Calibration of sonobuoy compass via arrival time inversion

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Abstract -**Onboard magnetic compasses allow sonobuoys to measure their orientation and form beams along true headings. Compass failure means true array heading is unknown and the buoy's beams cannot be used for target localization and tracking. We describe a method for recovering buoy orientation by inverting the pattern of signal arrivals at the individual hydrophones, and present results using data recorded at sea.**

I. NATURE OF THE PROBLEM

Sonobuoys that use a planar array of hydrophones can form horizontal receive beams to estimate target direction. But since the buoys may be slowly drifting and spinning in the ocean, their orientation must be measured for these beams to have geographic meaning to the user. This orientation is typically measured by an onboard magnetic compass. In the Littoral Warfare Advanced Demonstration (LWAD) 98-2 exercise, one of the buoys used in the exercise was later discovered to have had an unreliable compass, meaning that the data it had collected were difficult to interpret if processed by conventional means.

In this exercise, the sonobuoys were used to detect impulsive echoes reflecting from a target submarine. Since the impulse pulse arrives at slightly different times at each hydrophone, depending on each phone's distance from the pulse, the array's orientation is revealed by the pattern of the arrival times at each hydrophone, as shown in Fig. 1. However, this was complicated by the fact that the source was of sufficient strength that its arrival pulse saturated the buoy's hydrophones, causing clipping, as Fig. 2 illustrates. Section II details the approach we used to estimate the buoy's orientation from the direct blast arrival, while Section III shows the results.

II. APPROACH

We used two methods to estimate the direct blast's time of arrival at the individual hydrophones, and then compared this set of actual arrival times to the arrival times predicted over a range of hypothesized azimuths. The hypothesized azimuth with the lowest cumulative squared error between predicted time and actual time was then selected as the estimated buoy azimuth.

The first arrival time estimation approach was to detect the start of hydrophone clipping, as illustrated in Fig. 2. While this is a clear indicator of pulse arrival, the onset of clipping was not always clearly defined, as Fig. 3 shows, meaning accurate arrival time estimates were difficult to obtain.

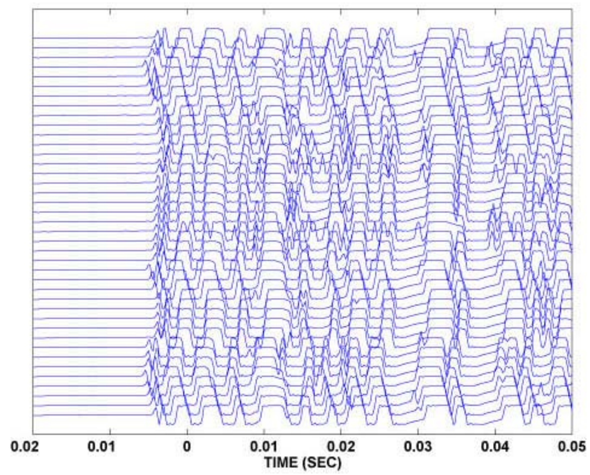

Fig. 1. Multiple hydrophone time series: individual hydrophones receive similar signals at slightly different times.

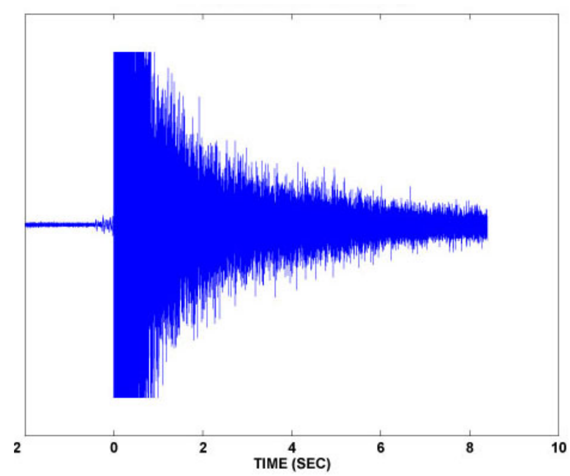

Fig. 2. Hydrophone time series: individual hydrophone time series, showing clipping due to impulse pulse arrival.

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Accordingly, we made the azimuth inversion algorithm more robust by disregarding estimated arrival times that were too far from the arrival times for the rest of the array's phones. Even so, occasionally this method resulted in poor estimates of buoy azimuth. Fig. 4 shows the cumulative squared error between the actual arrival time and the arrival time predicted for a range of hypothesized azimuths. This error has been normalized so that the maximum error equals one. The correlation method (described below) produced a smooth curve with a clear minimum. In contrast, the clipping method yielded an error curve in which the azimuth with the minimum error is not much better a match than the worst azimuth. In addition, in this example—with the buoy's magnetic compass working properly and true orientation known—the clipping method gave a significant azimuth estimate error.

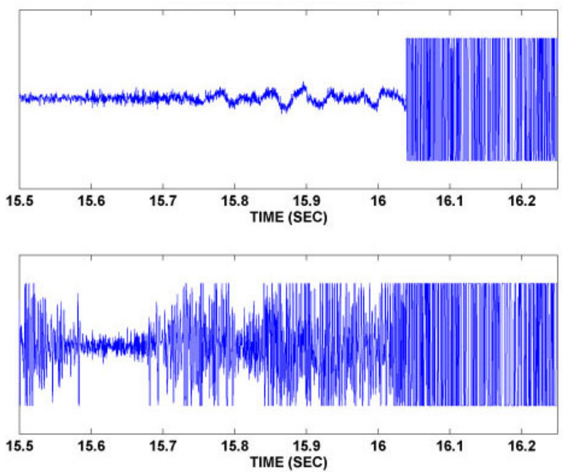

Fig. 3. Hydrophone time series: onset of clipping is not always clearly defined.

The second method of arrival time estimation used cross correlation between short segments of hydrophone timeseries. By finding the peak in the cross correlation function between hydrophone 1 and every other element, as shown in Fig. 5, we estimated the lag time between the pulse's arrival at hydrophone 1 and the other phones. This pattern of inter-element arrival times was then compared—as before—with the predicted element arrival times for a range of hypothesized azimuths. On the whole, as shown in Fig. 4, this resulted in more reliable azimuth estimates, although there were examples were the clipping method proved more accurate, as in Fig. 6. Accordingly, we compute the azimuth estimate with both methods and choose the estimate with the lowest normalized error.

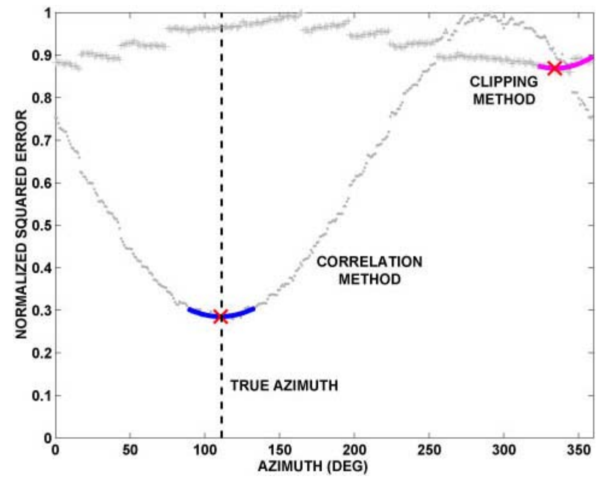

Fig. 4. Cumulative squared error: clipping method fails to show a clear minimum in cumulative squared error.

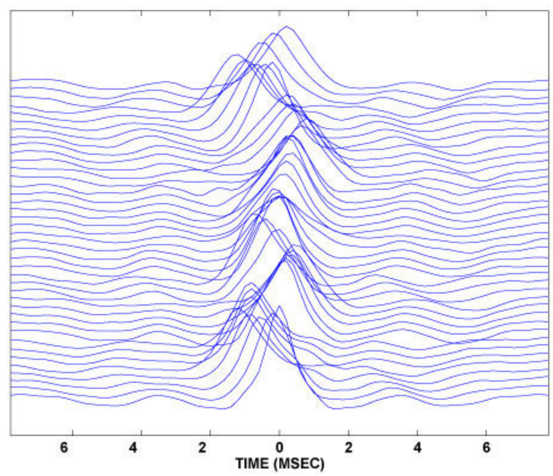

Fig. 5. Correlation function: peaks in cross correlation function reveals differences in pulse arrival times.

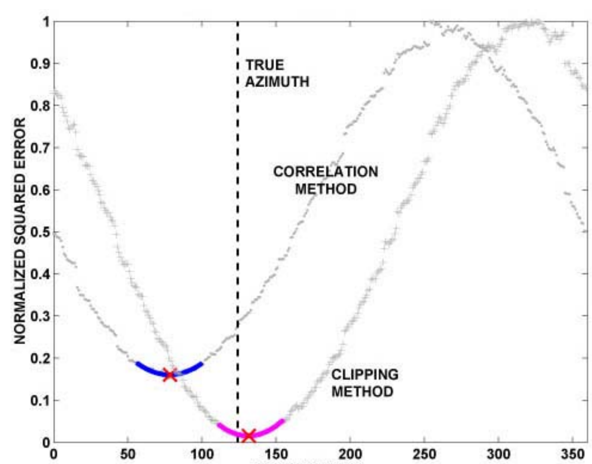

Fig. 6. Cumulative squared error: clipping method produces lower error than correlation method.

III. RESULTS

We see generally good agreement between the estimated azimuths and measured azimuths (from a buoy with an operating magnetic compass), as shown in Fig. 7, although a clear bias in the estimates is apparent. This is most likely because the source and receiver were not collocated with their deployment ships (where GPS positions were recorded), but were up to 1 km away. This causes an error in computing the blast arrival angle at the buoy and therefore an error in estimating receiver azimuth.

While this inversion technique seems to be a useful way to recover buoy orientation if the azimuth of the impulsive arrival is known, the lack of exact knowledge of the buoy and source positions represents a fundamental limit of estimation accuracy.

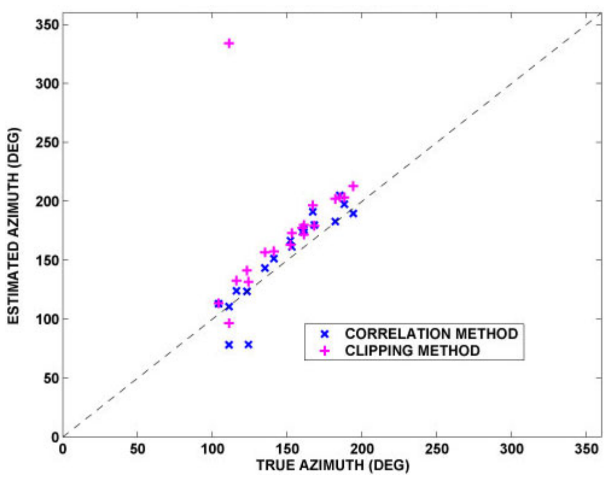

Fig. 7. Estimated azimuths are biased:
scatterplot reveals bias in azimuth estimates.