that the dolphin is positioned at the bite-plate when the acoustic window is open, we know the distance of the source from each hydrophone. This distance was used to correct for the spreading loss between the source and the hydrophone. After this correction was applied, a 2-dimensional cubic interpolation filter was applied to estimate the acoustic intensity at grid points spaced at 5 mm in the plane of the array. The high resolution acoustic intensity estimates were then passed to a contouring algorithm to identify the acoustic beam axis and the 1, 2 and 3 dB beam contours representing the area on the hydrophone array that receives the maximum acoustic intensity from the dolphin's echolocation beam for that click. By plotting these contours for each click, we produced acoustic movies of the dolphin interrogating the objects for the entire duration that the acoustic window was open. Some frames from one such movie are seen in Fig. 9 (b)–(f).

IV. Results and Discussion

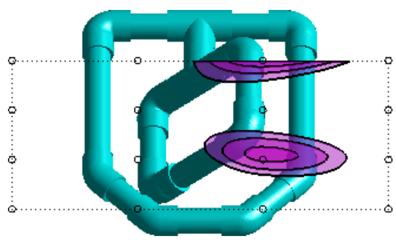
For the data analyzed in this paper Ginsan was correct on 12 out of 14 trials (86 percent correct, $p < 0.01$) which is comparable performance to sessions where no bite-plate was used and the dolphin was able to obtain information from different aspects relatively to the object. The results of the object shown here (Double Loop), is representative of all the objects and was selected because it best demonstrates his beam steering and because this object was best covered through the hydrophone array. The other three object were not completely covered by the hydrophone array and thus if the dolphin would scan some of the top features of these objects the peak intensity would be outside of the range of the array. The acoustic analysis revealed that he was scanning the objects through steering the center of his narrowly focused beam across the object. The information that he gained from beam steering thus must be enough to resolve the shape of the object. Overall all objects analyzed, the dolphin seemed to scan horizontally more then vertically (see Fig. 9) – this could either be an artifact of the hydrophones arrangement on the grid – the spacing along the horizontal axis was 20 cm between hydrophones and the vertical spacing 10 cm – thus recording more of the horizontal scan than the vertical scan. Different grid arrangements for the array in the future rectify this artifact if it was in fact



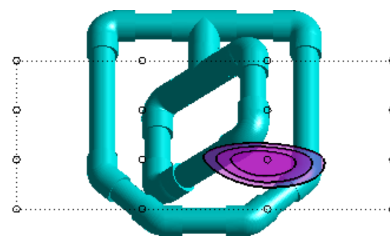
(a) Time series with the position of clicks in panels (b)–(f) marked by triangles



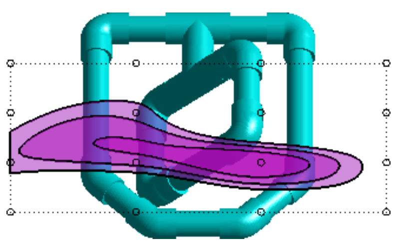
(b) Beam for click 5



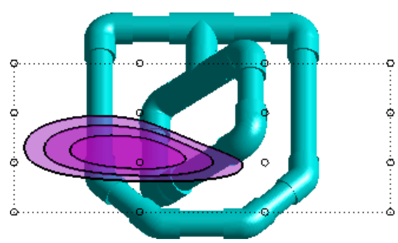
(c) Beam for click 13



(d) Beam for click 60



(e) Beam for click 105



(f) Beam for click 162

Fig. 9: The dolphin uses a train of echolocation clicks while interrogating the DL object. Panel (a) shows the time series of the clicks on the reference hydrophone. Panels (b)–(f) show the estimated beam location for various clicks in the series. The positions of the 16 hydrophones are marked as black circles. The estimated beam is represented by 1, 2 and 3 dB contour lines. The orientation of the object is slightly tilted backwards as the dolphin was positioned *below* the object as seen in the schematic of Fig. 1.

the case. Another possible explantation is that Ginsan used more horizontally distinct features to identify the individual objects – thus scanning across objects horizontally more then vertically.

The analysis also shows that the dolphin was able to control and change the beam width of his echolocation beam as has been previously described for the target detection test [8]. A single simple target will provide only one echo – in this case there is no ghosting problem, whereas a complex object provides multiple reflection points simultaneously when ensonified as a whole. A narrow beam might then provide an advantage as not all different features of the object reflect simultaneously, thus avoiding the previously mentioned problem of click-sensor association and therefore providing the dolphin with a “cleaner” representation of the object. Whether the dolphin was steering a more focused beam across the object only because his movement was restricted by stationing on the bite-plate or whether he would also use beam steering and focusing when his movement was not restricted remains to be explored.

The experiment shows that a synthetic aperture might not be as important to the dolphin to recognize shapes through echolocation and that it is probably one of several features including beam steering that can contribute to a better representation of an object. Beam steering might enable to dolphin to compensate for the loss of the synthetic aperture – at least enough to recognize the object inside the box. In the future we are planning to expand the tests to novel objects that the dolphin has not encountered previously to investigate to which degree familiarity with an object and its features contributes to his performance success in the current experiment. Furthermore we are planning to change the position of the bite-plate to more lateral aspects to investigate its influence on his ability to recognize the objects.

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