Proceedings of the Eighth European Conference
on Underwater Acoustics, 8th ECUA
Edited by S. M. Jesus and O. C. Rodríguez
Carvoeiro, Portugal
12-15 June, 2006

GLIDER TOWED ARRAY TESTS DURING THE MAKAI EXPERIMENT

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Abstract: Increasing interest in autonomous underwater vehicles for oceanography and other naval applications has motivated the development of low-drag and neutrally buoyant towed arrays for gliders and other autonomous vehicles. During the Makai experiment, a 15-element line array with an acoustic aperture of 21 meters was towed by a Webb Research Slocum glider. We will describe the design of this array, the glider deployment and the results of processing the acoustic data recorded on it during the experiment.

1 INTRODUCTION

The use of underwater gliders in the ocean presents intriguing possibilities for a variety of applications. In this paper, we present the results of deploying a low-drag, neutrally-buoyant towed array from a Webb Research Slocum glider off the coast of Kauai in Hawaii, during the Makai experiment in September 2005. Section 2 will describe the array sensor design and its recording system. Section 3 will describe the glider and how it is deployed. Section 4 will describe the deployment during the Makai experiment and present processing results.

2 SENSOR AND ARRAY DESIGN

SPAWAR (Space and Naval Warfare Systems Center) has been developing ultra-lightweight and low-power sensor systems for fifteen years for use in fixed deployable systems [1]. In the last three years, they have turned their attention to arrays that can be towed by small mobile platforms such as gliders, AUVs, and autonomous surface vehicles.

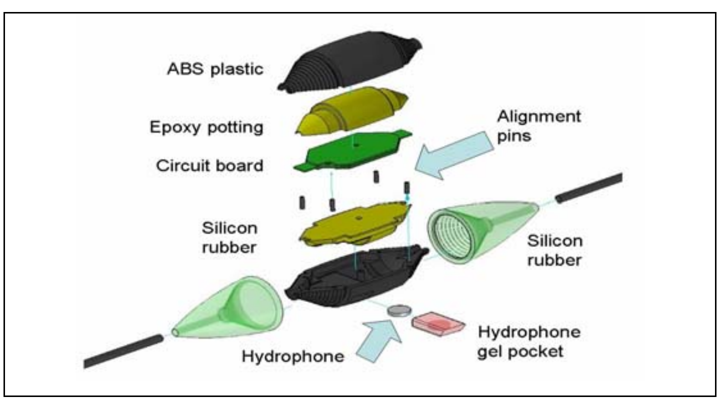

Fig. 1. Anatomy of a single array element.

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Figure 1 (above) shows the design that has evolved. The signal from the hydrophone is filtered and digitized at the element using the electronics on a small circuit board (shown in green), which is attached to the cable at both of its ends, encased in plastic and potted with epoxy (to fill all voids). The pressure sensor is a piezoelectric ceramic hydrophone (shown in its pink gel pocket), which is inserted into a slot in the plastic and wired to the circuit board, before also being potted with polyurethane gel (so that it is not in contact with any of the rigid surfaces). This assembly is then put in a mold and encased in silicon rubber to form an external shape that is streamlined and minimizes drag. Figure 2 (below) shows the stages in which a single array element is constructed.

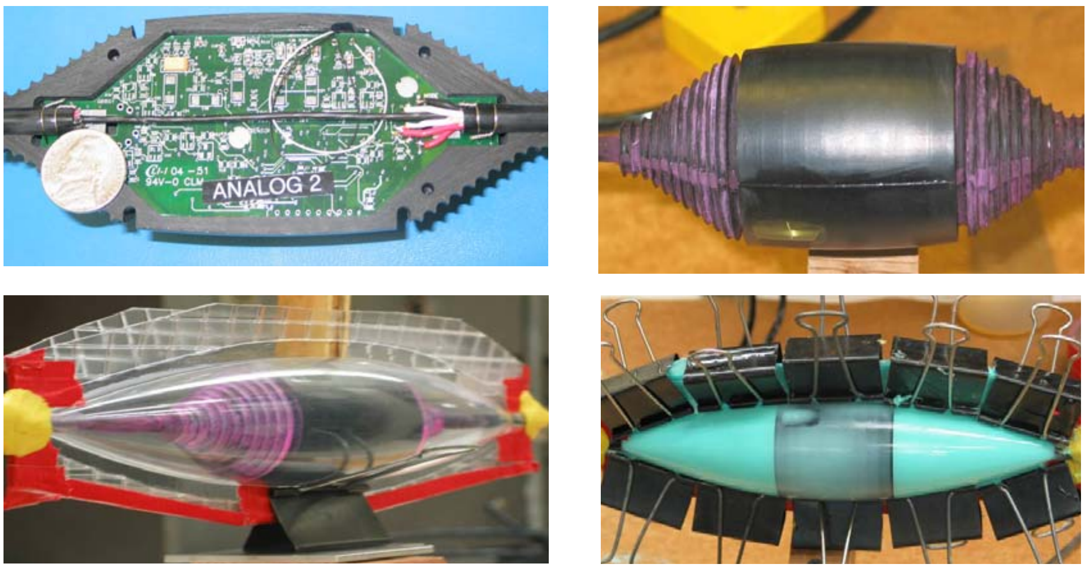

Fig. 2. Array element construction.

The total array length is 33 meters, with an acoustic aperture of 23 meters, with 15 elements spaced at 1.5 meter intervals (roughly half-wavelength at 500 Hertz). The cable consists of a single strength member and four conductors (power, ground, signal, and clock) that use a digital telemetry scheme based on time division multiplexing. The cable is exceptionally thin with a diameter of only 3 mm. Small floats are attached to the cable to distribute the buoyancy evenly along the entire array. As a result, the array weighs 4.5 kg in air and is neutrally buoyant in water. Although the amount of drag this array adds to the glider is already exceptionally small, the design can be further improved by making the array elements smaller by distributing the electronics over several smaller sized circuit boards (this is more expensive to build and to test).

The data is recorded at the glider payload by capturing the digital data with a Field Programmable Gate Array that streams it directly to a USB drive (a 3 GB FLASH drive). The sample rate of the electronics is 1562.5 Hz with a dynamic range of 16 bits. There are three depth sensors along the array for reconstructing the array tilt.

Both the streamlined array elements and the extremely thin cable result in an overall drag of 2 ounces at a tow speed of .5 knots. The array and its electronics, including the recording system, consume only 1.92 watts of power.

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3 GLIDER OPERATIONS

In this section, we will describe the glider deployment. The Webb Research Slocum glider [2] is 1.5 m long, has a diameter of 21 cm, and weighs 52 kg. It carries a 5 litre payload of weight 4 kg. The model used in the Makai experiment was the Coastal Glider, which can be operated to a depth of 200 meters, and (using alkaline batteries) can be deployed for periods up to 30 days over ranges of 800 nm (1481 km). The Slocum is driven by its buoyancy, which it controls by changing its volume. It has a GPS unit, a compass, and an altimeter. It is programmed either from a laptop using a cable (prior to launch), by line-of-sight RF link, or via an Iridium satellite link. A mission program consists of a heading (the glider reads its compass and uses a tail rudder to adjust its course), a dive profile (the two depths it must stay between, using its altimeter), and a mission duration (how long to operate before surfacing).

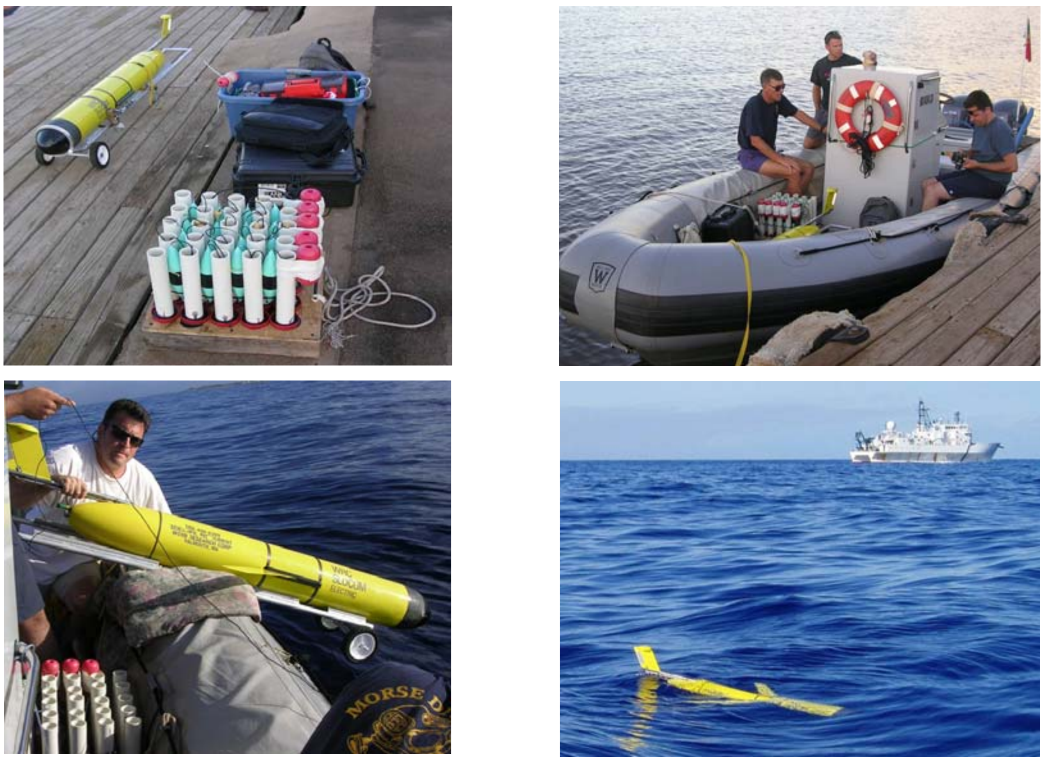

Fig. 3. Deploying the glider.

The upper panels of Figure 3 shows the glider, the array (stored in the "Hedgehog" unit), and the laptop used for communications with the glider, about to go to sea in a Rigid Hull Inflatable Boat (RHIB). The array is deployed by extracting one element at a time from the "Hedgehog" assembly of chutes and easing them into the water. Once the entire array is in the water, the glider is released from its trolley as shown in the lower left panel. The lower right panel shows the glider, afloat in the water, waiting for the command to start its mission (via RF). The Kilo Moana research vessel, where the (not so intrepid) signal processing crew was comfortably situated throughout the operation, tows the acoustic source in the background.

4 MAKAI EXPERIMENT

The Makai experiment was a collaboration of many research institutions [3] to study a variety of topics in high-frequency acoustics.

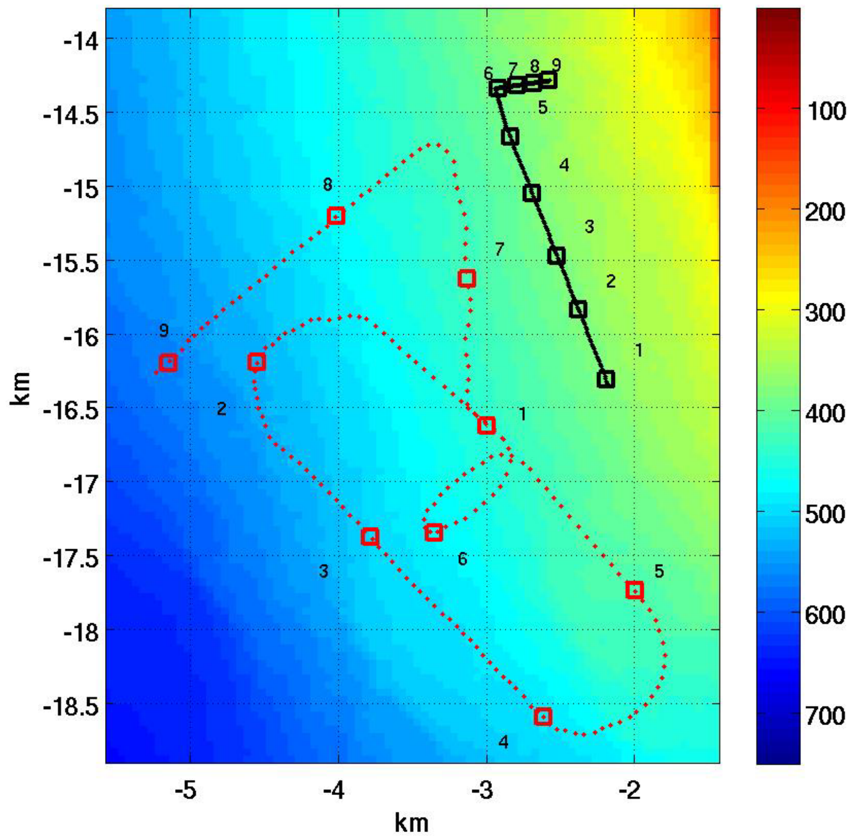

Fig. 4. Research vessel Kilo Moana (red) and glider GPS tracks (black) over bathymetry (in meters), with numbered waypoints corresponding to mission end-points and glider dive peaks.

Figure 4 shows the geometry for the glider towed array operations on 28 September 2005 during the Makai experiment. The island of Kauai (of the Hawaiian Islands) is several km to the east. The race track pattern, shown in red, was reconstructed from the GPS readings on the research vessel Kilo Moana (KM), from which the towed source was deployed. The glider positions, shown in black in the upper right hand corner, were reconstructed by interpolating between the GPS readings the glider made at the end points of its two missions. Each numbered square along the KM track matches a corresponding square along the glider track to indicate the locations of the two platforms throughout the experiment. Each numbered square also indicates either the start of a mission or the end of a dive (when the glider has returned to its closest approach to the surface, before diving again). The glider was programmed to stay between 30 and 120 meters in depth.

Figure 4 reveals some interesting aspects of operating gliders. The current measurements on the KM's ADCP were .2 knots to the northeast near the surface, negligible from 40-80 m, and unknown below 80 m [5]. As a result, we do not have independent current measurements for much of the glider's 30 to 120 meter dive profile. For the first mission (points 1 to 5), the glider was programmed to maintain a heading of 315 degrees (clockwise from north). The glider completed four dives during this mission, with high points at points 2, 3, 4 and 5. The currents increased the glider's velocity over ground from .4 to .62 knots (calculated from time and distance travelled) and forced it to follow a more northerly course. After making four dives, the glider surfaced and drifted on the surface from point 5 to 6, allowing it to be programmed for its second mission via RF link. It would have been unnecessarily risky to recover the glider just to orient it toward its programmed heading, especially with the array in the water. For the second mission (points 6 to 9), the glider was programmed to maintain a heading of 135 degrees (clockwise from north). The glider completed three dives during this mission with high points at points 7, 8, and 9. This time, the north-easterly currents kept the glider from making hardly any progress over ground.

The glider measures its own heading using its compass and uses its tail rudder to maintain its programmed heading. The glider cannot measure its progress relative to ground, unless it surfaces and gets a GPS reading (this was not done except at the endpoints of our two missions). At point 1, the glider is not necessarily pointed in its programmed heading, prior to its dive. At point 6, the glider is still pointed toward the northwest (as can be seen from the acoustic bearings), which is almost directly opposite its programmed heading of 135 degrees for mission 2. As a result, when it was commanded (via RF) to start its dive at the start of each mission, the glider not only had to dive but also to turn toward its programmed heading. As the acoustic data will show below, the array does not stay straight during these turns.

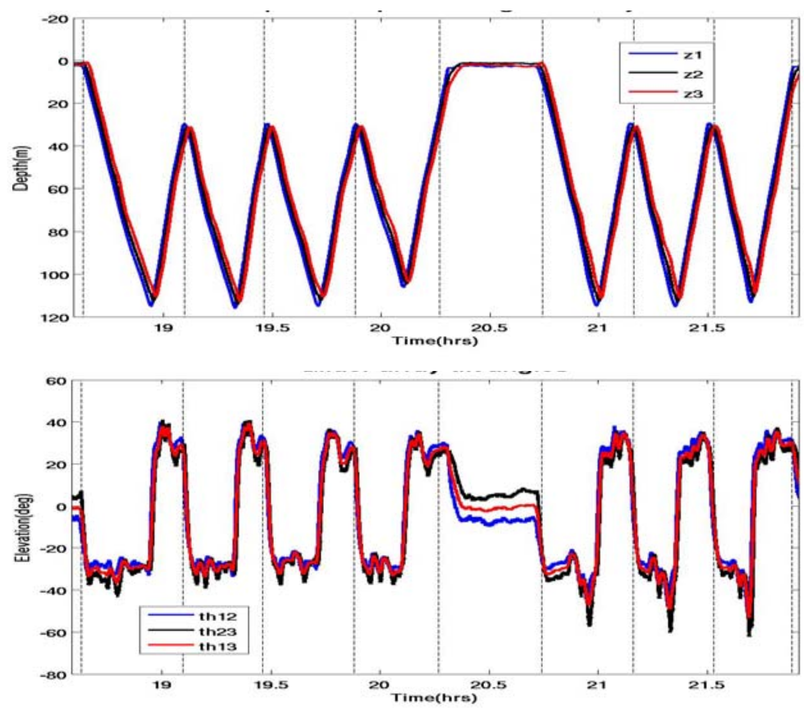

Fig. 5. Three depth loggers were attached to the array (front, middle, and tail). The upper plot shows the three depths over both missions. The lower plot shows array tilts calculated using three combinations of depth loggers (1:2, 2:3, and 1:3). The dashed vertical lines show mission end-points and dive peaks.

We will show three sets of measurements, GPS, depth loggers, and acoustic data, recorded on the towed array, which all had to be aligned in time in order to reconstruct what the glider and the array were doing throughout the experiment. Figures 5, 6, and 8 show a series of vertical dashed lines. These correspond to the waypoints shown in Fig. 4 (when the glider was at the start or end of a mission or at its closest point to the surface before diving again).

Depth loggers were attached at the front (z1), middle (z2) and end (z3) of the array. The depths measured by these three sensors are shown in the upper panel of Figure 5. The front of the array makes the earlier and sharper turns at the top and bottom of the dive profile. The array tilt between pairs of depth loggers was calculated from the ratio of the depth difference to the known length along the array between each of the three pairs of depth loggers (i.e. for depth sensors z1/z2, z2/z3 and z1/z3), producing the three curves in the lower panel of Figure 5. The angles for the two half-arrays (th12 and th23) coincide with the angle for the entire array (th13), indicating that the array was fairly straight most of the time. Comparing the upper and lower panels of Figure 5, we see that when the glider was on the surface (waiting to start its next mission), the array was not straight. Indeed, video recordings of the array near the surface indicate that the cable bows up between elements, held up by the distributed floats, and that the array does not stretch out in a line until the glider starts to move through the water. The array was also not straight during the initial dives in each mission, as the glider was turning toward its programmed heading and causing the array to lose its shape. The acoustic bearing tracks corroborate this.

The Kilo Moana was used to tow a Lubell Labs LL-1424HP underwater speaker [4] at a depth of 20 meters, transmitting pre-programmed alternating 1-minute intervals of LFM chirps and tones. The first minute contained six 5-second chirps sweeping from 100 to 500 Hz and repeated every 10 seconds (5-second gap between LFM chirps). The second minute contained a set of 5 tones (150, 221, 293, 351, and 445 Hz) played simultaneously for the entire 60 seconds. We will show the results of processing these transmissions using narrowband (phase-shift steered beamformer) and broadband processes (matched filter and time-domain beamformer).

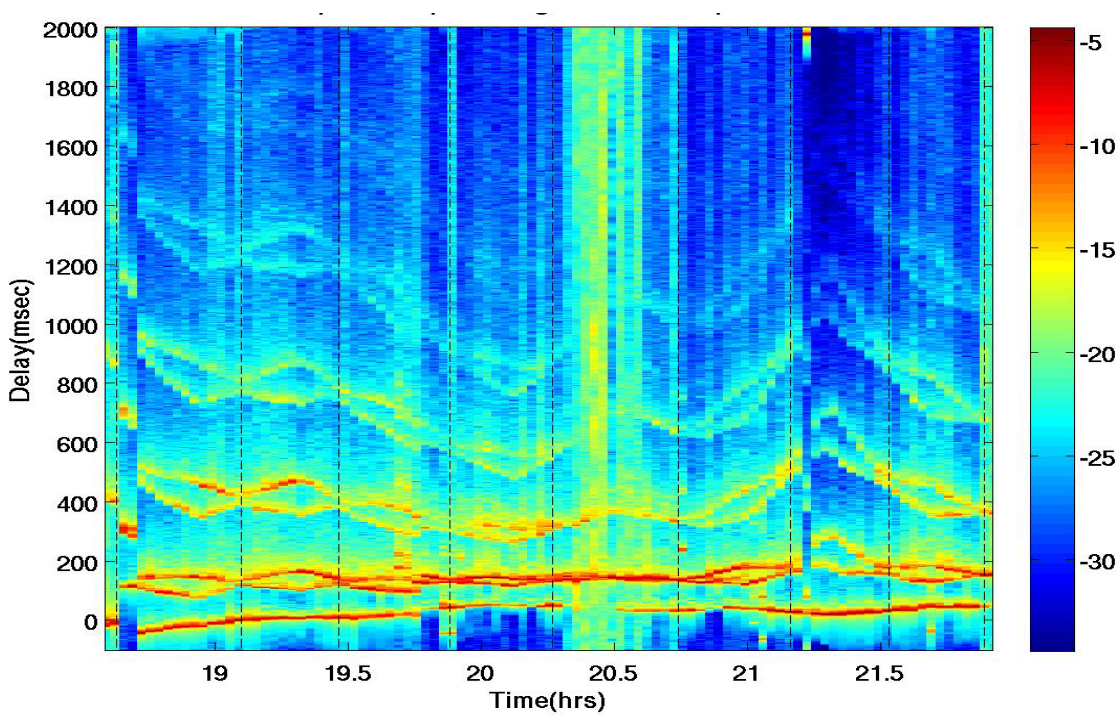

Fig. 6. Impulse response functions measured on the first element throughout the experiment. Arrival time is along the vertical axis (in ms) and geo or "slow" time is along the horizontal axis (in hours GMT).

Figure 6 shows the time-evolving impulse response function (i.e. multipath arrival pattern) from the KM towed source to the first element of the glider-towed array. The vertical axis, in milliseconds, shows the arrival time. The horizontal axis shows geographic ("slow") time in GMT hours throughout the two glider missions. Each column of this image contains the averaged envelope of the matched filter output corresponding to a set of six 5-second LFM chirps. The columns were aligned using column to column correlation, after a coarse initial alignment based on the known repetition interval of the chirp packets (every minute).

This plot shows a remarkably detailed structure. We clearly see five sets of arrivals throughout the entire operation. This picture shows a very distinct broadband multipath arrival pattern that we believe can be used to estimate the range and depth of a source [6]. After the first arrival (roughly at zero along the vertical axis), each set consists of two arrivals (a "doublet"). Each "doublet" opens as the glider moves away from the surface and closes as the glider returns to the surface. The vertical lines were manually selected from this plot to correspond to the times when the glider is closest to the surface. These times were lined up with the depth logger times at which the array was closest to the surface. Figure 5 shows that the two sets of times are very consistent.

Figure 6 also shows the closest point of approach (CPA), which is easily identified as the time at which the entire set of doublets has expanded the most. This follows from the fact that the differences in arrival times reach their peak when the source is closest to the receiver, because it is then that the range has least influence on the overall acoustic path distances. The CPA is between the 7th and 8th vertical lines, at roughly 21.25 hours. This is how the acoustic data timeline was lined up with the GPS tracks.

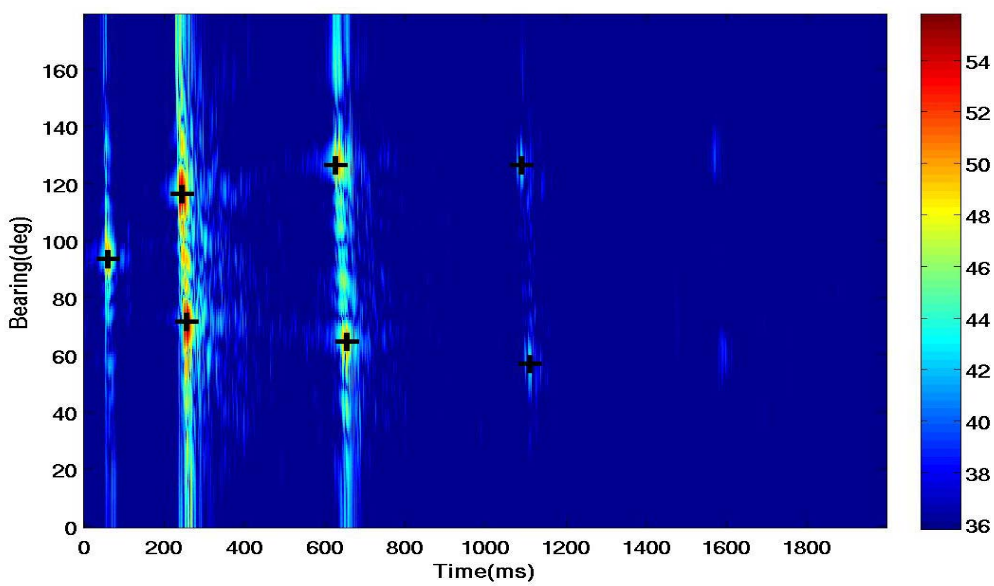

Fig. 7. Space-time structure of multipath arrivals for single LFM chirp (right panel), with conical angle on vertical axis and time of arrival along horizontal axis.

Figure 7 shows the result of applying a time-domain beamformer to a single chirp recorded on the entire 15-element array. The vertical axis shows the conical angle relative to the axis of the array (presumed straight). The horizontal axis shows arrival time in milliseconds. We clearly see the space-time structure of the multipath arrival pattern, with each "doublet" now seen to consist of an arrival from the surface and an arrival from the bottom. This space-time structure is a function of the relative geometry of the source and receiver, as well as the array orientation and tilt in the water.

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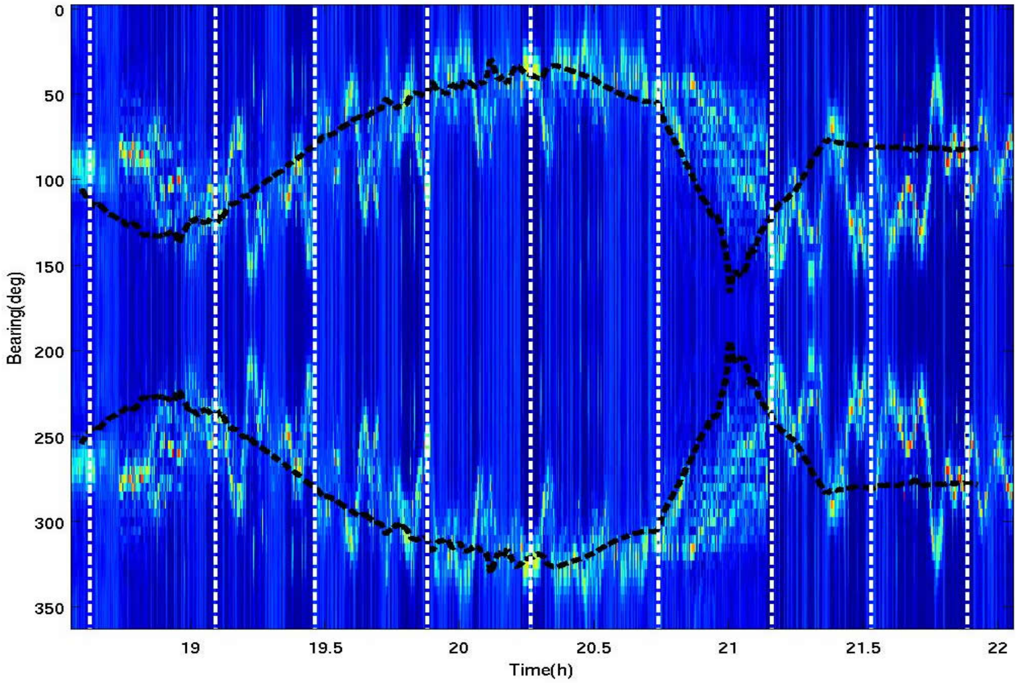

Fig. 8. Bearing time record over entire mission with an overlay of the true bearing calculated from the known GPS positions and the array tilt do to the glider following a saw tooth dive profile.

Figure 8 shows a bearing-time record of the entire dataset (beam outputs were averaged over the 100-500 Hz band). The white dashed vertical lines correspond to the waypoints shown in Figures 4, 5 and 6. The black dashed line was calculated from the GPS tracks, the programmed heading of the glider (which sets the array orientation), and the array tilt (as calculated from the depth loggers). In reconstructing the geometry, we assumed the array maintained a straight line shape behind the glider with an orientation parallel to the glider's programmed heading, regardless of the glider's progress over ground. This assumption seems justified by the bearing tracks in the first mission (vertical lines 1 to 5), but less clearly so for the second mission when the glider was facing into the current (vertical lines 6 to 9).

There are two tracks due to the left-right ambiguity of the line array. The bearing tracks during the first dive of each mission break up and do not match the predicted track (between vertical lines 1 and 2 for mission 1 and vertical lines 6 and 7 for mission 2). This is because the glider is making a turn toward its programmed heading during these dives and pulls the array after it, causing the array to lose its shape. The predicted track in the last quarter of hour 20 (between lines 6 and 7) does not match the measured track because: 1) we turned the glider the wrong way in our reconstruction (to the right instead of left), and 2) an inverse sine function is incorrectly switching quadrants (the track does not cross 180 degrees, as it should). Although the measured bearings match up very well on average with the predicted tracks throughout the first mission, they also swing up to 40 degrees above and below the predicted bearing track. The predicted track already accounts for the array tilt, so there must be another explanation for these bearing swings. Currently, we speculate these bearing swings are the result of the glider adjusting its heading. We are hoping that the compass readings and the rudder control commands from the mission file will explain this.

5 CONCLUSIONS

We have successfully deployed a glider towing a light-weight and low-drag array and have successfully demonstrated several beamforming processes on the acoustic data recorded on the glider-towed array. The data shown in Figs. 6 and 7 seems to support more advanced model-based algorithms that can yield a range and depth solution.

6 ACKNOWLEDGMENTS

The authors gratefully acknowledge support from the In-House Applied Research Program at SPAWAR Systems Center in San Diego. SSC's Unmanned Maritime Vehicle (UMV) glider team (Brian Granger, Lonnie Hamme, Medorian Gheorgiu, and Chris Mailey) assisted with array integration and operated the glider during test and evaluation. Matt Palanza (Webb Research Corp.) served as the on-site technical advisor for glider operations via an Office of Naval Research (ONR) Small Business Innovative Research contract. Dave Johnson of ONR provided the glider and helped fund the development of the low-drag towed array. The Makai experiment and subsequent acoustic data processing were sponsored by the ONR Ocean Acoustics program and the ONR PLUSNet program.

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