PASSIVE LOCALISATION WITH A COMPACT ARRAY.

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1 INTRODUCTION

PODtrack is a concept for a compact, easily deployable, receiving array for Passive Acoustic Monitoring (PAM), along with some novel localisation algorithms allowing enhanced detection and range and bearing estimation with a small array. The long term aim is that the array and algorithms should eventually be incorporated in a fully autonomous PAM buoy that will be hand-deployable from a small boat. A companion paper in these proceedings [1] demonstrates the potential requirement for such systems, which represent an intermediary between the relatively poor performance of single hydrophone systems [2,3] and the logistical complexity of larger systems such as towed arrays [4,5], distributed sonobuoys [6] or arrays of bottom-mounted sensors [7,8].

The angular localization algorithm was described previously [9], and this paper introduces a modification to the algorithm that potentially reduces computational load, then presents the results from a sea trial which demonstrate the ability to detect and localise dolphin whistles under adverse conditions.

2 MODIFIED CARDIOID BEAMFORMING

The azimuth localisation procedure described in [9] was based on rotating a cardioid directivity pattern to find a minimum in the signal level – a technique used in Radio Direction Finding (RDF) [10]. This relied on a conventional beamforming operation with complex weights to generate a cardioid pattern repeated at a sequence of null-steering steps through a complete 360°. This process proved effective in simulations, but is computationally expensive and limited in bandwidth. An alternative has been developed that requires a reduced level of computation.

2.1 DOUBLETS

The outputs from two hydrophone sensors, separated by a distance d, may be combined as a ‘doublet’, shown schematically in Figure 1 and defined as follows:

$$D(V_1,V_2,\tau) = V_1 - \frac{V_2}{e^{i\omega\tau}} \tag{1}$$

where V_1 and V_2 are the two inputs, $\omega = 2\pi f$ where f is frequency, and τ is a time delay. Effectively V_2, delayed by time τ, is subtracted from V_1. This will have the effect of cancelling signals from directions where V_1 and the delayed version of V_2 are in phase. The directivity pattern, $D(\theta)$, is approximated by the formula:

$$D(\theta) = \omega\tau\left(1 - \frac{d}{c\tau}\cos\theta\right) \tag{2}$$

where θ is the azimuth bearing.

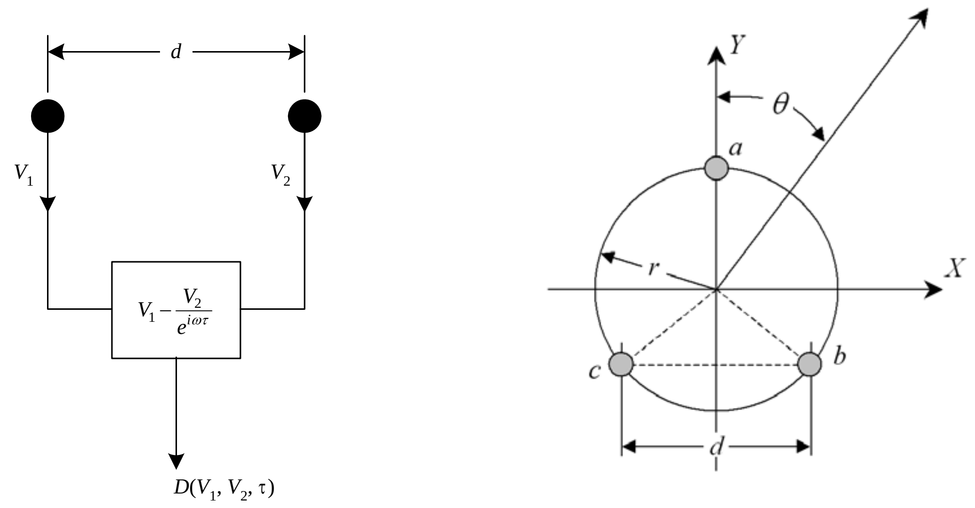

Figure 1: Doublet processing principle (left) and triplet geometry (right)

This results in a range of patterns, depending on the value of τ, from a dipole to a cardioid with all variations in between, as shown on the left in Figure 2. Nulls occur in directions where $\tau = (d/c)\cos\theta$. Note that, except for the cardioid case, nulls are symmetrical about the line joining the sensors, so null steering with a single doublet would result in ambiguous angular localization.

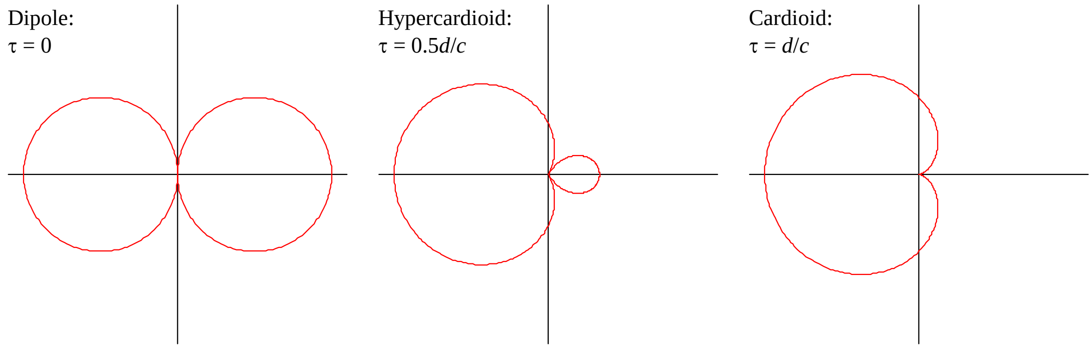

Figure 2: Range of directivity patterns obtainable from a doublet.

However, it can be seen on the right of Figure 1 that three doublets are available with a triplet hydrophone geometry – *ab*, *bc* and *ac*. These may be combined to produce a cardioid-like pattern with a single, steerable null. An example of three cardioid patterns with nulls steered to 45° and the outcome of combining these patterns by adding the output magnitudes and normalising the result is shown in Figure 3.

The combination pattern looks superficially like a cardioid pattern, but has a much sharper null. Widths of the nulls of both patterns in degrees are listed in Table 1 measured at -10, -20 and -30dB relative to the peak level. This reduced null width is likely to make azimuth localization more precise than possible with a rotating cardioid.

	Null Width deg	
Level dB	Cardioid	Combination
-10	135	74
-20	74	26
-30	42	8

Table 1: Null width for conventional cardioid compared with doublet combination at levels of 10, 20 and 30 dB below maximum.

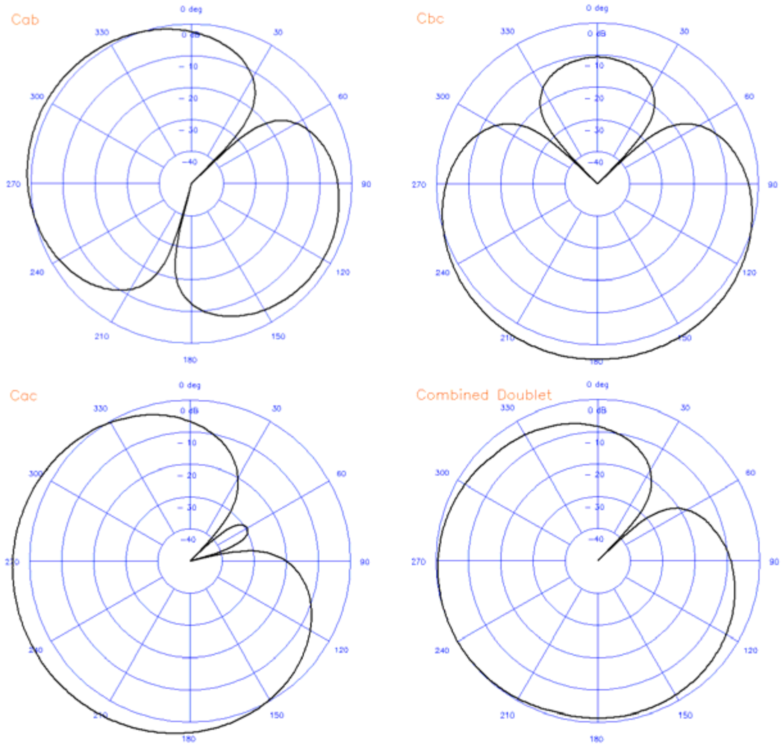

Figure 3: Cardioid patterns produced by doublets *ab*, *bc* and *ac*, and combination pattern (bottom right).

The computation involved in this process is potentially much less than the conventional beamforming considered previously in [9]. The delay and subtract process expressed in Equation (1) must be implemented for each of the three doublets and then the magnitudes added. The delay can be implemented as a simple FIR filter, although an analogue implementation is also feasible.

3 THE HARDWARE

3.1 THE ARRAY

The outline array design was described in [9], and the prototype was built at Florida State University. The basic array geometry as outlined in [9] is shown schematically in Figure 4 and the essential parameters are listed in Table 2.

Figure 4: Sketch of array geometry

Parameter	Value
Depth h	0.86m
Spacing d	0.04m
Radius r	0.05m

Table 2: Array design parameters

A photograph of the prototype array is shown in Figure 5, where it can be seen that the horizontal array comprises a plastic disc with the hydrophones, arranged as a triplet, mounted in holes cut in the disc. This disc is then mounted on the central rod. The Vertical Line Array (VLA) comprises five separate plastic blocks mounted on the central rod, with the hydrophones mounted in holes. The width of the blocks is 0.04m, so the hydrophones are correctly spaced when the blocks are touching. The plastic used for the construction is Acetron GP, an acetal copolymer thermoplastic similar to nylon with a density and sound speed close to that of sea water.

Figure 5: PODtrack prototype array

The hydrophones are model H1a from Aquarian Audio Products. Their response is flat over the 20Hz to 4kHz range, then rolls off at 6dB/octave up to 60kHz where it stabilizes at ~-220dB re 1V/μPa, so sensitivity at 20kHz is approximately –204dB re 1V/μPa. This was considered acceptable for the detection and localisation algorithms, but if problems were encountered, equalization could have been included in the signal conditioning unit.

3.2 SIGNAL CONDITIONING

A signal conditioning unit was built to provide amplification of signals to the level required for data acquisition, filtering, with a charge amplifier input to match the characteristics of the hydrophone. A total gain of 1000 (60dB) was chosen so that a dolphin whistle one metre from the hydrophone, with a source level of 140dB re 1μPa at 1m gives an output of about 3V rms or 9V pk-pk, just below the clipping level of the data acquisition unit.

Data acquisition was carried out using a National Instruments M-Series USB-6251 DAQ device with a BNC-2110 connection box that provides BNC connections for up to eight differential inputs, several analogue outputs and various other connections.

If the ambient noise level for calm conditions is assumed to be 40 dB re 1μPaHz-1, with a 20kHz bandwidth, the signal-free pre-amplifier output is about 4mV rms or 70dB below full scale input on the ±10V range. The dynamic range of a 16 bit ADC is about 80dB, so under quiet conditions the pre-amplifier output is just above the quantization noise floor.

A Labview application, DAQ Recorder V2.11, provided by Loughborough University, UK, was used to control the DAQ unit and record the data. This application has two main screens, the options screen and the main display screen, shown in Figure 6. The options screen controls input parameters such as DAQ unit channels to be recorded, sampling rate and voltage range, output parameters such as file location and length of files, and display parameters such as FFT window type. The main display screen shows the waveform, spectrum and spectrogram for a single selectable channel. There are additional screens showing spectra and waveforms for all channels simultaneously.

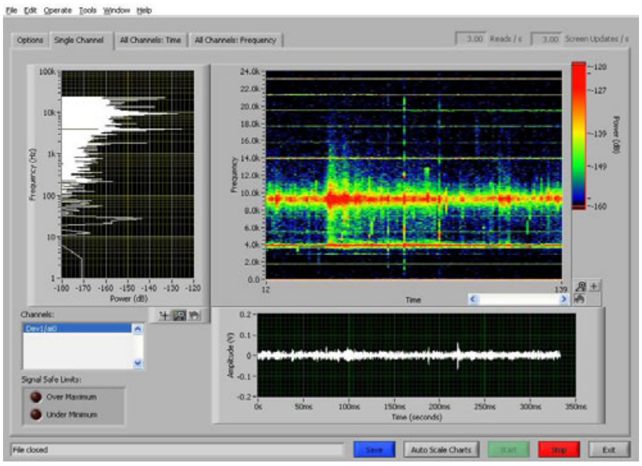

Figure 6: DAQ Recorder main display screen

Data are recorded in multi-channel WAV files, readable by most sound editing and manipulation applications. A sampling rate of 48kHz has been used for most recordings related to this project. Associated with each data file is a log file giving DAQ unit settings, date and time and other information.

4 THE SEA TRIAL

It was originally intended to trial the prototype array at the Florida State University (FSU) Coastal and Marine Lab, on the coast about 40 miles south of Tallahassee, Florida, but it turned out more convenient to do this at the Duke University Marine Lab (DUML) in Beaufort, North Carolina. The waterways around the lab location are shallow and sheltered, similarly to those around the FSU Marine Lab, and there is a normally a large population of Atlantic bottlenose dolphins (*tursiops truncatus*) in the area. It is noted that dolphins were seen a number of times close to the Marine Lab during the period while the equipment was being set up.

Assembling and testing the equipment started on Friday 18 April 2008. In the late afternoon, between about 15:00 and 18:00 EDT, test recordings were made with the array deployed from the Marine Lab dockside in about 3m water depth. No dolphins were seen during that period, and no whistles have been located in the recording.

It was planned to take the array out in on of the Marine Lab's Carolina Skiffs on Sunday 20th. However, a major storm broke early that morning and persisted for the remainder of our stay. Although there were calm periods, the local weather radar confirmed that storms were always in the area, and it was not considered safe to take a small boat out to sea.

By the afternoon of Tuesday 22 April, the plan to take the array out to sea was abandoned, but it was deployed from the dockside again and a continuous recording made for about four hours. Again, no dolphins were seen during this period, but a number of short groups of faint whistles were detected in the summed output from the vertical line array.

The background noise is very high in these recordings, consisting mainly of snapping shrimp, fish, mechanical noise from the dock, propeller noise from passing boats and, frequently, heavy rain. These whistles could neither be heard nor seen in any form of waveform or spectral display from the output of a single hydrophone channel. They could, just, be heard and seen in a spectrogram from the beamformed output of the VLA, confirming the advantage of the additional 7dB gain of a five-element array.

This is demonstrated in Figure 7 where, on the left, a spectrogram for a ten second period of the output from a single hydrophone shows no sign of dolphin whistles. On the right, however, a spectrogram for the same period of the output from the beamformed VLA shows a number of faint but clear whistles.

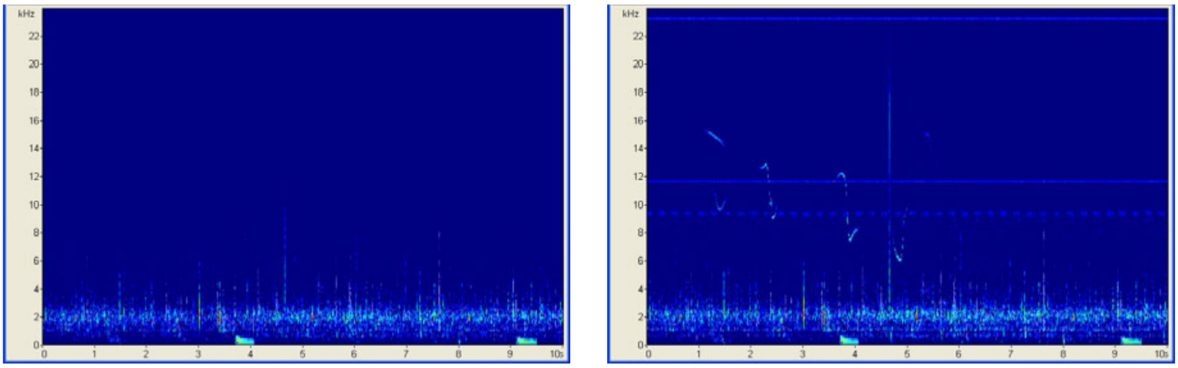

Figure 7: Spectrogram from a single hydrophone channel (left) and from the beamformed VLA output (right).

Having located the whistles, a number were used as matched filter kernels to search the entire data set for similar whistles in the beamformer output. One of these successfully found a sequence of nine similar whistles at intervals of ten to twenty seconds. Given a series of similar whistles over a short time period, it is reasonable to suppose that they were signature whistles from a single dolphin.

The horizontal array hydrophone channel outputs for this period were then passed through the matched filter with this kernel and, although not visible in the raw data, the whistles were all detected in each channel. The matched filter output was then passed to the azimuth localisation algorithm.

Figure 8 shows the bearings obtained plotted on a chart of the area around the Duke Marine Lab, and Table 3 lists the bearings and the difference between them.

Bearing	Difference
17.5	
31.325	13.825
51.381	20.056
71.169	19.788
85.145	13.976
107.653	22.508
131.43	23.777
151.802	20.372
166.771	14.969

Table 3: Estimated whistle bearings

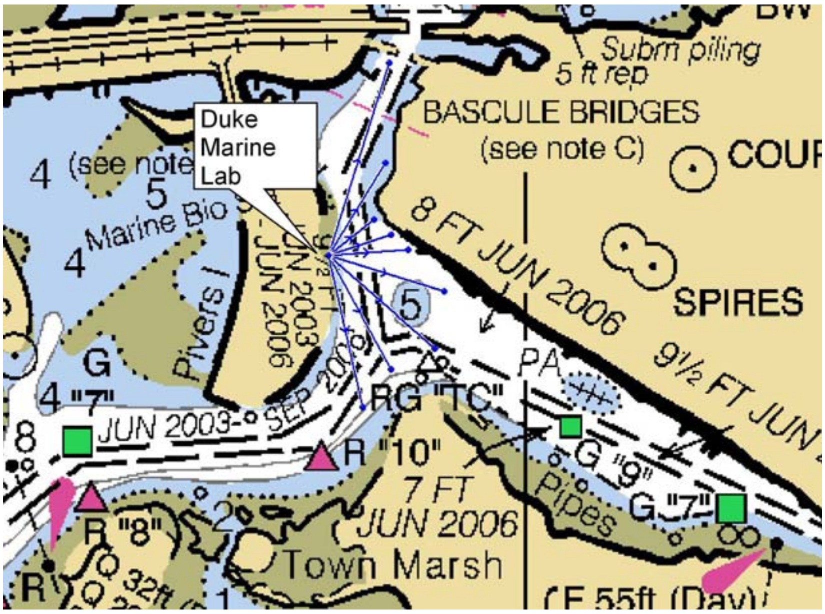

Figure 8: Area around the Duke Marine Lab with whistle bearings superimposed.

5 DISCUSSION AND CONCLUSIONS

The bearings obtained increase monotonically from 17.5° to 166.8°, with a mean step size of 18.7°. Looking at the chart, this is consistent with a dolphin travelling from the direction of the Bascule Bridges and more or less following the marked navigation channel, then swing to the West at the Southern end of Pivers Island. It is noted that dolphins had been observed following this route on the Saturday before the storm began.

The minimum width of the channel between Pivers Island and the mainland, just opposite the Marine Lab, is 100 m, so the dolphin was probably travelling about 50 m from the shore of Pivers Island. The rms noise level on a single hydrophone channel was typically 136 dB re 1μPa, and the maximum Source Level of a dolphin whistle is in the order of 140 dB re 1μPa @ 1m. Assuming cylindrical spreading in such shallow water, propagation loss would be about 17 dB, making the signal to noise ratio about -17 dB. This is entirely consistent with the whistle not being visibly in a single channel spectrogram, but just emerging in the beamformed output.

The mean time interval between whistles was 13.7 seconds, and at a distance of 50 m, a mean angular step of 18.7° is equivalent to a distance travelled of 16.9 m, representing a mean velocity of 1.24 ms^{-1} or 2.48 kt and, again, this is entirely consistent with a dolphin cruising slowly.

The dolphin was not observed, so its position was never known and the accuracy of the bearing estimates cannot be confirmed. However, the bearings increase monotonically, never overlapping, so if it is assumed the dolphin travelled at more or less constant velocity, the resolution of the localization must be less than the step between bearings. The minimum step was 13.8°.

In conclusion, although the data obtained from this trial was of very poor quality (although it is noted that this is usually the nature of PAM signals), the bearings obtained were entirely consistent with a possible dolphin track and indicated a resolution on the order of ±10°.

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