UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING AND THE ENVIRONMENT

Institute of Sound and Vibration Research

An investigation of underwater click sounds of biological origin in UK shallow waters

By

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Thesis for the degree of Doctor of Philosophy

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ABSTRACT

FACULTY OF ENGINEERING, SCIENCE AND MATHEMATICS

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AN INVESTIGATION OF UNDERWATER CLICK SOUNDS OF BIOLOGICAL ORIGIN IN UK SHALLOW WATERS

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This study investigated a clicking sound which is often heard when deploying a hydrophone in UK shallow waters. This sound has often been described as being produced by snapping shrimp yet very few snapping shrimp have been found in UK waters. This work has identified the sound of snapping shrimp and shown that a similar sound, while present throughout the year, is not the dominant component of the click field during the summer and autumn.

This work has shown that the click sounds are heard in the southern half of the UK only and that click activity has a strong dependence on the annual and diurnal cycles peaking in late summer and during daylight hours. It has also shown that the click activity is dependent on the bottom type with little activity over uniform sand or mud sea beds.

Three principal types of click have been identified although it is believed that a greater number of different species contribute to the click field. Localisation of the click sources using one, two and four hydrophone arrays has shown that the majority of the clicks are produced above but close to the seabed. There is also more click activity in the deeper channel than in the inter-tidal shallows at the main study site in the Fleet, Dorset. It has also demonstrated very little click activity over the nearby sand flats.

The use of cameras to try and capture pictures of an animal producing the clicks both in the wild and in aquaria and in rock pools has not been successful. This may be due to a number of reasons which are discussed in this report.

Although this work has failed to identify the click-producing species it has provided a much better understanding of the characteristics of the clicking sound and recommendations are made for future work that should lead to an identification of the click-producing species.

Table of Contents

List of Figures

DECLARATION OF AUTHORSHIP

I, Edward John Harland

declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

An investigation of underwater click sounds of biological origin in UK shallow waters

I confirm that:

- This work was done wholly or mostly while in candidature for a research degree at this University;
- Where any part of this thesis has previously been submitted for a degree, or any other qualification at this University or any other institution, this has been clearly stated
- Where I have consulted the published work of others this is always clearly attributed;
- Where I have quoted from the work of others the source is always given. With the exception of such quotations this is entirely my own work:
- I have acknowledged all main sources of help;
- Where the thesis is based on the work done by myself jointly with others I have made clear exactly what was done by others and what I contributed myself;
- None of this work has been published before submission.

Signed:

Date: 28th February 2017

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Acronyms and Abbreviations

Anon	Anonymous
BC1	BiClick 1 acoustic collection equipment
BC2	BiClick 2 acoustic collection equipment
BHRS	Black Hut Research Station
CBFNR	Chesil Beach and the Fleet Nature Reserve
CBVC	Chesil Beach Visitors Centre, Ferrybridge, Dorset
CI	Confidence Interval. The range of possible values that give a particular confidence that it contains the population mean value.
CMMP	Chesil Multi-Media project
DOSITS	The Discovery Of Sound In The Sea. A web site operated by the University of Rhode Island with funding from the US Office of Naval Research
ISHMAEL	Integrated System for Holistic Multi-channel Acoustic Exploration and Localisation. A software package from CIMRS Bioacoustics Lab, Oregon State University
MATLAB	MAThematical LABoratory. A software package available from The MathWorks Inc. Version R2014b was used to prepare the results in this report
MQC2	Miniclick 2 localisation equipment
NE	Natural England
PC	Personal Computer
pk-pk	Peak to peak. The amplitude of a signal measured as the range from the lowest negative value to the highest positive value.
PVC	PolyVinyl Chloride. The material used to make the acoustic equipment frameworks
QC1	Quadraclick 1 localisation equipment
QC2	Quadraclick 2 localisation equipment
RMS	Root Mean Square. RMS is the square root of the sum of the squares of sets of samples. It is calculated as: $RMS = \sqrt{\frac{1}{n}\sum_{x=1}^{n}\left(s_x^2\right)}$
SNH	Scottish Natural Heritage

SPL — Sound Pressure Level. The RMS sound pressure level expressed as a logarithm of the ratio to a reference level. In water the usual reference level is 1 µPa. SPL is usually expressed in dB relative to a reference pressure level (p_r) and calculated by:

$$SPL = 20\log_{10}\left(\frac{p_s}{p_r}\right)$$

sp. — Species. Used where more than one species is being referred to or the species is unknown

spp. — Species pluralis. A group of species

TDOA — Time Difference Of Arrival

UC1 — UniClick 1 The single hydrophone data collection equipment

UPS — Uninterruptible Power Supply

WoRMS — World Register of Marine Species

Chapter 1

Introduction

This project has its origins in the mid-1990's when the author was engaged in underwater acoustic work at various locations around the UK coast and along the western coasts of Europe and into the Mediterranean. Deploying a hydrophone in shallow waters (<20 metres depth) often resulted in a sound being heard that varied from a fast crackling sound to slow individual clicks. In many locations along the south coast of the UK it is the dominant component of the ambient noise field in the 2-20 kHz range as will be shown in this thesis.

A quick literature search suggested that the most likely cause of the sound were snapping shrimp, and yet the literature at that time also suggested that snapping shrimp are only found in warmer waters than those around the UK coast. Time did not allow this work to be pursued and the project to identify the source of the clicking was suggested to a number of other researchers. This work did not reach a conclusion and the source of the sound remained unidentified.

In 2008 after the author had retired from full-time employment the current project was pursued with the aim of identifying the source of the clicks.

The background noise in the sea is made up of many contributions e.g. wind, waves, precipitation and biological sounds (Wenz, 1962) and these sources have been well documented in the open ocean. This background sound will limit the performance of sonars by masking other signals so it is important to understand the background sound field and the characteristics of the constituent contributors. It is particularly import to understand the frequency characteristics of these contributors if they overlap the frequency band of operation of a sonar. It is also important to understand how the contributions vary through the tidal cycle, the lunar cycle and the annual cycle. If the sound can be associated with a particular species or clade[1] then this information may be used to survey for these animals.

The clicking sound studied in this work show a high degree of variability. Single loud clicks can be heard as well as a more continuous background crackling sound as many weaker clicks merge together. The frequency range is typically from a few hundred Hertz to over 50 kHz. The clicks can be repeated from 1 per minute to well over 200 per minute depending on site, time of day and time of year. The click rate varies through the day and through the year. The characteristics of the observed click spectrum can also be very site-dependant.

Establishing the species contributing to the clicking sound field is an important step in being able to predict the sound field in a given location and at a specific time of year.

The variability of amplitude and spectral content from click to click suggests that there is more than one species producing the sound. Some clicks have a low-frequency precursor, although many do not. Some have a significantly different frequency structure to others.

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[1] A clade is a group of animals with similar characteristics, often with a common ancestor. In this the reference is to an acoustic clade, a group with very similar acoustic characteristics.

Introduction

The aims of the work were to:

- Characterise the clicks to identify how many types of click were heard
- Identify the geographic distribution at local and regional level
- Identify the variation over time of the click sound field at one location
- Identify the habitats where the clicks are heard
- Localise the source of the clicks to obtain fine detail on their distribution
- Identify the species making the click

The work started with a review of the published work on the sources of sounds of biological origin in UK shallow waters in order to identify a list of candidate species that could be contributing to the clicking sound field. Species whose sounds have been well described and have not been found during this work were then eliminated from the list of candidate species. The review also identified species that have the potential to make a contribution to the sound field but whose sounds have not been described. To ensure confounding sounds were eliminated the review also identified relevant work on possible non-biological contributors to the click sound field. This review is presented in Chapter 2.

Chapter 3 describes the methods used to characterise the clicks, to measure their distribution in time and space and also describes the methods used to attempt to localise the clicks. The main study site used during this work is also described. Chapter 4 sets out the equipment assembled to implement the methods set out in Chapter 3.

Chapter 5 describes the click sounds heard while Chapter 6 presents the measured spatial distribution and temporal variation in click activity.

Chapter 7 presents the results of the work to localise the click sounds using 2 and 4 hydrophones. It also discusses problems encountered during the localisation work.

The attempts to identify the species producing the clicks are described in Chapter 8 and the difficulties encountered are also discussed.

Finally, Chapter 9 discusses the findings of this project and sets out possible future work needed to identify the species responsible for the clicking sounds.

Chapter 2

Literature review

2.1 Shallow water ambient noise

The oceans of the world are not quiet. The noise picked up by a hydrophone contains contributions from many sources (Wenz, 1962). This sound field is generally referred to as ambient noise. The most general definition of ambient noise is that it is the sound field that would exist if the measuring hydrophone were not present e.g. Richardson et al. (1995). However, some researchers exclude identifiable sources of sound such as passing ships e.g. Urick (1983). In some applications this is a reasonable definition, particularly in the context of activities producing sound such as active sonar. However, trying to remove sounds which are not under the control of the researcher may prove impossible due to the indeterminate nature of the contribution. In this work the more general definition is used.

The nature of ambient noise varies with a number of factors, including location and weather conditions. A number of researchers have attempted to summarise the characteristics of ambient noise. The first significant such summary was by Knudsen et al. (1948) which summarised the work carried out during World War II to understand ambient noise. This summary was later expanded by Urick and Pryce (1954). A comprehensive summary of ambient noise characteristics and contributors and including additional work was published by Wenz (1962). A further updated summary was provided by Urick (1984) although he states that the summary is incomplete because the data presented has to be unclassified. Later researchers have also provided similar summaries (e.g. Harland et al. (2005), Hildebrand (2009)) although these have resulted from the renewed interest in ambient noise resulting from civil applications for offshore energy.

The contributions to ambient noise generally fall into three classes: natural physical sources, biological sources and anthropogenic sources (Wenz, 1962). Physical sources include such sounds as that due to precipitation hitting the sea surface and waves impacting a beach. Biological sources include the calls of the whales and dolphins and the clicking of snapping shrimps. Anthropogenic sources include shipping and industrial noise.

In the deep oceans ambient noise has been well studied because of its importance to military sonar users (see for example Urick (1983), Wenz (1962)). Contributions to ambient noise in the open ocean may come from very distant sources. By contrast, shallow water ambient noise is generally more complex and less well studied because historically it has had less military significance. Contributions to the noise field in shallow water sites generally come from closer to the listening location, although sound velocity structuring can extend this range considerably (e.g. page 136 in Urick (1983)). At the higher frequencies where attenuation is greater (e.g. page 46 in Waite (2005) or page 103 in Urick (1983)) this range is reduced.

This project focussed on the click sounds which make a major contribution to the ambient noise field in many shallow water sites around the southern half of the UK.

2.2 Anthropogenic sources.

Activities by man can generate many underwater sounds. Many of these are impulsive in nature such as pile-driving (Robinson et al. (2007)), explosions (page 79, Urick (1983)) or the transmissions of echosounders. Many of the incidental sounds, such as clinking chains, boat clutch noise and shore-based construction noise have not been documented in the literature. Anthropogenic sources for the clicking sound studied here are considered to be extremely unlikely because of the widespread distribution of the clicking sound in the southern part of UK waters. There are no man-made processes with such a wide distribution, Further, many anthropogenic sources occur with a regular temporal pattern whilst others are narrowband in nature. Consequently the focus of the literature search was on natural sources of sound.

2.3 Physical sources

Physical processes such as surface waves and precipitation can produce underwater noise. Underwater noise levels increase with increasing wind speed and this produces a continuous spectrum of noise (Knudsen et al. (1948), Urick (1983)). Breaking surface waves occur at higher sea states and wind speeds and will produce impact noise and bubble oscillation noise (Deane, 1997). Rain noise is dependent on the size of raindrop and always contains an impact pulse as the rain hits the water surface and this can be followed by bubble oscillation (Medwin et al., 1992). Except for the short periods as rain starts and stops there are so many raindrop impacts that the individual sound sources run together to produce a continuous sound. The peak energy is between 1 and 20 kHz depending on the drop size (Heindsmann et al., 1955, Scrimger et al., 1987, Medwin et al., 1992).

Initial studies quickly established that the click activity is not related to the sea state, wind speed or precipitation rate. The only circumstances under which physical processes contributed to the click field at the main study site was when winds above Beaufort 5-6 opposed a strong tidal flow. This produced small breaking waves which produced bursts of sound some of which were click-like in nature. However, even under these circumstances the contribution to the click field was small and short-lived.

No literature was found suggesting that tidal effects could directly generate click sounds. Strong currents can cause sediments to move and this can generate noise (Thorne, 1986). This noise is a continuous sound similar to rain and does not contain resolvable clicks.

2.4 Biological sources

2.4.1 Introduction

There have been two previous studies of the clicking sound which is the subject of this study. Finfer (Finfer (2005), Finfer et al. (2007a) and Finfer et al. (2007b)) studied the source of the clicks as part of an MSc project. He observed sound at several locations along the south coast of the UK from Cornwall to the Solent and concluded there were multiple species producing the sounds but was unable to identify the species responsible. Coates et al. (2012) observed the clicking sounds in Holyhead Harbour, N Wales, and discussed the possible sources of the sound but were also unable to identify the species responsible. The clicking was also observed by the Durlston Marine

Project (Owens and Knowles, 2002) based at Swanage in Dorset, but no attempt was made to identify the source.

There are a wide range of marine creatures known to produce sounds. The following sections detail the broad species groups known to produce sounds. This allows candidate species known to produce noise to be identified and also to identify other biological sounds that may be encountered.

2.4.2 Marine mammals

The marine mammals are capable of producing a variety of sounds including whistles and echolocation clicks (Au (1993), Au and Hastings (2008)). The echolocation clicks are produced by animals within the order Odontocete. These have been well documented and would be good candidates for the origin of the clicks studied here, but there is a gross mismatch between the numbers of marine mammals observed on the south coast of the UK and the number of clicks heard. There were also many occasions when numerous clicks were heard but there were no marine mammals observed. Marine mammals were therefore eliminated from the list of candidate species.

2.4.3 Fish

There are 24,600 described species of fish in the world (Moyle and Cech (1996) citing (Nelson, 1994)) of which many can make sounds. Moyle and Cech (1996) suggest that the use of sound is common among fish. They suggest sound can be produced by one of three methods:

- Vibration of the swim bladder
- Rubbing hard body structures together (stridulation)
- Incidental sounds produced during other activities

This section presents information on those families and species of fish whose sounds have been described. It also lists those species within these families which are found in UK waters and which therefore will be relevant to this work. Many families of fish, including those found in UK waters, have not had their sounds described and are therefore not listed here but nevertheless may be contributing to ambient noise and perhaps also the clicking sound.

Vibration of the swim bladder generally produces sounds extended in time e.g. the hum from the midshipman fishes in the genus Porichthys (Bass and Marchaterre (1989), McIver et al. (2014)) or the drumming sounds from the drum fishes in the family Sciaenidae (Sprague and Luczkovich (2004), Locascio and Mann (2011)). Most of the sound energy produced by swim bladder vibration is below 1 kHz (DOSITS, 2014). The majority of the species producing this type of sound are tropical or warm water species and do not occur in UK waters other than as vagrants.

A chatter type sound heard both on and off the continental shelf is the sound made by cusk-eels (family Ophidiiformes). The sound made by the striped cusk-eel (*Ophidion marginatum*) is described as a rapidly pulsed sound with up to 27 pulses in the sequence in the frequency range 500 to 1800 Hz (Mann et al. (1997), Rountree and Bowers-Altman (2001)). The sound from this species was also studied by Mooney et al. (2016) who demonstrated that each pulse had frequency content to beyond 8 kHz.

Literature review

Members of the family Gadidae can excite the swim bladder using special sonic muscles to make a drumming sound (e.g. Hawkins and Amorim (2000)). Wilson et al. (2003) and Wahlberg and Westerberg (2003) have shown that the herring (*Clupea harengus*) can also produce a pulse sound by releasing air. Other families known to produce sound using the swim bladder include the searobins (family Triglidae) (DOSITS, 2016), the toadfish (family Batrachoididae) (Vasconcelos and Ladich, 2008), the grunts (family Haemulidae) (Fish and Mowbray, 1970) and the damselfish (family Pomacentridae) (Maruska et al., 2007).

Stridulation is the act of rubbing body parts together to produce sound. It usually involves a sharp edge rubbing against a ribbed surface to produce the sound. Examples include grinding the pharyngeal jaws[2] (Bertucci et al., 2014), the strumming of tendons (Fine and Parmentier, 2015) and by the movement of incisors during feeding (e.g. Pandey and Sukia (2015)). Sounds produced by stridulation extend much higher in frequency than those produced by vibrating the swim bladder. In some species the sound may be amplified by using the swim bladder as a resonator (Au and Hastings, 2008).

Some species of seahorse can produce stridulatory sounds by rubbing their skull against the coronet, a plate on the head of the fish (Colson et al., 1998, Fish, 1953). The northern seahorse (*Hippocampus erectus*) produced sounds with a peak frequency between 2 and 4 kHz and with a mean duration of 4 ms (Colson et al., 1998). These clicks were produced during feeding. Prager (2011) found that seahorses make a humming sound during courtship.

Two species of seahorse are found in UK waters: The short-snouted seahorse (*Hippocampus hippocampus*) and the long-snouted seahorse (*Hippocampus guttulatus*) also known as the spiny seahorse. *H. hippocampus* is found along the Channel coasts of the UK and the south coast of Eire (Sabatini and Ballerstedt, 2007). The population levels are not known. *H.guttulatus* is found along the southern coast of the UK and Eire and along the west coast of the UK as far north as Shetland (Neish, 2007). Again the population levels are unclear. No published information on sound production by either of these species was found.

Some members of the eel family (family Anguilla) can produce sound, including the common eel (*Anguilla anguilla*) (Lagardere and Ernande, 2004) and are found widely in UK waters (Avant, 2007). The sound is described as being pulsed with most of the energy being below 350 Hz. The method of sound production was not described.

The gobies (family Gobiidae) have more than 2000 species worldwide, of which seventeen are found in UK waters (Kay and Dipper, 2009). Twenty one goby species are known to produce sound (Parmentier et al., 2013). Amorim and Neves (2007) found that the painted goby (*Pomatoschistus pictus*), produces a series of thumps centred around 100 Hz during courtship. The gobies *Padagobius martensii* and *Gobius nigricans*, both freshwater species, also produced similar thumps centred around 100 Hz (Lugli et al., 2003). Pedroso et al. (2013) studied the sounds from the sand goby (*Pomatoschistus minutus*) and the painted goby (*Pomatoschistus pictus*) from the Baltic Sea. They showed that the thump sound was centred on 150 Hz for *P. minutus* and 230 Hz for *P. pictus*.

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[2] The pharyngeal jaws are a second set of jaws located in the throat or pharynx of some fish

Parmentier et al. (2013) studied the sound production mechanism in the rock goby (*Gobius paganellus*), and showed that the centre frequency of the pulsed call varied from 61 to 220 Hz.

The blennies (family Blennidae) are a large family of small fish living on or near the seabed. De Jong et al. (2007) showed that the rock-pool blennies in the Azores produced a grunt-like call during courtship centred around 30 Hz. In the UK six species are known of which two are rare vagrants (Kay and Dipper, 2009). The common species are: shanny (*Lipophyrys pholis*), tompot blenny (*Parablennius gattorugine*), Montagu's blenny (*Coryphoblennius galerita*) and the red blenny (*Parablennius ruber*).

Amorim et al. (2004) and Amorim and Hawkins (2005) described sound production and usage by the grey gurnard (*Eutrigla gurnadus*). The sound consisted of a series of pulse trains described as knocks or grunts with each pulse containing energy up to 1700 Hz. The gurnards are all members of the order Scorpaeniformes, family Triglidae, known as the sea robins. An example of the sound from a striped sea robin can be heard on the DOSITS website (DOSITS, 2016). Four species of gurnard are regularly found in UK waters (Kay and Dipper, 2009): the grey gurnard (*Eutrigla gurnadus*) and red gurnard (*Aspitriglas cuculus*) are common around the south and west coasts of the UK (Barnes (2008a) and (2008b)) as is the tub gunard (*Chelidonichthys lucernus*) (Kay and Dipper, 2009) while the streaked gurnard (*Trigloporus lastoviza*) is confined to the eastern English Channel (Barnes, 2008c). Kay and Dipper (2009) suggest that two other species are rare vagrants: the flying gurnard (*Dactylopterus volitans*) and the long-finned gurnard (*Chelidinichthys obscurus*). Of the gurnards, only sounds from the grey gurnard were identified in the literature.

Incidental sounds can be produced by fish in a number of ways. The most common of these occur during feeding. As an example a common source of sound around coral reefs is the crunching of the coral by parrot fish (DOSITS, 2015a, DOSITS, 2015b, Hays, 2011). There is also anecdotal evidence of fish producing clicking sounds during feeding. Personal communication with anglers suggests that some wrasse species can produce clicks when caught. There are a number of videos on the internet which appear to show fish producing clicks. A good example can be found on YouTube (Anon, 2011). Because these recordings are made in uncontrolled conditions they must be treated with caution as confounding species may not have been eliminated.

2.4.4 Crustacea

The sub-phylum Crustacea within the phylum arthropoda is paraphyletic and includes all the pancrustacea clade other than the hexapods (WoRMS Editorial Board, 2016). The structure of the sub-phylum is debated with the structures shown here based on the WoRMS database. There is some disagreement between authors on the detail, particularly at the superorder and infraorder levels. It is believed that the sub-phylum contains at least 67,000 species world-wide (Wikipedia, 2016) and includes six classes:

Branchiopoda: The brine shrimps

Remipedia: Worm-like free swimming animals in brackish water

Cephalocarida: The horsheshoe shrimps

Maxillopoda: The barnacles and copepods

Ostracoda: Small free swimming animals sometimes known as seed shrimps

Malacostra: Lobsters, crabs, prawns, krill, woodlice etc

Of these, only animals within the classes Maxillopoda and Malacostra have been identified as sound producers. No information was found on sound production within the other classes. The structure is shown graphically in Figure 2.1 for subclass Maxillopoda.

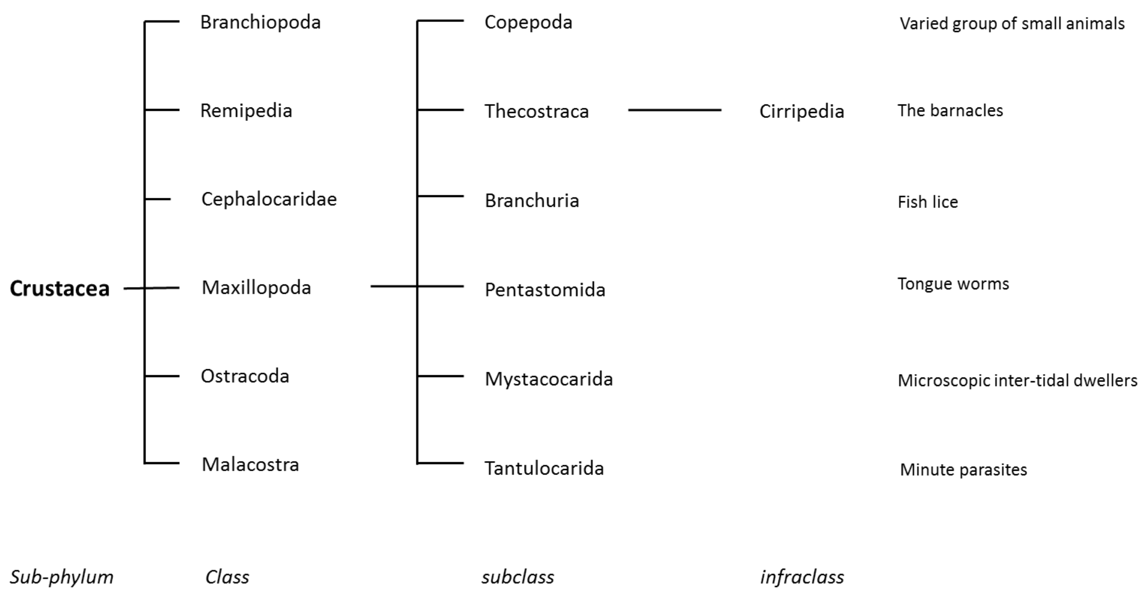

Figure 2.1 Class and subclass structure of Maxillopoda Crustaceans

2.4.4.1 Barnacles: Class Maxillopoda

Fish (1964) describes sounds from a number of species of barnacle. They can produce a number of low level abrasion sounds associated with feeding and a loud click. The purpose of the click and its method of production were not known. Although fairly low level clicks were heard from captive and wild specimens of *Balanus perforates* and *Balanus balanoides*, loud clicks were heard in the wild over extensive beds of the barnacle *Balanus eburneus*. However, some *Myitilus* specimens were also found and the clicks may well have emanated from these as described in Section 2.4.5.1 below. Barnacles are mostly found in the inter-tidal zone, but can occur in huge numbers.

In the UK there are at least eleven species of barnacle (Gibson et al., 2001). Five of these are described as common or frequent.

2.4.4.2 Lobsters, crabs and prawns: Class Malacostra

The class Malacostra contain around 40,000 species and is divided into three sub-classes:

Phyllocarida: A primitive group of animals living on the seafloor from the inter-tidal to deep oceans

Hoplocarida: The only extant order within this sub-class are the Stomatopoda, the mantis shrimps.

Eumalacostra: This sub-class contains the majority of the living species of Malacostra.

The subclass Eumalacostra is again divided into three superorders:

Syncarida: All are fresh water species

Peracarida: 9 orders, including amphipods, isopods, comma shrimps and opossum shrimps

Eucarida: The crabs, lobsters, prawns and krill

The superorder eucarida is further divided into three orders:

Euphausiacea: The krill

Decapoda: Lobsters, crabs and prawns

Amphionidacea: A single species whose classification is unclear

The superorder peracarida is divided into a number of orders. The classification of the species within this superorder is debated but only four of the orders are of interest within this study:

Amphipoda: Small crustacea with flattened bodies and no carapace

Isopoda: The woodlice and sea slaters

Mysida: The opossum shrimps

Tanaidacea: Small bottom-dwelling shrimps

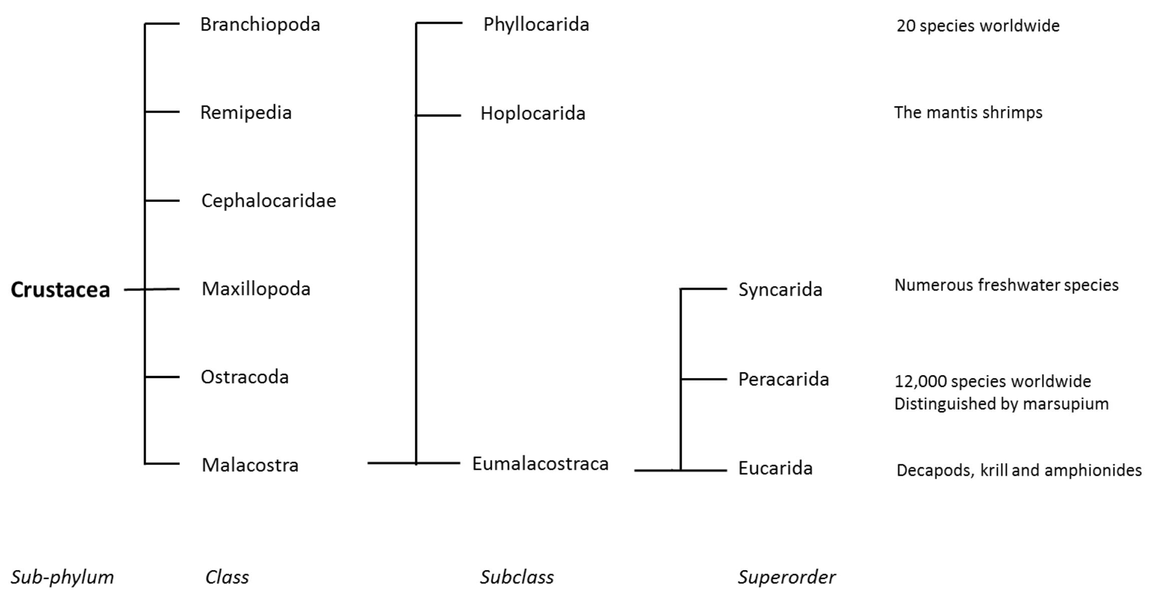

Figure 2.2 Subclass and Superorder for Class Malacostra

The other orders were excluded from the literature search either because they are freshwater species, or their range does not include UK waters or they do not appear to have any means of producing sound.

Literature review

Prawns and shrimps (Superorder Eucarida, order Decapoda)

This group contains fifteen superfamilies of animals and includes all of the commercially valuable species. The only superfamily known to produce sound directly are the snapping shrimps (superfamily Alpheoidea). The other superfamilies can produce sound by other means e.g. the cleaner shrimps 'tapping' call (Chapuis and Bshary, 2010), although one news report from Radio Australia (Australia, 2009) suggested that one of the cultivated species of prawn can produce a sound during feeding but did not identify the species.

Snapping shrimp (Family Alpheidae, order Decapoda)

The noise made by snapping shrimp has been known for over 80 years but its precise cause was not investigated until sonar became widely used by the military during the Second World War ((Johnson et al., 1947), (Everest et al., 1948)). Work during and immediately after the war identified the loud crackling sound widely heard in tropical shallow waters as coming from the various species that make up the genera *Alpheus* and *Synalphus*, collectively known as the pistol or snapping shrimps. These shrimps have the common characteristic of having one claw enlarged and, in many species, modified to allow the animal to make a very loud impulsive sound (Williams (1965) cited by Schein (1977).

The click sound from snapping shrimp was initially described by Everest et al. (1948). They described the ensemble spectra from a large area inhabited by snapping shrimp. They also identified a peak in activity at dawn and dusk. An example of the waveform was shown. Two species were identified as causing the noise: *Synalpheus lackingtoni* and *Crangon californiensis*.

The sound was investigated further by Knowlton and Moulton (1963) who investigated the beds of snapping shrimp around Bermuda. They discussed previous work to identify how the sound was produced and concluded that there was no clear mechanism of sound production. They further described the ensemble spectrum and the characteristics of individual clicks.

They also investigated the type of seabed where the snapping shrimp were found and identified that they mainly occur in sea beds that afford some shelter and were rarely found on sea beds of only mud or sand. In deeper water they also noted that the clicking was clustered in space.

Au and Banks (1998) measured the sound from the snapping shrimp *Synalpheus paraneomeris* in Hawaii. They showed the click was typically 83 µs long and that there was significant energy to beyond 200 kHz. The peak-peak source level varied between 180 and 190 dB re 1 µPa@1 m.

Ferguson and Cleary (2001) used a linear array to investigate the noise from snapping shrimp along a jetty in Sydney Harbour, Australia. There are two dominant species found in the area: *Alpheus euphrosyne richardsoni* and *Alpheus edwardsii*. They measured a mean peak-peak source level of 187 dB re 1 µPa@1 m.

The full description of the sound produced by a snapping shrimp *Alpheus heterochaelis* was provided by Versluis et al. (2000) and Schmitz et al. (2000). They showed the main click had a low-frequency pre-cursor starting 0.75 ms before the main click. This pre-cursor is attributed to the cavitation bubble resulting from the claw snap expanding and then collapsing.

The majority of the snapping shrimps are warm water species but two species are regularly found along the south and west coasts of the UK: *Alpheus ruber* (synonym *Alpheus glaber*) and *Alpheus* *macrocheles*. Rowley (2008) and Smaldon et al. (1993) provide some distribution information for *A. ruber* while Smaldon et al. (1993) suggests that *A. macrocheles* is found off the south and south-west coasts of the UK. Hayward and Ryland (2012) suggest that *A. macrocheles* is an inshore and shallow water species while *A. ruber* is found in deeper water. Along the Dorset coast personal observation suggests that *A. macrocheles* is found right up to the spring low water mark. From personal observation of a captive animal the click is very loud, and very painful if one's finger is too close.

A search through the literature, the internet and personal communication with other researchers has resulted in the map shown in Figure 2.3 showing all of the identified sites where these animals have been found. The full list of the source of this information can be found in Appendix A. The finds were by both amateur and professional surveyors so the species identification may not be completely reliable. However, the enlarged claw of snapping shrimps is so distinctive that the animal found is very likely to have been a snapping shrimp, so it is the classification to species level which may not be reliable.

All of the finds were for small numbers of animals apart from the survey of Kimmeridge Bay in Dorset which located 60 animals.

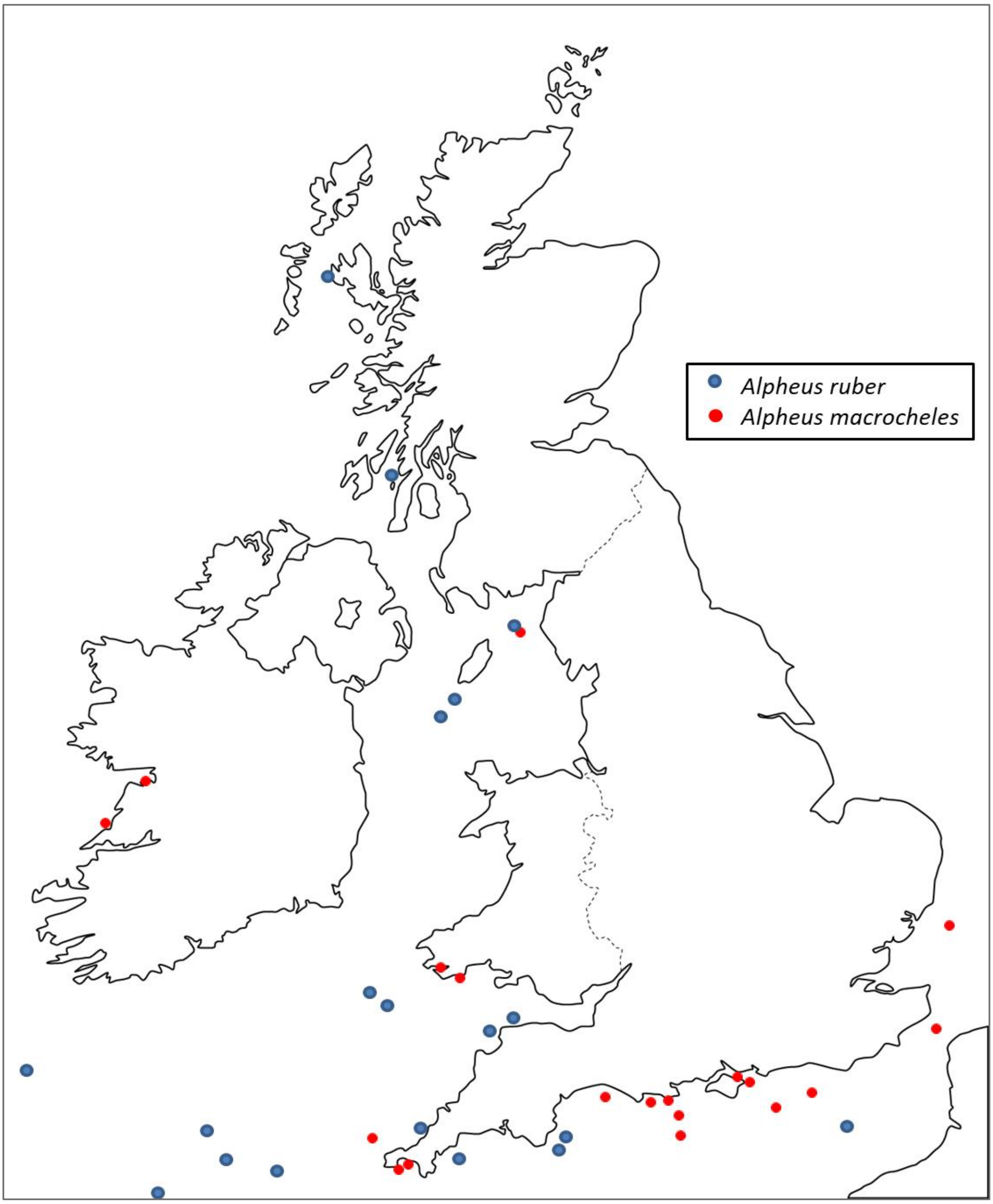

Figure 2.3 Location of Alpheus *spp finds in British waters*

Other Prawns and shrimps (infraorder Caridea, order Decapoda)

Cleaner shrimps (*Periclimenes longicarpus*) have been found to advertise their services by knocking their claws together (Chapuis and Bshary, 2010). The physical contact produces a click sound an example of which is available from Chapuis (2010). This sound was noted but not fully documented.

Forty four species of caridean shrimp and prawn occur in the waters around the UK (Smaldon et al., 1993). From personal observation the most common species off the Dorset coast are believed to be *Palaemon serratus* and *Palaemon elegans*. Also found, but in fewer numbers, are *Palaemon longirostris* and the hooded shrimp (*Athanas nitescens*). The hooded shrimp is part of the family Alpheidae, which includes the snapping shrimps, but the asymmetry of the first pereiopods[3] in *A. nitescens* is slight compared with other members of the family (Smaldon et al., 1993) so it is unlikely to produce the loud click characteristic of the snapping shrimps. There are no reports of sound production by *A. nitescens*.

Lobsters (Family Nephropidae, order Decapoda)

Various species of lobster have been shown to produce sounds. One method of sound production is to vibrate the carapace to produce a low frequency tonal sound. Henninger and Watson (2005) showed that the American lobster (*Homarus americanus*) produced this sound with a mean frequency of 183.1 Hz and which lasted from 68 to 1720 ms.

The MARLIN database (Wilson, 2008) shows the common lobster (*Homarus gammarus*), also known as the European lobster, as being common along the whole coastline of the UK. It can be found in inshore waters from the low tide mark down to around 60 m depth with some animals venturing down to 150 m depth. No scientific reports of the common lobster producing sounds were found but being very similar to the American lobster it is likely that it too will produce the low frequency sounds. A number of anecdotal reports suggest that they do produce a low frequency rumble when handled.

Crayfish (Superfamily Astacidea, order Decapoda)

The crayfish are all freshwater species similar to the lobsters. Buscaino et al. (2012) reported that the red swamp crayfish (*Procrambarus clarkia*) produced a series of clicks. This is a freshwater species found originally in the USA but is now an introduced species in rivers in the UK. No information could be found on sound production by the UK native species of crayfish, *Austropotamobius pallipes,* or the other introduced crayfish species *Pacifastacus leniusculus*.

Spiny lobster (Family Palinuridae, order Decapoda)

The UK marine species called a crayfish by many fishermen is actually the European spiny lobster (*Palinurus elephas*) (Jackson and Marshall, 2007). The sounds produced by this species have been described by Buscaino et al. (2011) and Patek (2002). The sounds consist of rasps lasting typically 90 ms with frequency content to over 100 kHz. The sounds are produced as a defensive mechanism.

JNCC (2010) suggest that *P. elephas* can be found along the western coasts of the UK where it is widespread but uncommon. The MARLIN database suggests the species is found as far up the English Channel as the Isle of Wight (Jackson and Marshall, 2007).

Fiddler crabs ((Family Ocypodidae, order Decapoda)

Fiddler crabs (Subfamily Ucinae) produce sound, usually at night, as part of their courtship ritual. The sound is produced by rapping the substrate either with the major cheliped[4] or the legs (Salmon (1967), Salmon (1984)) depending on the species. The sounds produced are described as

[3] The pereiopods are the thoracic limbs. The first pereiopod is the limb with the main claws
[4] The chelipeds are the pair of legs that end in the claws or pincers

either a ‘rasp’ when the cheliped is used or a ‘honk’ when using the legs. The only species of fiddler crab found in European waters is *Uca tangeri* and this is confined to the south-western shores of the continent (Crane, 1975). The UK species sometimes referred to as a fiddler crab is the velvet swimming crab (*Necora puber*) which does not have the enlarged claw characteristic of true fiddler crabs.

Ghost crabs (Family Ocypodidae, order Decapoda)

Salmon (1984) reported that ghost crabs (sub-order Ocypodinae) call from within burrows and that only the males call. The call is a rasp similar to the call of the fiddler crab but it can also be accompanied by a lower level sound probably produced by stridulation. Most of the ghost crab species are only found in tropical waters but one species found in European waters is *Ocypode cursor*, the tufted ghost crab, and this is found only in the Mediterranean Sea.

Hermit crabs (superfamily Paguroidea, order Decapoda)

Hermit crabs can produce two types of sound. During aggressive interaction with conspecifics they rap their shells together to decide which animal is superior (Briffa and Elwood, 2000, Briffa et al., 2003). They can also produce a sound like a squeaking gate or rusty hinge by stridulating the chelae (Field et al., 1987). A good example of this sound is provided by YouTube ((Stephens, 2008)). The sound is described as a series of pulses repeated at rates between 30 and 300 per second and with a peak frequency in the range 6-8 kHz. Freeman et al. (2014) suggests that a significant source of sound from coral reefs in the Line Islands is produced by the hermit crab *Clibanarius diugeti* rubbing its shell against the coral.

Mantis shrimp (Sub-class Hoplocarida, Order Stomatapoda)

Members of the Stomatopoda, the Mantis shrimps, produce a low frequency rumble as a defence mechanism. Patek and Caldwell (2006) investigated the rumble produced by *Hemisquilla californiensis* and found the rumble was in the frequency range 20-60 Hz. These shrimps also possess a powerful striking claw which can produce a loud click from the mechanical impact of the claw and also from the collapse of the cavitation bubble produced by the high speed of the strike.

Two closely related stomatopod species are found in UK waters: *Rissoides desmaresti* and *Platysquilla eusebia*. Both species are on the northern limit of their range and are found in the shallow waters around the southern half of the UK. Both species have only been found in very small numbers. The known distribution of *R. desmaresti* is described by Neish (2003) with an extensive colony found off North Wales (Ramsay and Holt, 2001). No distribution maps could be found for *P. Eusebia* but it is known to occur off western Ireland (Ceidigh, 1970) and it appears in various lists of species found in UK waters e.g. Picton and Howson (2000). No description of the sounds produced by either of the UK species could be found.

Amphipoda (Superorder Pericarida, order Amphipoda)

A group of generally small animals (<10 mm) that are shrimp-like, but with no carapace and generally with flattened bodies. Although a few are predators the majority are scavengers. No reports on sound production by Amphipoda were found, but Chapman (2007) suggested that some species have a stridulatory mechanism in the form of teeth on the rear of the gnathopods[5]. These species are found within the genus Isaeidae, Melitidae and possibly Phoxocephalidae. Schmitz (2002) in her review of sound production in crustacea, also mentions stridulation by a number of amphipods, but provides no information on the sound characteristics. Chapman (2007) also showed that some species have gross asymmetry of the gnathopods similar to the snapping shrimps while Mattson and Cedhagan (1989) found that the males of *Dysopedos porrectus* defend territories by snapping their enlarged gnathopods fiercely.

2.4.5 Other invertebrates

2.4.5.1 Molluscs (Phylum: Mollusca)

A mussel is held in place on a rock by byssal threads (Yonge, 1949). These are secreted from the foot and harden to form a very strong elastic tether to keep the animal attached to the substrate. The animal can move by breaking the threads on one side and then growing new threads in the direction it wants to move (Yonge (1949), Williamson (1907)). The thread is broken by increasing the tension in the thread until it snaps and this produces a click sound.

Fish (1964) described this click sound made by the common mussel (*Mytilus edulis*) as a variable, high amplitude, pulse-type sound of relatively short duration. Sounds were recorded from captive specimens to ensure the sounds of other species were eliminated. The measuring equipment used appears to have a limited frequency response so the described spectrum may be incomplete.

No information could be found on more recent measurements of the sounds from mussels. Also, no information has been found on snap rates for individual animals or snap rates for whole mussel colonies.

In UK waters there are three species of mussel: the common mussel (*Mytilus edulis*), the horse mussel (*Modiolus modiolus*) and the fan mussel (*Atrina fragilis*). The common mussel is found right around the UK coastline (Tyler-Walters, 2008b) while the horse mussel is only found off northern coasts (Tyler-Walters, 2007). The fan mussel is now very rare due to habitat disturbance and is only found off the west coast of Scotland and the south coast of Cornwall (Tyler-Walters, 2009). Mussels are found from the intertidal zone down to around 150 metres depth.

2.4.5.2 Sea urchins

Radford et al. (2008) studied the sea urchin *Evechinus chloroticus* found on North Reef off the coast of northern New Zealand. They found that as the animal grazed it made a scraping sound which excited the test[6] of the animal as a Helmholtz resonator. This produced a burst of near tonal sound in the frequency range 800-2800 Hz. This spectrum was shown to correlate with an observed dawn and dusk chorus over the frequency range 400-4000 Hz observed near the reef when sea urchins are known to feed.

In the UK there are two species of sea urchin: the green sea urchin (*Psammechinus miliaris*) and the edible sea urchin (*Echinus esculentus*). Both species are found all around the coasts of the UK but are most abundant along the west coasts from Cornwall to Shetland. Both species are found

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[5] The gnathopods are the claws on the first periopods

[6] The test is the ovoid calcareous skeleton of the animal which forms the outer layer bearing the spines.

only sparsely from Dorset eastwards along the Channel and then northwards to the Humber estuary (Jackson (2008), Tyler-Walters (2008a)).

2.4.5.3 Bivalves (scallops, clams etc.)

Di Iorio et al. (2012) found that scallops can produce a sound while expelling waste material from their shells. The sound consists of a click or crack followed by a 'coughing' sound as the shell closes. They found that this sound can be heard out to 10 m. It is likely that other bivalve species produce sound in a similar manner although there is no evidence of this in the literature to date.

2.4.6 Zooplankton

Many organisms, including many of the crustacea, start life among the zooplankton to be found drifting in the water column. It is possible that some of the sound-producing organisms may also produce sound during this stage of their life cycle. However, at present there is no evidence to confirm or reject this hypothesis.

2.5 Review of soniferous species literature search

From the literature survey it would appear that there are two very likely candidate species: the common mussel and the snapping shrimp. While these both may contribute to the click field the initial field evidence suggested they are not the major contributors in the main study area used by this work.

In order to generate the level of clicking observed over a wide area the source needs to be very common and widespread. It appears that from the initial search, the total number of specimens of snapping shrimp caught in the UK in the last 10 years numbers less than 50. However, snapping shrimp are very difficult to find as they live in burrows or under rocks so assessing the true population level is difficult. The literature suggests that the snapping shrimp click activity is constant throughout the year and this should help identify any snapping shrimp contribution to the click field.

In the main study area there is a high level of click activity, but very few mussels. There used to be a small population some years ago but from personal observation their numbers reduced considerably during a major die-off around twenty years ago and today only a very small number remain.

Fish are possible sources of noise and information on the species that have been found in the main study area can be found in the proceedings of the three Fleet Study Group symposia (Carr et al., 2000, Ladle, 1981, Ladle, 1984). Although seahorses are found in the study area, they are only found in very small numbers and only inhabit the eel grass beds. The literature suggests that the most common fish species in the study area are corkwing wrasse, ballan wrasse, bass, grey mullet, common eel, sand smelt, tompot blenny and four species of goby. There are also many small fry of a number of species.

The most common crustaceans found in the study area are shore crabs, barnacles and the prawn *Palaemon elegans*. Less common are swimming crabs and the prawns *Palaemon longirostris* and *athanas nitescens*.

There is no clear single candidate mechanism for the clicks observed on the South Coast of the UK. This project aims to explore the potential sources of these sounds. The initial hypothesis was that whilst snapping shrimp and common mussel contribute to the clicking sound, they do not account for the majority of the clicks heard.

The aims of the work are therefore:

- Identify the types of click making up the observed clicking sounds
- Investigate the spatial distribution of the clicks over different spatial scales at the national, regional and locally within the study site
- Investigate the temporal distribution
- Localise the clicks so that cameras can obtain a video sequence of the species producing clicking
- Identify the species producing the various clicks

2.6 Localisation of the clicks

2.6.1 Introduction

In order to identify the species making the clicks it is of assistance to be able to localise the source of the click. The underwater visibility in the study area is rarely sufficient to be able to use video techniques. Therefore methods of acoustic localisation of animal calls were investigated.

Acoustic localisation was first used to track tagged fish (e.g. Mitson and Storeton-West (1971)). It became increasingly recognised that passive acoustic monitoring of marine mammal calls could be an alternative to the visual monitoring previously used (e.g. Zimmer (2011)). Acoustic localisation in bioacoustics now covers a wide range of frequencies and applications and has been an area of research for many years (Mellinger et al., 2007). There is a large body of work looking at the performance of the animals own acoustic sensors to locate prey, predators or con-specifics (e.g. Au and Snyder (1980), Goodson (1997), Madsen et al. (2004)). Other work has looked at tracking and localising the underwater calls of a variety of species including marine mammals, snapping shrimp and fish and the airborne calls of bats, crickets, birds and mammals (e.g. Cummings and Holliday (1985), Abileah et al. (1996)).

Acoustic localisation and tracking techniques have applications beyond bioacoustics. These have been primarily developed for military use (e.g. Waite (2005), Urick (1983)) but have also been used for tracking smaller objects both in marine and terrestrial environments(e.g. Woodward and Goodson (1989), Blumstein et al. (2011)).This includes active sonar and/or the use of acoustic tags to label the object to be tracked (e.g. Stein et al. (2001), Levenson (1978), Miller and Potter (2001), Anon (2016b)) but active sonar methods were not applicable to this work because the target was not known.

In this project the acoustic localisation has to use passive sonar and take place in very shallow water (<10 metres) with multiple reflections off the surface, seabed and other obstructions so techniques capable of working in this environment are particulary relevant.

2.6.2 Underwater tracking of animals

Much work has been carried out over the last 50 years looking at methods of tracking marine mammals using their calls e.g. (Clark and Charif, 1998, DiMarzio et al., 2005, Nosal and Frazer, 2006). This work has primarily been aimed at tracking the larger whales in the open ocean using their low frequency tonal calls. Techniques used include sparse arrays of sensor (Jarvis et al., 2003, Chappell et al., 1996), towed arrays (Miller and Tyack, 1998, TNO, 2005), bottom-mounted hydrophone arrays (Jarvis et al., 2003) and multi-path ranging (Nosal and Frazer, 2006).

By comparison there has been very little work on tracking marine mammals using their echolocation clicks. This is primarily because the transmitted sound is at a much higher frequency, with consequent higher attenuation, and because the sound is transmitted in a very narrow beamwidth (Au, 1993). This means that acoustic localisation and tracking is only useful under some very limited conditions.

The one echolocating marine mammal that has been extensively tracked is the sperm whale. This animal makes a very loud pulsed call with frequency components from 40 kHz down to a few kilohertz (Wahlberg, 2002, Thode et al., 2002). Early work used two-hydrophone towed arrays (e.g. Gillespie and Chappell (1998)) using Time Difference Of Arrival (TDOA) bearing estimators. These give an ambiguous bearing which is resolved by the tow ship manoeuvring to provide multiple ambiguous bearings leading to the location of the animal. This is possible when the animal is in the far-field of the array and the assumption is made that the animal was close to the surface. A number of software packages still incorporate simple TDOA bearing estimators e.g. ISHMAEL (Mellinger, 2004) and PAMGUARD . More recently multi-path ranging of sperm whale clicks has been investigated and shown to work well with some constraints (Laplanche et al., 2005, Tiemann et al., 2006, Nosal and Frazer, 2006).

Work with the smaller animals with echolocation pulse energy in the range 10 kHz to 150 kHz and with beamwidths down to 10 degrees has been limited to tracking animals around fishing nets. Connelly et al. (1997) used a multi-hydrophone array to track common dolphins around the mouth of a trawl net. They used the look-up table approach where the hydrophone time delays from each possible location are pre-calculated to a give a look-up table indexed by measured time delays for a received click with each entry in the table giving the x, y, z location of the click source. The look-up table approach can give a very fast solution but requires very high sample rates to give sufficient spatial resolution resulting in a very large look-up table.

As well as the interest in tracking the marine mammals there has also been work on localising the snaps of snapping shrimp. Ferguson and Cleary (1999), (2001) used a wide aperture horizontal array to estimate range using the wavefront curvature method. This technique uses the curvature of the wavefront to estimate the range of the click source. They used three hydrophones spaced 9.7 metres apart and this was used to plot the distribution of the snapping shrimp along a jetty. Miklovic and Bird (2001) used a multi-element array with wavefront curvature processing to detect snapping shrimp clicks in the Timor Sea.

Beng et al. (2003) used a four hydrophone tetrahedron array with 1 metre spacing to study snapping shrimp noise. It was claimed that with the tetrahedron array 4 metres above the seabed clicks were localised out to 80 metres range. The paper gives no indication of the method used to calculate the source location.

Although many species of fish produce sound, passive acoustic tracking is not the preferred localisation method used by researchers and surveys. The most frequently-used technique to track individual and groups of fish is active sonar (e.g. Au and Benoit-Bird (2003), Weston and Revie (1971)). However, passive acoustics are used extensively to identify the fish species from the calls they make and to study fish behaviour (e.g. (Colleye et al., 2009, De Jong et al., 2007, Wood, 2002, Ladich, 1997)).

2.6.3 In-air tracking of animals

Passive acoustics are used extensively to recognise the calls of bats, birds and crickets (e.g.(Potamitis et al., 2014), (Vaughan et al., 1997, Potamitis et al., 2007)) and to obtain coarse localisation information using distributed arrays of independent sensors (e.g. Dawson and Efford (2009)). Passive acoustics is not used to accurately localise any of these groups of species from their calls.

Radar is widely used to study bird migration (e.g. Anon (2016a)) and passive acoustic systems are being developed to recognise the calls to identify the species migrating (e.g. Schrama et al. (2008)). Radar has also been used to study insect behaviour, particularly bees (Chapman et al. (2011), Woodgate et al. (2016)

Photographic/video techniques are often used to track bats within confined spaces (e.g. Schnitzler et al. (1987)) with some use of multi-microphone arrays (Schnitzler et al., 1987, Seibert et al., 2013) but the directional nature of the emitted calls makes the application of acoustic techniques challenging in the wild.

Much work has considered localisation and crickets. This work focusses on how the animal uses its own sensors to localise sound (e.g. Hedwig and Poulet (2005)). Passive acoustics are not widely used to localise the insects from their calls.

2.6.4 Localisation techniques applicable to this project

2.6.4.1 Singe hydrophone

A single stationary hydrophone can only provide a sample of the sound field at a single location. However, if that hydrophone is moved then it can provide additional information about the sound field which can help to localise the source of the click. The most basic form of this is to move the hydrophone to optimise the amplitude of the received signal. It is then likely that the hydrophone is close to the sound source. Over the short ranges and in the shallow waters required by this project this is a feasible option. A more advanced use would be synthetic aperture sonar in which the hydrophone moves in a very controlled manner (Hayes and Gough, 2009). This technique only works if the location of the hydrophone is known very accurately and the received signal is present over the time it takes to move the hydrophone. This technique is not suitable for this project because of the multiple sources with a significant spatial distribution and the instability in the acoustic environment over the required spatial and temporal scales.

In environments where surface and bottom reflections are present it is possible to obtain range information from a single stationary hydrophone by looking at the time of arrival of the signal via the different paths. This technique is very dependent on knowing the bathymetry and the sound velocity profile and how both vary across the area of interest. Many papers have been published on the subject of multipath ranging but these are mostly in the military application (e.g. Waite

(2005)) and cover ranging over large geographic scales and at low frequencies. A few papers have looked at multi-path ranging of sperm whale clicks (e.g. Laplanche et al. (2005), Tiemann et al. (2006)). Au and Hastings (2008) and Zimmer (2011) have presented the more general case using either surface reflection only or surface and bottom reflections. Multipath ranging has not been applied in the very shallow water and short ranges required by this project. Early observation of received clicks suggests that only the surface reflection is present. Because of the small time differences between the arriving signals the reflected path signal often overlapped the direct path signal. Further, it should be noted that multi-path ranging can only provide range information, it does not provide bearing information and both are needed to localise a sound source.

2.6.4.2 Two hydrophones

If a second hydrophone is included in the system then additional information on the sound field is available. Provided the sound source is in the far-field then the difference in arrival time at the two hydrophones can be used to estimate the bearing of a received signal (Au and Hastings, 2008, Zimmer, 2011). The method only gives the 3-D cone on which the signal must lie and does not provide range information. In shallow water the cone reduces to two possible bearings. This method has been used extensively to track sperm whales (e.g. Ura et al. (2004), Nosal and Frazer (2006), Nielsen and Mohl (2006)). The method relies on estimating the time difference of arrival of the signal between the two hydrophones. If the signal is strong then the time difference can be estimated by a simple envelope threshold crossing technique. A potentially more accurate method, particularly at low signal/noise ratios, is to use cross-correlation techniques. However, the click signals studied here although they have a high bandwidth are very short in length and suffer severe multipath distortion so correlation processing is not helpful in this situation.

Best accuracy of the bearing estimate is obtained if the hydrophones are widely spaced, but in the very shallow water required by this project this can lead to significant inaccuracies in estimating the arrival times due to signal distortion, with consequent errors in the estimation of the bearing. This technique has also been used to study the distribution of snapping shrimps. However, if the sound source is in the near field there is no longer a simple relationship between bearing and time-difference and more hydrophones are needed to resolve the range (e.g. Ferguson and Cleary (1999))

2.6.4.3 Multiple hydrophones

Multiple hydrophones can be organised as linear arrays (e.g. towed arrays), planar arrays, volumetric arrays or extended arrays and all of these have been used in localisation experiments.

Linear arrays may consist of from three hydrophones up to very long towed arrays of several thousand hydrophones. Close spaced arrays can be used over a limited bandwidth using conventional time-delay beamforming (e.g. page 50 in Urick (1983) or Chapter 2 in Waite (2005)). Wider spaced arrays can be used over a wider bandwidth by using techniques such as wavefront curvature estimation (Section 8.2 in Waite (2005)). Simple beamforming techniques will only provide a bearing estimate but advanced techniques such as focussed beamforming or TDOA combined with wavefront curvature can provide estimates of both range and bearing. Note that the bearing estimate will be a cone rather than a single value, but this will be reduced to an annulus if range can be estimated.

Similarly, planar arrays can be close-spaced to allow time-delay beamforming to be used or wide-spaced to allow wideband techniques such as TDOA to be used (Au and Hastings, 2008). The advantage of planar arrays is that they provide information on azimuth and elevation rather than the single angle of linear arrays. Planar arrays require a minimum of three hydrophones but can extend up to hundreds of hydrophones in some military applications.

Volumetric arrays generally use time delay techniques to estimate both range and bearing in three dimensions (Zimmer, 2011). A favoured configuration is four hydrophones at the apexes of a tetrahedron (e.g. Beng et al. (2003)). However it has been shown by Schmidt (1972) and later by Spiesberger (2001) that five hydrophones are required to obtain a unique solution.

Extended arrays use very wide-spaced sensors operating independently to listen for calls and provide coarse location information of the source. This technique is widely used in the study of bat and bird behaviour (e.g. Blumstein et al. (2011)). The sensors may be spaced over scales ranging from tens of metres to several kilometres.

2.6.5 Application to this project

Three localisation techniques are adopted within this project. A single hydrophone is used for simplistic presence-only survey work and can also be used as a mobile sensor to try and locate the source of clicking by maximising received amplitude.

A two-hydrophone system is used in two ways. The hydrophones can be aligned parallel and perpendicular to the shore to investigate the coarse angular distribution of the clicks and also the longer term stability of the click distribution. The other mode of use would be to separate the hydrophones as much as possible and then place one hydrophone in an area of interest with the other hydrophone some distance away to investigate the differences in click activity. As an example of this one hydrophone could be placed in a wrecked pontoon with the other in open water some distance away.

A multi-hydrophone volumetric array was also constructed to allow full localisation of the clicks using the method suggested by Spiesberger (2001), and Zimmer (2011).

Chapter 3

Methods used

3.1 Introduction

To achieve the aims of the work as set out in Section 2.5 a variety of methods and systems for opportunistic, short and long term monitoring and localisation are needed. This chapter describes these methods and also describes the study site chosen for the long-term monitoring work.

3.2 Characterise the clicks

The aim of this element of the work was to investigate the detailed spectral and temporal characteristics of the clicks. It sought to describe the clicks and to determine if there were multiple click types present. If multiple click types are found then what are the distinguishing features of these clicks?

This work was carried out by making sample recordings at a variety of sites covering different habitats and water depths and at different times throughout the year. The individual clicks were then studied in the time and frequency domain to determine whether they could be separated into distinct groups.

3.3 Spatial distribution of the clicking

By investigating the spatial distribution of the click activity at various sites and over various spatial scales it should be possible to obtain information about habitat preferences of the clicking species and this should aid identifying the species. The investigation looked at the distribution around the UK coast to identify any wide scale habitat preferences and also looked over local spatial scales to determine any seabed type preferences.

This work was carried out by using a single hydrophone deployed on an opportunistic basis to make recordings for at least 5 minutes. The recordings were then investigated to determine the mix of click types and to produce a measure of click activity. Assessing click activity is discussed in some detail in Section 3.8. Supporting data collected included seabed types, weather, time of day, time of year and other environmental factors.

3.4 Temporal variation of the clicking

The temporal survey work aimed to establish how the click activity varied through the annual, lunar, diurnal and tidal cycles.

This work was carried out by deploying a fixed hydrophone on the seabed at the main study site described in Section 3.7. This allowed signals to be cabled ashore and connected to a computer and recorder to allow full 24 hour monitoring. A full description of this equipment is provided in Section 4.2.

The results of this work are presented in Chapter 6.

3.5 Localise the source of the clicks

The click localisation work focussed on studying the spatial distribution of clicks over a very limited area at the main study site. The aims were to establish the following:

- Is the click source mobile or sessile?
- Do the clicks originate from the seabed or mid-water?
- Is the spatial distribution stable or changing?
- Can the clicks be localised with sufficient accuracy to allow video cameras to be used to identify the click source?

This work was carried out by using a single hydrophone system (Uniclick) and two multi-hydrophone arrays; BiClick and Quadraclick.

3.5.1 Uniclick

Uniclick is a single hydrophone on a pole and is used to walk the shallows along a shoreline to obtain information on the broad distribution of click activity. The equipment is described in detail in Section 4.4.1. The results are presented in Chapter 8.

3.5.2 BiClick

An initial investigation of click distribution used a two-hydrophone system known as BiClick the development of which is described in Section 4.4.2. This allowed a maximum hydrophone separation of 10.5 metres. BiClick has the advantages of being lightweight and easy to deploy compared with Quadraclick, the four-hydrophone system.

Measuring the time-difference of arrival with two hydrophones allows the source to be localised onto a hyperboloid (e.g. page 212 in Zimmer (2011)). In the far-field this approximates to a cone and in shallow water this further approximates to one of two possible bearings and this approximation has been widely used to study and track sperm whale clicks. However, for the work described here it is likely that neither approximation is valid as the click source is likely to be in the near-field and in water where the range is comparable with the water depth. However, the method can still yield useful information about how click activity varies with apparent bearing and how stable the click field is with time. If multiple types of click are found then differences in the distribution with apparent bearing can also be determined.

If the two hydrophones are deployed in a vertical line then the resulting apparent angles can be used to determine if the clicks are originating on the seabed or mid-water.

3.5.3 Quadraclick

Subsequent localisation work was carried out with a four-hydrophone array known as Quadraclick which allowed full localisation of the clicks using the method set out by Spiesberger (2001). The equipment and its development is described in Sections 4.4.3 and 4.4.4. It consists of four hydrophones at the vertices of a tetrahedron with sides of approximately one metre.

This equipment can be used to localise clicks occurring within and around the array. The aim being to investigate the spatial and temporal stability of the sources of clicks. It was also hoped to identify the click source locations to the level where a video camera could be used to identify the species responsible.

Methods

Spiesberger (2001) points out that with four hydrophones there are two possible solutions for the source location. It was anticipated that one of these would be the correct solution and one could be eliminated either by it being located above the surface of the water or below the seabed, or else eliminated by comparing the amplitude of the signals. Clicks occurring at very short ranges can have a significant difference in amplitude even with such closely spaced hydrophones. Localisation of the clicks in three-dimensional space within a limited volume would provide information about the spatial distribution and behaviour of the source of the clicks and this will assist in identifying the species making the clicks.

3.5.4 Methods used

The spatial and temporal survey work was used to suggest suitable locations for the localisation work.

Coarse localisation of the clicks was achieved by using the two hydrophones of BiClick to achieve a bearing only solution. The aim of this work was to establish whether the click distribution was consistent or varied with time. The two hydrophone system also allowed the click field to be investigated over a limited area by varying the spacing and then comparing the clicks heard.

Fine localisation was achieved using the four hydrophones of the Quadraclick system. This was a far more cumbersome system than the two hydrophone system so was deployed at one location only.

For both the two and the four hydrophone systems the data was processed using MATLAB programmes specifically developed for this work.

The results of the two and four hydrophone work are presented in Chapter 7.

3.6 Identify the species making the clicks

This part of the project sought to identify the species making the clicks. The aim was to be able to identify down to a single species or group of species for each click type.

The work was carried out using a variety of methods including:

- Deploying a hydrophone with captive animals in aquaria
- Using animals from the wild and held in temporary aquaria with a hydrophone
- Deploying a hydrophone with a camera in rock pools
- Deploying a hydrophone with a camera off beaches with a variety of seabed types
- Deploying a camera with Quadraclick to try and capture a click both acoustically and visually

The camera equipment used is described in section 4.9. The general aim was firstly to back up the acoustic observations with general observations of species present in an area, then to combine cameras with the localisation work and finally to isolate candidate species to ensure that clicks heard were from that particular species.

The results of attempting to identify the species producing the clicks are presented in Chapter 8.

3.7 The main study site

Early in the work it was identified that a specific study site should be found where the bulk of the work could be carried out. The preliminary studies along the Dorset coastline suggested sites at Swanage, Weymouth, Portland Harbour and a site located in the southern end of The Fleet, Dorset. After considering the logistical implications of each location the site in the Fleet was chosen.

The Fleet is a shallow lagoon between Chesil Beach and the mainland and is connected to the sea in Portland Harbour via a link channel. The link channel becomes a narrow deeper channel at the lower end of the Fleet and this can be seen as the blue band in the inset in Figure 3.1. It also shows as the darker water adjacent to the Black Hut Research Station (BHRS) in Figure 3.2. The study site is located adjacent to the BHRS where the main channel moves away from Chesil Beach and turns towards Ferrybridge Bridge and out into Portland Harbour. The primary study site extends for 20 metres either side of the Black Hut and across the Fleet although some work extended the site down to Ferrybridge and beyond.

This site was primarily chosen because the acoustic survey work showed that the clicking sound was prevalent in the channel at this location and also because a research station was available on the beach adjacent to the site with power and a fibre-optic data link back to the Chesil Beach Visitors Centre (CBVC). The Black Hut Research Station (BHRS) is owned by the Chesil Bank and The Fleet Nature Reserve (CBFNR) and operated by the Chesil Multi-Media Project (CMMP). It is normally used to monitor the little terns (*Sterna albifrons*) that nest in the area and to collect data for CMMP purposes. The site also has the advantage of being remote with little disturbance from the public.

Figure 3.2 shows an aerial photograph of the site taken looking south along The Fleet towards Portland.

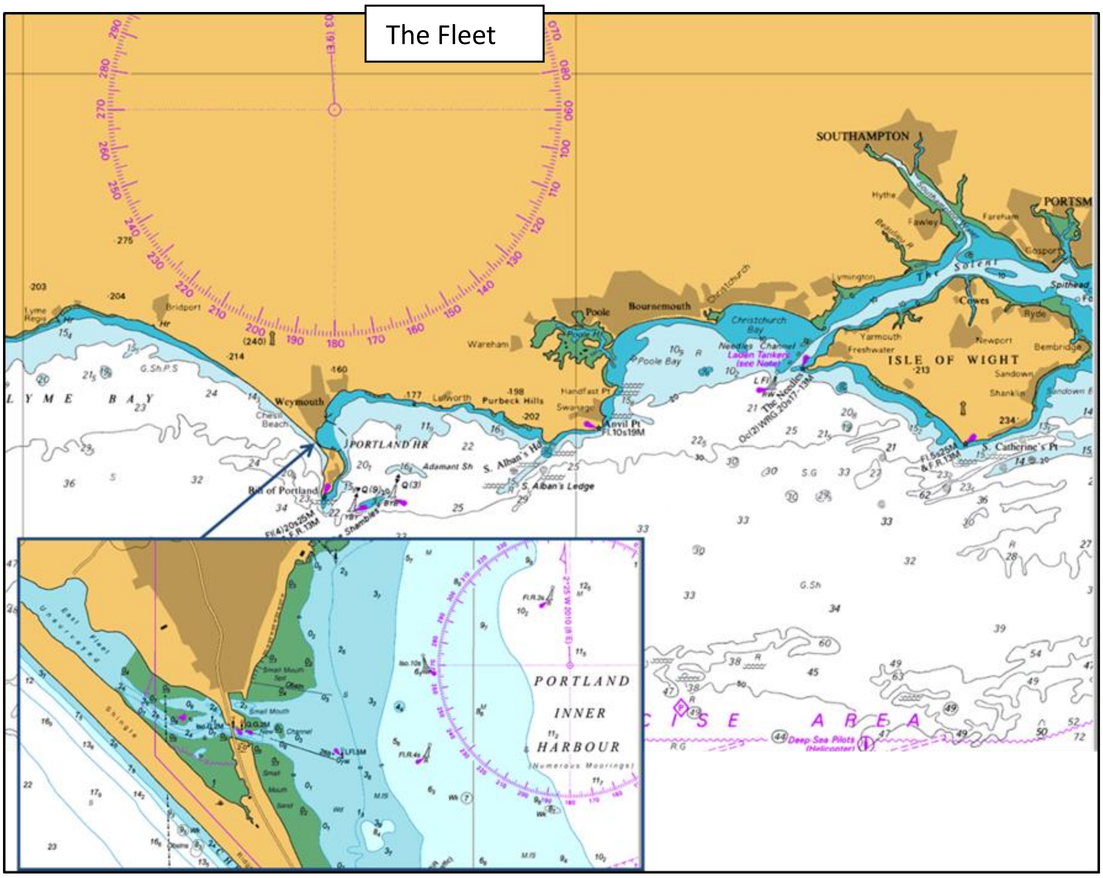

Figure 3.1 Location of main study site

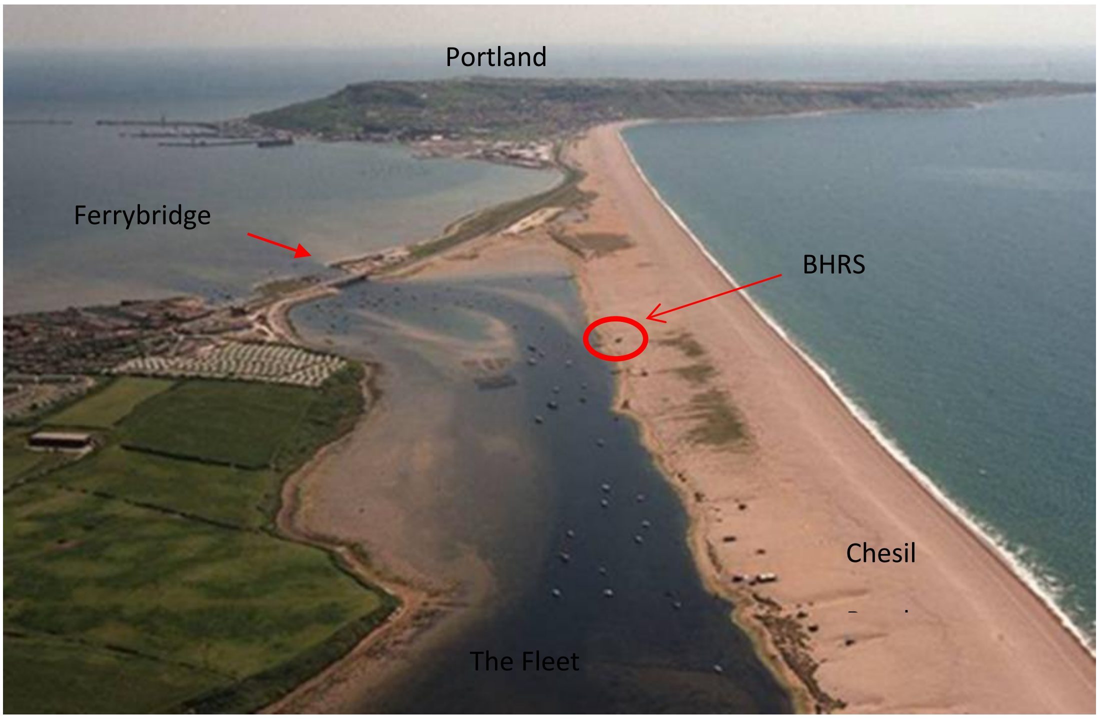

Figure 3.2 Aerial view of the main study site showing the location of the Black Hut Research Station

The Fleet adjacent to the BHRS is 270 metres wide. The eastern side has extensive sandflats while the main channel passes close to the western bank, The link channel adjacent to the BHRS is 110 metres wide and slopes gently down to about 1 m depth at mid-water then drops steeply to 2 m before sloping more gently to about 3-4 m depth in mid-channel as shown in the cross-section in Figure 3.3. The tidal range is about 1 m on neap tides and 2.3 m on spring tides. This area has a double low tide during spring tides. The peak tidal current in the main channel during spring tides is ~2 knots.

The channel seabed is mud and sand overlaying shingle but there is also a lot of anthropogenic debris on the sea bed ranging from discarded tins and bottles through railway wheels up to a complete marina pontoon.

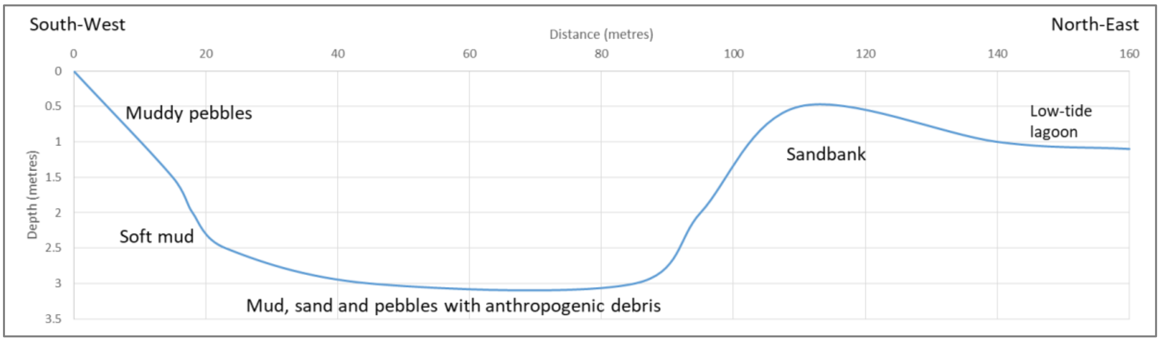

Figure 3.3 Cross-section of channel at BHRS

Acoustically, the water is generally well mixed although complex structuring can occur under calm conditions and a rising tide as the incoming water from Portland Harbour starts to flow over the exposed sandbanks. In the autumn a large quantity of eel grass (*Zostera maritima)* and tasselweed (*Ruppia maritima*) dies off and drifts down from the mid and upper Fleet and this can severely foul deployed equipment.

Under storm conditions, and generally throughout the winter, there are large amounts of sediment suspended in the water column which can reduce underwater visibility to less than 10 cm making it very difficult to deploy or retrieve equipment or carry out underwater tests. Under severe storm conditions it is too dangerous to access the site because of the very strong winds and the possibility of the beach collapsing underfoot as the pebbles become mobile due to water coming through the pebble bank.

The research station is shown in Figures 3.4 and 3.5.

Figure 3.4 The main study site and the Black Hut Research Station

Figure 3.5 The Black Hut Research Station

The hut was originally built as a fisherman's hut but was acquired by the Chesil Bank and The Fleet Nature Reserve to support their activities along this section of Chesil Beach.

CMMP operate an underwater camera adjacent to the BHRS the pictures from which are displayed in the Chesil Beach Visitors Centre for public engagement purposes. The camera is located inside a wrecked pontoon on the seabed and provides information on species present. However the pictures only show the larger species and those species which will enter the enclosed space of the pontoon. A weather station located on the observation tower adjacent to the BHRS (see Figure 3.5) was also operational for part of the lifetime of this research project.

3.8 Assessing click activity

One problem that presented itself early in the work was to devise a method of reliably and consistently assessing click activity from data collected at multiple sites, at different times and using different uncalibrated acoustic systems. Initially a simplistic method of automatically counting the clicks that exceeded a fixed threshold in a fixed time and from a single set of acoustic equipment was used but it was found that it suffered a high level of false alarms. The false alarms mainly occurred in periods of raised ambient noise conditions for example during storms or during the passage of boats. To mitigate false alarms a moving window click detector was used to identify clicks within the acoustic data. A block diagram is shown in Figure 3.6.

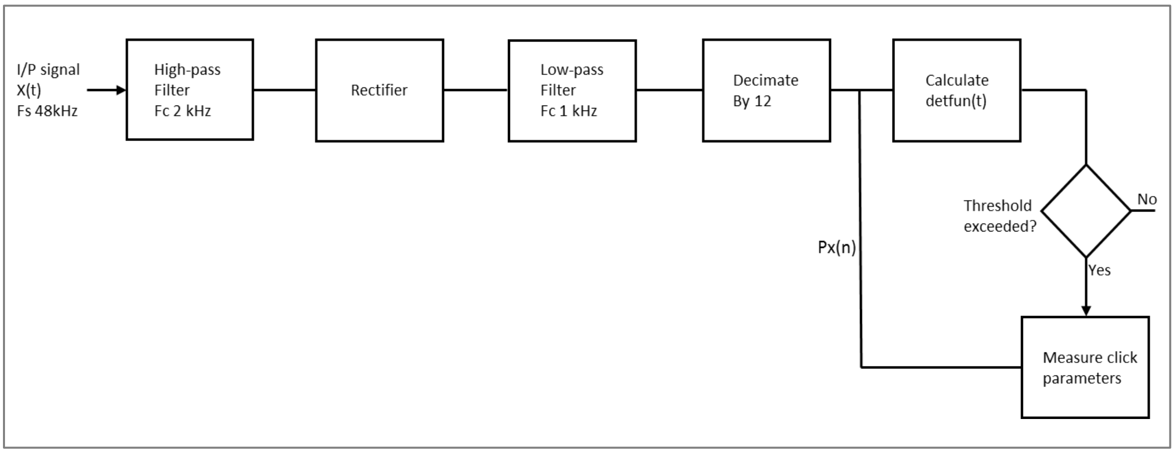

Figure 3.6 Click processing block diagram

The incoming signal is high-pass filtered at 2 kHz, then full-wave rectified before being low-pass filtered at 1 kHz. The data is then decimated by 12.

A click is detected using the following function:

$$detfun = \sum_{n=t-1}^{t+1} px(n) - 2\sum_{n=t-12}^{t-10} px(n) - \sum_{n=t+12}^{t+14} px(n)\ . \tag{3.1}$$

A click is detected if the detection function is greater than zero. For an incoming sample rate of 48 kHz, the sum of three samples (0.8 ms) at t=0 has to be greater than twice the sum of three samples 2.8 ms before t=0 and the sum of three samples 3.3 ms after t=0 as shown in Figure 3.7.

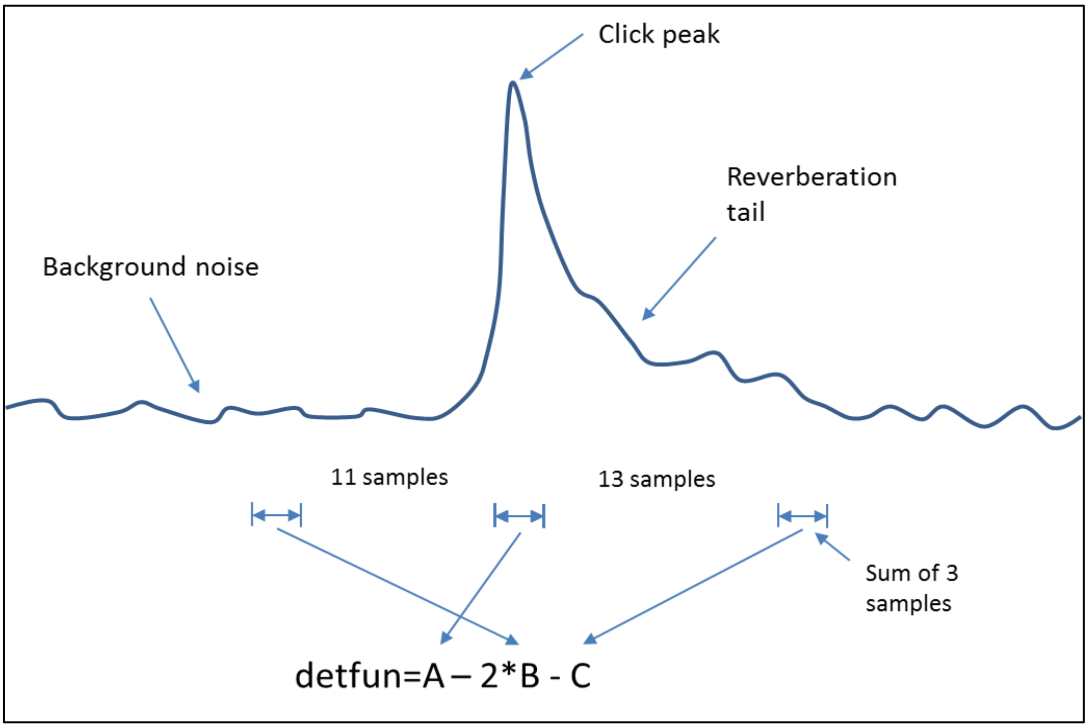

Figure 3.7 Operation of the automatic click detector

Comparing the reference point with the sample 2.8 ms ahead detects the leading edge of the click which has to be twice the level of the preceding data. Comparing the reference point with the point 3.3 ms after the reference point eliminates signals that are extended in time compared with the click of interest. The time separation and comparison levels were chosen empirically by visually inspecting a large number of clicks and by trying various separations when processing early samples of clicks. An example of the detection function with real data is shown in Figure 3.8.

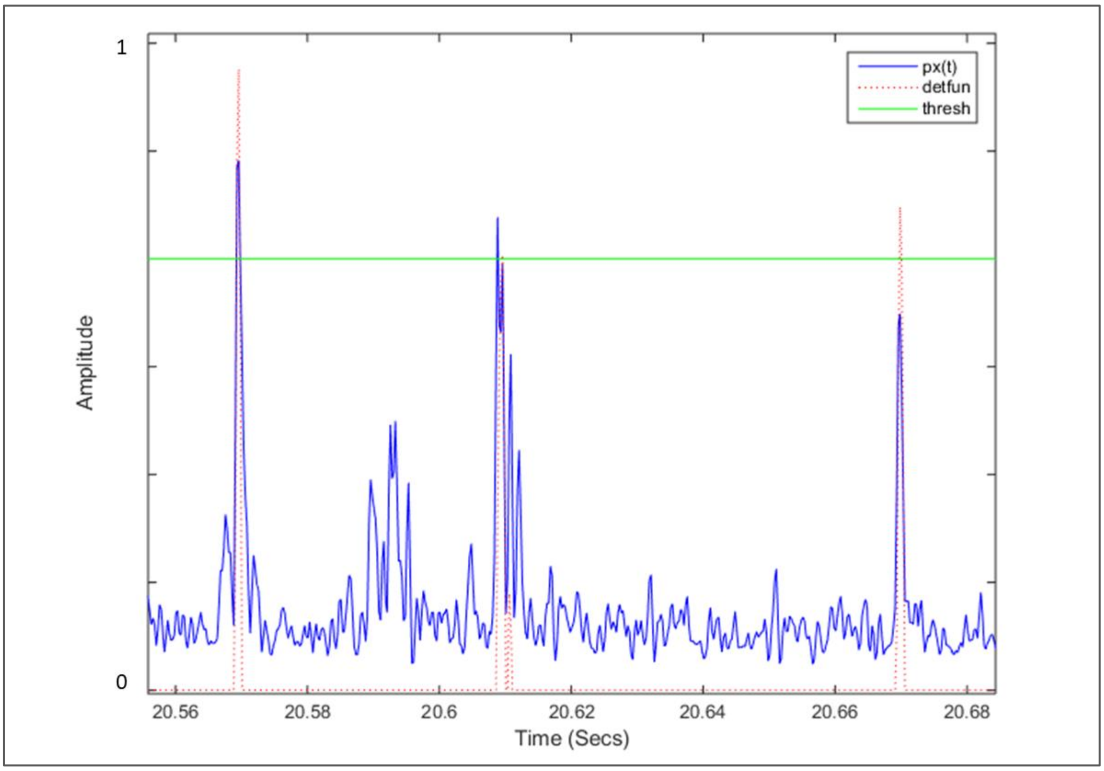

Figure 3.8 Example of click detection operation

The blue trace is the processed signal sampled at 4 kHz. The red dotted line is the resulting detection function which is zero when no candidate click is present. In this example four candidate clicks are present as shown by the red line becoming non-zero. The green dashed line is the amplitude threshold so in this case only two of the four candidate clicks exceed the threshold. For this study a threshold corresponding to an absolute sound pressure level of 99.2dB re 1 µPa was chosen.

If a click exceeds the amplitude threshold the processing then saves the peak level, click width and click energy from the signal. These are defined as:

Peak signal: The highest signal value between the threshold crossings

Click width: The number of samples between the threshold crossings

Click energy: The click energy calculated between the threshold crossings

These values are stored for every click that exceeds the detection threshold and can be used for later analysis. A count of the number of detected clicks is kept for each minute. The data for each day is stored on the system hard disk as a single file.

Although the click detection processing adapts to the changing ambient noise conditions, the final detection threshold is fixed. The aim was to try and make results comparable under varying acoustic conditions. However, this method is imperfect and there is an increased number of false alarms under some high noise conditions. If the ambient noise levels approach the threshold level then a high number of false alarms occur and this can happen under storm conditions.

It should also be noted that the threshold level affects the number of clicks detected and the measured click width. Throughout the measurement period care was taken not to make any changes to the equipment set-up that could affect the gain as this would affect the detected click rate.

The two most common sources of false alarms were from passing boats and bad weather. Some passing boats produced a signature with high transient content which met the detection criteria. One particular weather-related problem can occur when the wind opposes the tide and produces small breaking waves which result in a sequence of clicks.

The fixed hydrophone experiences tidal currents up to 2 knots. This will generate flow noise around the hydrophone. However, the level is very low and except under very quiet conditions was undetectable. The level is well below the threshold used. There is a potential for sediment transport noise but at no time during the study was this observed.

This detection scheme has been used with the fixed hydrophone at the study site throughout the period of this work. However, a number of difficulties were encountered which prevented the use of this click detection scheme for the spatial survey data. These included:

a. All of the acoustic data collection hydrophones were uncalibrated so it was not possible to set a consistent amplitude threshold for all the data.
b. The various acoustic data collection equipment had different frequency responses which modified the wideband clicks.

Methods

c. The observed click field characteristics depended on the hydrophone deployment depths due to the way the sound waves propagated in the very shallow water.
d. The characteristics of the background ambient noise varied considerably from site to site. Measurements in harbours were a particular problem because of the high number of mechanically-generated clicks originating from engine noise, boat transmission noise and mooring-related noise.

To avoid these problems a simplified method of aural assessment was used. Three categories were defined as:

1. No clicks heard
2. Less than approximately 50 clicks per minute
3. More than approximately 50 clicks per minute

The choice of 50 clicks per minute was subjective and was introduced to try and separate sites where there is a lot of click activity from those with very little activity. The most active sites could have up to 250 clicks per minute. The count was made subjectively by listening to the clicks. It was found that the first category was easy to distinguish but the boundary between categories 2 and 3 was more difficult to distinguish. However, the aim was not to produce an accurate count, more to separate sites with a very high level of activity from sites with a low level of activity. It should be noted that there is generally a continuum of click amplitudes and the apparent number of clicks can be affected by higher levels of ambient noise masking the weaker clicks. A fixed equipment gain was used at all survey points to avoid any variation in the apparent number of clicks. The gain was set to give reasonable listening levels at a quiet site.

The standardised listening period for the spatial survey was 5 minutes. This was chosen as being achievable at most of the sample sites. Many of the sites used were in areas open to the general public and from experience five minutes was about the longest achievable without an interruption.

Chapter 4

Equipment used

4.1 Introduction

This chapter describes the equipment used to carry out the spatial and temporal surveys and the localisation work proposed in Chapter 3. All of the acoustic equipment was designed and built specifically for this work. Table 4.1 summarises the equipment produced and its role.

Table 4. 1 Summary of equipment used

Equipment	Abbreviation	Role	No. hydrophones
Initial survey equipment	SHU1	Spatial surveys	1
Improved survey equipment	SHU2	Spatial surveys	1
Sandflat unit	SFU	Sandflat investigation	1
Black Hut fixed hydrophone		Temporal survey	1
UniClick	UC1	Localisation, spatial	1
BiClick	BC2	Localisation	2
Quadraclick	QC2	Localisation	4
Mini-QuadraClick	MQC2	Localisation	4

The methods of processing the collected data are also set out and performance limitations discussed. The methods of checking equipment operation during deployment are also discussed.

4.2 Survey equipment

4.2.1 Initial single hydrophone equipment

A small, easily portable acoustic system was designed and built to collect the click characterisation and spatial survey data away from the main study site. The equipment is shown in Figure 4.1 while a block diagram is shown in Figure 4.2.

The wet end unit contains the Graseby Instruments 20 mm ceramic ball hydrophone together with a preamplifier providing 32 dB gain. The preamplifier contains a high-pass filter rolling of at 6 dB/octave with a cut-off frequency of 720 Hz. The hydrophone has a resonant frequency of 75 kHz and is useable to 130 kHz. The preamplifier gain is 3 dB down at 300 kHz. The differential output signals drive a screened, twisted-quad core cable to the surface terminal unit.

Equipment

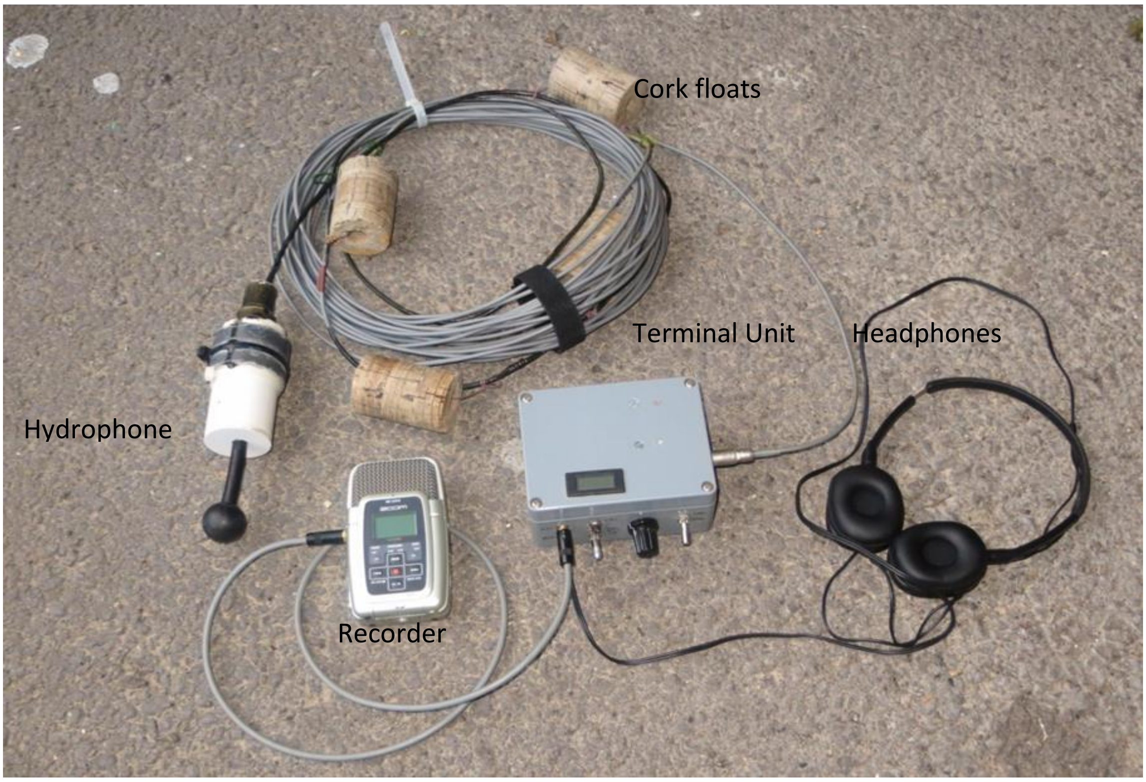

Figure 4.1 Initial survey equipment

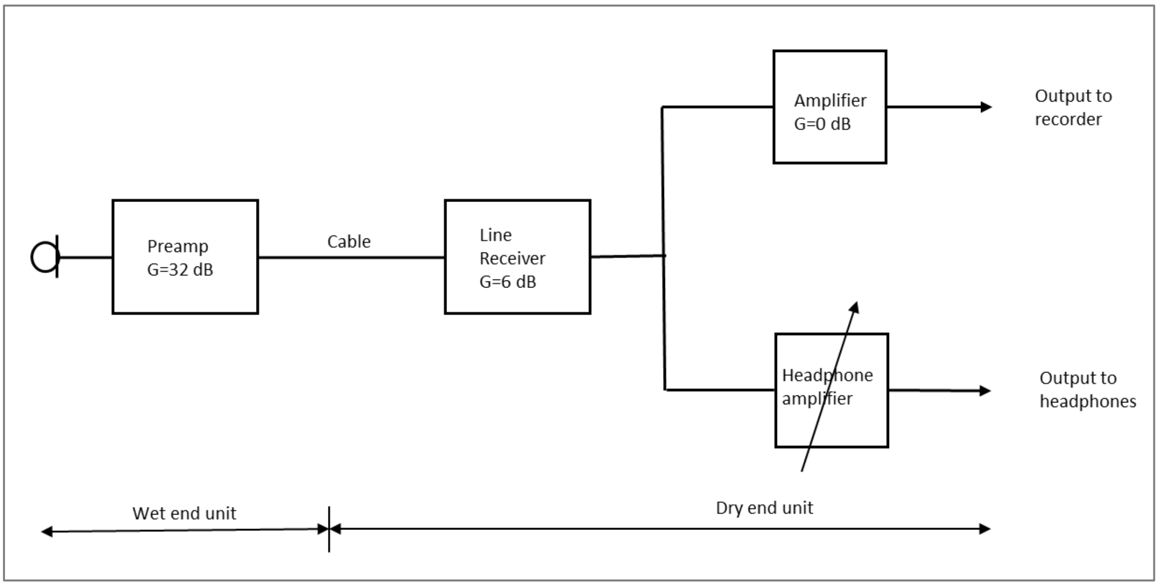

Figure 4.2 Block diagram of initial survey equipment

The wet end electronics are encapsulated in polyurethane and contained within a short section of uPVC 40 mm diameter water pipe. A length of sheet lead is wrapped around the outside of the uPVC pipe to make the unit negatively buoyant.

For deployments from a boat a number of cork net floats can be added as shown in Figure 4.1 and shown diagrammatically in Figure 4.3.

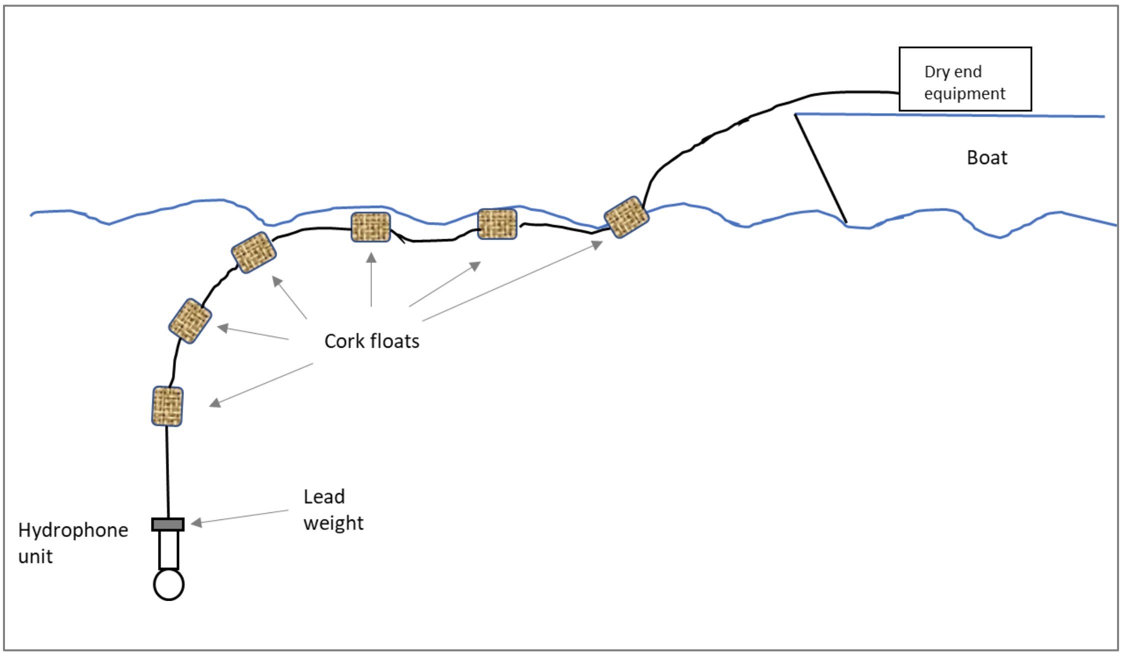

Figure 4.3 Diagram of cork float arrangement

The floats help to decouple the hydrophone from surface waves and from boat acoustic noise conducted down the cable. Cork was chosen over modern plastic net floats because it was found to be much quieter than the plastic floats. The float noise originates either from waves impacting the floats or from small movements of the cable within the floats. The hard plastic floats are very prone to abrasion noise compared with the cork floats which are softer and have a higher surface roughness and restrain any cable movements more effectively. Typically 5-7 floats are used. A small amount of lead is added to the hydrophone to ensure the first or second float is always under water.

The floats are not used when deploying from a quayside. Instead, the cable passes through the rings of a fishing rod and this is used to keep the hydrophone away from the quay wall.

The terminal unit contains a wideband instrumentation amplifier as a differential line receiver with 6 dB gain. An operational amplifier drives the recorder output and is suitable for driving many of the memory-card audio recorders currently available. The terminal unit also provides an output to drive headphones so the operator can monitor the signals. The unit is powered by two internal 9 Volt PP3 batteries.

When portability was important a Zoom H2 recorder was used as shown in Figure 4.1. The Zoom H2 has a problem when the input channels overload. Specifically, this can result in an internal low frequency oscillation. This could be triggered by a loud nearby click. The H2 was only used when small equipment size was important e.g. when travel to site included a flight. For most deployments a Fostex FR2LE recorder was used. Both recorders use memory cards as the recording media which can then be inserted into suitable card readers connected to a PC for data archiving and analysis.

4.2.2 Improved single hydrophone equipment

Later in the project the lightweight survey equipment terminal unit was replaced with a more capable unit. The new terminal unit allowed a wider range of gains to be set, could work with a variety of hydrophones, including the hydrophone shown in Figure 4.1, and included selectable high and low pass filters and an analogue click detector. A block diagram is shown in Figure 4.4 and the equipment is shown in Figure 4.5.

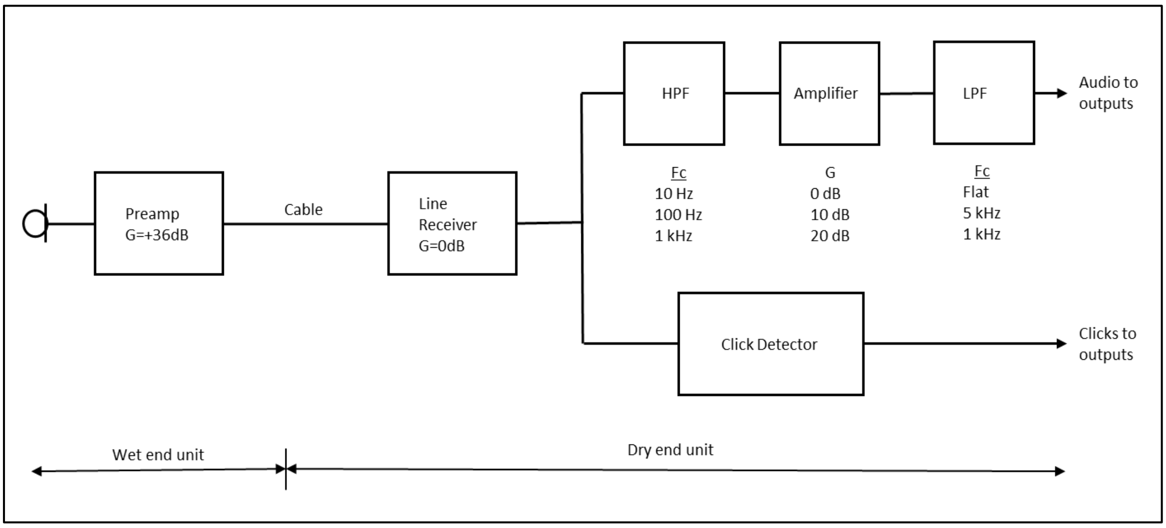

Figure 4.4 Block diagram of the improved survey equipment

The line receiver gain can be set by internal links to be either 0, 10 or 20 dB.

The new unit is powered either by two internal PP3 9 Volt batteries or from an external 12 Volt supply. The external supply allowed longer deployments to be carried out.

Figure 4.5 New lightweight survey equipment

A new smaller hydrophone unit was designed and constructed and this is shown in Figure 4.6. This hydrophone unit was physically smaller than the previous hydrophone unit and had a longer cable allowing greater portability and deployment from higher quaysides. The corks could be added for boat deployment as described earlier.

The Zoom H2 and Fostex FR2LE recorders were replaced with the newer Tascam DR100 MKII memory card recorder capable of recording with bandwidths up to 48 kHz and with 24 bit sampling. This recorder was smaller and lighter than the FR2LE and gave better audio quality than either of the two recorders previously used.

Figure 4.6 New hydrophone unit

The click detector allowed clicks with energy outside of the recorder bandwidth and outside of the range of human hearing to be detected. It consists of a 15 kHz fourth-order high-pass filter which also gives a gain of 6 dB, a full-wave rectifier followed by a 2 kHz low-pass filter as shown in Figure 4.7.

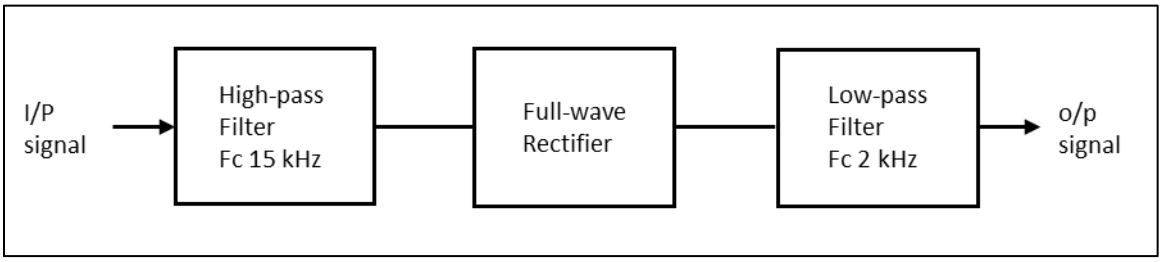

Figure 4.7 Block diagram of click detector

This circuit is used to look for ultrasonic clicks such as dolphin echolocation clicks.

4.2.3 Sandflat unit

A variant of the single hydrophone unit was built to investigate the clicking activity over sandflats. This used an identical hydrophone unit to that shown in Figure 4.6 together with a minimal terminal unit consisting of just the line receiver set to +20 dB gain, the Zoom H2 recorder and batteries all housed in a waterproof case. A block diagram is shown in Figure 4.8 and the assembly is shown in Figure 4.9.

Equipment

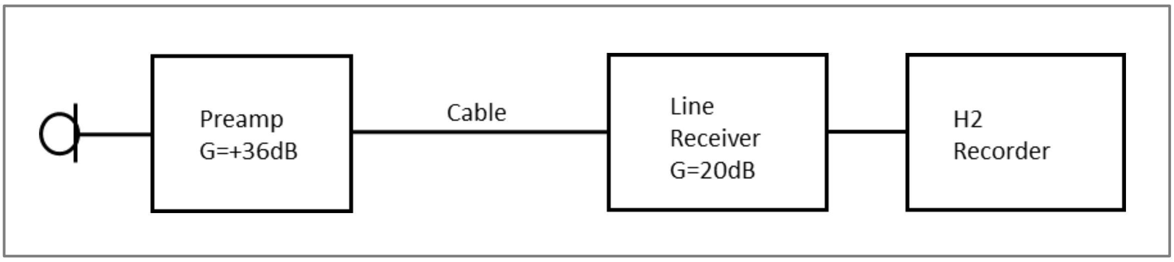

Figure 4.8 Block diagram of Sandflat Unit

Figure 4.9 Sandflat Unit assembly and deployed in Portland Harbour

The unit was deployed by walking the unit out to the required location and then leaving the unit with the recorder running for the requisite period. The pipe framework also included mounting arms for two GoPro cameras.

4.3 Temporal survey

4.3.1 Equipment

A further variant of the single hydrophone unit was installed at the study site to investigate the temporal variation of click activity. An omnidirectional hydrophone was installed on the seabed at the main study site adjacent to the BHRS. At mid-water it is approximately 12 m from the shore in a water depth of 3 m. The 20 mm diameter ball hydrophone is held 70 cm above the seabed using an arrangement of PVC pipes as shown in Figure 4.10. The hydrophone signal is amplified by 38 dB by a preamplifier contained within the PVC pipe. The hydrophone has a resonant frequency of ~75 kHz but is useable to over 140 kHz. The differential outputs of the preamplifier drive the signal up a twisted-quad core screened cable to the shore.

This picture was taken after the unit was recovered in February 2015 to repair a damaged cable. There is considerable fouling of the PVC pipework. The hydrophone was kept clear of this fouling while deployed by snorkelling down and hand cleaning the hydrophone and vertical pipe. This was necessary every 2-3 weeks in early summer when the algae is growing quickly but less often through the rest of the year. Excessive fouling of the pipes by dead eelgrass floating in the water column was also removed by snorkelling. The fouling occurs when the eelgrass dies off at the end of the summer and drifts onto the vertical pipe of the hydrophone stand. On most occasions the fouling was removed as part of the routine cleaning but on two occasions early in the five-year deployment the increase in the drag combined with a strong tidal current was sufficient to turn the unit on to its side. On both occasions the problem was corrected within days. Inspection of the acoustic data suggests that the impact on the collected data was undetectable. The eelgrass fouling problem was cured by laying two steel bars across the horizontal part of the PVC framework.

Figure 4.10 Temporal survey seabed equipment after recovery in February 2015

The signals are cabled ashore to the BHRS where a terminal unit provides power to the preamplifier and also provides further gain. The signals are then buffered to the PC, recorder and headphone outputs. The system block diagram is shown in Figure 4.11 and the terminal unit and SM2 recorder in Figure 4.12.

Equipment

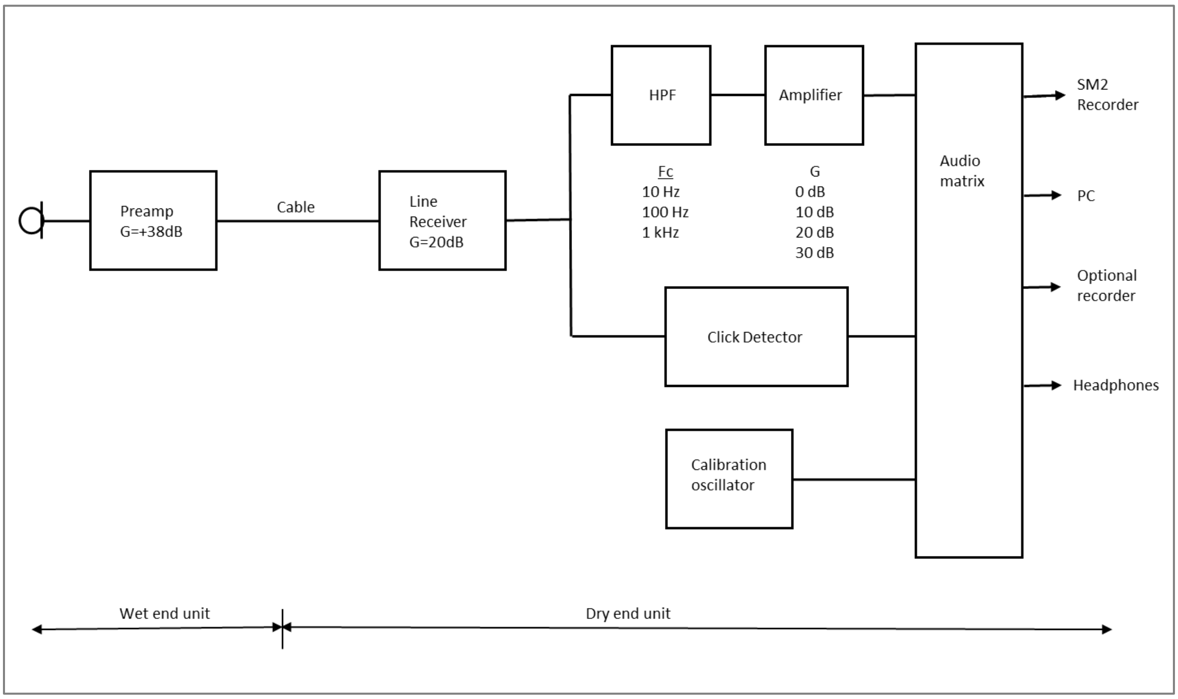

Figure 4.11 Diagram of BHRS equipment

Figure 4.12 Temporal survey terminal unit (grey box) and SM2+ recorder (green box)

A PC processed the acoustic signals, initially running the ISHMAEL[7] spectral analysis and recording package but later used the MATLAB[8] analysis software. A MATLAB function was written to automatically detect the clicks and gather statistics on the click activity.

Later in the project a Wildlife Acoustics SM2+ recorder became available (see Figure 4.12) and this was used to obtain raw acoustic recordings from the hydrophone. This recorder can run continuously for ten days on internal 'D' batteries or longer using external batteries. It samples the data at 48 kHz using 16 bit digitisation.

The temporal survey data-gathering equipment has run from 2009 until the present day. Initially there were a number of gaps in the data due to power cuts but this was mostly overcome by providing an Uninterruptable Power Supply (UPS) unit. One large gap occurred when the power

[7] Details of ISHMAEL can be found at www.bioacoustics.us/ishmael.html
[8] Details of MATLAB can be found at uk.mathworks.com/products/matlab

was cut off for eight months during the rebuilding of the Chesil Beach Visitors Centre which provides power to the BHRS. Gaps in the data have also been caused by a MATLAB memory leakage problem crashing the PC.

4.3.2 Click processing

The MATLAB function that was used to collect and process the data provides a number of displays and capabilities. Note that the displays are used only to assess system operation during data acquisition and therefore are sparsely annotated to maximise the available screen space for the plots. The system acquires acoustic data for the first 50 seconds of every minute at a sample rate of 48 kHz using a standard PC sound card. The first display, shown in Figure 4.13, has four sub-displays that allow the operator to assess the quality of the data being acquired. This display is refreshed every minute. Axes are unlabelled to save screen space.

The top left-hand panel displays the incoming waveform while the bottom left-hand panel displays the spectrogram of this data using 512 point FFTs. The top right-hand panel is the mean spectrum for the 50 seconds of data calculated using 256 point non-overlapping spectra. The bottom right-hand panel shows the variability plot for the acquired data. The variability plot is formed by calculating non-overlapping 256 point spectra for the 50 second period and then counting the number of times each frequency-amplitude bin is found in those spectra. This panel shows the resulting plot colour coded with the number of times each frequency-amplitude point was found. This allows a quick visual assessment of the degree of short-term variability in the data. This panel is not relevant to this project and was included to aid a separate study.

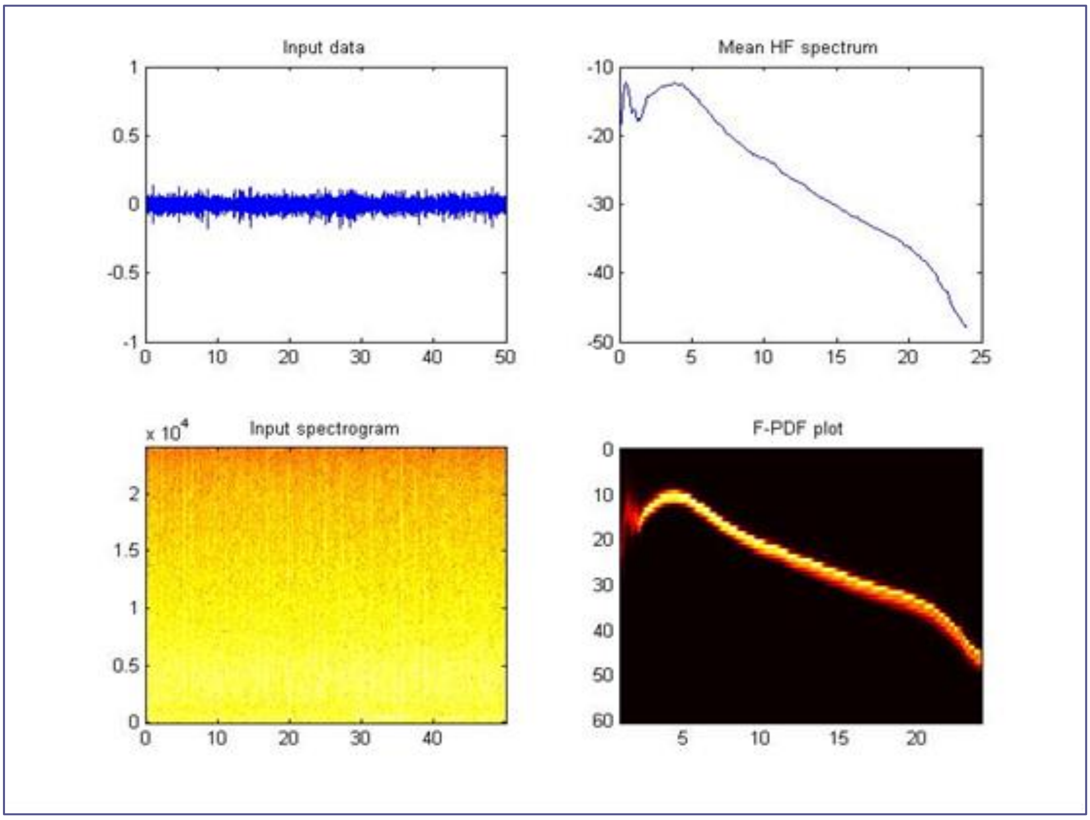

Figure 4.13 Input data displays provided by the temporal processing
(Frequency scales are 0-24 kHz, input amplitude normalised to FSD, time scales are 0-50 seconds. Spectra vertical scales in dB)

Equipment

The second display, an example of which is shown in Figure 4.14, is the mean spectrum for each minute plotted as a spectrogram for a period of one hour. The mean spectrum is calculated using non-overlapping 512 point FFTs across a 50 second data collection period. The data is decimated by 12 to form the LF spectrogram. The use of averaged spectrograms is a useful way of compressing long-term data into manageable displays and has been used by a number of researchers (e.g. Wiggins et al. (2016))

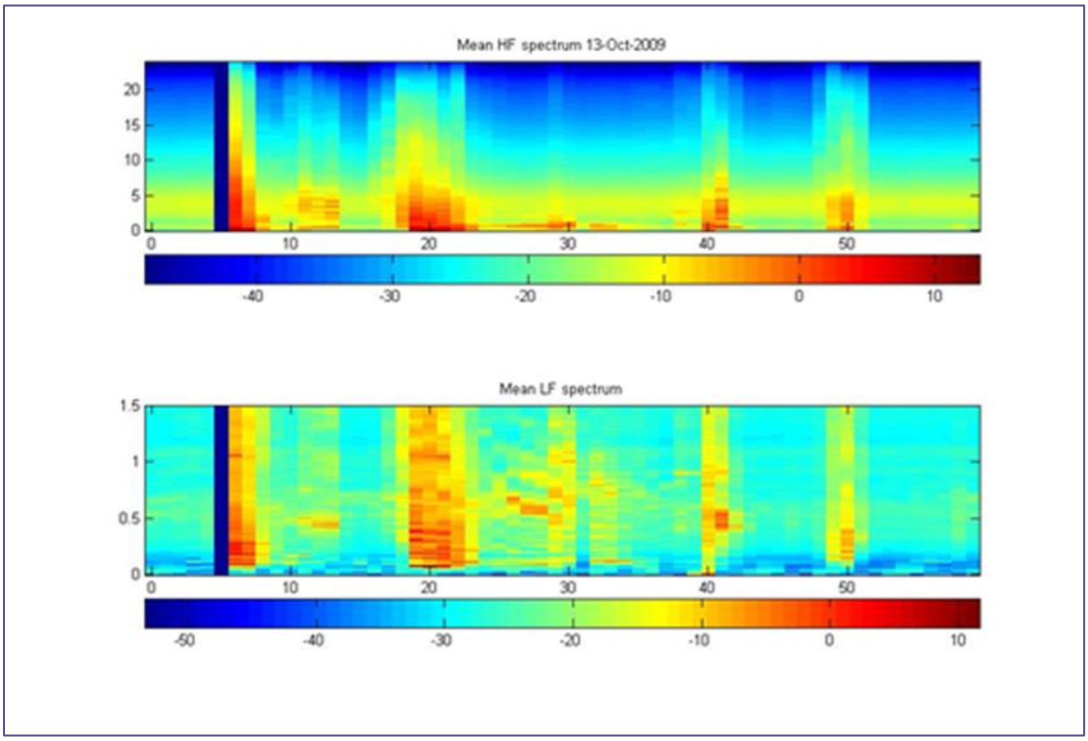

Figure 4.14 Mean spectrograms for a one hour period
(Each spectrum is the mean of 50 seconds, hor. scale 0-60 mins, vert. scale frequency in kHz)

The top display covers the frequency range 0-24 kHz while the bottom display expands the frequency scale and covers the range 0-1.5 kHz. The dark blue vertical bar indicates where the next update will occur. The plots show boat activity with four close passes (7, 20, 41 and 50 minutes) and some more distant activity in the background

The full twenty-four hours of mean spectrogram is also displayed. This uses the same spectra as the one hour display but displays twenty four hours of data. This display is saved to hard disk at midnight each day, the display cleared and the daily spectrogram for the following day then starts to build. An example of this is shown in Figure 4.15. The narrow bright vertical lines are boat passes. The vertical dark blue lines are one minute gaps in the data caused by the processing and occur every four hours. They are not always visible due to the way MATLAB compresses the spectrogram to fit the number of pixels available. The broad horizontal bars at approximately 1 kHz are shingle noise resulting from wave action on the nearby beach.

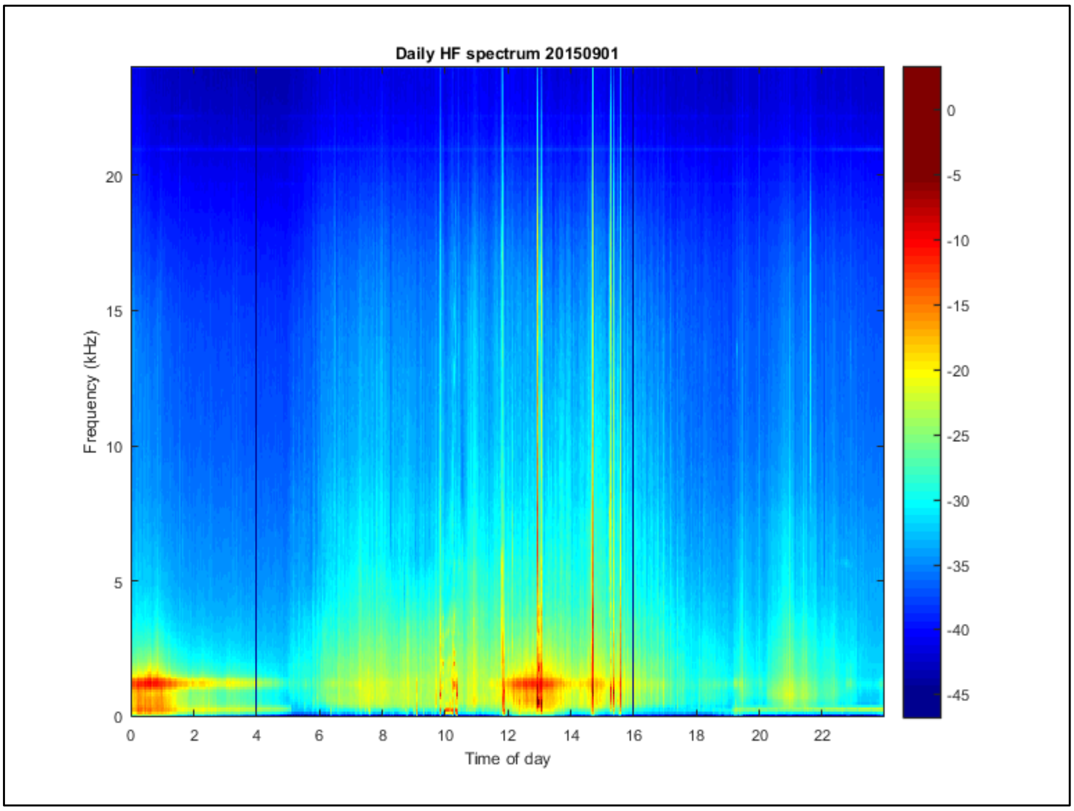

Figure 4.15 Example of daily spectrogram

After displaying the data the processing then searches the 50 seconds of data for clicks using the click detector described in Section 3.8. The detected click counts are displayed to the operator and also stored in a file on the computer hard disk for each twenty four hour period for later analysis. Figure 4.16 shows a typical click count display.

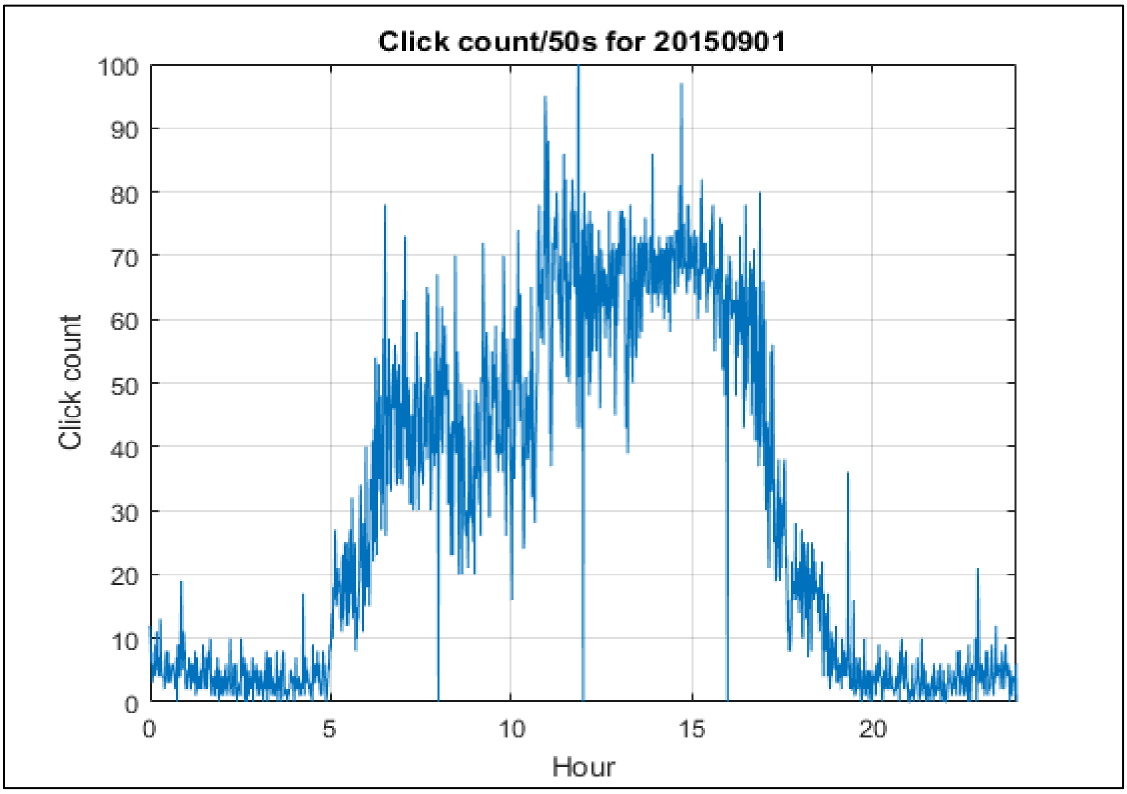

Figure 4.16 Example of variation of click count for each 50 s period over one day

Equipment

The click count is the number of detected clicks in each 50 second processing period. The RMS level of each 50 second period is also calculated and displayed. An example is shown in Figure 4.17. The Sound Pressure Level (SPL) is calculated based on the estimated calibration factors shown in table 4.5.

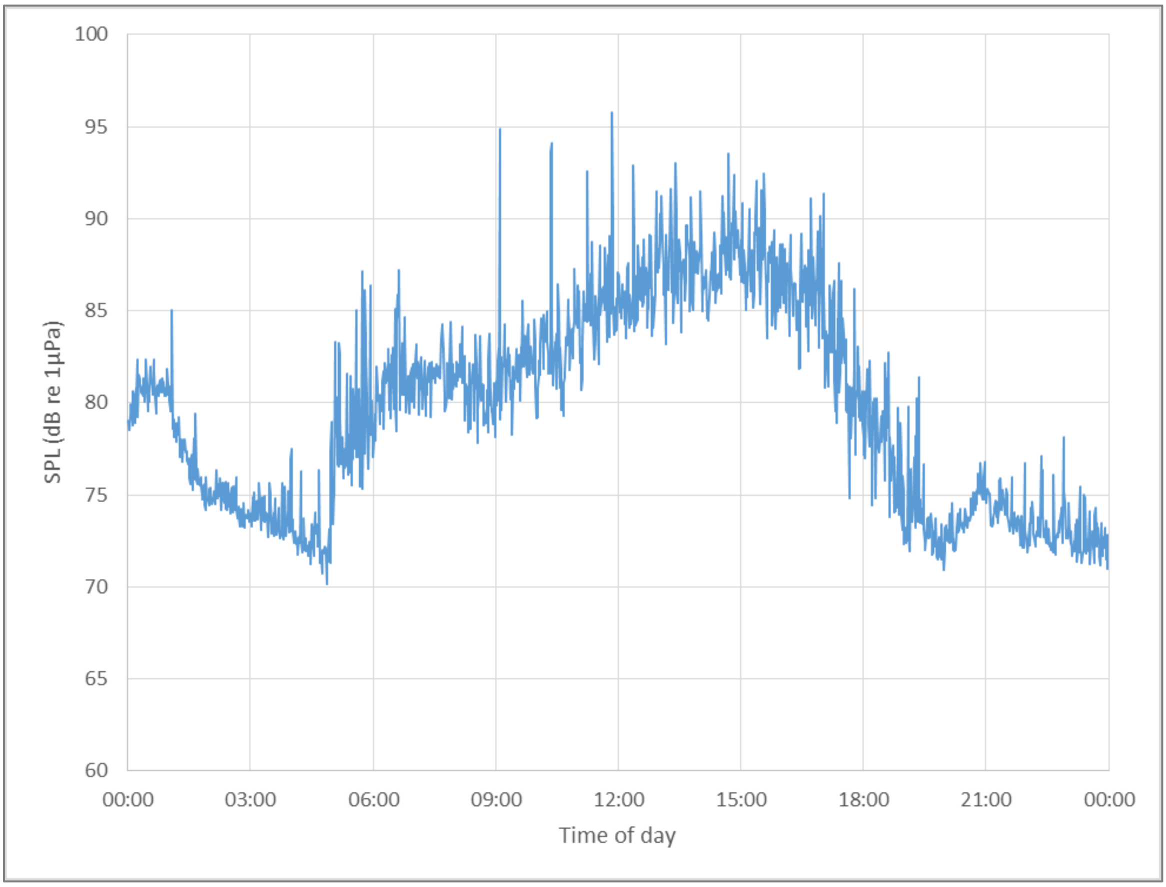

Figure 4.17 Example of the variation of the RMS wideband sound level over one day

The software stores the click counts and other measured data as a packed binary file. It also saves the click count, daily spectrogram and RMS plots as MATLAB figures.

4.4 Click localisation

4.4.1 Single hydrophone

A single hydrophone system with two GoPro video cameras was assembled for walking surveys to obtain coarse localisation data along a stretch of shoreline. The system, known as UniClick1 (UC1) is shown in Figure 4.18. The equipment is held in the hand while walking but is rested on the corner of the 'L' shape on the seabed while making recordings. However, it was found that with the base resting on the sea bed abrasion noise due to small movements of the pole was a major problem, particularly on sand. A soft cushion was added to the corner of the 'L' as shown in Figure 4.18 and later the rest of the pole was wrapped in hessian. A fishing rod rest was also obtained so that the operator did not need to hold the pole while recordings were made and this is shown in Figure 4.19. This reduced the noise to acceptable levels allowing survey work to be carried out but was still not wholly satisfactory. The main problem remaining was that the rod rest does not penetrate the sea bed sufficiently to prevent the pole from toppling over in strong currents.

A redesigned hydrophone support that further decouples the hydrophone from the seabed and the operator and which prevents water currents from toppling the whole arrangement is needed for any future work of a similar nature.

An unexpected hazard encountered when using this system was attacks on the operator by shore crabs. The work required the operator to stand very still for about seven minutes while the recordings were made to minimise unwanted noise. After 3-4 minutes a number of crabs would start crawling over the operator’s feet and attempted to feed on any exposed flesh. Future work will need to reconsider the whole methodology of how this system is used in order to minimise this problem.

Figure 4.18 UC1 walking survey equipment with two GoPro cameras mounted

UC1 uses the same terminal unit and recorders as the improved survey equipment described in Section 4.2.2

Figure 4.19 Walking survey equipment wet-end deployed on fishing rod rest

4.4.2 BiClick

BiClick uses two hydrophones to investigate the distribution and stability of the click field as set out in Section 3.5.2. The first iteration, known as Biclick1 (BC1), used two hydrophones each with integral preamplifiers, anchored individually to the seabed and supported using cork floats. However, it was quickly found that this arrangement was only usable in static water otherwise the hydrophones moved about unpredictably. To overcome the problems with BC1 a new arrangement was constructed, known as Biclick 2 (BC2). The hydrophones were now rigidly supported on uPVC stands 0.25 metres above the seabed as shown in Figure 4.20.

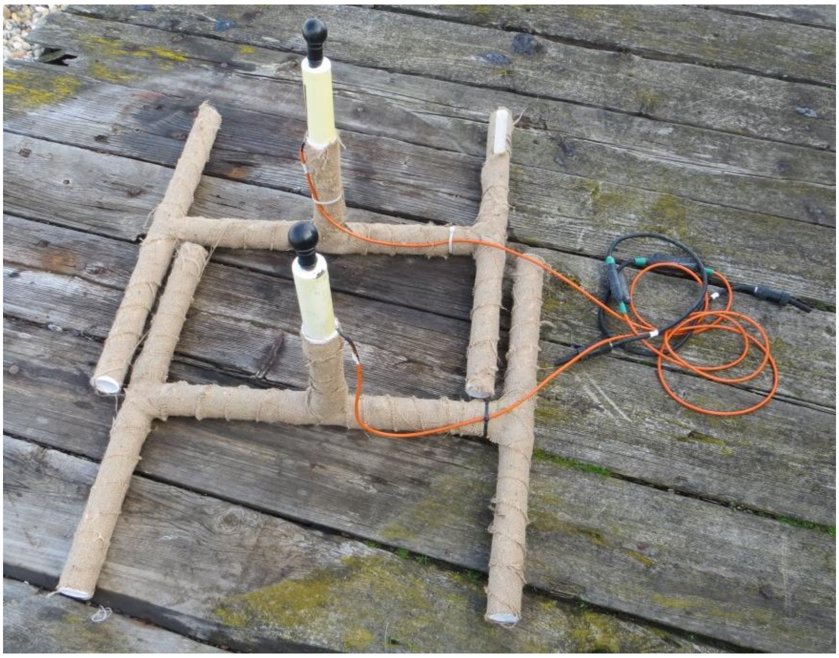

Figure 4.20 BiClick 2 hydrophone assemblies

The cabling allowed separations of up to 10.5 metres. The separation was set by using a measured length of rope with loops at each end that could slip over the hydrophones. The first hydrophone was deployed and the second hydrophone then positioned so the rope was tight. After deployment the measurement rope could be removed. Calibrated ropes were available for 4, 6 and 10 metres separations.

The unit was weighted using lead sheet inside the horizontal tubes. More lead was added on the lower outside of the vertical tubes to try and deaden biological abrasion noise as described in Section 4.4.5.

BC1 and BC2 use the same shore cable and dry-end terminal unit. The terminal unit is shown in Figures 4.21 and the block diagram of the system is shown in Figure 4.22.

Figure 4.21 Biclick dry end terminal unit

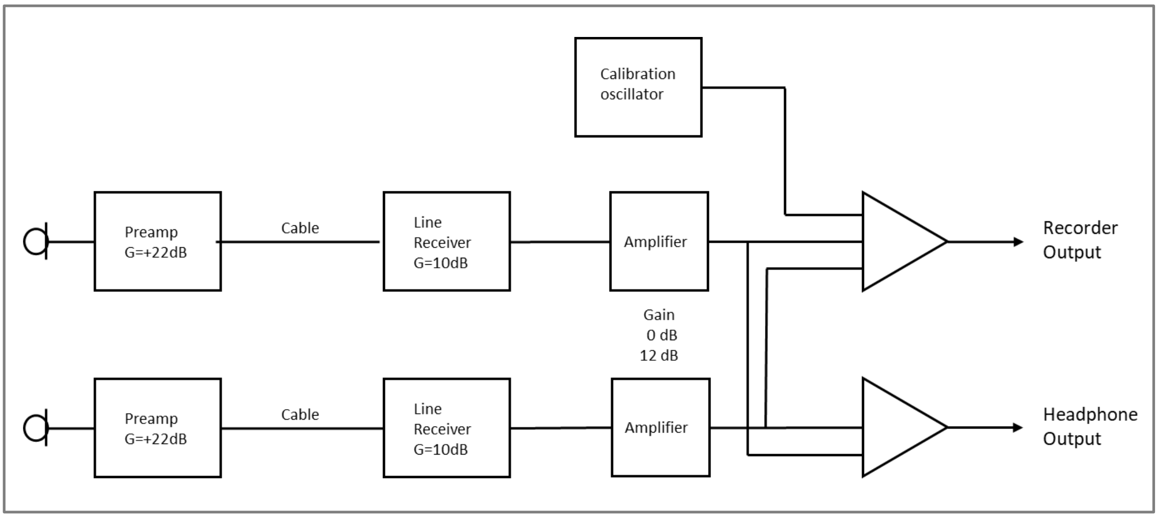

Figure 4.22 Block diagram of BiClick 2

The inputs from the hydrophones feed wideband instrumentation amplifier line receivers with a gain of 10 dB. An additional gain of 12 dB can be selected via a front panel switch. A button on the front panel allows a calibration tone to be injected into the output to the recorder. The unit provides differential outputs to the Tascam DR100 MK II recorder. There is also a separate headphone amplifier output to allow the operator to monitor the signals using stereo headphones.

The unit is normally powered by an external 12 Volt battery but it can also be powered from internal PP3 batteries for short term deployments and testing.

4.4.3 Quadraclick

Two versions of Quadraclick were produced as part of this project. The first version (QC1) used 40 mm uPVC pipework for the frame but this proved very difficult to deploy by walking it into position and also proved too weak once deployed allowing movement of the hydrophones in the tidal current. To overcome the problems of QC1 a new framework, Quadraclick 2 (QC2) was constructed. This was built using 32 mm diameter uPVC pipework and with two struts supporting the vertical section. Figure 4.23 shows the framework with hydrophones and cameras mounted.

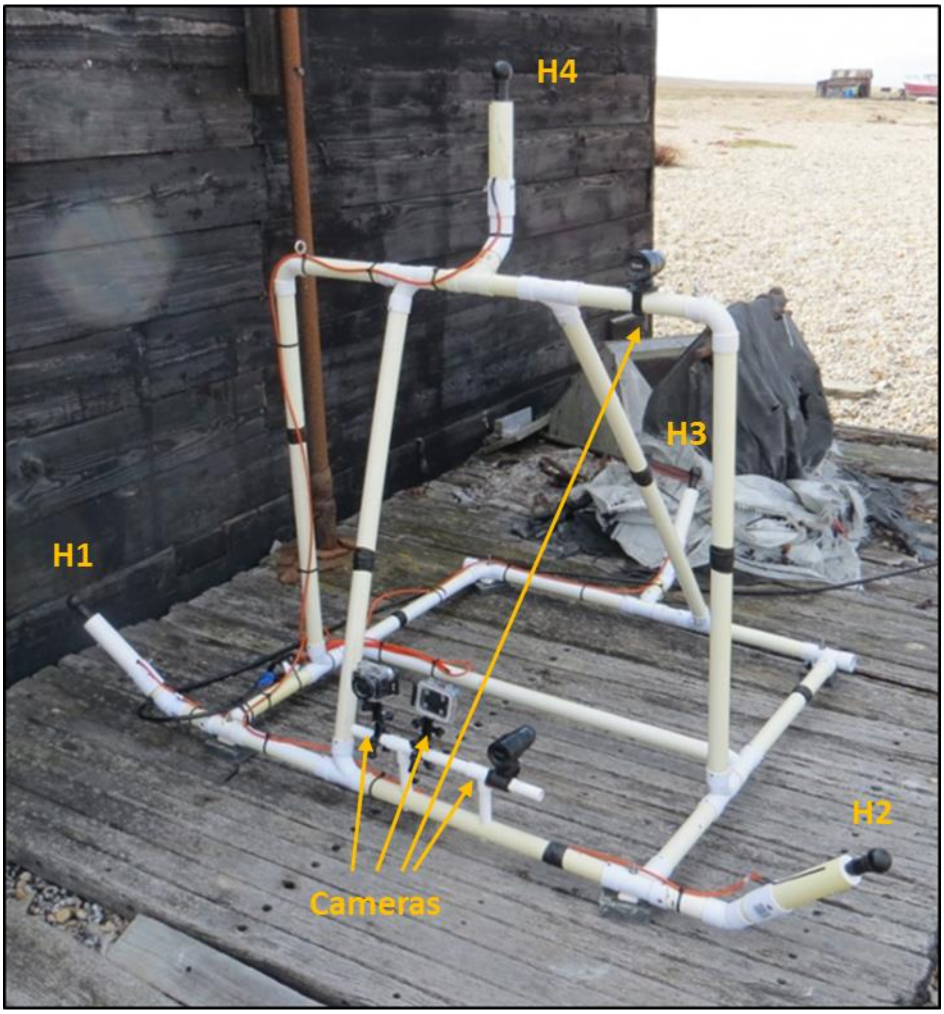

Figure 4.23 Quadraclick 2 assembly with cameras mounted ready for deployment

This framework was much improved compared with QC1 with less movement of the upper hydrophone and easier handling. QC2 used the same hydrophones as QC1 with size adapters to allow them to be mounted on the smaller pipes of the new framework. QC2 also used the same shore cable and dry-end terminal unit as QC1.

Each hydrophone channel consisted of a 25mm ball hydrophone with integral preamplifier giving 22 dB gain. The preamplifier rolls-off at 6dB/octave below 100 Hz and is flat to beyond 200 kHz. The dry end unit consists of a differential line receiver with a gain of 15 dB followed by unity-gain buffers for the signals to the DR680 recorder. A block diagram of the QC2 equipment is shown if Figure 4.24.

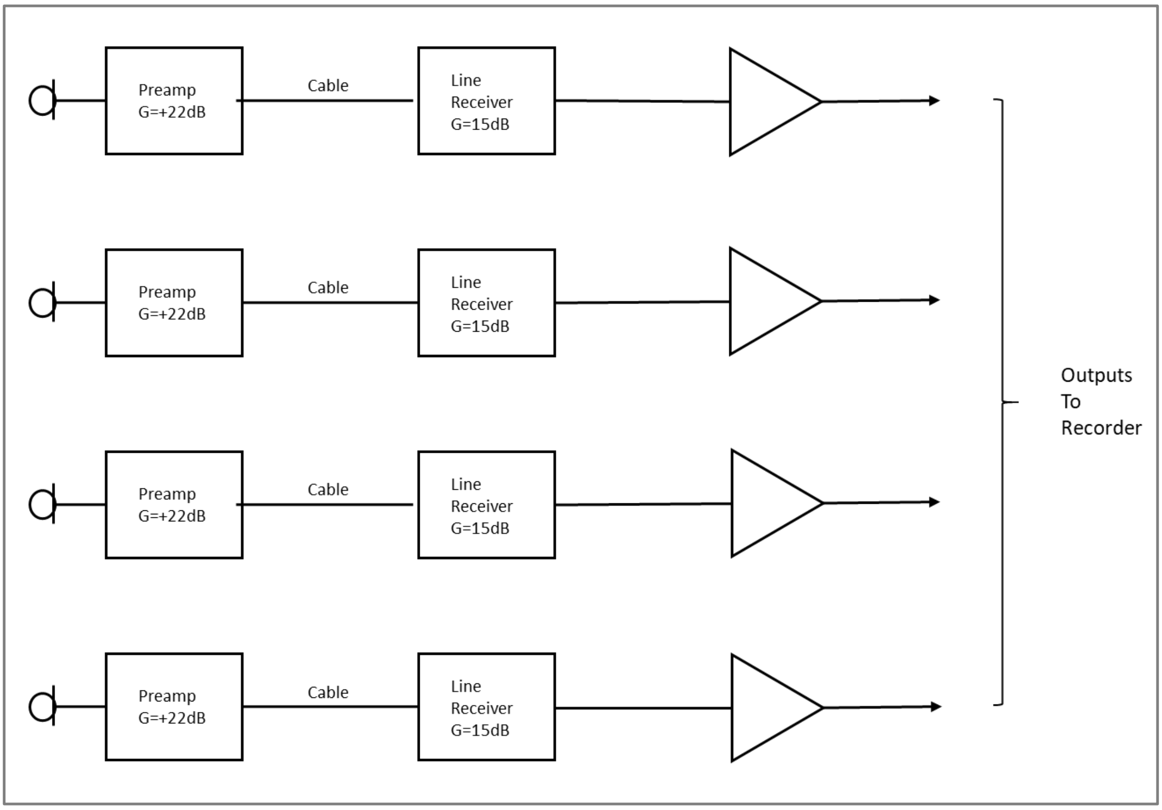

Figure 4.24 Block diagram of the Quadraclick 2 equipment

The QC2 hydrophone locations relative to hydrophone H1 are shown in Table 4.2 below and identified relative to the axis in Figure 4.25.

Table 4.2 Hydrophone locations for QC2, spacings in metres

Hydrophone	X	Y	Z
H1	0	0	0
H2	1.69	0	0
H3	0.82	1.61	0
H4	0.824	0.35	1.09

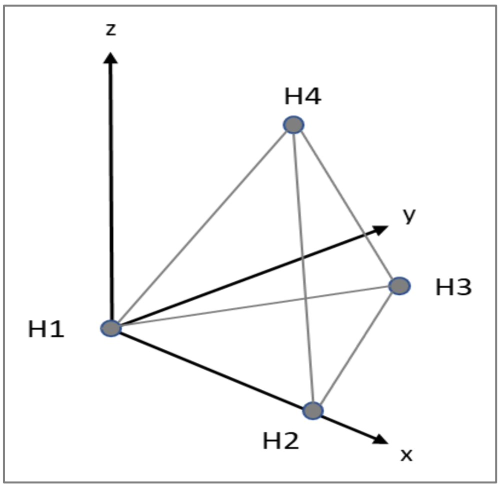

Figure 4.25 Location of hydrophones

Equipment

The QC2 framework was used to acquire data in the shallow water on the edge of the Fleet but it proved too cumbersome to control when deploying in the deeper water of the channel, particularly if there was a tidal current. To allow deployments in the deeper water an even lighter version of the framework known as Mini QuadraClick 2 (MQC2) was then constructed.

4.4.4 MiniQuadraClick 2

The assembled MQC2 is shown in Figure 4.26. It uses a rigid inner framework of 21.5mm uPVC pipe with the hydrophones on protruding arms to achieve a spacing of approximately 1.1 metres. Although this reduced system could only cover a reduced volume with comparable accuracy to QC1/2 it was felt this limitation was acceptable in view of the much easier handling. In practice MQC2 did prove to be rather more delicate than QC2 because of the smaller size pipes and the protruding hydrophone arms.

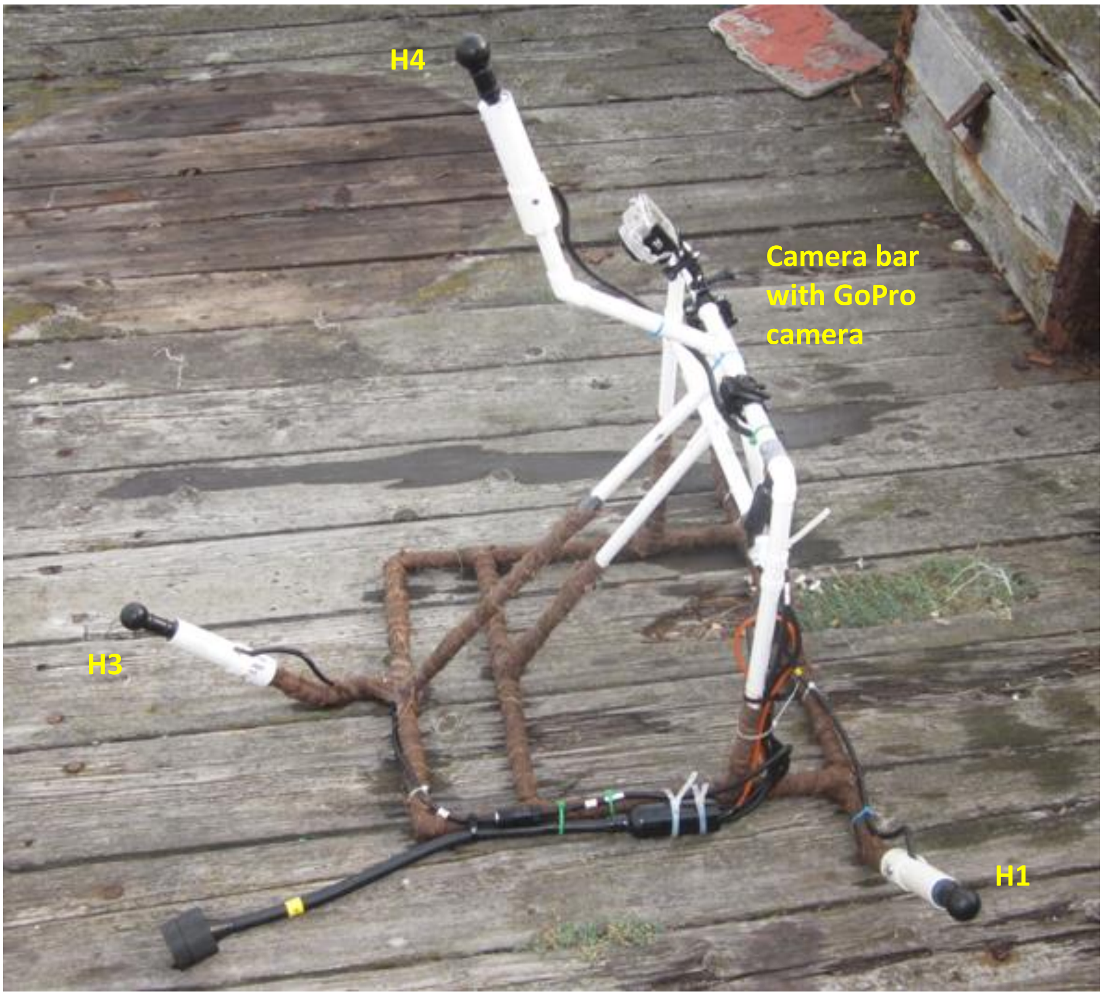

Figure 4.26 MQC2 assembly with one camera mounted

The alignment of the hydrophones on the axes are the same as for QC2 and shown in Figure 4.25. The hydrophone locations for MQC2 are shown in table 4.3.

Two cameras can be mounted along the top bar of the framework.

Table 4.3 Hydrophone locations for MQC2, spacings in metres

Hydrophone	X	Y	Z
H1	0	0	0
H2	1.17	0	0
H3	0.54	0.895	0
H4	0.598	0.473	0.647

For MQC2 a new set of hydrophone/preamplifiers were built to cater for the reduced pipe diameter. The hydrophones were the same type as used on QC2 but the preamplifier was housed in 32 mm uPVC pipe and encapsulated in polyurethane. A PVC size reducer was then used to mount the unit on the 21.5 mm diameter arms. The gain of the preamplifier was increased to 28 dB. As with the QC2 hydrophones the frequency response of the preamplifier rolled off below 100 Hz at 6 dB/octave and was flat to over 200 kHz.

4.4.5 Biological noise problem

Initial deployments of BC2 and QC2 were marred by unwanted biological noise. PVC pipes are very sensitive to the scraping sound produced by shore crabs crawling on the structure. Early versions of BiClick and Quadraclick included a bait holder with the aim of attracting the species making the clicks, However, it only succeeded in attracting even more shore crabs with resulting abrasion noise so its use was abandoned.

An initial attempt to reduce the abrasion noise used sheet lead wrapped around each hydrophone arm to stop sounds travelling along the PVC arms to the hydrophones. This resulted in a reduction in noise levels but did not solve the problem.

For later deployments of MQC2 and BC2 all of the lower pipework was wrapped in hessian sheet glued on with a latex-based rubber glue as can be seen in Figures 4.20 and 4.26. This reduced the crawling noise to a very low level that did not cause problems during click localisation.

4.5 Calibration and noise level

The aim of this project is to understand the clicks and to identify what species may be producing them. Although accurate calibration of the hydrophones would have allowed accurate measurements of click levels and ambient noise levels the cost of these calibrations was beyond the available budget. However, it is useful to establish approximate ambient noise levels at the various sites when attempting to compare click activity and it would be useful to be able to estimate the source level of the clicks during the localisation work.

All the electronic equipment constructed for this project was calibrated for gain and frequency response using standard laboratory test equipment. For the hydrophones, where the manufacturer’s hydrophone sensitivity was known this was used, otherwise the sensitivities shown in Table 4.4 were used.

Equipment

Table 4.4 Hydrophone sensitivities

20 mm ball hydrophone	-200 dB re 1V/µPa
25 mm ball hydrophone	-197 dB re 1V/µPa
30 mm ball hydrophone	-194 dB re 1V/µPa

These figures are an average across data from a number of hydrophone manufacturers. There can be a large variations in sensitivity for similar size hydrophones from different manufacturers and the figures quoted here may be up to +/-6 dB in error.

Table 4.5 below sets out the calibration information for each of the systems used.

Table 4.5 Equipment calibration factors

Unit	Cal tone level	Cal. Factor	Gain settings
Initial survey unit	900mV	-155 dB re 1µPa/V	N/A
Improved survey unit	25mV	-168 dB re 1µPa/V	0/10/20/30 dB
Sandflat unit	N/A	-154 dB re 1µPa/V	fixed
BiClick	80/320 mV	-157 dB re 1µPa/V	0/+12 dB
QC2/MC2	N/A	-166 dB re 1µPa/V	fixed
Fixed hydrophone	50mV	-147 dB re 1µPa/V	0/+20 dB

Most of the equipment included a gain selection switch. The calibration factor shown is with the switch set to the lowest gain.

The largest source of calibration error could come from the recorders used. They were all intended for the high quality audio market where accurate calibration is not a requirement. Analogue gain controls on the record inputs are usual and can easily be knocked during field work. To overcome this most of the dry end equipment included a signal source with a known output level, a calibration tone, which could be activated by the press of a button. This allowed a known signal to be inserted at the start and end of each recording.

The hydrophone units all use an OPA1641 JFET operational amplifier as their first stage of amplification. The manufacturer's data sheet gives an input noise level of 5 nV/√Hz above 1 kHz. Below 1 kHz the noise level starts to rise due to the 1/F noise associated with junction FETs. Assuming a hydrophone sensitivity of 197 dB re 1 µPa then this noise level corresponds to a sound pressure level of 31 dB re 1 µPa. This is below sea state 0 noise (Waite, 2005) to 10 kHz and below sea state 2 noise to beyond 100 kHz.

4.6 Acoustic propagation

4.6.1 Introduction

In the very shallow water encountered during this project the spectral content of the very wide bandwidth of the clicks is likely to be considerably modified by the propagation conditions. This section discusses how the clicks may be modified and the potential impact on the measurements made.

4.6.2 Absorption

As an acoustic pulse propagates the higher frequencies are absorbed more than the low frequencies (e.g. Figure 3.2 in Waite (2005)). At 100 kHz this may be as high as 60 dB/km. giving an additional 0.6 dB loss compared with low frequencies at 10 metres range. Although this effect is small at the low ranges encountered during this project it does contribute to the increasing distortion of the click with increasing range.

4.6.3 Multi-path

A click radiated from a near omnidirectional source will interact with the sea surface and sea bed. These paths will be longer than the direct path and will have the effect of smearing the click in time. As an example, a mid-water click in 2 metre deep water and at 10 metres range with a single reflection from the surface will travel 0.77 metres further compared with the direct path resulting in a 0.71 ms delay while a single reflection from both the sea surface and the seabed will travel 2.8 metres more than the direct path resulting in a 1.87 ms delay. These delays are comparable with the click pulse widths observed.

In addition to the smearing in time, as the contributions from the multiple paths add together nulls and peaks will be introduced into the spectral content. In its simplest form this will introduce the Lloyds mirror effect (e.g. see Figure 5 in Kuperman and Roux (2007) or page 123 in Urick (1983)) of regularly spaced nulls and peaks. In the complex multi-path environment of very shallow water there may be many such contributions, each with their own null spacing, resulting in a very complex spectrum. This is further complicated by the short pulse lengths of the clicks meaning that not all contributions arrive at the same time so the complexity of the spectral content will vary through the observed pulse length.

If the click source is buried in the seabed then it is likely that a further propagation path will exist through the seabed. The speed of propagation is likely to be faster than that through a water-only path so this may introduce an early arrival path further increasing the time dispersion of the observed click.

In the cluttered environment encountered during this work it is also possible to get reflections from anthropogenic debris on the seabed. Within the study area there are a number of large metallic objects either discarded or used as moorings. These include a metal hip bath, a railway wheel and a framework from a marina pontoon. These reflections will generally be more distant than the sea bed or sea surface and will further increase the time extension of the click.

Under some tidal conditions and during windy weather there will be increased surface wave activity and this will increase the surface area contributing to the multiple arrival paths and further complicate the effect of surface reflections.

4.6.4 Dispersion

An effect sometimes seen on wideband pulses propagating in shallow water is dispersion in time where the velocity of propagation is dependent on frequency. This effect often results in the lower frequencies travelling more slowly than higher frequencies. The effect is more pronounced on clicks travelling from greater ranges. It was particularly observed during the deployment of the sandflat unit (SFU) (see Section 6.3.2) where clicks originating from the channel have to travel through water only 2 metres deep and over ranges approaching 100 metres.

4.6.5 Impact on the work

The combination of the various propagation effects mean that the click arriving at a monitoring hydrophone may suffer considerable distortion and bear little resemblance to the original click. The combination may vary considerably from one click to the next as small changes in the location of the click source or small changes in the environment can have a major impact on the received click characteristics. This meant that the click characterisation work could only use short range clicks in order to get a reasonable facsimile of the originated clicks. It also meant the high degree of variability made automated recognition of the click types very difficult.

4.7 Processing the acoustic data

4.7.1 Introduction

The acoustic data gathered using the systems described in Sections 4.2 to 4.4 needs to be processed to extract relevant information. In the case of the BiClick and Quadraclick system the data needs to be processed to extract time of arrival information for each click. This can then be further processed to provide localisation information.

The acoustic systems can provide a very large quantity of data. As an example, 10 minutes of data from MQC2 is a 675 MB file. This section provides information on the method used to process this data.

4.7.2 Waveform display and time-of-arrival measurement

The first stage of processing the data consists of a visual inspection of the time series of each click displayed using the BiClick or MC2click MATLAB function. The BiClick routine displayed two channels while the MC2click function displayed four. An example of the initial display of one second of the waveform from each of the four MQC2 hydrophones is shown in Figure 4.27. The horizontal scale is sample number, the vertical scale is amplitude with offsets added to separate the traces. The amplitude scale is not calibrated and is adjusted to maximise the dynamic range to allow best choice of click starting time.

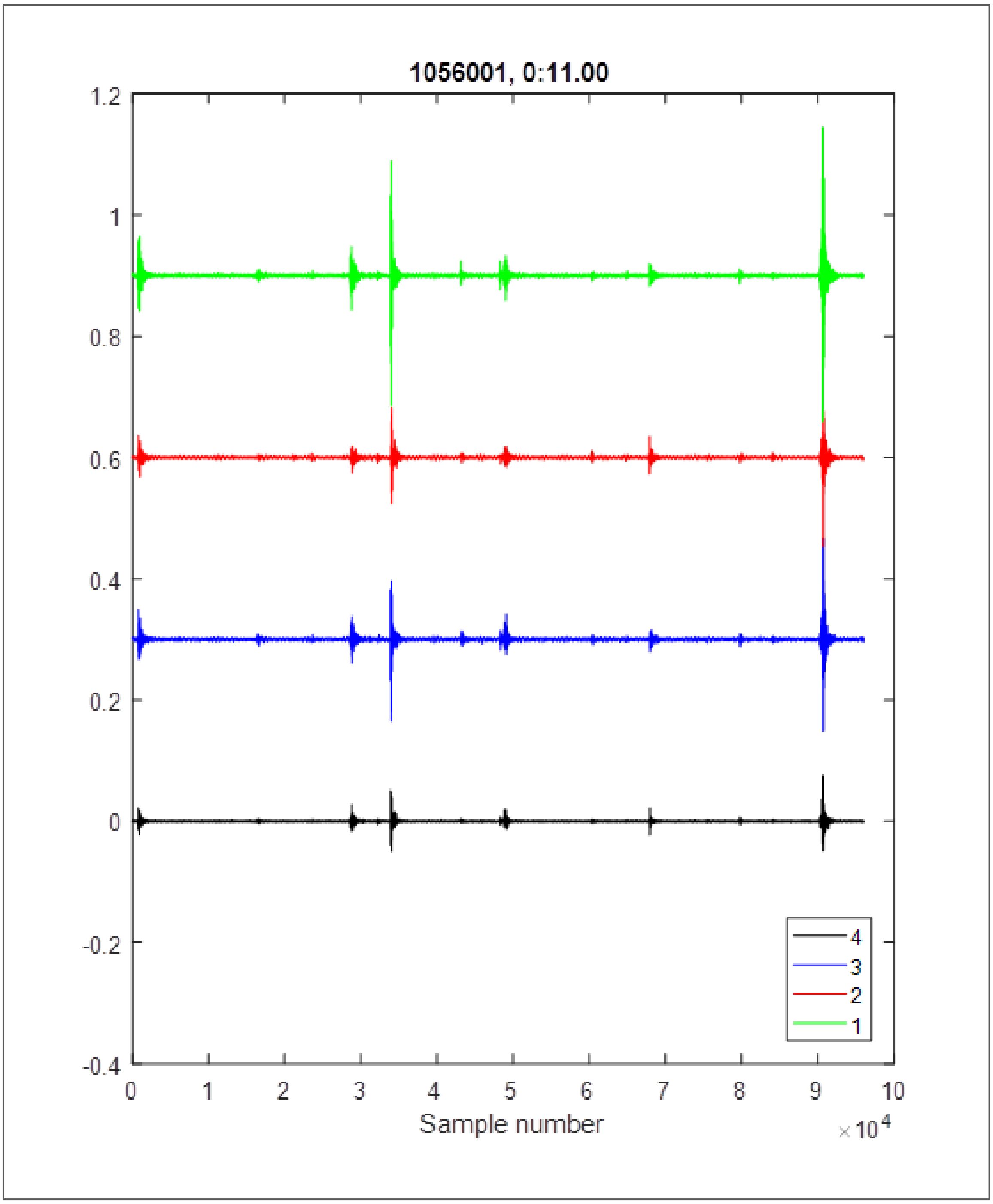

Figure 4.27 One second of data displayed by the MC2click function
(Vertical scale +/-0.4 of FSD with offsets of 0, 0.3, 0.6, 0.9, horizontal scale 1-96,000 samples i.e. 1 second of data)

The hydrophones run in order from hydrophone 1 on the bottom trace (black) to hydrophone 4 on the top trace (green). The operator then uses the MATLAB expand function to zoom in on a click of interest, as shown in Figure 4.28. This shows the click at 33,900 samples in Figure 4.27 expanded ready to select the start times. A cross-hair cursor is then activated and moved using the mouse to select a feature near the start of the waveform that is identifiable from all four hydrophones. Some clicks could not be processed further either due to distorted waveforms, overlapping clicks or interfering noise. In this example the click is close to hydrophone 1 and between hydrophones 1 and 3. The start sample is measured starting with hydrophone 1 and then in order to hydrophone 4. These start times are stored to a file.

Figure 4.28 also illustrates how different the waveforms from the hydrophones can be. Hydrophone 4, the uppermost hydrophone shown by the green trace, is often affected by surface reflections and can show a waveform very different to the other three hydrophones.

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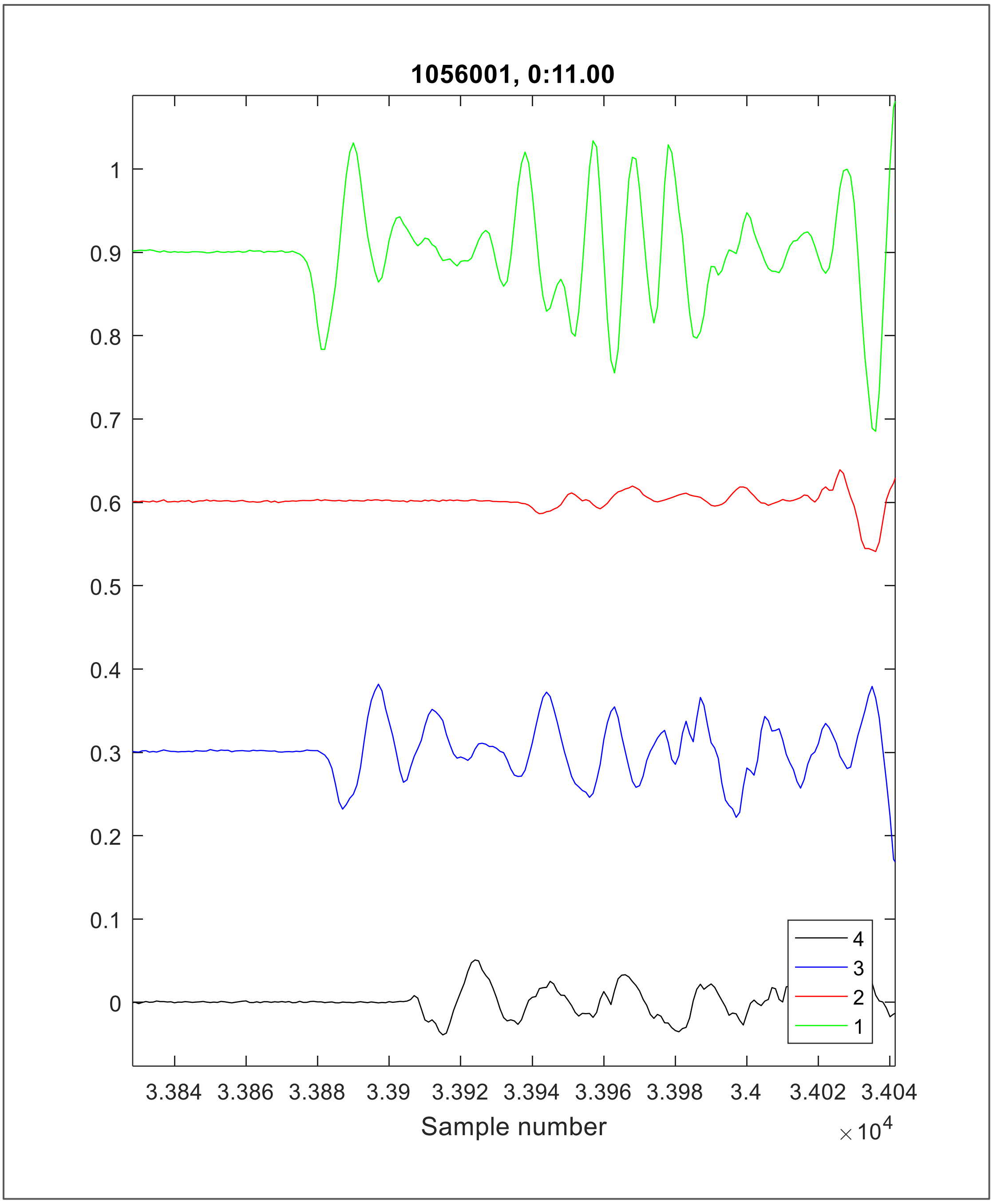


Figure 4.28 Expanded display of the click at 33,900 samples in Figure 4.27

The process is repeated to build up a list of clicks containing the start times for each hydrophone. The list is then output as a CSV file for further processing in EXCEL.

4.7.3 BiClick processing

For BiClick signals the time delay was then plotted as a time history and as a histogram an example of which is shown in Figure 4.29. The left hand pane shows the time history of the clicks while the right hand pane shows the count of clicks in each ¼ millisecond interval. The interval used depends on the hydrophone separation and is chosen to give a suitable number of bins to demonstrate the click distribution and ranges from 0.05 to 0.5 ms. In this example the plots extracted from 80 seconds of data from a BiClick deployment at the study site described in Section 3.7 that took place in October 2013 are shown.

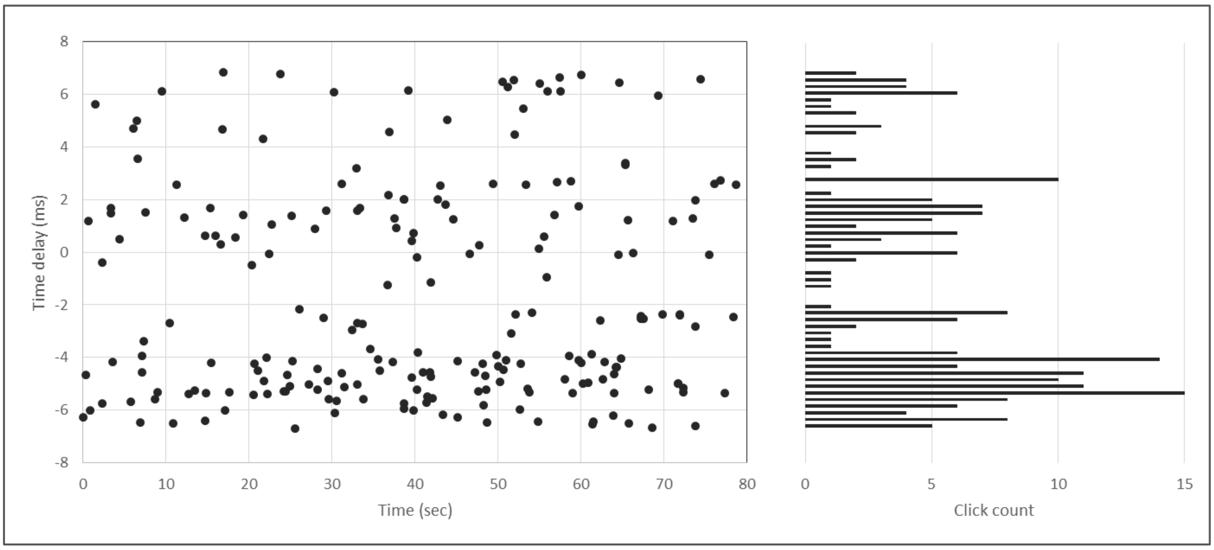


Figure 4.29 Example of Biclick data plots. Hydrophones parallel to shore NW-SE direction. NW is top, SE is bottom of plot.

The time delays can also be converted into a far-field arrival angle using equation 4.1.

$$angle = \cos^{-1}(deltime / endtime) \tag{4.1}$$

where: *deltime* is the difference in arrival time,
endtime is the time difference along the axis of the array

The expected delay distributions were investigated using a uniform field of click sources. Two hydrophone separations were investigated: 4 and 10 metres. For each separation three cases were calculated: free field, a seabed at -0.25 metres and a seabed at -0.25 metres combined with the water surface at +2 metres. The time difference of arrival (TDOA) at the hydrophones was calculated for a three-dimensional array of click locations spaced 0.02 metres apart. The velocity of sound used was 1500 m/s. The histogram of the TDOAs was then calculated and the results for the two separations are shown in Figures 4.30 and 4.31.

For these plots a maximum click detection range of 12 metres is used as this is similar to that achieved with real clicks. The histogram bin width for the 4 metre separation is 0.1 ms and for the 10 metre separation is 0.25 ms. The vertical axis is the count of locations that could contribute to each bin in the histogram normalised to the count from the free space bin with the highest number of contributors.

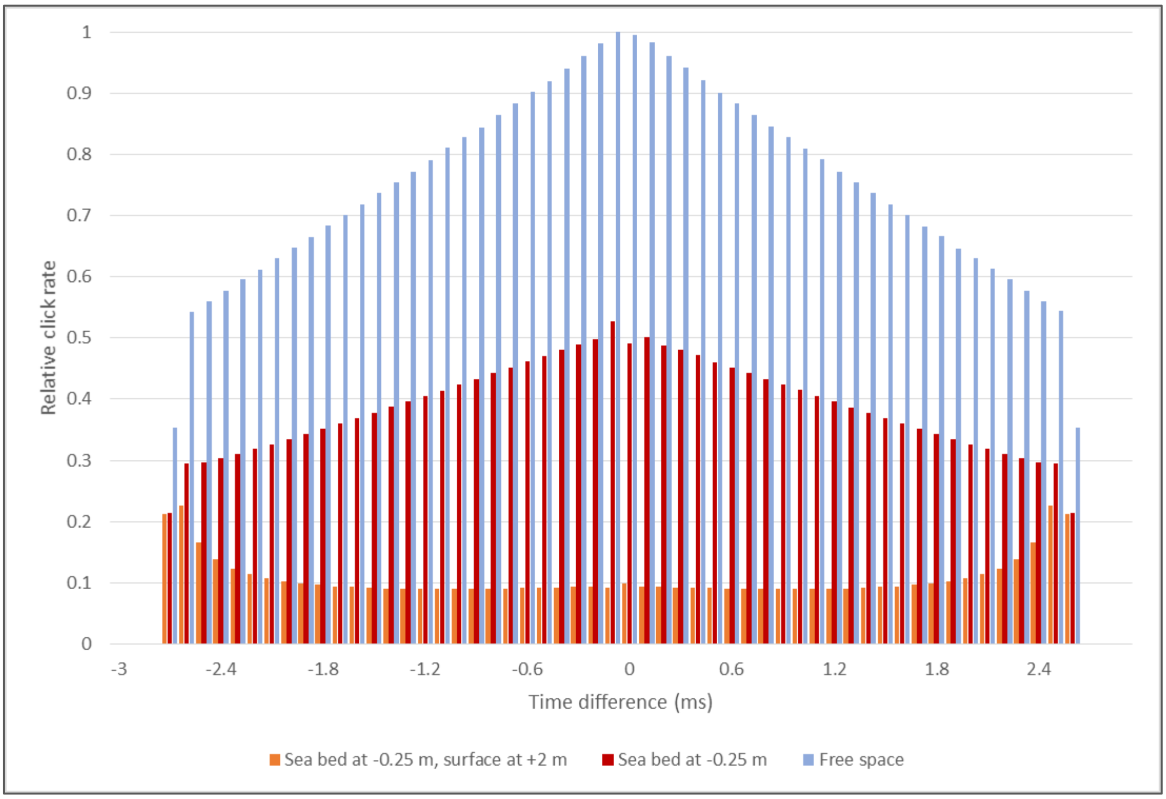


Figure 4.30 Click distribution plot for 4 metre hydrophone separation

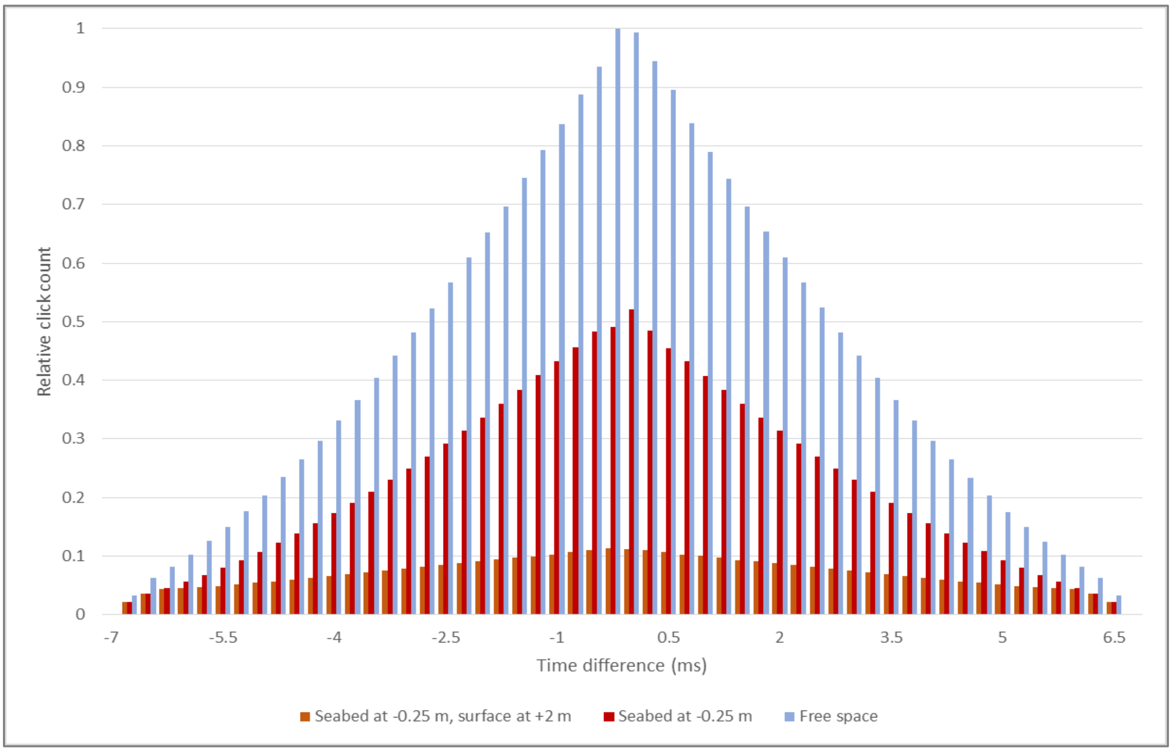


Figure 4.31 Click distribution plot for 10 metres hydrophone separation

The asymmetry apparent on the plots around the zero delay is due to an interaction between the sampled location and the histogram sampling.

In the free field case the total number of locations contributing is determined by the common volume of two intersecting spheres of diameter equal to the maximum detection range and centred on each of the hydrophones. When the seabed and surface are present then this common volume is constrained by the plane surfaces.

The volume contributing click locations to a histogram bin lies within a hyperboloid centred along the line between the hydrophones and limited in range by the maximum detection range. When this hyperboloid is further constrained by the presence of the sea bed and sea surface the broadside directions are affected first then as the seabed and sea surface approach the line of the array the hyperboloids corresponding to increasing TDOAs are progressively intersected and the count reduced leaving only the endfire hyperboloids unaffected. This effect is most apparent in the 4 metre separation case and results in peaks in the endfire directions.

4.7.4 Quadraclick processing

For the Quadraclick data, the time delays were then processed using the method set out by (Spiesberger, 2001) and later by (Zimmer, 2011) implemented as a function in MATLAB.

The distance between the nth hydrophone at r_n and the click source at s is given by

$$R_{sn}^2 = (x_n - x_s)^2 + (y_n - y_s)^2 + (z_n - z_s)^2.$$

We do not know the individual ranges to each hydrophone but it is possible to measure the time-difference of arrival at each hydrophone t_{n1} relative to a reference hydrophone r_1.

$$R_{sn}^2 = c^2(t_{n1} + t_1)^2.$$

Where c is the velocity of sound and t_1 is the travel time from hydrophone 1 to the source

This expands to give

$$r_x(n)s_x + r_y(n)s_y + r_z(n)s_z = \frac{1}{2}\left[r_x^2(n) + r_y^2(n) + r_z^2(n)\right] - c^2 t_{n1} t_1.$$

Re-writing using matrix notation gives

$$\mathbf{s} = \boldsymbol{R}^{-1}\mathbf{b}/2 - c^2 t_1 \boldsymbol{R}^{-1}\boldsymbol{\tau}, \tag{4.2}$$

where $\mathbf{R}^{-1}$ is the inverse of $\mathbf{R}$.

For four hydrophones

$$\mathbf{R} = \begin{pmatrix} r2(x) & r2(y) & r2(z) \\ r3(x) & r3(y) & r3(z) \\ r4(x) & r4(y) & r4(z) \end{pmatrix};$$

$$\mathbf{b} = \begin{pmatrix} \|\mathbf{r}_2\|^2 \\ \|\mathbf{r}_3\|^2 \\ \|\mathbf{r}_4\|^2 \end{pmatrix};$$

$$\boldsymbol{\tau} = \begin{pmatrix} t_{21} \\ t_{31} \\ t_{41} \end{pmatrix} .$$

Solving equation 4.2 for t_1 gives

$$t_{1n} = \frac{ca_2 \pm \sqrt{c^2 a_2^2 - \left(c^2 a_3 - 1\right) a_1}}{2c\left(c^2 a_3 - 1\right)} \ ,$$

where

$$a_1 \equiv (\mathbf{R}^{-1}\mathbf{b})^T(\mathbf{R}^{-1}\mathbf{b}),$$

$$a_2 \equiv (\mathbf{R}^{-1}\boldsymbol{\tau})^T(\mathbf{R}^{-1}\mathbf{b}),$$

$$a_3 \equiv (\boldsymbol{R}^{-1}\boldsymbol{\tau})^T(\boldsymbol{R}^{-1}\boldsymbol{\tau}).$$

The two possible positions are then found by substituting t_1 back into equation 4.2

$$position(n) = \mathbf{R}^{-1}\left(\mathbf{b} + t_{1n}\left(n\right)c^2\boldsymbol{\tau}\right) \ . \tag{4.3}$$

The processing gives two possible answers and these are displayed to the user who then manually selects the correct answer. The selection is based on whether a result is impossible (above the surface or below the seabed) or by visually comparing the expected arrival times and amplitudes from each location with those observed. If an error is made in selecting the start times of each click the algorithm may provide an incorrect complex solution which is then discarded.

The time delays and resulting locations are saved to a file of type CSV for later use. The locations are also plotted as a MATLAB 3-D display.

4.7.5 Digitisation errors

The data from the MQC2 array is recorded on a digital recorder so the effect of choice of sampling frequency on localisation accuracy was investigated. A simulation of a clicker moving past the MQC2 array was written in MATLAB and then used with the localisation processing function to investigate the degradation in performance due to timing errors introduced by the lower sample rates. The routine calculated the delays from each clicker position to each hydrophone. These delays and the same delays converted to the nearest integer number of samples were processed by the MATLAB routine and the resulting locations plotted.

Figures 4.32 to 4.34 show the progressive degradation of performance as the sample rate reduces from 192 kHz to 48 kHz. In each plot the red squares shows the first calculated location and the blue stars show the second calculated location using un-digitised data. The magenta and green squares similarly show the two possible locations calculated using the digitised data.

For these plots x steps from -4 to +4 metres in steps of 0.1 metre, y is fixed at -1 metres and z is fixed at 0.1 metre. The four hydrophones are shown in the figures as black circles. The array orientation relative to the axis is the same as that shown in Figure 4.25 i.e. the z axis is the vertical axis.

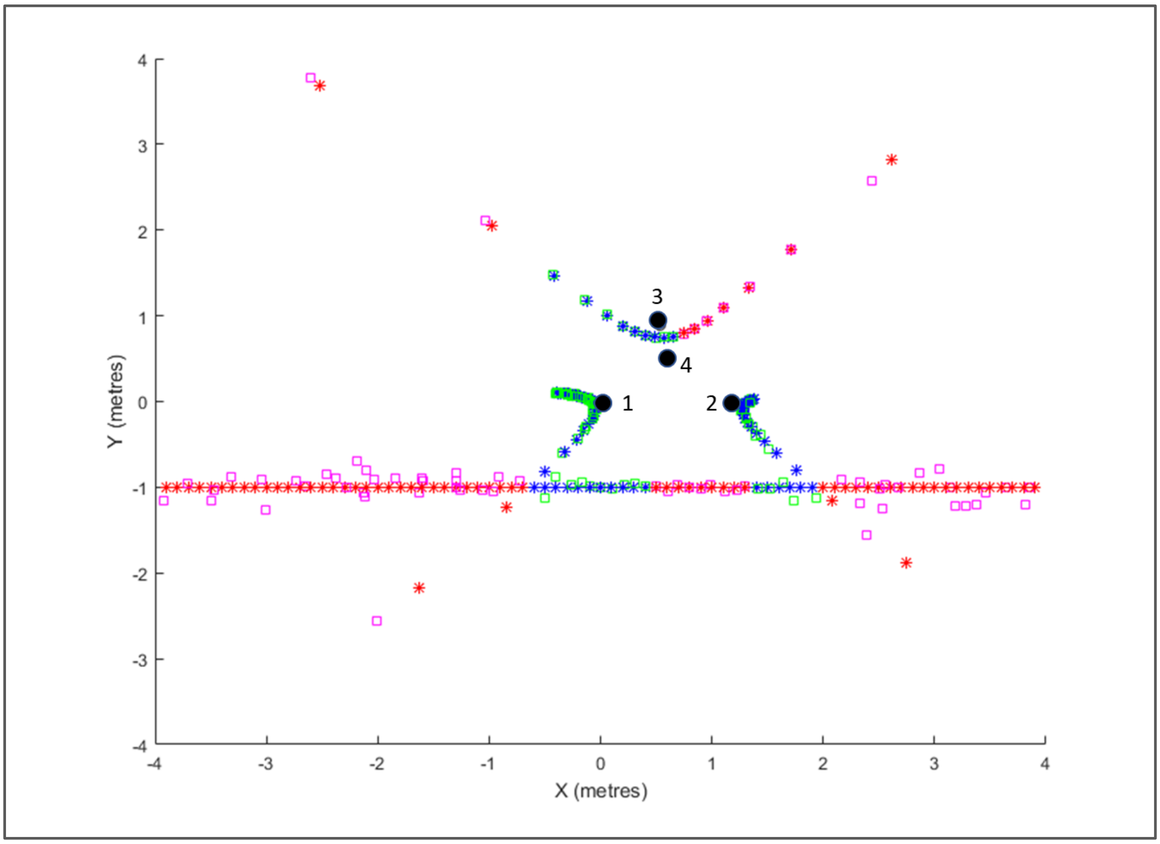


Figure 4.32 Effect of 192 kHz sampling. x varies -4 to +4 m while y fixed at -1 m and z fixed at 0.1 m.

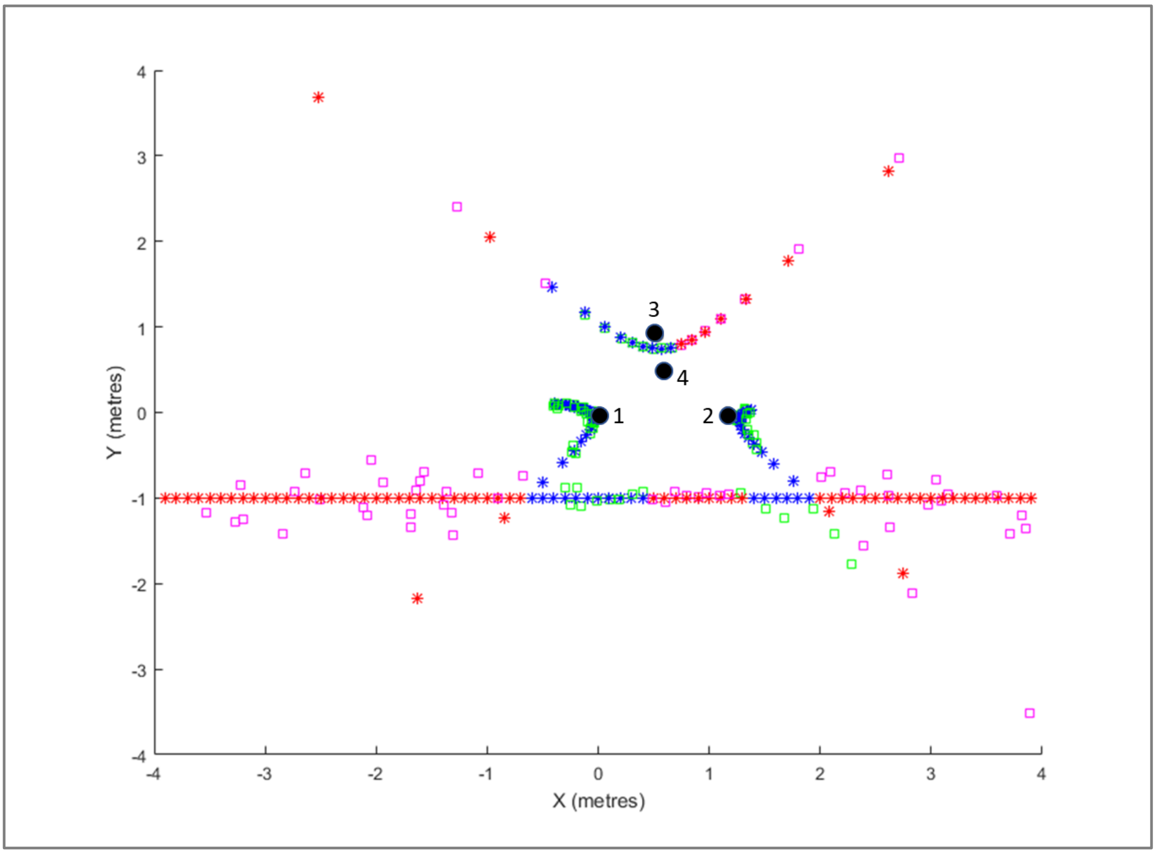


Figure 4.33 Effect of 96 kHz sampling. x varies -4 to +4 m while y fixed at -1 m and z fixed at 0.1 m.

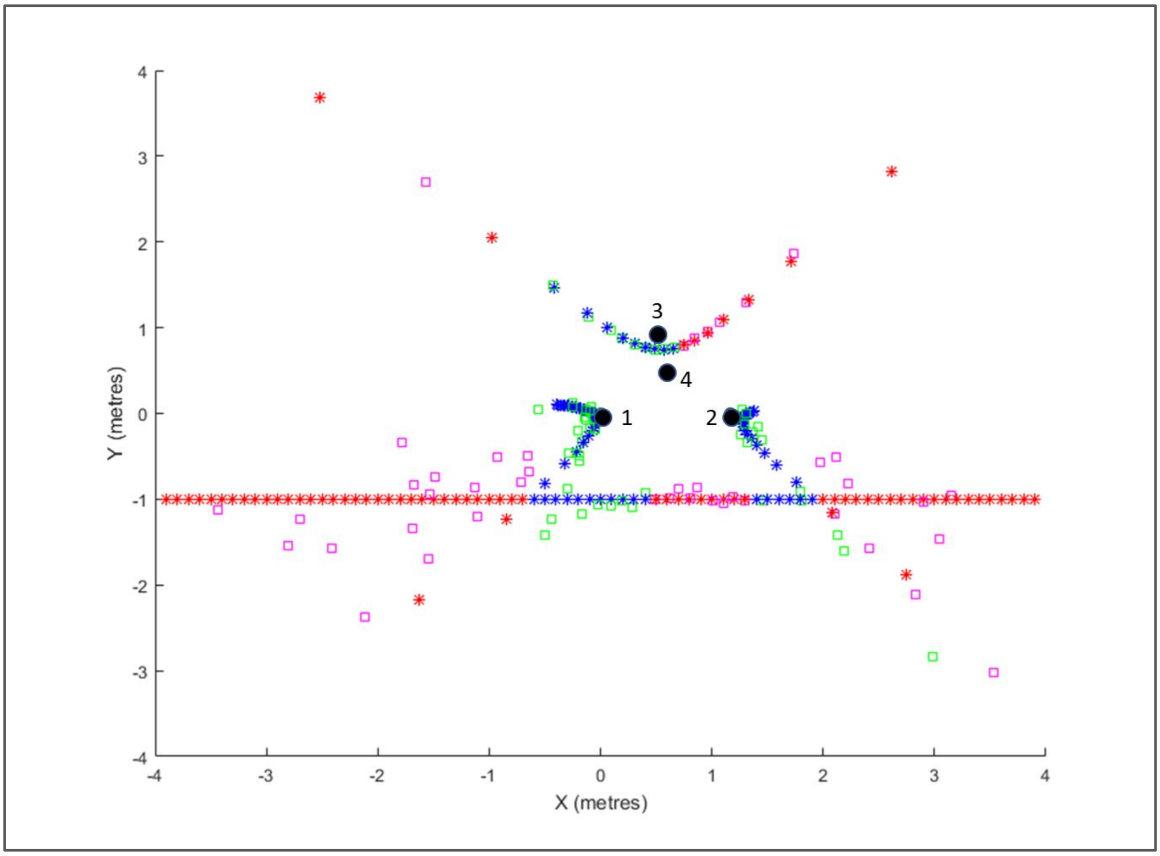


Figure 4.34 Effect of 48 kHz sampling. x varies -4 to +4 m while y fixed at -1 m and z fixed at 0.1 m.

The effect of sampling was further investigated by letting x and y vary over -4 to +4 m in steps of 0.1 m. At each x, y location the RMS of the difference between the calculated locations using real and integer times was calculated as z varied from 0 to +4 metres in steps of 0.1 metre.

$$RMS_{x,y} = \sqrt{\frac{1}{N_{real}} \sum_{z=0}^{4} (p_{act} - p_{calc})^2}$$

Where

RMS_{xy} is the RMS error distance along the z axis at each x, y location,
N_{xy} is the number of non-complex calculated locations,
P_{act} is the actual location,
P_{calc} is the calculated location.

Each calculation of location gives two possible locations. The location used for the RMS calculation is the location closest to the true location. A complex location result can occur when the input data does not yield a real result due to timing errors. Complex results are not included in the RMS calculation. The results are presented in Table 4.6.

Table 4.6 Effect of sample rate on localisation accuracy

Sample rate	RMS distance error	Complex points	Error points
192 kHz	1.19	11.8%	45.4%
96 kHz	1.89	16.6%	56.5%
48 kHz	2.58	21.6%	62.9%

The final column is the percentage of points that give a real result but which exceed an error of 30 cm. This was chosen as being the worst acceptable error for the localisation work within this project. As expected the errors reduce with increasing sample rate.

The RMS error was unexpectedly high so to further understand how these errors were distributed a plot was made in which x and y varied from -4 to +4 m in steps of 0.1 m while the RMS error was calculated along the z axis from 0 to +4 metres in steps of 0.1 m. The result is shown in Figure 4.35. The colour coding represents the RMS error distance in metres.

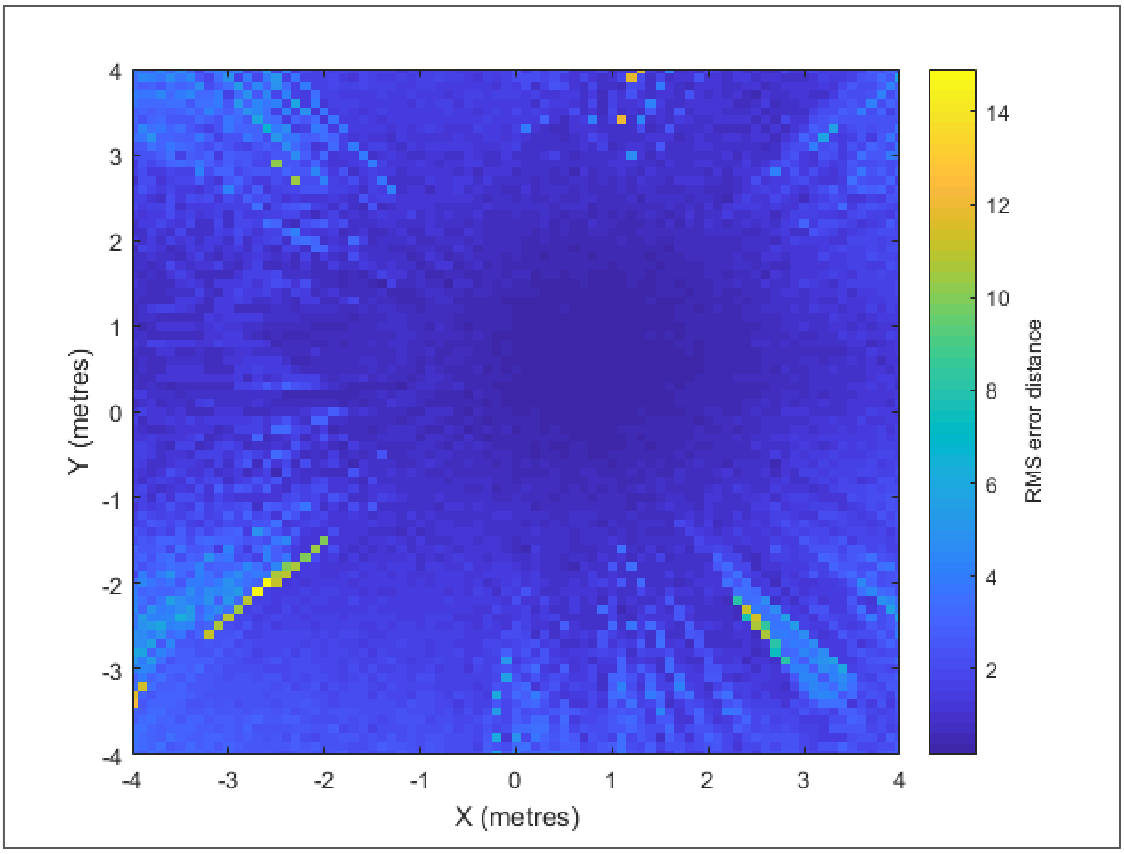


Figure 4.35 Error distribution in X and Y calculated along Z=0 to 4 metres for 96 kHz sampling

It can be seen that most of the errors occur beyond 2 metres from the array and that a small number of the points have very large errors and these dominate the RMS calculation.

For this work a Tascam DR680 recorder was chosen as a compromise between performance and cost. This allowed 96 kHz sampling of four input channels. It was accepted that errors would occur at the longer ranges but since the primary interest of this work was the volume within and close to the hydrophones the errors would be within acceptable limits to gain an understanding of the distribution of the click sources.

4.8 System testing

System operation was checked by carrying out a test run at the start of each deployment. This consisted of swimming as straight a line as possible past the deployed equipment while operating a pulsed sound source. A number of methods to generate a pulsed sound were tried including knocking two pebbles together but the best was found to be a dog training clicker of the type shown in Figure 4.36. These use a bistable strip of metal which produces a loud click as it moves from one state to the other. Although intended for use in air, they still produce a usable click underwater. The amplitude was sufficient to get a clean signal to beyond 10 m and the device could be operated by one hand. A typical click received on the two BiClick hydrophones is shown in Figure 4.37. Note that the upper trace has an offset of 1.2 added to it for clarity. The lower frequency precursor to the click appears to be caused by the act of pressing the clicker.

A wideband biological click is shown in Figure 4.38 for comparison. Although the click from the dog clicker is longer, only the leading edge of the waveform is used to extract timing information.

Figure 4.36 Dog training clicker

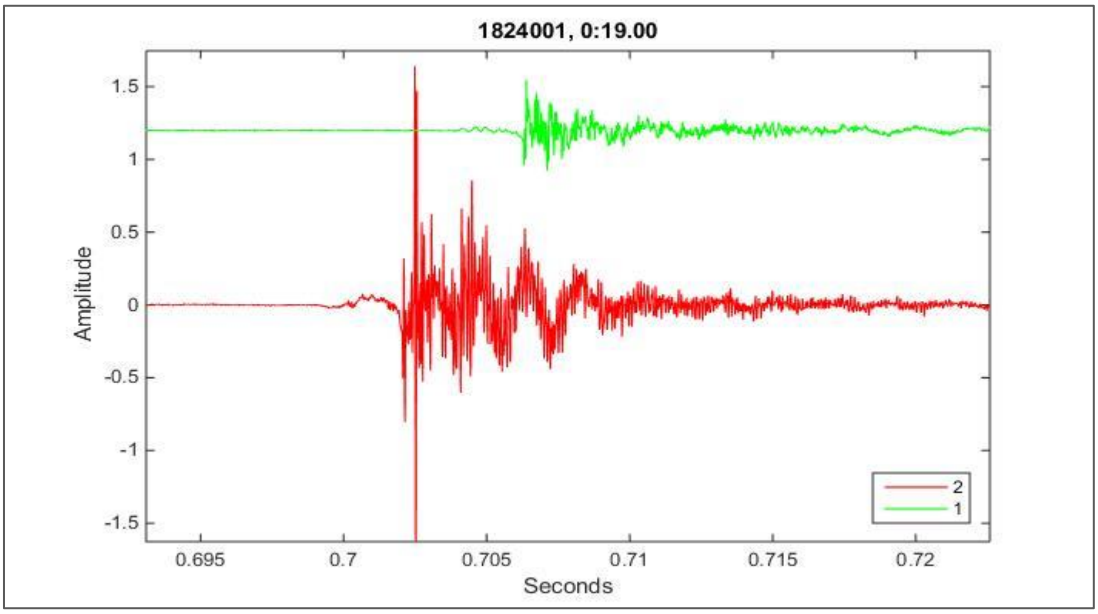


Figure 4.37 Signal from the dog clicker received on the BC2 hydrophones

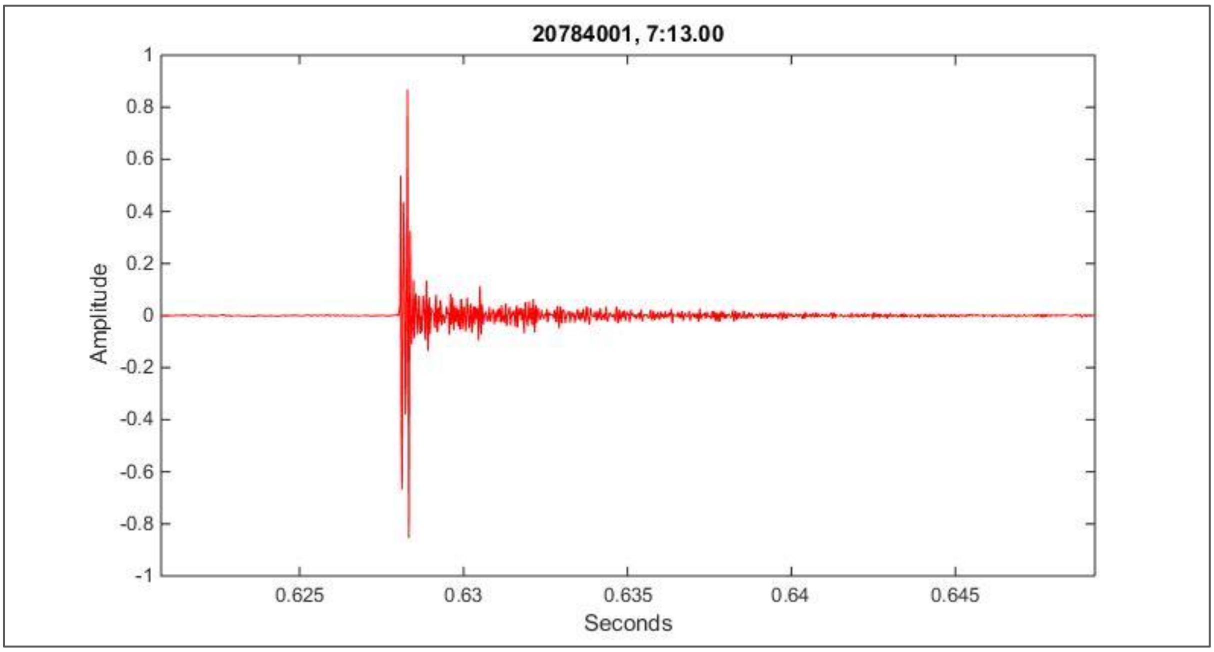


Figure 4.38 Example of click type B

Equipment

Figures 4.39 to 4.42 show the results of two test runs carried out using the QC2 equipment deployed on the seabed at the main study site in the Fleet. Each blue dot is an estimated click position and each 'O' on the triangle is a hydrophone location. During the processing of these clicks, complex points have been discarded and for each calculated location the result nearest to the estimated location was used. A small number of calculated locations gave results that were both wrong and these were also discarded.

The equipment is orientated during deployment so the line H1-H2 is aligned with a landmark on the shore whose direction is known. This allowed the swimmer to follow a track aligned with the equipment. The click source was held approximately 0.4 m deep during the runs.

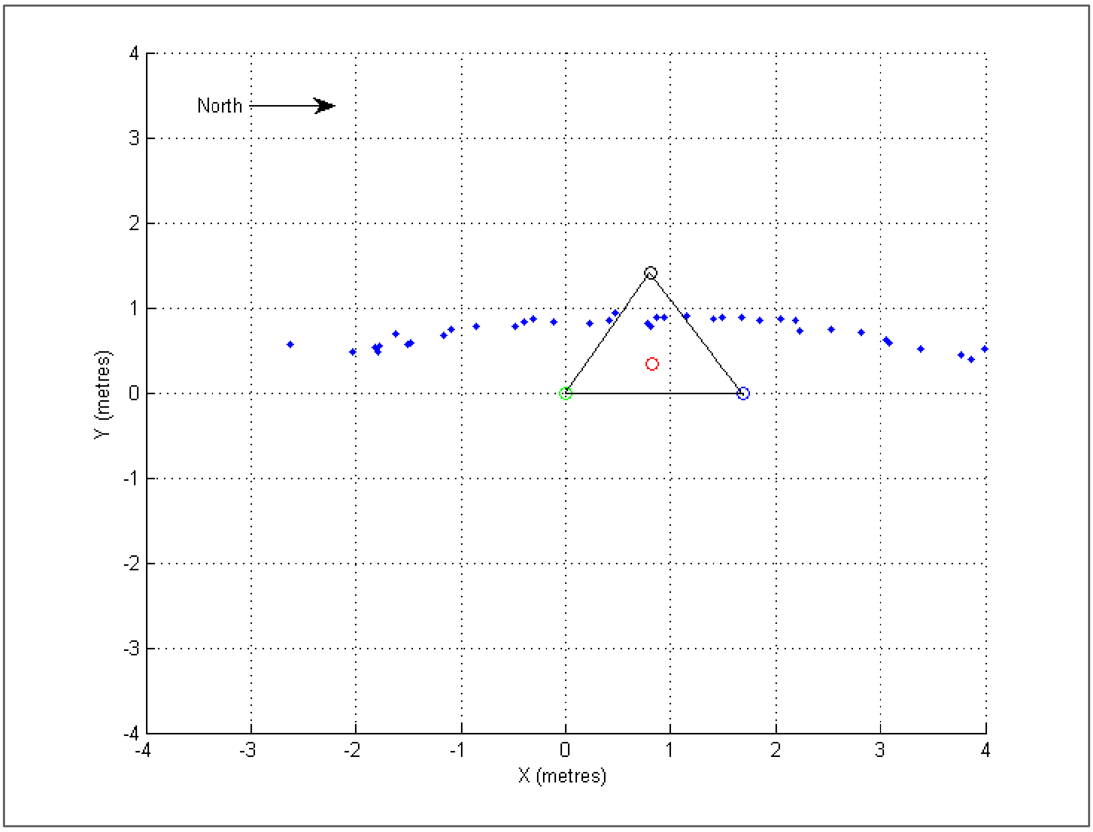


Figure 4.39 Test track using QC2, sound source travelling north to south, estimated locations shown as blue diamonds.

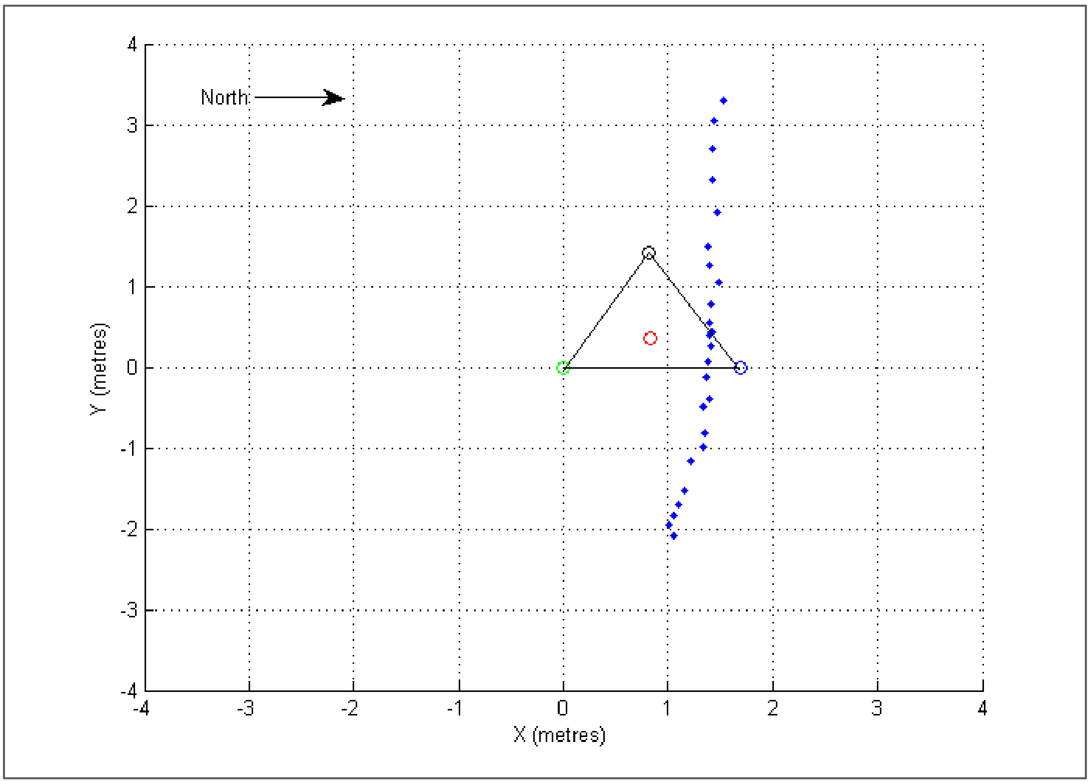


Figure 4.40 Test track using QC2, sound source travelling west to east, estimated locations shown as blue diamonds

For these two runs QC2 was deployed on the edge of the channel in approximately 2 m water depth. The sound source travels at a depth of approximately 0.4 m. The channel edge shelves from west to east. The plots in Figures 4.39 and 4.40 show the plan view of the track. The elevation views of the same two tracks are shown in Figures 4.41 and 4.42.

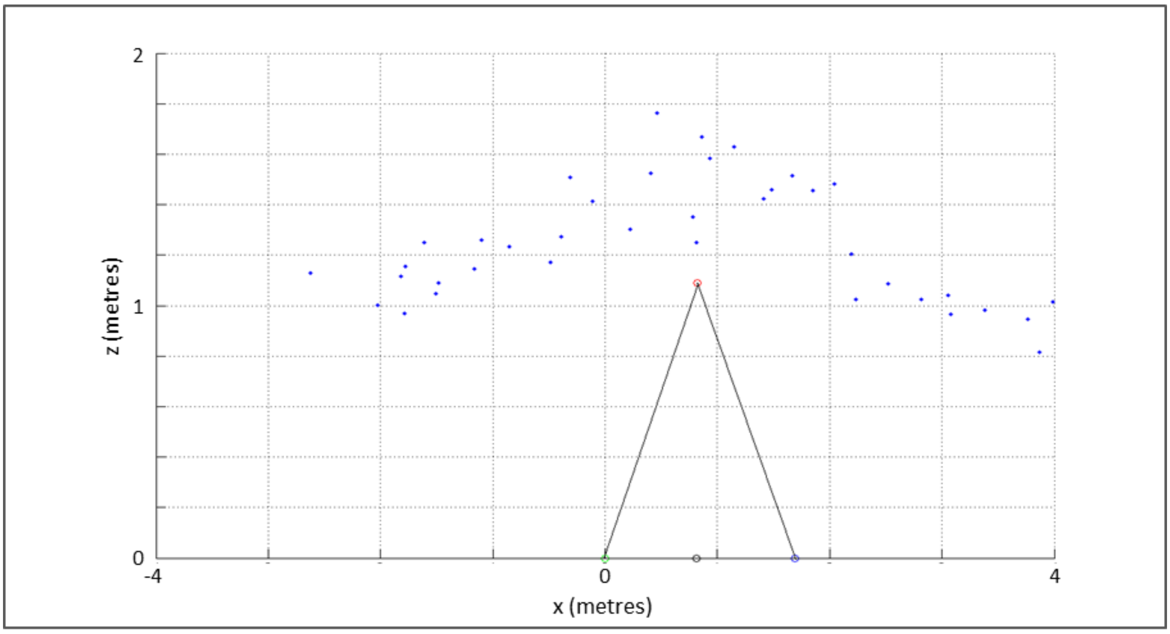


Figure 4.41 Elevation view of the north to south test track

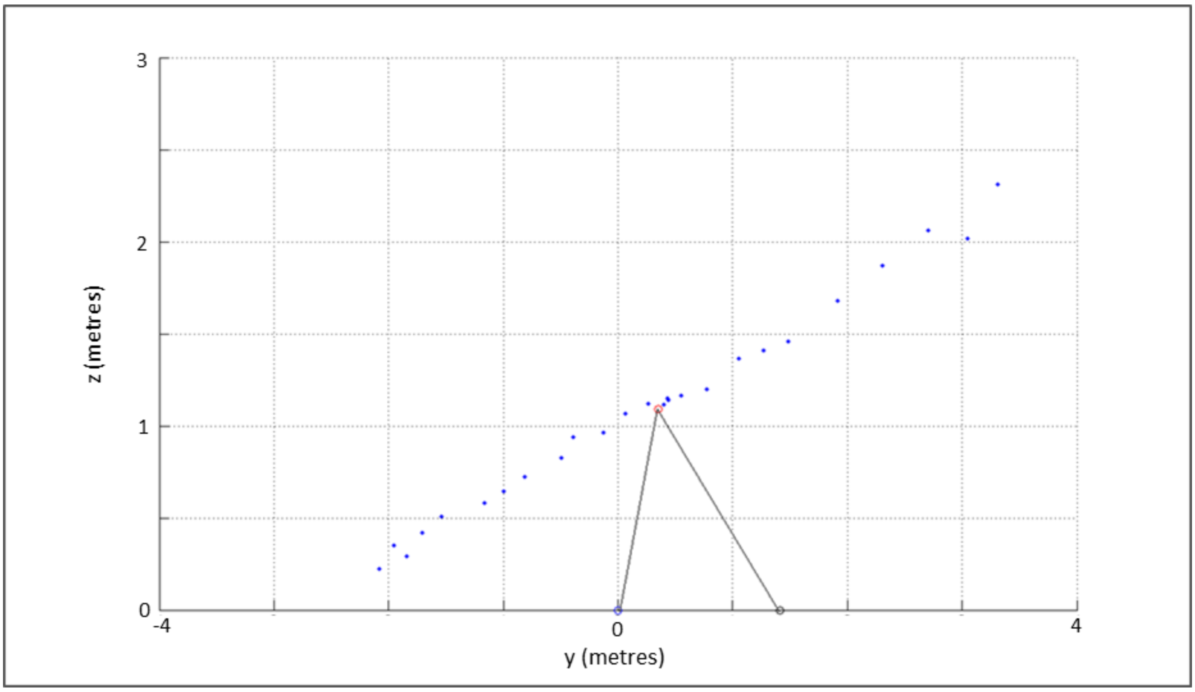


Figure 4.42 Elevation view of the west to east test track

The decrease in depth close to the equipment in Figure 4.41 is consistent with the swimmer attempting to avoid contact with the top hydrophone. The increased scatter in depth may be due to the swimmer needing to use the hand with the clicker to maintain position against the tide. In Figure 4.42 the inclination of the track is possibly due to the angle at which the QC2 equipment is deployed on the edge of the channel. The seabed slopes down from the shore to the main channel which means the hydrophone tripod is not level and so this angle is reflected in the apparent inclination of the track. The channel runs approximately north-south so the tripod is level along the north-south direction but is tilted towards the east along the west-east direction.

Within the limited accuracy of this experiment the estimated locations for each click form a consistent track for the swimmer and give a high level of confidence in the localisation methodology.

4.9 Camera equipment

Most deployments of UC1, QC2, MQC2 and BC2 included at least one video camera to record species around the hydrophones. It was hoped that the click-producing species would appear on the cameras and allow identification.

Five types of cameras were used. These were the Oregon Scientific ATC3K, AEE action camera, GoPro Hero 2, GoPro Hero 3 and a GoPro Hero basic. All of the cameras use SD cards as a recording media. The ATC3K was limited to standard SD cards so could only record for 1 hour. The AEE camera will accept SDHC cards while the GoPro cameras could take up to SDXC cards in which case the record time was limited by the life of the internal battery.

Figure 4.43 GoPro camera on MQC2

The GoPro Hero 2 proved unsatisfactory because of internal fogging when deployed in cold water. Attempts to minimise this using absorbent pads met with marginal success. None of the other cameras suffered from this problem. The GoPro Hero 2 eventually failed due to water ingress through a faulty seal and was then replaced with the GoPro Hero 3 and this did not suffer from fogging. The ATC3K had a narrower field of view compared with the GoPro cameras so the two were often used together to give both a wide view and a narrower view with more detail. For later deployments the ATC3K was replaced by the GoPro Hero basic camera which gave much improved picture quality although with a wider field of view.

Two AEE action cameras were also used and were much lower cost than the GoPro cameras while giving comparable picture quality. Their mounting arrangement was compatible with the GoPro cameras so they could be used interchangeably.

An Olympus TG3 Tough camera became available near the end of the project and was used either hand-held or mounted on a BiClick hydrophone stand.

4.10 Summary

This chapter has described the equipment used to study the clicking sound and the methods of using the equipment. It has set out how the collected data has been processed and described the limitations in performance encountered. The methods used to check equipment operation in the field have also been described. Operational tests of the localisation equipment have been described and shown to give acceptable results.

The camera equipment used to support the acoustic work and aid in species identification have been described.

Chapter 5

Description of the click sounds

5.1 Introduction

In the course of the work a number of transient sounds have been identified and these are described in this section. At the main study site in the Fleet there are three types of click which can be distinguished and these are described along with a number of other sounds which have been recorded elsewhere in the course of this work. It should be noted that most of these sounds have been recorded in very shallow water, i.e. less than 4 metres depth, in a complex acoustic environment with multiple arrival paths so there is a high level of variability in the waveform.

Only very strong clicks which are thought to originate close to the hydrophone are used when describing the clicks. With increasing distance the click is considerably modified by the environment and its characteristics are determined more by the propagation path than by the method of production as discussed in Section 4.6.

Effects observed include multiple arrival paths overlapping and stretching the click, severe bandwidth changes on a click by click basis and dispersive media effects. At times the delayed arrival path was stronger than the direct arrival path.

Possible reasons for this extreme variability are:

- **Varying acoustic propagation**
  In shallow waters the water structuring can change very quickly due to turbulent currents. Waves and tides can also affect surface reflections.
- **Varying aspect of the click source**
  A mobile species can move or turn and a different part of the click radiation pattern is presented to the receiver.
- **Varying click characteristics**
  It is not known how reproducible the click production mechanism may be.
- **Dispersive media effects**
  Propagation through multiple paths with different velocities of sound can cause smearing of the click in time. In very shallow water this can change the click to be a down-sweep with higher frequencies travelling faster.
- **Multiple sources**
  Multiple click types may appear as variability rather than distinct sources.

This extreme variability made defining a set of rules to describe a click very difficult. The detector for the fixed hydrophone described in Section 3.8 was very much a compromise that worked adequately for that particular site. Attempts to use it with data from other sites were less successful.

5.2 Click type A with low frequency pre-cursor

The type A click is a wideband click distinguished by having a low frequency precursor sound. In different acoustic environments this pre-cursor can appear quite differently. Three examples are shown in Figures 5.1 – 5.3. Figure 5.1 was recorded using the survey equipment in the channel under Ferrybridge at the lower end of the Fleet. Figures 5.2 and 5.3 were recorded from the fixed hydrophone at the BHRS. Figure 5.3 illustrates an extreme form of the variability of this type of click. The effect is believed to be due to multi-path propagation.

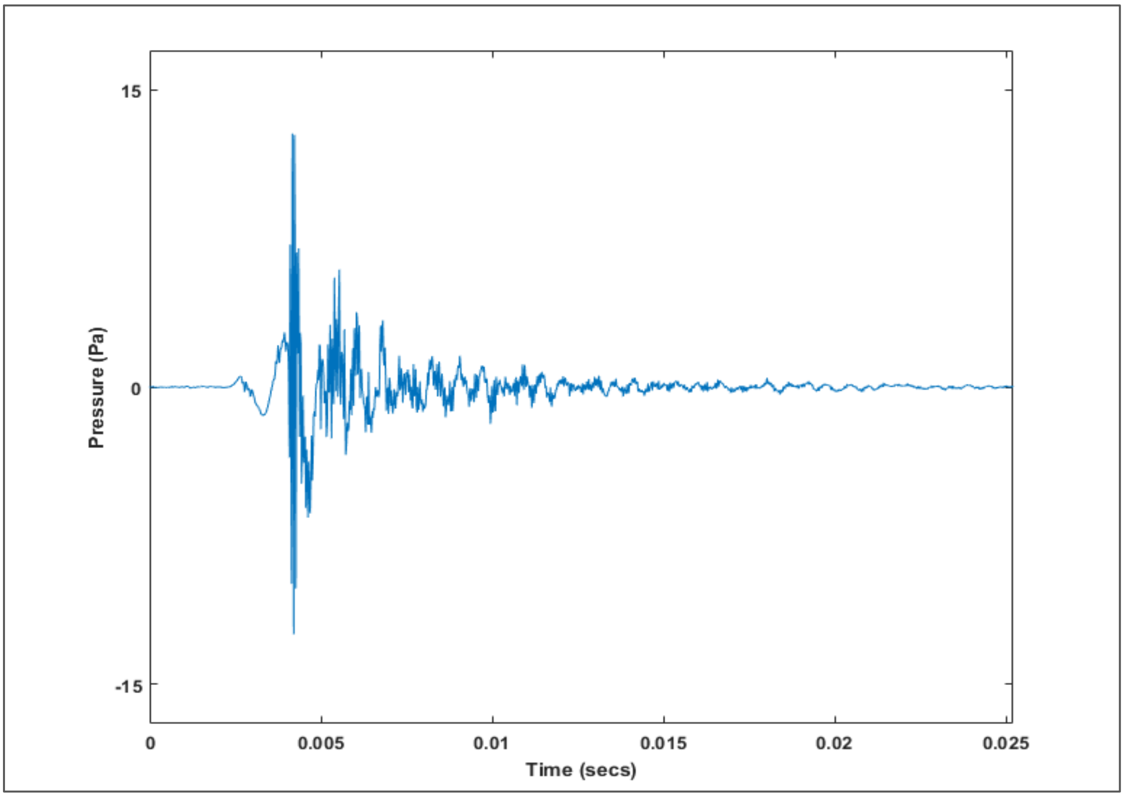


Figure 5.1 Type A click from UC1 equipment at Ferrybridge

Click characteristics

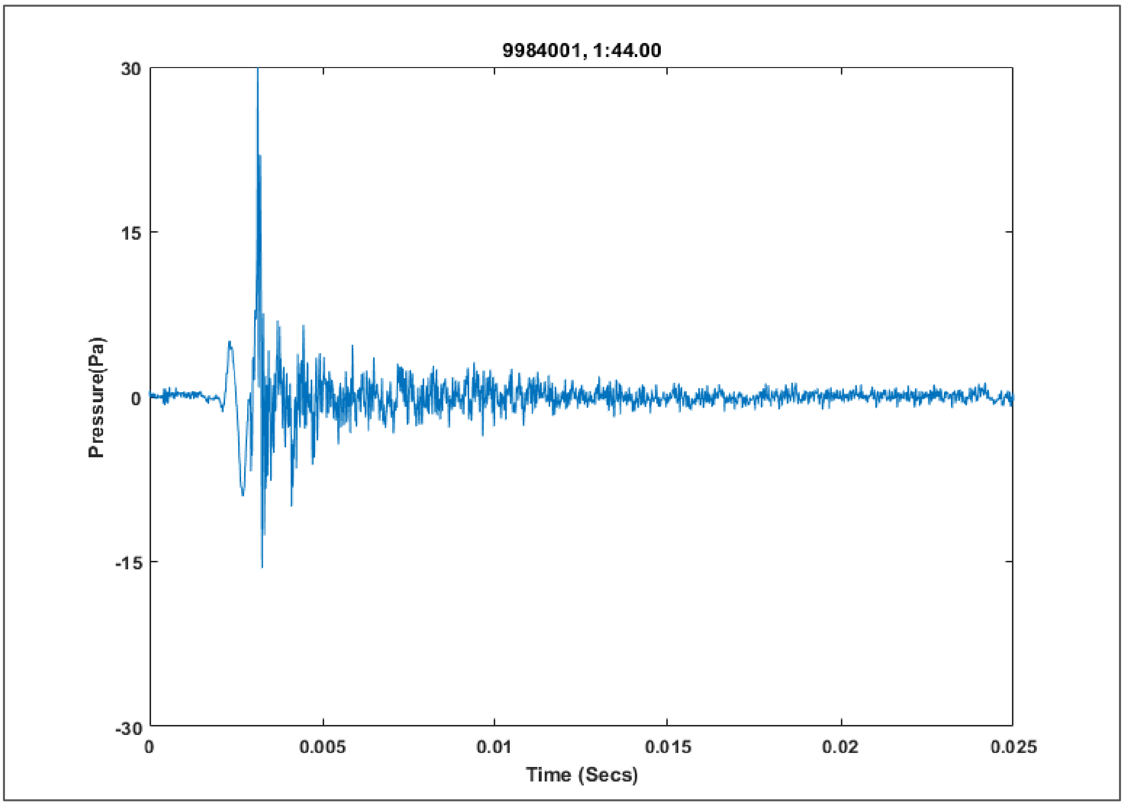


Figure 5.2 Type A click from fixed hydrophone at BHRS

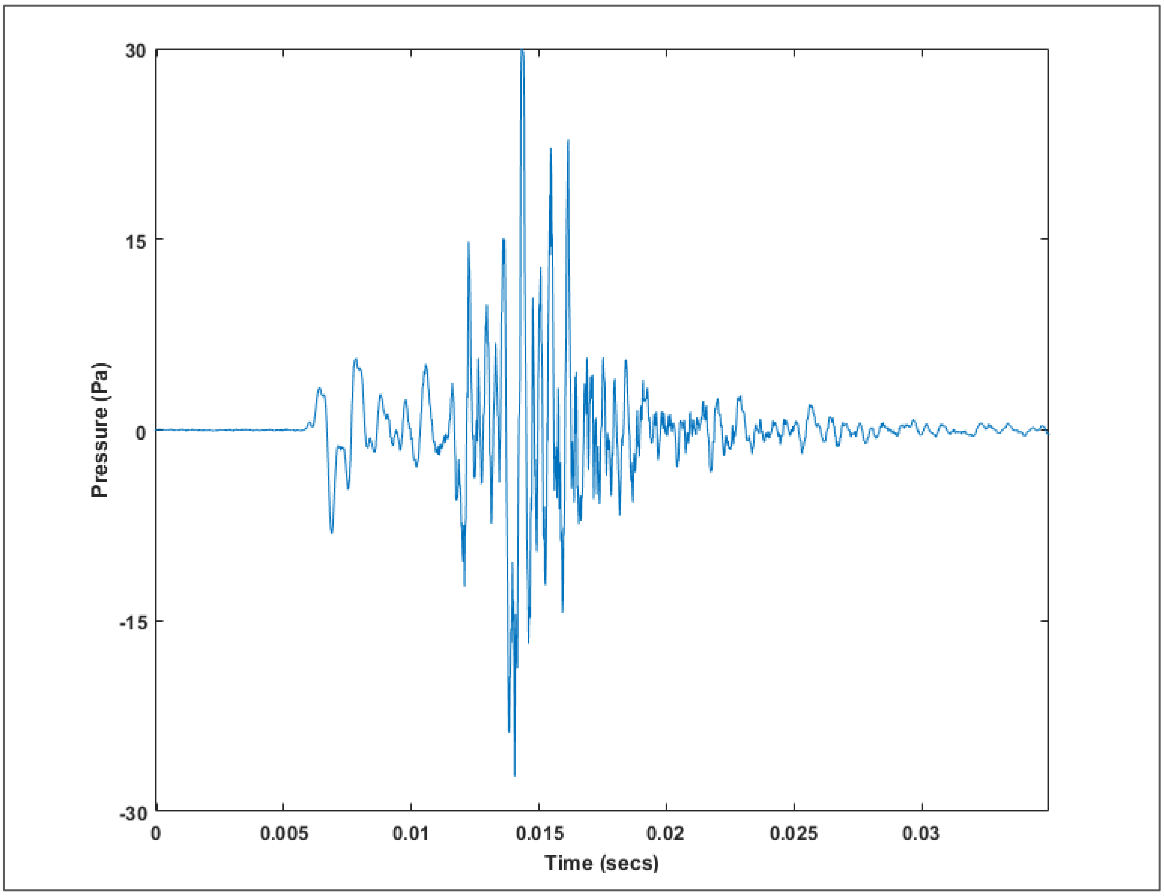


Figure 5.3 Type A click from fixed hydrophone at BHRS

It should be noted that the waveform in Figure 5.3 is slightly clipped but is included to illustrate the variability observed. A variation of the type A click often seen is shown in Figure 5.4.

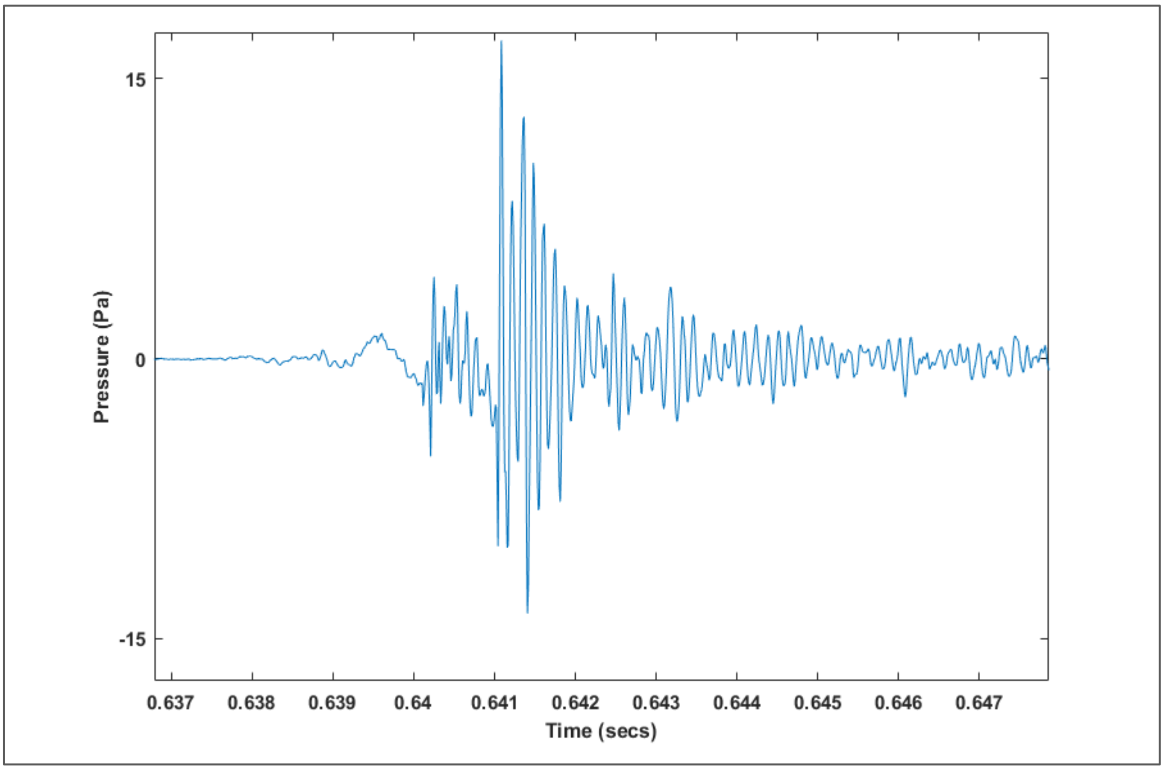


Figure 5.4 Type A click from fixed hydrophone at BHRS with multipath arrivals

There are two main arrival paths with the second path higher in amplitude than the first. There are two possible explanations for this. The first is that the two paths are the direct path and a surface reflection path. In this example this would occur for a click at 2.7 metres range. The other possibility is that the first path is through the seabed with a higher speed of propagation while the second path is through the water column. The seabed at the BHRS is small pebbles with mud, sand and broken shell. No published information on sound velocity in such a seabed could be found but if a value of 2000 m/s is assumed then a click source at 2.8 metres would give this difference in arrival time. To produce either effect the click source would need to be on or below the seabed and this would fit with the snapping shrimp hypothesis as these animals live buried within the seabed.

The variability is further illustrated in Figure 5.5. This shows four clicks of similar amplitude occurring during a two minute period on the 2nd October 2014. These were recorded using the MQC2 equipment deployed near the BHRS. The signal was from hydrophone 1.

The spectrogram displays were produced using 128 point FFTs with 50% overlap and Hanning weighting. The sample rate was 96 kHz. The colour scale has an 80 dB range with 0 dB equivalent to the maximum signal. The spectrograms are scaled 0-48 kHz and show a 70 ms segment of data.

Click characteristics

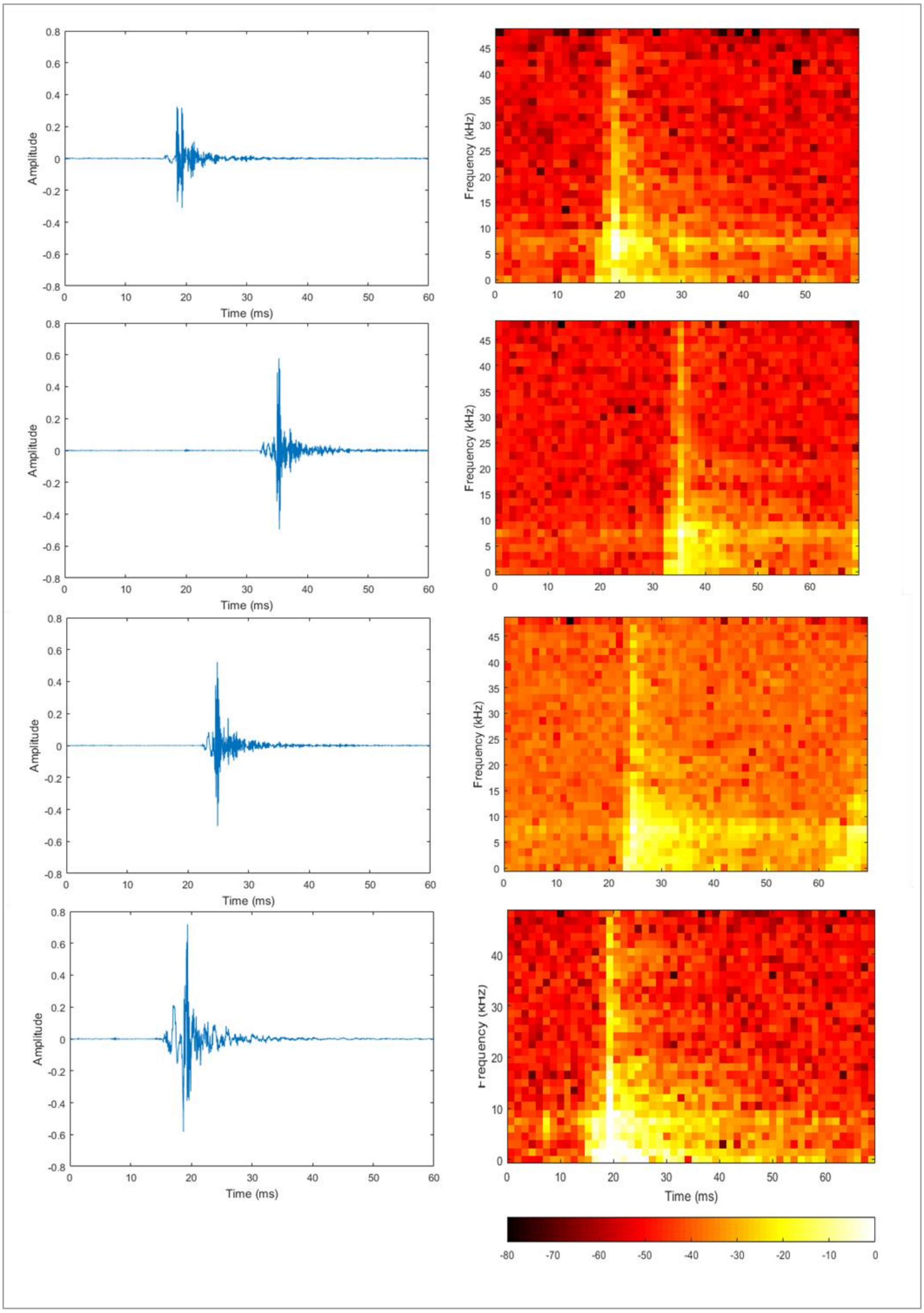
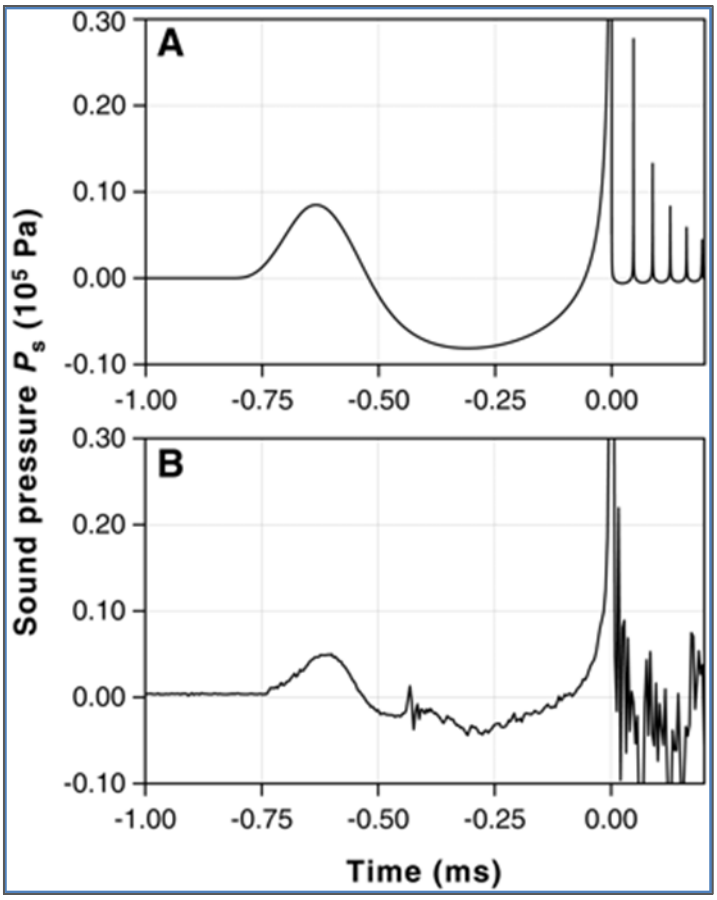


Figure 5.5 Four examples of type A clicks over a 2 minute period from MQC2 hydrophone 1

Versluis et al. (2000) looked at the detail of the snap from the big claw snapping shrimp *Alpheus heterochaelis,* found off the coast of California. Figure 5.6 is adapted from Figure 4 in their report. Figure 5.7 shows the waveform in Figure 5.2 expanded to allow comparison with their results.



This figure is taken from Versluis et al, 2000. Box A shows the predicted sound pressure plot while box B shows the experimental sound pressure plot.

Figure 5.6 Predicted and measured waveforms for a single snap

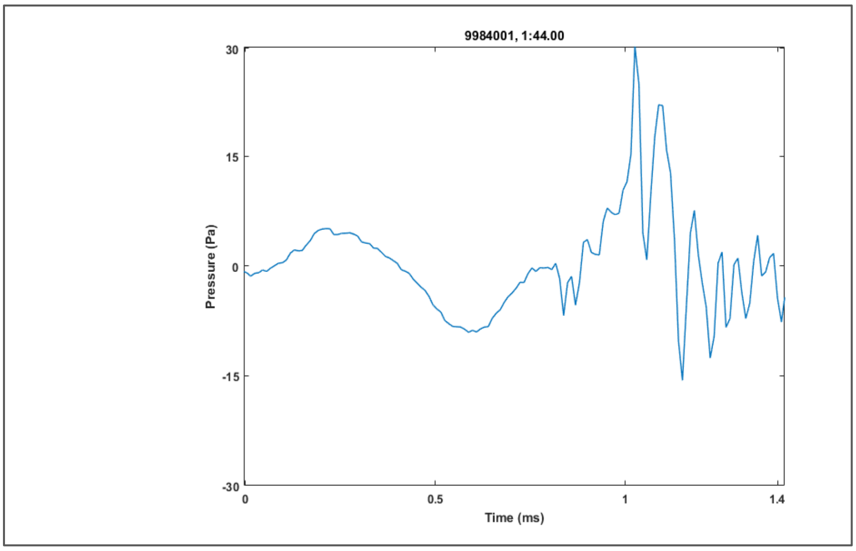


Figure 5.7 Expanded waveform of click in Figure 5.2

There appears to be good agreement between the two waveforms. The species in UK waters is not *Alpheus heterochaelis* which is a warm water species. The most likely species is *Alpheus macrochaelis*, which is roughly half the size of *A. heterochaelis*. However, the presence of the low frequency precursor and the good agreement between the timing of the waveforms means that it is highly likely that type A clicks are from snapping shrimp. Visual sampling of recorded data taken throughout the year from the fixed hydrophone at the BHRS suggests that type A clicks are present all the year round and are heard at a rate of approximately 10 per minute.

Click characteristics

The data in figure 5.6 was obtained with a hydrophone 4 cm from the claw. The click shown in Figure 5.7 was from an unknown distance but assuming it was at a range of 1 metres and assuming square-law spreading then this would give a source pressure level at 4 cm of 18,750 Pa based on the calibration figures shown in Table 4.5.This compares with the 30,000 Pa shown in Figure 5.6. The UK species is a smaller animal so it is likely to have a lower source level and Versluis *et al* (2000) make the point that the cavitation bubble resulting from the claw snap is not spherical so the sound level radiated will be aspect dependant.

While there is good agreement with the published data for snapping shrimp, there is some evidence from the localisation work that this type of click may also be produced by a mobile species. A very similar pulse has been observed using the localisation equipment and shown to originate above the seabed and is seen when sand smelt are in the immediate area of the array. The main difference appears to be that the low-frequency precursor is extended and the main click is lower in amplitude. More work is needed to establish whether there are two sub-types of this click, or whether they are coincidental observations or artefacts of the acoustic environment.

5.3 Type B click

Type B clicks do not have the low frequency precursor of the type A clicks. They are also generally lower in amplitude and often, but not always, have a reduced bandwidth. Figure 5.8 shows a typical example of a type B click. This waveform was recorded on the 13th August 2014 using the BiClick2 equipment deployed at the main study site in 2 m of water.

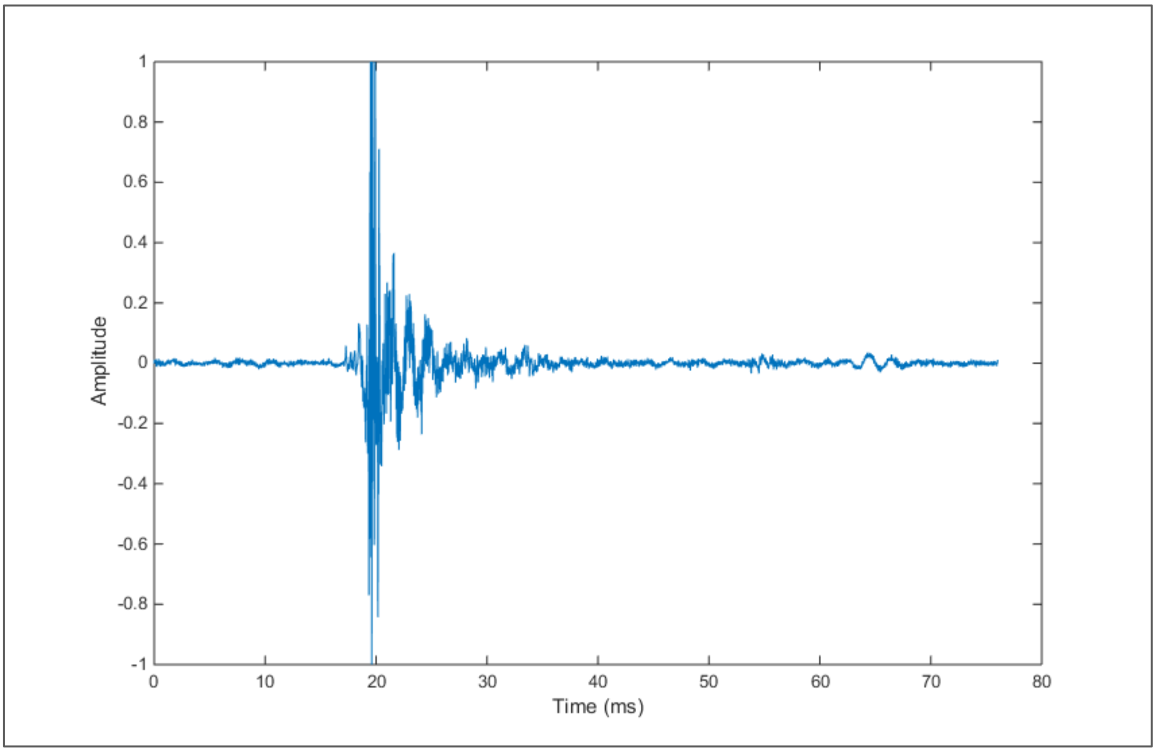


Figure 5.8 Typical type B waveform

The spectrogram of this waveform is shown in Figure 5.9.

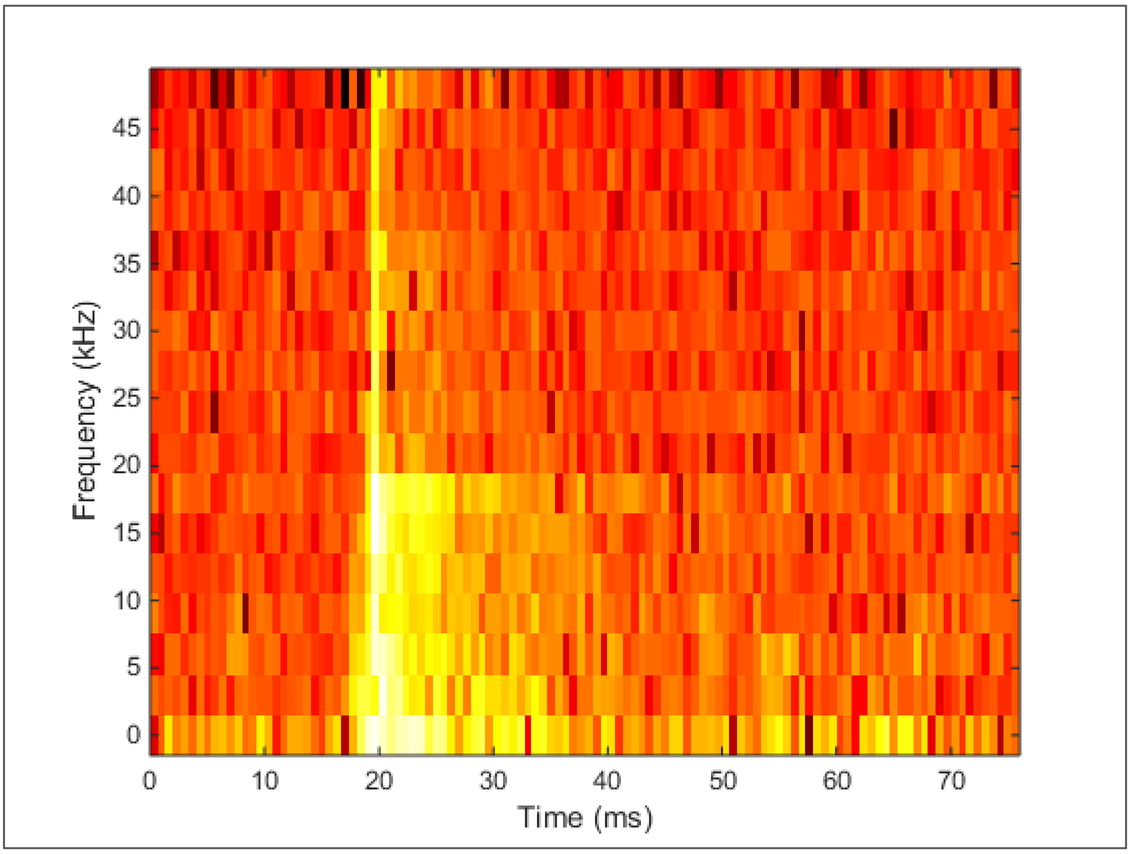


Figure 5.9 Type B click spectrogram (64 pt FFT, Hanning window, 50% overlap)

The direct path has energy to beyond 50 kHz with peak energy between 5 and 20 kHz. This type of click is the most common during the peak in click activity through summer and autumn.

5.4 Type C click

The type C click is a narrowband click with pulse length typically around 1.5 ms and centred on a frequency around 8-10 kHz. An example of this click is shown in Figure 5.10. The right-hand pane shows an expanded plot of the click. These clicks have been heard at the main study site and other parts of the Fleet. Similar clicks have also been heard in rock pools with centre frequencies ranging from 5 kHz up to 20 kHz.

Click characteristics

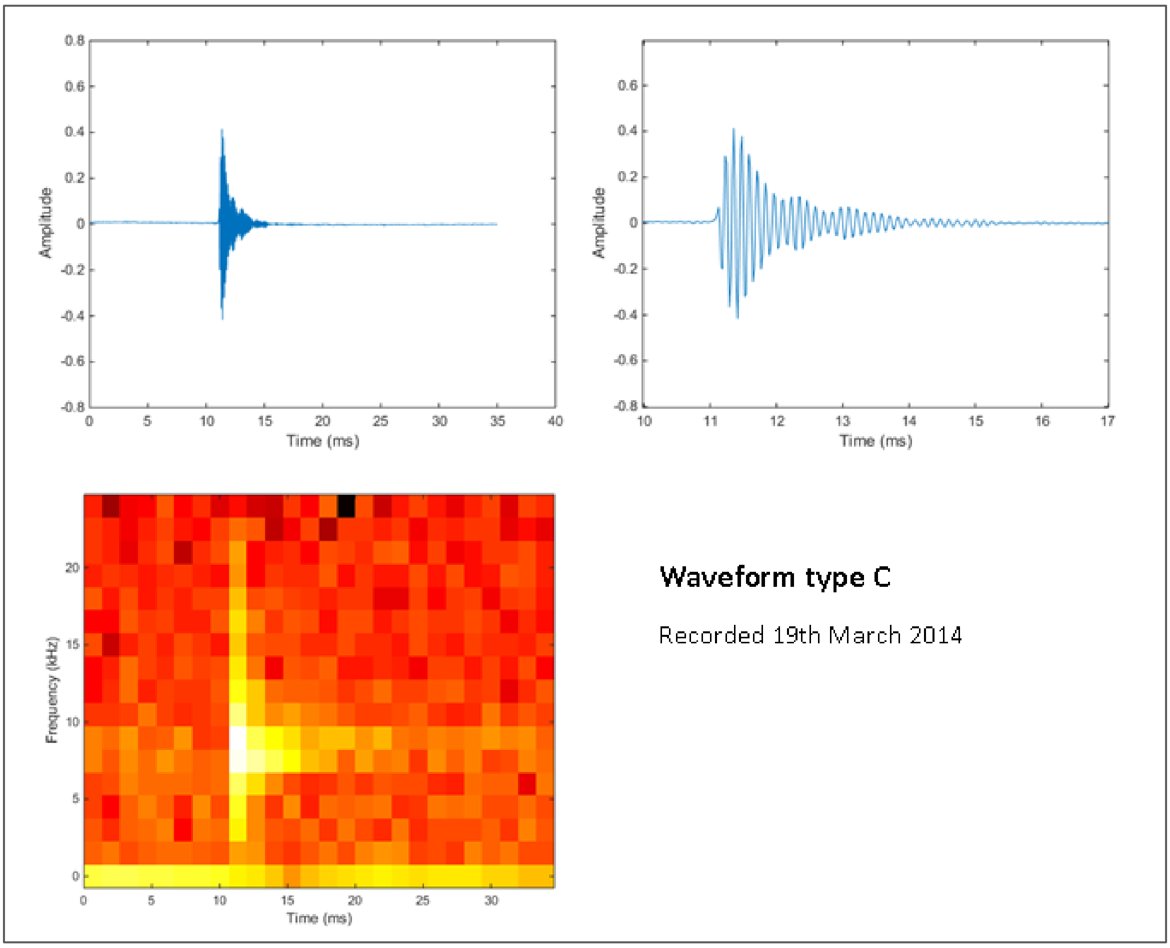


Figure 5.10 Typical type C click

5.5 Other click types

The three groups described above can only be distinguished for strong local signals. It is likely that there are a number of clicking species, all with different characteristics, which when combined with the high degree of variability combine to give a continuum of click types for the weaker clicks. Only the three principal types have been described here.

There was a suggestion of a fourth type of click which had a reduced bandwidth compared with the type B click but which had a low-level short precursor click 200-300 µs ahead of the main click. This precursor was seen on a number of occasions but it was not possible to arrive at a definitive description of the composite click.

5.6 Other biological sounds

Biological sounds recorded in a range of environments including rockpools were analysed to identify other possible biological sounds of a transient nature. These sounds are presented in Section 8.3.

5.7 Non-biological sounds

A clicking sound occasionally encountered at the main study site is shown in Figure 5.11. This is heard when there is a strong breeze, typically force 4-5, running against the tide causing small breaking waves. Simultaneous visual and aural monitoring suggested that when a wave broke over or near the hydrophone a sequence of clicks were generated and Figure 5.11 is a single click from such a sequence. The spectrogram of the click is shown in Figure 5.12. This is calculated using a 64 point FFT with Hanning weighting and 50% overlap. The click length is typically around 1.5 ms.

It is likely that the clicks are generated by bubble formation as the wave breaks.

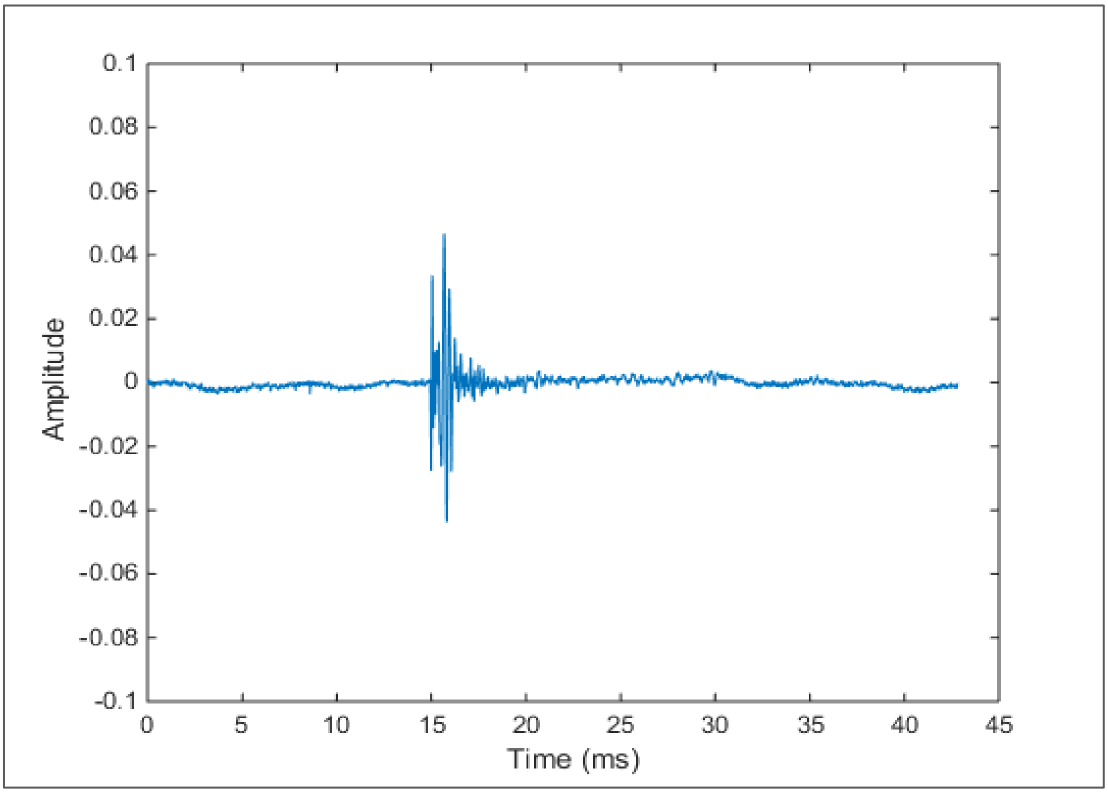


Figure 5.11 Waveform of click due to breaking wave at the study site

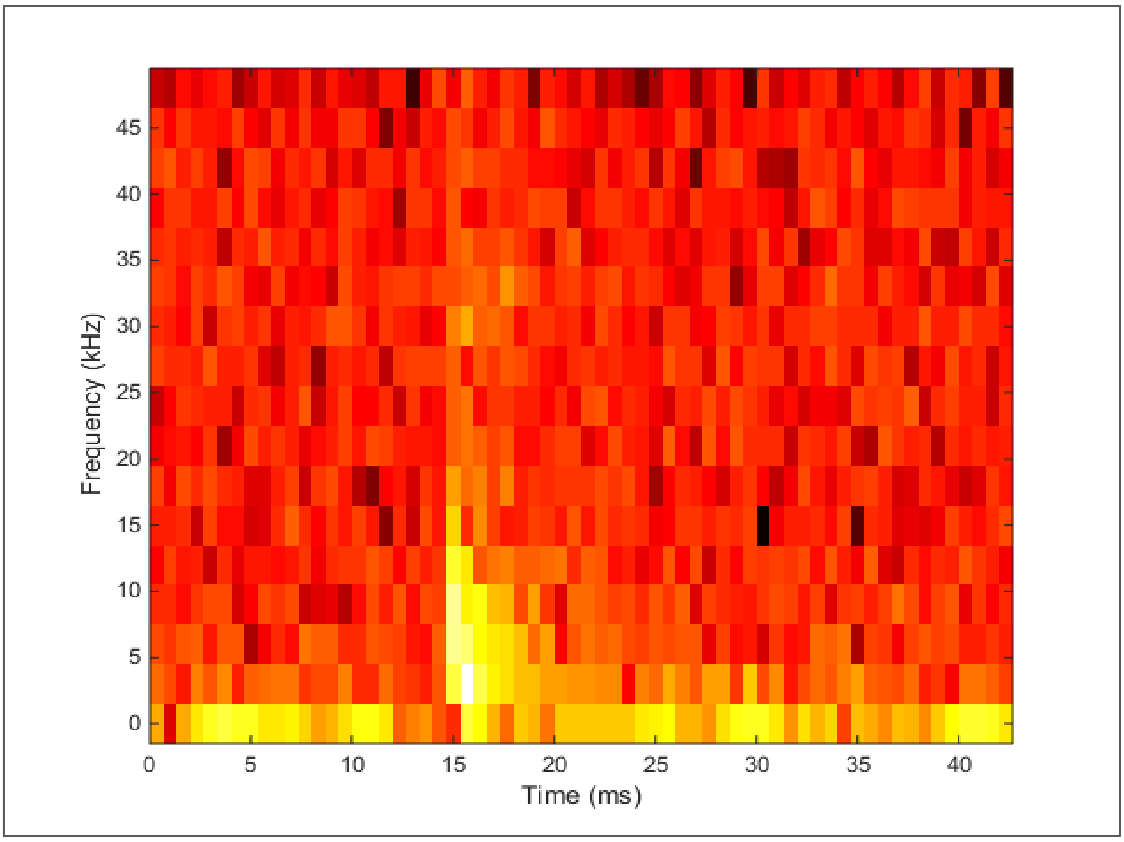


Figure 5.12 Spectrogram of click due to breaking wave at the study site

5.8 Summary

This chapter has proposed that there are three main types of click observed during this work. The type A click has been shown to be very similar to the clicks observed from snapping shrimp. The type B click lacks the low-frequency precursor and is generally lower in amplitude than a type A click and often has reduced bandwidth. This click type is the most common during the peak in activity in late summer. A third type of click, the type C click, has a much reduced bandwidth and amplitude compared with the types A and B and has been observed at the study site and in rockpools.

Other click types have been noted but it has not been possible to arrive at a definition of these other click types. Clicks from a non-biological source have also been described.

Chapter 6

Spatial and temporal distribution

6.1 Regional distribution

The regional survey was carried out on an opportunistic basis and as such this was a non-rigorous study meaning that the spatial and seasonal coverage is considerably under-sampled. The aim was to investigate whether there was any significant trend in the distribution of the clicking sound around the UK coastline.

The survey was carried out as described in Section 3.3 using the equipment described in Section 4.1. The click activity was categorised subjectively into three categories corresponding to no activity, low activity (less than approximately 50 clicks/min) and high activity (greater than approximately 50 clicks/min). In all cases a five minute listening period was used. It was found to be very difficult to distinguish between low local activity and high level activity some distance away as discussed in Section 3.8.

The results for the regional survey are shown in Figure 6.1 and the data collected is listed in Table B.1 in Appendix B. All of the data presented has been collected by the author as part of this project with the exception of two points where data has been provided by other researchers (Hawkins, Pers. Comm. (2012), Coates et al. (2012)). In addition, two points collected by the author were primarily for other projects (Orkney and Cromarty data).

The distribution shown in Figure 6.1 strongly suggests that the observed clicking is only found in the southern half of the UK and Eire. The extensive datasets available for Cromarty and Orkney covered most of a year and with full twenty-four hour periods and these were searched in some detail and no clicks of the types observed further south were found. A very small number of similar clicks were heard but they could all be attributed to local mechanical sources.

The three data points in Northern England (Heysham, Whitby and Humber Estuary) were all taken over soft mud seabed where there was a low probability of clicking being heard so these points should be treated with caution. Similarly, the zero count in Portleven Harbour, Cornwall, is explainable by the rocky seabed and very exposed site.

Future work could expand on this survey and in the light of information from this study collect more metadata to allow firmer conclusions to be drawn.

6.2 Dorset distribution

The results for the Dorset coastline survey are shown in Figure 6.2 and the data collected presented in tabular form in Table B.2 in Appendix B. The main focus of this work was along the East Dorset coast and the aim was to understand where the clicking activity occurred and to understand any habitat preferences. An initial aim was to identify a main study site where the majority of the work would be carried out.

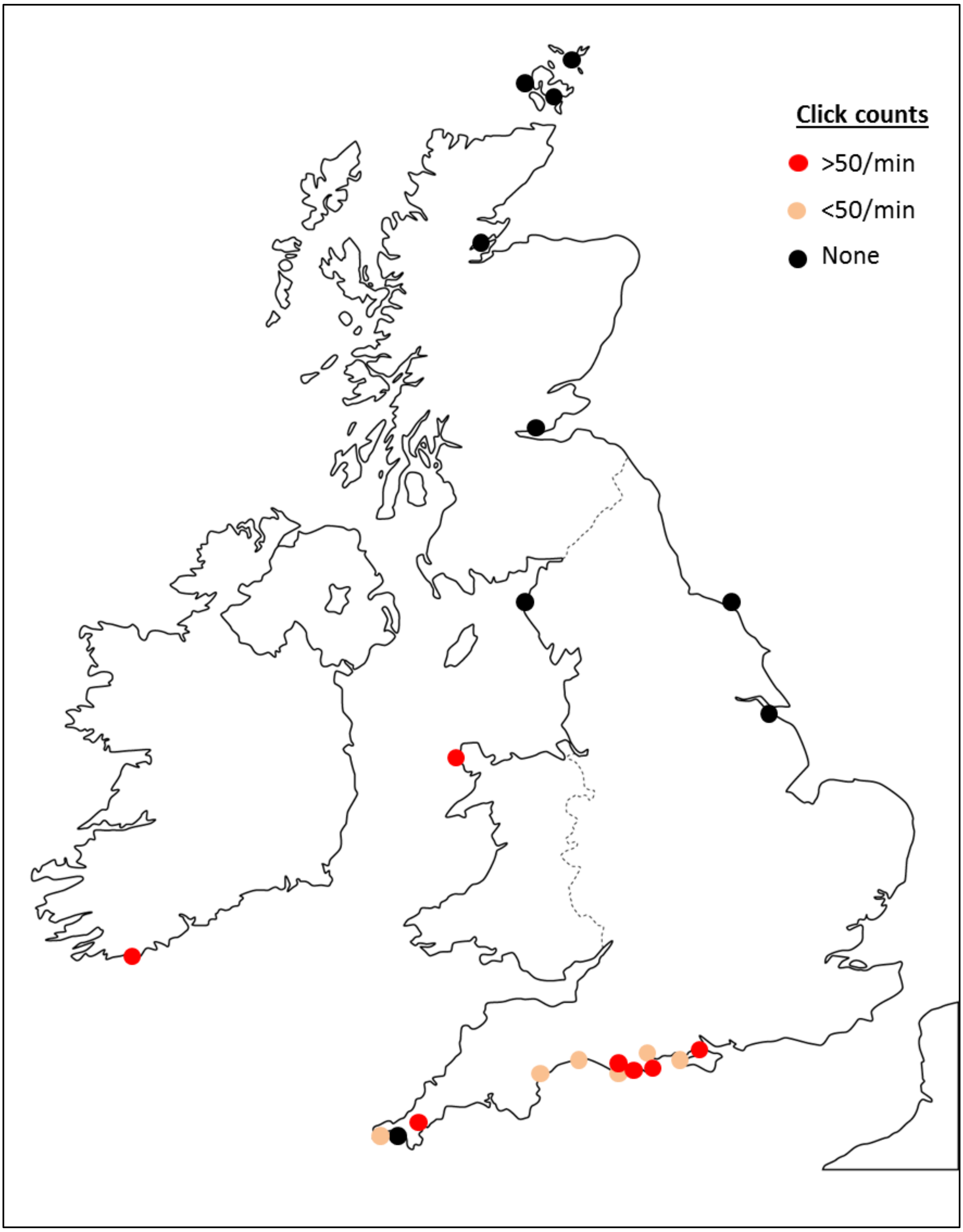


Figure 6.1 Results of the regional survey showing locations surveyed and clicking rates found

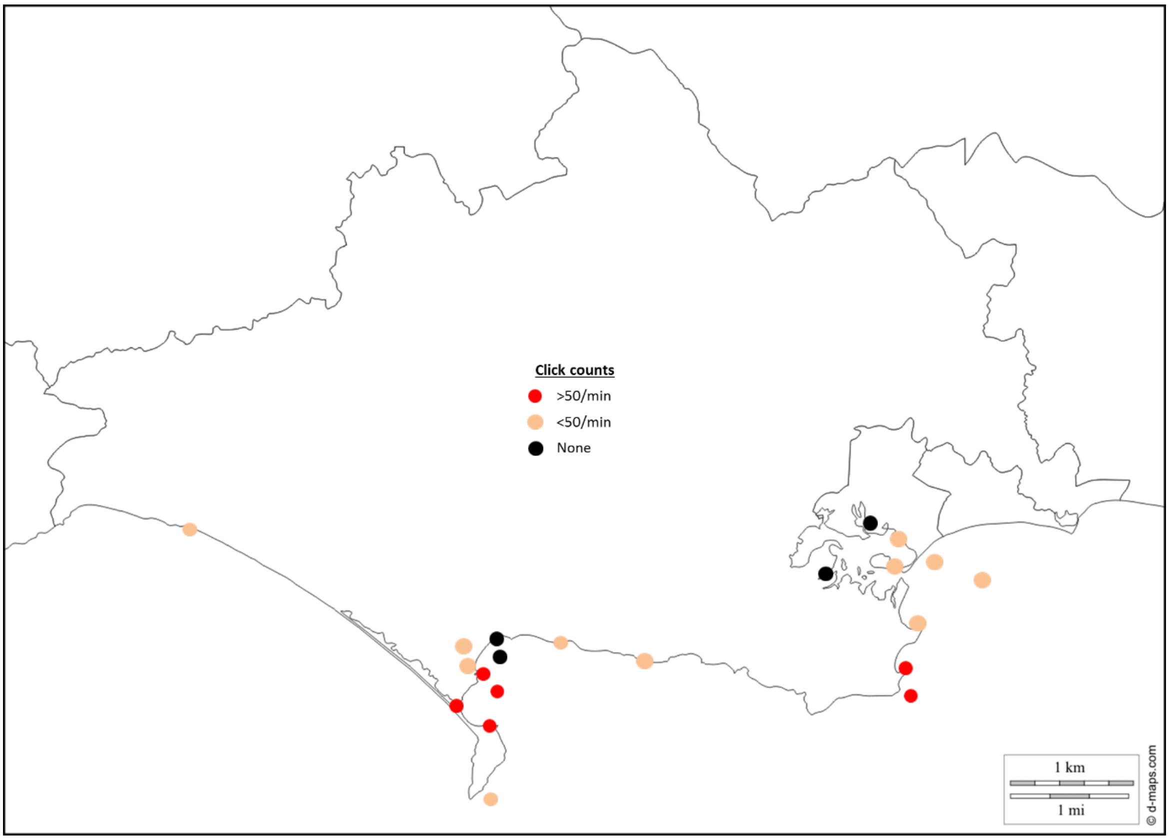


Figure 6.2 Results of surveys along the Dorset coast showing rates of clicking found

The data for the Dorset coast should also be treated with caution as again most of the data was obtained on an opportunistic basis with no control over time of day and time of year when it was collected. Also, most of the data was obtained early in the project before the temporal survey had shown the considerable variation in click activity during the diurnal and annual cycles (see later in this chapter for details).

Inspection of the tabulated data for the Dorset surveys strongly suggests that the areas with no clicks heard correspond to uniform sea beds of either sand or mud. The areas with the highest click levels were mixed sea bed types. The presence of a man-made structure such as a breakwater or stone pier also appears to result in an increase in click activity.

The most active areas found in the course of this project are the Portland Harbour breakwater and the channel under the Ferrybridge road bridge.

It would be useful to expand the coverage of this survey with improved supporting metadata and multiple site visits to better understand the spatial and temporal variation of click rates.

6.3 Study site distribution

6.3.1 Introduction

This work aimed to establish the coarse distribution of click activity within the lower Fleet and also to explore some very specific habitats in an attempt to isolate click sources.

Spatial and temporal distribution

6.3.2 Single hydrophone survey findings

The UC1 hand-held hydrophone system with cameras as described in Section 4.4.1 was used to map click activity along the southern edge of the main channel of the Fleet from the Black Hut Research Station out into Portland Harbour. The survey was carried out over two days on the 31st July and the 3rd August 2015. The survey points achieved are shown as A to N on the chart in Figure 6.3. They are also tabulated in Table 6.1. The channel in this area has steep sides so it was hope to achieve a good acoustic path from the channel edge to any clicking activity within the channel. A number of points away from the channel were also investigated (D, E, F and N).

This survey encountered a number of difficulties. The principal problem was access to the edge of the channel. Very soft muddy sand was encountered at survey points C and F and the side of the channel at points L and M was unstable due to undercutting resulting in a tendency to crumble away when weight was put on it. This meant that the data at these points had to be collected a safe distance away from the channel edge.

The location of the channel and seabed bathymetry shown in the chart in Figure 6.3 should be treated as a guide only. The actual location of the channel and the depth of water over the sand bars varies with the winter storms. This chart has not been re-surveyed for some years. Points G to K are all located on the edge of the channel.

Each survey point is identified in red with the number of clicks heard at each location shown as the black number on a white background. The click counts were made by extracting five minutes of data from the recordings made at each site. This was then passed through a click detector as described in Section 3.8. Since the same equipment was used for all the data collection the results are comparable. Using the hydrophone calibrations set out in Section 4.5 the chosen detection threshold corresponds to a sound pressure level of 109 dB re 1uPa.

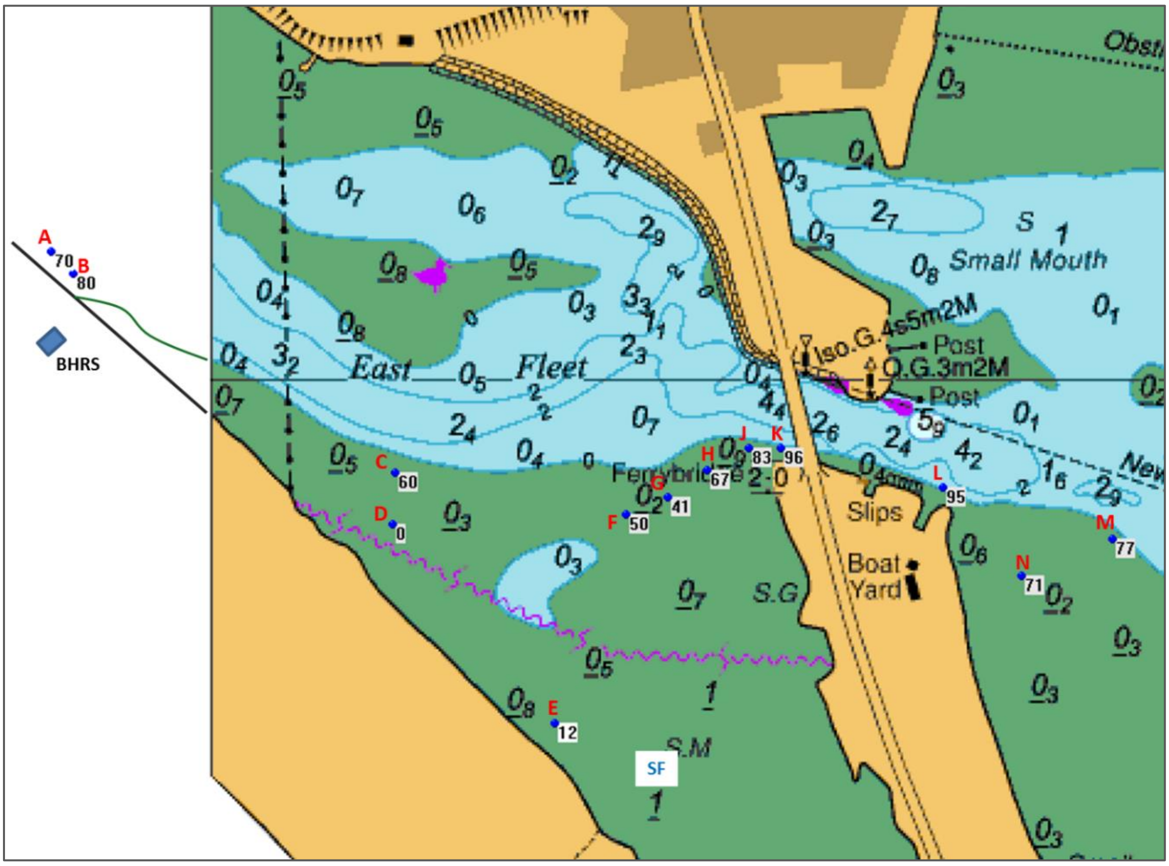


Figure 6.3 Single hydrophone survey locations

Table 6. 1 Single hydrophone survey points

Survey point	Location	Seabed	Clicks detected (5 min)
A	Near wrecked pontoon	Mud and pebbles	80
B	Near pipeline	Mud and sand	70
C	Edge of channel on sandbar	sand	60
D	Shallow lagoon behind sandbar	Muddy sand	0
E	Sandflat near winch base	Muddy sand	12
F	Sandflat away from channel edge	Soft sand	50
G	On sandflat ~5 metres from channel edge	Sand with some pebbles	41
H	Edge of channel	Sand, pebbles algae	67
J	Edge of channel	Pebbles, sand algae	83
K	Bridge revetment	Concrete, then soft sand	96
L	End of railway track bed	Soft sand	95
M	Sandbar on edge of channel	Soft sand	77
N	On sand flat away from channel	Firm sand	71

Clicking was heard at all locations. The most active area was under and adjacent to the bridge at Ferrybridge (points J, K, L) with activity slightly lower in the channel away from the bridge (points

A, B, C, G, H upstream and point M downstream). Away from the channel points D and E showed a low level of activity. At point D seven weak clicks were audible but they were not strong enough to exceed the detection threshold. Point D was in a very shallow lagoon behind a sandbar so was screened from most of the activity in the channel. Point E was also in shallow water but with no sandbar screening it from the channel activity. Point N was also well away from the channel but the water was deeper and there was no sandbar screening the channel activity.

At a number of the survey sites the types of clicks were investigated by listening to a 30 second period and manually classifying the clicks to be types A, B or C as defined in Chapter 5. The results are shown in Table 6.2 below.

Table 6.2 Percentage of click types

Survey point	Location	Type A	Type B	Type C
A	Shallows near channel	61	39	0
B	Shallows near channel	57	41	2
C	Edge of channel	69	31	0
D	Isolated sand pool	0	25	75
J	Edge of channel	69	30	1
L	Edge of channel	65	28	7
M	Edge of channel	63	35	2
N	Sandflat pool	61	23	16

From this it can be seen that in the main channel there are roughly twice as many type A clicks as there type B clicks with very few type C clicks. Away from the channel there are more type C clicks.

The main outcome of the survey is that clicking activity was high throughout the channel from the BHRS through Ferrybridge and out into Portland Harbour with a peak under the bridge. There was no indication that the click activity was localised into any particular areas.

This survey was then extended by deploying the sandflat unit described in Section 4.2.3 on the sand flats to the south of survey points E and F at location SF in Figure 6.3. Additional survey points were also investigated using the UC1 equipment and these are tabulated with the results obtained in Table 6.3.

Table 6.3 Additional single hydrophone survey points

Location	**Results**	**Notes**
Large saline lagoon near car park	Small number of type C clicks	Very poor visibility (~4 cms)
Small low-tide pool on sand flat near winch base	No click activity	Many tiny crustacea
SFU deployment on sand flats	Low click activity, ~7 clicks/min	In 1.5 metres water depth, Sept 2015
Saline puddle under Ferrybridge	No click activity	Transient puddle left by spring tide waves. High traffic noise level

The saline lagoon by the car park, the low-tide sandflat pool and the puddle under the bridge are transient features that dry out at various times so few clicks were expected. The puddle is a hollow in the revetment above the high tide mark so only fills by wave action during bad weather. The sandflat pool contained many young crustacea of unknown species, but most probably *Palaemon* spp. The saline lagoon is the longest-lived feature and this fills on spring tides but is isolated from the Fleet during neap tides.

The deployment of the sandflat unit was carried out in September 2015 at high tide and sampled three locations. The locations were within a 30 metre circle and were used in case of a local problem at any one site e.g. crab abrasion noise. It was found that results from the multiple locations were very similar. It was not possible to use the automatic click detector as used for the other survey sites because the equipment used had a different frequency response and because of a high level of non-biological noise. This noise was mainly caused by wave slap against the vertical support and by abrasion noise from shore crab activity.

With so few clicks recorded by the SFU it was possible to manually examine every click and of these approximately half could be identified to be a particular type. The remaining clicks were all low amplitude and either overlapped or were contaminated with noise preventing identification of the type. It was found that 65% of the clicks examined were type B wideband clicks and many contained features that suggest they were propagating in from the main channel. These features included low amplitude compared with clicks in the channel, the attenuation of high frequencies and a low-frequency cut-off between 2 and 8 kHz compared with around 500 Hz in clicks heard in the channel. Many clicks exhibited dispersion with the lower frequencies travelling more slowly. Although 65% of the clicks inspected were allocated to be Type B clicks, it is likely that an unknown proportion of these were type A clicks with the low-frequency precursor removed by propagation through the very shallow water.

A quarter of the clicks examined resulted from mechanical noise e.g. waves breaking near to or impacting the equipment, or crabs crawling on the pipework. Type C clicks made up 10% of the clicks inspected.

6.3.3 Single hydrophone survey results

This work has shown that the click activity is concentrated in the deeper water in the main channel that runs down the Fleet and under Ferrybridge. The highest level of activity is under and adjacent to the Ferrybridge road bridge. Activity on the sandflats away from the channel is low or very low.

Investigation of the low-tide sandflat pool and the pool under the bridge showed no click activity while the large lagoon by the car park showed a low level of Type C click activity.

The clicks in the main channel are a mix of type A and B clicks with very few type C clicks. In the shallows away from the channel type C clicks are heard more often with fewer type A and B clicks

6.4 Annual variation

The fixed hydrophone at the Fleet study site, described in section 4.3.1, was used to acquire almost continuous acoustic data over an extended time period. For the processed click data using the processing described in section 4.3.2 this period is six years. Recording of unprocessed data started in April 2015 and is still continuing. This raw acoustic data allows a more detailed investigation of click activity to be carried out.

The click activity data for 2014 is shown in Figure 6.4.

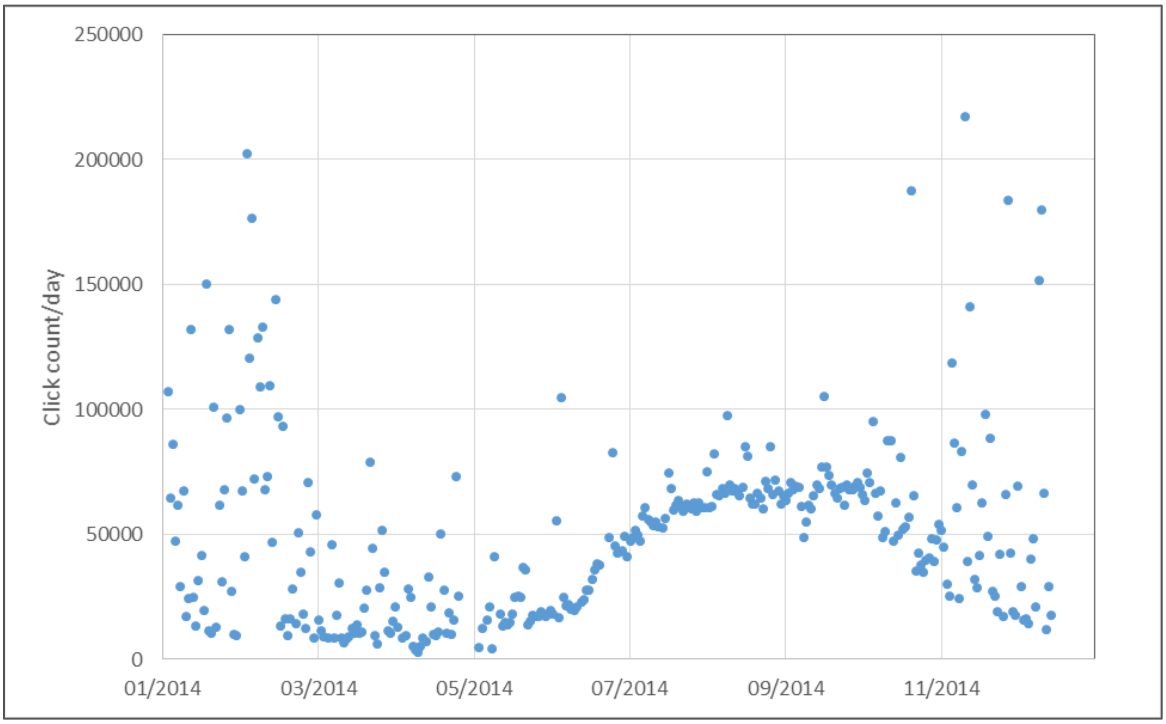


Figure 6.4 Daily click counts for the BHRS fixed hydrophone in 2014

The click counts which are well above the general trend line are due to increased noise levels resulting from a number of causes. The main noise sources are storms and passing boats. Some boats have propellers/gear boxes that can generate many high frequency clicks that can result in false alarms in the click detector. Floating algae and other debris that fouls the hydrophone or its supporting pipework can also cause mechanical abrasion noise that causes false alarms in the click detector. It was also found that under some wind/tide conditions the nearby pebble beach can become mobile and the moving pebbles can generate high levels of click activity. This usually only lasts for periods up to 30 minutes but the false alarm rate can be very high.

The ambient noise plot for the same period is shown in Figure 6.5. Each point is the RMS value for the whole day. The increased levels during the winter months can be seen. The increase in level through the summer is primarily caused by the increased click activity and tracks the activity level shown in Figure 6.4. There is increased boat traffic during the summer months but because each pass only last for a minute or less the effect on the RMS level is small compared with a prolonged storm.

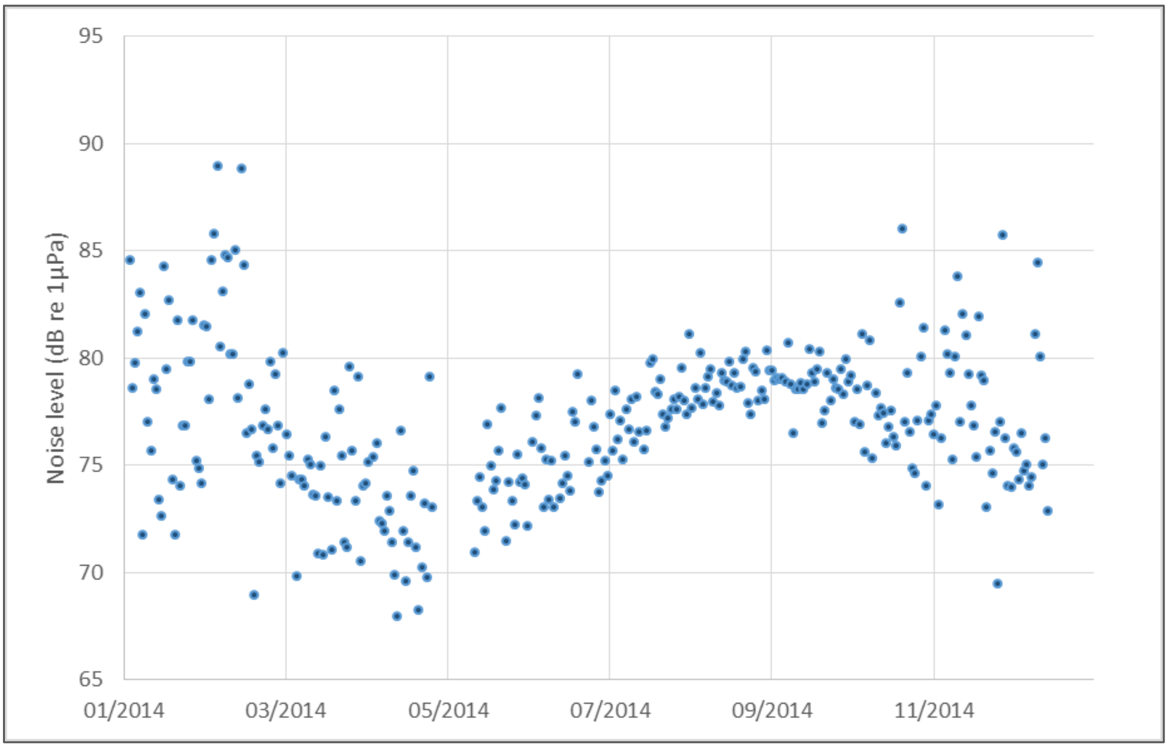


Figure 6.5 Daily mean ambient noise levels measured by the BHRS fixed hydrophone for 2014

Figure 6.6 shows the same data as Figure 6.4, but here all the data for days with elevated ambient noise levels due to adverse weather have been removed. The points to be removed were initially identified by inspecting meteorological data from a station located in Portesham close to the upper Fleet. Days with winds above force 4 on the Beaufort scale were candidates for removal. However, this meteorological station is located about a mile inland from the upper Fleet so the data is not always consistent with conditions at the study site. As a second level of checking the acoustic data for each of these days was inspected manually to ensure the sounds were consistent with those of bad weather.

There are still some remaining elevated click counts and these are due to the effects described elsewhere i.e. mobile pebbles, passing boats or debris abrasion noise. The most accurate click counts occur on very quiet days. Since false alarms add to the counts the trend in click activity is best described by the lower bound of the range of click counts. The click activity is then seen to be very low January to March and then starts to increase peaking in late summer before declining again through November and December.

Spatial and temporal distribution

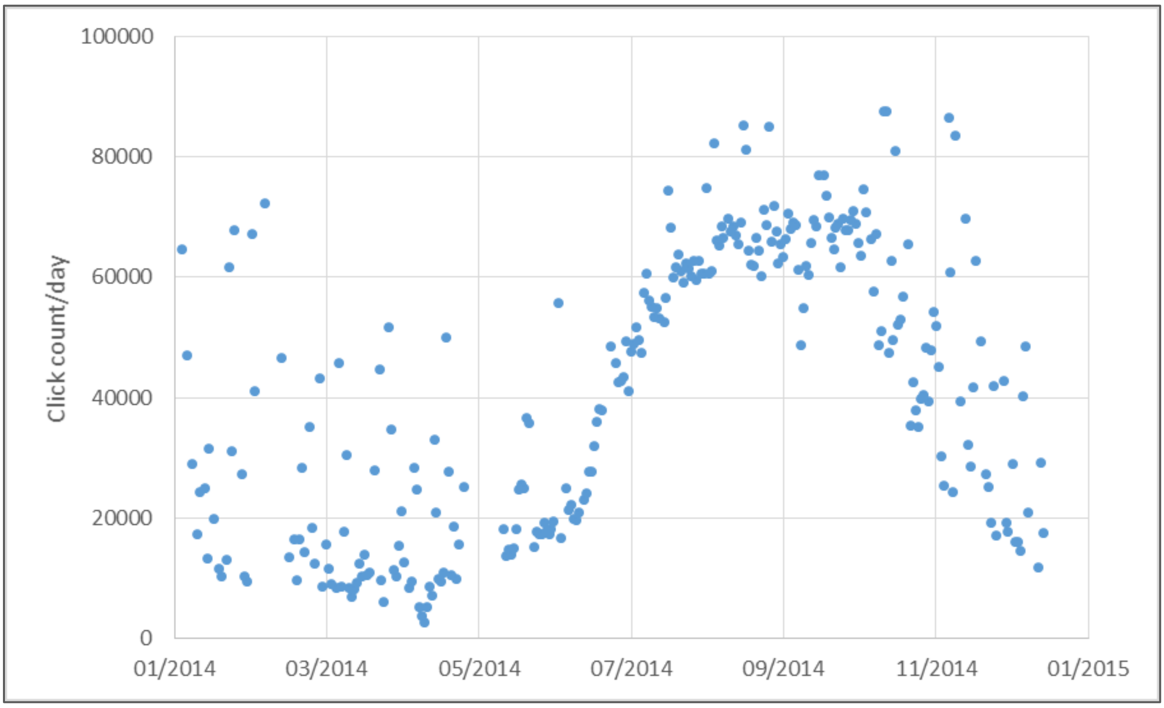


Figure 6.6 Daily click counts for 2014 with adverse weather days removed

Figure 6.7 shows the daily click activity for 2015 with the adverse weather days removed. The long gap in January/February was caused by storm damage to the hydrophone cable.

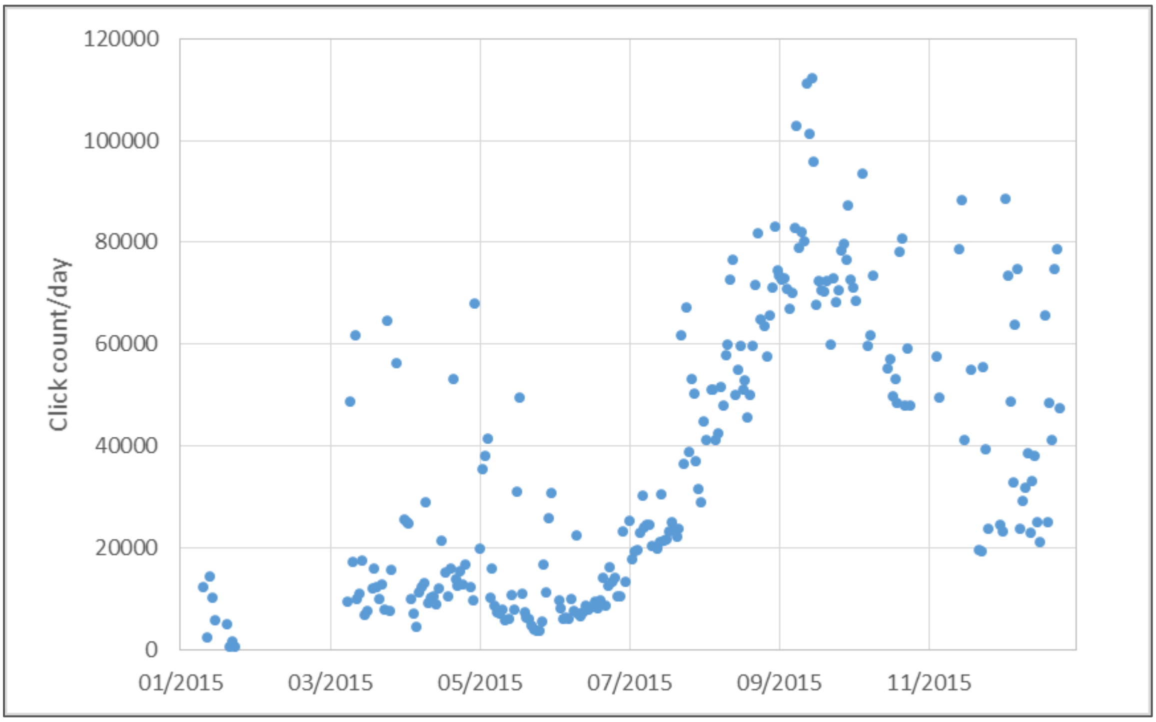


Figure 6.7 Daily click counts for 2015 with adverse weather days removed

The click activity is very similar to 2014 but the increase in activity through July occurs several weeks later compared with 2014.

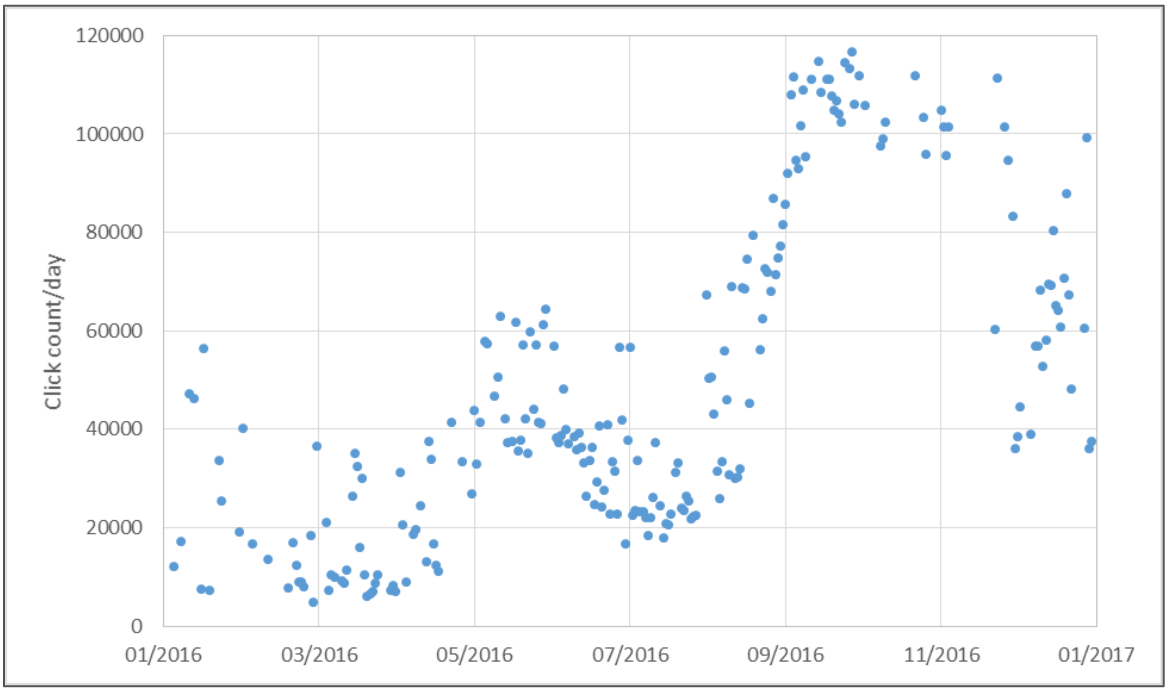


Figure 6.8 Daily click counts for 2016 with adverse weather days removed

The pattern in 2016 shown in Figure 6.8 seems to be somewhat different. The click activity starts to increase earlier in late April but then reduces again through June to a level comparable with 2015 before increasing again through August. The high level of activity is maintained later into the autumn than the previous two years.

The water temperature for the same area is available and is shown in Figure 6.9. The water temperature is measured at around 14:00Z on each visit to the BHRS using a Meteorological Office sea temperature bucket by wading out from the shoreline by the BHRS into about 1 metre water depth. The measurement is repeated until two consecutive readings are the same. The plots for ten years are superimposed to show the general trend in temperature and the year to year variation. The positive peaks during June, July and August correspond to exceptionally warm periods of weather.

The water temperature for 2016 is highlighted as the thick red line. This suggests the water temperature during the first half of 2016 was consistent with previous years and does not explain the early increase in activity followed by the dip in click activity in July. One possible cause is that, from personal observation, the underwater visibility was noticeably worse in spring 2016 compared with the two previous years. In the second half of the year the water temperature is on the high side of the range of measurements and this may account for the prolonging of the click activity until later in the year.

Spatial and temporal distribution

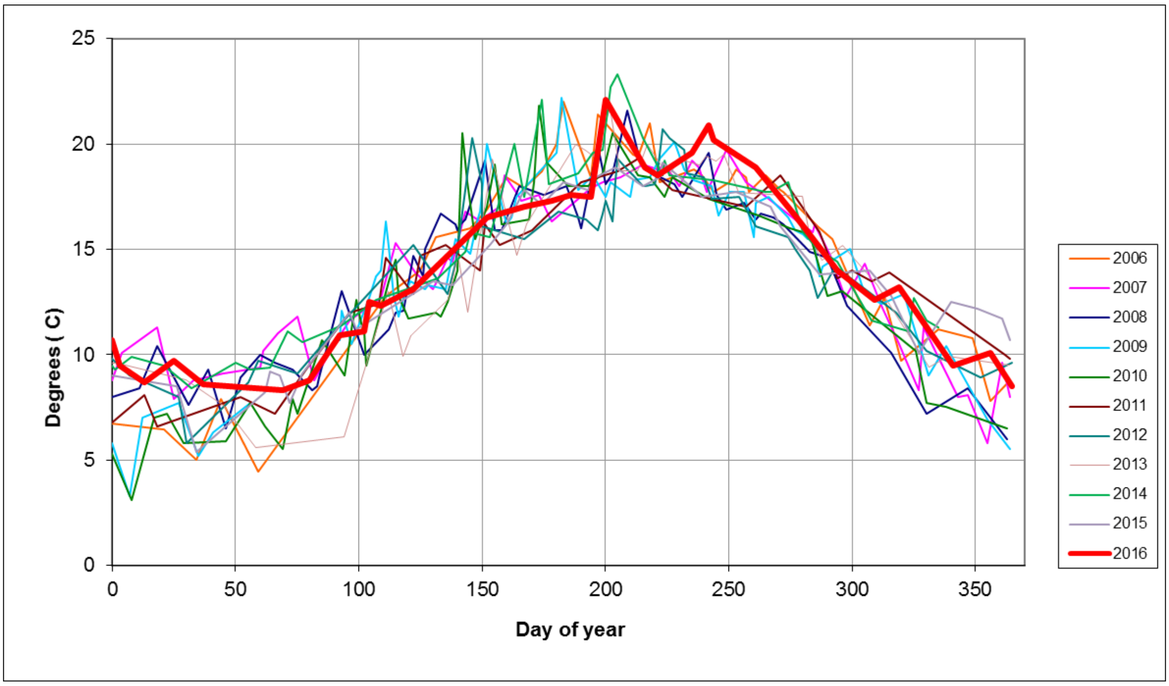


Figure 6.9 Water temperature measured near the BHRS 2006 to 2016

The water temperature variation leads the click activity curve by approximately one month. It is not clear if there is a direct link between water temperature and click activity, a second order link, or a coincidental link.

6.5 Diurnal variation

The click activity is measured by the BHRS fixed hydrophone system with a resolution of one minute and this data can be plotted on a daily basis. Figure 6.10 shows typical plots obtained during July/August 2014.

These four plots show the click counts for the whole day through a spring/neap tide sequence. The minimum tidal range occurred on the 5th August. The rise in click activity around 05:00 corresponds to local sunrise while the reduction in activity to 20:00 corresponds to local sunset. Note that all times are in GMT.

The vertical spikes on the plots correspond to noise from passing boats. High tide each day is shown by a red bar along the top of each plot and low tide by a green bar. This area has a double low tide during the spring tides and this is shown by an extended green bar. At high tide measured click activity increases by up to 40%. This peak may be due to an actual increase in click activity, or it may be due to other factors such as a change in acoustic propagation with the increased water depth resulting in clicks from a wider area being heard. At the location of the fixed hydrophone at the study site the water depth typically varies from 2.3 to 3.4 metres in a neap tide cycle and 1.7 metres to 4.1 metres on a spring tide cycle.

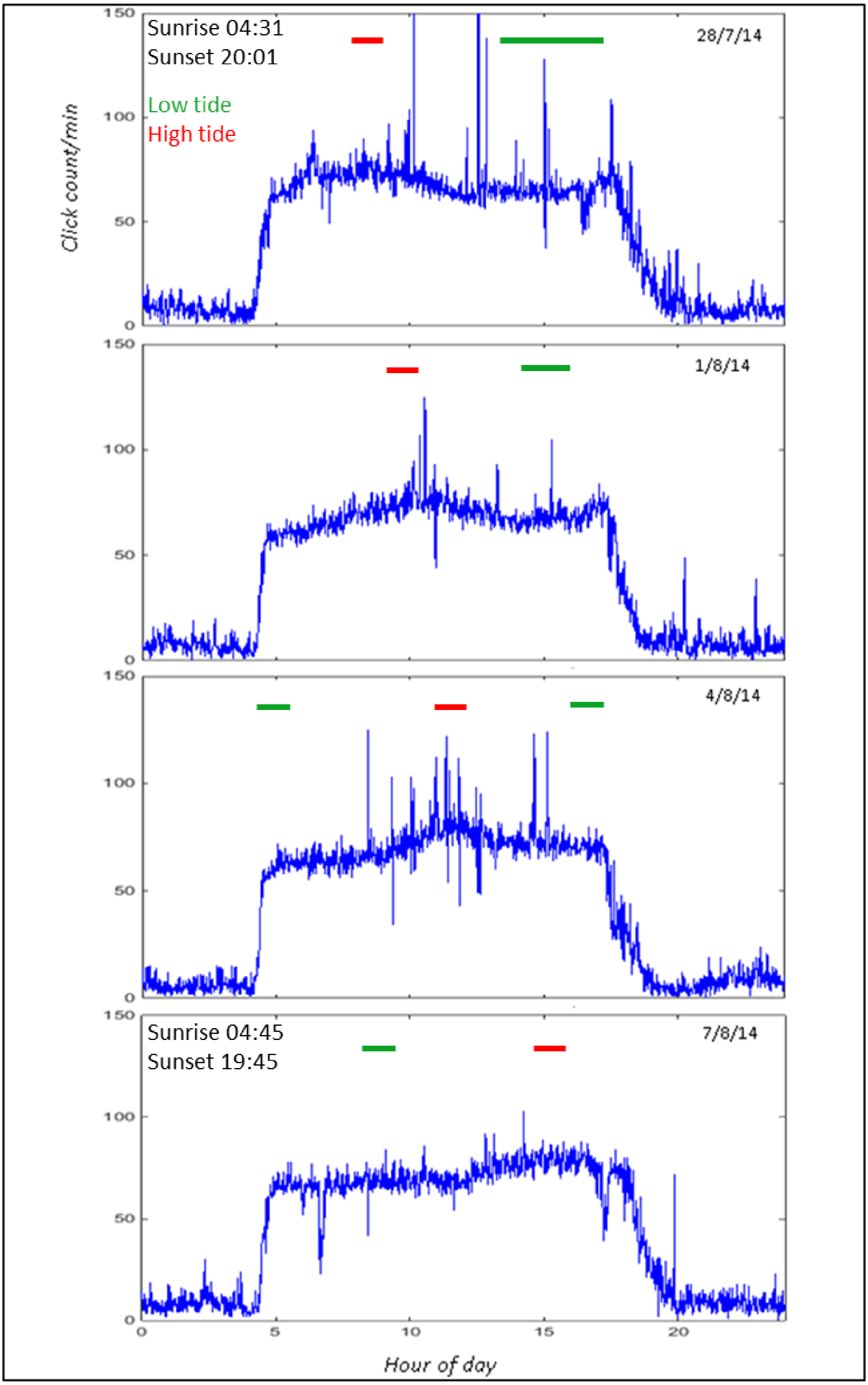


Figure 6.10 Fixed hydrophone click counts for 4 days in July and August 2014

Figure 6.11 shows the plot for the 13th August 2014 at the peak of spring tides with high tide at 09:00 approximately.

Spatial and temporal distribution

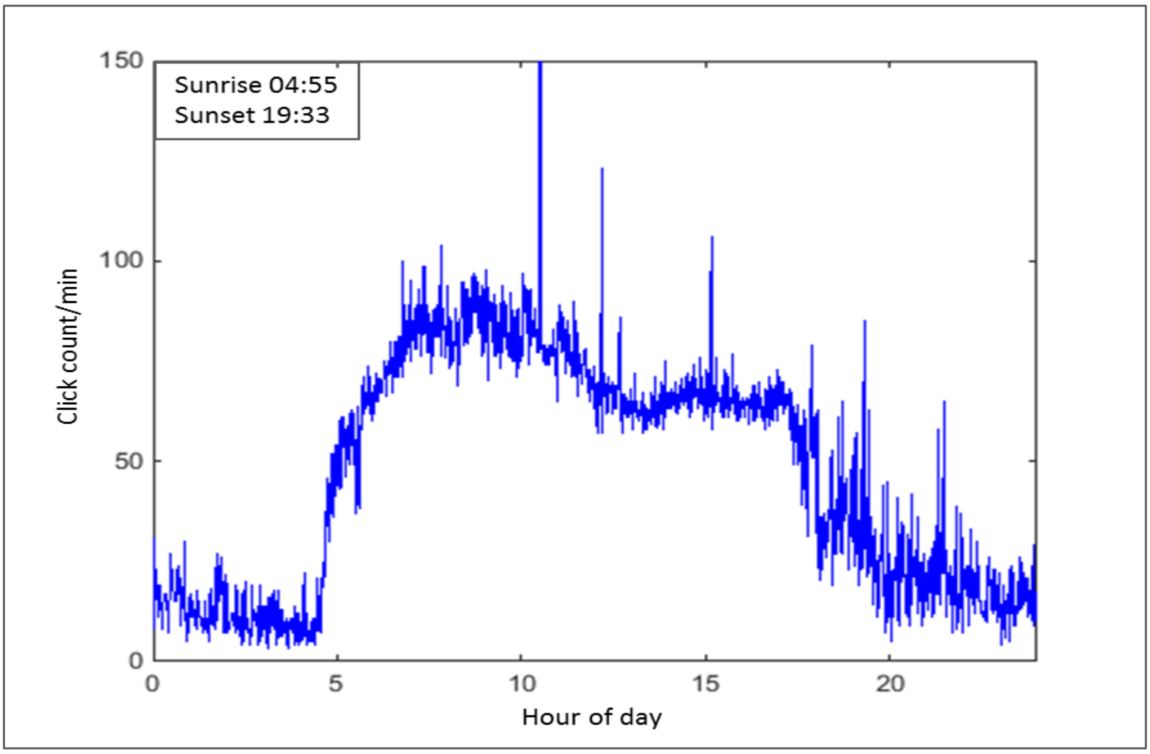


Figure 6.11 Click counts for a peak spring tide on the 13th August 2014

The click activity peaks in August and September and the distribution shown in Figure 6.11 is representative of the diurnal variation through this period. The activity then starts decreasing and by November has reduced considerably with distinct peaks at dawn and dusk as shown in Figure 6.12 for the 3rd November 2014.

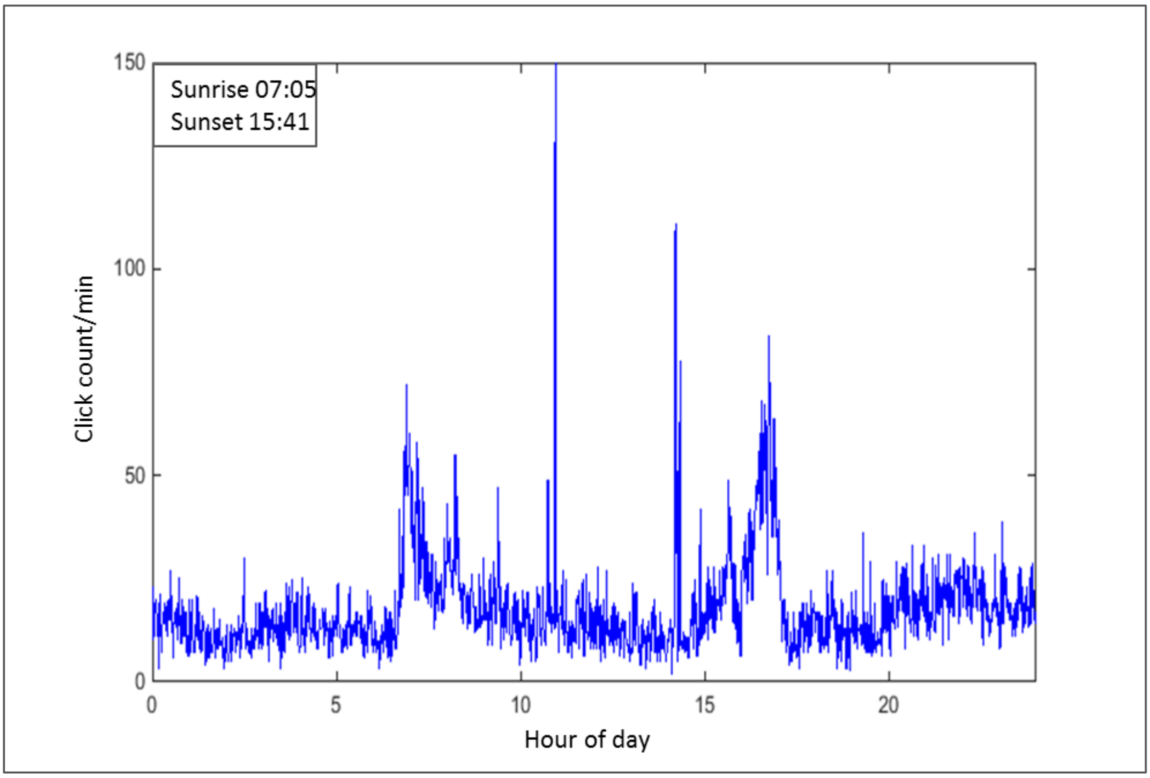


Figure 6.12 Click counts for the 5th November 2014

Through the winter there is a constant low level of click activity as shown in Figure 6.13 for the 3rd March 2014.

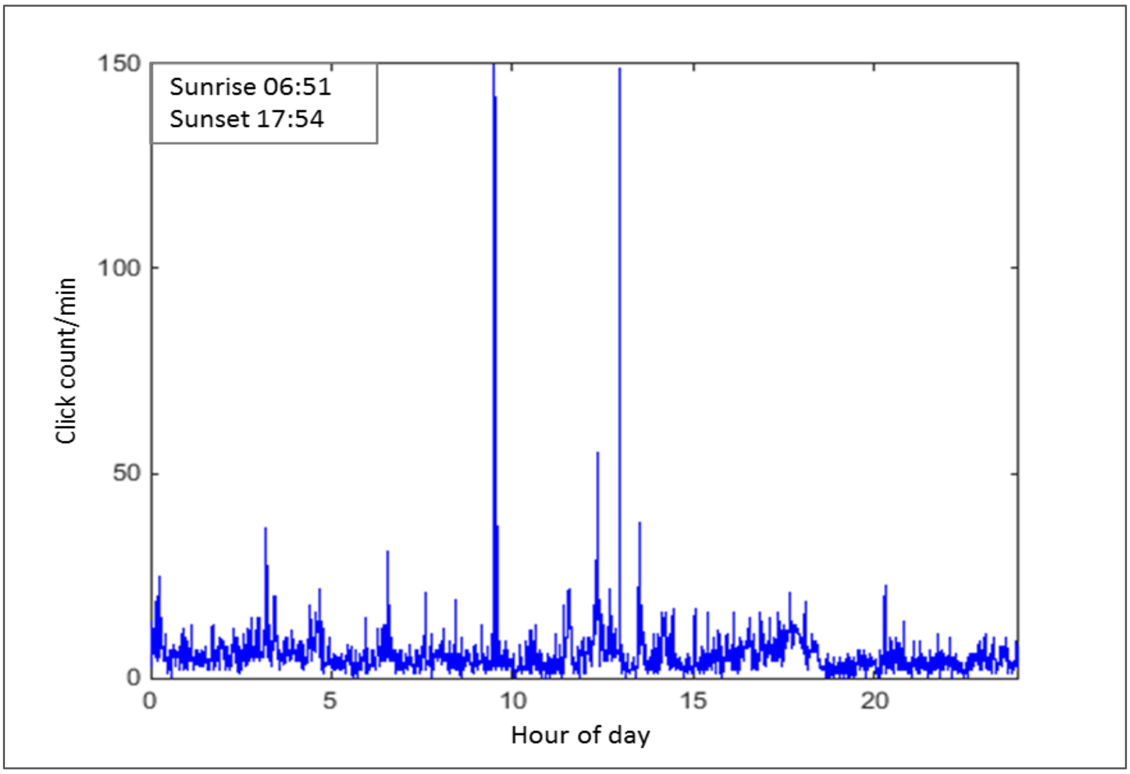


Figure 6.13 Click counts for 3rd March 2014

The clicking activity starts slowly increasing in April - May. Figure 6.14 shows the activity on the 8th June 2014. The peaks at sunrise and sunset are less prominent in the spring and often absent. The clicking then increases quickly through July to peak in August/September as shown in Figures 6.6 to 6.8.

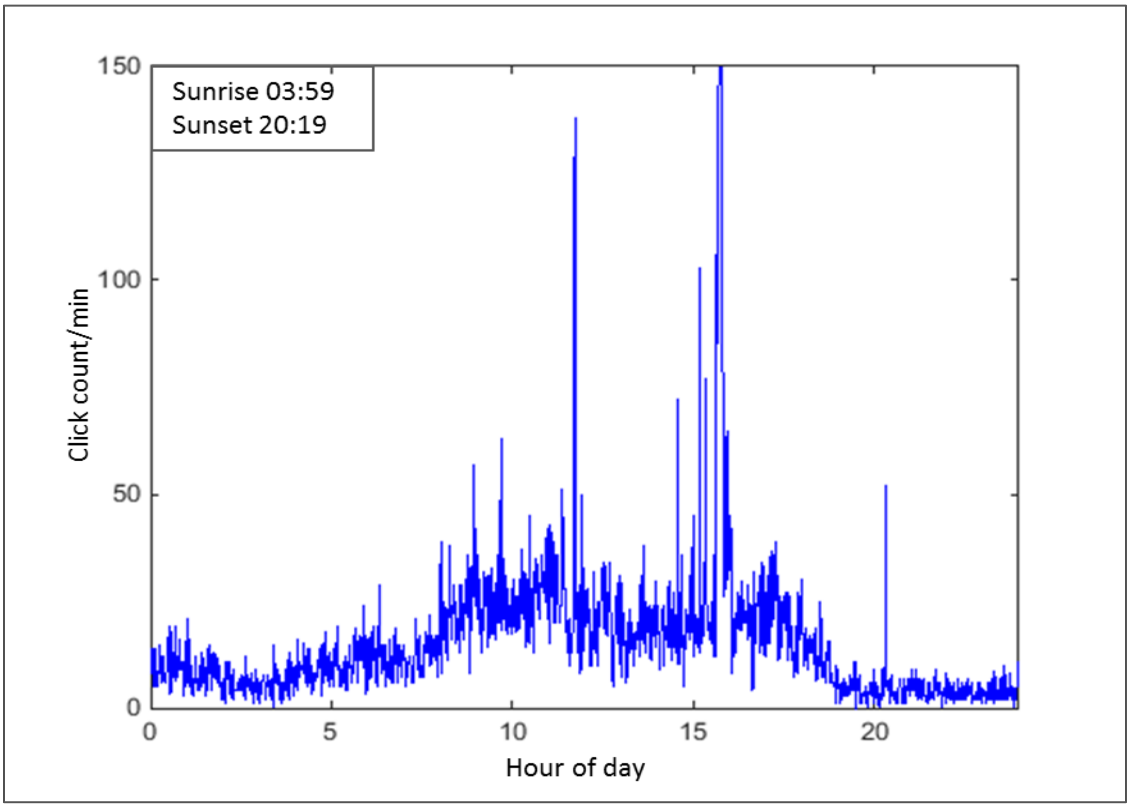


Figure 6.14 Click counts for the 8th June 2014

6.6 Summary of click distribution results

The national survey work strongly suggests that the observed clicking is only found in the southern half of the UK and Eire while the Dorset surveys strongly suggests that the areas with no clicks heard correspond to uniform sea beds of either sand or mud. The areas with the highest click levels were mixed sea bed types. The presence of a man-made structure such as a breakwater or stone pier also appears to result in an increase in click activity.

The study site survey has shown that the click activity is concentrated in the deeper water in the main channel that runs down the Fleet and under Ferrybridge. The highest level of activity is under and adjacent to the Ferrybridge road bridge. Activity on the sandflats away from the channel is low or very low.

The click activity at the Fleet study site varies through the annual cycle with low levels of activity from January to March and high levels of activity through August and September. This variation of activity closely aligns with the variation in water temperature at the site. However, other factors such as underwater visibility, may also affect the level of click activity.

The increased level of activity through the summer months occurs during daylight hours although there is still a low level of activity through the hours of darkness. The low level of activity through the winter occurs throughout the 24 hour cycle.

There is a weak dependence of measured click activity on the tidal cycle with a higher level of activity at high tide compared with low tide and an increase in activity on spring high tide compared with neap high tide. However, it is not clear if this is a real increase in activity or an apparent increase resulting from changing acoustic propagation conditions with water depth varies.

Chapter 7

Localisation of the clicks

7.1 Introduction

Section 3.5 set out the proposed methodologies to be employed to localise the source of the clicking with the eventual aim of identifying the source of the clicks. Chapter 4 described in some detail the equipment constructed to meet these aims.

This chapter presents the results achieved when localising the source of the clicks and also details difficulties encountered in achieving this aim.

7.2 Two and three hydrophone surveys

7.2.1 Introduction

Four deployments of the BiClick2 equipment described in Section 4.4.2 were carried out at the main study site to investigate various aspects of the click activity distribution. Cameras were also deployed on the hydrophone stands to look for species in the area. The deployments were:

a. Comparison between the deeper main channel and the shallows

   The seabed of the main channel is rather different to the shallows and hosts a different set of species. The channel is primarily mud, sand and pebbles with anthropogenic debris while the shallows are mostly small pebbles and mud with algae.

b. Comparison between within and away from a wreck

   There is a wrecked pontoon abandoned and sunk in the shallows. The pontoon structure provides a firm base for many species and some mobile species shelter within the wreck, particularly young corkwing wrasse and two-spot gobies.

c. Comparison across a sandflat

   Three hydrophones were located away from the channel and close to the algae line on the Chesil Beach shoreline.

d. Comparison along shoreline

   The hydrophones were located on the edge of the channel and used to investigate the time-difference distribution and the temporal stability.

For each deployment recordings were made for at least 10 minutes. These were then copied onto a PC and a MATLAB routine used to manually search the data for clicks using the following criteria:

Localisation

- No interfering signals from passing boats
- Level at least 10dB above background
- No overlap with adjacent clicks
- Distinguishing feature common to both channels to allow accurate measurement of differential arrival time

The start times of the click in each channel were then passed to an EXCEL spreadsheet for subsequent analysis.

7.2.2 Comparison between the main channel and the shallows

The two BiClick2 hydrophones were deployed at the main study site on 12th August 2015. The layout is shown in Figure 7.1. Hydrophone 1 was located in 1 metre of water on muddy, pebbly sand close to the algae line. Hydrophone 2 was located in the main channel in 2.5 metres of water on a mixture of sand, mud, pebbles and anthropogenic debris. The centre point between the hydrophones was on the edge of the channel.

Calibration runs were carried out using a dog clicker to verify system operation and to measure the hydrophone separation. This showed a maximum time difference of arrival of 4.9 ms. The water temperature was 19.1^{o}C and a salinity of 35.5ppt was assumed. The equation for the velocity of sound suggested by Leroy et al. (2008) and based on water temperature, salinity and depth gives the velocity of sound as 1520 m/s and this suggests a hydrophone separation of 7.45 metres.

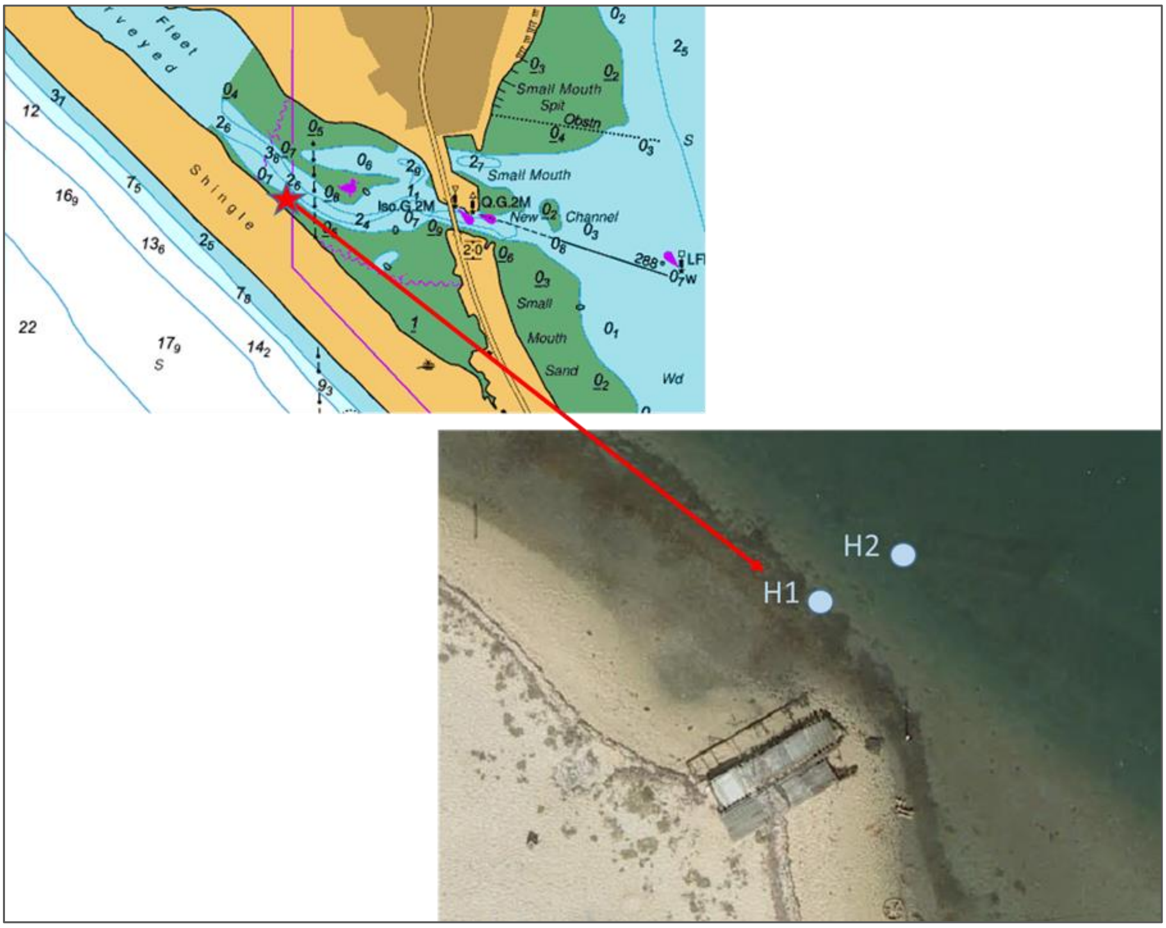


Figure 7.1 Location of the hydrophones for the shallow/deep comparison

A fifteen-minute recording was made from which a five-minute segment with no boat noise was chosen. This segment was analysed to determine the time difference of arrival for each click that could be identified from both hydrophones. These are plotted in Figure 7.2.

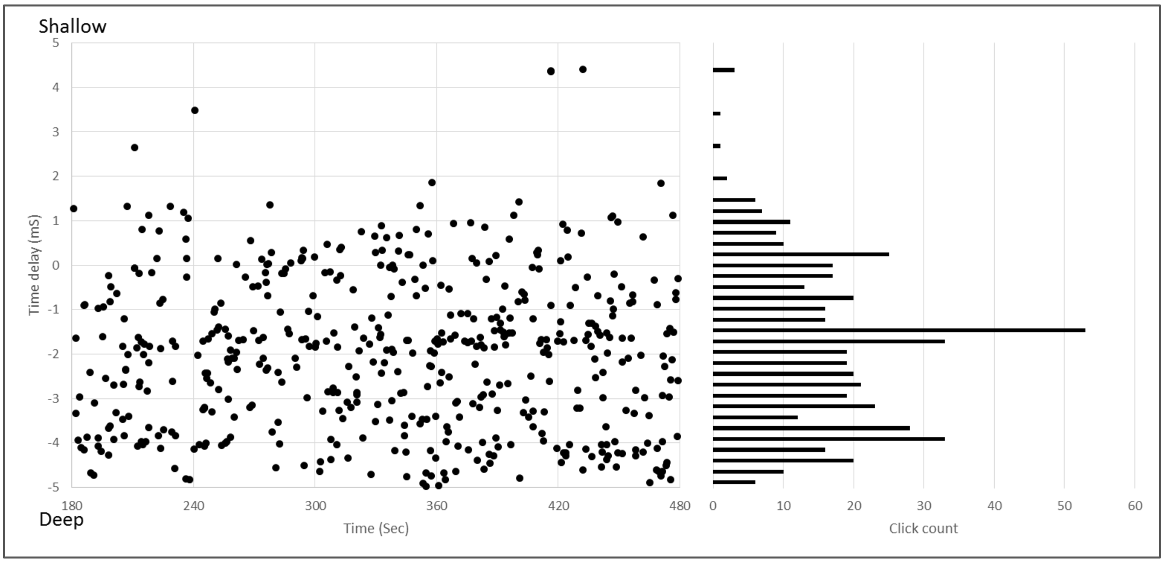


Figure 7.2 Plot of time difference of arrival for the shallow/deep comparison

For this plot negative delays correspond to clicks arriving at H2 before H1 so they originate from the H2 side of the midline of the array i.e. from the channel. Positive delays correspond to clicks arriving at H1 first so they originate from the shallow water. The results obtained are shown in Table 7.1.

Table 7. 1 Results for channel comparison

	Click count	**Percentage**
Towards channel	431	85.2%
Towards shore	75	14.8%

The plot shows a clear preference towards the deeper water of the channel (95% Confidence Interval is 6.2%).

7.2.3 Wreck comparison

The two BiClick2 hydrophones were deployed inside and outside of a wrecked pontoon at the main study site in March 2015. The pontoon is believed to be of WWII origin and was abandoned in its current position in the 1960's. At the time of the data gathering the water depth at the hydrophone locations was 1.5 metres. The location is shown in Figure 7.3.

Localisation

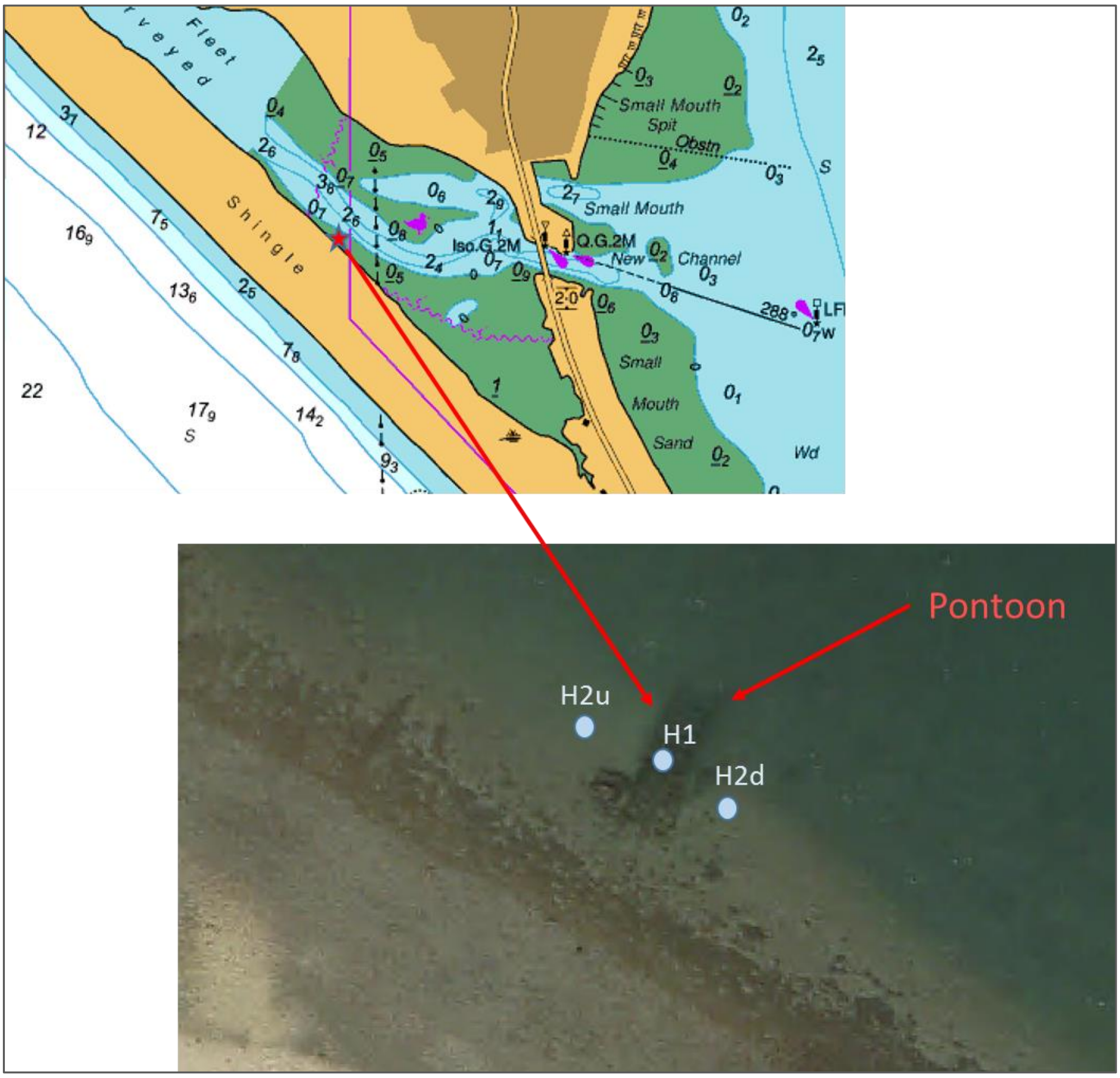


Figure 7.3 Location of hydrophones for the wreck deployment

Figure 7.4 shows the view into the wrecked pontoon. It is a series of vertical supports with cross bars well covered in marine growth. It is made of wood but the decking has rotted away leaving just the framework sitting on the seabed on the slope from the shallows towards the channel. It is 2 metres wide and approximately 20 metres long and is covered in a variety of algae, sponges and other marine creatures and provides shelter for a variety of mobile species.

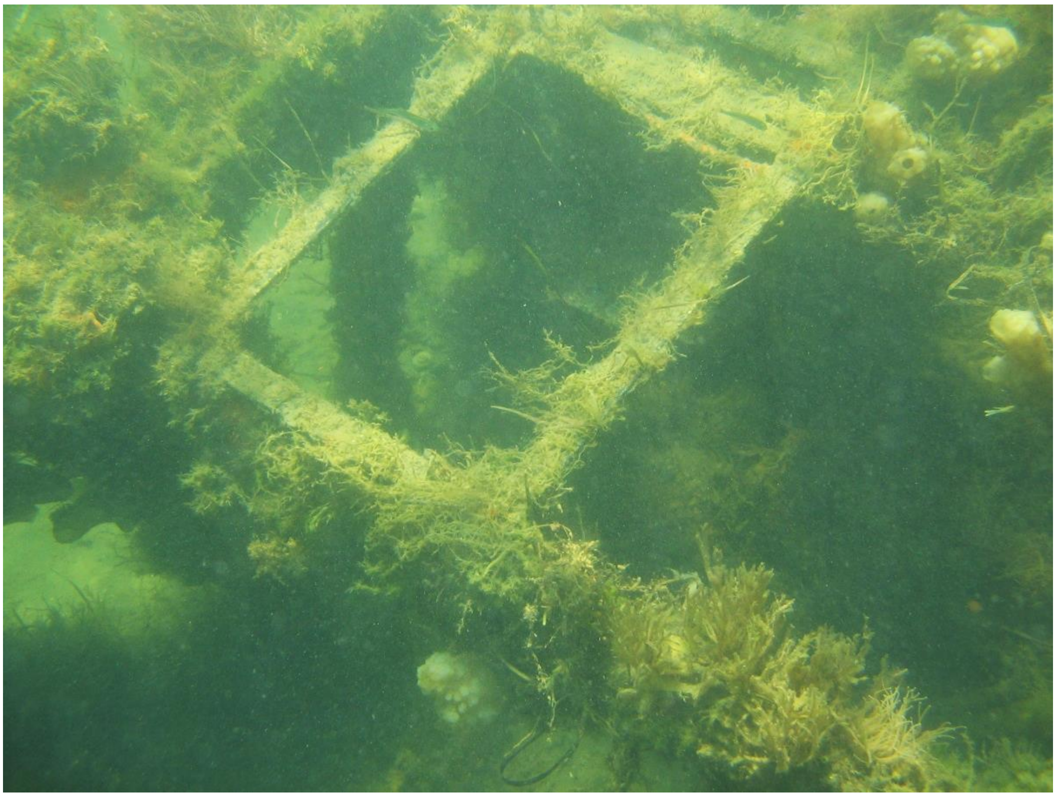


Figure 7.4 View of wrecked pontoon

Hydrophone 1 remained at a fixed location suspended within the pontoon while hydrophone 2 was initially placed upstream of the pontoon (H2u in Figure 7.3) on soft mud with a separation of 9.9 metres. The second hydrophone was then moved to the downstream site (H2d in Figure 7.3) on firmer muddy pebbles with a separation of 8.9 metres. A recording was made at each location and the data then analysed to extract the time difference of arrival for each click that could be identified in both hydrophones.

Figure 7.5 shows the data for hydrophone 2 in the upstream location while Figure 7.6 shows the data for hydrophone 2 in the downstream location. The gap in the data in Figure 7.6 around 150 seconds was due to the calibration work with the dog clicker. A positive delay is for clicks originating in the direction of the sunken pontoon while negative delays are for clicks originating in a direction away from the pontoon. This applies to both configurations.

The left-hand pane shows the time history of the clicks while the right-hand pane shows the count of clicks arriving in each 0.5 ms bin.

Localisation

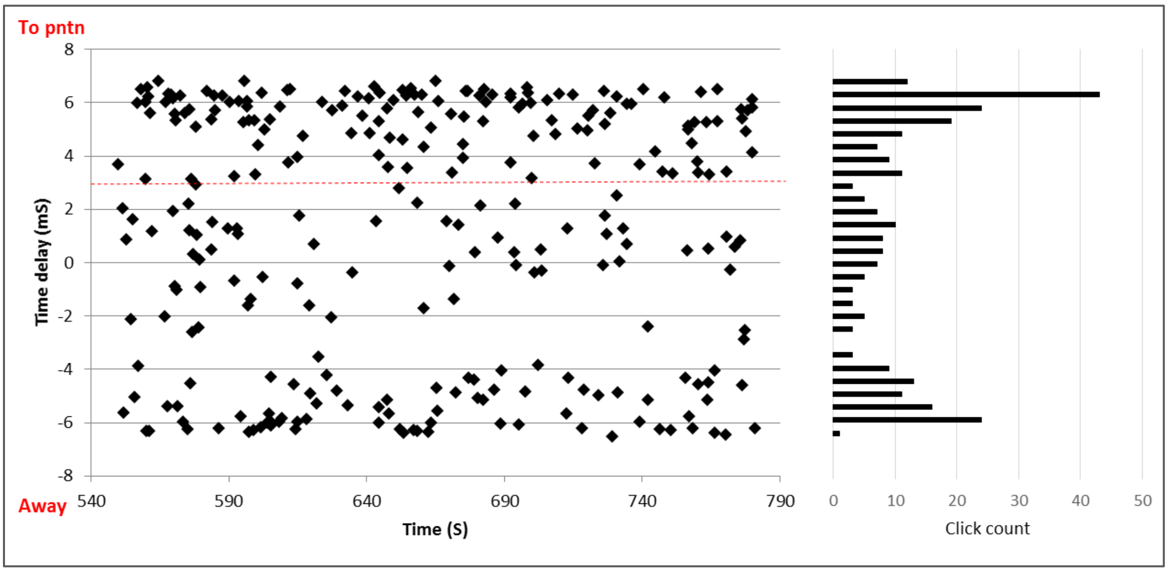


Figure 7.5 Time difference of arrival with hydrophone 2 in upstream position

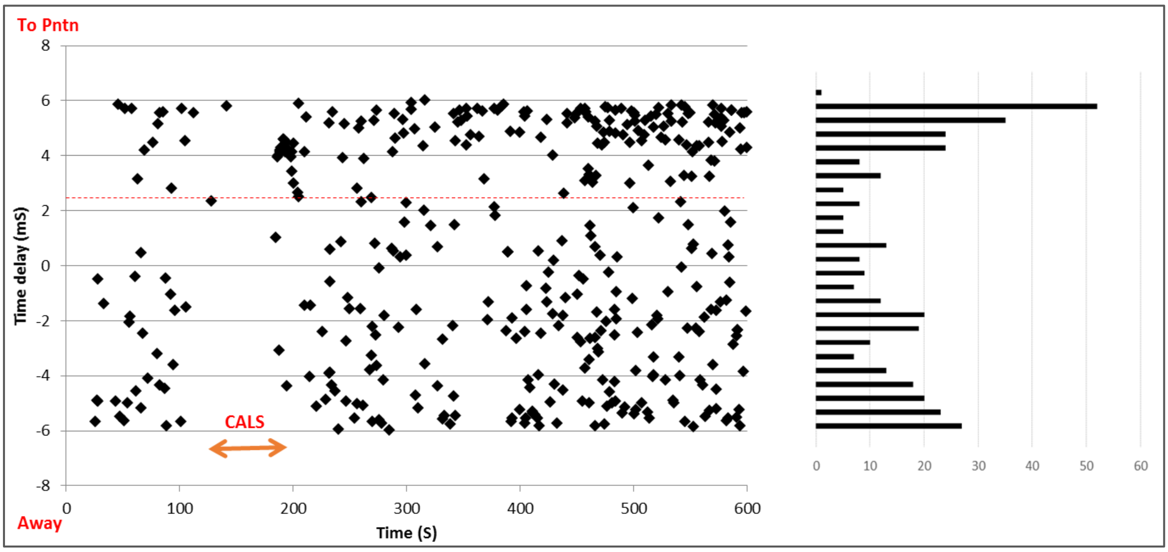


Figure 7.6 Time difference of arrival with hydrophone 2 in downstream position

For a click to originate within the pontoon it must have a delay greater than +0.27 ms with the first configuration and +0.23 ms in the second. These delays are shown by dashed red lines in Figures 7.5 and 7.6. The number of clicks with time delays within the range to be from the pontoon were counted for each configuration and compared with the number of clicks over the same range of time delays but with the opposite sign i.e. they originated from the other side of the hydrophone array midline. The counts are shown in Table 7.2.

Table 7.2 Click counts for the two hydrophone positions

Configuration	Towards pontoon	Away from pontoon	% towards	CI
Upstream	174	132	56.8%	±5.6%
Downstream	139	78	64.1%	±6.4%

The last column of Table 7.2 is the 95% Confidence interval (CI). This is calculated as:

$$CI = p \pm \left(1.96 \times SE\right),$$

Where: p is the proportion of clicks originating from the direction of the pontoon,
SE is the Standard Error.

The Standard Error (SE) is given by:

$$SE = \sqrt{\frac{p(1-p)}{(n-1)}} \ ,$$

Where n is the total number of clicks.

The CI gives the range within which there is a 95% confidence that the actual population percentage lies.

We can test whether there is a significant bias towards the pontoon using the chi-square test:

$$\chi^2 = \frac{(c_p - c_a)^2}{c_a} \ ,$$

Where: c_p is the number of clicks from the direction of the pontoon,
C_a is the number of clicks away from the pontoon.

Because there is only one 1 degree of freedom Yates correction is applied (Fowler et al (1998)) so the calculation becomes:

$$\chi^2 = \frac{(\left|c_p - c_a\right| - 0.5)^2}{c_a} \ .$$

This gives chi-square values of 13 and 46 for the upstream and downstream deployments respectively. Both of these values exceed the critical value of 3.84 at *P*=0.05.

Although these results show a significant bias towards the direction of the pontoon.it is perhaps somewhat less than may be expected if the clicking species have a clear preference for the sheltered habitat of the wreck. The presence of the wreck has affected the very local bathymetry resulting in the water at the channel end of the wreck being deeper than the area either side so the clear preference by the clicking organisms for the channel demonstrated in Section 7.2.2 may mean that the clicking organisms are using the deeper water created by the presence of the wreck.

The RMS level of the clicks in the downstream configuration were plotted to investigate if there was an amplitude difference between the two hydrophones. The RMS values were calculated over a 2.1 ms window starting at the time determined by the operator as being the start of the click. The amplitude units are MATLAB units. The amplitude range was split into 0.001 bins and counts made of clicks whose RMS level fell within each bin. The resulting plot is shown in Figure 7.7.

Localisation

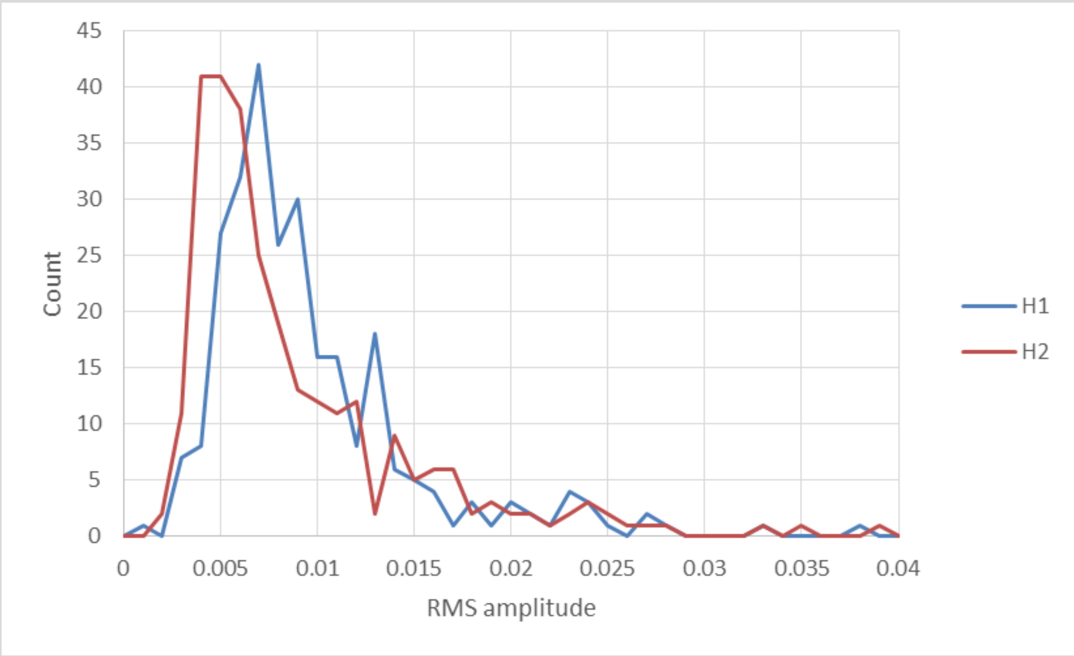


Figure 7.7 Amplitude distribution for hydrophone 2 in downstream position

For H1, The hydrophone within the pontoon, the mean is 0.013 and the mode 0.0054 while for H2 the mean is 0.011 and the mode is 0.0062. This difference is smaller than may be expected if the click-producing species were attracted to the pontoon.

It is noticeable that within the time difference of arrival plots there appear to be sequences of clicks that may form the track of a mobile species. Both Figures 7.5 and 7.6 contain such sequences. Figure 7.8 shows the time delays from Figure 7.6 with a number of potential tracks highlighted in red.

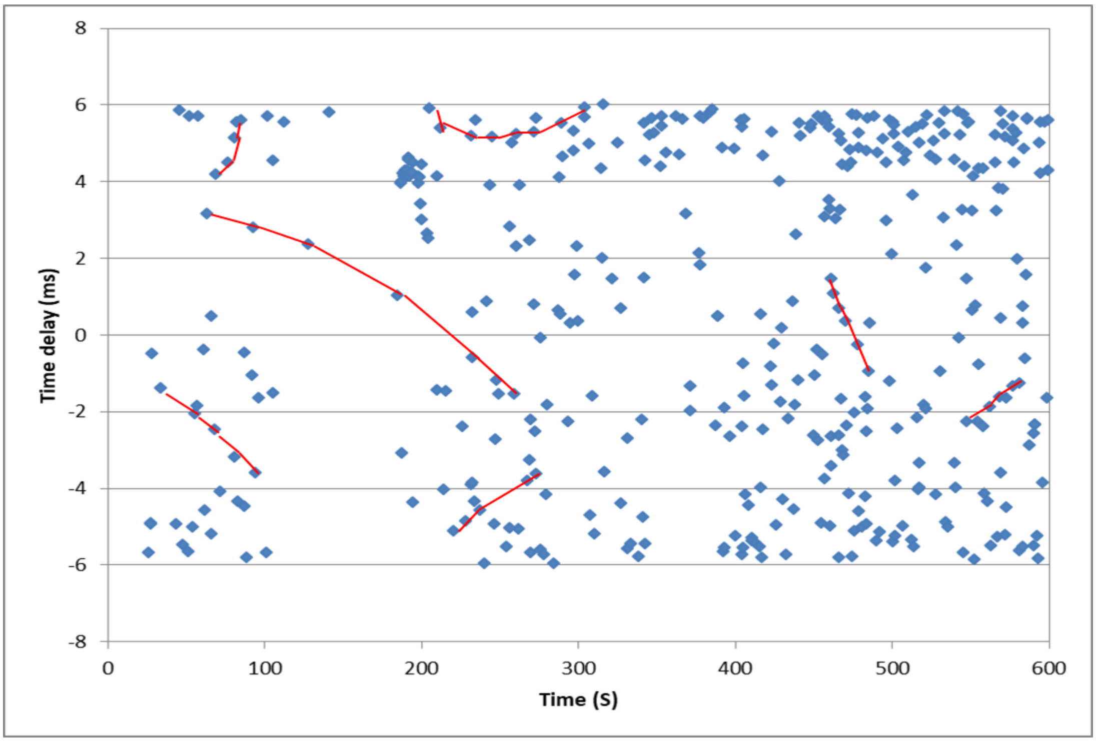


Figure 7.8 Time delays from Figure 7.6 with possible tracks highlighted

Time did not permit this aspect to be pursued but future work could investigate this by associating specific click types to possible tracks.

7.2.4 Sandflat comparison

Three hydrophones were deployed on the sandflats to the south of the BHRS in April 2015 as shown in Figure 7.9. These were the two hydrophones of BiClick2 arranged perpendicular to the shoreline (1 & 2 in Figure 7.8) and the UC1 hydrophone deployed parallel to the shore and to the north of the inner hydrophone of BiClick2 (3 in Figure 7.9). The separation of hydrophones 1 and 2 was set by using a calibrated rope.

The shoreline is a bank of small pebbles butting onto a flat seabed of mud and sand. Hydrophone 1 was located on firm muddy sand while hydrophones 2 and 3 were located on softer sandy mud. The water depth was 1.4 metres and was the same for all three hydrophones. The shallows extend out to 70 metres from the shoreline to the edge of the main channel. The depth then increases rapidly to around 3 metres. Hydrophones 2 and 3 were approximately 8 metres from the algae line that marks the boundary between the pebble beach and the sand flats.

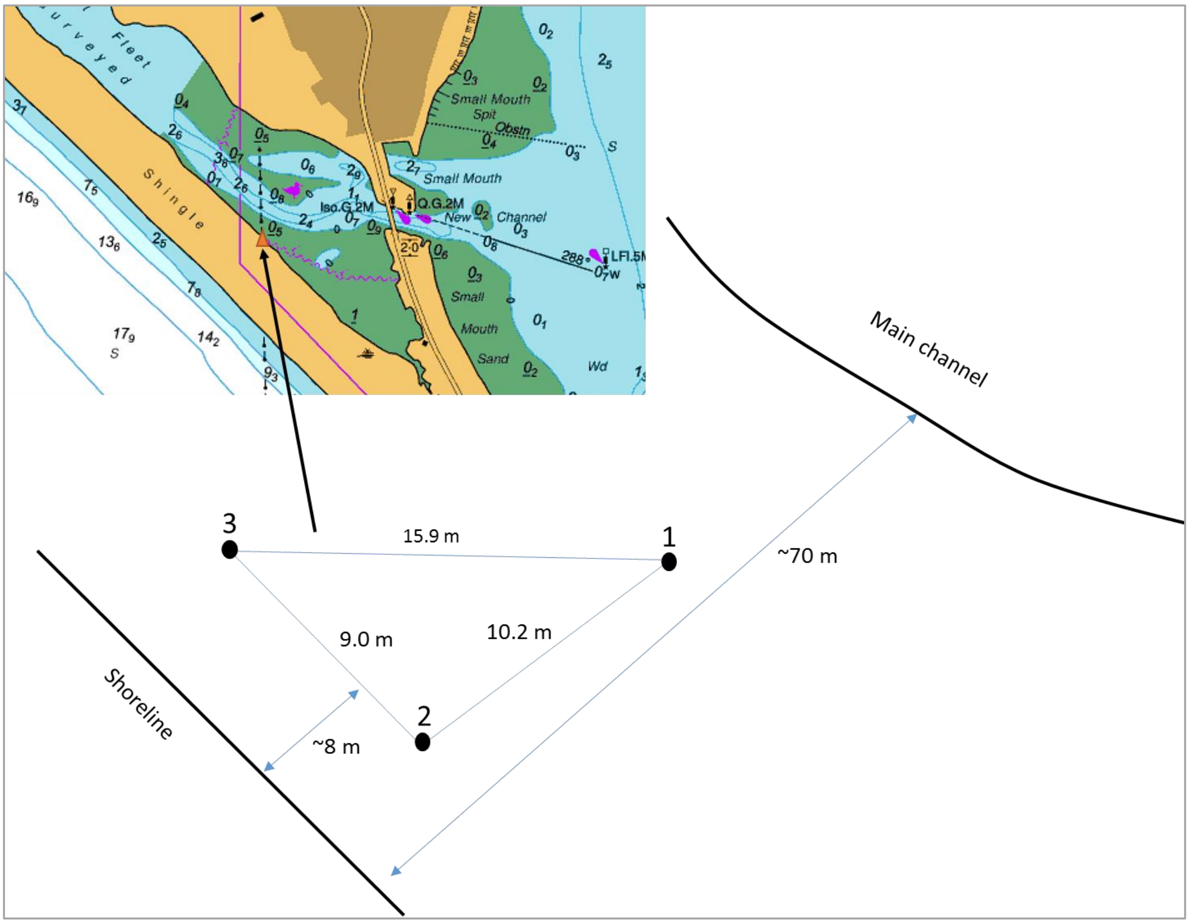


Figure 7.9 Location of hydrophones for sandflat comparison

Two fifteen minute recordings were made. The first recording was of the biological clicking while the second was a series of calibration clicks using the dog clicker described in Section 4.8. The calibration results were used to check system operation and to calculate the separation of the hydrophones. A major problem on this deployment was abrasion noise from shore crabs crawling on the supporting pipework

The data was then analysed to show the time difference of arrival. Five minutes of the data uncontaminated by biological abrasion noise was chosen and each click examined to ensure the signal could be identified on all three hydrophones. The times of arrival were then measured and this data is shown for hydrophones 1 and 2 in Figure 7.10, Figure 7.11 for hydrophones 2 and 3, and Figure 7.12 for hydrophones 1 and 3. The left-hand pane shows the time history of the difference in arrival time for each click. The right-hand pane shows the count of clicks in each 0.5 ms time difference interval.

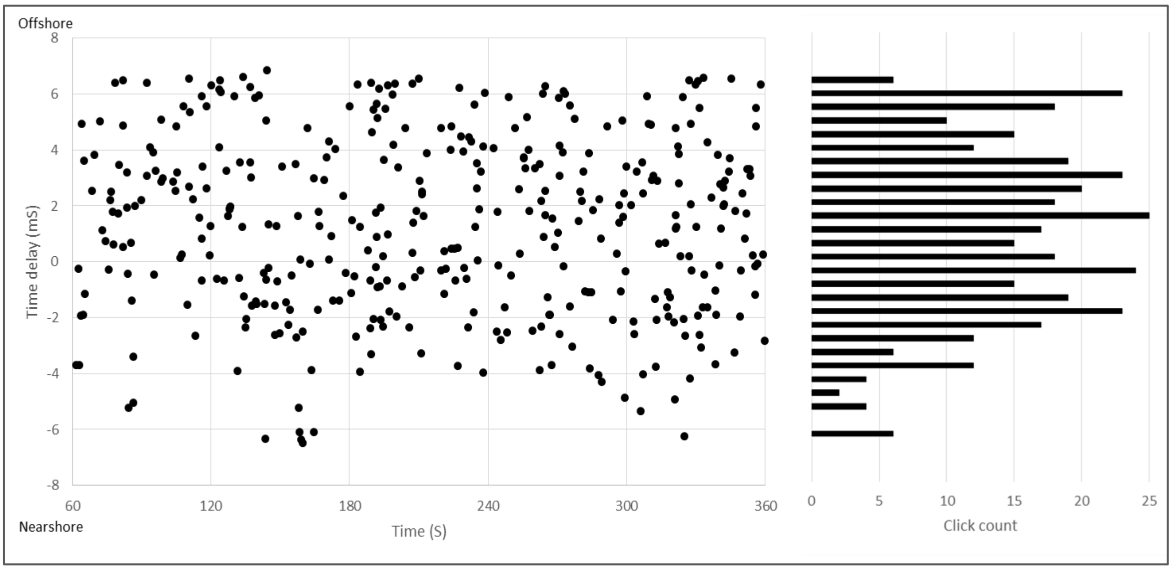


Figure 7.10 Time difference of arrival for hydrophones 1 and 2

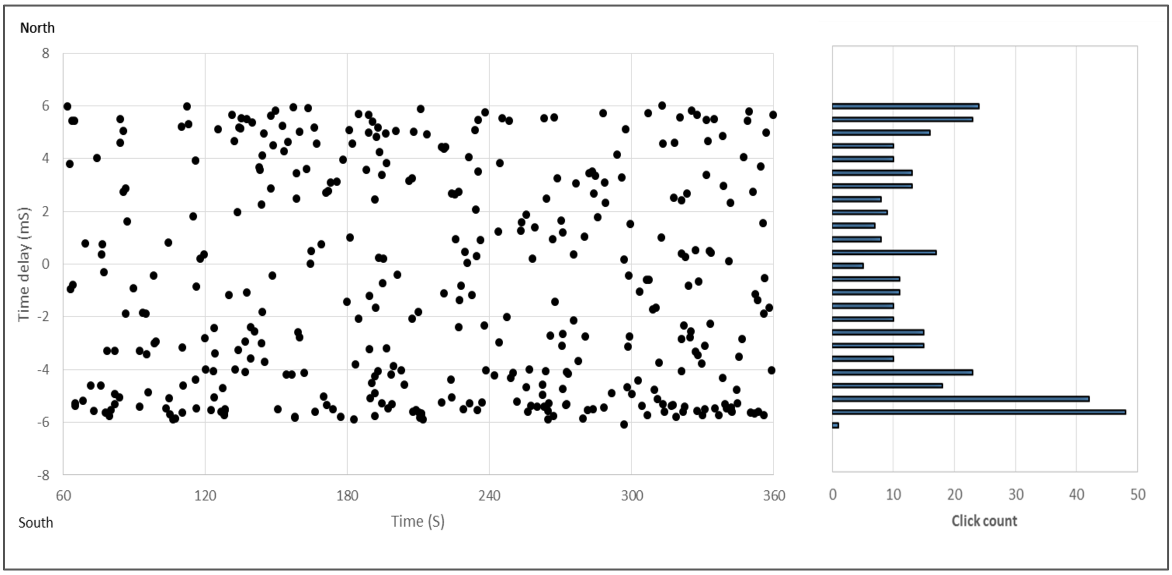


Figure 7.11 Time difference of arrival for hydrophones 2 and 3

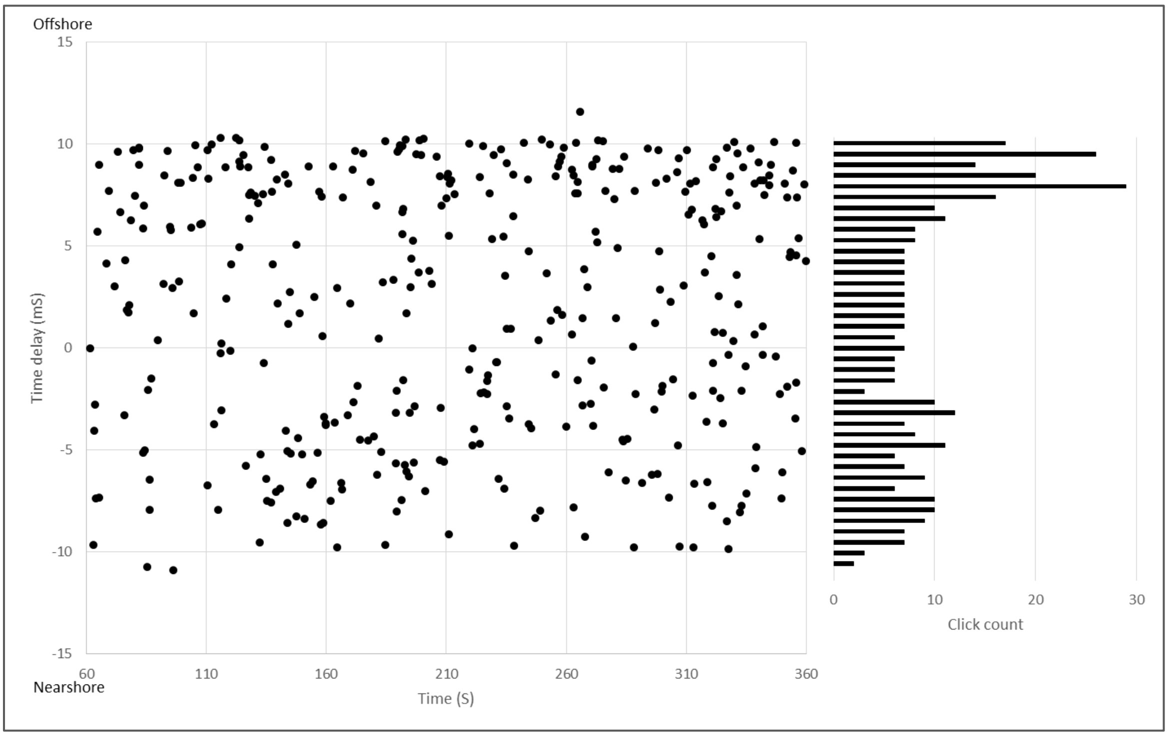


Figure 7.12 Time difference of arrival for hydrophones 1 and 3

Figure 7.10 shows that most of the clicks arrive from the direction of the channel (221 compared with 144 from the inshore direction). Figure 7.12 also suggests that many of the clicks arrive from the direction of the main channel but also that a significant number of clicks are originating in the shallows. Figure 7.11 suggests the majority of these come from either near the hydrophones or along the axis of the hydrophones, particularly to the south.

The peak amplitudes of the clicks heard on hydrophones 1 and 2 were measured. The amplitude units are arbitrary MATLAB units. For H1 the mean was 0.131 and the mode was 0.12 while for H2 the mean was 0.084 and the mode was 0.057. This also supports the hypothesis that the majority of the clicks are arriving from the main channel.

As in the previously described deployment there is some evidence of possible tracks in the plots.

7.2.5 Spatial distribution and temporal stability

A deployment of BiClick (BC2) was carried out in October 2014 adjacent to the BHRS at the main study site. The two hydrophones were located in 1.5 metres water depth in the shallows on the edge of the main channel and roughly parallel to the channel edge. The hydrophone separation was 6 metres set by using a measuring rope. The equipment layout is shown in Figure 7.13.

The water temperature was 18.2^{o}C and the sea was calm. The tide was close to high neap tide.

Localisation

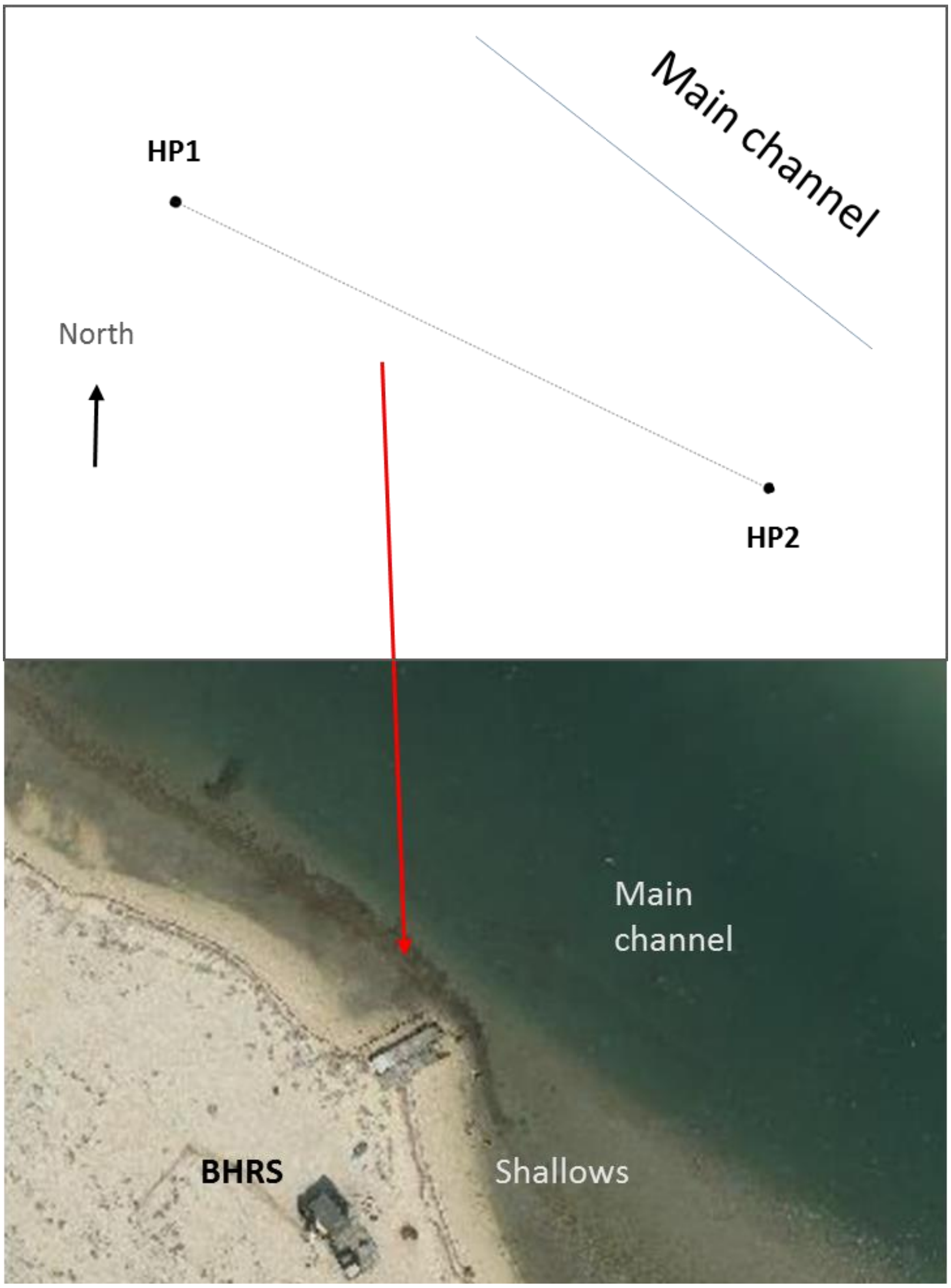


Figure 7.13 Location of BiClick hydrophones for deployment on 2nd October 2014

Three recordings were made from the BiClick2 equipment including two calibration sequences using the dog clicker covering a period of 65 minutes. Three segments of the data were analysed in detail:

1. A 4 minute period starting at 13:15:30
2. A 1 minute period starting at 13:42:10
3. A 4 minute period starting at 14:05:00

The processed data is shown in Figures 7.14 to 7.16. The left-hand pane shows the time delay for each click with time while the right-hand pane shows the count of clicks occurring in each 0.5 ms interval.

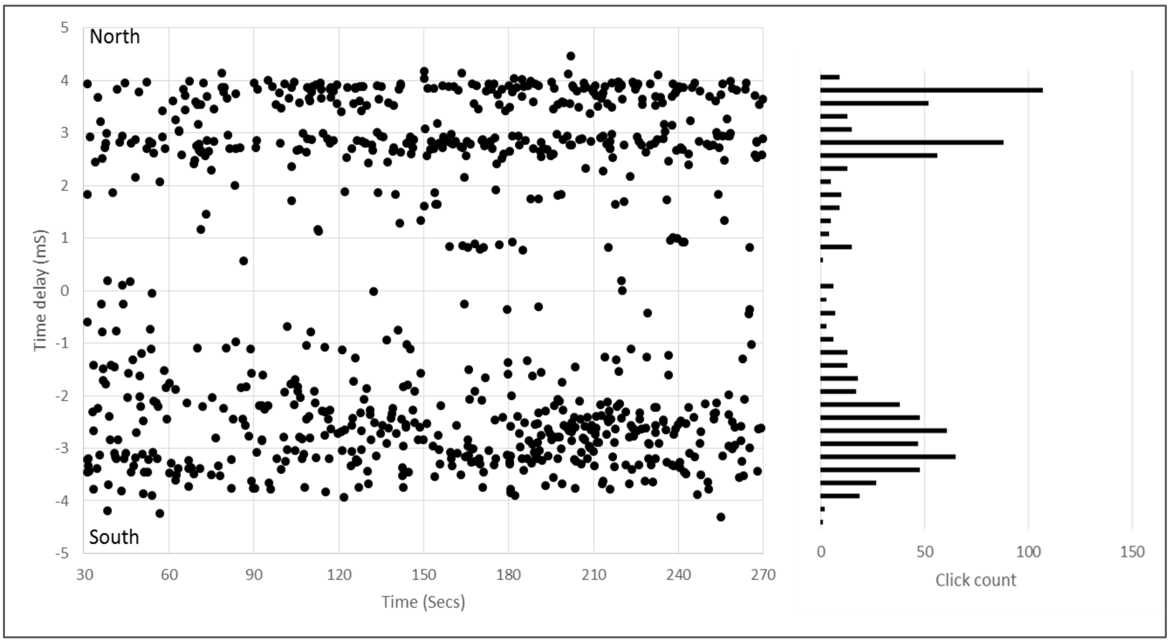


Figure 7.14 Time difference of arrival for segment 1

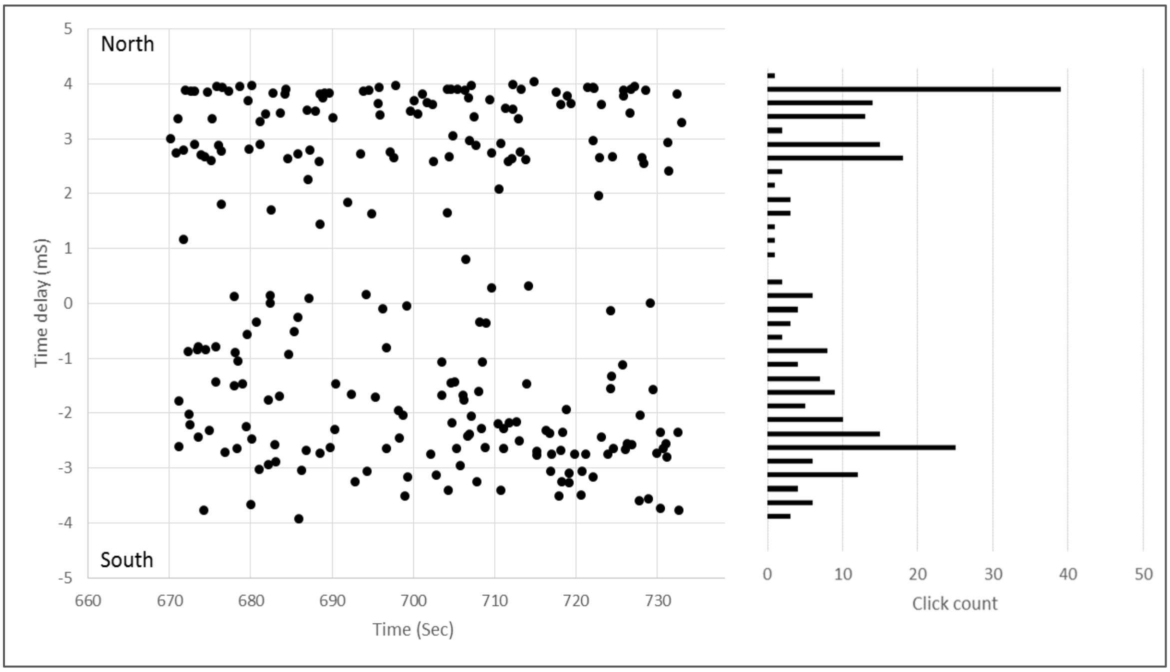


Figure 7.15 Time difference of arrival for segment 2

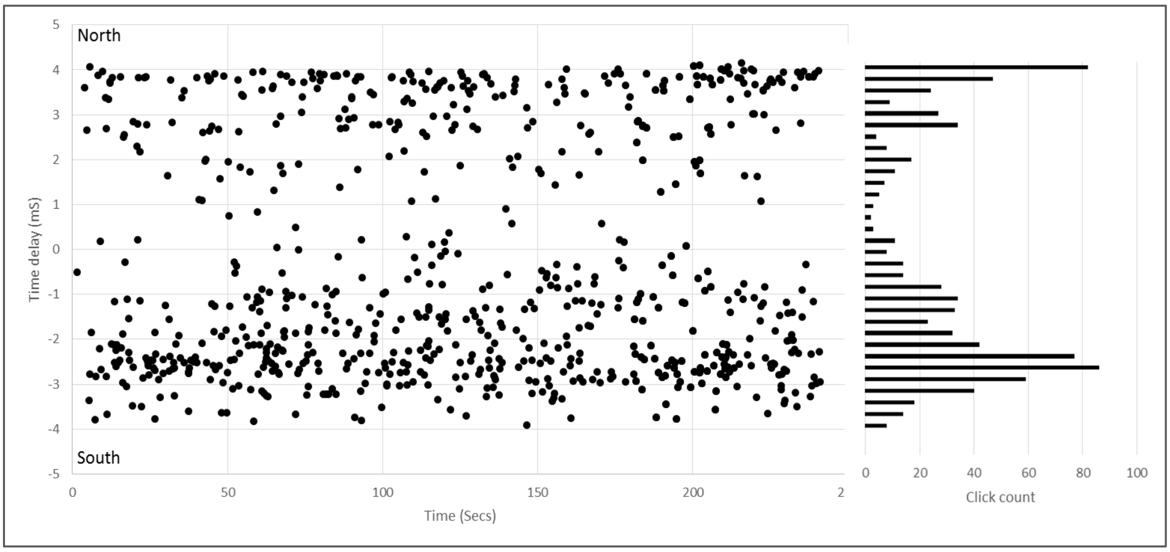


Figure 7.16 Time difference of arrival for segment 3

The hydrophones are oriented so that positive delays originate north-west of the array centre. There is an angle of ~15 degrees between the line of the array and the edge of the channel such that the line of the array points into the shallower water to the north-west and out into the channel to the south-east.

Across the 54 minute period the distribution of click activity appears to be fairly stable. There appear to be three preferred directions for the clickers that persist through the full period. There is a broad peak to the south which includes clicks originating in the channel but there are also two narrower peaks looking away from the channel

The distribution of clicks supports the findings that most clicks originate in the direction of the channel but also that some originate in the shallows.

7.2.6 Summary of two/three hydrophone results

The two and three hydrophone work has shown that the click activity is predominantly in the direction of the main channel. A smaller number of clicks do originate in the shallow water and the algae line along the shoreline. It has shown that there is little increase in click activity within the wreck compared to the adjacent areas. There is a degree of stability in the angle of arrival of the clicks over a period approaching an hour.

7.3 Four hydrophone system (QC2, MQC2)

7.3.1 Introduction

For this part of the work a four hydrophone system as described in Sections 4.4.3 and 4.4.4 was used using the methodology described in Section 3.5.3 to investigate the fine scale spatial distribution of click activity. It was hoped the array would provide localisation of any click originating within a 4 metre cube centred on the array. Cameras were included on the array to obtain video images of any species moving within their field of view.

Two arrays have been deployed as described in Section 4.4.3. The QuadraClick2 (QC2) array is based on a 1.5 metre element spacing but proved very cumbersome to deploy so most of the data collected was with the smaller, lighter Mini QuadraClick2 (MQC2) array based on a 1 metre spacing.

The calibration runs for the QC2 deployment were analysed to ensure the system was operating correctly but the click data was not analysed in detail due to the deployment difficulties of manually handling such a large piece of hardware. This meant that the deployments were in water that was shallower than was anticipated resulting in the top hydrophone being very close to the surface. The resulting multi-path distortion made it very difficult to identify the start of the click. Effort was therefore focussed on deploying and analysing the MQC2 system.

One successful deployment of QC2 and two successful deployments of MQC2 were achieved at the main study site as shown in Table 7.3. Time only permitted a detailed analysis of the two MQC2 deployments to be carried out.

Table 7.3 Four hydrophone array deployments

Date	Syst	Cams	Purpose	Comments
30/8/2013	QC2	2	Channel edge	Neap high water
2/10/2014	MQC2	2	Channel edge	Neap high water
28/8/2015	MQC2	2	Main channel	Spring low water

7.3.2 MQC2 deployment 2nd October 2014

This deployment of the MQC2 equipment coincided with the deployment of the BiClick2 equipment as described in Section 7.2.5. The layout of the equipment is shown in Figure 7.17. The alignment of the MQC2 hydrophones 1-2 axis was on a bearing of 135^{o}T. This is approximately 15 degrees to the channel edge.

The water depth during the deployment was 1.5 metres and the water temperature was 18.2^{o}C. The tide was near to a neap high tide.

Localisation

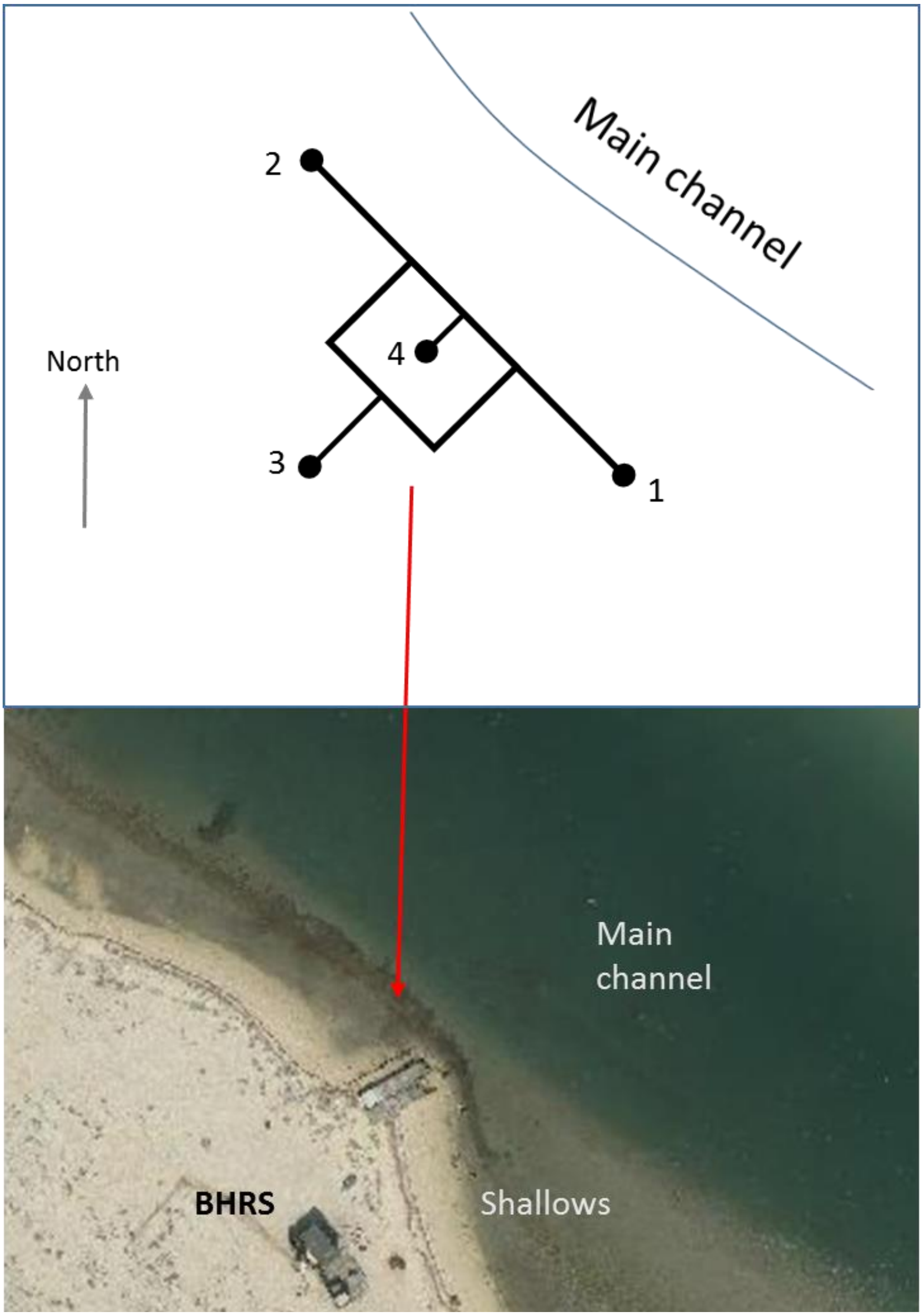


Figure 7.17 Location of MQC2 equipment 2nd October 2014

The recorded data was copied to a PC and manually searched for clicks that met the following criteria:

- No interfering signals from passing boats
- Level at least 10dB above background
- No overlap with adjacent clicks
- Distinguishing feature in all four channels to allow accurate measurement of differential arrival time

It was found that identifying a distinguishing feature common to all four channels was a major problem. Hydrophone four was close to the surface with multi-path interference distorting the signal and preventing comparison with the other channels. Figure 7.18 shows an example of such a click.

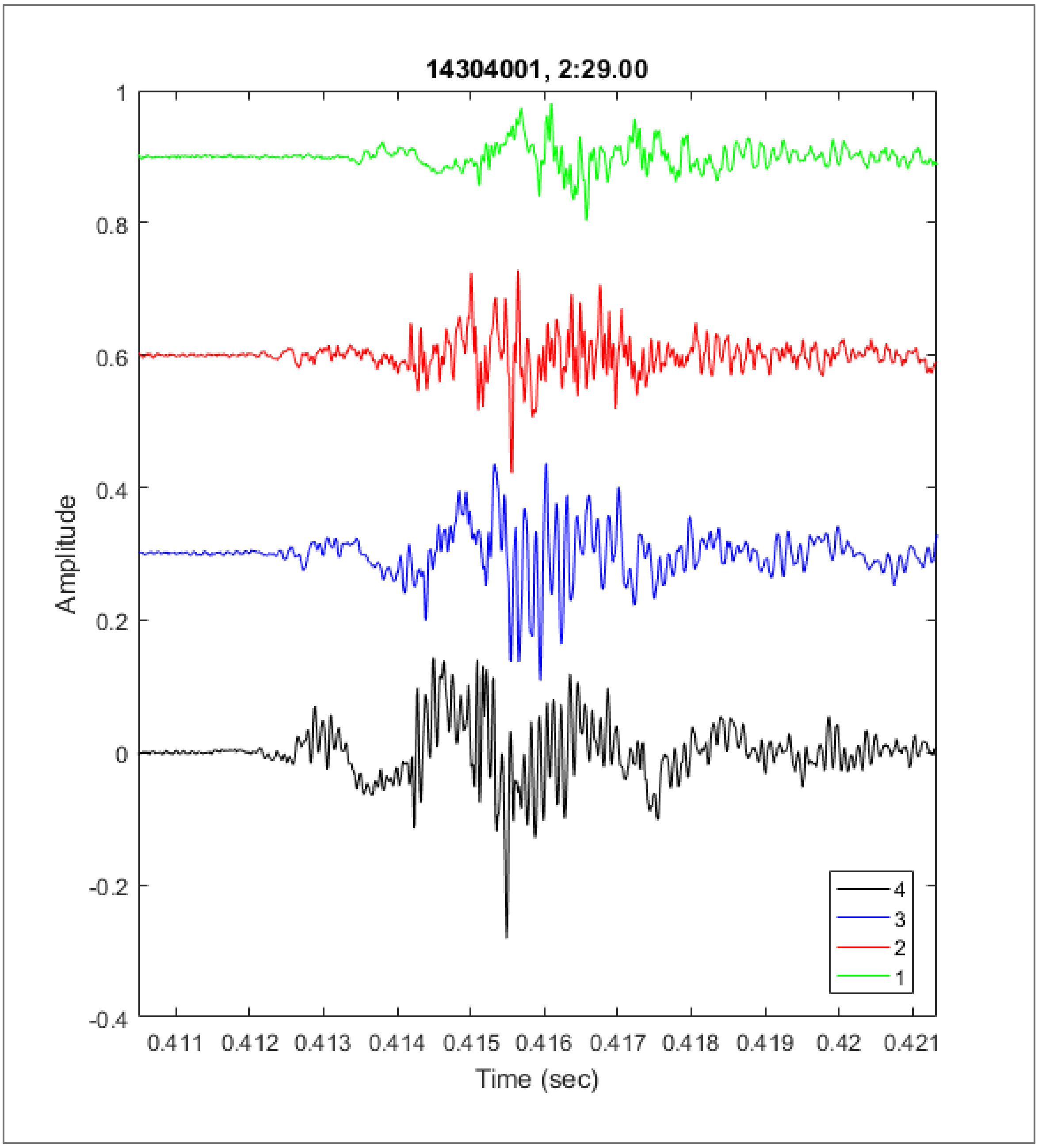


Figure 7.18 Example of unusable click from the MQC2 deployment with no distinguishable feature

This figure shows the data presented to the user and shows the data from hydrophone 1 at the top down to hydrophone 4 at the bottom. Hydrophone 4 is the uppermost hydrophone, hydrophone 3 is the hydrophone nearest the shoreline. An amplitude offset of 0.3 is added to successive channels to separate them on the screen. Figure 7.19 shows a second example of a click that could be used.

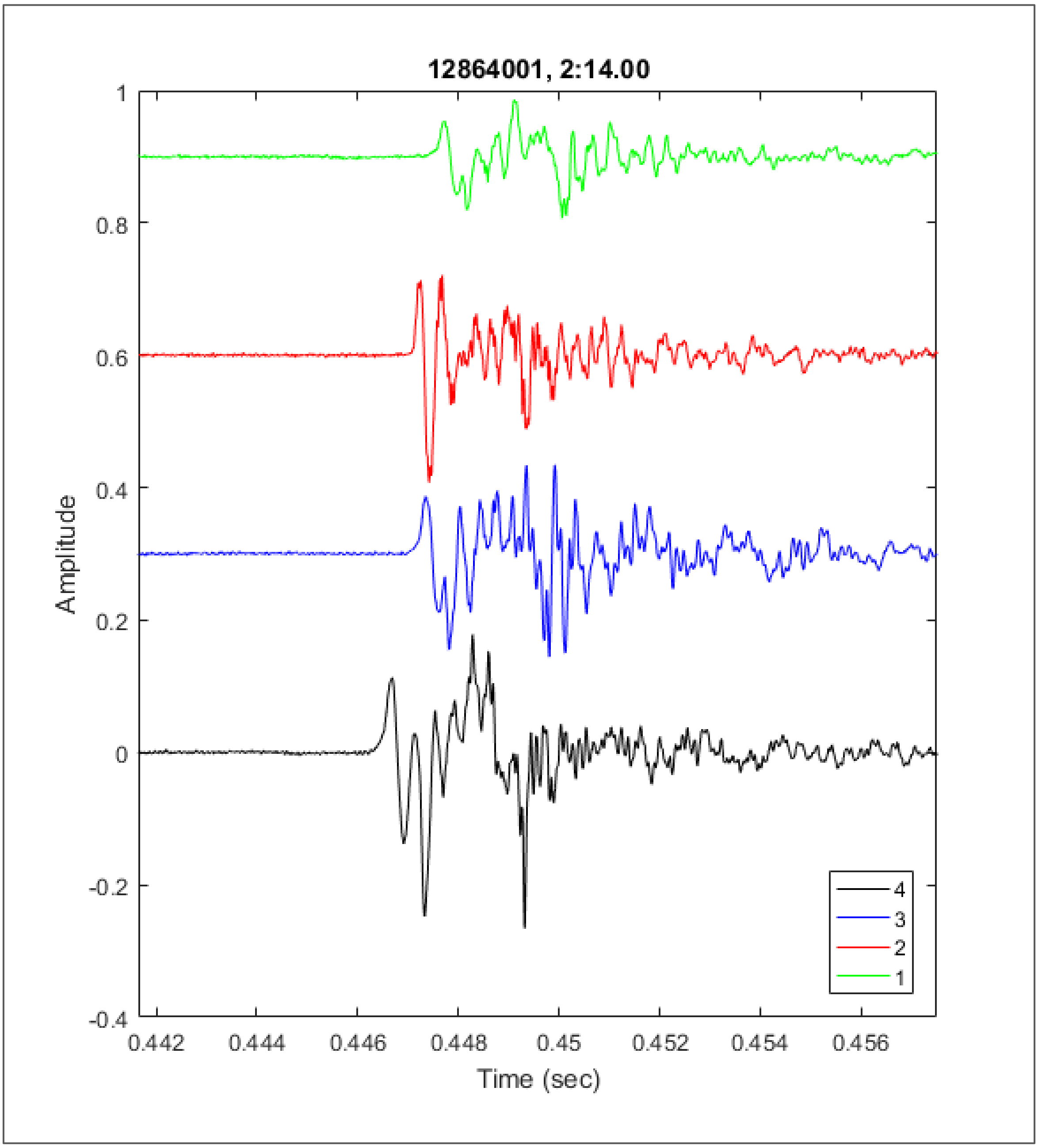


Figure 7.19 Example of usable click with clear distinguishable feature

The first eight minutes of the recording were examined and 173 clicks found that met the criteria. An additional thirty clicks were found but were discarded as unusable because the measured time delays were outside of the maximum possible given by the hydrophone spacing. These were clicks which had a large difference in amplitude between the hydrophones making it difficult to visually correlate features which in turn gave erroneous measurements of time. There were also many other clicks with lower amplitude that were not investigated because of time constraints.

The measured time delays for these 173 clicks between the three pairs of hydrophones in the horizontal plane are shown in Figures 7.20-7.22.

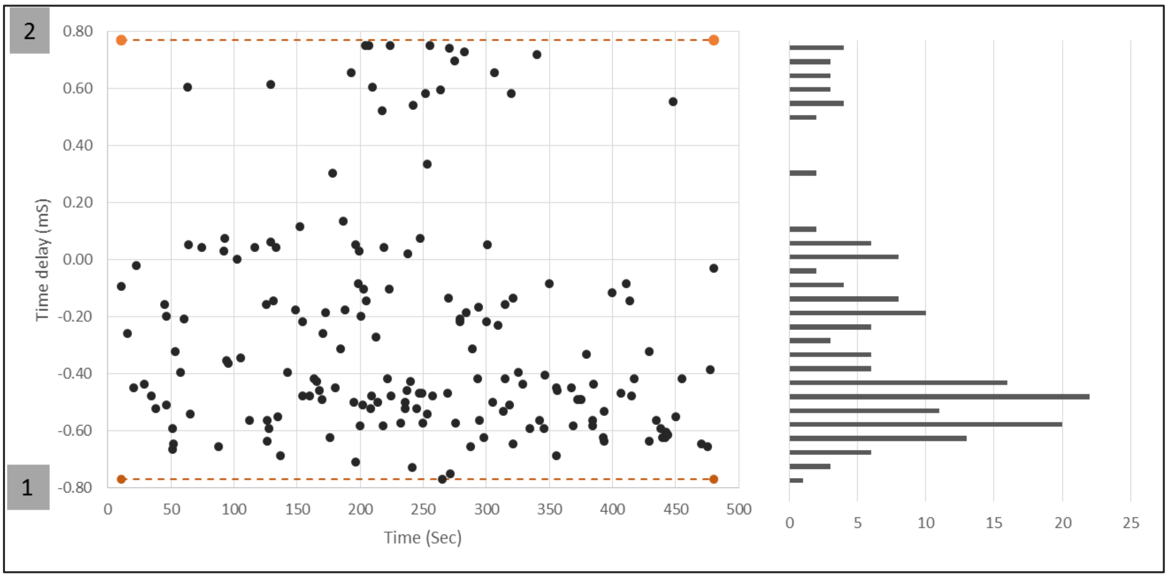


Figure 7.20 Time difference of arrival for hydrophones 1 and 2

The dashed orange line is the maximum possible time delay for the hydrophone spacing used. The bars in the right-hand pane are the counts of clicks occurring in 0.05 ms bins. The hydrophone locations are denoted with the grey 1 and 2.

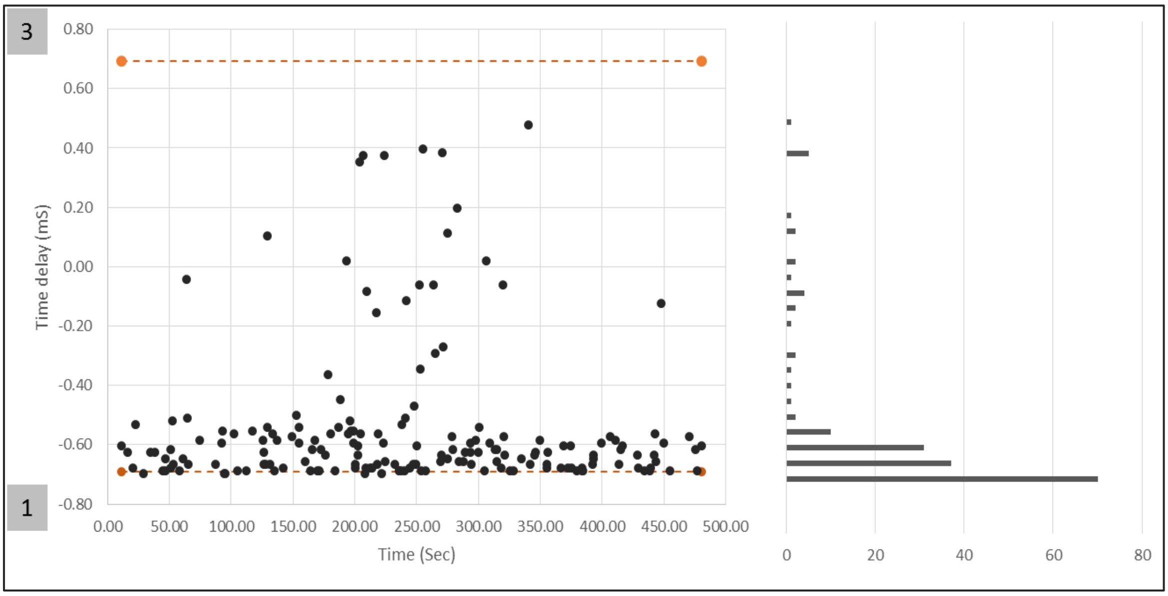


Figure 7.21 Time difference of arrival for hydrophones 1 and 3

Localisation

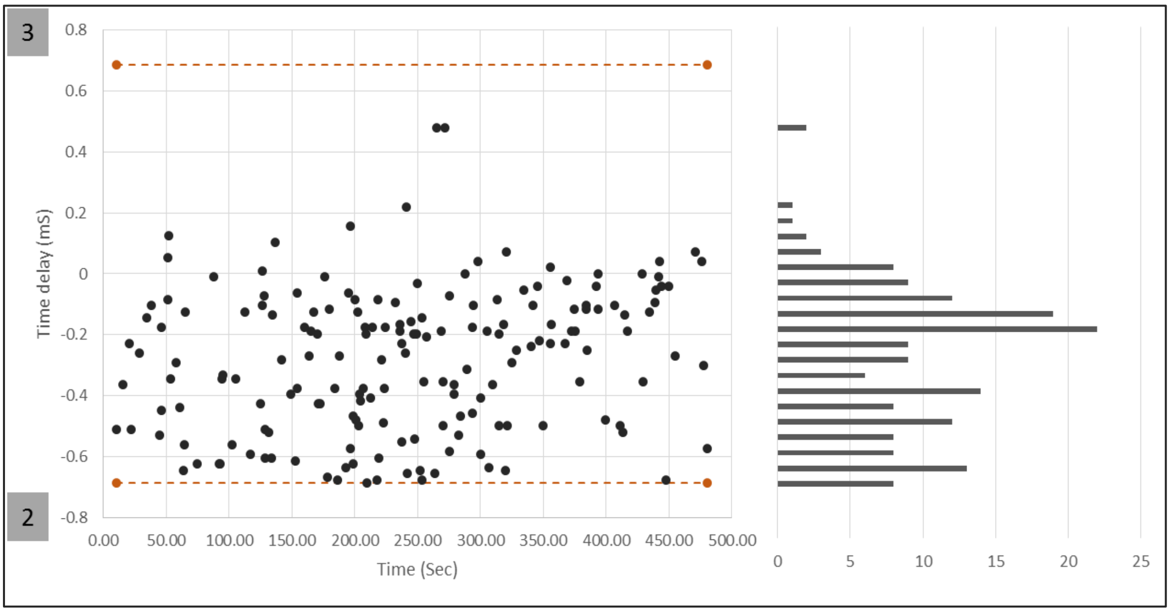


Figure 7.22 Time difference of arrival for hydrophones 2 and 3

These plots suggest there are very few clicks produced close to or inshore of hydrophone 3. This is the hydrophone closest to the shore.

Figures 7.23 to 7.25 show the time delays between hydrophone 4 and each of the hydrophones in the horizontal plane. The red dotted line shows the maximum possible time delay.

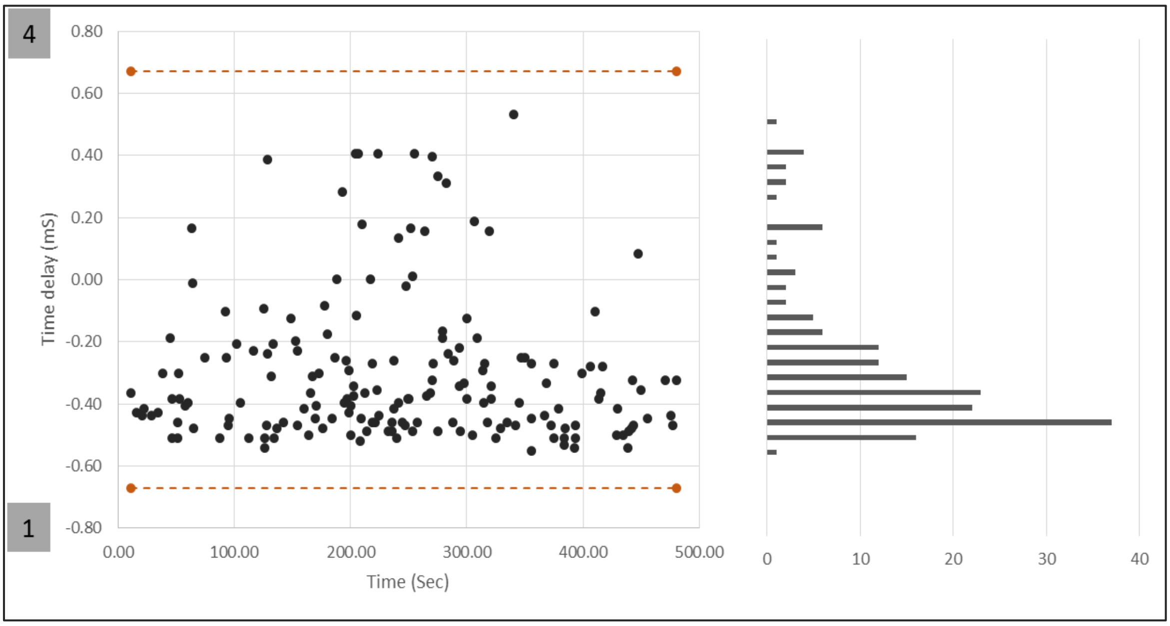


Figure 7.23 Time difference of arrival for hydrophones 1 and 4

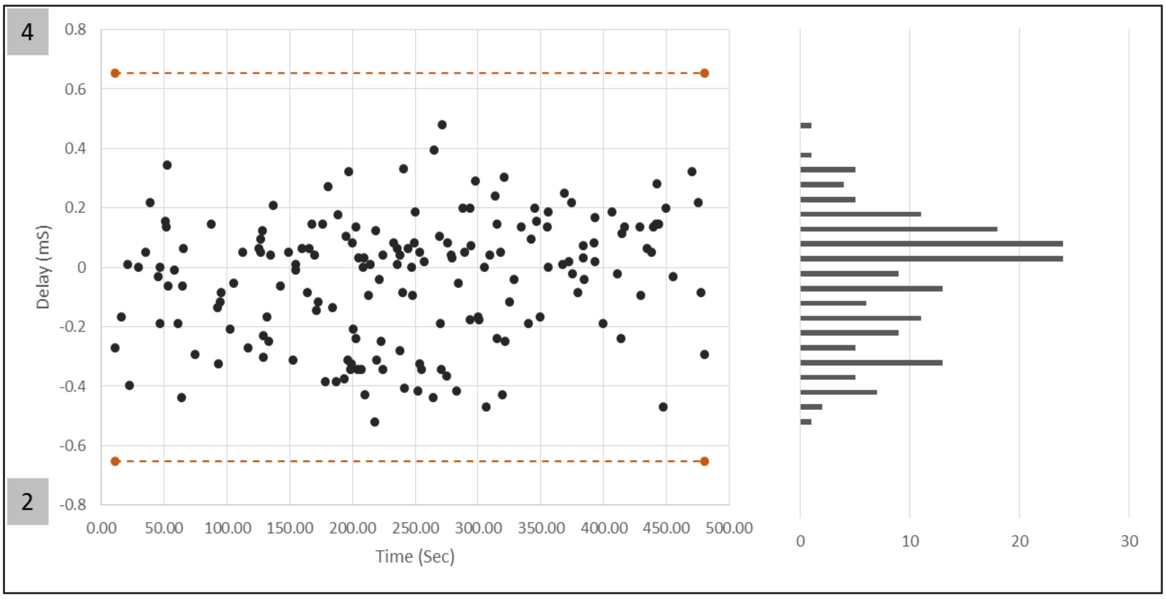


Figure 7.24 Time difference of arrival for hydrophones 2 and 4

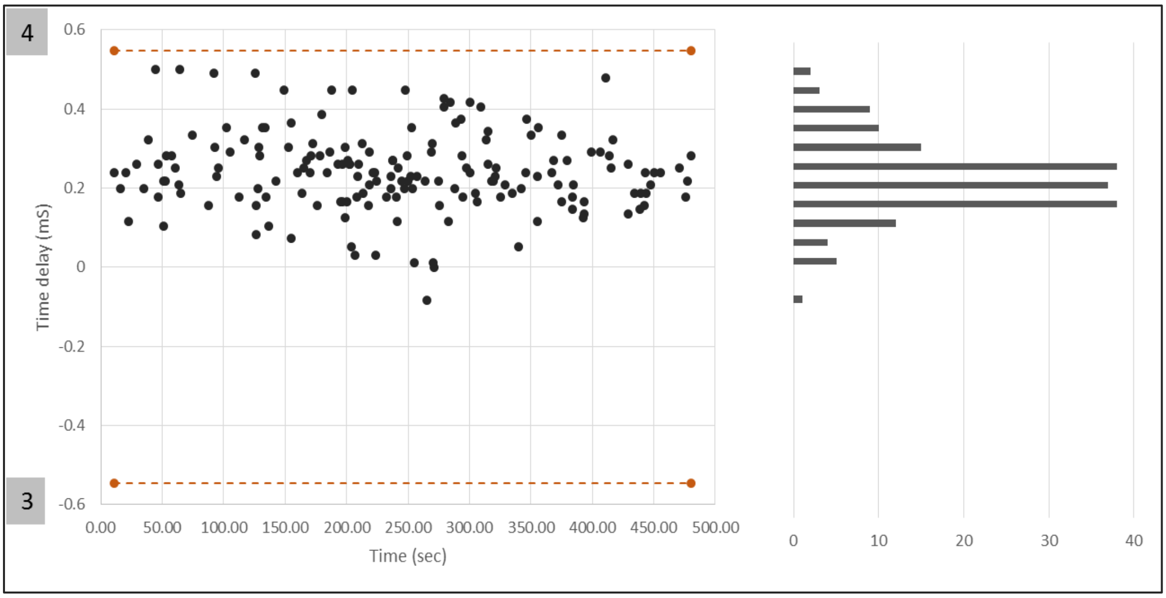


Figure 7.25 Time difference of arrival for hydrophones 3 and 4

These plots suggest that the majority of the clicks originate close to hydrophone 1.

The click data was then processed using the Speisberger method as described in Section 4.7.4 to obtain a location for each click source. The velocity of sound used was calculated using the measured water temperature in the Leroy equation (Leroy et al., 2008). This processing provided a set of x,y,z locations for each click.

Thirty-three of the clicks could not be used because they gave a complex result, possibly due to errors in the time delay measurements, leaving 141 clicks. The processing provides two possible solutions and these were examined manually to determine which of the two was correct. During this manual examination it became clear that for a number of the offered pairs of solutions neither solution was correct. When choosing which of the two possible solutions were correct a simple test was applied looking at amplitudes and the time of arrival at pairs of hydrophones. As an example, if a click arrived at hydrophone 1 before hydrophone 2 then the x position must be less than the mid-point between the two hydrophone. In a number of cases this was not true for either solution so both solutions must be in error. Similarly, solutions below the seabed or above the sea surface must be incorrect. This problem is discussed in more detail in Section 7.3.4. Eighteen click locations were rejected having failed this test. The plots of the remaining 123 clicks are shown in Figures 7.26 to 7.28 for the x-y, x-z and y-z plane views of a 3-D plot. All dimensions are in metres. The hydrophones are colour coded as:

Green hydrophone 1

Red hydrophone 2

Blue hydrophone 3

Black hydrophone 4

It should be noted when interpreting these plots that the unit is sat on a sloping seabed. An attempt was made to level the tripod but it may not have been wholly successful. The seabed rises towards the shore i.e. along the positive y axis while it falls away into the channel along the negative y axis. It was not possible to measure the gradient.

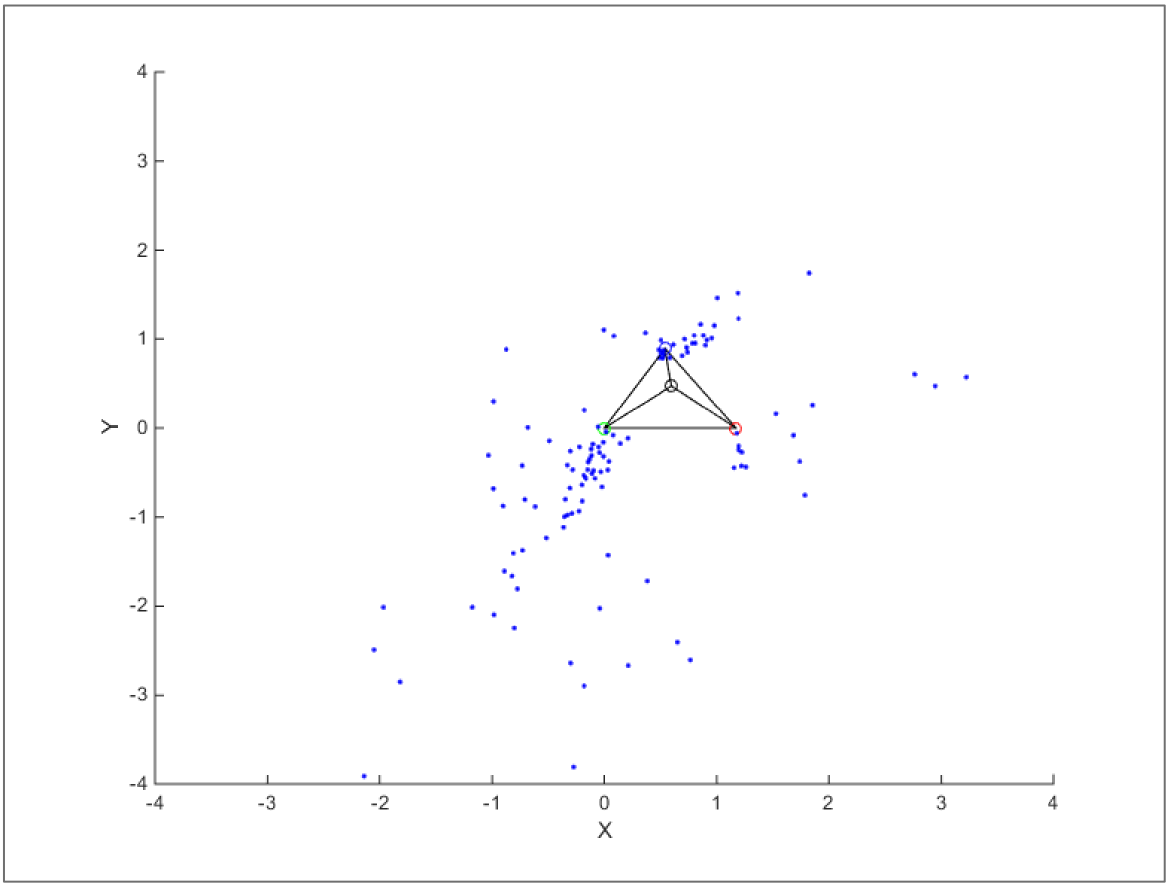


Figure 7.26 x-y plot of click locations

The z=0 plane is the plane of the lower hydrophones. Physically this is approximately 0.2 metres above the seabed.

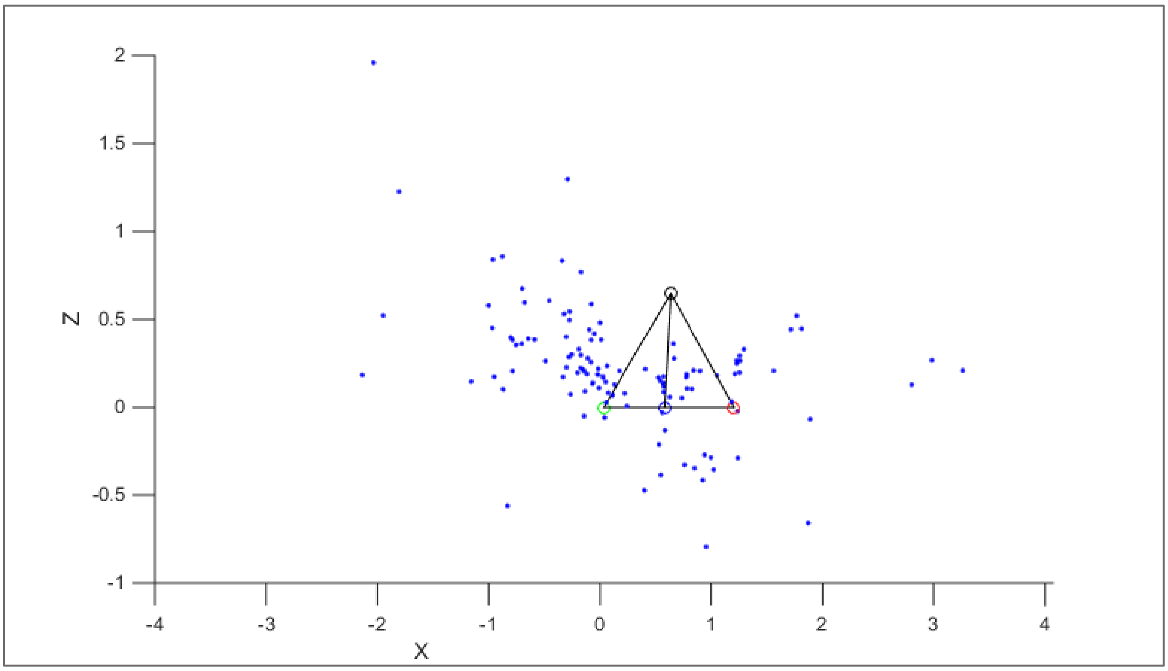


Figure 7.27 x-z plot of click locations

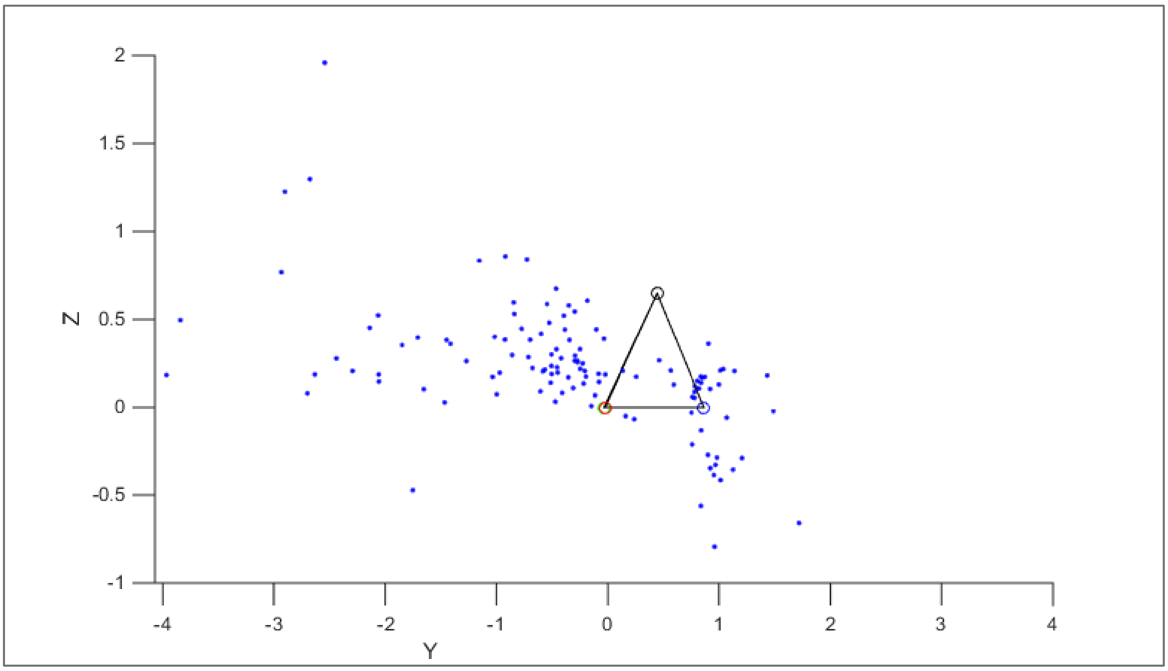


Figure 7.28 y-z plot of click locations

The apparent lack of click sources within the hydrophones may be primarily due to processing problems. Most of the clicks rejected by reason of giving a complex result were very loud and appeared to originate within the confines of the hydrophone tripod. It should also be noted that there are still an unknown number of erroneous points in the plot as discussed in Section 7.3.4.

The click distributions shown in Figures 7.26 to 7.28 agree with the two hydrophone TDOA plots in Figures 7.23 to 7.25 in showing that nearly all the clicks originate in the vicinity of hydrophone 1. This gave some confidence that the location processing was providing useful data.

The clouds of click sources adjacent to hydrophones 1 and 3 align approximately with the tidal flow observed in the area. Although not apparent from the static location plots presented, an animated 3-D plot shows a number of tracks building up as click sources appear to move through the area.

From this data the following conclusions can be drawn:

- The click sources are mostly located within 1 metre of the seabed
- The majority of the click sources are located above the seabed
- Many of the click sources appear to be mobile
- Click sources have been observed to move while emitting a train of clicks
- The click sources may be attracted by the presence of the hydrophones

The results presented must be treated with a degree of caution. Only a small fraction of the clicks recorded were processed. They were chosen because they were the strongest clicks recorded and amplitude was taken as a surrogate for range. It is quite possible that some of the weaker clicks were lower amplitude click sources close in to the hydrophones. Processing the clicks manually is very time-consuming so to process more would need an automated data collection system. Despite several attempts at implementing such a system this proved impossible within the time and budget constraints of this project.

7.3.3 MQC2 deployment 28th August 2015.

A second deployment of the MQC2 equipment took place on the 28th August 2015. The aim was to put the equipment into the deeper water of the main channel. The BiClick2 deployment described in Section 7.2.2 suggested the majority of the clicks were coming from the channel rather than the shallows. It was also hoped that the greater depth of water would result in the top hydrophone being further from the sea surface and this would reduce the impact of multi-path interference on the waveform shapes.

The location of the equipment is shown in Figure 7.29. The underwater cable for the Quadraclick arrays was too short to reach out into the channel so it was extended using an additional 25 metres of normal PVC-covered cable. This allowed the hydrophone array to be placed in the main channel in a water depth of 2.4 metres. The dry end equipment was placed on the nearby pontoon.

A diver's compass was attached to the equipment crossbar so that it could be aligned east-west. The water temperature was 17.5^{o}C and the tide was a low spring tide.

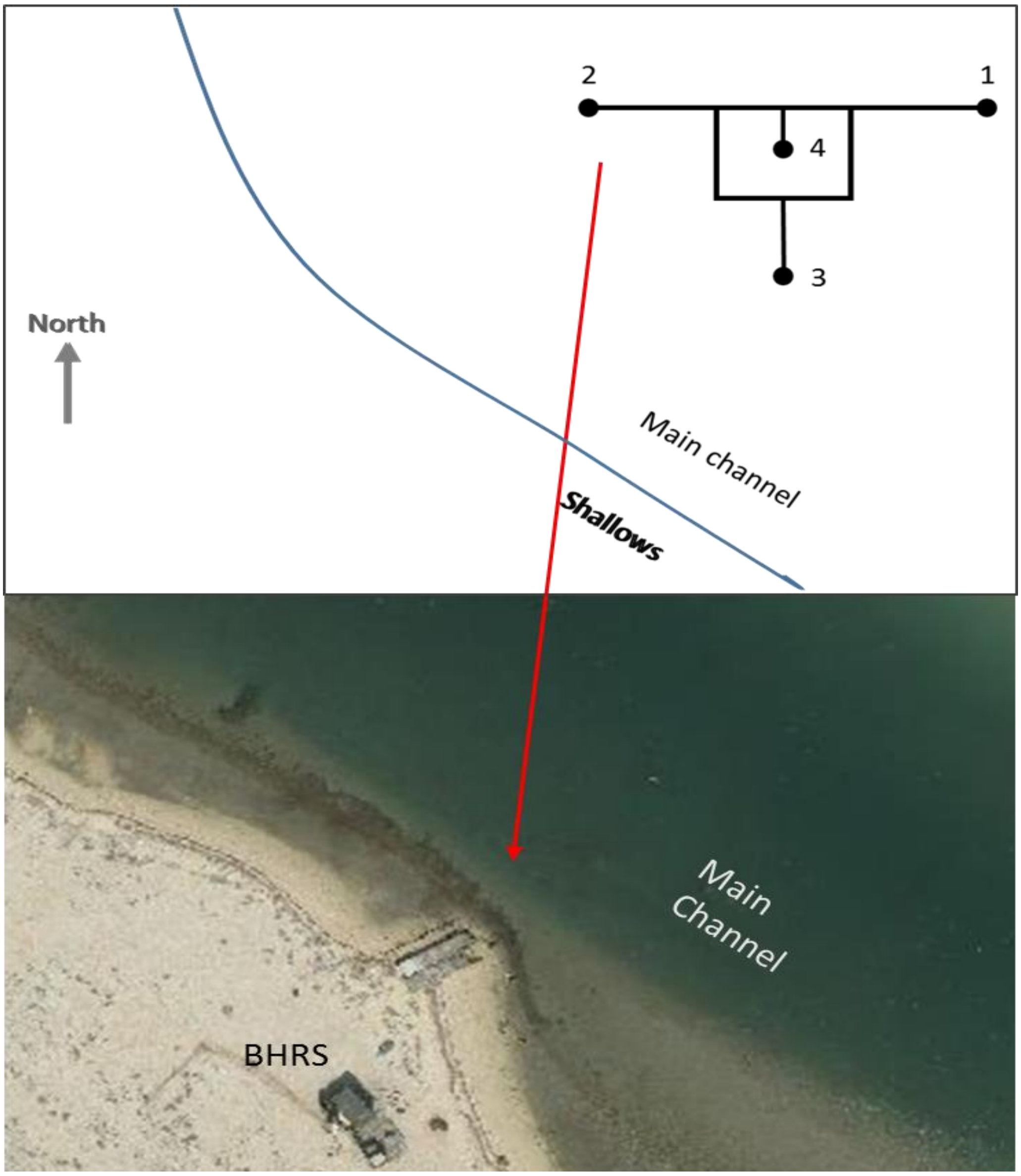


Figure 7.29 Location of the MQC2 equipment 28th August 2015

Two files were recorded. The first contains the dog clicker calibration data while the second contains the biological click data. The data from this second recorded file was analysed in some detail. A total of 6 minutes of data was inspected but a passing small fishing boat generated noise for about a minute so there is a gap in the processed data leaving five minutes of processed data. 201 loud clicks were identified, of these 26 could not be used due to distorted waveforms.

The time delays between the three hydrophones in the horizontal plane are shown in Figures 7.30 to 7.32 and the time delays for the vertical pairs are shown in Figures 7.33 to 7.35.

The dashed orange lines show the maximum possible time delays for each hydrophone pair.

Localisation

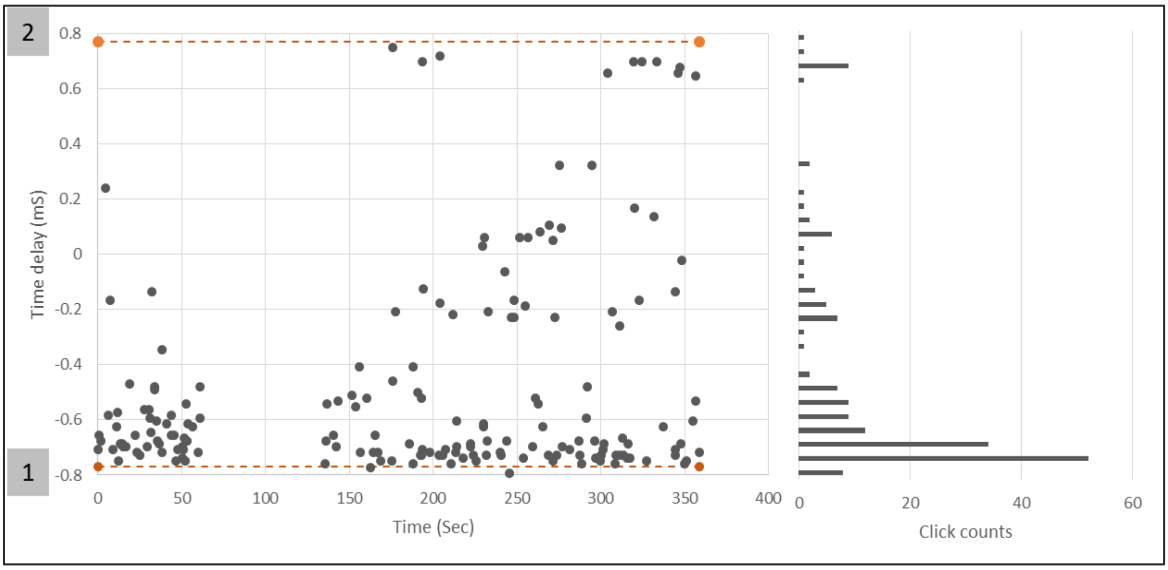


Figure 7.30 Time difference of arrival for hydrophones 1 and 2

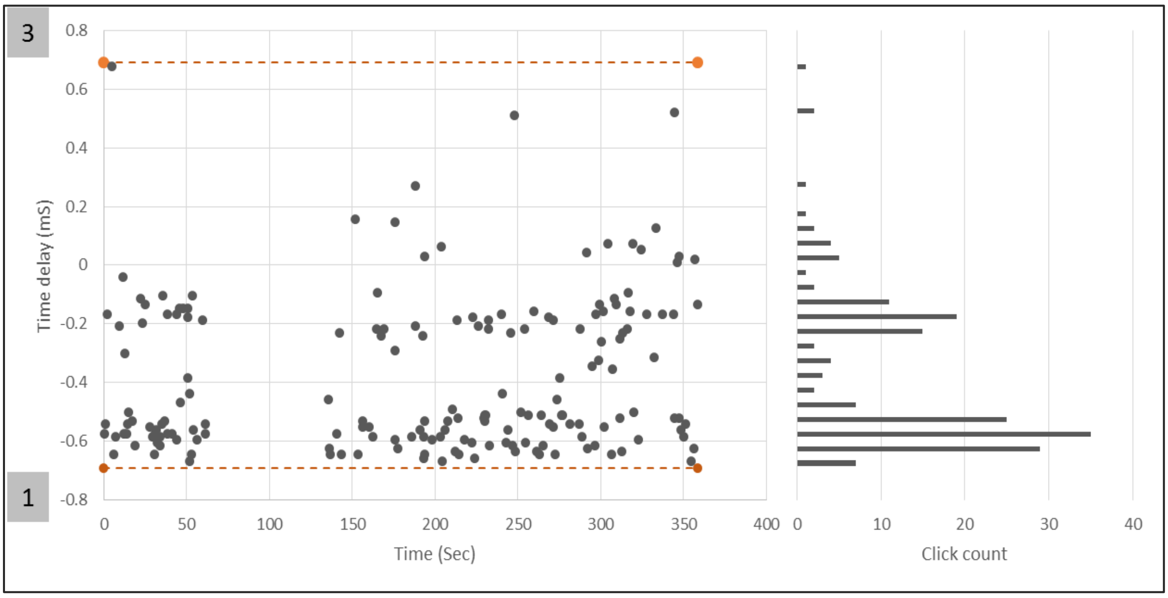


Figure 7.31 Time difference of arrival for hydrophones 1 and 3

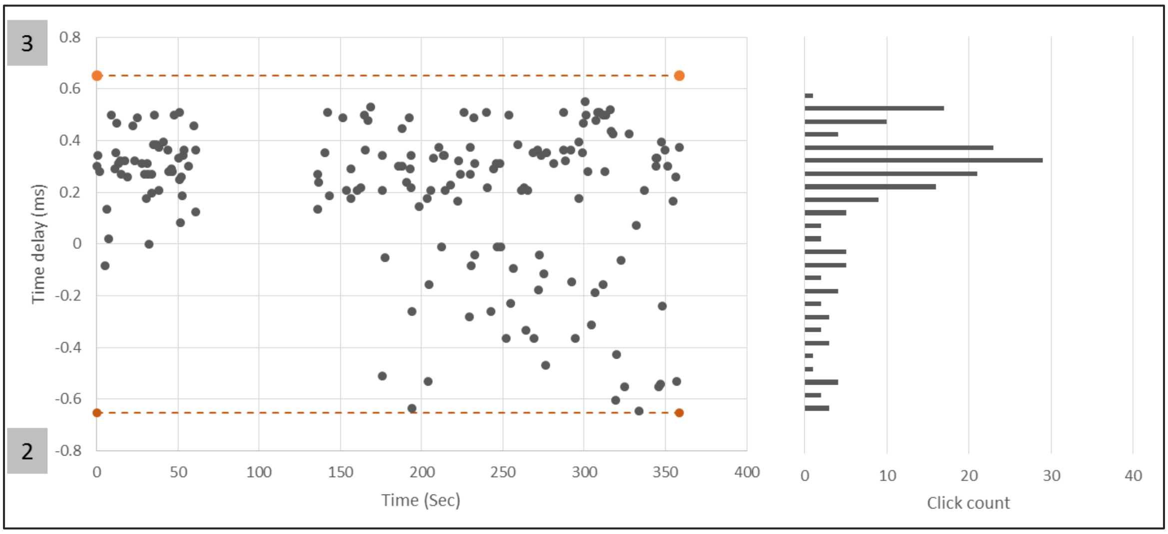


Figure 7.32 Time difference of arrival for hydrophones 2 and 3

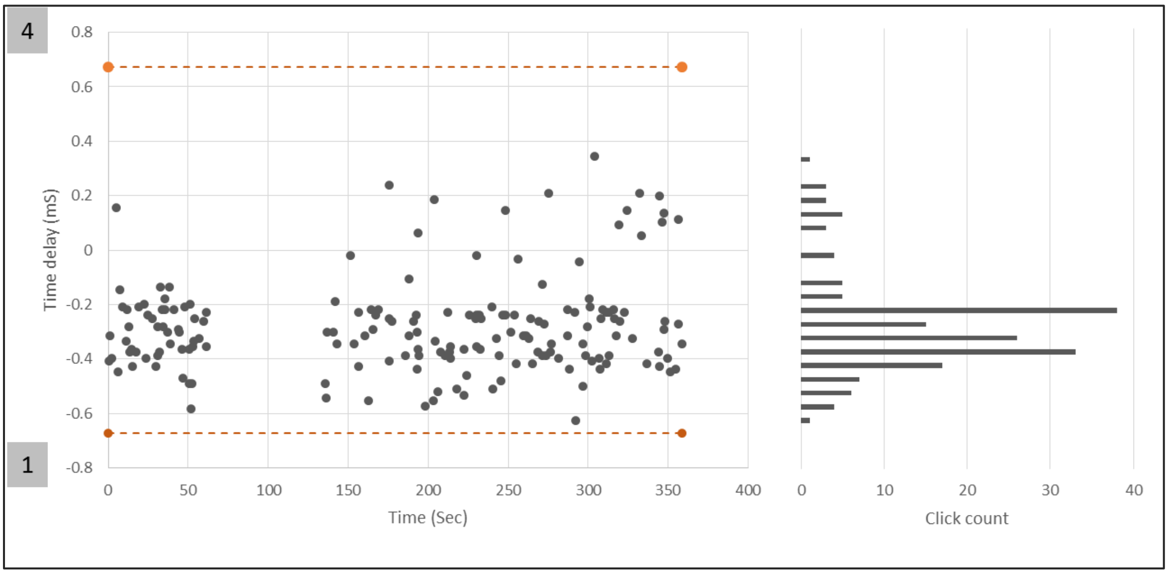


Figure 7.33 Time difference of arrival for hydrophones 1 and 4

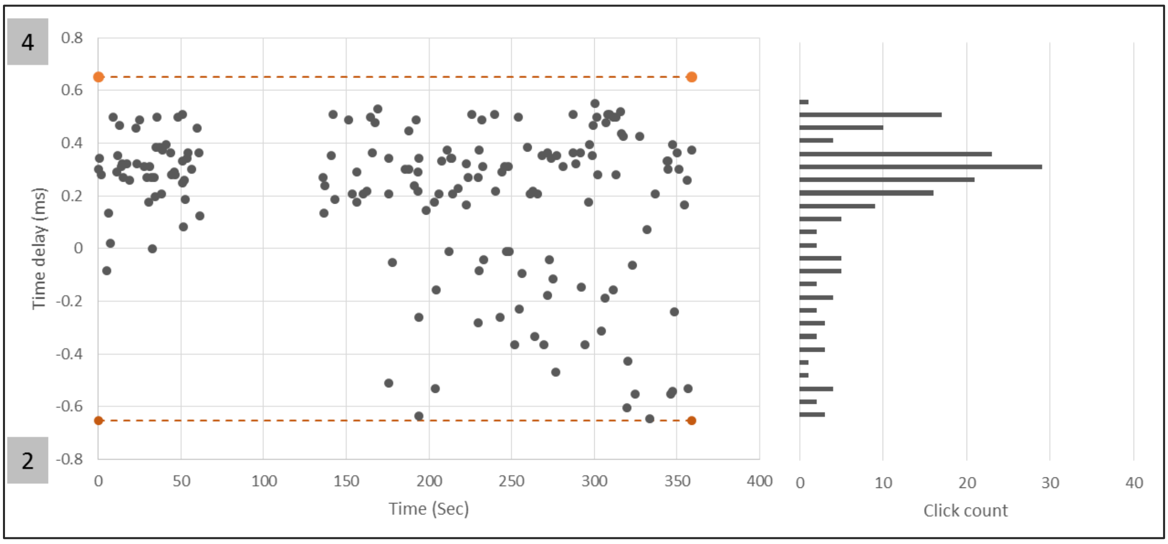


Figure 7.34 Time difference of arrival for hydrophones 2 and 4

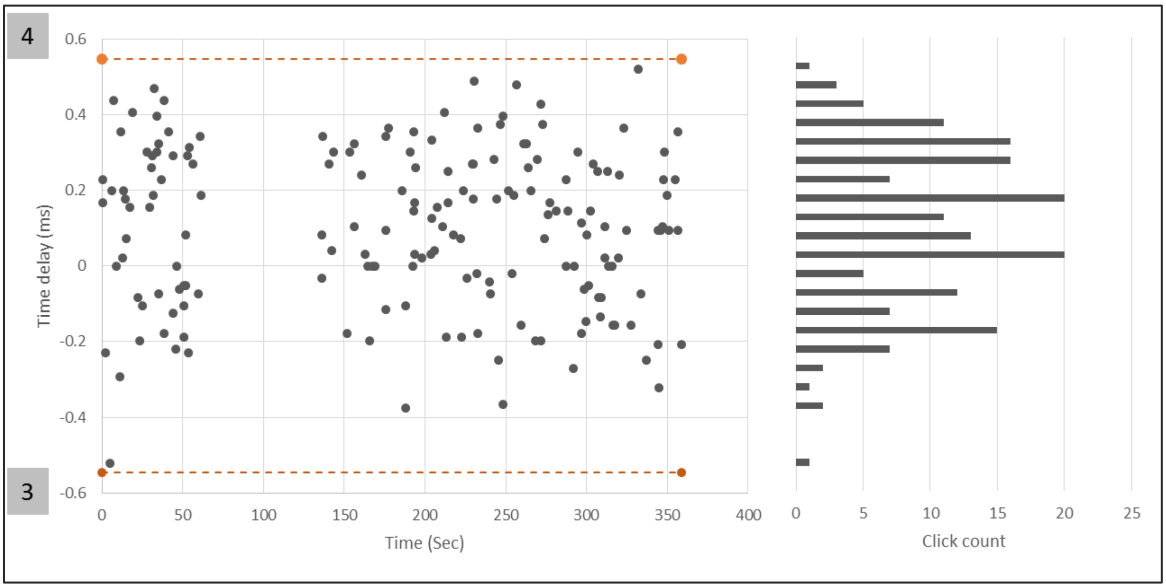


Figure 7.35 Time difference of arrival for hydrophones 3 and 4

Localisation

The total of 175 clicks were then processed to obtain their 3-D locations. The two possible solutions suggested by the processing were then inspected manually as described in Section 4.7.4 Any unrealistic locations were rejected leaving 131 clicks. These are plotted in Figures 7.36 to 7.38 for the x-y, x-z and y-z planes.

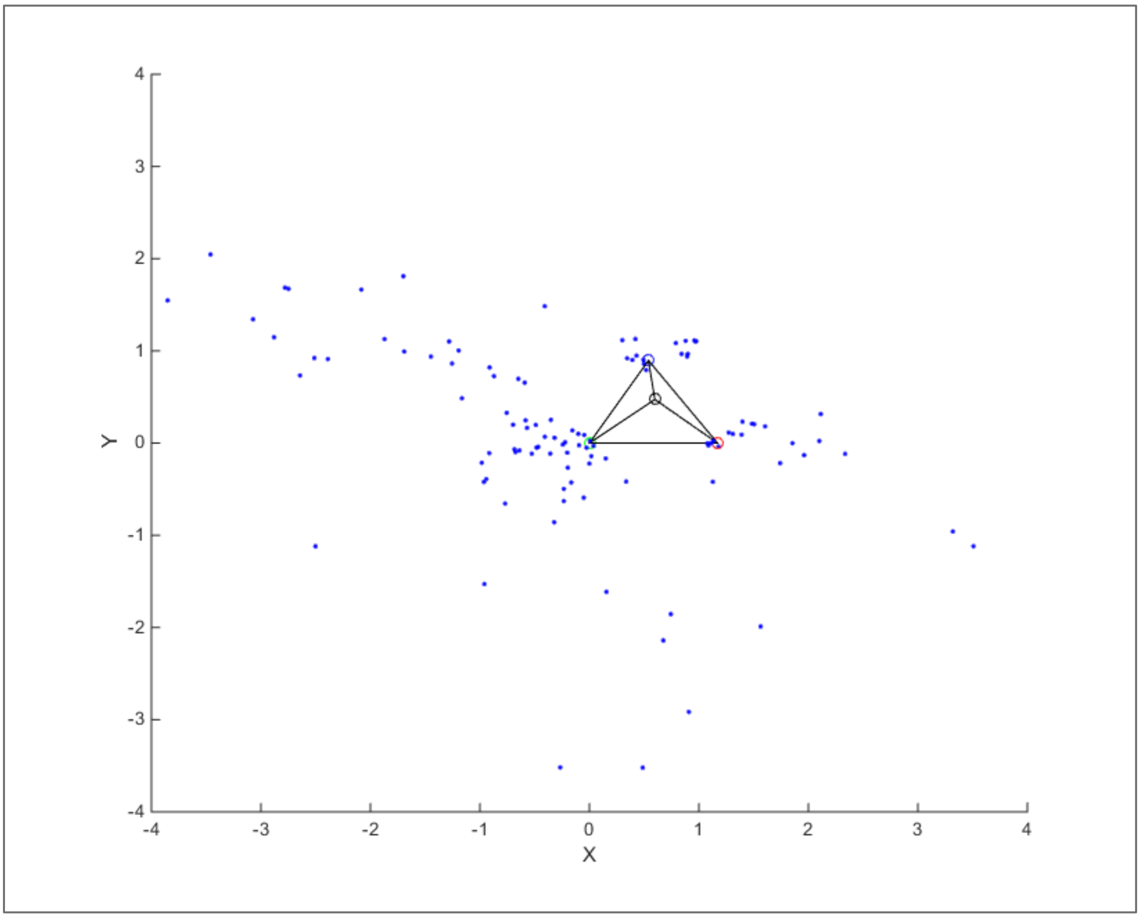


Figure 7.36 Click locations, x-y view

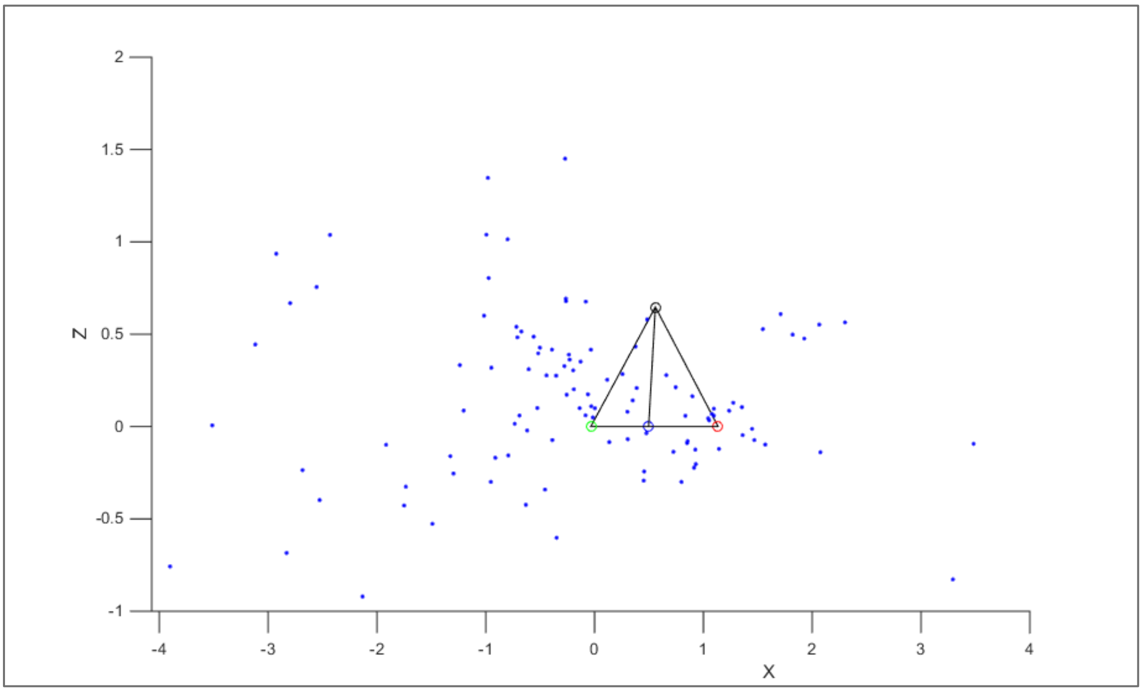


Figure 7.37 Click locations, x-z view

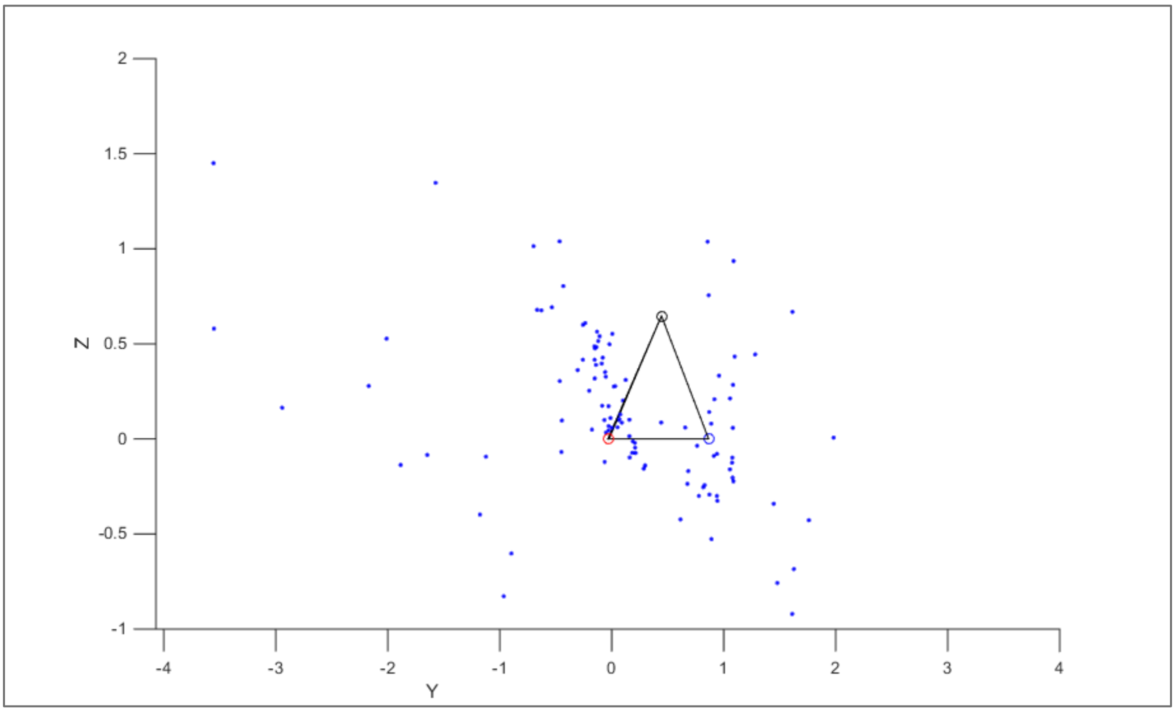


Figure 7.38 Click locations, y-z view

As in the previous deployment, the lack of clicks within the array was again due either to distorted waveforms or to the processing giving a complex solution for these very loud clicks.

A partial explanation of the problem with high level clicks may be that some of these clicks are from a different biological source to the mid-water clicks and are originating within the seabed. The highly variable nature of the seabed in this area due to natural and anthropogenic debris may affect the signal paths to each hydrophone differently. The velocity of propagation through the seabed will be higher than for an all-water path and this may be a contributory reason why the localisation algorithm fails.

As noted above and discussed in detail in the next section, the localisation data still contains an unknown number of erroneous points. Any clicks located below -30 cm will be at least 10 cm into the seabed so are likely to be in error. There do appear to be a few clicks at the right level to be on or close to the seabed. However, the majority of the click locations are well above the seabed and appear to be clustered around hydrophone 1, with secondary clusters around hydrophones 2 and 3.

An animated version of the click location display suggests that there are a number of click sequences that appear to form a track of a mobile species. These are not apparent in the click location plots because the small number of clicks in such a sequence quickly get swamped by all the other clicks that are plotted. However, study of the time difference of arrival plots for each hydrophone pair does show a number of such sequences (e.g. Figures 7.22 and 7.34).

7.3.4 Localisation problems

As discussed above a significant number of clicks could either not be processed or gave unrealistic locations. The algorithm used was demonstrated to work as described in Section 4.6 so it was not clear why so many clicks were giving incorrect locations.

Localisation

A simple test was carried out in which a simulated click source travelled past the array using the same test conditions as used in Section 4.7.5. Figure 7.39 shows a typical plot of the result with the two possible solutions coded in red and blue and the hydrophone locations in black.

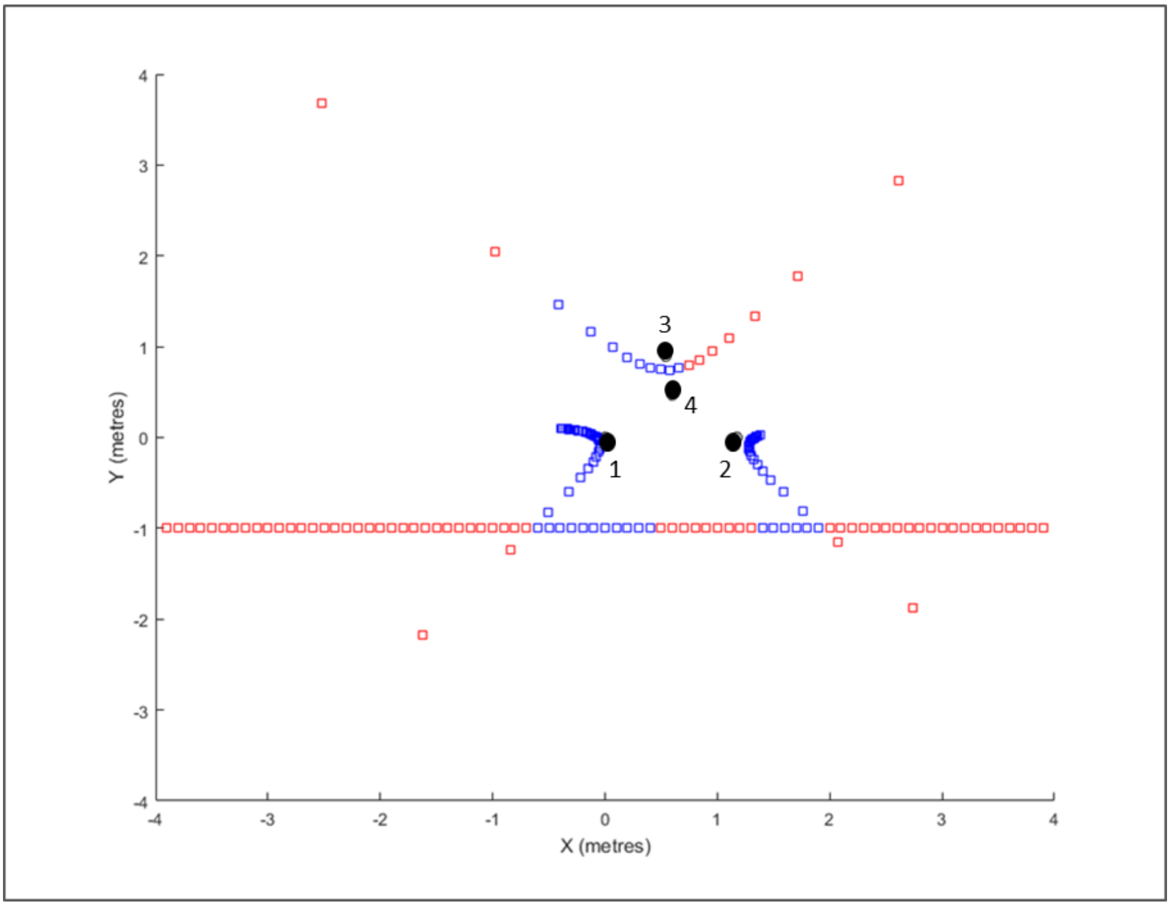


Figure 7.39 Localisation test output. x varies -4 to +4 metres with y fixed at -1 metre and z fixed at 0.1 metre.

This example is of a clicker moving along the x axis in steps of 0.1 m with y=-1.0 m and z=0.1 m. One of the possible solutions always lies on the correct point. An extensive investigation showed that this was always true except for the x=0.0, y=0.0 or z=0.0 lines which always gave a complex result. This did not explain the number of wrong locations being found.

After further investigation, it was found that an error in the velocity of sound could give large errors in position. As an example, the plot above was made with an assumed velocity of sound of 1510 m/sec for both test data generation and the four-hydrophone processing. Figure 7.40 repeats this plot but adds results using a sound speed of 1500 m/s for the four-hydrophone processing. The estimated locations are shown in magenta and cyan.

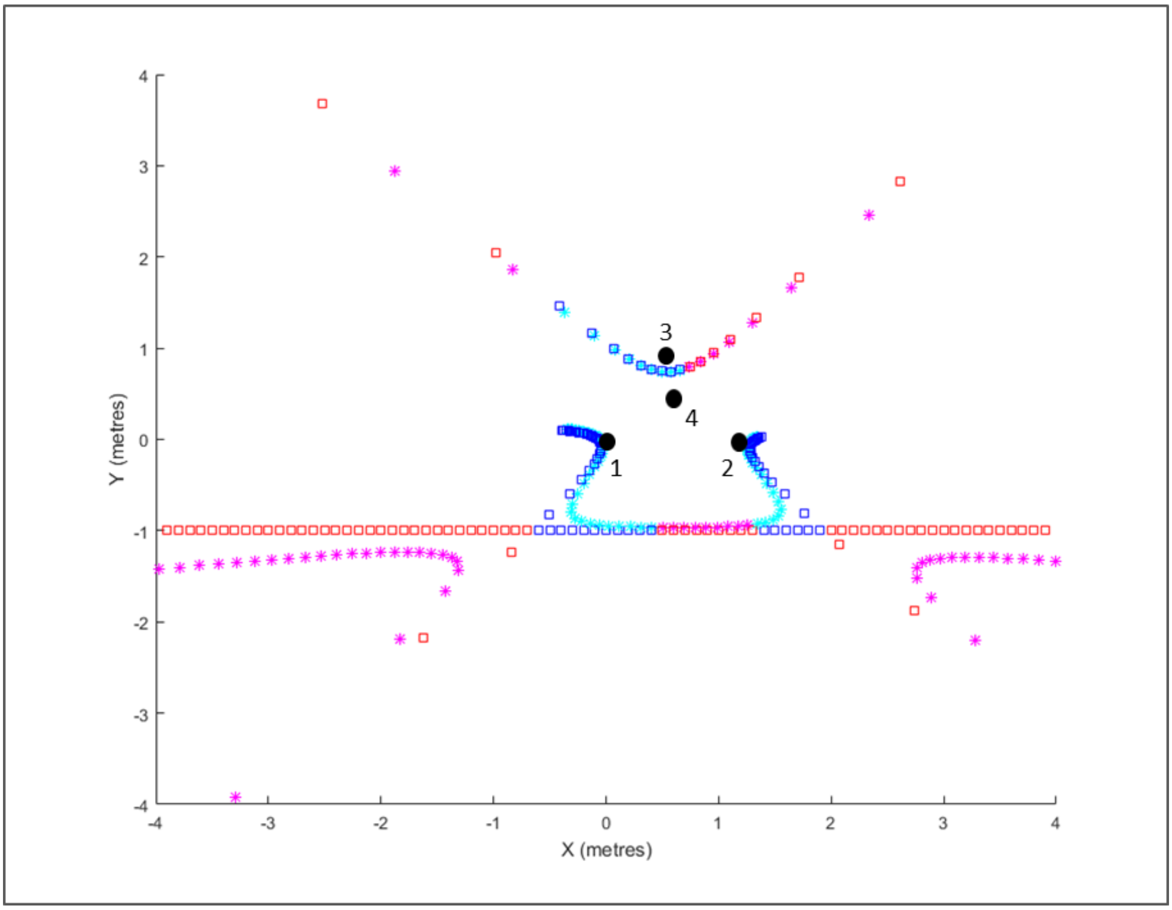


Figure 7.40 Localisation error with 10 m/s error in velocity of sound. X varies -4 to +4 metres with y fixed at -1 m and z fixed at 0.1 m.

It can now be seen that only a few points near x=0 come close to the expected position with especially large errors around x=-1 and x=2.

The velocity of sound depends on the water temperature, depth and salinity. The velocity of sound used when carrying out the localisation processing was calculated using the Leroy equation from measured temperature and depth and an assumed salinity. To investigate the problem further a MATLAB function was written to calculate the error at each 0.1 metre step in the range -4 to +4 metres in the x and y dimension and 0 to +4 metres in the z dimension. As a measure of the total error the root mean square of the error distance was calculated across all of the points. If the result was complex it was not used in the RMS calculation.

A problem with using the RMS value is that the calculated error can be dominated by a few grossly erroneous points as the localisation algorithmic can give very large errors. A second measure of the errors was chosen which counted the number of points where the error distance exceeded a pre-set value. For this work this distance was chosen to be +/-30 cm as it was thought that this was highest value that would still give acceptable localisation information.

The test used carried out the following processing:

At each x,y,z location:

Calculate the time of arrival at each hydrophone using the true velocity of sound

Calculate the estimated location using the erroneous velocity of sound

Localisation

Test the two calculated locations and use the location nearest to the actual location

If the results are complex then add to complex count

If the error distance is greater than a set error threshold increment the error count

Add to the total RMS calculation

An example of the output from the processing is shown in Figure 7.41. In this plot x and y vary in 0.1 metre steps while the RMS error is calculated in 0.1 metres steps along the z axis. The hydrophone array is located such that hydrophone 1 is at 0,0 and hydrophone 2 is at 1.17,0.

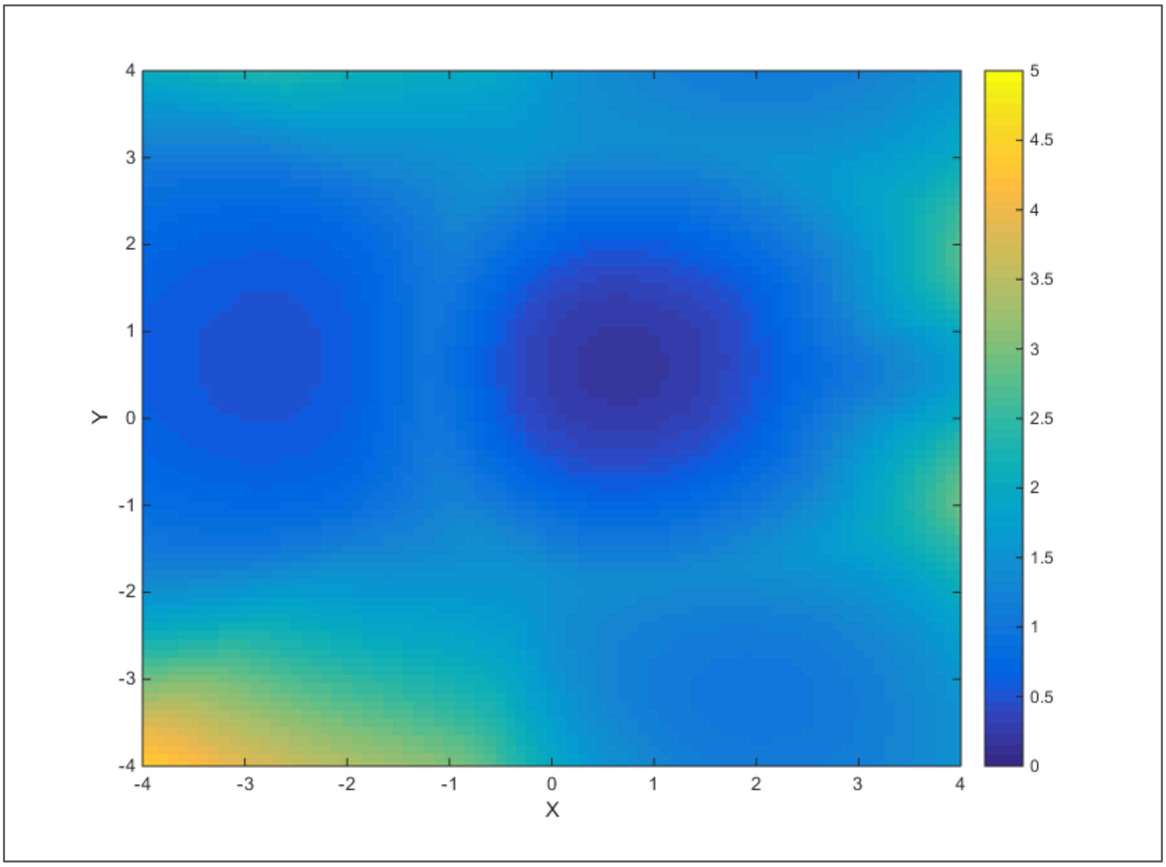


Figure 7.41 Example of RMS error plot for 10 m/s error in velocity of sound

Only in the immediate region around the hydrophone array are the errors acceptable. For this example the total RMS error was 1.482 metres and 87% of the points had an error exceeding 30 cm.

Figure 7.42 shows a plot of total RMS error for an expected velocity of sound of 1500 m/s and Figure 7.43 shows a plot of the percentage of points that either give a complex result or the error exceeds 30 cm.

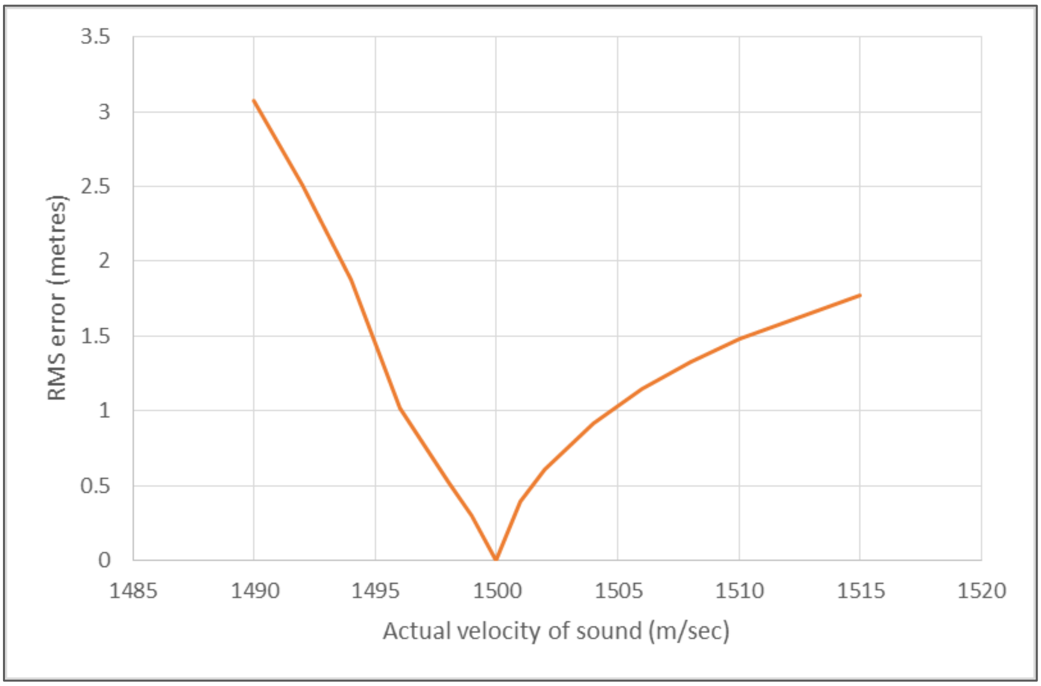


Figure 7.42 RMS error at expected velocity of sound of 1500 m/s

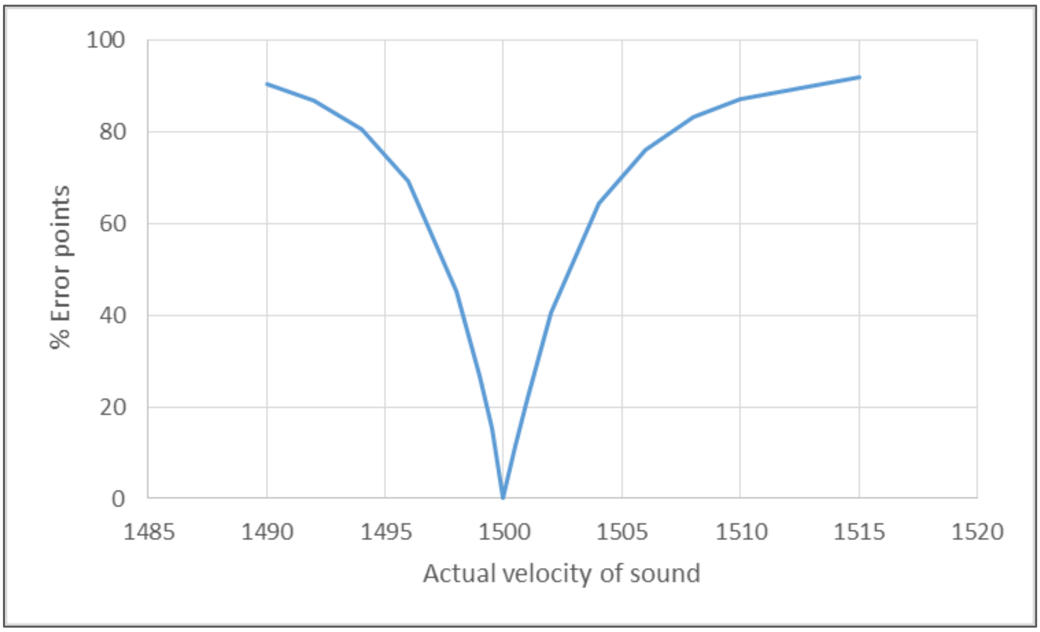


Figure 7.43 Percentage of erroneous points

From these Figures it can be seen that the velocity of sound has to be known to a high degree of accuracy. Current commercial instruments claim an accuracy of +/-0.02 m/s (SeaBird Instruments, Valeport) in deep water but this degrades to +/-0.05 m/s in shallow water (SeaBird Instruments). At +/-0.05 m/s there is still an RMS error of 0.05 metres and 3.3% of the points exceed the 30 cm error criteria.

In the very shallow water environment used by this project the water depth variation of 0.65 m between the lower and upper hydrophones results in a velocity of sound change of 0.1 m/sec. Vertical variations in water temperature are typically around 0.2°C but can be up to 0.5°C at mid tide during the Spring and Autumn and up to 2°C during a hot summers day on a rising tide. These correspond with velocity of sound variations of +/-0.5 m/s in spring and autumn and +/- 5 m/s in summer. At +/-0.5 m/s the RMS error is 0.175 metres and 15% of the points exceed the +/-30 cm threshold.

7.3.5 The fifth element

Both (Spiesberger, 2001) and (Zimmer, 2011) suggest that to uniquely resolve the location of a click five hydrophones are needed. In order to evaluate the sensitivity of a five hydrophone array to variation in the velocity of sound the test programme was modified to add a fifth hydrophone at 0.6,-0.5,0.5. This position was chosen because it is where a fifth hydrophone could easily be added to the MQC2 array. The processing is implemented using the method suggested by Zimmer (Zimmer (2011), p200).

The example plot for the five hydrophone array using the same parameters as for the four hydrophone array (see Figure 7.39) is shown in Figure 7.44.

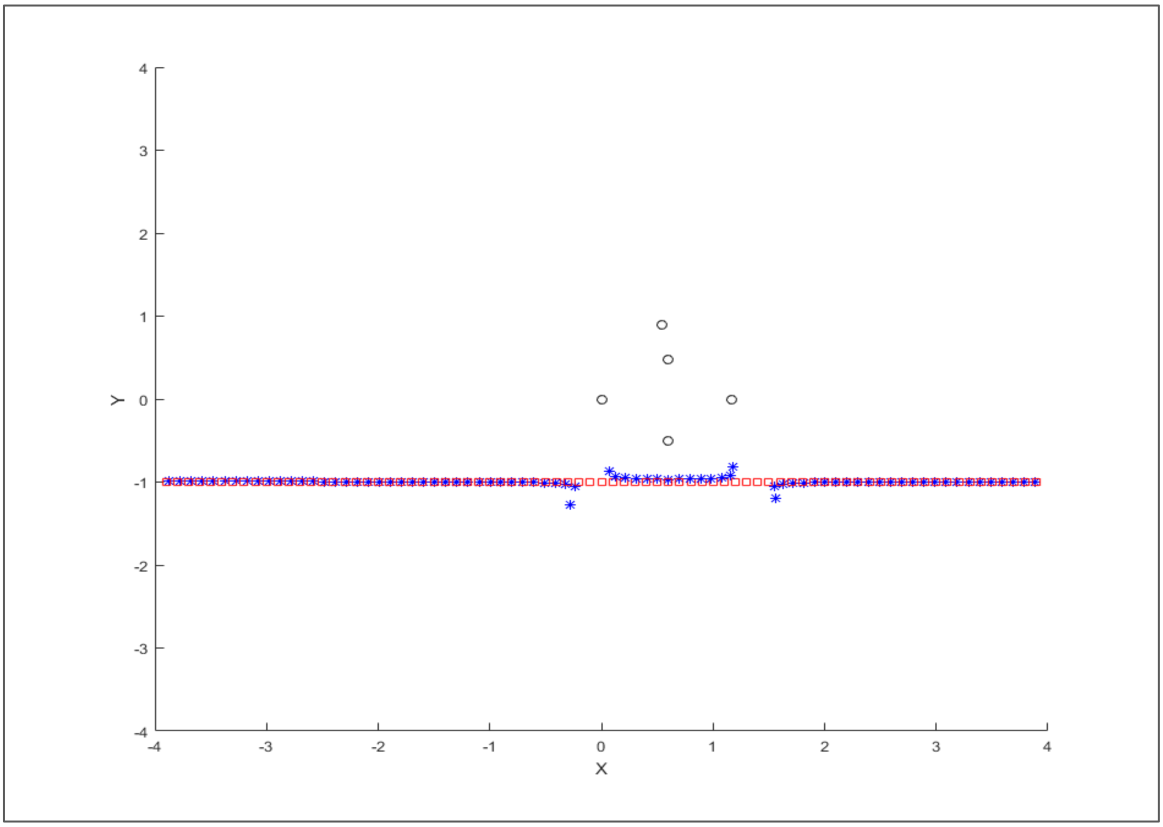


Figure 7.44 Effect of a 10 m/s error in velocity of sound for the five hydrophone array

(Red squares are the correct location, blue stars are the calculated locations using the incorrect sound velocity)

The five hydrophone processing only gives a single real result. The red squares in Figure 7.44 are for a sound velocity of 1510 m/s while the blue stars are for an actual sound velocity of 1510 m/s but processed using a sound velocity of 1500 m/s. The hydrophones are shown as black circles.

A typical RMS error plot for the five hydrophone system using the same test parameters as for the four hydrophone system is shown in Figure 7.45. The colour scale for Figure 7.45 is much greater than in Figure 7.41 to accommodate the larger range of errors. To allow direct comparison Figure 7.46 shows the five hydrophone errors using the same colour scale as Figure 7.41.

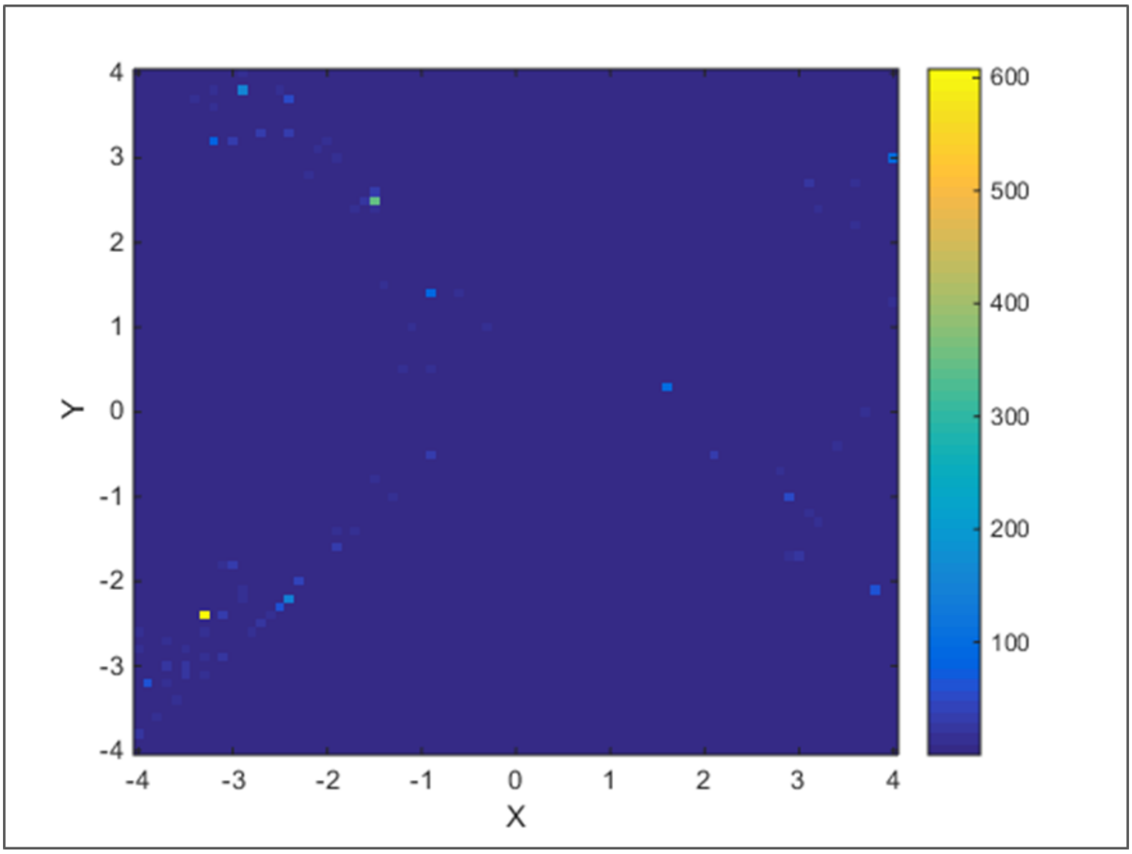


Figure 7.45 RMS error distance plot for the five hydrophone array

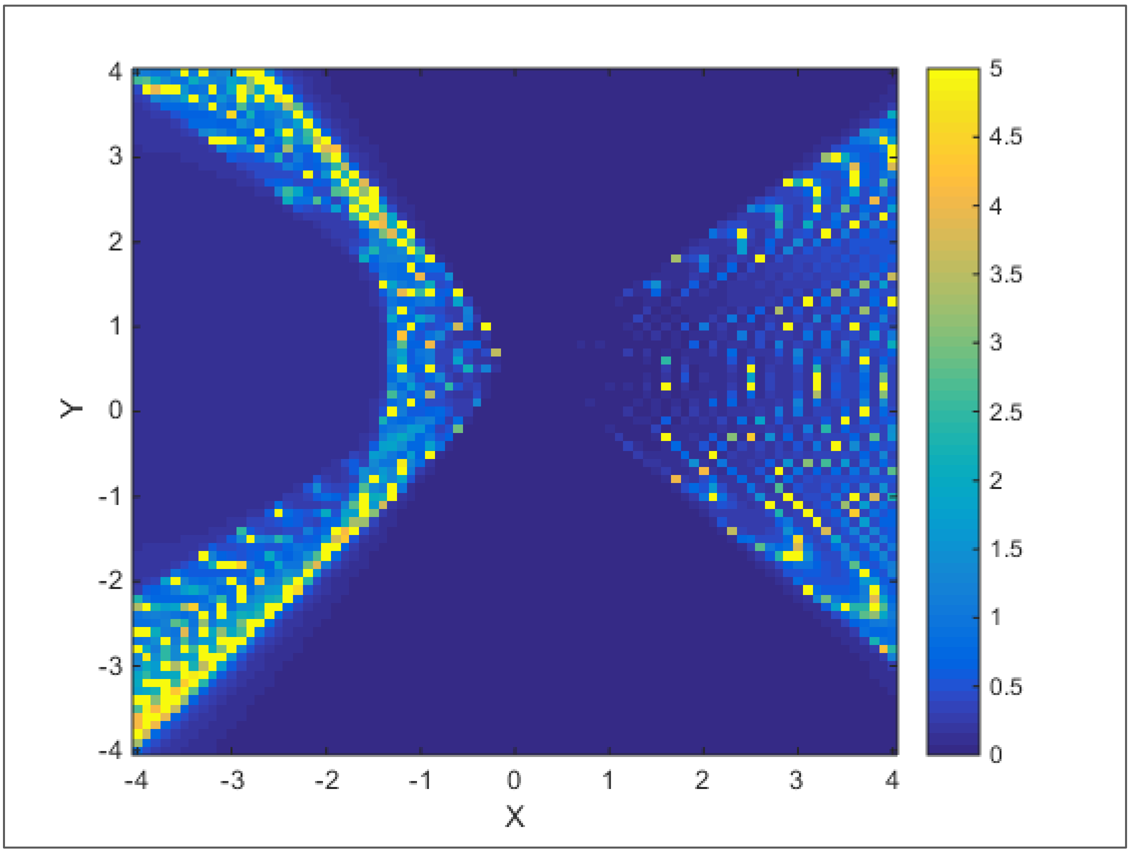


Figure 7.46 RMS error distance plot for five hydrophone array with expanded scale

From Figure 7.45 it can be seen that a small number of large errors dominate the RMS calculation. This is further demonstrated in Figure 7.47 below which shows a comparison between the calculated RMS errors for the four and five hydrophone arrays as the actual velocity of sound is varied.

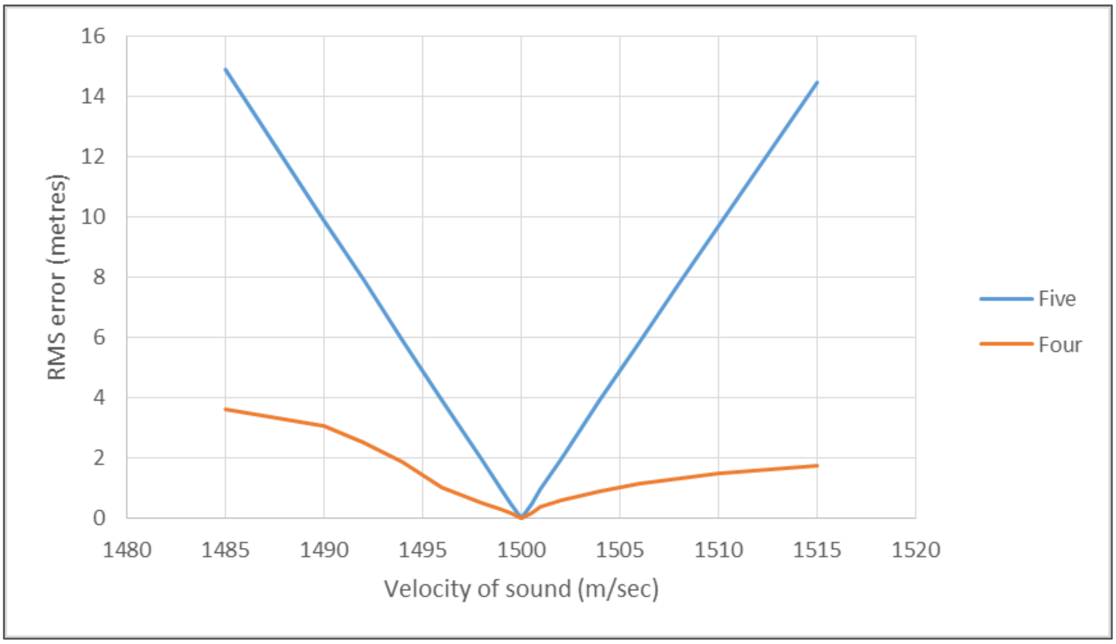


Figure 7.47 RMS errors for the four and five hydrophone arrays

Figure 7.48 shows a comparison of the percentage of points that exceed an error of 30 cm for the four and five hydrophone arrays.

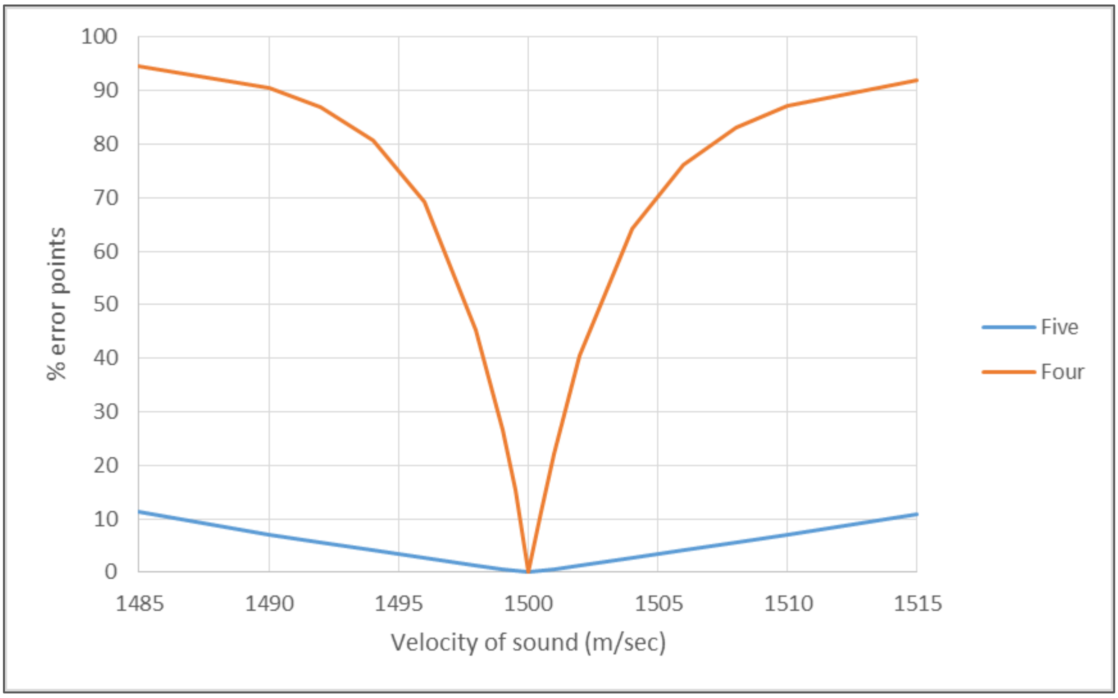


Figure 7.48 Percentage of points exceeding 30 cm error for the four and five hydrophone arrays

It can be seen that although far fewer points exceed the error threshold for the five hydrophone array, the RMS error is higher because of the small number of points with very large errors. These large values also exist in the four hydrophone array but because the processing chooses the better of two possible results these large values have less effect on the RMS calculation.

In practice these very large values can easily be identified and the points discarded. In Figure 7.49 the RMS error plot for the four hydrophone system (Four) are compared with the plot for the unconstrained five hydrophone system (Five U) and five hydrophone system with errors exceeding 4 m removed (Five C). The constrained five hydrophone array now shows considerably lower RMS errors than the four hydrophone array.

Although points with gross errors can be discarded a few erroneous points will still remain but will form a small percentage of the total number of points.

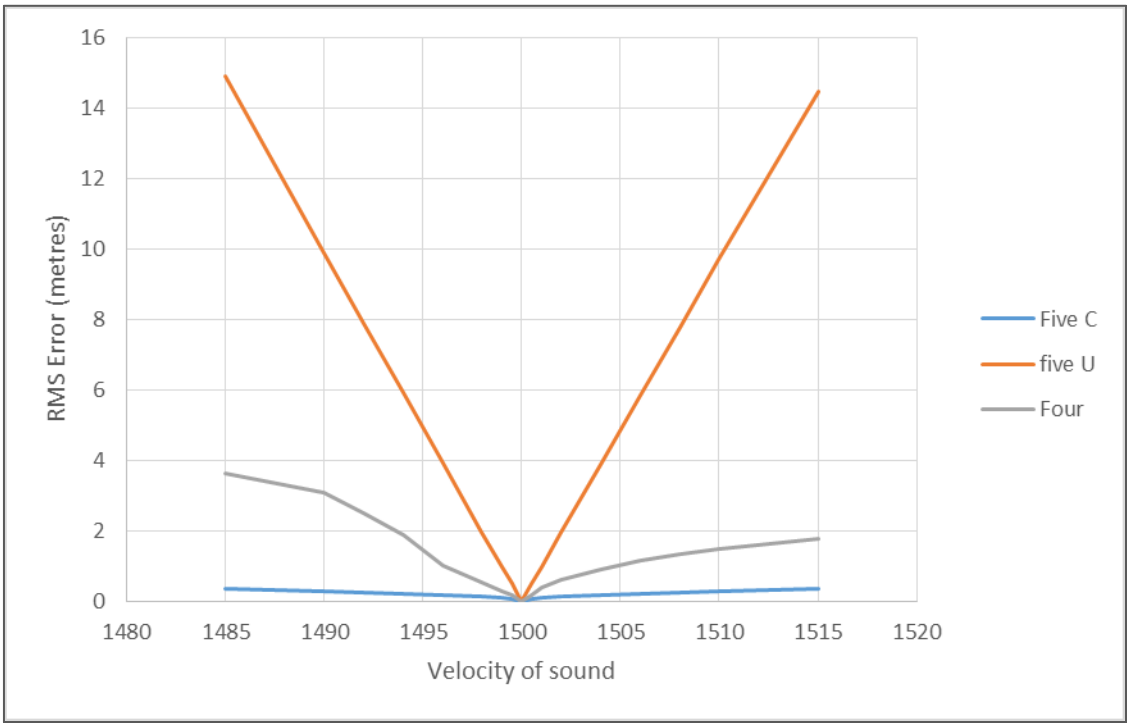


Figure 7.49 Comparison of RMS errors when errors exceeding 4 metres are discarded

For the five hydrophone array, an error in the velocity of sound of 0.05 m/s results in 0.03% of points exceeding the error threshold of 30 cm with an RMS error of 0.02 m (c.f. 3.3% and 0.05 m for the four hydrophone system). At +/-0.5 m/s, the likely error due to variations in the velocity of sound during the measurements, the five hydrophone array would give 0.32% of points exceeding the error threshold with an RMS error of 0.06 m. (c.f. 15% and 0.17 m for the four hydrophone system)

Unfortunately it was not possible to investigate the actual performance of a five hydrophone array due to budget and time constraints.

7.3.6 Four hydrophone results

The localisation work with the four hydrophone array has shown that the clicks mostly originate close to but above the seabed. A small number originate on or below the seabed. Most of the click sources appear to be mobile and may associate with the hydrophone array. Personal observation has shown a number of species of small fish will associate with the hydrophone array. It is thought they may be attracted by the disturbance of the seabed by the act of deploying the equipment.

The equipment used has been shown to have severe limitations in performance with respect to sampling rate, size and number of hydrophones. The accuracy will also be impaired by using an incorrect estimate for the velocity of sound. Despite these limitations it is believed that the localised data still provides an acceptable indication of where the clickers may be.

7.4 Localisation results

The localisation work has demonstrated that the clicking can be heard at the study site throughout the channel from the BHRS through Ferrybridge and out into Portland Harbour. There is some variation in activity level along the channel with most activity under Ferrybridge. There is reduced click activity on the sandflats to the south of the channel where most clicks heard come from the direction of the channel. However some clicks appear to originate in or close to the algae line where Chesil Beach and the sandflats meet. There was no click activity in the saline puddle and sandflat pools tested but the larger saline lagoon near the Visitors Centre car park had a low level of type C activity. There was no significant increase in click activity associated with a wreck pontoon at the study site.

At the BHRS study site the spatial distribution of click activity is stable over a period of one hour. The click sources are mostly located above but close to, the seabed in both the shallows and the channel. However, a small number of clicks appear to originate on or in the seabed. The click sources include mobile species as well as sessile species and these mobile species may be associating with the hydrophone array.

The four hydrophone array used in the 3-D localisation work has been shown to have some major limitations to its performance.

Chapter 8

Species identification

8.1 Introduction

A primary aim of this project was to identify the species producing the click sounds. The acoustic work provided a guide on where and when the clicking took place. In this chapter the work to try to identify the species is described.

8.2 Captive animals

A number of tests were carried out using captive animals held in aquarium tanks. At the BHRS animals were captured from the wild and held in a small aquarium for short periods i.e. less than one hour, before being returned to the wild. Many of the animals could not be classified at the species level although the family or order could be visually identified.

Specimens for study were collected using a sweep net and plankton net in the shallows by the BHRS. Species tested included:

- **Plankton**
  A plankton net was deployed from a mooring for 15 minutes and the collected contents then put into the aquarium. The catch included a variety of small crustacea and other species.
- **Prawns**
  A sweep net was used to capture specimens from the algae line near the BHRS. Three species were found, *Palaemon elegans* was the most common with *P. longirostris* also frequently caught. Less common were the hooded prawn, *Anthanas nitescens.*
- **Crabs**
  Shore crabs are very common in the main study area. Other species occur but were not captured.
- **Molluscs**
  Netted dog whelks, *Nassarius reticulatus*, are common in the study area and captured by hand.
- **Fish**
  A number of small fish were caught including small gobies and the young of a gadidae species, most probably Pollack *Pollachius pollachius*
- **Algae**
  Several species of algae were tested, including bladder wrack, bootlace weed and sea lettuce.

These tests were carried out throughout the year to sample a range of species although the majority of tests were carried out in the July-October period when the click activity was at its highest. Samples were also taken from another site in the south of Portland Harbour.

Throughout all these tests no clicks were heard. There are a number of possible explanations why this may be. The most likely is the limited time the animals were held in the tank in order to ensure their survival. It is possible that they did not have long enough time to acclimatise and start clicking again. Also, the aquarium was a bare glass tank which perhaps did not encourage click activity.

It is also possible that none of the species that make the clicks were captured. In particular, no sand smelt, *Atherina presbyter*, one of the most common small fish in the area, were caught. Sand smelt are open water shoaling fish which venture into the shallows to feed. They are very sensitive to intrusion and almost impossible to catch with a sweep net.

Tests at the aquarium at the National Oceanographic Centre, Southampton, UK did provide some clicks. A hydrophone was deployed in a number of tanks containing a variety of species but the only time clicks were heard was during encounters between a corkwing wrasse *Crenilabrus melops* and a prawn, probably *Palaemon elegans*. Both of these species are common in the study area. The prawn was dropped into the tank containing the wrasse. The wrasse then approached the prawn and at the point of contact there was a loud click and both species moved backwards at high speed. This was repeated several times with the same result. However, it was not clear which species had made the click, and how or why it was produced.

This line of investigation was not pursued further in the expectation that the acoustic work would eventually provide a pointer to which species or group of species to concentrate on.

8.3 Rockpool tests

8.3.1 Introduction

Rockpools can be regarded as well-established aquaria with a captive set of animals when the tide is low. For the smaller shallow water species this was thought to provide the best chance of hearing the click sounds in a reasonably controlled environment. A hydrophone was deployed in rockpools at Newtons Cove near Weymouth, Dorset, Lyme Regis beach, Dorset, Porlock Weir beach, Somerset and at Wembury Cove in South Devon. Eleven sounds were identified and these are described below.

Newtons Cove and Lyme Regis beaches only have very shallow pools (<5cm depth) which are only submerged for short periods at high tide. The only sounds of biological origin heard in these pools was the scraping sound (sound 8) and one wideband click (sound 5) in a Lyme Regis pool,

Porlock Weir beach is made up of large cobbles but also had rockpools that are wider and deeper than Newtons Cove or Lyme Regis and some sounds were recorded in them. These were mainly scraping sounds (sound 8) very similar to the sounds recorded at Wembury. There were a small number of click sounds (sound 5) similar to those heard at Wembury and close to the Type B click described in Section 5.3.

Wembury Cove has a much more extensive area of pools, some of which are much larger in extent and much deeper than those at the other areas investigated. The pools are hollows in granite and have a sandy sea bed. A number of sounds were recorded at the Wembury site and these are described below. Unfortunately this was an opportunistic visit and time did not allow an investigation of the sounds in more detail or to identify the source of the sounds.

Clicks with a degree of similarity to the type B (Sound 5) and type C (Sounds 1 & 2) clicks described in Chapter 5 were found. This investigation of rockpools should be pursued in the future and could yet provide identification of the source of the clicks.

8.3.2 Sound 1

Each pulse is approximately 1 ms in length and has a centre frequency of 9 kHz. This is similar to the type C click described above.

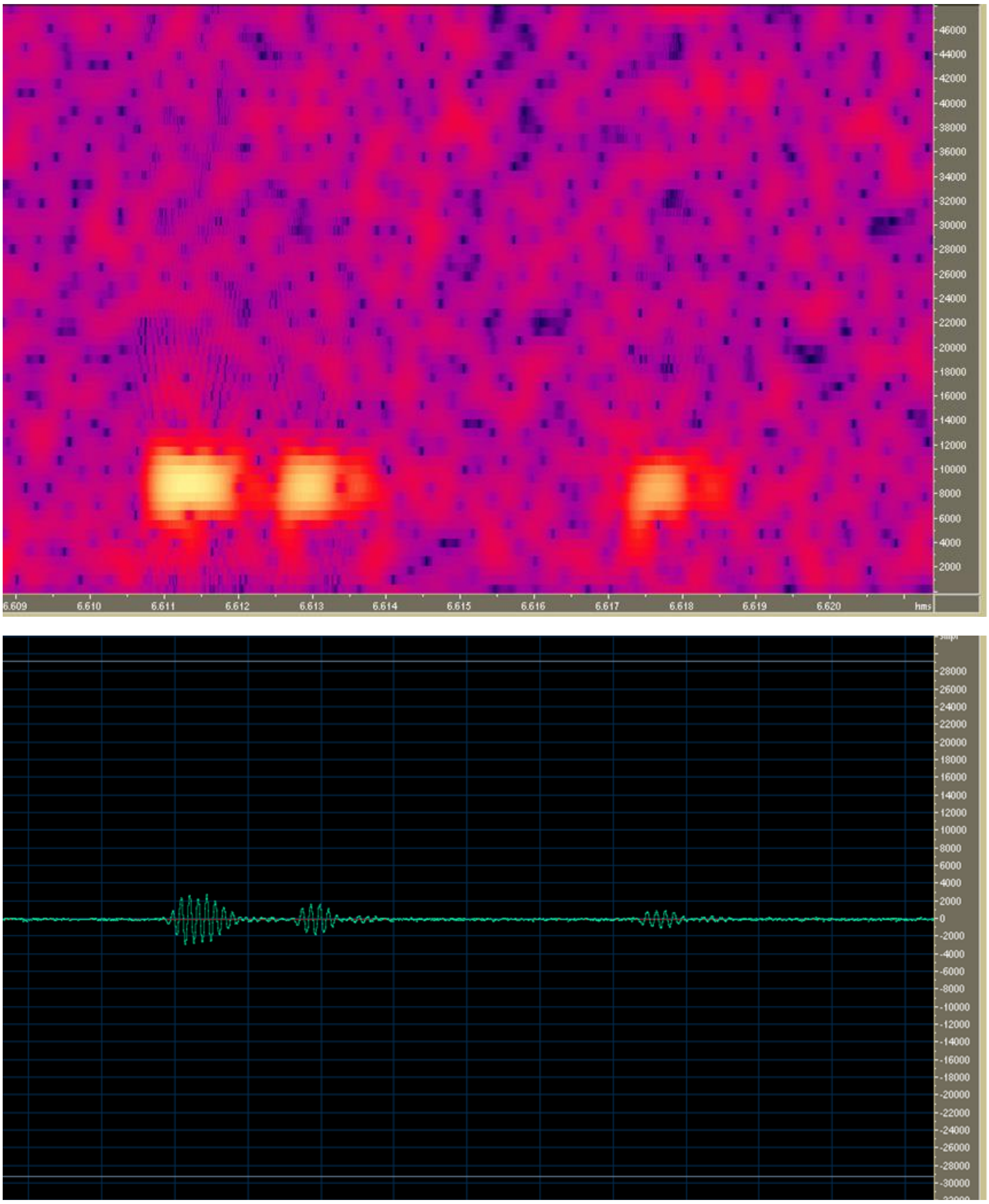


Figure 8.1 Spectrogram and waveform for sound 1

(64 point FFT, Hamming weighting, 50% overlap, Horizontal scale 1 ms intervals, spectrogram 0-48 kHz)

8.3.3 Sound 2

This was a single click with peak frequency at 7.5 kHz. There is little energy above 14.5 kHz. This may be a variant of the type C click described in section 5.3.

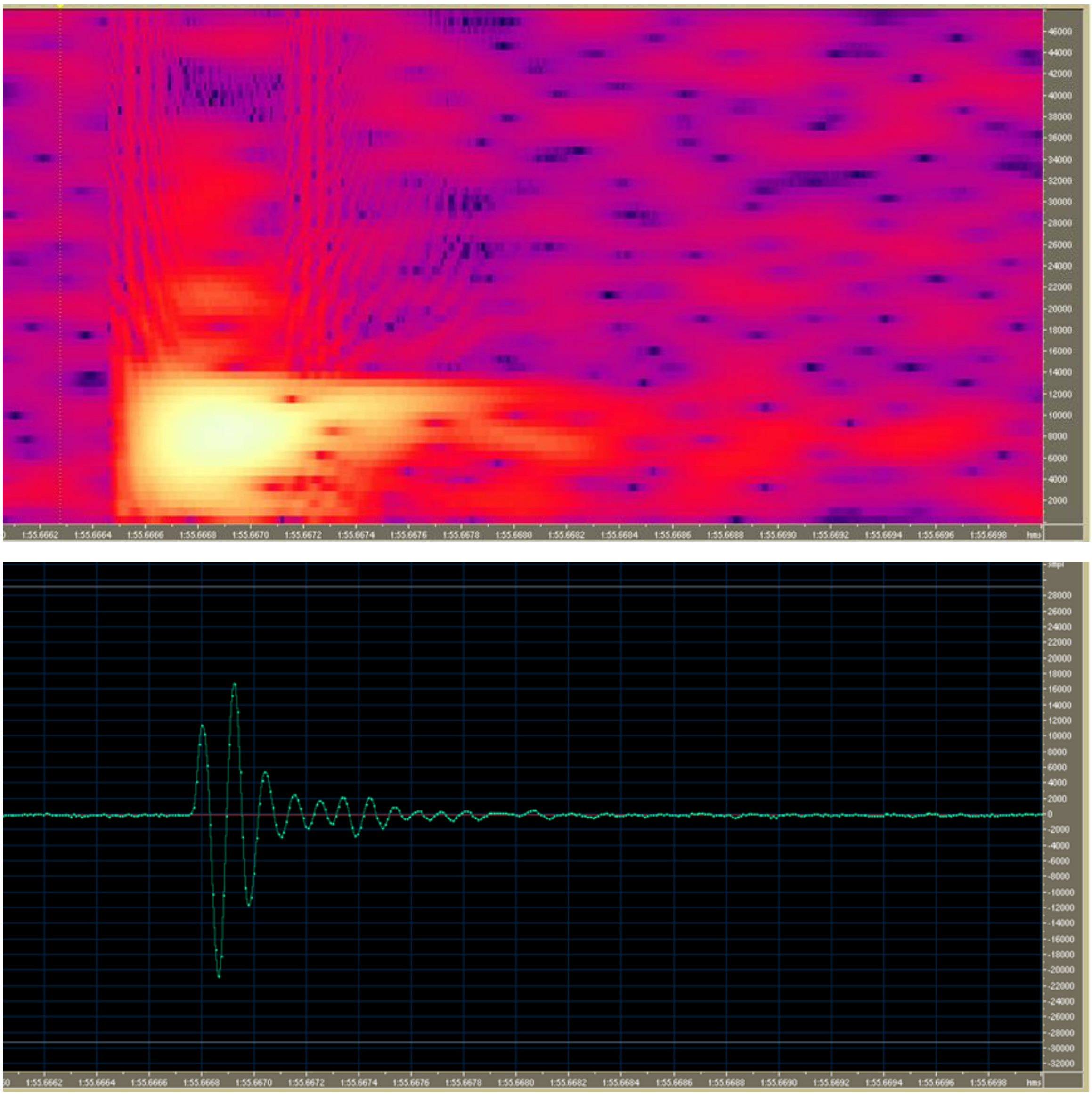


Figure 8.2 Spectrogram and waveform for sound 2

(64 point FFT, Hamming weighting, 50% overlap, Horizontal scale 0.2 ms intervals, spectrogram 0-48 kHz)

8.3.4 Sound 3

This was a series of pulses with peak energy at 15.7 kHz. The interval between pulses slowing from 1 ms to 6 ms. Initial clicks have higher frequency energy content. There are a variable number of outlying clicks following each burst. Several such sequences were recorded from different pools at Wembury.

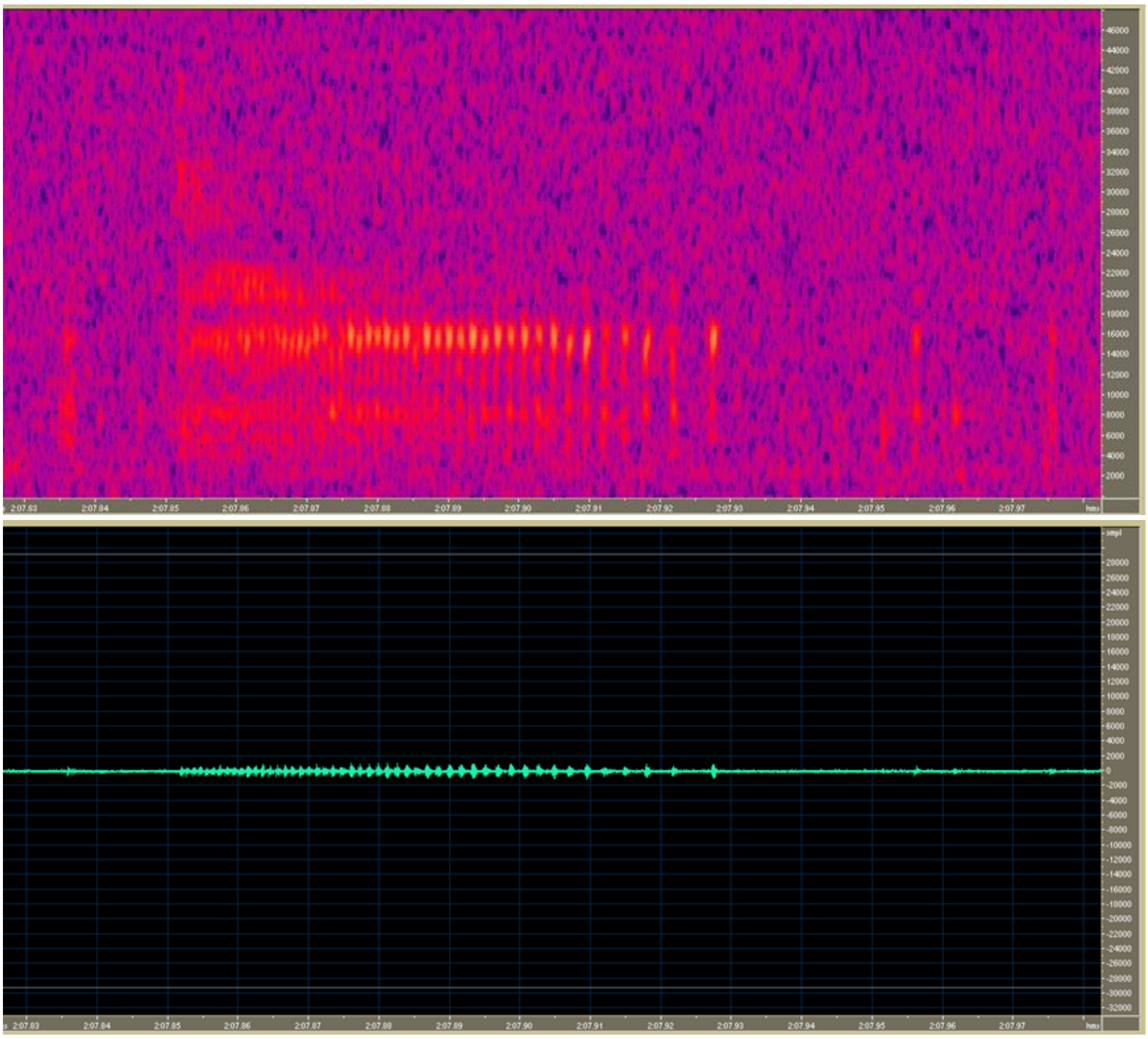


Figure 8.3 Spectrogram and waveform for sound 3

(64 point FFT, Hamming weighting, 50% overlap, Horizontal scale 10 ms intervals, spectrogram 0-48 kHz)

8.3.5 Sound 4

Sound 4 is a rough waveform with energy between 2 and 14 kHz. The sequence lasts for around 230 ms. The spectral modulation may be part of the spectral characteristics, or it may result from the Lloyds mirror effect if the sound source is moving.

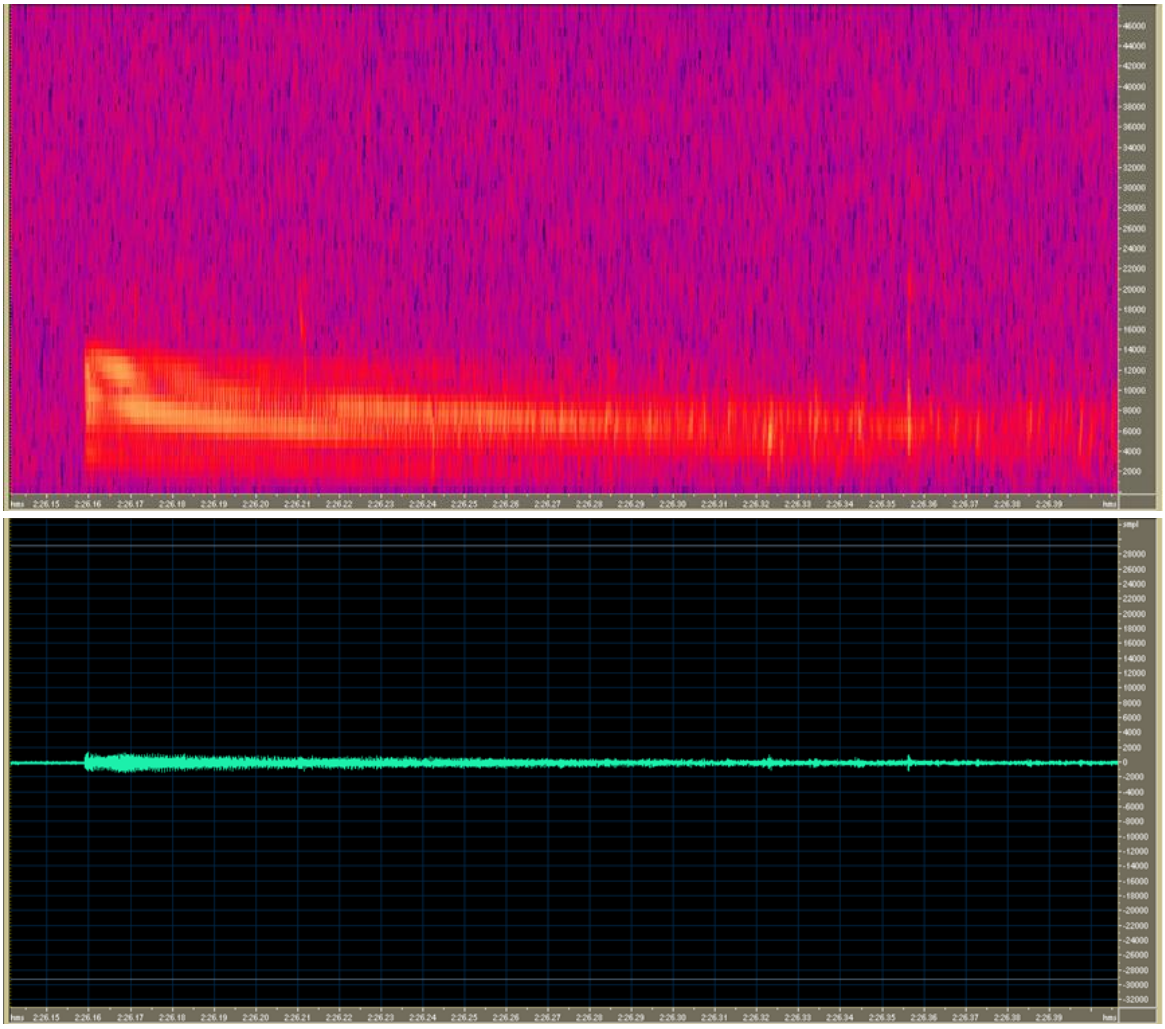


Figure 8.4 Spectrogram and waveform for sound 4

(64 point FFT, Hamming weighting, 50% overlap, Horizontal scale 10 ms intervals, spectrogram 0-48 kHz)

8.3.6 Sound 5

A single, loud, isolated wideband click. This is the closest sound to the type B click described in section 5.2 above. It was heard at Wembury, Porlock and Lyme Regis.

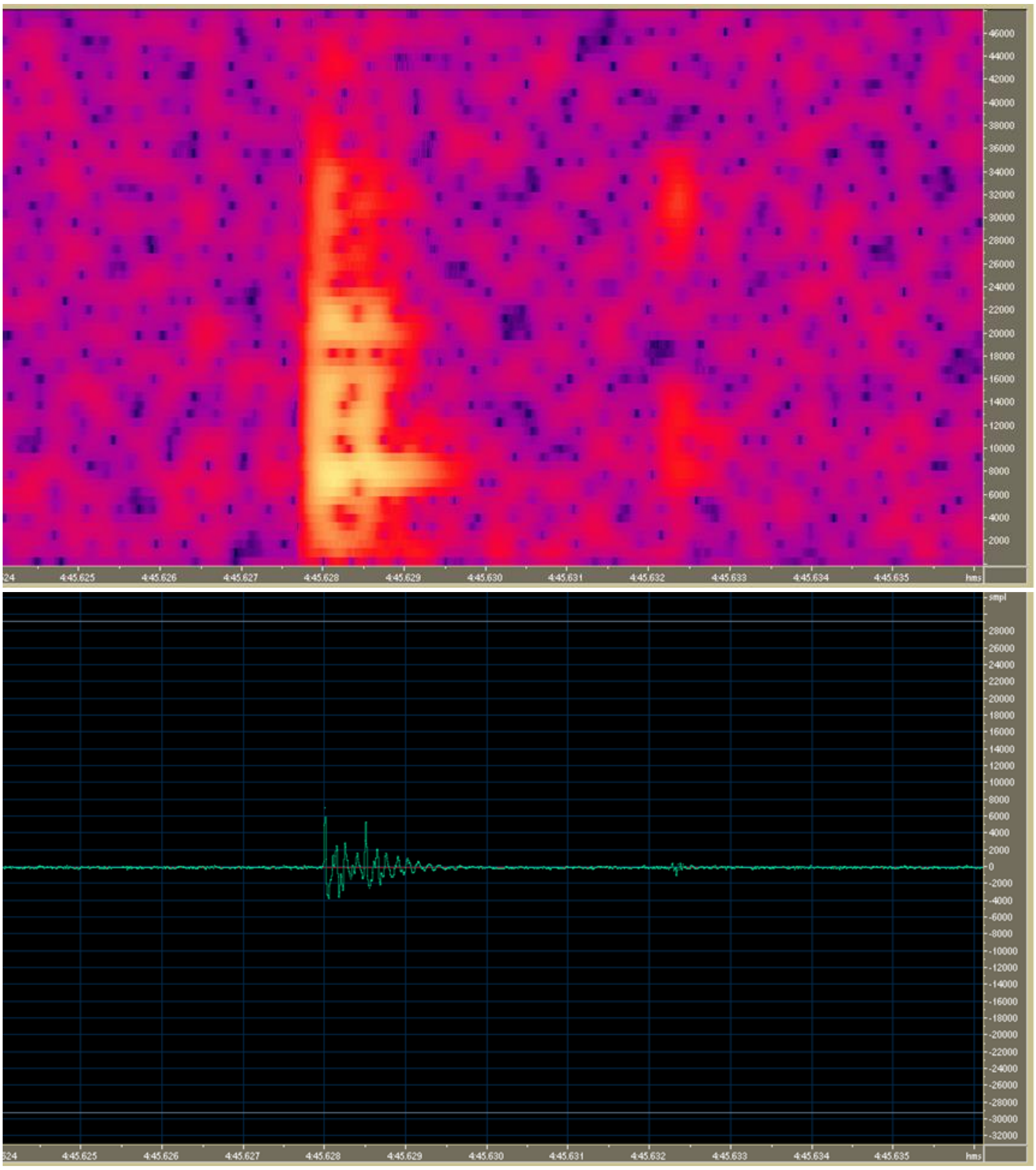


Figure 8.5 Spectrogram and waveform for sound 5

(64 point FFT, Hamming weighting, 50% overlap, Horizontal scale 1 ms intervals, spectrogram 0-48 kHz)

Species identification

8.3.7 Sound 6

A series of pulses with 8.2 kHz centre frequency of each click, each pulse is approximately 1.2 ms long, the sequence length is 65 ms. This sound may be related to sound 1.

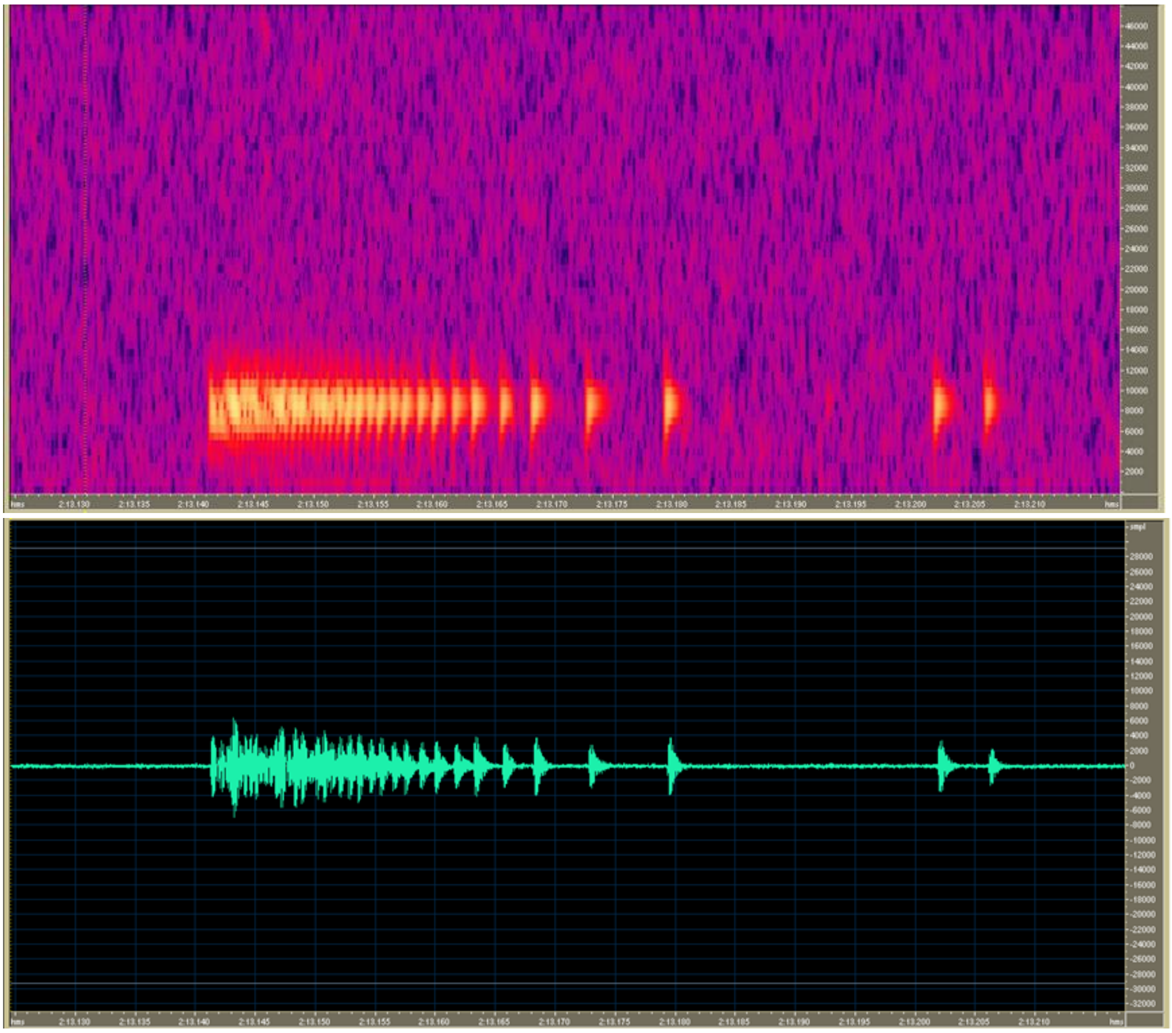


Figure 8.6 Spectrogram and waveform for sound 6

(64 point FFT, Hamming weighting, 50% overlap, Horizontal scale 1 ms intervals, spectrogram 0-48 kHz)

8.3.8 Sound 7

This sound was very weak but it is believed to be a sequence of pulses with sequence length around 100 ms. The waveform covered a frequency range from 48 kHz down to 14 kHz.

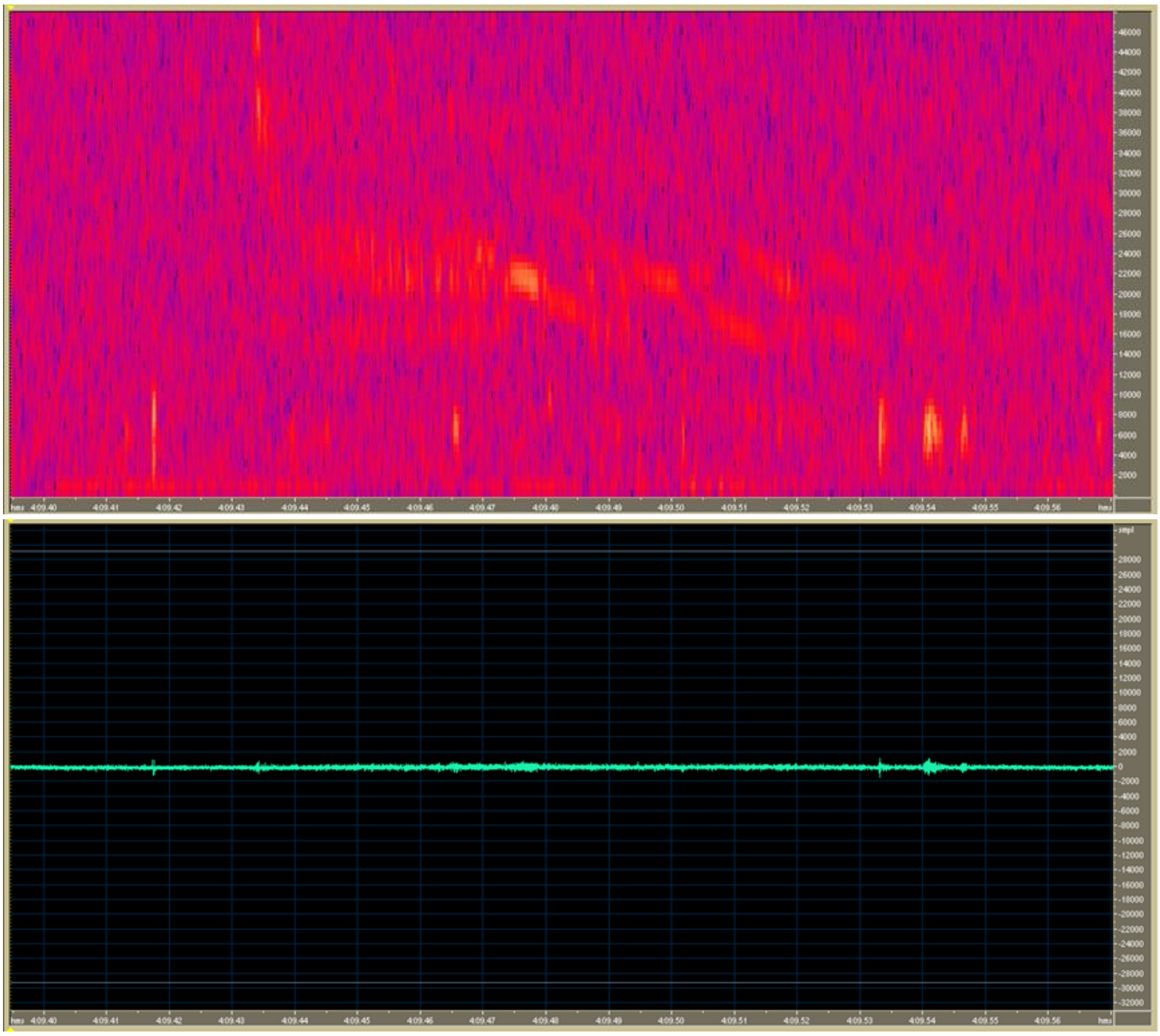


Figure 8.7 Spectrogram and waveform for sound 7

(64 point FFT, Hamming weighting, 50% overlap, Horizontal scale 10 ms intervals, spectrogram 0-48 kHz)

Species identification

8.3.9 Sound 8

A series of paired clicks in a sequence 145 ms long, the centre frequency is 5 kHz and the pair separation is typically 2.5 ms. This sound was heard in most pools sampled.

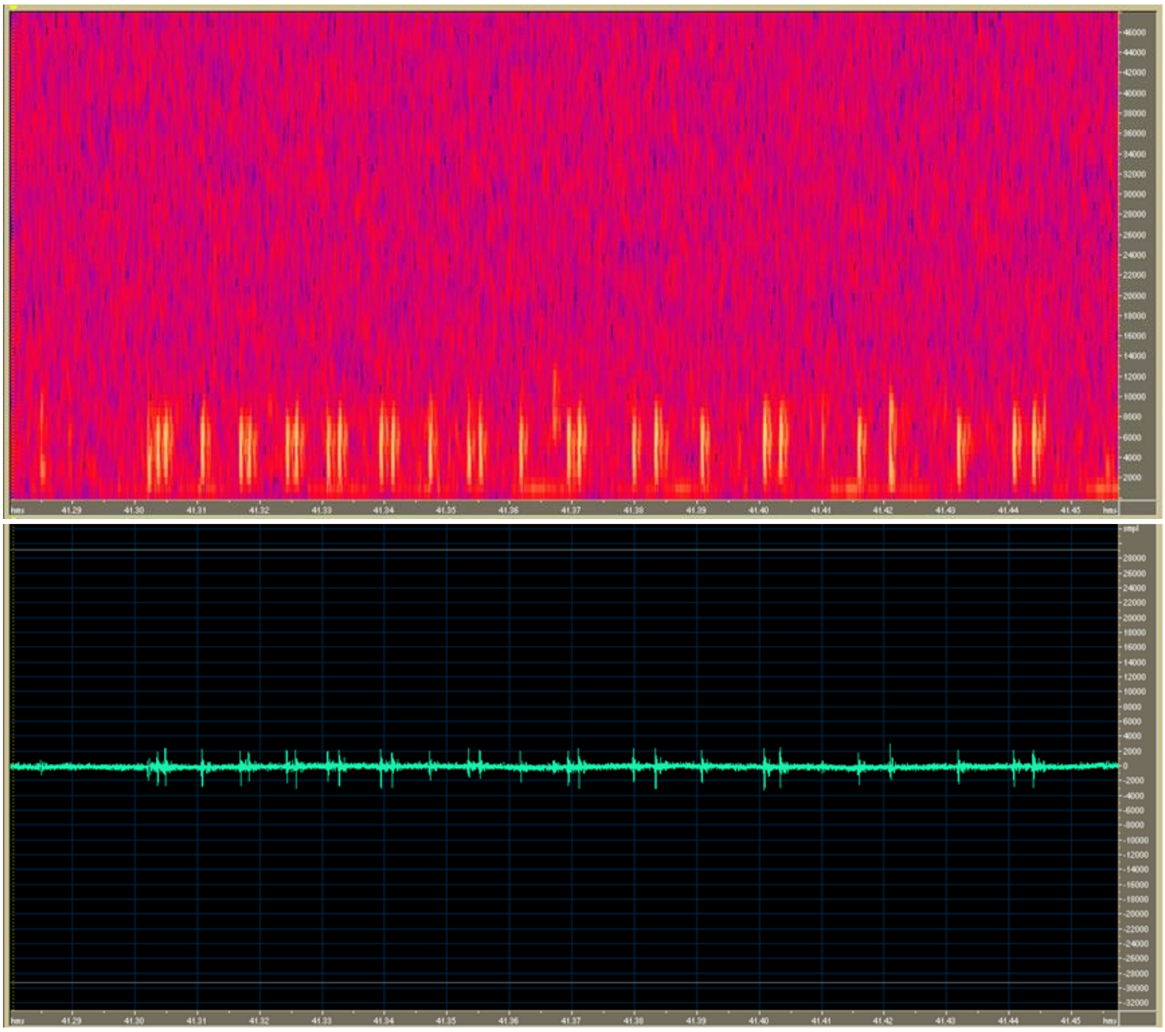


Figure 8.8 Spectrogram and waveform for sound 8

(64 point FFT, Hamming weighting, 50% overlap, Horizontal scale 10 ms intervals, spectrogram 0-48 kHz)

8.3.10 Sound 9

A sequence of 2 pulses with centre frequency 16.5 kHz and length approximately 2 ms. Note that this is the higher frequency sound in the spectrogram. The lower clicks are from a different source.

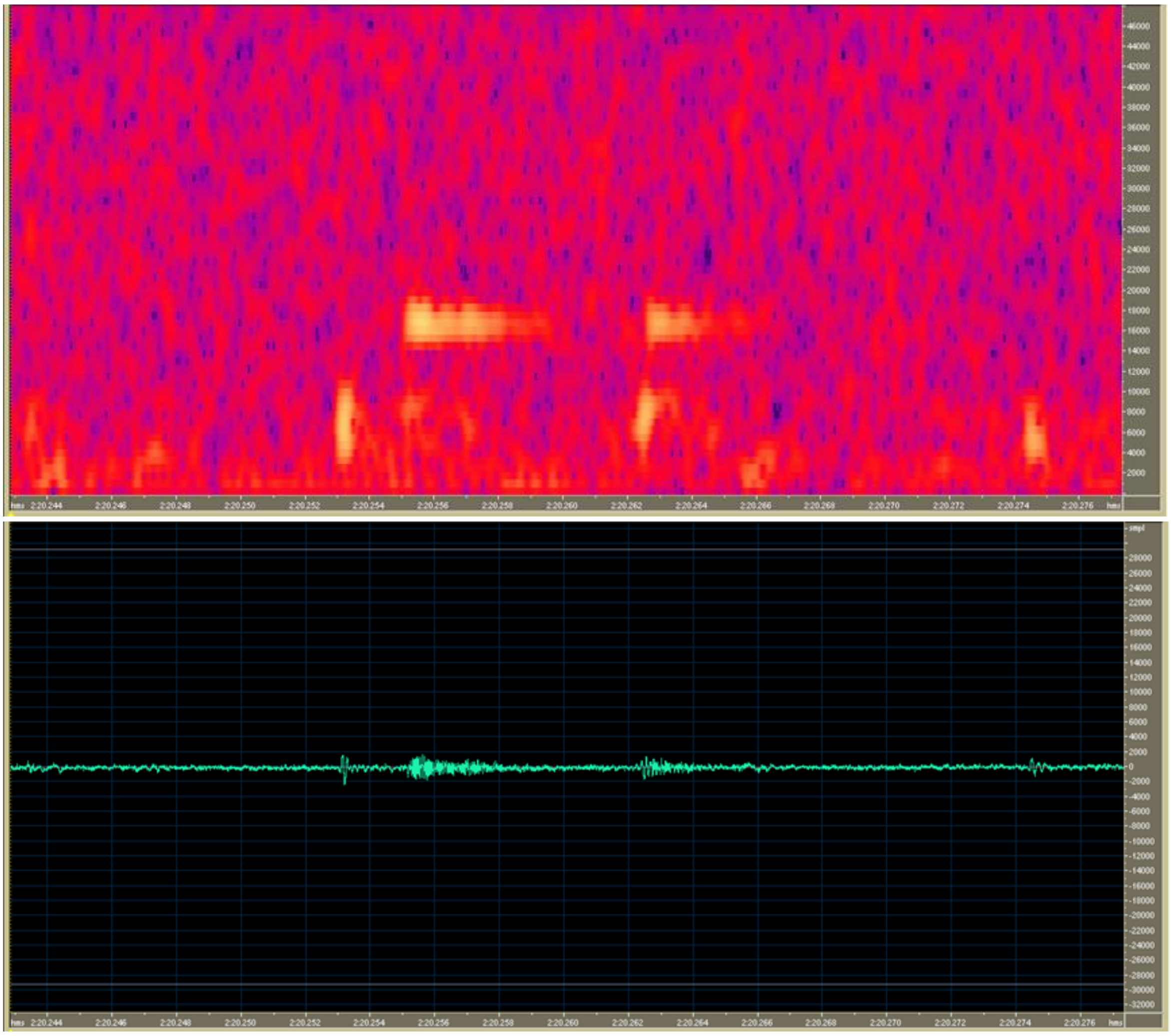


Figure 8. 9 Spectrogram and waveform for sound 9

(64 point FFT, Hamming weighting, 50% overlap, Horizontal scale 2 ms intervals, spectrogram 0-48 kHz)

Species identification

8.3.11 Sound 10

Sound 10 was a repeated series of clicks with an initial fast burst followed by slower clicks. The slow clicks separation is around 13 ms and the sequence length is around 2 seconds. The pulses gradually get weaker. Centre frequency of the clicks is around 8 kHz.

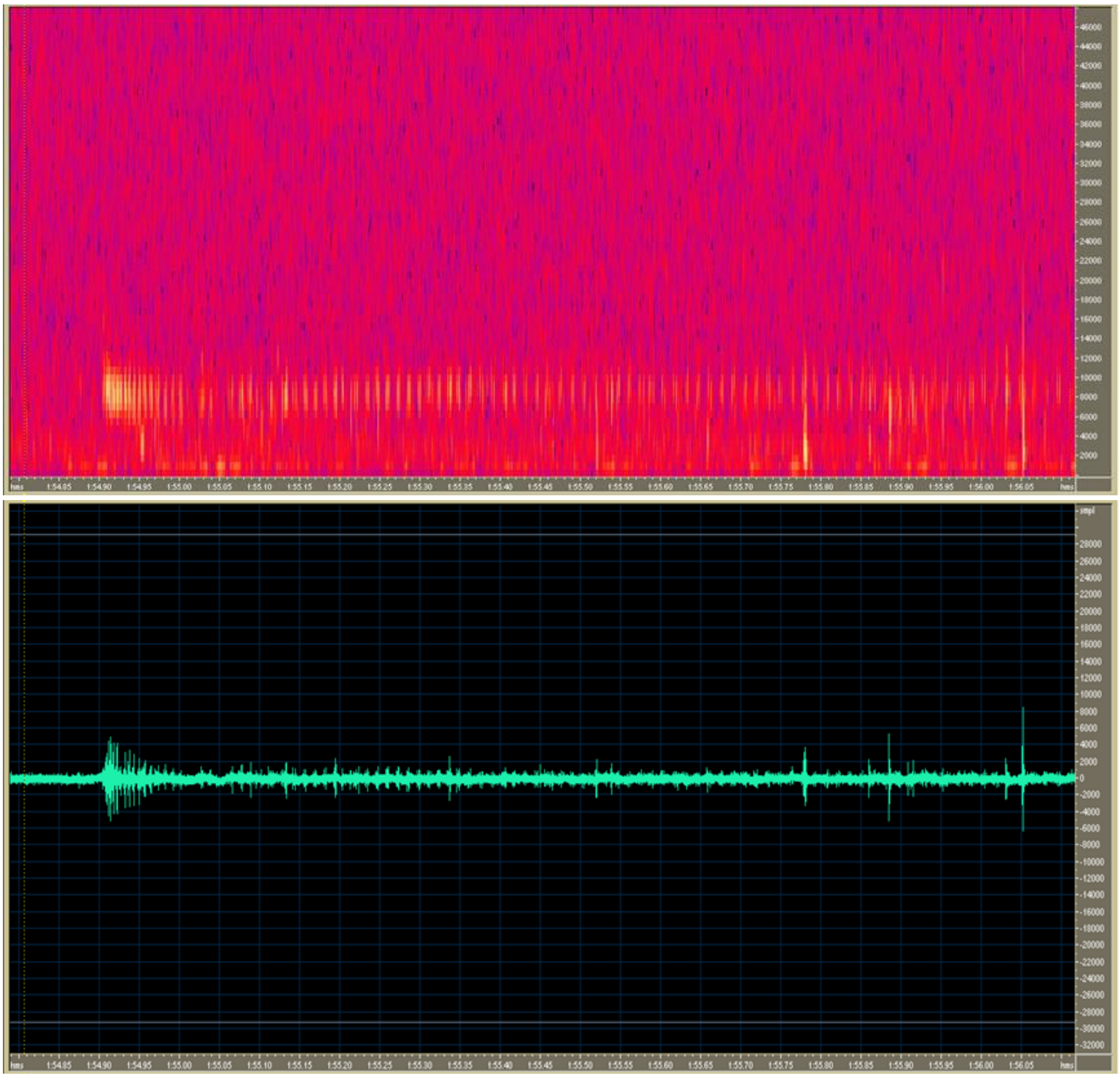


Figure 8.10 Spectrogram and waveform for sound 10

(64 point FFT, Hamming weighting, 50% overlap, Horizontal scale 50 ms intervals, spectrogram 0-48 kHz)

8.3.12 Sound 11

This is a long pulse followed by a short pulse. Centre frequency is around 22 kHz. The long pulse is 4 ms long, the short pulse length is 0.5 ms. The separation of the two pulses is 2.5 ms.

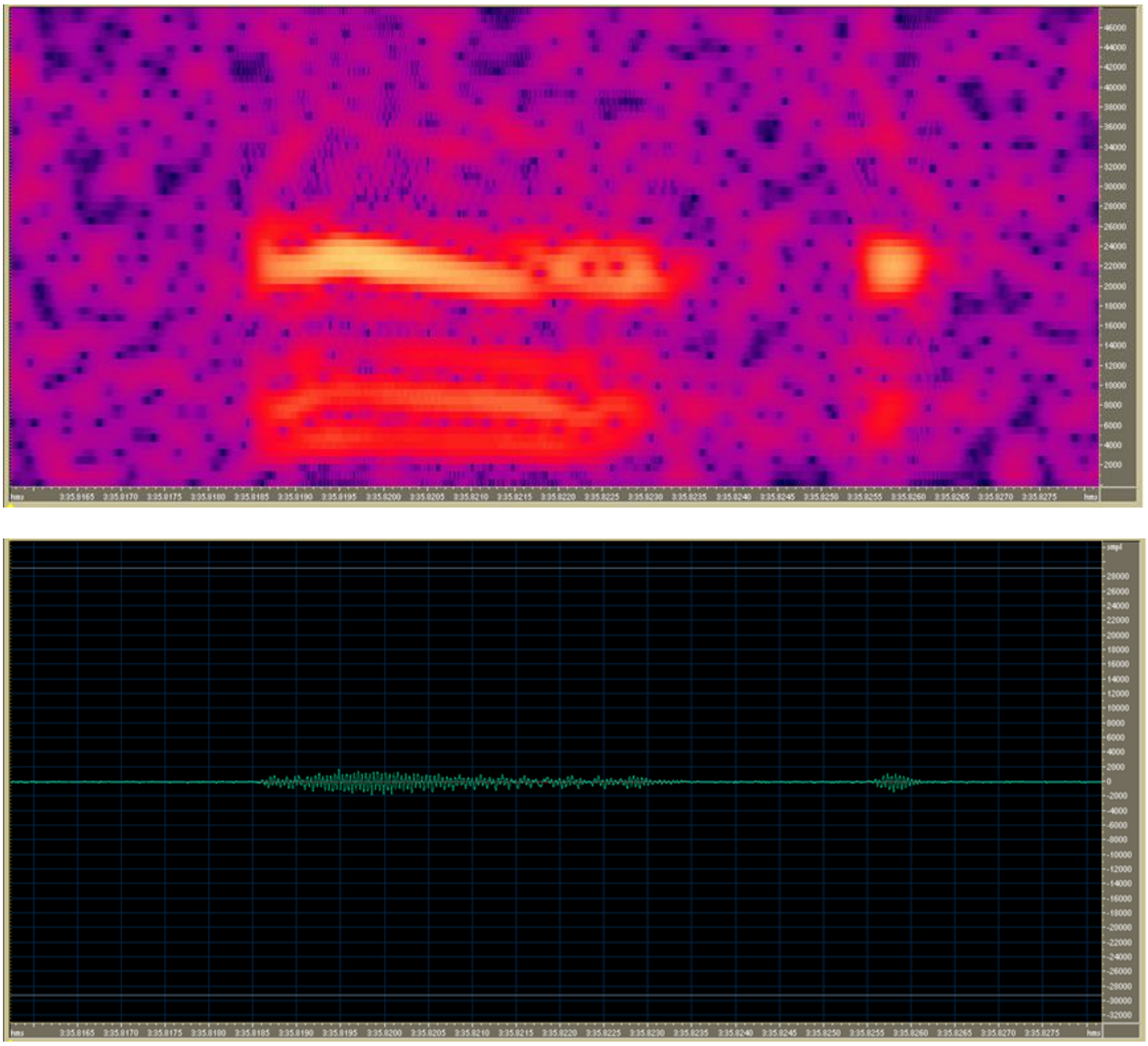


Figure 8.11 Spectrogram and waveform for sound 11

(64 point FFT, Hamming weighting, 50% overlap, Horizontal scale 0.5 ms intervals, spectrogram 0-48 kHz)

It is likely that some of these sounds are produced by the feeding processes of the animals in the pools, particularly the pulse sequences. It would be interesting to re-visit Wembury Cove with suitable equipment to allow identification of the species generating each of the sounds.

Species identification

8.4 Deployed cameras

Video cameras were deployed as described in Chapter 4.9. These were mostly deployed on the BC2, QC2 and MQC2 localisation equipment but they were also deployed during the UC1 spatial survey and on a free-standing framework to try and identify species in the main study area.

The cameras included an audio channel using an in-air microphone within the camera body but it had extremely low sensitivity and limited bandwidth once the camera was in its underwater housing. This impaired audio performance made synchronisation between the sound and video very difficult and was a major hindrance to the work to correlate clicks with animal activities in the cameras field of view. Snapping the dog clicker within the field of view of the camera worked at the start of a deployment but all of the cameras split the video into sub-files with an unknown gap between the segments. No satisfactory method could be found to maintain synchronisation between the video recordings and the audio recordings for the whole deployment.

The species identified at the main study site are shown below. These have been identified by the use of the deployed cameras, by walking the shore at spring low tide and by personal observation while snorkelling in the area.

Those marked with a red star are rare in the study area while those marked with a green star are very common in the study site.

Table 8. 1 Species found at the study site

Fish		
Grey mullet*	Corkwing wrasse*	Two-spot goby*
Bass*	Ballan wrasse	Common goby*
Fifteen-spine stickleback	Pollack fry*	Goby spp (>3 species)
Flounder	Common eel*	Tompot blenny
Black-face blenny*	Lumpsucker*	Bream*
Sand smelt*		
Crustacea		
Shore crab*	Velvet swimming crab	Prawn (P.elegans) *
Spider crab (> 2 species)*	Hermit crab	Prawn(A. nitescens)
Shrimp (Mysidacea(spp)	Barnacle (>3 species) *	Prawn (P.longiristris)
Shrimp (Gammaridae spp)		
Others		
Black mussel*	Netted dog whelk*	Cowrie*
Clams (>5 species)	Periwinkle (several species)	
Tube worms (>2 species)	Fan worms (2 species)	Sea anenomes (>3 species) *

Many other species are present but the above are the larger species that can easily be identified without specialised equipment. The commonest fish species are corkwing wrasse, sand smelt, the goby species and the grey mullet.

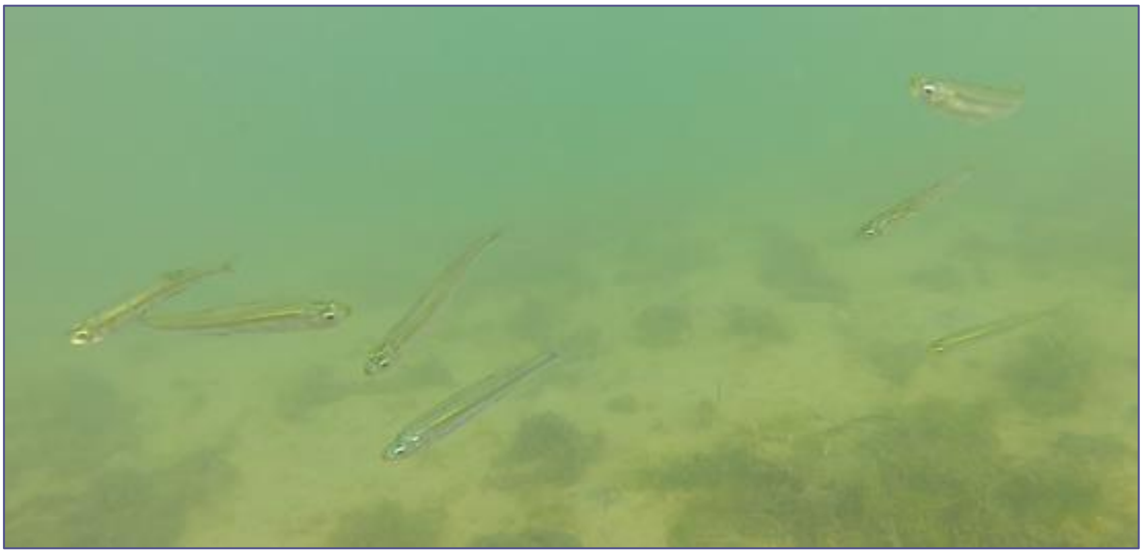


Figure 8.12 Sand smelt near MQC2 equipment

Figure 8.13 Goby near the MQC2 cable

A notable omission from this list are the Alpheid snapping shrimps. These occur along the Dorset coast and the acoustic work suggest they are present in the Fleet. However, none were seen or caught in the netting work. This is not surprising as they live in burrows below the spring low tide line and often hidden under seabed debris. To catch one would mean a significant disturbance of the seabed and make it impossible to return the animal to the burrow.

During the deployment of the two and four hydrophone localisation systems, the common species seen were two species of goby, sand smelt, shore crabs and netted dog whelks. Other species seen in low numbers included ballan wrasse, spider crab, and grey mullet. For the first MQC2 deployment (Oct 2014) a large number of sand smelt were present and in the area where clicks were localised by the acoustic work. For the second deployment, there was a much stronger current running and the cameras were unfortunately not looking at the area where the clicks appeared to originate. Sand smelt were seen in the shallows as the equipment was being deployed but when at the final position in the channel only shore crabs and gobies were seen.

Species identification

Corkwing wrasse are very common in the Fleet, but prefer to stay close to or under cover. They were always present on the CMMP fixed camera within the wrecked pontoon but were only rarely seen on the cameras on the acoustic equipment. Conversely, the sand smelt, which prefer open water, were very often seen on the equipment cameras, but in seven years of watching have not been seen on the CMMP fixed camera within the pontoon.

Throughout all of the videos taken across four years and during a variety of deployments on only a few occasions did a localised click correspond with the presence of an animal in front of the video and this animal was the sand smelt, *Atherina presbyter*. It is not clear whether this was coincidencal or whether it is a true source of the clicks. Sand smelt have been present on many occasions, but despite careful study of the videos no correlation between the click sound and a specific activity of the fish could be found. They do have a characteristic way of swimming in which they drift slowly in the water column and then move very quickly for a short distance. It is possible the click is generated by this sudden movement. This work was hindered by the lack of synchronisation between audio and video described above.

Ballan wrasse were observed feeding in front of the camera on a number of occasions, but, within the limits of the sound/video synchronisation, no clicks were attributable to this activity.

There are a large number of algae species present at the study site. The majority have an annual cycle of growth such that they are most abundant through May and June. A smaller number peak in abundance in the autumn to take advantage of the die-off of the spring species. No clicks were heard when they were placed in the test tank.

Figure 8.14 Ballan wrasse feeding near the MQC2 cable

8.5 Annual variation

Chapter 7 showed that the clicking activity varied on an annual basis, peaking in late August and September. Personal observation showed that the numbers of some species in the study site seemed to follow this general trend. These include:

- Corkwing wrasse
- Ballan wrasse
- Two spot gobies
- The young of several species of large fish
- Sand smelt
- Bass
- Prawns (*Palaemon* spp)
- Shore crabs

Although the other goby species are present through the year, the numbers increase considerably in late summer. It is likely that other species also track this annual cycle.

Many of the sessile species also have a reduced presence during the winter months including the fan worms, sea squirts and sea anemones. Insufficient is known about the life cycle of these animals to comment on why this may be.

8.6 Species identification results

The species identification work has failed to identify a particular species as being the main source of the clicks. However, it has identified the following:

- Type A clicks likely to be from snapping shrimp are present all year round in small numbers but no snapping shrimp were observed at the study site
- The increase in click activity in late summer coincides with the increase in numbers of a variety of mobile and sessile species
- Algae is at its most abundant in late spring when click activity is low. Algae then dies off through the summer as the click activity increases so algae is unlikely to be a source of the clicks
- The combined video and acoustic work has failed to positively identify a source of the clicks
- Circumstantial evidence suggests that sand smelt may be a significant contributor to the click activity

Chapter 9

Discussion

9.1 Introduction

This project set out with the aim of investigating the clicking sound and with the eventual aim of determining the source of the clicks. Whilst the investigation aspects have gone well, the identification of the source of the clicks has proven elusive. This chapter discusses what has been achieved, what did not work and what future work could be done to finally identify the source of the clicks.

9.2 What is a click?

The most fundamental part of this work also proved to be one of the more challenging aspects of the work. There is a very high degree of variability between observed clicks as described in section 5.1. Without a set of rules defining a biological click and which separate biological clicks from other natural and anthropogenic click sources it is not possible to automate the detection process.

The most significant of these unwanted clicks are clicks from passing boats and weather-related clicks. These have slightly different characteristics to the biological clicks, but they sufficiently overlap in characteristics to make discrimination very difficult. This problem was bypassed for the spatial survey work by not collect data when these effects were present, but the temporal survey data using the automated detector was contaminated by these unwanted sounds requiring the manual removal of adverse weather days.

Three broad types of biological click were identified in Chapter 5 but it was only possible to make this distinction for strong local clicks. Click types A and B could look like each other or even like a type C click when propagating over any significant distance.

It is highly likely that there are actually many sources of biological clicks, each with slightly different characteristics, but the variability has merged them into a continuum of types from which only the three main classes can be distinguished and then only when they occur close to the hydrophone. The three types of click described should perhaps be regarded as classes of click appropriate to the production mechanism rather than to individual species.

9.3 Is one site more active than another?

It was hoped to be able to compare click activity at different sites in order to understand how activity is affected by the environment, but, as discussed in the previous section, counting the biological clicks in a reliable and reproducible manner proved to be very difficult. Initially a simple fixed threshold click detector was used but this did not take into account varying ambient noise levels and differing acoustic propagation conditions. The automated detector used for the fixed hydrophone work and described in Section 3.8 works satisfactorily at the main study site, but does not work in some other sites because of the differing way the clicks are modified by acoustic propagation conditions and/or a different mix of interfering signals.

With these difficulties this project was forced to adopt a simple subjective detection method for the spatial surveys in which the operator allocated activity to three categories: no clicks, low activity, high activity and these was used for the spatial distribution work described in Chapter 6. This was not an ideal solution but within the timescales and resources of this project was the only method available. Such a broad classification of activity could only provide guidance on the general distribution of click activity.

Most of the data collected for the surveys presented in Chapter 6 were collected early in the project before it was appreciated how much variation of activity there can be through the diurnal and annual cycles. Fortuitously, most of the data was collected during daylight hours and during the warmer months of the year when the click activity is highest.

More work is needed in this area to understand the factors affecting the results obtained and to ensure that when comparing sites one is comparing like with like. Careful control of equipment characteristics, measurement methodology and timing should allow site comparisons to be more meaningful.

9.4 Where are the clicks heard?

The single hydrophone system was used to investigate rock pools, sandflat pools, shallow intertidal areas and transient lagoons. Although various biological sounds were heard in these environments, as described in Chapter 8, few of the type A or B clicks identified in Chapter 5, were heard. Once the hydrophone was moved into the deeper water of the study site the clicks were heard. Based on the limited measurements made, the ideal habitat for the click producers appears to be a mixed seabed of sand, mud and rocks or debris. The presence of a jetty or pier also encourages click activity. Monotype sea beds such as sand or mud have a low level of click activity compared with the mixed seabed areas.

The regional survey showed that the clicking activity appeared to be confined to the southern half of the UK. While the two null locations in Cromarty and Orkney are good data, some of the points taken further south and particularly along the east coast are more questionable. In the light of information from the temporal survey a more controlled set of data collection locations would be more representative of the true distribution. Despite the shortcomings there is a consistent story that the click activity is found only in the southern half of the UK. More data points would help to be more specific where the reduction in clicking occurs and that may provide guidance on the species causing the clicks.

Away from the study site the click producers seem to prefer estuaries or harbours, but can still be heard over wide areas of offshore waters off the coast of Dorset. Areas where they could not be heard included the extensive sandy areas in Weymouth Bay and the muddy areas in Poole Harbour.

The most active areas found in the course of this project are the Portland Harbour breakwater and the channel under the Ferrybridge road bridge. It was not possible to carry out temporal or detailed spatial surveys at these sites. Permission to access the breakwaters was not forthcoming and the area around the bridge is open to the public and has very strong currents.

Discussion

It is not clear whether the spatial data from the study site is representative of other sites or specific to this particular site. It would be useful to study one or more additional sites in sufficient detail to allow a comparison.

9.5 When are the click heard?

The temporal survey work at the study site showed that there is a strong annual dependence on click activity with most activity late summer and early autumn and least activity late winter and early spring. This trend coincides with the trend in numbers for a number of both sessile and mobile species and also coincides with the trend in water temperature at the study site. Some activity continues through the winter at a very low level compared with the summer peak.

During the summer peak there is a very strong diurnal variation in activity with high levels of activity during the day and low levels at night. During the autumn and early winter as activity diminishes there are peaks in activity at dawn and dusk. This suggests that the dominant clicking species at that time needs light to carry out whatever activity produces the clicks. This in turn suggests that it is most likely a mobile species. Many species of fish become dormant during the months when the water temperature is lowest but no information could be found on their behaviour during the transition from the active summer months to the dormant winter months. It is not clear why the peaks at dawn and dusk occur in the autumn and not in the spring. It may be a period of feeding activity by the click producing species.

It has not been possible to extend the temporal survey to other sites so it is not clear how representative the data from the Fleet is of other sites. It would be useful to carry out similar monitoring at one or more additional sites to establish how activity varies in comparison with the Fleet site.

9.6 How are the click sources distributed in space?

An important part of characterising the clicks is understanding how they are distributed in the water column. A key question is whether they originate on the sea bed or in the water column as this will help in identifying whether the click source is a mobile or sessile species.

It would have been useful to have deployed two hydrophones vertically to further investigate this but with the limited resources available concentrated on the BiClick and Quadraclick development, deployment and analysis this did not prove possible.

The 3-D localisation work suggested that the clickers are predominantly located above the seabed. However, because of the possible errors identified in the method used, it was not possible to be certain what percentage of clicks heard were from the seabed and what percentage were from the water column. It was not possible to use data from the hydrophone pairs within the MQC2 array to establish the vertical distribution because their axes were all well away from being vertical.

Further work should investigate the vertical distribution using a vertical pair of hydrophones to check where in the water column the clicks originate. There needs to be several deployments at different locations within the study site. It should be possible to modify the hydrophone mounting arrangement in BiClick to achieve a vertical separation of 1 m.

The horizontal distribution of the click sources over smaller scales than that of the regional spatial survey was investigated using single and dual hydrophone systems.

The single hydrophone survey investigated the click distribution within the study site as described in Section 6.3. This work was hampered by the problem of access to the channel edge. It would be useful to repeat this work from a small boat that could be anchored in a controlled series of locations.

The two-hydrophone systems were deployed on a number of occasions to try and establish click activity distribution over scales up to a few tens of metres. This work proved the most successful of the localisation experiments showing that there was little click activity over the sandflats, that most of the clicking is from the channel rather than the shallows and that a small wreck was not a significant source of click activity. The BiClick2 equipment proved very reliable and easy to deploy.

One problem encountered with the two hydrophone system was that the clicks were identified manually, which made data reproducibility a problem. With a suitable automated click detector and classifier this process could be speeded up and improve both the reproducibility and comparability of the resulting data. However, enough clicks could be manually selected to make the presented data meaningful.

A fully automated system that could process the data in real-time, combined with a live video camera, could be used to go hunting for click sources rather than waiting for click sources to come to the equipment. It could also be used to quickly assess a range of habitats. If the click processing could be suitable packaged it could be used by a diver to quickly assess an area for click activity.

9.7 How are the click sources distributed in three dimensions?

A key part of the project was to try and localise the click sources down to less than a metre so that video cameras could capture the creature ‘in the act’ of clicking. A four hydrophone array was used to localise the clicks while cameras deployed on the structure of the array recorded any animals in the vicinity.

The data presented in Section 7.3 suggests that the majority of the clicks originate above the seabed. However, there were a number of factors contributing to errors in the localisation data as discussed in Section 7.3.4. The localisation accuracy could be improved by increasing the hydrophone spacing to reduce the impact of errors arising from any errors in the hydrophone locations and from errors due to the low sampling rate. Newer recorders than were available to this project are now available with higher sampling rates. It is essential that the velocity of sound is measured accurately at the time the measurements are made.

However, since the purpose of the hydrophone array was to provide guidance on where the cameras should look the degradation associated with the system used to collect the data presented was deemed acceptable. The tests with the dog clicker demonstrated that the system could provide useful localisation data.

The waveform from the four hydrophones in the array proved surprisingly variable between the hydrophones. The greatest hydrophone separation was under 1.2 metres yet for many of the clicks received the waveforms from the four hydrophones were very different. It was particularly variable for the top hydrophone when deployed in shallow water where it was close to the sea surface, but all of the hydrophones suffered on occasions. It was also apparent that some clicks were very similar across the four hydrophones while others were different in all four channels.

This variability of the waveforms between the hydrophones made selecting the start times very challenging and slowed the data processing considerably. It may have also have had the effect of skewing the data, since only those clicks where four times could be measured were processed and displayed. It was very noticeable while going through the clicks that often the click waveforms would fit into a small number of type groups. This may be due to the clicks originating in the same small volume of water and suffering the same propagation effects, or it could be due to a mix of species causing the clicks.

Another problem encountered was that very loud clicks, which presumably originated close to the array, could never be processed. Although good waveforms were obtained and what seemed like good start times measured, they always gave a complex result from the processing software and had to be discarded. The cause of this is not clear, but it meant that the clicks which could have yielded good video images could not be used. One possibility is that they came from organisms buried in the seabed which meant the propagation path was partially through the seabed with a different velocity of sound and this gave arrival times that the software could not process.

While processing the clicks it became apparent that a surprising number were giving two wrong positions from the processing. After some investigation, it became apparent that the prime reason for this was likely to be an incorrect assumption of the velocity of sound. There are a number of equations which allow the velocity of sound to be calculated based on a knowledge of the water temperature, salinity, depth and other parameters. The Leroy equation was used because it is fairly easy to implement in software and has given good agreement when used on previous projects. However, investigation of the effect of using a wrong velocity showed that even a small error gave a large number of erroneous points. If this type of array is used for future work it is strongly recommended that an accurate method of measuring sound velocity be employed.

For this project, simple logic based on arrival times and waveform amplitude applied by the operator allowed many of the erroneous points to be eliminated. Further investigation of automated methods to reject erroneous locations may prove useful in reducing the number of false locations plotted.

It must also be remembered that there is a variation in the velocity of sound with depth when working in such shallow water. The Leroy equation suggests that increasing depth from 0.5 to 1.5 metres will change the velocity of sound by 0.03 m/s. At present the localisation processing ignores this variation, but in view of the sensitivity of the algorithm to velocity variations then perhaps it should be included.

The deployments of BiClick and Quadraclick gave a tantalising glimpse of what appeared to be tracks. These were sequences of up to six clicks which appeared in a short time sequence and appeared to change TDOA with time. Unfortunately this could not be followed up due to time constraints and software limitations. These brief tracks also appeared in the click localisation plots from MQC2 and appeared to be located above the seabed. They could be seen in the animation of the data but were quickly mixed up with other data points and would have needed a major re-write of the software to pursue further. However, if they are real tracks, they do support the hypothesis of the click source being a mobile species. More work to investigate these tracks by manually examining the extent of the tracks by associating amplitude and spectral content of the clicks may prove fruitful.

The use of a five hydrophone array was also investigated and the simulation work suggests that such a system is more robust to errors in the velocity of sound. However, the effects of errors introduced by low sample rates and by uncertainties in hydrophone positions have not been investigated. Provided such an investigation gives positive results the use of a five hydrophone array is recommended for future use.

Once all the clearly erroneous click locations have been eliminated there will still remain points which are false The results obtained are presented in Chapter 7, but the reader is cautioned that without further considerable work the results may be misleading since some species' clicks may have been lost and the locations for a significant percentage of the clicks may be incorrect to an unknown degree of error. However, the test data shown in Section 4.6 does give some confidence that sufficient good data is available for the results to be useful within the scope of this project.

9.8 What is making the clicks?

It was hoped that the acoustic work would provide sufficiently accurate localisation information to allow cameras to film the click production in action. Despite many hours of video recording not a single click event has been identified. Cameras have been deployed on single, double and quadruple hydrophones systems and also on stand-alone mounts, yet no click events have been identified. An improved camera system which gave good synchronisation between audio and video and with good quality audio would have helped this investigation.

The four hydrophone results clearly suggest that in late summer the majority of the clicks are coming from a mobile species that may associate with the presence of the hydrophones and which are located a few tens of centimetres above the sea bed. This is a very good match for the behaviour of the sand smelt, which are present in the Fleet in large numbers and which are frequently seen on the video cameras on the acoustic equipment doing exactly as described above. Yet careful study of the video does not reveal any action that could be associated with a click. Perhaps the click originates during swimming. They are often seen to swim slowly for a while, then suddenly speed up for a short time. Perhaps the action necessary to generate that high speed also generates a click. If this click comes from a cavitation bubble then perhaps the waveform will be very similar to that from a snapping shrimp.

Against the sand smelt hypothesis is that they tend to congregate around the equipment after deployment when the seabed has been disturbed and they can be seen feeding. With time the feeding stops and the numbers reduce and they are then only seen occasionally but this is not reflected in the number of clicks heard. Perhaps they just move out of the field of view of the cameras, or perhaps the clicks are not coming from the sand smelt.

The only other species of fish seen in large numbers by the cameras are the gobies. Three species are common in the Fleet, but they are all bottom dwellers. They live in, on or very close to the sea bed. They have been seen on every deployment of the acoustic equipment. The literature search found that they can make a low frequency thump as part of their mating behaviour (e.g. Malavasi et al. (2009)), but there has been no suggestion of a click sound, and there were no sounds heard from the captive animals held in an aquarium.

The weight of evidence resulting from this project suggests that:

- Type A clicks may come from snapping shrimp buried within the seabed. They will not be seen on camera, may give arrival time delay data in the four element array that cannot be processed and are present all year round. A variation of the type A click may be from a mobile species, most probably a small fish such as a sand smelt.
- Type B clicks come from a number of species, some are present in the Fleet in small numbers all year round while others appear during summer and autumn. These are mostly, but perhaps not all, mobile species.
- Type C clicks come from a number of small species found in pools and shallow water. They have a range of centre frequencies, 5 kHz to 20 kHz were observed, suggesting they may come from a range of different sizes of animal. They are most likely species which are sessile or have limited mobility.

There may be an alternative explanation of why the click production has not been seen by the cameras. That is that the production of many of the clicks may be by an animal too small to be seen by the cameras. Many animals within the order Amphipoda are very small, yet many have the asymmetric gnathopods similar to the snapping shrimps. No information could be found on sound production by the Amphipoda, but it must be a possibility, and their small size would explain the lack of video evidence. Against this hypothesis is that it is difficult to see how such a small animal could produce a loud click with the frequency range extending below 1 kHz. It is more likely that they may produce some of the Type C clicks observed. This area may be worth pursuing in future work.

9.9 Suggested future work

The following is suggested as a way forward to identify the source of the clicks.

An improved automated click detector and classifier is needed to allow fully automated assessment of click activity while rejecting non-biological clicks. The single hydrophone survey data collection method needs to be more tightly controlled to allow reliable assessment of click activity at multiple sites. Better supporting data is needed.

An improved two hydrophone data collection system combined with live video and real-time processed data presented to the operator would allow more habitats to be explored and opens up the possibility of searching for click activity by moving the system while watching the processed data and video. If hand portable this could be used as a direction-finder to try and locate a click source. The addition of one or more hydrophones would minimise possible ambiguities.

Improve the three-dimensional localisation equipment by using five hydrophones with increased hydrophone spacing and better handling methods allowing deployments in a variety of seabed types and water depths. Real-time data processing combined with cameras controlled in pan, tilt and zoom should optimise the chances of locating a click source.

Investigate the possible tracks seen from both the two hydrophone and four hydrophone data. The data can be manually searched for such click trains associated by amplitude and spectral content to explore the full extent of tracks rather than just the clicks that pass the data processing test requirements.

Conduct further studies of captive animals in aquaria or rockpools to try and identify the source of the clicks. Extending the holding time may allow the animals to settle and may encourage click production. Using an established facility where the animals are held long-term may also be better.

Chapter 10

Conclusions

This work set out to investigate the characteristics and source of a clicking sound of biological origin which can be heard over large parts of UK shallow waters. It was hoped to be able to identify at least some of the click producing organisms. While it has failed to identify the main source of the clicks it has provided a better understanding of the temporal and spatial distribution of the clicks and their characteristics. Three main types of click were identified.

Across the UK it has shown that there is little activity along the north-east coast from Humber to Shetland with most activity along the south coast of England, Ireland and around the Welsh coast. Along the Dorset coast it has identified high activity areas at Swanage, Weymouth Harbour and Portland Harbour and also identified very low activity areas in Weymouth Bay and Poole Bay.

Attempts to localise the clicks down to a few metres were successful. They showed that in the main study area in the Fleet that in late summer most of the click activity was in the main channel, that there was little activity over the sandflats and that a local wreck did not attract significant numbers of the species making the clicks.

The temporal survey work showed that the click activity was highest during daylight hours, but that a low level of activity continued through the night. It also demonstrated that the activity was at a low level through the winter and spring but increased through the summer peaking in September then dropping quite quickly in late autumn to reach winter level by mid-December.

It was not possible to positively identify any species generating a click but it is believed that snapping shrimp and small fish, particularly sand smelt, do contribute to the click field. There may also be a contribution from some members of the Amphipoda.

Recommendations have been made for future work to establish the identity of the clicking species and these are:

- An automated click detector and classifier combined with improved data collection methods to allow reliable assessment of click activity
- Improved two dimensional data collection system allowing live video and real-time processed data to be presented to the operator
- Improved three-dimensional localisation equipment using five hydrophones, increased hydrophone spacing and better handling methods allowing deployments in a variety of water depths
- Further studies of captive animals in aquaria or rockpools to try and identify the source of the clicks

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Appendix A: *Alpheus* spp findings

This appendix lists the finds of *Alpheus macrocheles* and *Alpheus ruber* (synonym *Alpheus glaber*) around the coasts of the UK and Eire. Figure 2.3 is reproduced here and the data used in its preparation shown tabulated below.

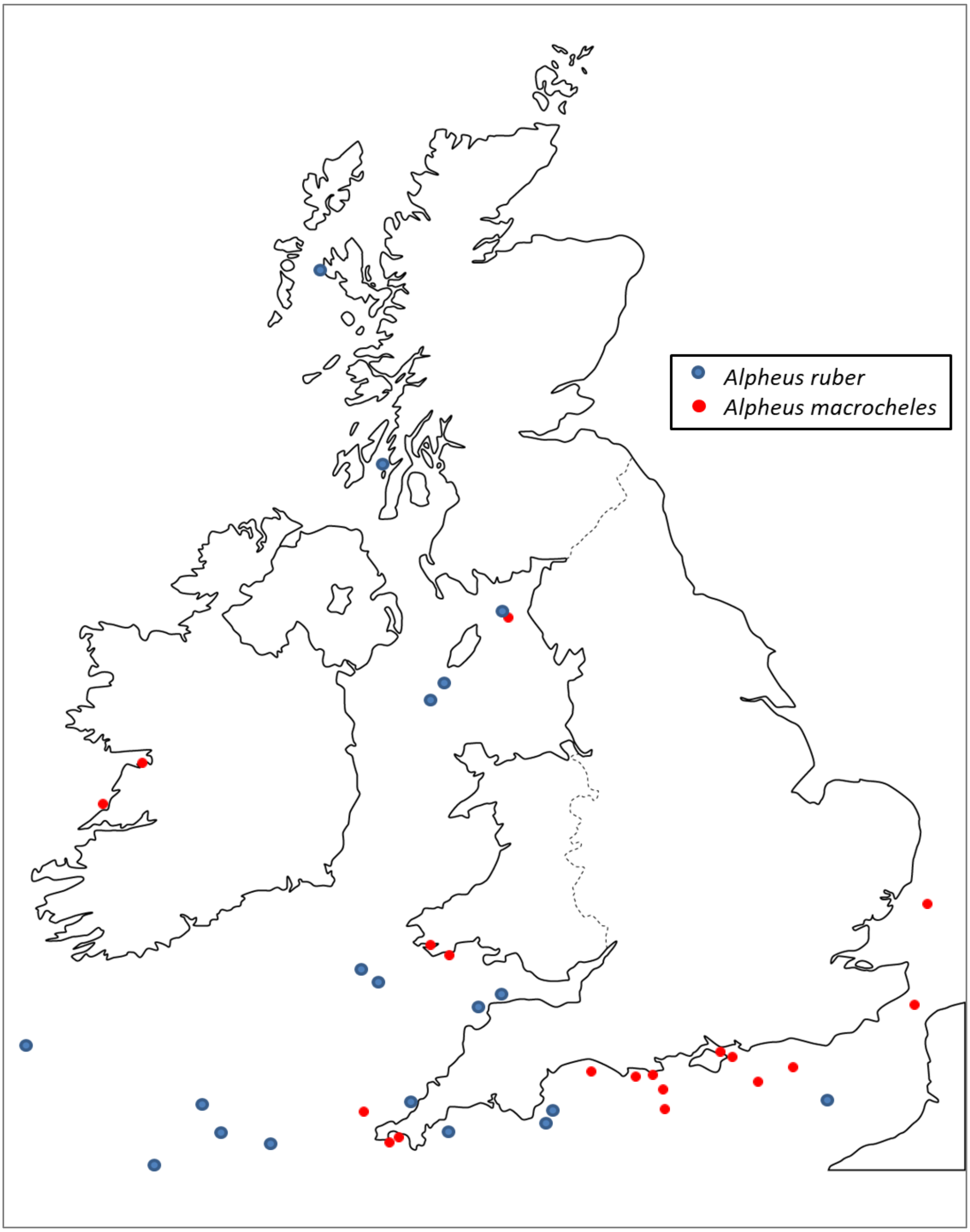

Figure A.1 Alpheus finds in UK and Irish waters

Alpheidae findings

The table below shows the locations where the two Alpheidae species have been found in UK and Irish waters. Where the precise species is not clear they are shown as *Alpheus* sp. Where the number of animals found is not given it is shown as 1.

Table A. 1 Locations of Alpheidae findings in UK and Irish waters

Species	Number	Place	Source
A. ruber	2	Hele Bay, Barnstaple, Devon	National Biodiversity Network atlas. nbn.org.uk
A. ruber	5	6 m off SW tip of IOM	
A. ruber	1	Loch Dunvegan, Skye	
A. ruber	1	Loch Sween, Kintyre	
A. ruber	2	Cheyne Beach, Ilfracombe	
A. ruber	5	SW Approaches	Ocean Biographic Information System iobis.org
A. ruber	3	Off Start Point, Devon	
A. ruber	1	Off Heysham, Lancs	
A. ruber	1	Off Milford Haven, W. Wales	
A. ruber	1	Off S. Cornwall	
A. ruber	1	Mid Channel, S of Beachy Head	
A. ruber	1	Off N Ireland	
A. macrocheles	1	Off Folkestone, Kent	Global Biodiversity Information Facility www.gbif.org
A. macrocheles	2	Kimmeridge Bay, Dorset	
A. macrocheles	1	Bembridge, IoW	
A. macrocheles	1	Off Folkestone	
A. macrocheles	1	S of Swanage, Dorset	
A. macrocheles	1	Weymouth Bay	
A. macrocheles	1	Off Felixstowe	
A. macrocheles	1	Off Brighton	
A. macrocheles	2	South of Bognor Regis	
A. macrocheles	1	Sandy Haven, Pembroke	
A. macrocheles	5	Off Pendeen Watch, Cornwall	
A. macrocheles	1	Off Ryde, IoW	
A. macrocheles	1	Doughmore Bay, Eire	
A. ruber	1	N. Cornwall, 50 32N, 5 21W	
A. macrocheles	1	Lydstep Haven, Tenby, Wales	www.Ispotnature.org

A. macrocheles	60	Kimmeridge Bay, Dorset	Torpedo, April 2010 (see Note 1)
A. macrocheles	1	Bembridge Ledges, IoW	www.flickr.com
A. macrocheles	2	Kimmeridge Bay, Dorset	Personal Observation
A. macrocheles	1	Dog Leg Reef, off Lyme Regis, Dorset	Seasearch survey (see Note 2)
A. macrocheles	>1	Auginish Shoal, Galway Bay, Eire	Linane, 2003 (see Note 3)
Alpheus sp.	2	2 m south of Pendennis Point, Cornwall	Daily Telegraph, 29th July 2017
Alpheus sp.	1	Marazion, Cornwall	www.cornwalls.co.uk/photos/snapping-shrimp-alpheidae-4369.htm

Notes:

1. Torpedo is the marine life news bulletin of the British Marine Life Study Society and can be found at www.glaucus.org.uk/Torpedo2.htm.

2. Wood,C. Seasearch surveys in Lyme Bay, June 2007. A report by Seasearch to Natural England, 2007. (Available from www.publications.naturalengland.org.uk/file/188304)

3. Linnane,A.,Ball,B.,Munday,B.,Browne,R.,Mercer,J.P. Faunal description of an Irish cobble site using airlift suction sampling. Proceedings of the Royal Irish Academy, 103B,1, p41-48. 2003.

Appendix B: Survey locations

This appendix lists the locations visited during the spatial survey. Table B.1 shows the locations included in the UK-wide survey while Table B.2 shows the locations used for the Dorset-wide survey.

Table B.2 UK-wide survey locations

Place	Date	Count	Seabed	Notes
West of Sanday, Orkney	Multiple samples throughout 2010	0	Rock	Drifting and deployed hydrophones
West of Mainland, Orkney		0	Rock and sand	Deployed hydrophone and sonobuoy
Scapa Flow, Orkney		0	Sand, stones, mud	Deployed hydrophone and seabed recorder
Cromarty Firth entrance channel	Continuous data March-September 2014	0	Mud	Data from seabed recorders and deployed hydrophones
Cromarty Firth, Nigg quayside		0	Mud, rock, debris	Cabled seabed hydrophone
Firth of Forth	6/5/2009	0	Rock, sand, gravel	Multiple sites around Inchcolm Island
Whitby Harbour	21/2/2009	0	Mud and debris	Two sites on north side of the harbour
South side of Humber	20/2/2009	0	Soft mud	One site near mouth of the Trent
Cowes Harbour, IOW	26/9/2008	High	Mud, debris	One site on west side of the harbour
Yarmouth Harbour, IOW	11/9/2008	Low	Mud, sand	Three sites around harbour
Swanage Pier	28/9/2007	High	Sand, debris	South side of outer pier
Weymouth Stone Pier	Multiple visits throughout the year	High	Rock, sand, debris	North side of outer pier
West Bay Harbour	31/5/2007	Low	Sand, mud	Two sites on east side of harbour

Exmouth Harbour	30/9/2009	Low	Mud	One site. Area recently re-developed for housing
Exmouth Quay	30/9/2009	High	Mud, sand, debris	One site on fish quay
Mylor Yacht Marina, Cornwall	23/6/2009	High	Mud and debris	Three sites on pontoons
Porthleven Harbour, Cornwall	21/6/2009	0	Rock, mud debris	Two sites on west side of harbour
Penzance Harbour, Cornwall	22/6/2009	Low	Mud and debris	One site in inner harbour
Lough Hyne, SW Eire	Not known	High	Mud and rock	Pers. Comm with A.D. Hawkins
Holyhead Harbour, Anglesey, N. Wales	2003 and later	High	Sand, mud, debris	From Coates et al, 2012. Clicks heard on breakwater and reefs
Heysham, Lancs	May 2005	0	Soft mud	One site on North side of harbour

Notes for UK-wide data

Although collected by the author, the extensive data sets from the Orkney Islands and Cromarty are owned by SNH. Access to the Orkney data was by permission from the European Marine Energy Centre, Stromness, Orkney. Access to the Cromarty data was by permission of Ecofish Ltd, Motherwell, Scotland.

The Lough Hyne data was obtained by personal communication with A. Hawkins who has an extensive dataset obtained as part of his work studying fish acoustics.

The Anglesey data was published in a conference paper in 2012 (see (Coates et al., 2012)). It is included here as an important data point in the survey coverage.

Survey locations

Table B.3 Dorset-wide survey locations

Place	Date	Count	Seabed	Notes
Poole Bay	Several occasions during 2007-2010	High	Various	Drifting with deployed hydrophone. Clicking is patchy
Poole Quay Boat Haven		Low	Rock breakwater, Mud	Single site on pontoons
RNLI College quay, Poole		Low	Steel piling, mud, debris	Single site at western end of fencing
Round Island Channel, Poole		0	Soft mud	Deployed hydrophone. Seal present every visit
Brownsea Island East Pier	15/9/2010	High	Sand, gravel, mud	Single site on east side of pier
Handfast Point	Several occasions during 2007-2010	High	Sand, debris	Anchored for up to an hour with deployed hydrophone on north side of point
Swanage Pier	28/9/2007	High	Wood pier, sand, debris	Single site on south side of pier
Durlston Bay	Many occasions 1997-2010	High	Rock, sand	Cabled seabed hydrophone and deployed hydrophone
Durlston Head	Several occasions during 2007-2010	High	Rock, sand	Drifting with deployed hydrophone
Man o War Bay, Lulworth	10/9/2007	High	Sand, stones, kelp	Two sites. Handheld hydrophone while wading in 1 metre deep water
Ringstead Bay	6/9/2007	High	Pebbles, stones	Single site near western end of reef as it meets the shore
Bowleaze Cove pier	7/8/2007	0	Concrete pier, sand	Single site

Weymouth Bay	7/8/2008	0	Sand	Single site, 2 hours listening
Weymouth Pleasure Pier	Many occasions throughout the project	Low	Wooden quay, sand seabed	Several sites around outer jetty
Weymouth Stone Pier		High	Stone quay, rocks, sand, mud	Single site on eastern side of pier
Weymouth Inner Harbour		Low	Stone quay, mud seabed	Many sites around eastern side of inner harbour
Portland Harbour North Breakwater	30/11/2003	High	Boulders over sand and mud	Single site near Vernon building on Northern Arm
Fleet link channel	Numerous occasions	High	Mud, sand, pebbles, debris	
Castletown Pier	Numerous occasions	High	Mud, stones, debris	Single site on end of ferry jetty
East of Portland Bill	27/5/2007	High	Rock, sand	Single site. Deployed hydrophone while drifting
West Bay Harbour	31/5/2007 22/8/2016	Low	Sand, mud	Two sites on east of harbour

Notes for Dorset-wide survey locations

The Castletown pier has since been demolished

The various sites in Poole Bay were covered while drifting with a deployed hydrophone at 4 metres depth. These showed that click activity was patchy and peaked over areas of mixed seabed.