ON CLICKING SOUNDS IN UK WATER AND A PRELIMINARY STUDY OF THEIR POSSIBLE BIOLOGICAL ORIGIN

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1 INTRODUCTION

Many methods exist for assessing bio-diversity in a given underwater location, including visual observation by divers, bottom sample collection, and passive acoustical studies. A plan was developed to observe acoustically waters in which clicking could be heard. Passive acoustic observations are particularly non-invasive, straight-forward to perform (in that a human does not need to be deployed into the water to collect data), and so are ideally adapted to bio-distribution observations especially where the acoustic environment is dominated by biogenic noise

In 2001, a hydrophone was fixed off the coast of the Durlston Marine Reserve under 7 m of water [1] so that researchers and centre visitors could observe sounds within the local waters. When listening to the output of this hydrophone, audible clicking sounds were noted to be usually present. The clicking sound observed at Durlston Marine Reserve and was reported by Wareham[1] and Harland to the remaining authors of this paper. It was observed that the bandwidth of a single transient, one click, in a recording was generally in excess of the maximum observable frequency of 20 kHz, and that the duration of these clicks ranged from a few milliseconds to a few tens of milliseconds. Subjectively, the signal can be described as being not unlike the sound of food frying, and very similar to the noise observed in waters which have been colonised by snapping shrimp [2], a type of crustacean animal well-known to colonise in tropical, and some sub-tropical, waters. The usual assumption is that UK waters are too cold to support these species as discussed below.

Knowlton and Moulton [3] reported that specimens of snapping shrimp collected in the Bahamas kept in glass aquaria survived well as long as the water temperature remained between 14 ^{o}C and 24 ^{o}C. However, they also reported that the 11 ^{o}C winter sea-surface isothermal line seemed to mark the approximate northern and southern limits of the range in which snapping shrimp live. Johnson *et al.* [4] point out that the 11 ^{o}C isothermal line of the time passed some 7^{o} latitude (almost 800 km) South of southernmost England [5]. However there is some historical evidence of snapping shrimp in UK waters. Johnson *et al*. [4] acknowledged in 1947 the “not uncommon” presence of a European species of shrimp, *Crangon Ruber*, off the Ram's Head near Plymouth, England, disagreeing with biological guides to the region. According to Hayward and Ryland’s 1990 key to marine fauna for UK waters, all *Alpheidae* are listed as “scarce” or “very scarce” [6] around the UK.

The Marine Biological Association maintains an online Marine Life Information Network (MarLIN) for Britain and Ireland. That website for that network states that *Alpheus glaber* is distributed off the Southwest and West coasts of England, and off the east, south, and west coasts of Ireland. This species has also been recorded off the west coast of the Isle of Man, with numerous records in the Celtic Sea, and a record off Sellafield in the east Irish Sea.

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[1] Durlston Marine Reserve, Dorset UK

Biological sources are not the only candidate mechanism for this ambient noise source; physical mechanisms, such as electrical- or weather-related sources, must be considered. However these alternatives have been dismissed as less likely for the following reasons. The noise has been repeatably recorded and ambient clicking has been observed, without exception, in every location surveyed along the approximately 125 mile stretch of shore reaching from Falmouth, Cornwall in the West to Havant, Hampshire in the East. Those investigations employed a variety of different sensors and recording equipment and are described in more detail by Finfer [7] and Finfer *et al.* [8]. This repeatability rules out an artifact or electrical interference as a potential source of the noise. Observations suggest that the noise does not increase with sea state, so is unlikely to be surface generated or weather related. Indeed the recordings analysed in this paper were made in unusually calm conditions but constitute one of the clearest examples of this ambient noise source we have obtained.

In the absence of a candidate physical mechanism for the noise source the most likely source remains a biological one. Over 1000 species of fish are known to produce sounds [9], some of which are classified as “clicking” [10] and “knocking” –type sounds [11]. However the sounds of interest in this paper have been recorded in clear and shallow water when no obvious large fauna were visible. There remains a possibility that a species of small fish is the source.

A further possible biological source for the noise are molluscs [12], in particular it is noted that some of our previous recordings are made near known mussel beds.

This paper describes in detail the work performed in documenting the snapping sound at Kimmeridge Bay with the goal of providing evidence regarding the physical distribution of sources of this noise in the water column. Since shrimp predominantly dwell on the seafloor, evidence that the noise arises from that region would provide evidence in favour of snapping shrimp being the source of the noise, but would certainly not constitute unambiguous proof, since, for example, mussels occupy similar locations.

2 KIMMERIDGE BAY

Kimmeridge Bay (50° 35’ 29” N, 02° 03’ 56”) is on the Southern Coast of England, in Dorset, between Poole and Weymouth, see Figure 1. In July 2006, clicking sounds were recorded off Kimmeridge Bay from a sailing vessel using a four-element array on a calm day, sea state 1.

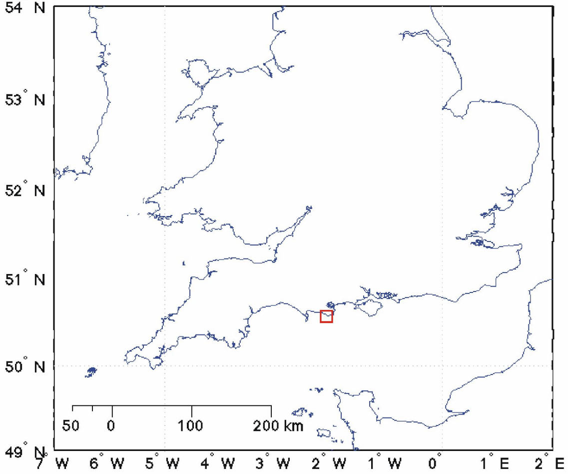

Figure 1. A map of the Southern United Kingdom, Kimmeridge marked by the red square. Mapping data US National Geophysical Data Center (NGDC) [13].

To reduce flow noise over the array, the boat was allowed to drift during measurements. The water depth during measurements reported here was between approximately 5 and 7 m, the array was suspended such that the lowest sensor was 4.5 m below the sea surface. Drift currents, swell (~0.5 m) and variable bathymetry resulted in variations in the height of the hydrophone above the sea-floor during each measurement period. As the acoustic depth-finder was turned off during measurements, so detailed information regarding the water depth as a function of time is unavailable, the quoted depths represent values measured before and after recordings were made.

The array geometry, shown in Figure 2, a compact was designed for ease of transport and deployment. The acoustic elements used were low-cost transducers manufactured by Aquarian Audio Products (model AQ-9). These hydrophones, while not precise, are useful for surveys of this type in that they are rugged, low-power (battery operated) and are self-contained. Data acquisition was performed using a personal computer; synchronously sampling each channel at a rate of 44.1 kHz using the Capture16 software package (http://www.maritime-acoustics.co.uk/).

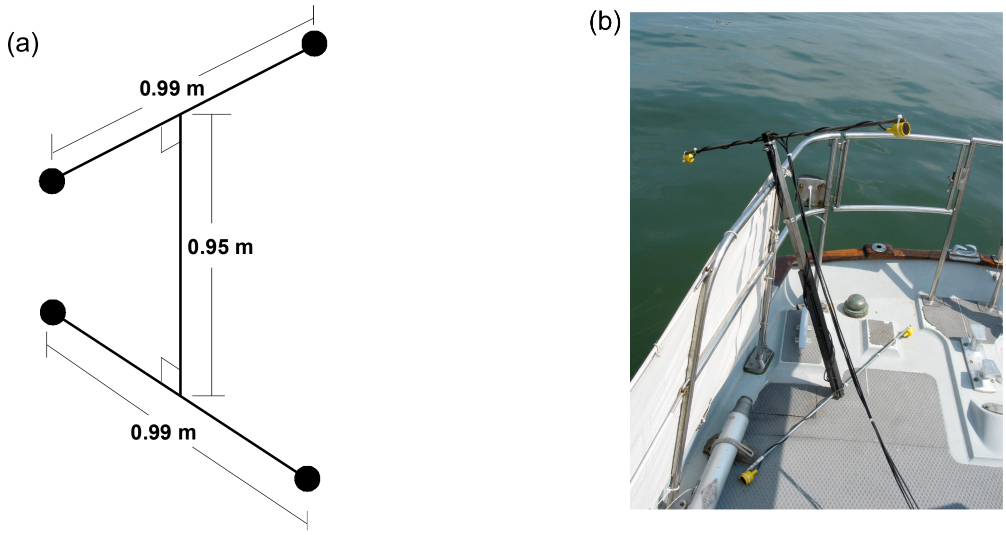

Figure 2. A diagram showing the dimensions of the hydrophone array used for data acquisition
(a) Sketch of the array showing dimensions, with acoustic elements represented by circles.
(b) Photograph showing the array resting on a stern rail; the acoustic elements are coloured yellow.

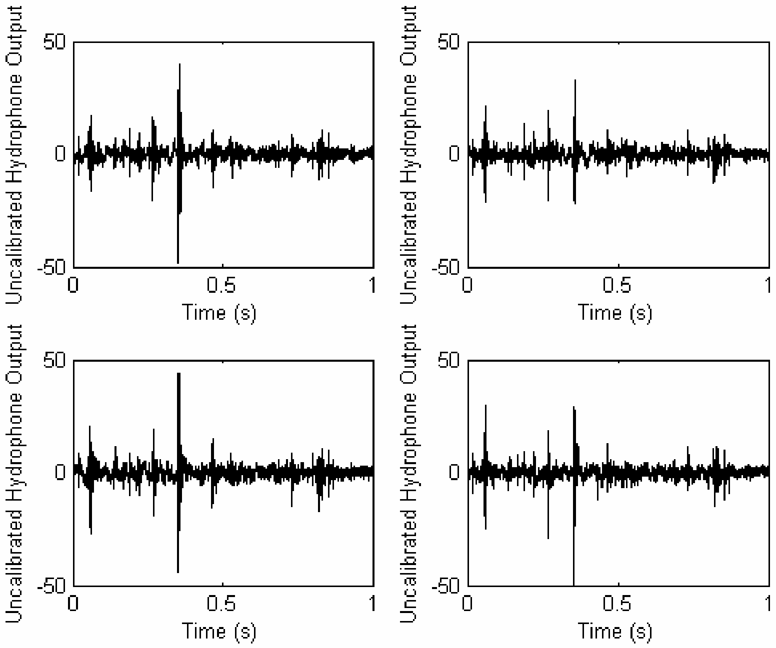

Figure 3. Recorded time series from the hydrophone array. The top 2 frames correspond to data collected on the lower elements in the array; the lower frames show data from the upper elements.

Acoustic signals were recorded for time periods ranging in length from one to six minutes. Source localisation was performed during post-processing based on the measured time delays between channels.

Figure 3 shows a typical 1 second segments from this data set, recorded on the hydrophones in the array shown in Figure 1(a). Note the clear transient occurring at roughly 0.35 s, which is evident in all 4 recordings.

The calm conditions (sea state 1) meant that strong reflections from the sea-surface were observed regularly. Figure 4 shows the strong pulse in Figure 3 on an expanded time axis. The expanded figure reveals that the signal consists of two impulses. By cross-correlating these two signals, it can be shown that the second impulse is approximately a copy of the first impulse but reversed in polarity. This is strongly indicative of the second pulse being a surface reflection of the first. Assuming a sound speed of 1470 m s^{-1}, the 5.7 ms delays corresponds to a path length difference of 8.4 m, which is consistent with the array depth of 4.5 m.

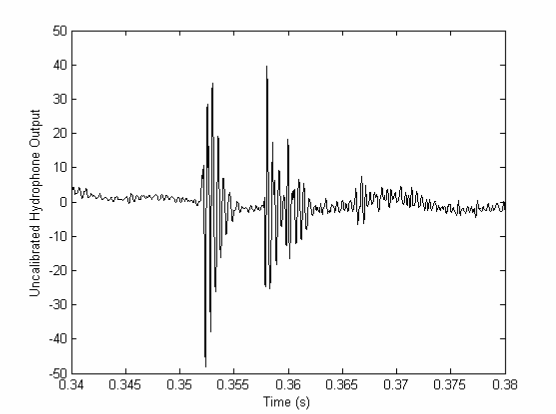

Figure 4. Expanded version of pulse seen in Figure 3.

3 SOURCE LOCALISATION

In order to test the hypothesis that the clicking sound emanates from shrimp colonies, we seek to determine whether the sound radiates from the sea-bottom, where shrimp predominantly reside. To that end, the data collected using the array was processed as described here.

The source location procedure is based on Time Differences Of Arrival (TDOA). According to this method the delays between transients received on each of the sensors are estimated. This information can be used to infer the source location, assuming that sufficient sensors are available [14]. For localisation in three dimensions an array with a minimum of 4 elements (such as the array used for this investigation) is required. Such a configuration does not possess any redundancy, adding to the ill-conditioning of the problem. Furthermore, the use of 4 sensors does not permit completely unambiguous localisation in three dimensions [14]. Ambiguities do exist as a result of multiple solutions for a limited set of source locations. In the case where multiple solutions exist, the ambiguities are always between a point internal to the array and a point external to it. All the ambiguities can only be completely removed if a fifth sensor is deployed.

The process of source localisation consists of three distinct phases; firstly detecting the individual transients, secondly estimating the time delays between transients and finally the source locations are inferred from the estimated time delays. Source detection is performed using a whitened energy function. A background noise spectrum is estimated for each of the channels using a median operation. The median serves to build-in robustness with respect to transients in the time-series [15]. The mean of these background noise spectra is used to design a single whitening filter which is applied to the data in each channel. The energies of these whitened signals are computed to generate test statistics to which a threshold can be applied before detection decisions are made.

The transients which are detected in all 4 channels within 0.8 ms of each other are assumed to be from the same source. The value 0.8 ms is slightly larger than the maximum delay that is physically realisable between any pair of sensors in the array. The estimation of the delay between sensors is based on a robust variation of the correlation function. Specifically we define the delay to between two channels as

$$m_{pq} = \arg\min \left\{ \sum_{n} \left| x_p(n) - x_q(n-m) \right| \right\} \tag{1}$$

where m_{pq} is the estimated delay between the sampled signals $x_p(n)$ and $x_q(n)$ that represent the data on the p^{th} and q^{th} channels respectively. These delays are collected together in a delay vector $\mathbf{d}$. To see the relationship between (1) and correlation one should recognise that if the function being minimised were the sum of squared errors then the problem would be equivalent to finding the peak in the cross-correlation function. Hence the above minimisation can be regarded as a robust replacement for correlation. Its robustness derives from the fact that using a mean squared error cost function places greater emphasis on large errors than does the method based on (1). Hence outlier points are not so influential in the above formulation. The presence of multi-path and temporally close transients makes the robust formulation beneficial in this application.

The process of estimating the delays remains a challenging issue. The results are manually checked to ensure that the estimated delays can be used to compensate the time series and align the transients.

The final stage of processing is to convert the time delays into estimates of source location. This can be formulated in several ways. The simplest is to use closed form solutions, which are extremely efficient [16]. However, for small arrays, they can fail to provide physically meaningful solutions in the presence of modelling errors. Typical errors derive from inaccuracies in the array dimensions, hydrophone calibration and the assumed sound speed. A more robust method is to adopt an optimisation approach [17]. One can construct a forward model $\Delta(\mathbf{p})$ which predicts the delays observed on the array for a given source position $\mathbf{p}$. Over the short ranges considered herein a simple isospeed model suffices and the model $\Delta(\mathbf{p})$ involves simple geometric operations. The model does require one to assume a sound speed. Direct sound speed measurements were not made during the sea trial. A sound speed of 1470 m s^{-1} was assumed for the purpose of calculations, being a typical sound speed for near surface conditions at these latitudes.

It is sufficient for the localisation scheme to model the delays between a single sensor and each of the remaining sensors, in this case generating 3 delay estimates. Alternatively one can compute all the possible delays between all pairs of sensors. For this experiment, such a technique would yield 6 delays. In principle the set of 6 delays can be reconstructed from the set of 3. That is, theoretically the additional delays proffer no additional information. However, in the presence of noise these additional delays can act as further insurance against the influence of outliers, so we adopt a strategy based on modelling delays between all sensor pairs.

The source location algorithm consists of solving the minimisation problem:

$$\mathbf{p}_s = \arg\min \left\{ \log\left(\left\| \Delta(\mathbf{p}) - \mathbf{d} \right\| \right) \right\} \tag{2}$$

where $\| \ \|$ denotes the Euclidean norm and $\mathbf{p}_s$ is the estimated source location. The logarithm has been introduced into the cost function for practical reasons. In principle the logarithm, being a monotonic function, does not affect the location of the minimum, so the theoretical solution to (2) is not affected by the presence of a logarithm. However the solution for (2) is obtained numerically, and the performance of the numerical routine is dramatically improved with the presence of the logarithm, since it serves to emphasise the low amplitude behaviour of the cost function.

The solutions to (2) are obtained using a Nelder-Meade optimisation routine [18]. This routine is started using 100 random initialisations; the random starting conditions are generated using uniform random numbers generated over the region [-5, 5] independently for each of the 3 coordinates. The final solution is obtained by selecting the solution which has the smallest cost function value from the 100 realisations.

4 RESULTS

Before presenting the results from measured data sets we shall present the results of a simultation study to demonstrate the effects of errors on the estimated source location. The effect of such errors is strongly dependent on the true source location, and so can be difficult to quantify in real data. The approach adopted here is to demonstrate the effect of a single form of error on simulated data. This provides a guide for the size of errors that might be anticipated but is far from an ideal form of error analysis.

Data were simulated using sources randomly distributed over a hypothetical disk of 2 m radius, oriented in the horzitonal plane 1 m below the source (a vertical displacement of -1m in Figure 5.) Data were simulated on the sensors using the forward model to predict the delays. Errors were introduced by rounding these delays so that they represented an integer number of samples assuming a 44.1 kHz sampling rate. The simulated transients were uniformly distributed in time and consisted of 100 sample bursts of Gaussian white noise. Background white noise was added at a SNR of 50 dB. This high SNR was chosen to ensure that the only errors present were those due to the quantization of the delays. The resulting estimates for source location are shown in Figure 5.

From Figure 5 one can observe the sensitivity of this configuration to relatively small errors. This sensitivity dictates that solutions only be sought for the loudest transients, as such events maximise the signal-to-noise ratio (SNR). Such loud events offer benefits in two ways. First, the high SNR helps to ensure that the delay estimates are accurate, a feature which is aided further by the large in bandwidths associated with the loud clicks. Second, if all sources are assumed to have approximately equal sound power, then the received level should vary with distance from the array. This means that louder sounds are more likely to have been emitted by sources near the array. This helps because the proposed methodlogy is better conditioned for sources near the array.

Figure 6 depicts the results obtained from 6 minutes of data in a water depth of approximately 5 m. The vertical co-oridinate is defined so that its origin coincides with the depth of the lowest elements in the array. From this figure one can obsverve that the majority of the transients have an estimated source location below the array. There are 102 transients measured to construct Figure 6 of these 91 (89%) are below the mid-point of the array. Figure 7 shows a histogram of the depths of the source which lie in the range -5 m to 5 m. Our defintion of the vertical co-ordinates implies that negative values are below the array. The majority of the sources (62%) lie at depths between -2.5 m and 0 m, i.e. are below the deepest array elements and above the estimated maximum sea-floor depth during the recording. This suggests that the distribution of the locations of the sound sources is heavily biased towards the region below the array. This observation is consistent with the sound having originated from on or near the sea-floor. The lack of precision in these measurements foregoes the possibility of accurately defining the source locations in this preliminary study.

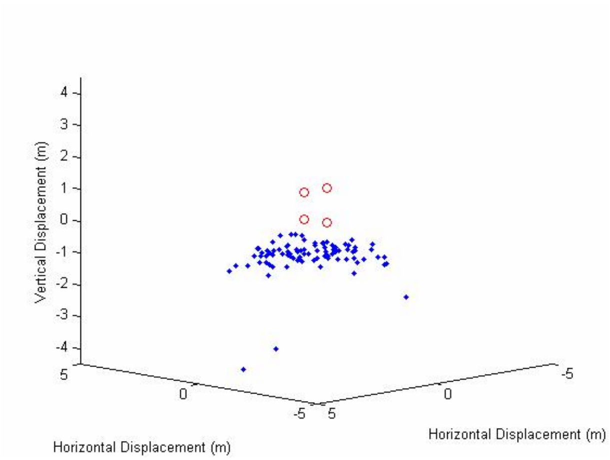

Figure 5. Estimated source locations for synthetic data. Red circles indicate the sensor locations, blue points are the estimated source locations. The sources were originally in a plane with a vertical displacement of -1 m.

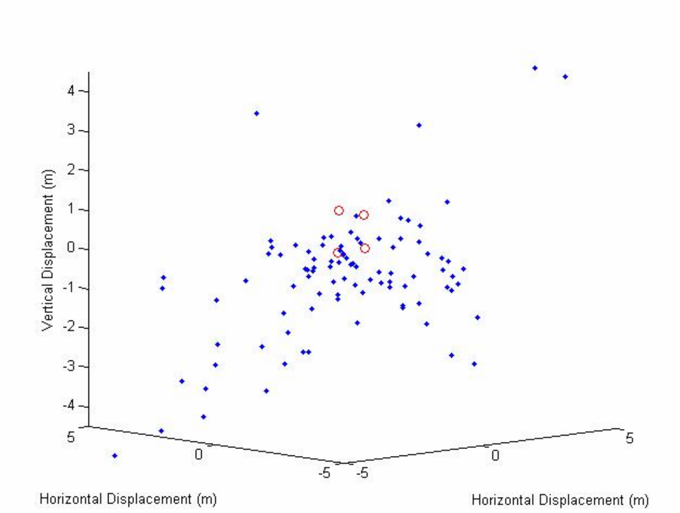

Figure 6. Estimated source locations for measured data. Red circles indicate the sensor locations, blue points are the estimated source locations.

5 CONCLUSIONS

An impulsive contribution to ambient noise in coastal British waters has not been widely reported. Ambient noise, in which this impulsive (clicking) sound clearly evident, was recorded using a four-element array off Kimmeridge Bay, Dorset, and the resulting data was then processed to estimate the locations of the sources generating the clicking sounds constituting the impulsive noise component. We have shown that most of the acoustic transients observed during this study seem to emanate from the sea-floor. This is consistent with the thoery that this noise is generated by snapping shrimp.

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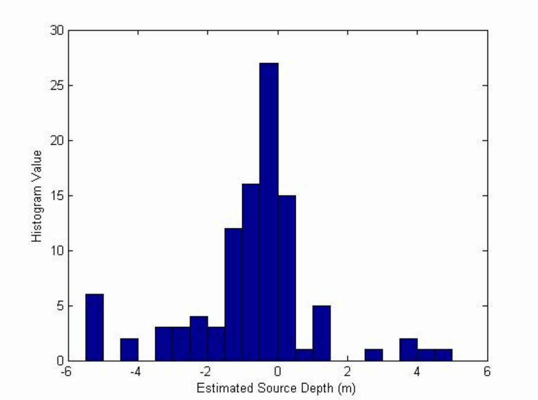

Figure 7. Histogram of estimated source depths. A source depth of 0 m corresponds to the depth of the lowest two elements in the array.

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