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The density and behaviour of marine mammals in tidal rapids

Sea Mammal Research Unit
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1 Executive Summary

Harbour porpoises (*Phocoena phocoena*) are one of Europe's most common cetaceans and they are protected under European law. The current expansion of the tidal energy industry has highlighted concerns about anthropogenic activity in tidal habitats, particularly whether deployed turbines may pose a collision risk to animals. However, the ecological significance of tidal habitats for harbour porpoise is poorly understood and little data exists to inform on the potential risk that tidal turbines may pose. One key metric that needs to be measured to inform on this risk is the depth distribution of animals, for example, if harbour porpoises spend the majority of their time at the surface in tidal habitats then collision risk with deeper turbines will be very low. This report details the results of a three year project to develop, test and survey with a system capable of accurately determining the position of harbour porpoises underwater.

Determining the dive depths of animals is difficult. Tags are a possibility, however, there are no tagging programmes in the UK and the likelihood any one tagged animal would spend a significant time in tidal areas may be small. Passive acoustic monitoring (PAM) is a methodology which can detect the presence, classify the species and localise the position of animals, by listening to their vocalisations. Harbour porpoise use high frequency echolocation clicks almost continually for orientation, prey detection, navigation and social interactions, making them ideal candidates for studies using PAM. However, in order to achieve the accurate underwater tracking required to determine a depth distribution, a large dispersed array of multiple underwater receivers (hydrophones) is required.

Deploying such an array in a tidal habitat is difficult. Fixed structures would be inordinately expensive to deploy in areas with up to 8.5 knots of current and therefore a drifting hydrophone array was developed. The array consisted of 10-12 hydrophones, deployed between 3-45m underwater, from a small research vessel. The practical considerations for such a system are numerous; the array must be quickly recoverable and deployable, any movement underwater must be measured precisely and the delicate electronics used must be sufficiently rugged to remain operational in the particularly harsh environmental conditions present in tidal rips.

In addition to these considerations there are general issues with PAM. Porpoise have narrow beam profiles and hence are easy to miss if facing away from the hydrophone array. Noise and multiple animals clicking at the same time can also be problematic. Many of these issues were overcome by utilising new localisation and tracking methods developed during the project, however, difficulties remain in the fact that usually only fragments of tracks, rather than entire dive profiles, are detected. For the purposes of determining a depth distribution this information is adequate. However, it makes studies on the fine scale behaviour of animals more challenging.

Six tidal sites were surveyed over three years. Over 8514GB and 234 hours of data were collected resulting in 5210 tracks of animals. These were used to create depth distributions for each dive site. Two sites, Corryvreckan/the Great Race and Kyle Rhea contained by far the highest number of detected porpoise vocalisations per hour. Both sites are comparatively deep and porpoises had remarkably similar depth distributions during the day with animals spending 75% of time in the upper 38-40m of the water column. Kyle Rhea was the only site surveyed at night and showed a shift in the depth distribution, with animals spending more time in shallow waters.

The data summarised here provide the first substantial general dataset on porpoise depth distributions and underwater behaviour in tidal rapids. Given that virtually no data existed before, the data presented here can be used to improve collision risk estimates. However, the variation between sites evident in this dataset emphasises the importance of collecting data on a site by site basis.

The continual development of hardware, open source accessible software and PAM localisation methods during this project mean that a methodology now exists to determine depth distributions of harbour porpoises in tidal sites. However, this only forms a subset of the data required to inform on

the ecological significance of such an area. Further work needs to focus on combining fine scale tracking of animals with visual/acoustic surveys and long term data recorders.

2 Abbreviations and definitions

POL	The probability that an array will localise an animal at different depths.
χ^2	In the context of this report, χ^2 is a measure of how well the expected time delays for an animal at a certain position correspond to the actual observed time delays. It is therefore an indication of how realistic a localisation result is.
Cluster Array	The small array placed at the back of the research vessel containing 4 closely spaced hydrophones.
CTD profile	Conductivity, temperature and depth profile. A series of measurements of salinity, temperature and depth of a water column.
Geo-referenced	A point with a latitude, longitude and depth, rather than a point relative to an hydrophone array, e.g. (x,y,z) m from array.
Large Aperture Array	A hydrophone array in which the maximum spacing between hydrophone is on the order of 1/10 of the intended localisation range.
NBHF	Narrowband high frequency.
PAM	Passive acoustic monitoring.
POL	Probability of localisation.
TOADs	Time of arrival differences.
Track fragments	A section of an animal’s dive track. This term is specifically used as entire dives of animals were rarely recorded.
Vertical Array	The large aperture section of the array consisting of a weighted rope with 6-8 hydrophones attached.

3 Introduction

In recent years the rapid expansion of marine renewables in Scotland has highlighted concerns about anthropogenic activity in marine habitats, especially in areas which have so far been exposed to little or no major industrial activity. Tidal habitats, in particular, are often remote areas which generate large amounts of untapped energy, but comparatively little is known about their ecological significance, especially in relation to marine mammals. Extracting energy from these sites requires the deployment of one or more underwater tidal energy devices. These often take the form of an underwater turbine with tidal flow rotating two or more blades. The tip speeds of such blades can reach up to 12ms-1 which poses a potential risk of injury to fish, birds and marine mammals (Wilson, 2007). The focus of this report is on the most common UK marine mammal, the harbour porpoise; how they use tidal habitats and how their underwater behaviour may affect collision risk.

At many temperate European and North American tidal sites harbour porpoises are the most commonly encountered marine mammal species (Hammond *et al*., 1995). To predict their potential risk of collision with tidal turbines and determine the ecological importance of tidal habitats requires knowledge of the absolute density and distribution of harbour porpoises along with an understanding of their diving behaviour and underwater movements. An understanding of the fine scale movements of animals can be used to determine the likelihood that any one animal will encounter a turbine during a dive. Combined with density estimates this can then be scaled to determine how many porpoises might encounter a turbine blade over a period of time. In addition to collision risk, density estimates and fine scale underwater movements, along with an understanding of acoustic behaviour, can provide important information on how animals utilise tidal areas, in particular whether these are important foraging sites.

Harbour porpoises are small, shy and often difficult to detect visually in all but the calmest of sea states. This makes any visual study of animals particularly difficult in tidal areas where fast moving currents can produce significantly higher sea states than in surrounding areas. However, harbour porpoise are highly vocal animals that use uniquely identifiable high frequency bio sonar, six times above human hearing range, to sense their surroundings and hunt for prey (Verfuß *et al.*, 2009). The high frequency narrow bandwidth ‘clicks’ of porpoise can be detected on specialised hydrophones and data acquisition systems. The advantages of this methodology, referred to as passive acoustic monitoring (PAM), are numerous and well documented, however, for tidal areas the main advantage of PAM systems is that they are relatively unaffected by sea state, can detect animals underwater, not just at the surface and can be used just as effectively at night

Traditional line transect surveys are therefore greatly enhanced by utilising passive acoustic monitoring systems, typically a stereo towed hydrophone array. Combing visual and PAM allows for more accurate density estimation and such techniques have been successfully used in Welsh tidal areas; one such site registered one of the highest harbour porpoise densities recorded (Gordon *et al*., 2011). There are still issues in tidal rapids with towed arrays being pushed off survey tracks by currents and more development is needed to create more specialised systems for tidal habitats. Many of these issues and further development trajectories are detailed in Macaulay *et al*., (2015). However, the present report focuses on the fine scale movements of harbour porpoises underwater, something which neither visual nor traditional towed hydrophone arrays can measure.

Determining porpoise dive depth and underwater behaviour in tidal rapid sites is challenging. Telemetry using tagging is difficult with this species and has so far only been successful at locations (such as the Bay of Fundy and the Baltic) where fixed fishing traps result in the entrapment of wild porpoises. At some of these sites telemetry packages are applied to porpoises as part of a release program and several groups have had success with both satellite telemetry and archival devices (Westgate *et al*., 1995; Linnenschmidt *et al*., 2013). There are no fisheries that catch live porpoises close to most areas with strong tidal currents. In addition, tidal rapids are such a small proportion of the total available habitat for harbour porpoises that it is very unlikely that any particular tagged individual would spend a significant proportion of time in such areas of interest. For these reasons it was important to devise a system that could detect and track animals within a specified area. PAM provides the ideal basis to track animals in a specific area, but traditional towed systems or static data loggers cannot provide the kind of fine scale information required to calculate animal tracks.

Widely spaced or large aperture hydrophone arrays have been used for decades to track the movements of cetaceans underwater (Watkins & Schevill, 1972; Wahlberg *et al*., 2001; Ura *et al*., 2006; Miller & Dawson, 2009). By analysing the time of arrival differences between a vocalisation detected on multiple distributed hydrophones, it is possible to determine the position of the vocalising animal. Some attempts have been made to use such systems to determine locations of harbour porpoises, primarily to determine the range to animals for source level measurements (Villadsgaard *et al*., 2007; Kyhn *et al*., 2013), however, most have only been able to track animals to a few tens of metres. To determine animal locations to the order of a few hundreds of metres, a much larger array and number of hydrophones is needed. In addition, most of the above studies have required manually marking or validating vocalisations to determine the time of arrival difference of clicks on different hydrophones and in this study over 234 hours of data recorded on 6 to 12 hydrophones were collected. Manually marking out porpoise vocalisations from such a data set would take one person just under 3 working years so automatic detection, classification and localisation algorithms were developed to analyse the 8514GB of data collected.

In this report the data presented were collected over three years at six different tidal sites using a drifting wide aperture hydrophone array. Details on how a large hydrophone array can be practically deployed in tidal rapids are discussed along with how to analyse the vast quantities of acoustic data collected on such a system. Over 850,000 porpoise vocalisations were detected, resulting in 94106 localisation measurements and 5210 3D geo referenced animal tracks. These were used to produce porpoise dive depth distributions at the six different tidal sites, providing the first information on underwater behaviour in tidal rapids which could be used to inform collision risk models for turbines in such areas. More importantly, the methodology can be applied in the future to collect relevant data at specific development sites.

4 Methods and field work

4.1 Hydrophone array design

Strong and unpredictable currents, rough sea states and rapid changes in bathymetry make deploying any hydrophone array in a tidal habitat a particularly challenging problem. An ideal hydrophone array, capable of determining the precise positions of animals, would consist of at least four hydrophones, distributed evenly in three dimensions on a fixed structure with the exact position of each hydrophone known precisely. The spacing between the hydrophones must be large enough to provide an accurate localisation, a rule of thumb suggesting around 1/10th of the required range for accurate positions, but also spaced sufficiently close so that individual vocalisations are coherently picked up on multiple elements. Harbour porpoises (Koblitz *et al*., 2012) and dolphins (Finneran *et al*., 2014) have highly directional vocalisations hence a large number of hydrophone elements is desirable to increase the probability that an animal will ensonify sufficient hydrophones for localisation to be achieved.

In a tidal area, any hydrophone array with a large number of widely spaced elements spread evenly in three dimensions would require either a large fixed structure on the sea bed or a complex rigid frame deployed from a vessel. Fixing any large structure on the sea bed with water speeds exceeding 8 knots requires a large investment in boat time and technology, and poses significant technical problems in getting data to shore and in addressing water flow noise. A rigid drifting system is equally difficult, as any structure will be on the order of tens of metres and has to be capable of being both rapidly deployed and recovered. A large vessel would thus be required which is both expensive and usually impractical for narrow tidal races.

A hydrophone array deployed in tidal rapids must therefore be a compromise between practicality and an optimal design for accurately tracking animals. One solution is a flexible heavily weighted vertical array of hydrophones deployed from a drifting vessel. Such an array consists of an inelastic rope with multiple hydrophones attached and a substantial weight to hold it steady in the water column. It can be deployed and recovered quickly by using a winch, allowing a drifting vessel to safely traverse tidal rapids. However, the flexible nature of the array also poses several problems. Even a large weight does not prevent the array from moving underwater due to strong differential currents, wind against tide or the boat rocking in waves, producing a pendulum-like effect on the rope (Macaulay, 2010). Any such movement poses two substantial problems. The first is that the positions of the hydrophone elements are not known precisely. Any error in the positions of hydrophone elements propagates into substantial error in the localised positions of animals. The second is slightly more abstract. A linear vertical hydrophone array can only provide the depth and range of a sound source (in this case the porpoise). This can be visualised as an animal being located anywhere on a circle centred on and perpendicular to the array. The radius of the circle is the range to the animal and the depth of the circle is the depth of the animal. If the array begins to move off a vertical angle then the circle also moves and changes angle, with one end moving downwards and the other moving upwards. This introduces a large ambiguity in depth that is impossible to resolve and thus any vertical array must remain almost completely vertical to provide useful information on animal diving behaviour; even a 2^o change in angle results in a depth error of 5m at 100m. A flexible array in strong currents is usually subject to substantial movement and hence a vertical array on its own cannot provide accurate information on animal diving behaviour, even if the array's position underwater can measured. These issues can be resolved with the addition of a 'cluster' of four hydrophones rigidly fixed to the boat, and depth and orientation sensors to measure the angle and orientation of the vertical array. The closely spaced cluster, based on tetrahedral array system used by Yack *et al*., (2013) and Datta *et al*., (2010) can provide a 3D bearing to the animal and orientation sensors allow for the movement of the vertical array to be precisely modelled, enabling correction of the depth estimate error. Intuitively the cluster can be visualised as producing a 3D bearing to an animal which intersects the circle of possible locations produced by the vertical array, allowing the full 3D location of an animal to be determined. Hence if a vertical array begins to sit at an angle, it is known at what point on the circle the animal is located, removing any fundamental ambiguity in depth and range. This is not to say that the locations are error free but instead that the cluster overcomes theoretical limitations of linear arrays that are not precisely vertical in the water column.

4.2 Hardware

4.2.1 Hydrophone Array

Taking into consideration the practical and theoretical considerations discussed above, a hydrophone array was designed consisting of vertical array with 4-8 hydrophones that could be deployed in several different configurations depending on water depth together with a cluster of four hydrophones, each separated by 50cm, deployed rigidly at the back of the vessel. All hydrophones were Magrec HPO3 with a sensitivity of ~-201 dB re 1V/µPa @150kHz. The exact spacing between hydrophones varied slightly over the three survey years due to ongoing developments; however, the overall design remained the same. A deep water extension to allow for deeper diving animals to be more readily detected was used in 2014, adding two more hydrophones and increasing the overall length of the array to ~45m.

A chain weighing 80kg was used to weight the vertical array (Figure 1). This was lowered and recovered using a winch and dedicated lifting rope, allowing hydrophones to be lifted out of the water by hand and preventing any damage to the sensitive hydrophone elements.

In order to obtain geo-referenced acoustic localisation, the exact position and 3D orientation of the vessel and the vertical array has to be known accurately. An IS-2-30 inclinometer was used to measure pitch and role and a Hemisphere vs100 GPS deployed to measure the precise heading, latitude and longitude of the vessel. Inertial measurement units were attached to the vertical array in order to measure movement and orientation. In 2012, this consisted of a mobile phone attached above the sea surface however, in 2013/14 between 2 and 5 Loggerhead Open Tag™ with integrated depth and temperature sensors were attached to the vertical array at different depths. These recorded data from 3 axis magnetometers, accelerometers and gyroscopes every 0.01 seconds and temperature/pressure every second.

Porpoise vocalisations are narrow band and high frequency and therefore require specialised signal conditioning and data acquisition systems to record acoustic data. In 2012 and 2013 signals were conditioned and amplified using a 4 channel custom ETEC and 2 channel HP27 amplifiers. In addition to providing gain these also applied a 20kHz high pass filter. Signals were digitised using synchronised NI 6356 and 6352 DAQ cards. In 2014 data were conditioned, amplified and digitised using three synchronised SAIL DAQ cards. In all surveys PAMGUARD (Gillespie *et al*., 2008) was used as the primary recording software and acoustic data from each hydrophone were sampled at 500kS/s.

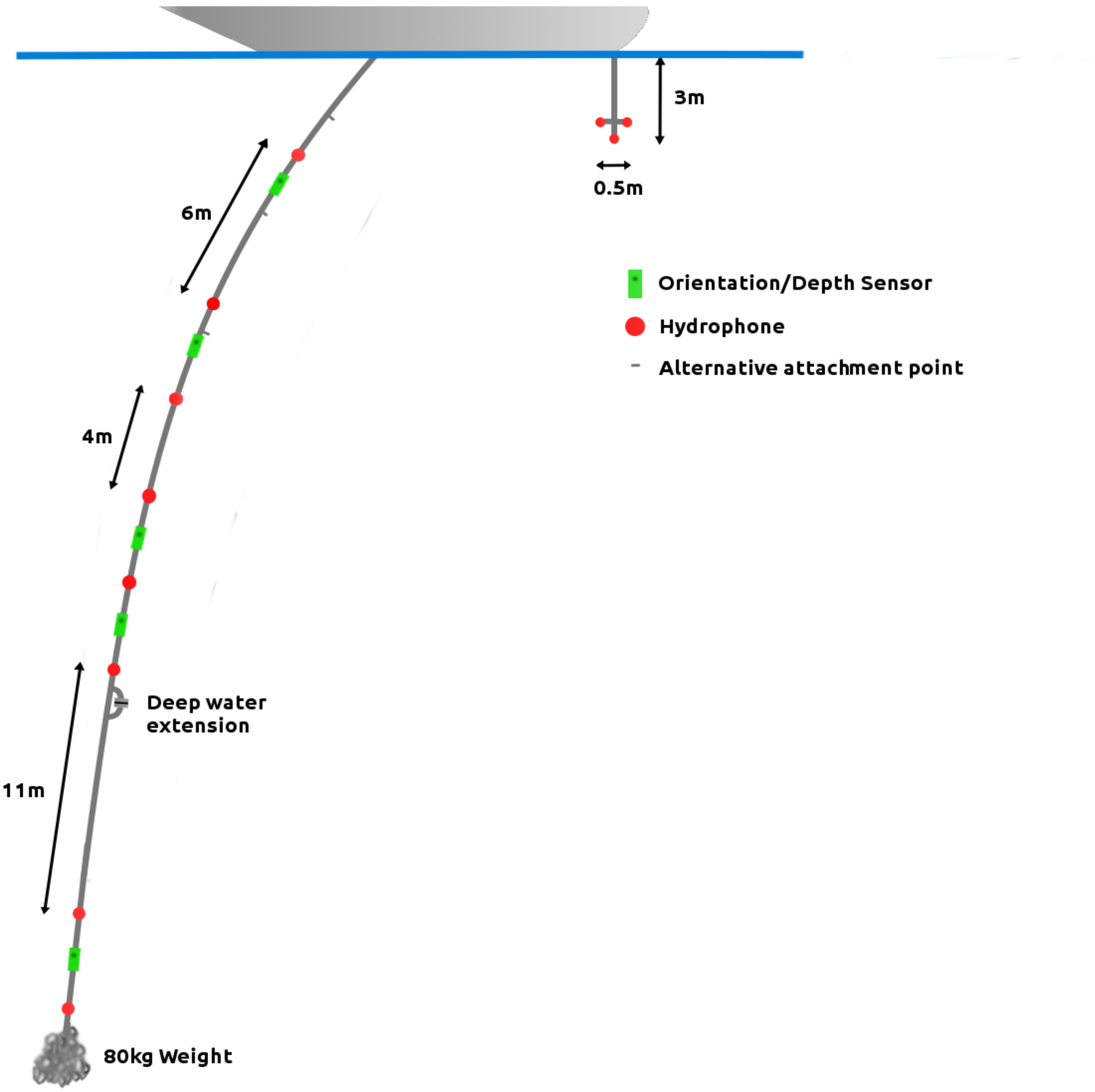

Figure 1. Diagram of the hydrophone array used roughly to scale. The array consisted of a vertical component and a small rigid cluster deployed at the back of the research vessel. A deep water extension was added in 2014 to help detect animals at greater depths.

4.2.2 Pinger system

To test the accuracy of each type of array a sound source capable of broadcasting simulated porpoise click signals was constructed. A custom MATLAB script was used to produce a single channel .wav file containing a burst of 25 porpoise clicks. This was output through an NI 6252 DAQ card using PAMGUARD. The signal was amplified by a Sony XPLOD amp and then output through a Neptune Sonar HS150 hydrophone, used as transducer, on a 30m cable. The system could be operated from a small inflatable boat that could then drift at different ranges from the array while the deployment depth of the transducer was adjusted. An Aladdin dive computer and Loggerhead Instruments Open Tag™ were used to record the depth of the output hydrophone and a GPS used to record the position of the vessel carrying the 'pinger' system.

4.3 Research Vessels

The research vessel used during the 2012 field season was the *Ruby May*, a 12 metre fiberglass motor catamaran shown in Figure 2. This vessel was chosen because she provided a useful dry working space for electronic equipment, a crane capable of deploying the large weight needed for the hydrophone array, and suitable maximum speed to travel quickly between different tidal sites.

Figure 2. The Ruby May, used in the 2012 field season.

During the 2013 and 2014 field seasons the *Silurian*, a motor sailing vessel, was used (Figure 3). This vessel is much slower than the *Ruby May*, however, it has room for researchers to live aboard (and to work at night), space for electronics and suitable attachment points for both the vertical and cluster array.

Figure 3. The *Silurain*, used in the 2013 and 2014 field seasons.

4.4 Acoustic analysis

4.4.1 Detecting porpoise clicks

Over 8.5 terabytes, equating to over 234 hours, of acoustic data were collected over the three seasons and 41 days at sea. Although there were a few isolated issues with equipment failure the vast majority of data consists of high quality calibrated recordings without significant engine or electrical noise.

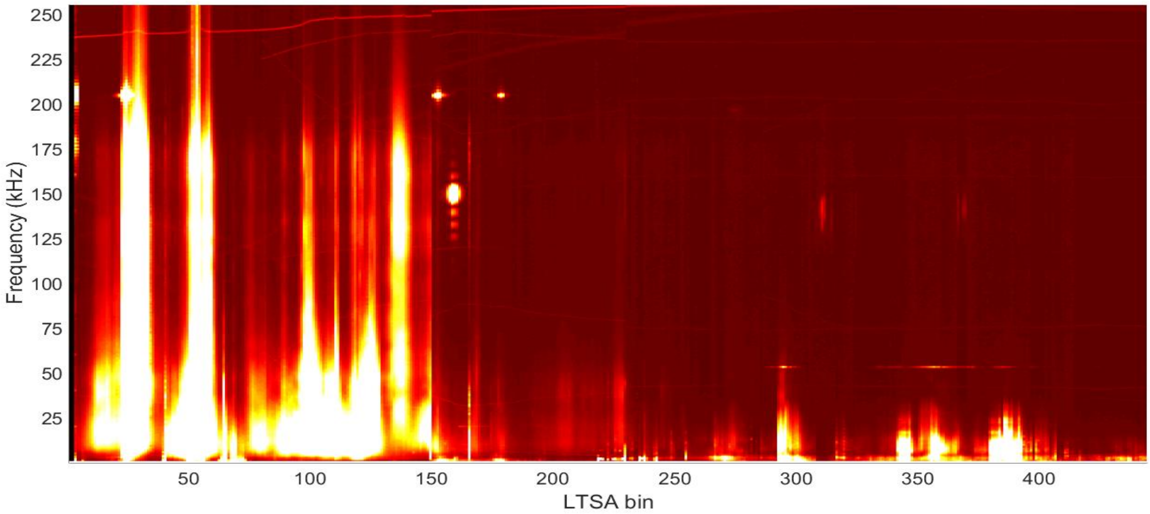

Figure 4. Long term spectral (average over 4 hours) in the Sound of Islay. The first 1.5 hours contains significant sediment noise which extends to the porpoise frequency band, masking the acoustic detection of animals present. This is the worst example of tidal noise experienced over the six study sites.

4.4.1.1 Noise

Noise affects the detection efficiency of any PAM system and it has been observed that sediment movement and rough sea states can produce significant high frequency noise in tidal areas (Gordon *et al*., 2011). The recordings show that most noise in the areas studied was well below the porpoise frequency. However, in some areas, most notably the Sound of Islay, isolated areas produced high frequency noise severely compromising the detection of porpoise clicks as shown in Figure 4.

Other sources of high frequency noise were anthropogenic. Tourist boats, yachts, fish farm vessels and fishing boats all pass through tidal areas, producing varying degrees of noise in the porpoise frequency band from both engines (specifically propeller cavitation) and echo sounders. Powerful outboard engines are particularly noisy at high frequencies making porpoise detection unlikely if any vessel is passing nearby.

Porpoises produce narrow band high frequency clicks centred at around 130kHz (Villadsgaard *et al*., 2007). A typical click waveform and its spectrum are shown in Figure 5.

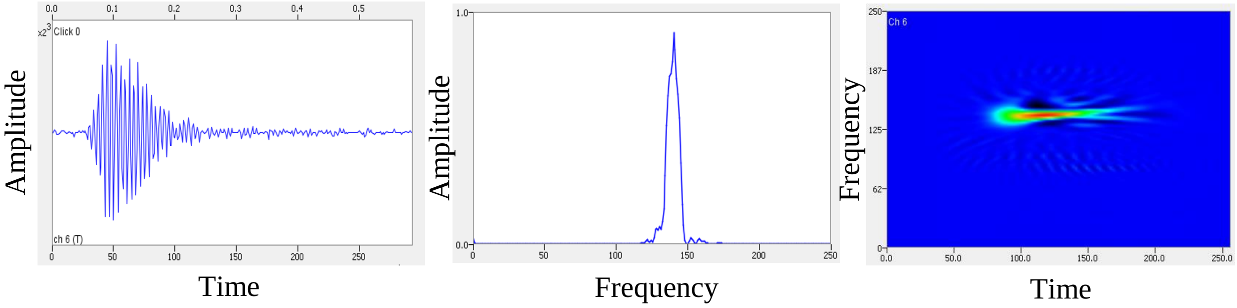

Figure 5. A typical porpoise click (a) waveform, (b) spectrum and (c) Wigner plot. Porpoise produce short click-like vocalisations and do not whistle. Clicks are high frequency, centred around 130 kHz and are very narrow band compared to most toothed whales.

Due to the volume of data collected and the high vocalisation rates of harbour porpoises the use of an automatic click detector was essential. In this instance the PAMGUARD click detector was run separately for each channel of data. This begins by looking specifically at the porpoise frequency band, between 100kHz and 150kHz, then compares two averaging filters, one which responds slowly to changes in sound intensity and the other which responds much more quickly. If the difference between the two filters is greater than the defined threshold a click like sound is detected and a small snippet of the raw waveform saved.

A classifier which measured and compared click parameters such as duration, peak frequency and frequency distribution was then used to determine whether each detected click likely belonged to a porpoise. The clicks classified as belonging to a porpoise were used to localise the positions of animals. (Gillespie *et al*., 2008)

4.4.2 Click detection

4.4.2.1 Localising porpoises on large aperture arrays.

The theoretical process of localising an animal is relatively simple. A porpoise click is detected on multiple hydrophones, the time delays between the clicks’ arrival at different hydrophone is measured and from this a position can be determined, either by direct calculation or using an iterative search algorithm (Wahlberg *et al*., 2001; Thode, 2005). However, in a real environment there are several problems which must be considered, such as the beam profile of a porpoise click and a porpoise’s acoustic behaviour and movement patterns, all which can impact the likelihood of click detection and acoustic localisation.

Perhaps the most significant issue with large aperture arrays is the fact that porpoises and all other echo-locating cetaceans produce highly directional clicks (Au, 1993), rather than a spherically propagating pulse of sound. The bio sonar of a harbour porpoise can be imagined as flashlight, with a porpoise only ensonifying an array when facing a particular subset of directions at different ranges.

Figure 6 shows the simulated beam profile of a harbour porpoise emitting 190dB clicks calculated using data collected from captive porpoises (Koblitz *et al*., 2012) and several assumptions from studies of dolphin beam profiles (Finneran *et al*., 2014). Behind the porpoise almost no acoustic energy is present, with a likely detection range of a few tens of metres at most. However, in front of the porpoise, directly on axis, a click could conceivably be detected around 500m from the animal. In addition, tag data have shown that porpoises occasionally stop vocalising underwater, making detection using any kind of PAM system impossible during these periods (Linnenschmidt *et al*., 2013). This was certainly a rare but present factor in all three field seasons, where animals would occasionally be visually sighted very near and heading towards the research vessel without any corresponding vocalisation detected.

Hence when using large aperture hydrophone arrays it is rare that the entire dive of an animal is ever recorded. Instead track fragments are measured, the sections of a dive during which a porpoise has ensonified a minimum number of hydrophones on the array to allow for localisation. To an extent these fragments can be joined up, however, in many instances large proportions of the dives are missing.

4.4.2.2 Narrowband high frequency (NBHF) clicks

Porpoise clicks are relatively long, narrowband pulses centred around 130kHz. Although this makes clicks relatively easy to identify it can be problematic when determining time delays. The standard technique for determining the time delay between two signals is to use a cross correlation algorithm. This involves sliding one signal past the other and determining a cross correlation value by multiplying both signals together. For a broadband sound this will produce an obvious peak for the time delay at which signals overlap. For a narrowband porpoise click however, large cross correlation values can occur for delays of one or more wave lengths resulting in many peaks in the cross correlation function as shown in Figure 7. This is further complicated by the porpoise beam profile which, as well as altering the amplitude of clicks, also significantly distorts the amplitude envelope depending on the angle between the porpoise and the receiver (Gotz *et al*., 2010). As such it is easy for the highest peak in the cross correlation function to represent the wrong time delay value. Polynomial interpolation is used by PAMGUARD to try and compensate for this. However, it does not help with off-axis clicks. For the purposes of the array, average time delay error was estimated to be one cycle out, equivalent to an error in hydrophone position of ~1cm. Although not significant for the widely spaced elements in the vertical array, it can alter the angle estimation from the cross array by ~2^{o}.

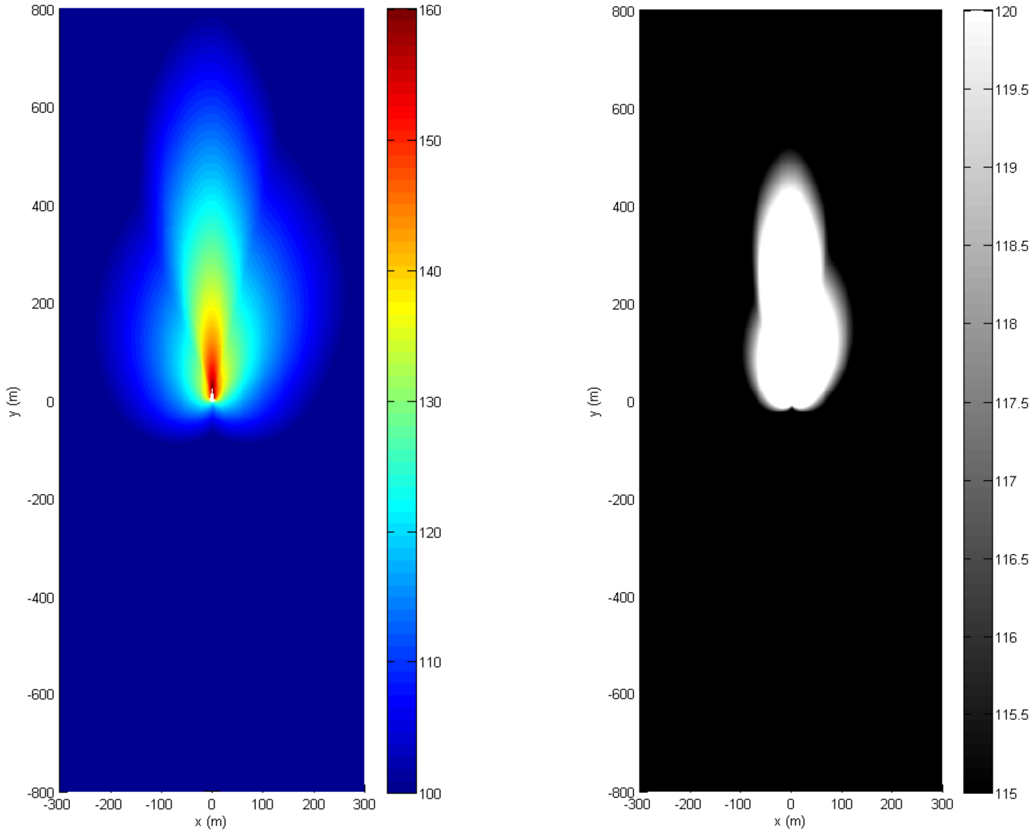

Figure 6. The beam profile of a harbour porpoise with an axis source level of 190dB re 1μPa. The porpoise is orientated facing the top of the graph. In Figure 6a the received level of a click on a hydrophone at any given location around the porpoise is mapped. Figure 6b is a binary representation of Figure 6; it assumes a hydrophone array with a noise floor of 110dB and indicates in white the area in which the porpoise click would be detected.

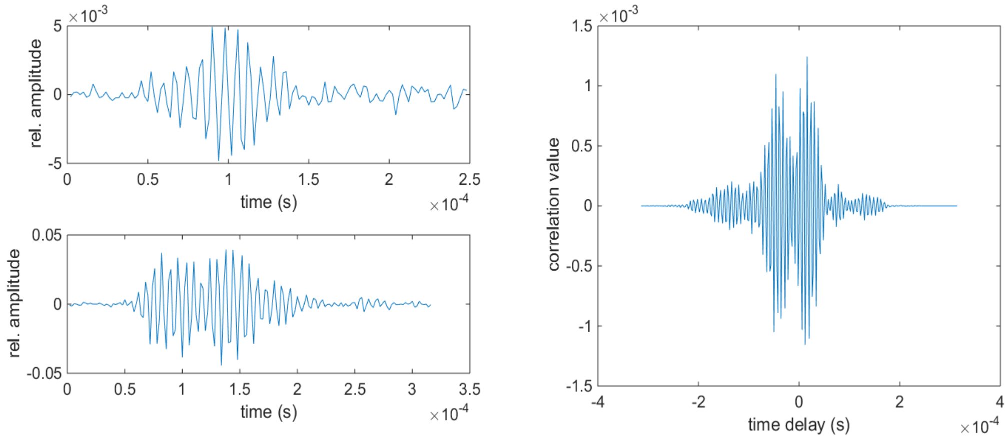

Figure 7. Cross correlation function for between two porpoise clicks detected in Kyle Rhea. The result of the cross correlation function should contain one definite peak. Multiple similar peaks can make determining accurate time delays difficult. Picking the wrong cross peak in this instance would result in a bearing estimation error of 17.5°

4.4.2.3 Sound speed profiles

The speed that sound travels through water is an important parameter in localisation. Standard localisation algorithms assume that sound travels in a straight line and at a constant speed from the position of a source, in this case a harbour porpoise, to each hydrophone in an array. However, changing temperature and salinity with depth can cause significant distortions in sound speed and hence bending of acoustic rays as they travel towards a receiver; such distortions in turn propagate to large errors in the localised positions of animals (Thode, 2005; Ameer & Lillykutty, 2010).

Two approaches can be used to compensate for this. More sophisticated localisation algorithms can use measured temperature, salinity and depth data (CTD profiles) in a study area to compensate for bending of acoustic arrays. However, this can be computationally intensive and requires accurate instruments and extra research time to collect the relevant data. If the variation in sound speed is not too great, a more crude approach is simply to propagate uncertainty in sound speed through localisation algorithms which assume straight line travel.

As tidal waters are likely to be well mixed it was expected that sound speed would be relatively uniform. However, studies in non-tidal areas have shown that ray bending in habitats used by harbour porpoises can be a significant problem, as shown in Danish waters by DeRuiter, (2000) and Figure 8.

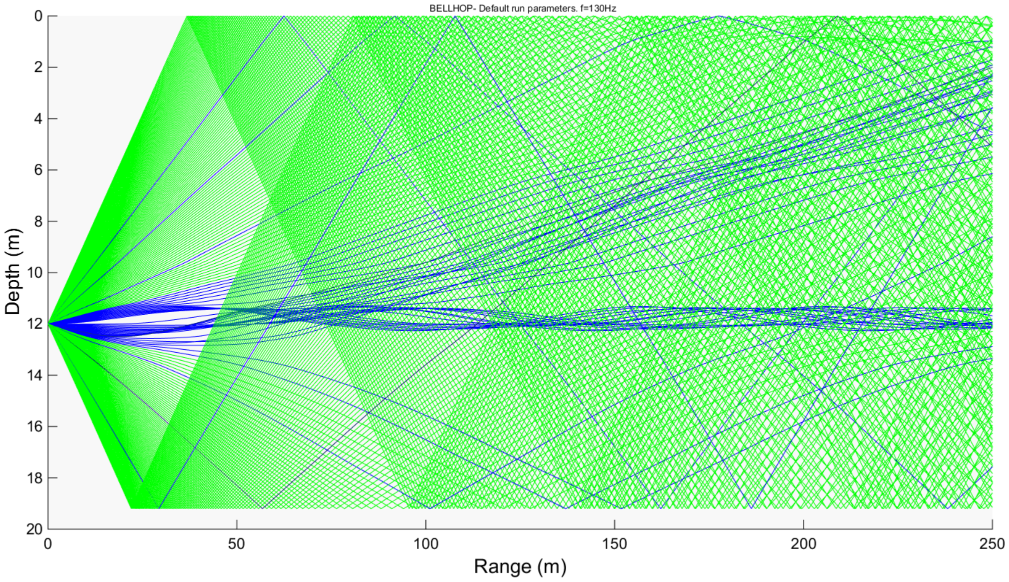

Figure 8. Ray trace diagram of a simulated porpoise click @130kHz using CTDD data collected in Kerteminde, Denmark. The blue lines show sections of the beam are focused due to a waveguide effect introduced by minima in the sound speed profile. Localising such a click would introduce large errors in animal locations.

Therefore archived CTD profiles from BODC (BODC, 2014) were used along with ACTUP software (Duncan, 2014) to get an idea of the potential error in sound speed for all tidal study sites. As expected, all showed that no significant temperature and salinity gradients existed which would affect 120-150 kHz signals; an example is shown in Figure 9. Thus a liberal estimated error of 20ms^{-1} was added to the sound speed for all locations and standard straight line localisation algorithms were utilised.

4.4.2.4 Match uncertainty

For small aperture arrays, the time delay between detections of a vocalisation on different hydrophones is often less than the vocalisation rate of the animal and the delay before an echo. It is therefore relatively easy to match vocalisations on different hydrophones; they are simply those closest in time. However, this assumption does not hold for larger aperture arrays. For example a harbour porpoise has a click rate sometimes exceeding 600 clicks per second (Verfuß *et al.*, 2009). A single click on one hydrophone could therefore have up to six possible corresponding clicks on a hydrophone 15m away with echoes and the other vocalising animals adding to this number. For a species with indistinguishable individual vocalisations, such as a harbour porpoise, it becomes almost impossible to match detections on different hydrophones, a problem termed *match uncertainty*. A simplified example of this is shown in Figure 10.

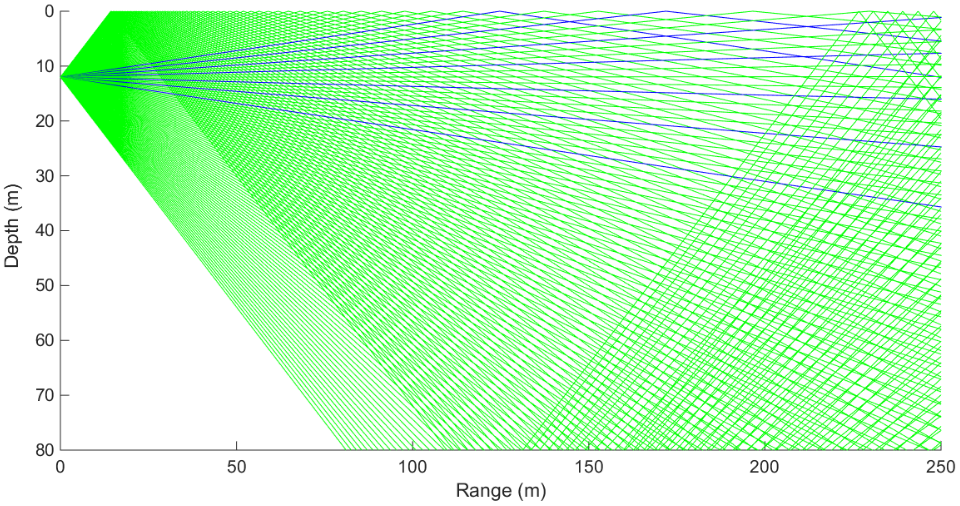

Figure 9. Ray trace diagram of a simulated porpoise @ 130kHz click using CTD data from the BODC archive in the Great Race (56.15817, 5.78467). In this instance no or very little distortion of acoustic rays takes place.

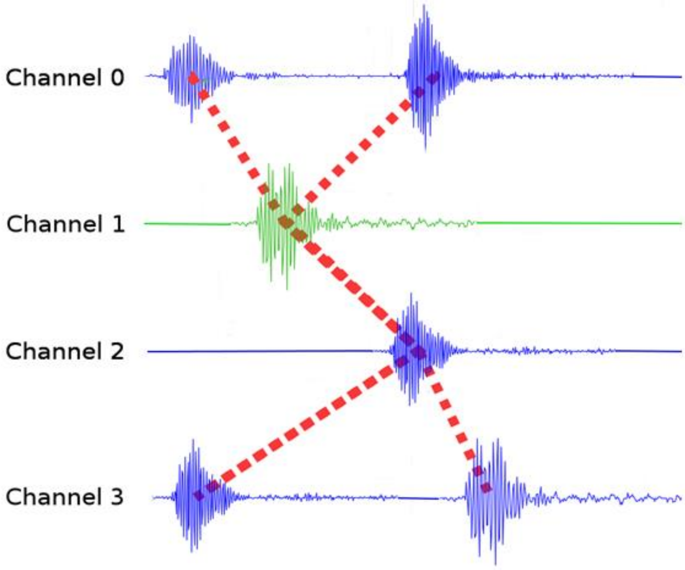

Figure 10. Example of match uncertainty. A detected click on channel 1 (in this example coloured green) should also be detected on channels 0, 2 and 3. As the position of the animal is unknown, to find the same click on another channel it is necessary to look *t* seconds before and after the primary click where *t* is a time related to the distance between hydrophones. In this time window there maybe several clicks detected due to a variety of factors including echoes, high click rates or other vocalising animals. As porpoise clicks from different individuals and echoes are essentially indistinguishable, finding the correct combination of clicks is difficult. One solution is to localise every possible combination, shown here by red dashed lines. Incorrect combinations will either be localised to unrealsitic locations, e.g. above the sea surface, or poorly fit the localisation algorithm used, resulting in a high X^2 value.

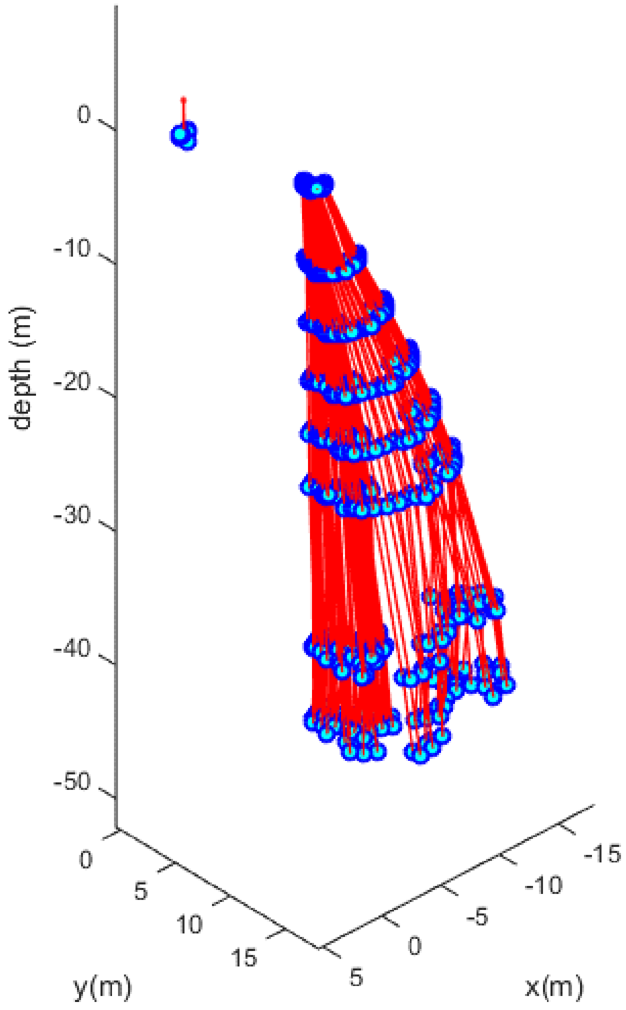

Figure 11. Hydrophone movement over a 5 minute period after deployment and in a strong tidal current in Kyle Rhea. The vertical component moves significantly in the current, necessitating the use of accurate orientation sensors to record the position of the vertical array underwater.

One solution to match uncertainty involved localising all possible combinations of detections. For a vocalisation detected on a specified hydrophone all other possible detections on other hydrophones are determined. This is achieved by detecting all clicks within a time window on each hydrophone (the size of the time window being proportional to the distance between hydrophones). Every possible combination of detections is then mapped and a source position for each calculated. Many of the calculated positions for incorrect combinations will be unrealistic, located above the sea surface or at an improbable range. These are discarded and out of the remaining results the combination with the lowest χ^2 value (best fit to the localisation algorithm) is selected. This method requires a position to be calculated for every combination of time delays. The number of combinations, especially for a 10 channels system can quickly reach the order of thousands and thus fast localisation algorithms are required. In this case, computationally efficient hyperbolic and simplex algorithms were used to find the solutions with lowest χ^2 value. Those likely solutions were then localised with a far more computationally intensive Markov chain Monte Carlo simulation (MCMC), in order to accurately estimate location errors (Gilks, 2005).

Using this method it is possible to localise multiple animals at the same time, discard echoes and deal with rapid vocalisation rates.

4.4.3 Determining array movement

Knowing the positions of hydrophones within an array accurately is essential for accurate localisations and a particularly challenging problem for a dynamically moving array. The position of the rigid cluster array is relatively easy to measure by combining heading data from the vector GPS, and pitch/roll measurements from the IS-2-30 inclinometer. The positions of hydrophones on the vertical array were determined by interpolating between orientations measured by several OpenTag sensors. Each OpenTag sensor measures its heading, pitch and roll every 0.01 seconds. As the position of OpenTags on the vertical array is known, the orientation of the vertical array can be determined by assuming a constant rate of changes in angle between the different OpenTags locations.

Results show the vertical array moves significantly in the current, especially soon after deployment when the array is both settling into position and in the strongest section of the tidal rip, an example of which is shown in Figure 11. However, for much the deployment periods the array remained relatively steady.

4.4.4 Tracking algorithm

A localised click results in a 3D data point: latitude, longitude and depth. Errors in localisation can be introduced at any stage in the localisation process, from badly correlated clicks producing spurious time delays to errors in the hydrophone positions, or echoes being localised instead of directly arriving clicks. Thus the final localisation results need to be filtered. Most spurious results have high χ^2 values and anything above or below the sea bed can be removed. The remaining results then consist of a 3D scatter of animal positions. The number of scatter points in any track fragment is dependent on the animal's vocalisation rate as well as its range from the vessel and orientation. For this reason it is necessary to interpolate track fragments in order to ensure data used for determining depth distributions are not biased.

If only one animal is present this is a relatively straightforward process, simply joining up the dots. In order to deal with any spurious points still present, a Kalman filter can be used; a standard method for such tasks. The Kalman filter essentially uses a measure of the standard deviation in porpoise acceleration to predict where an animal may be, compares that result to real data and then combines both the prediction and the localisation result to create a more sophisticated moving average Kalman, 1960.

However, multiple animals add a layer of complication. Simply joining dots or using a standard Kalman filter will result in interpolation between two different animal tracks and so a more sophisticated process is required. To this end a multi-track Kalman filter technique was developed, inspired by image tracking (Sorensen *et al*., 2008; Macaveiu *et al*., 2014; Dave, 2014).

Localisation data were binned into 0.5 second time periods. Localisation points within each time bin were clustered and the average of each cluster taken to be the position of an animal. A Kalman filter was then started for each cluster. For each Kalman filter the predicted location of the animal was determined for the next time bin. These predictions were then matched to actual locations of animals using a Hungarian assignment algorithm. If a location was found near to the prediction this was used as the next point for the Kalman filter. The process then repeats and moves to the next time bin. For any clusters not matched, a new Kalman filter was started, and any filter which failed to match to any localisation point over a certain number of bins was stopped.

Using this algorithm, it was possible to automatically trace out and interpolate individual dive fragments and deal with spurious localisations with multiple animals present. This type of problem is often referred to as *a pattern recognition* problem, something which humans are particularly good at solving as opposed to computers (Basu & Ho, 2006); further work to improve the algorithm is discussed in section 'Conclusion: Further Work'.

4.4.5 Depth distribution

Interpolated dive tracks can provide the information required to generate a depth distribution. As current methods do not allow for animal density to be calculated from the array, the depth distribution is relative rather than an estimate of the true average number of animals at different depth bins.

Interpolated tracks are sub-sampled (every 0.5 sec) and samples are allocated to 50 depth bins. The number of interpolated track points in each bin then provides information on the relative density of animals in that bin.

However, this assumes that the localisation of animals is equally probable at all points around the array up to its maximum effective range (around 200m). Given the narrow beam profile of harbour porpoise clicks this is highly unlikely. For example, an animal tens of metres under the array will likely only be detected if it is facing upwards towards the array, whilst an animal near the sea surface or within the array depth is likely to be detected whether it's facing upwards or downwards. Thus, depth distributions derived from track fragments may need to be scaled by a function reflecting relative probability of localisation (POL) to depth.

To estimate a POL function, clicks were reanalysed from data collected using the vertical array with an extension in 2014. Usually at least one hydrophone on the cluster array must be ensonified for a localisation to be attempted due to theoretical constraints imposed by moving vertical arrays.. In order to determine a POL, localisation requirements were relaxed to allow a localisation to take place if clicks were detected on as few as three hydrophones within the vertical array, providing a depth and range to an animal (but not a 3D location). For all these localisations using the relaxed criteria, the percentage of clicks detected on the quad array at different depths bins was determined. This was then averaged between all quad array hydrophones. As the standard results require at least one quad array hydrophone to be triggered this was taken as a measure of the relative POL.

Figure 12 summarises these results. As expected the POL decreased with depth. Within the depth of the array, 45m, the POL fell only slightly with depth but then increased rapidly beyond approximately 60m, 15m below the array. From this point the POL would be expected to continue to fall towards zero. One possible explanation is that below this depth the likelihood of detecting anything on the array for an animal diving towards the sea bed is near zero. Thus only surfacing animals or animals which happen to briefly face upwards are detected on the array. Hence the spike may be due to the fact that the majority of animals detected are surfacing and thus are more likely to ensonify the quad array. This is supported by analysis of the distribution of animal orientations between 0-60m and 60-120m (Figure 13). The distribution between 60-120m shows that relatively more porpoises facing the sea surface are detected. Conceding that *'what comes up must go down'*, the percentage of clicks detected on the quad array for depths between 60-120m was divided in two. The resulting POL with depth is more convincing (Figure 14). However there is a 'tail' starting at ~ 75m when it might be expected that the POL should continue approaching zero. This may be due to the sparse number of localised points and hence large error at these depths, or another artefact so far not identified.

It is noted that various assumptions without particularly good evidence have been made here and the accurate calculation of probability of localisation function should be the focus of further work. Nevertheless this gives an initial indication of what a POL might look like and was used to estimate depth distributions below the hydrophone array.

4.4.6 Software used in the analysis.

All acoustic data were analysed in PAMGUARD, a comprehensive open source software suite for PAM. The PAMGUARD click detector was used to detect all transient sounds in the 100-150kHz band. Each detected transient sound was then passed through a click classifier to check whether it was a likely porpoise vocalisation.

A custom MATLAB script, using the LoggerHead OpenTag library, was created to combine data from Open tags, the vector GPS and inclinometer and to calculate a time series of hydrophone positions every 0.25/0.5 seconds in a format suitable for importing into PAMGUARD.

The PAMGUARD multi element array localiser (MEAL) module was then used to localise the position of animals. This module had been developed specifically for this project with Scottish Government support (Macaulay, 2012) and includes algorithms to deal with match uncertainty mentioned above. GPS data, including ship headings were imported using the PAMGUARD GPS module, and the time series of all hydrophone positions was imported using the PAMGUARD Hydrophone Array module. The localiser module was then able to combine GPS data, hydrophone positions and detected clicks to determine the geo-referenced positions of animals.

A tracking algorithm developed in MATLAB was then used to convert localised points into dive fragments. All data plots were created in either MATLAB, Microsoft Excel or GIMP.

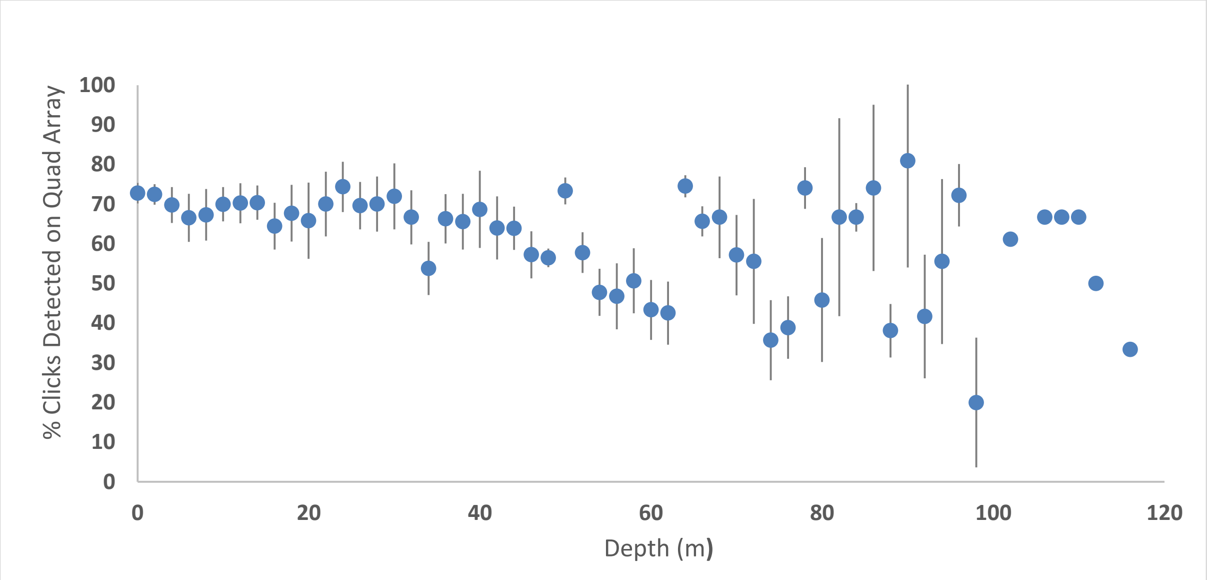

Figure 12. Initial results to determine a probability of localsiation function. Results show the percentage of clicks detected on the 'cluster array' for porpoises localised at different depths on the vertical array using clicks detected on three or more hydrophones. Initially the POL appears linear with depth, but the relationship breaks down at about 60m.

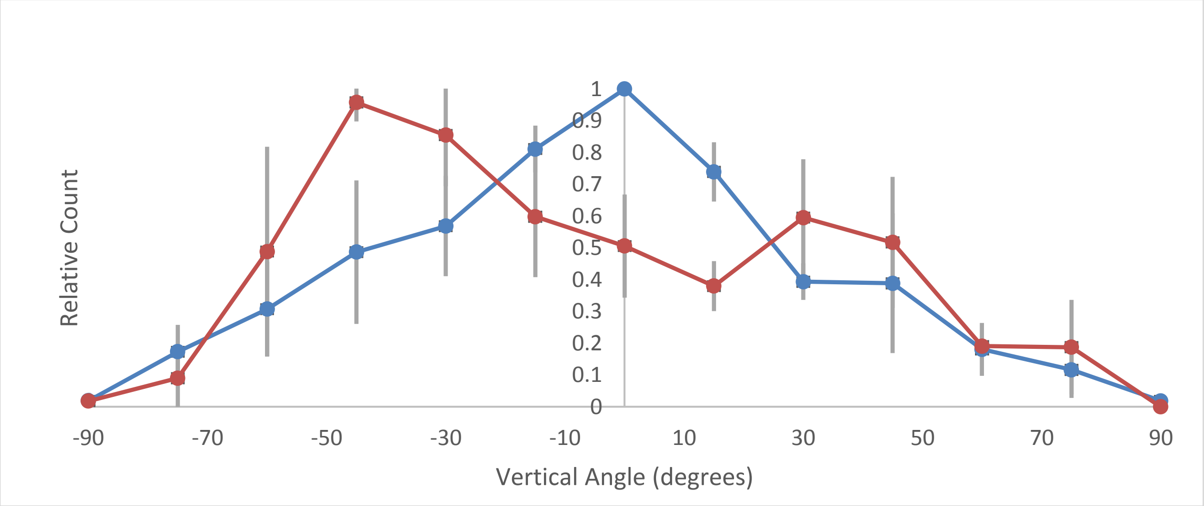

Figure 13. The distribution of porpoise vertical orientations, calculated from interpolated track fragments, for porpoises between 0-60m (blue) and porpoises between 60-120m (red). -90 degrees is the porpoise facing upwards and 90 degrees is the porpoise facing downwards. The distribution of orientations shifts at 60-120m with many more porpoise facing upwards rather than downwards.

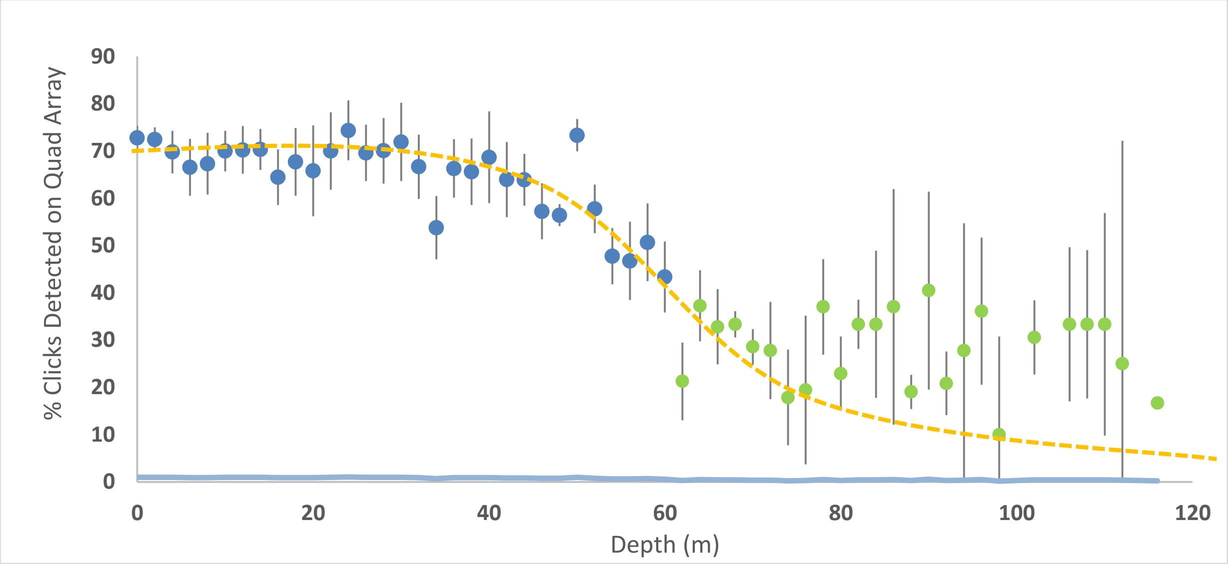

Figure 14. An intial attempt to determine a probability of localisation function with depth. Blue data points are the percentage of clicks detected on the quad array for porpoises localised at different depths. The green data points are the percentage of clicks detected on the quad divided by 2 in order to compensate for the fact that it is likely very few animals are detected diving below the vertical array. The blue line is a smoothed moving average of all data points and was used to compensate for depth distributions for probability of localisation. The dotted orange line is an example of what type of shape might be intuitively expected for a POL indicating that this requires further investigation.

5 Results

5.1 Study area and effort

Six sites were studied with varying degrees of acoustic survey over three field seasons, from 2012 to 2014 (Figure 15). Bathymetry from Digimap, the INIS Hydro survey, and coastline GSHHG (Global Self-consistent, Hierarchical, High-resolution Geography Database), coastline data were used. In Figures 15 to 28 tidal sites are shown with heat maps of both total acoustic effort and the number of clicks detected in area bins divided by acoustic effort.

5.1.1 Studies in 2012

All survey operation in 2012 took place in tidal areas within the Orkney Isles.

5.1.1.1 Sound of Longataing

The Sound of Longataing contains two very shallow inlets in which water from Rousay Sound creates a fast flowing current on the flood tide. The two inlets were too shallow to deploy hydrophone arrays, however, the immediate surrounding area (itself highly tidal), was deep enough for survey operations.

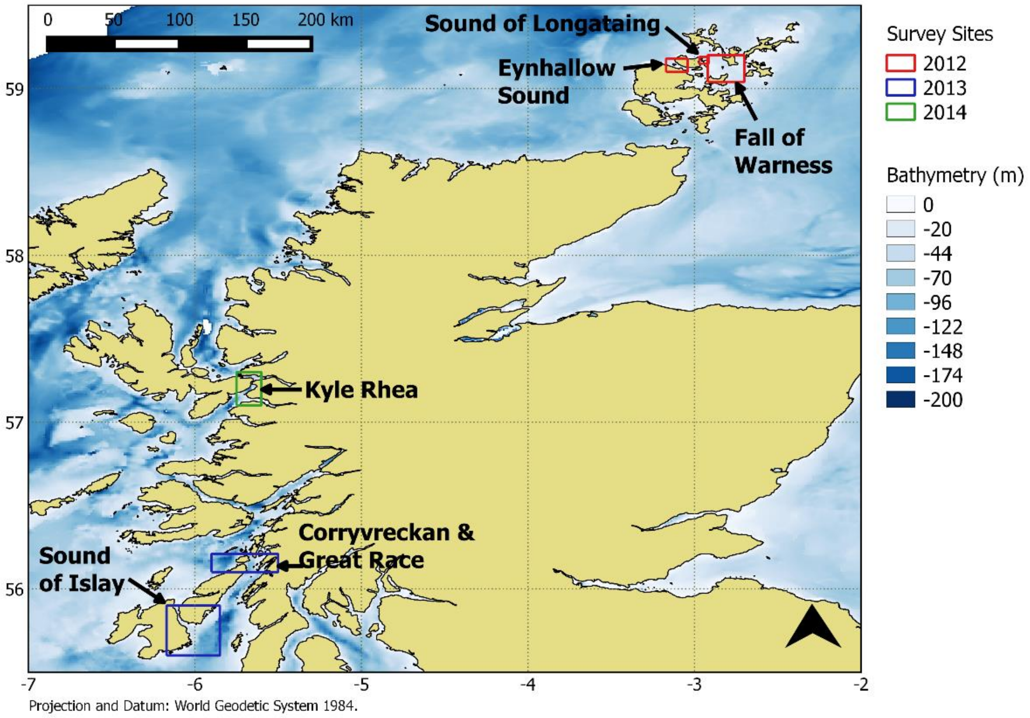

Figure 15. All survey sites between 2012 and 2014.

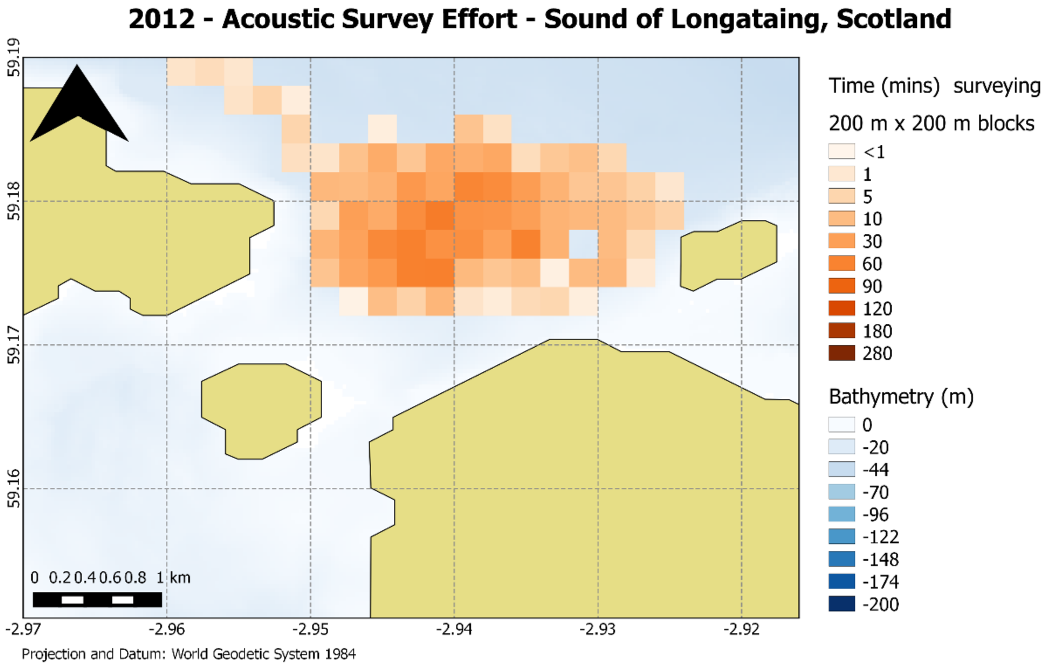

Figure 16. Acoustic effort in the Sound of Longataing. The two small inlets are too shallow to deploy the vertical hydrophone array. However, the immediate area after the inlets is deep enough for survey operations and contains a tidal rip.

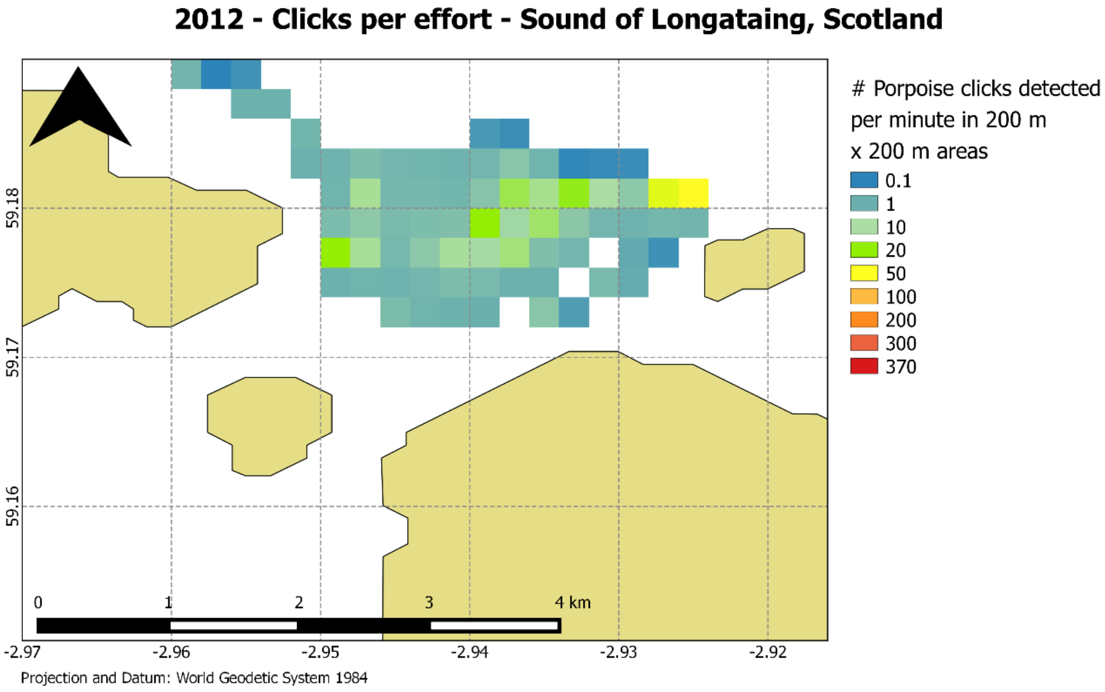

Figure 17. Average number of porpoise clicks detected per minute in the Sound of Longataing. Any area with less than one minute of acoustic effort has been excluded.

5.1.1.2 Fall of Warness

The Fall of Warness sits between the Muckle Green Holm and the south-west side of Eday. Prototype tidal turbines are in operation at these locations, making drifting operations impossible, however, the tidal rips directly to the south, north and west were surveyed.

5.1.1.3 Eynhallow Sound

Eynhallow Sound sits between Rousay and mainland Orkney. The island of Eynhallow is located in the middle of the sound, splitting tidal waters between a shallow reef, the Reef of Burgar, and a deeper but very narrow channel to the north. Both channels were unsuitable for surveys but create large tidal rips to the west of Eynhallow where the majority of survey operations took place.

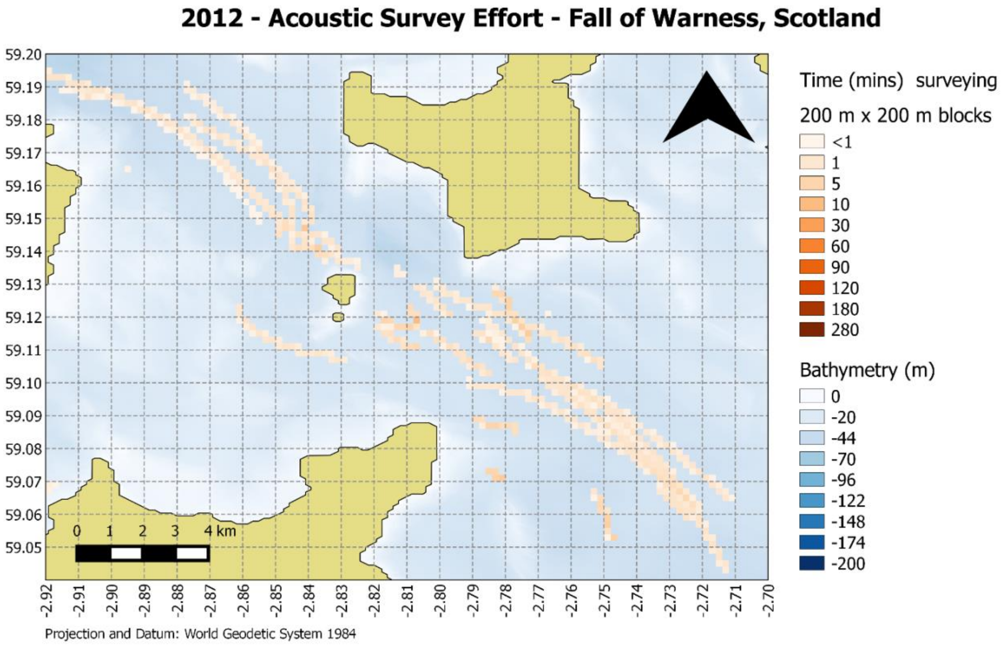

Figure 18. Acoustic effort in the Fall of Warness and surrounding area during the 2012 survey. This is a relatively large geographic area compared to Eynhallow Sound or the Sound of Longataing with much longer drifts taking place.

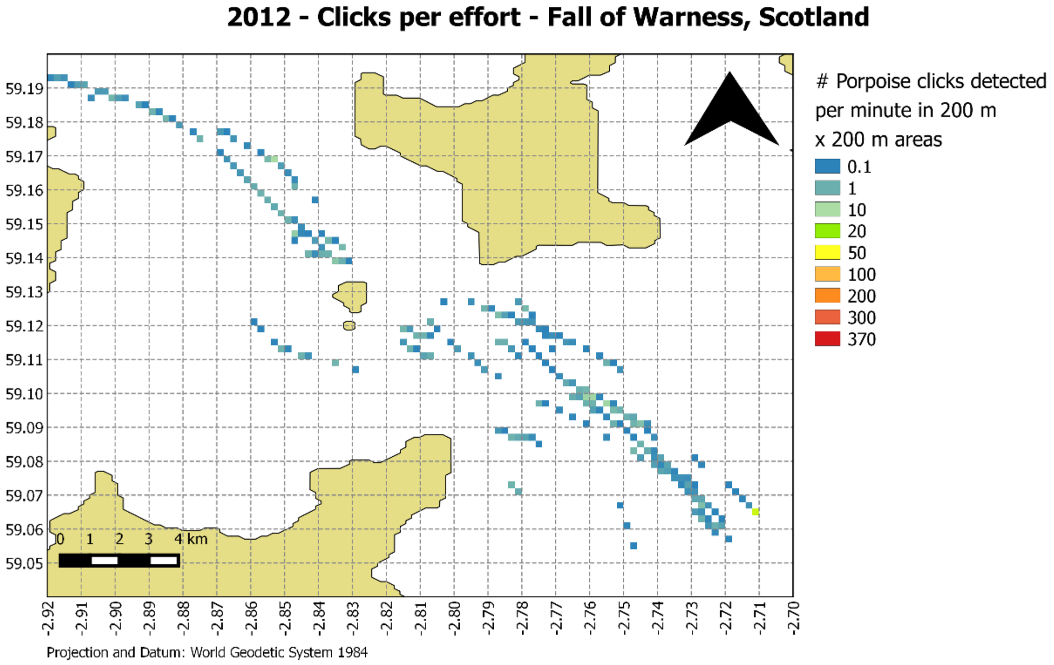

Figure 19. Average number of porpoise clicks detected per minute in the Fall of Warness. Any area with less than one minute of acoustic effort has been excluded. Very few porpoises were detected in this area. Any area with less than one minute of acoustic effort has been excluded.

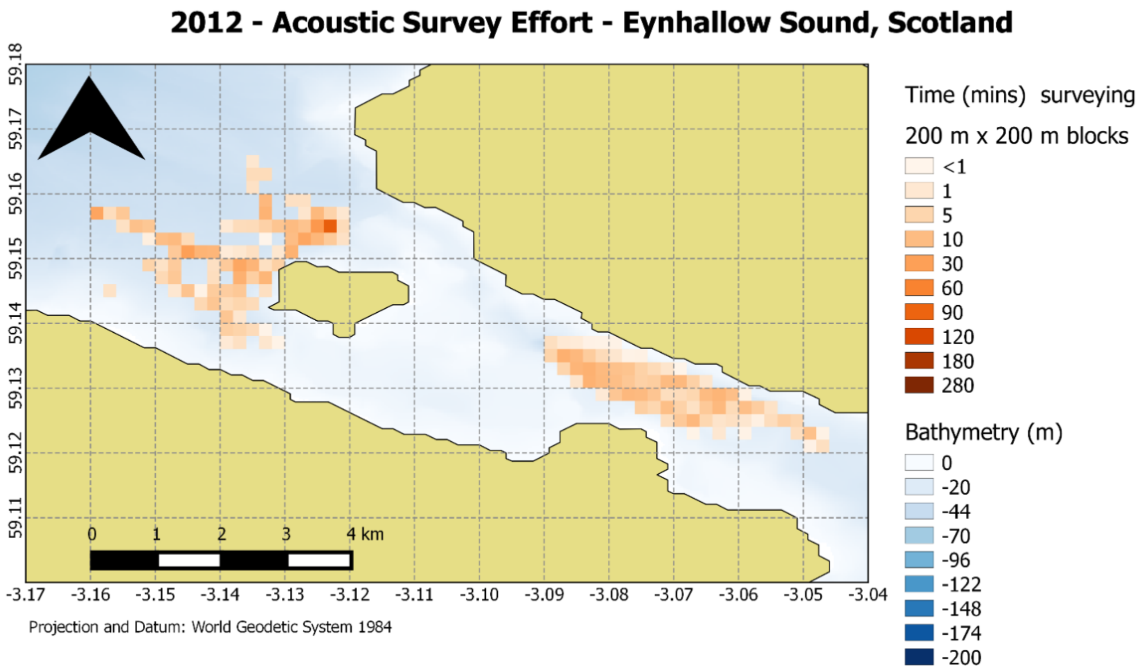

Figure 20. Acoustic effort in Eynhallow sound during the 2012 survey.

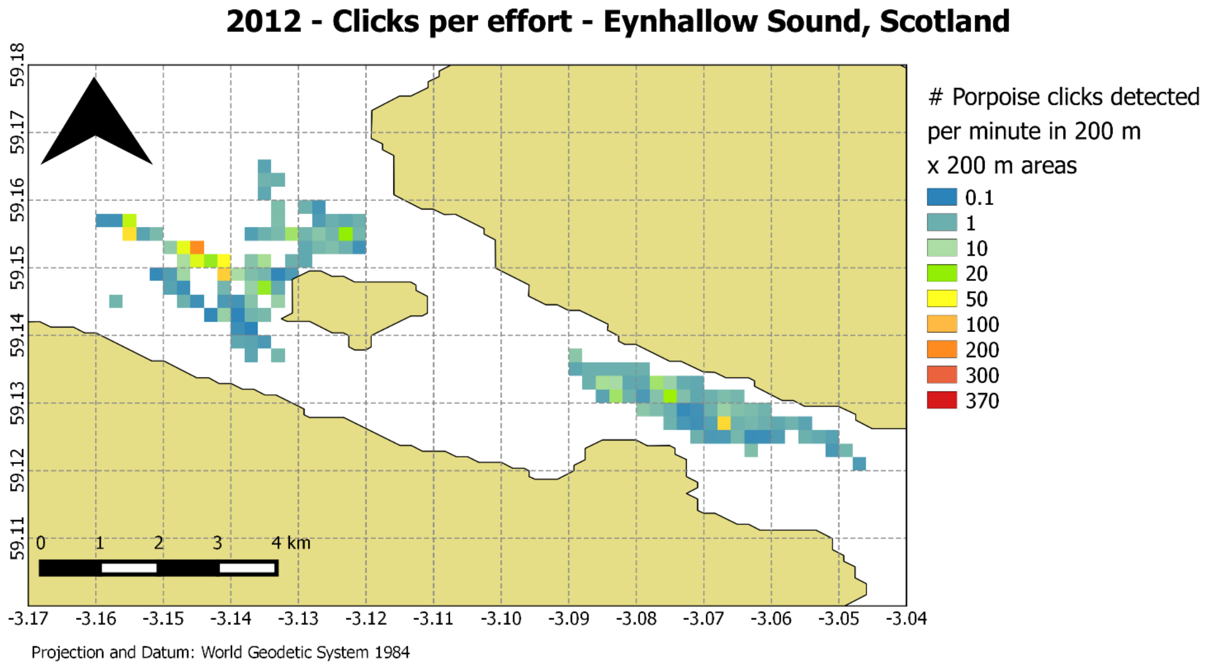

Figure 21. Average number of porpoise clicks detected per minute in Eynhallow Sound. Any area with less than one minute of acoustic effort has been excluded

5.1.2 Studies in 2013

In 2013 survey operations were split between the Sound of Islay and the Great Race/ Corryvreckan.

5.1.2.1 The Great Race, Corryvreckan and Sound of Jura

The Gulf of Corryvreckan is a deep (up to 200m) channel which lies between Scarba and Island of Jura. A large body of water travels through the channel generating a significant tidal race with speeds up to 8.5 knots and resulting, on the flood tide, in a plume of water extending west as shown in Figure 24. This area is named the Great Race. The survey operation was focused in the Great Race with occasional drifts through Corryvreckan and into the Sound of Jura.

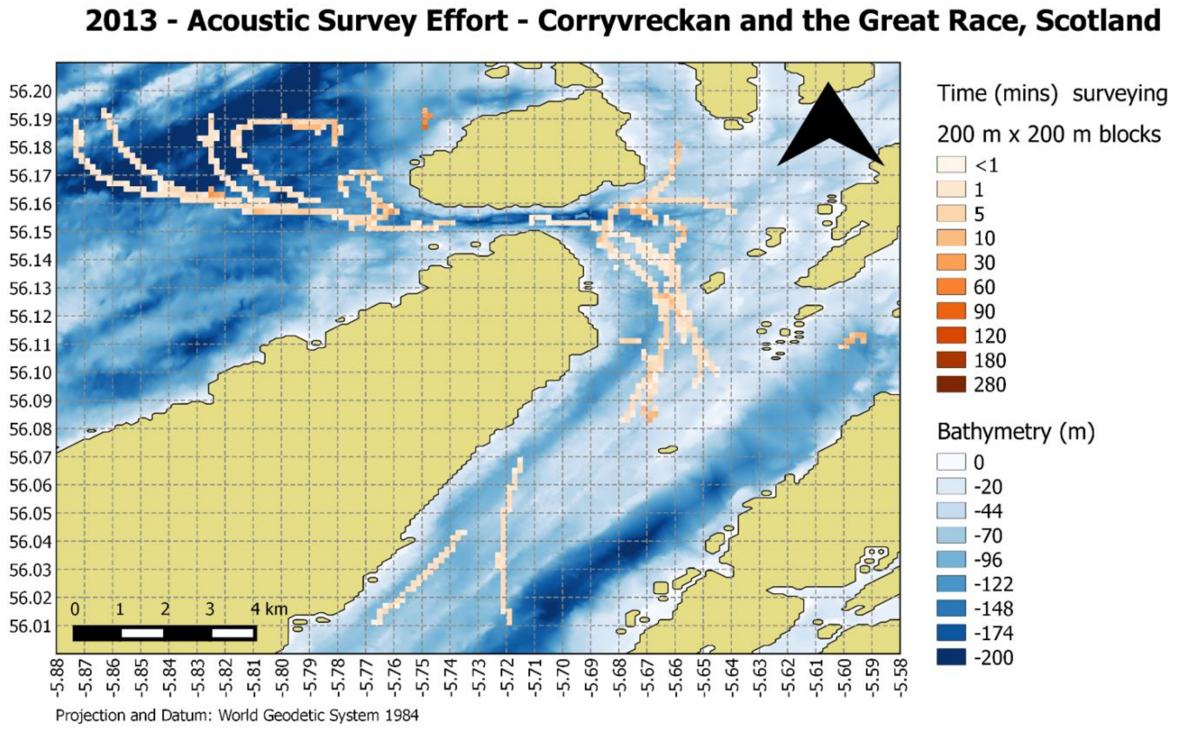

Figure 22 Acoustic effort in The Great Race/Corryvreckan and Sound of Jura during the 2013 survey. Note that this is a relatively large geographic area compared to other sites. Drifts here were generally longer than in other areas.

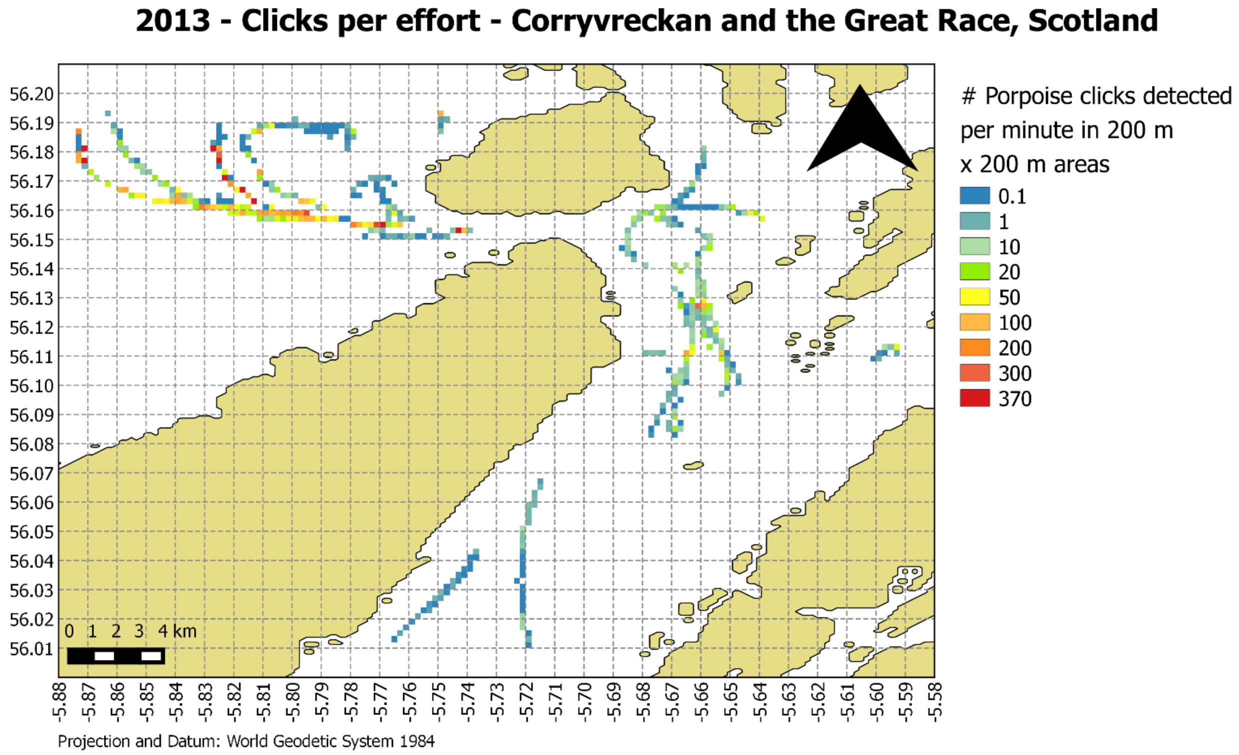

Figure 23. Average number of porpoise clicks detected per minute in the Great Race/ Corryvreckan and Sound of Jura. Significant numbers of porpoises were acoustically detected and visually sighted in the Great Race. Any area with less than one minute of acoustic effort has been excluded.

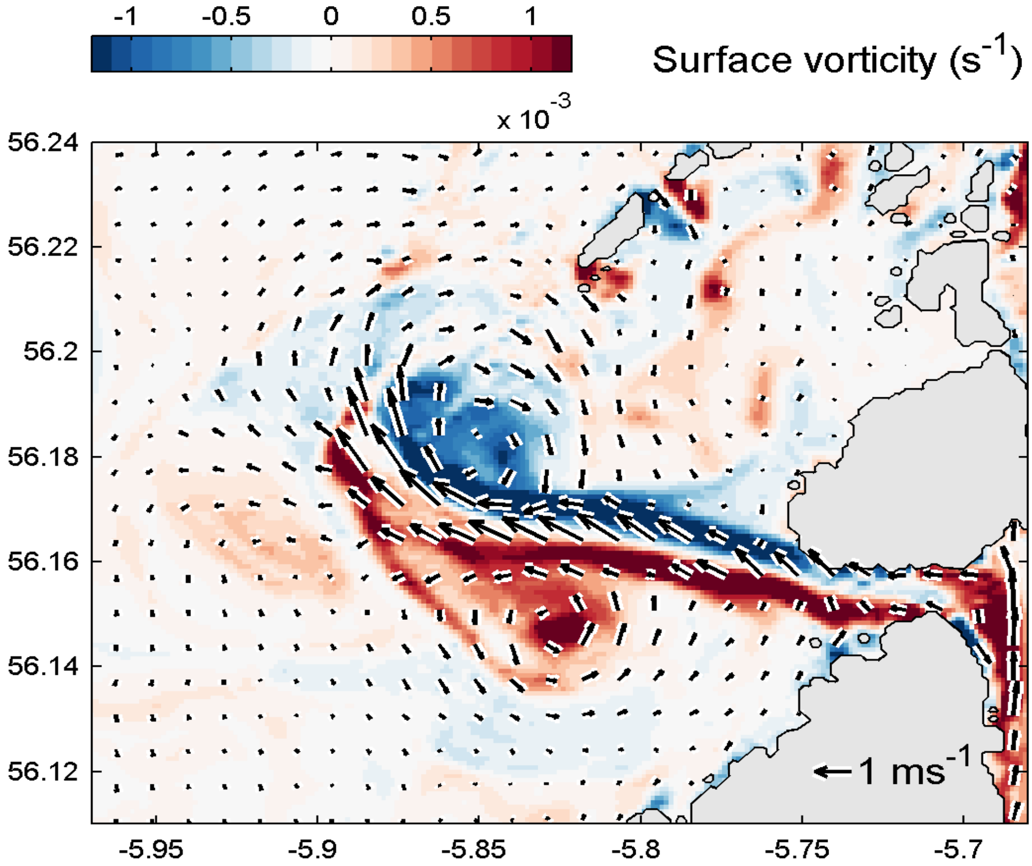

Figure 24. Current vectors and vorticity in the Great Race and Corryvreckan, showing a plume of water being shot into the Atlantic form the Gulf of Corryvreckan. Vorticity refers to the strength and direction of eddies with blue showing clockwise rotation and red anti clockwise rotation. (Dale *et al*., 2011)

5.1.2.2 Sound of Islay

The Sound of Islay sits between the islands of Jura and Islay. The sound is relatively shallow, which restricted the depth of the vertical array. Due to this, bad weather conditions and substantial high frequency noise, probably due to sediment, less effort was spent surveying than in the Great Race/ Corryvreckan.

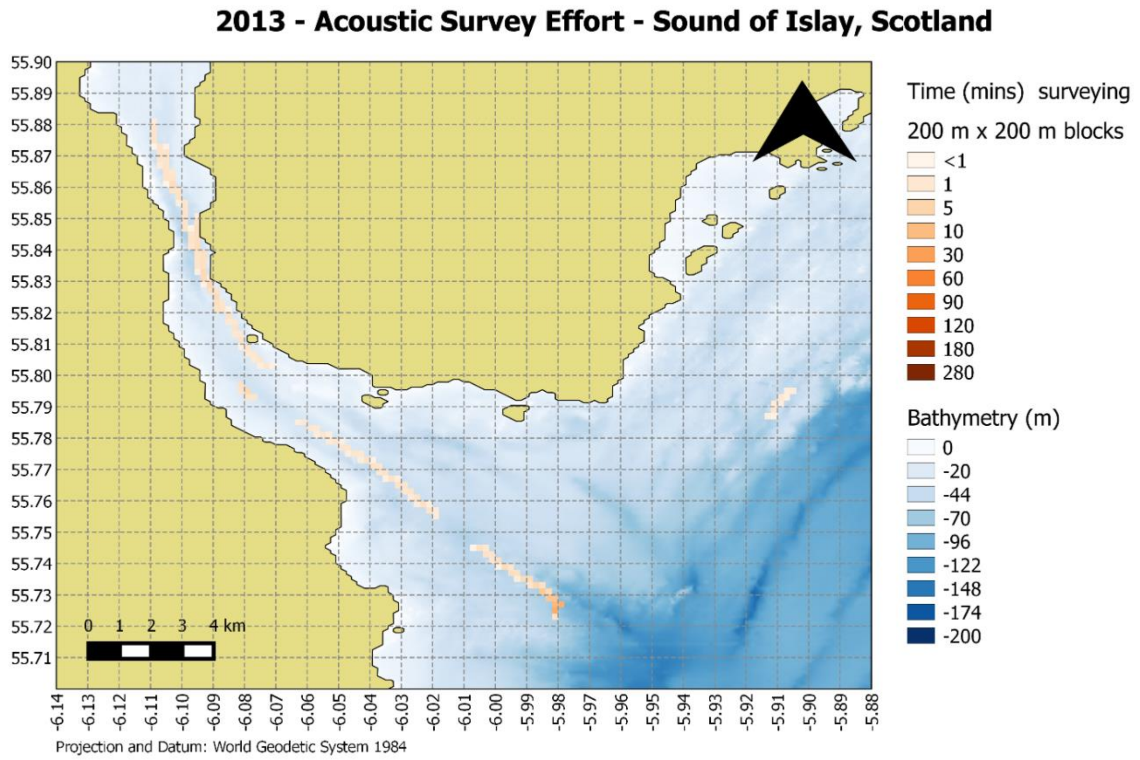

Figure 25. Acoustic effort in The Sound of Islay during the 2013 survey. Due to high frequency sediment noise and poor weather conditions acoustic effort is significantly less here than in the Great Race/ Corryvrekkan.

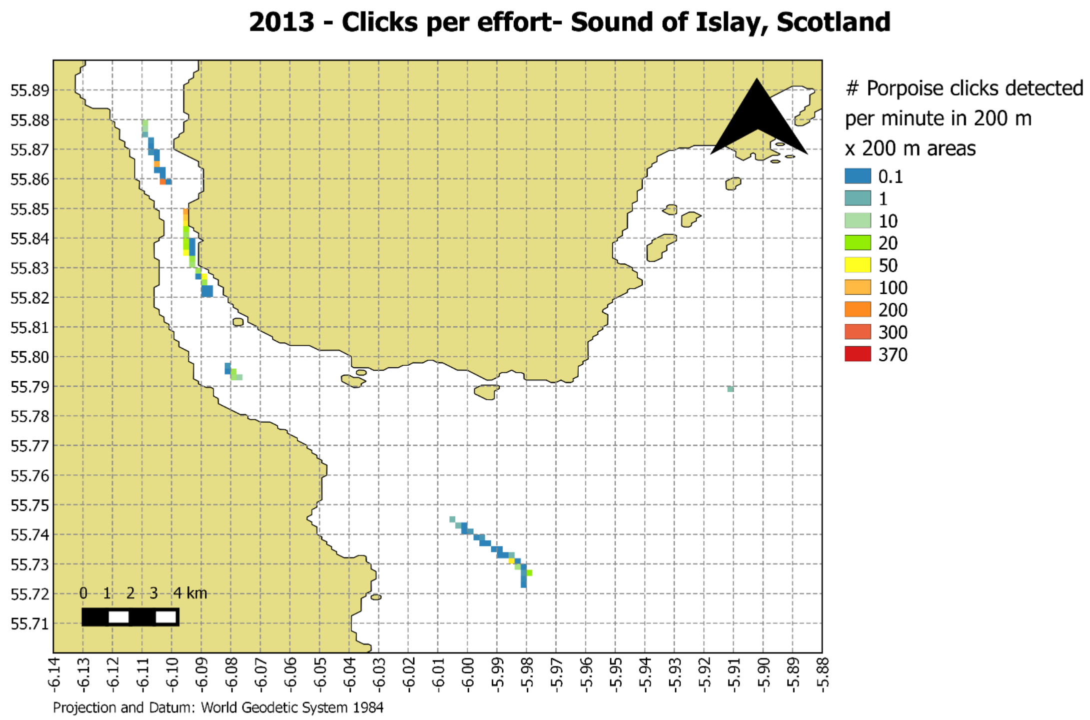

Figure 26 Average number of porpoise clicks detected per minute in the Sound of Islay. Any area with less than one minute of acoustic effort has been excluded.

5.1.3 Studies in 2014

All survey operation in 2014 took place in Kyle Rhea.

5.1.3.1 Kyle Rhea

Kyle Rhea is a relatively shallow sound which sits between Skye and mainland Scotland. A narrow channel, in which the vertical array could not be deployed, produces a tidal race flowing up to 6 knots and then opens out into a much deeper channel to the south with a slower current around 2.5 knots (Carter, 2013). In this area it was possible to continue working around the clock and achieve 24 hour coverage.

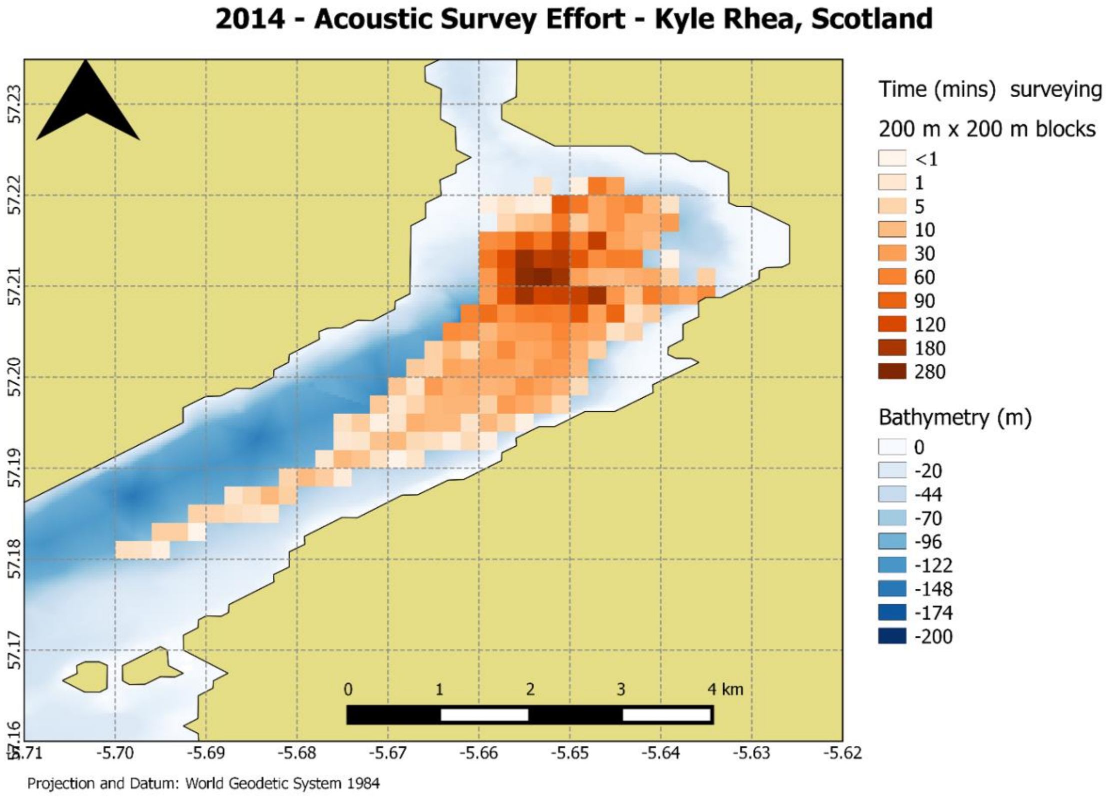

Figure 27. Acoustic effort in Kyle Rhea.

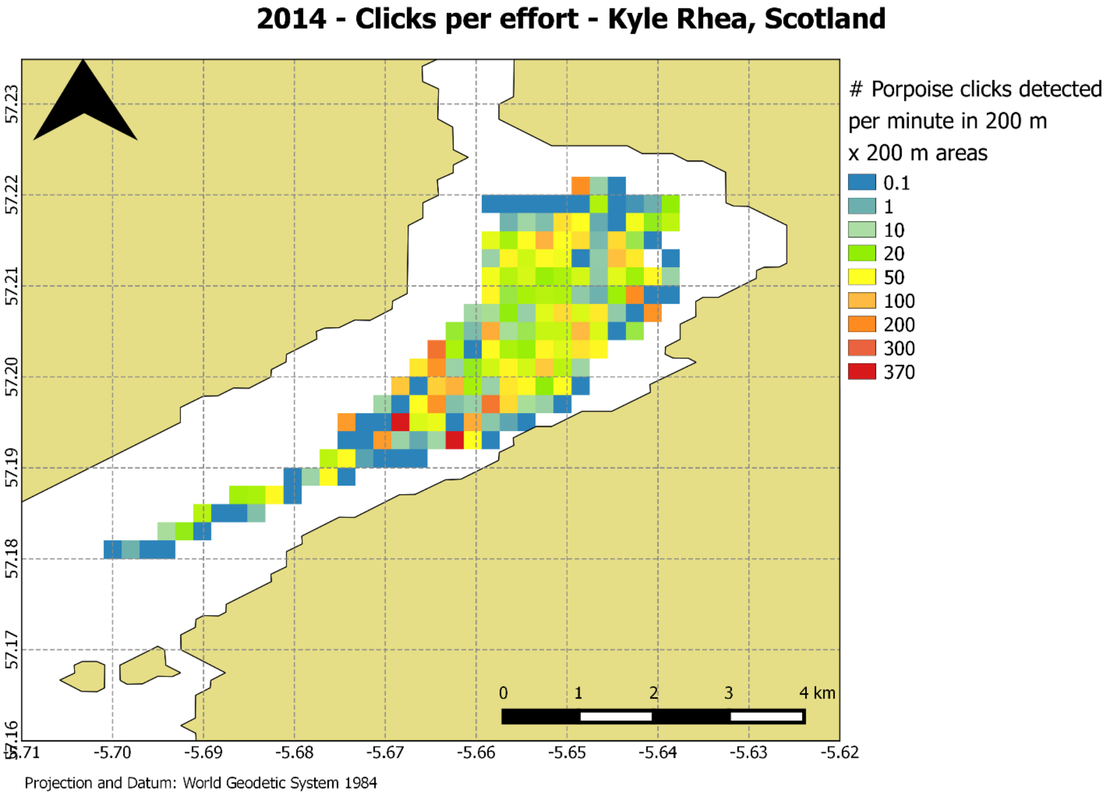

Figure 28. Average number of porpoise clicks detected per minute in Kyle Rhea. Kyle Rhea contained the highest average number of porpoise clicks per minute of all six tidal areas. Any area with less than one minute of acoustic effort has been excluded.

5.2 Data collection summary

A summary of the data collected at all the tidal sites is given in Table 1.

Table 1. Data collected at the tidal study sites. The number of detected porpoise clicks is the number of clicks detected on all hydrophones divided by the number of hydrophones in operation. No. of localisation points is the number of localisation results after filtering. No. tracks is the number of track fragments calculated by the tracking algorithm described above.

	Sound of Longataing	**Eynhallow Sound**	**Fall of Warness**	**The Great Race/ Corryvreckan**	**Sound of Islay**	**Kyle Rhea**
GB of data collected	865.17	722.23	638.83	2520.24	248.5	3474.92
No. hours of recordings	24.0014	20.0421	17.7384	72.82	7.18	91.1329
No. detected porpoise clicks (average per hydrophone)	14121	15304	747	176120	9539	636510
No. detected porpoise clicks per hour average per hydrophone)	672.4	728.8	35.6	2418.6	1328.6	6984.4
No. localisation points	4315	2230	115	24057	884	61200
No. tracks	268	90	7	1227	491	3488

5.3 Localisation accuracy

The array was calibrated in 2013 using simulated porpoise clicks from a source at known positions and depths. The positions of the pinger producing the simulated clicks and the localised positions of those clicks are shown in Figures 29, 30 and 31. These data were then used to estimate the depth and range accuracy shown in Figures 32 and 33.

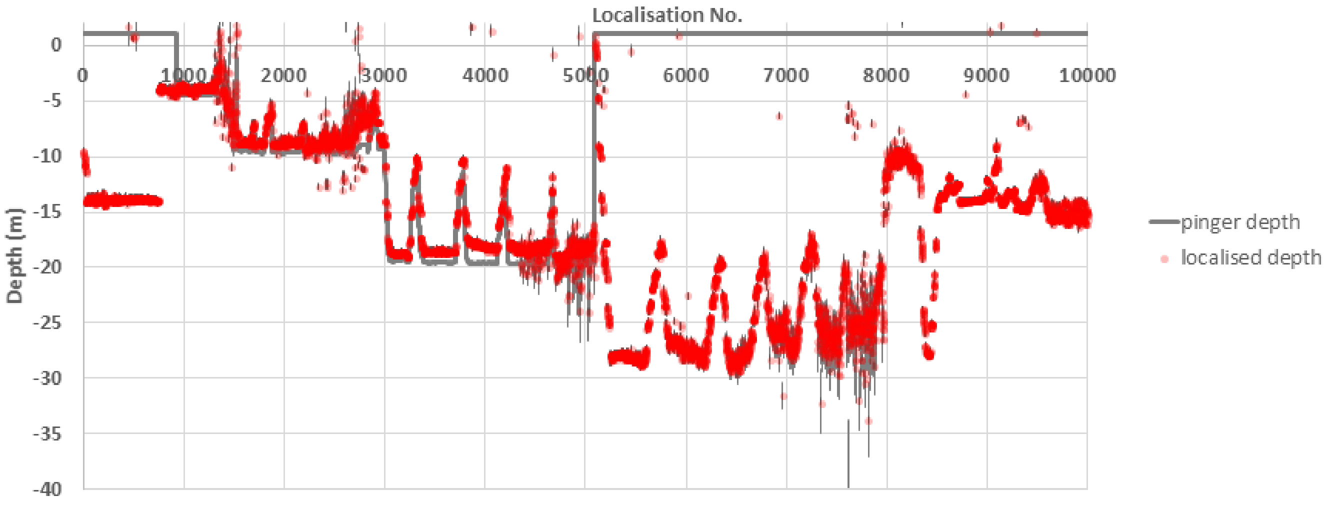

Figure 29. Plot of depth versus localisation number. Red points are localisations of simulated porpoise clicks and the grey line represents the location of the pinger producing the clicks. Due to equipment failure there are no pinger data from localisation 5000+, however, localisation data corresponds to the expected depth (alternating between 20-30m) of the pinger at that time.

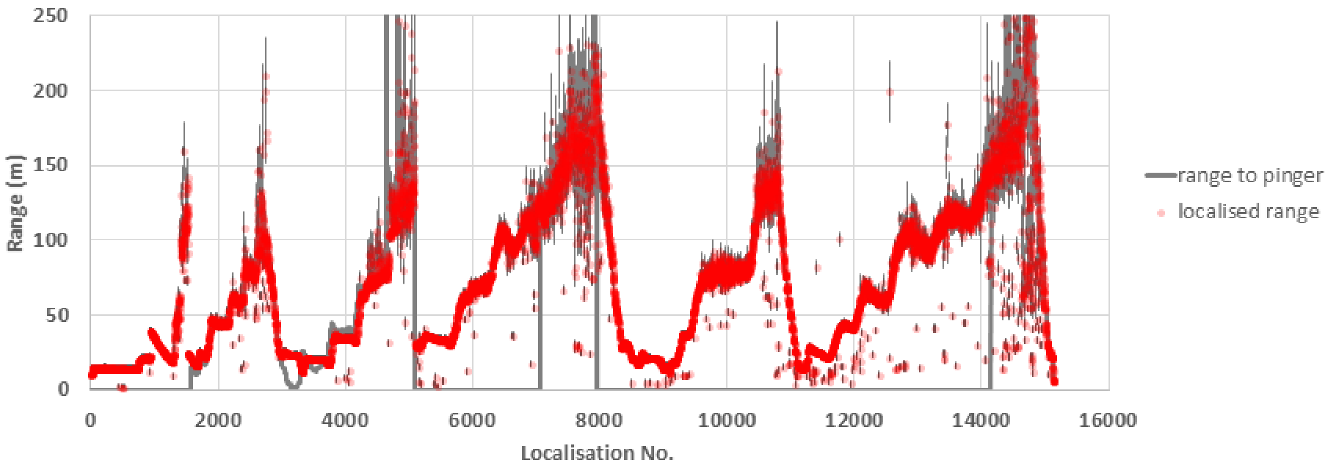

Figure 30. Plot of pinger range from the research vessel versus localised range. Red points are localisations of simulated porpoise clicks and the grey line represents the location of the source vessel from pinger GPS. Due to equipment failure pinger range measurements are missing during some periods

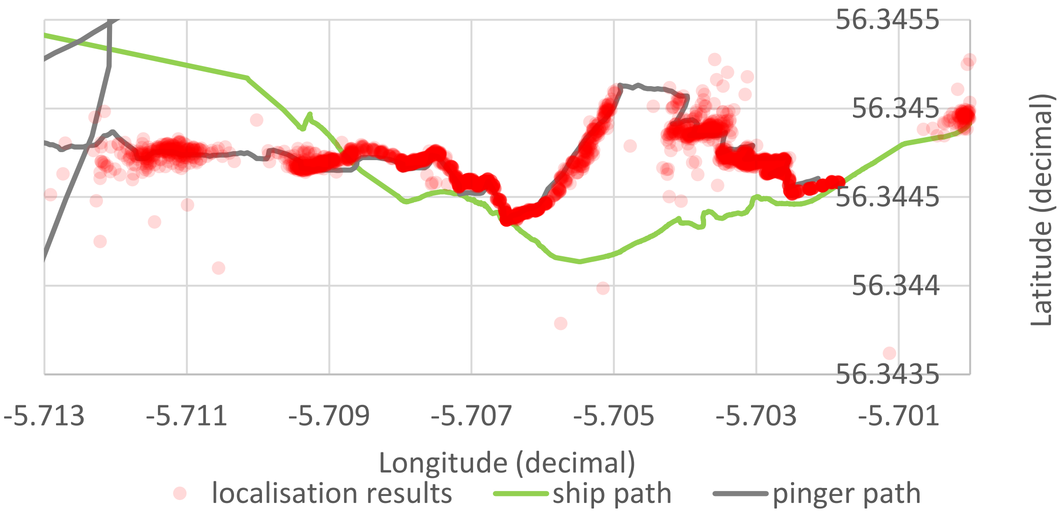

Figure 31. Path of the pinger producing simulated porpoise clicks (grey), the array (green) and geo referenced localisation points (red). The array can accurately localise the latitude and longitude of simulated porpoise clicks.

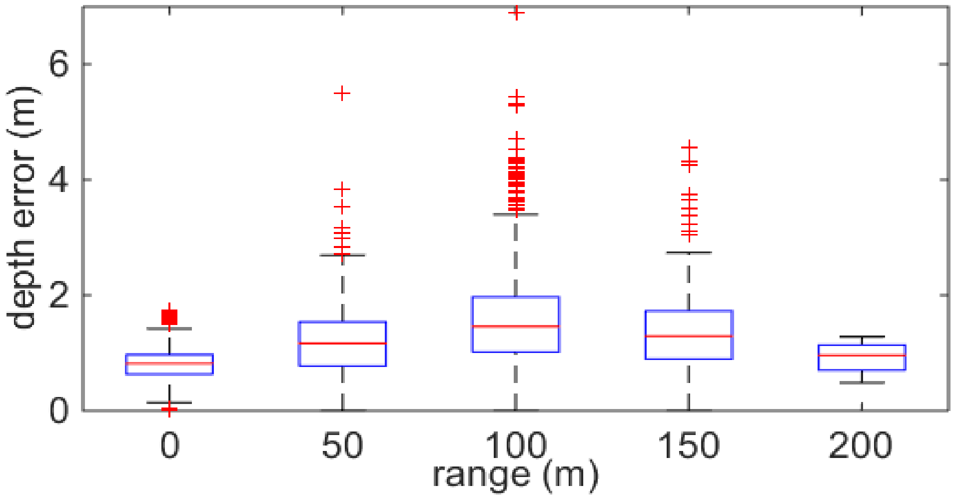

Figure 32. Box plots of depth error versus range. The smaller error at 200m is likely an artefact of the fact fewer simulated clicks were detected, due to being near the maximum detection range of the pinger system. In reality it would be expected that depth error would increase substantially at 200m+.

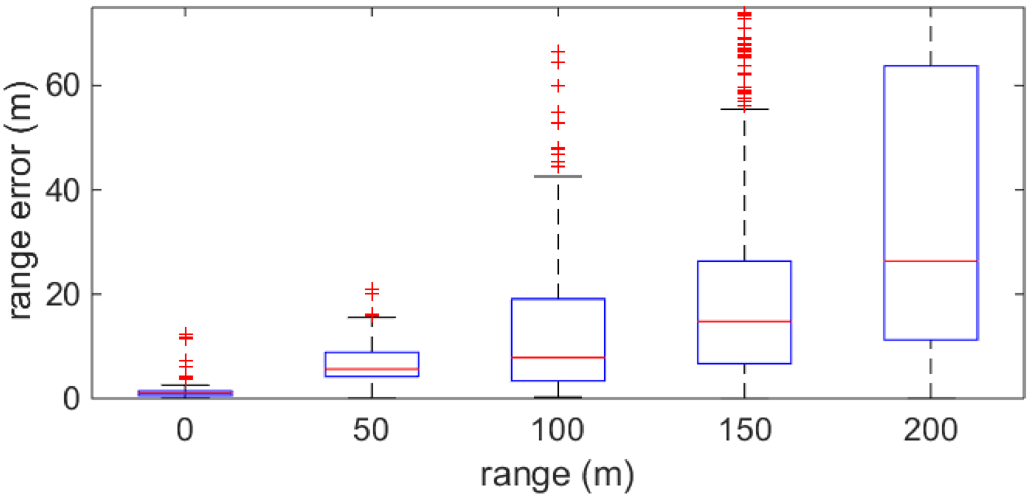

Figure 33 Box plots of range error versus range. Error substantially increases as range increases. This error propagates to errors in the geo referenced localisation points, i.e. error in latitude and longitude.

5.4 3D tracks

Figures 34 to 43 show the 3D tracks of animals along with bathymetry data from INIS (Hydro survey) and Digimap (Bathymetry).Within these figures, several magnified examples are also shown in order to better visualise tracks. It should be noted that in some cases (<8%) the quad array section was either non-functioning or removed due to poor weather conditions. In these cases only information on animal depth and range is available; for completeness these have been plotted by assuming the animal is directly ahead of the vessel. Each track fragment is coloured differently and hence can represent different animals or different sections of one individual’s dive. Note that vertical and occasionally horizontal scales have been exaggerated to best visualise the data.

5.5 Depth distributions

Depth distributions were calculated for each tidal site using interpolated track fragments and a probability of localisation function described above. Tracks were split into 2m depth bins up to a maximum depth of 150m. Errors for each depth bin were calculated by bootstrapping the associated localisation errors for each interpolated track point; 500 bootstrap iterations were used per depth distribution (Figures 43 and 44).

5.5.1 Eynhallow Sound

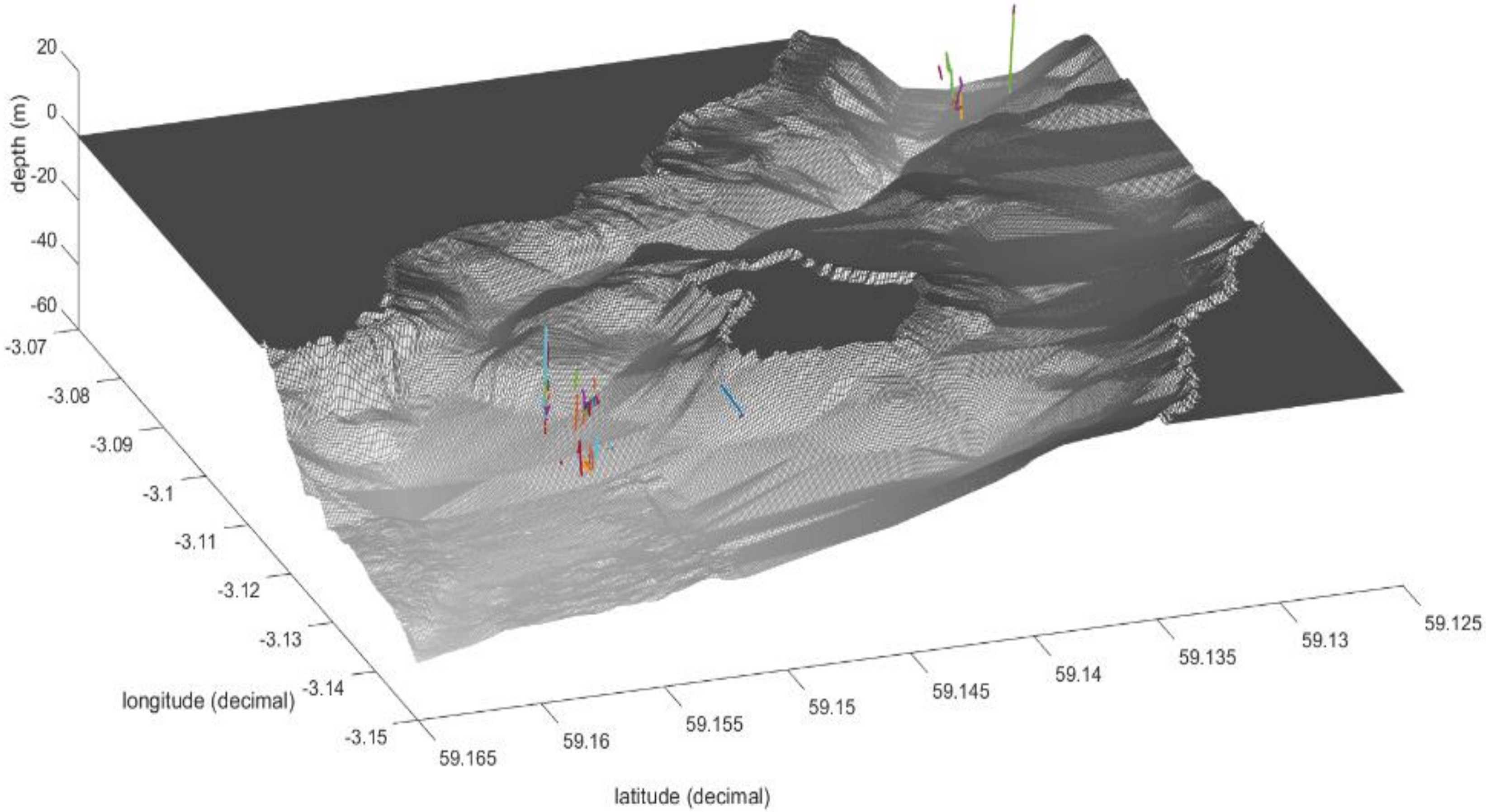

Figure 34. All tracks from Eynhallow sound. Eynhallow Island sits in the middle of the sound splitting the tidal rip between a narrow channel to the north and a much shallower reef to the south.

5.5.2 Sound of Longataing

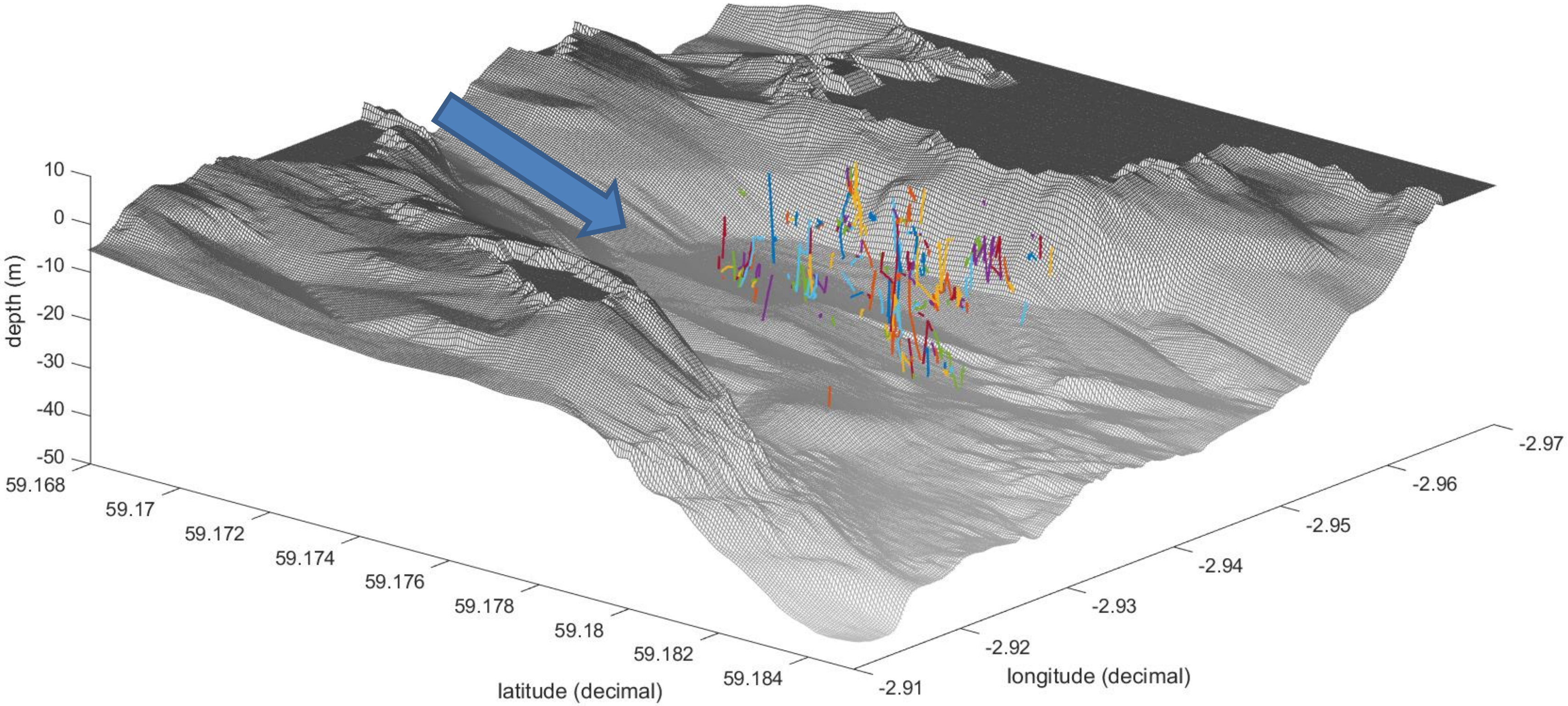

Figure 35. All porpoise tracks calculated in the Sound of Longataing. The arrow shows the direction of tidal flow during a flood tide.

5.5.3 Fall of Warness

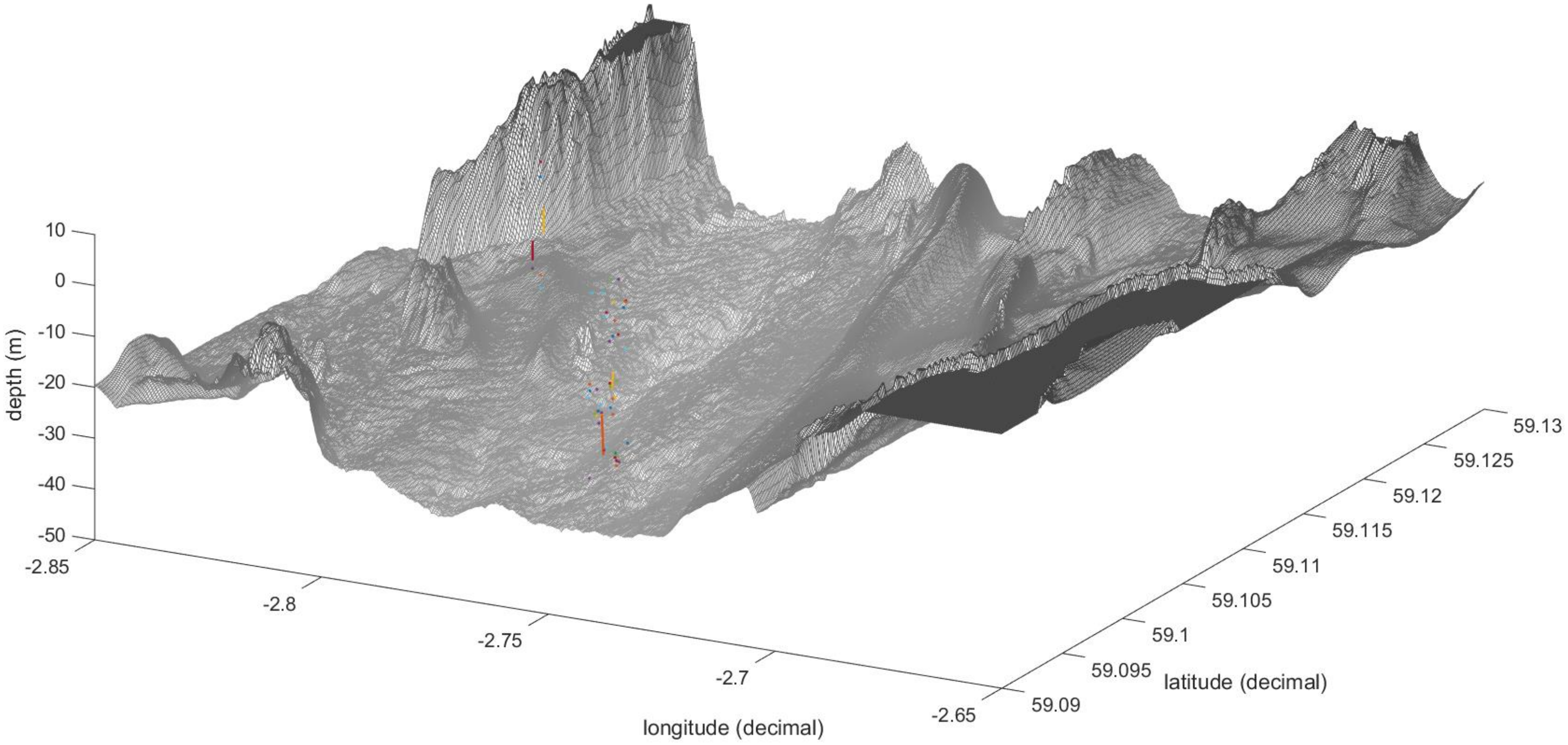

Figure 36. All porpoise tracks detected in Eday Sound. Very few porpoises were detected in the Fall of Warness and surrounding areas.

5.5.4 Great Race and Corryvreckan

The Great Race/Corryvreckan. Entire Site.

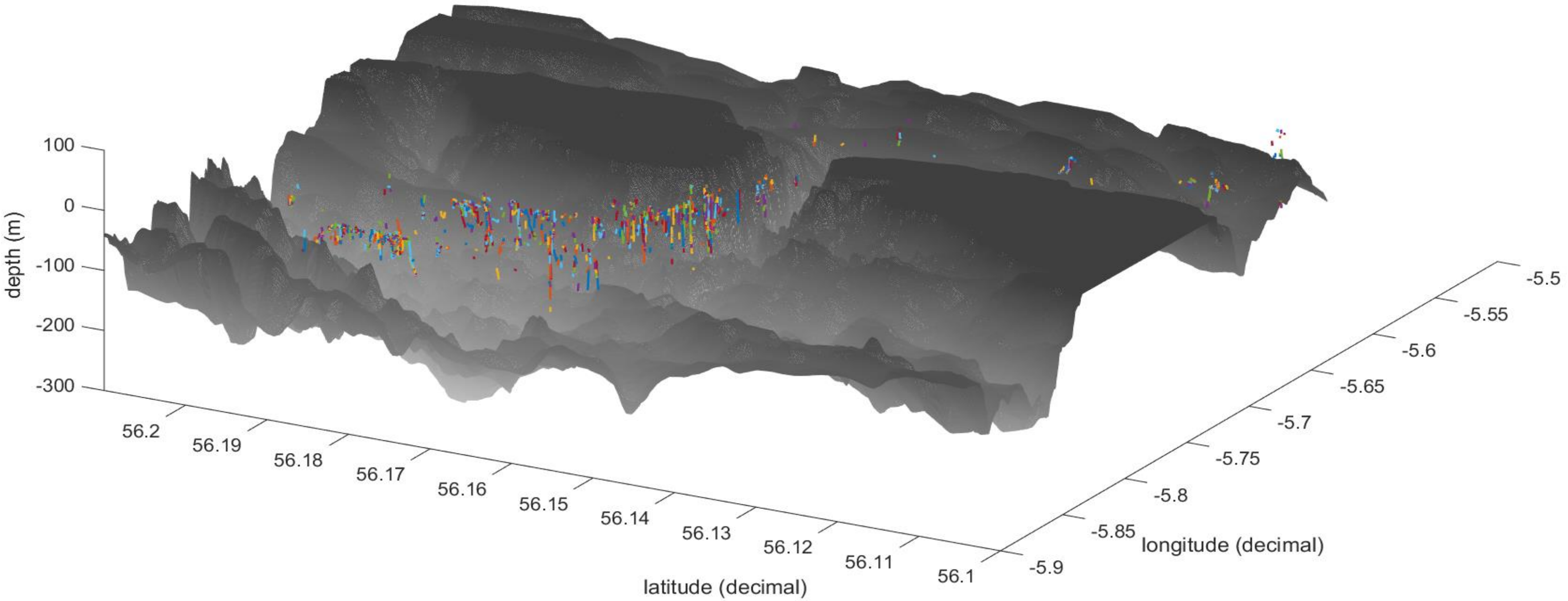

Figure 37. All animal tracks from the Corryvreckan /Great Race area during the 2013 survey. The narrow channel in the middle of the graph is Corryvreckan, an area with an exceptional tidal rip. To the west of Corryvreckan is the Great Race, a large plume of water which travels into the Atlantic on each flood tide; this was where the majority of porpoises where detected.

Corryvreckan magnified

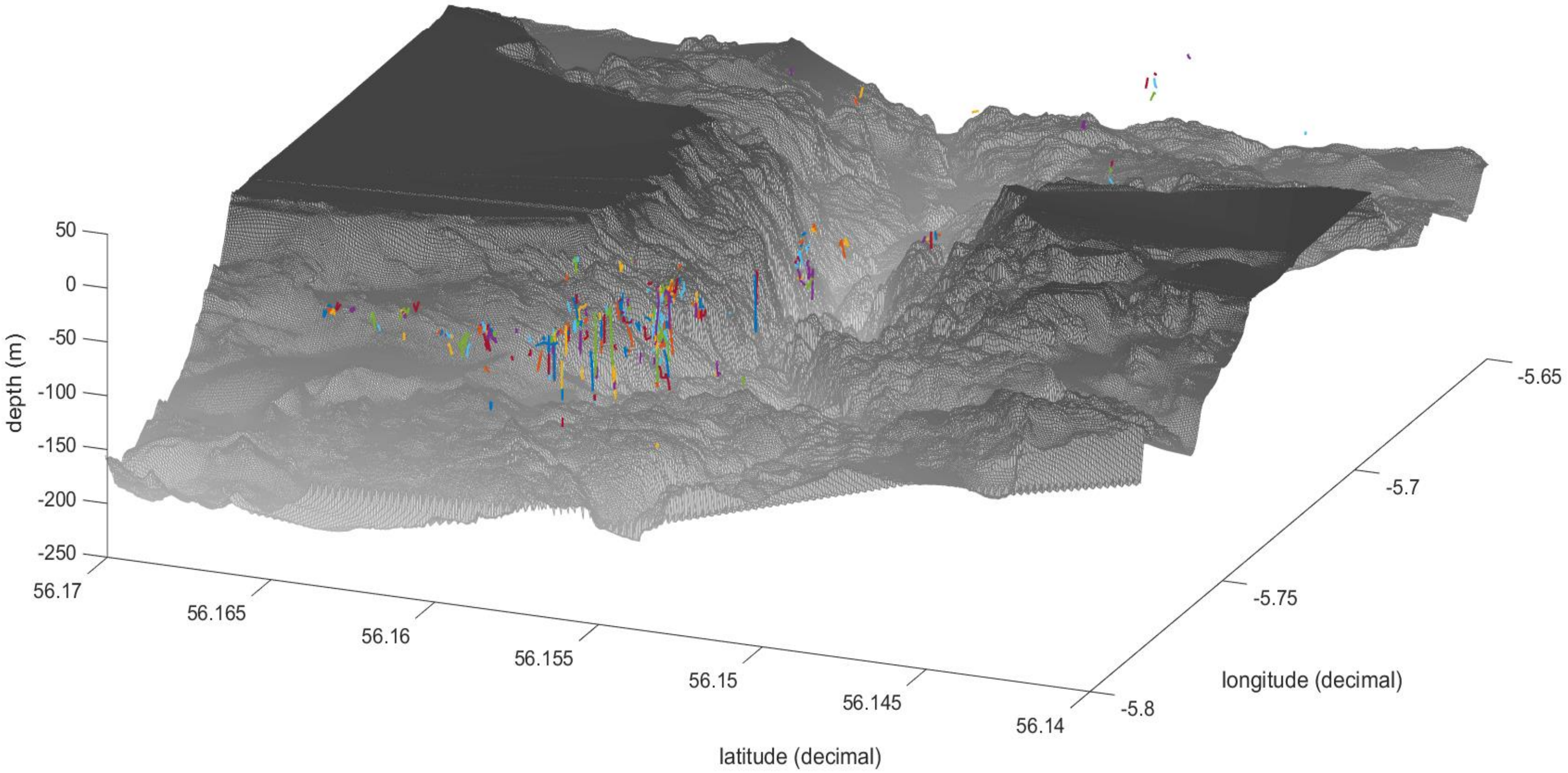

Figure 38. Corryvreckan is a deep 200m channel with an exceptionally fast tidal rip at peak flow, with water speeds in excess of 8 knots . For this reason it was hard to spend a significant amount of time drifting directly in the channel., however, a few porpoise were detected showing animals diving to depths of ~150.

Great Race magnified

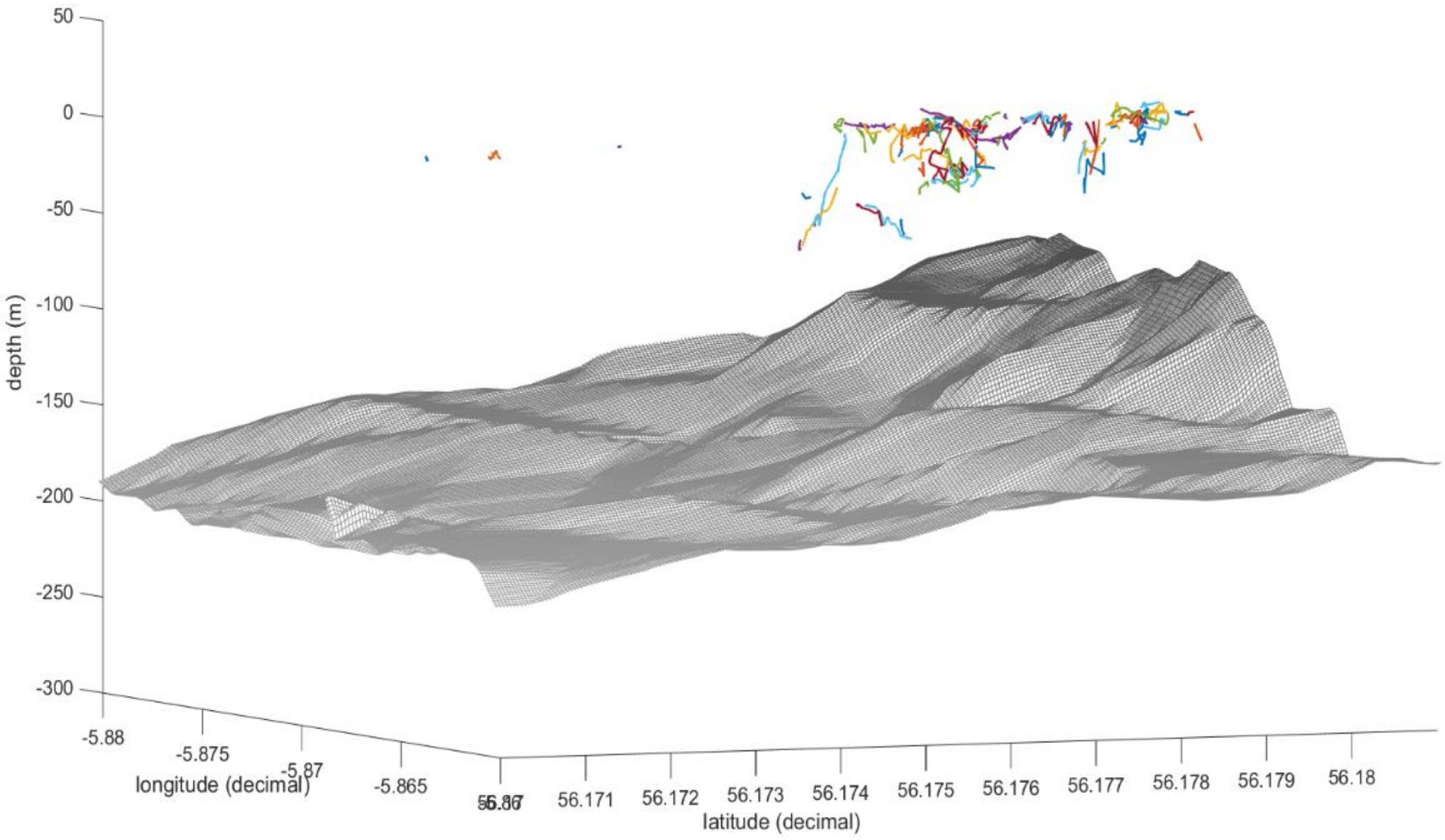

Figure 39. An area of the Great Race. The Great Race covers a large geographic area with relatively deep for an inshore area. This graph shows a section of the Great race with associated porpoise tracks. Note that some track fragments are relatively long whilst others are much shorter. This is due to the orientation and acoustic behaviour of animals during a dive.

5.5.5 Sound of Islay

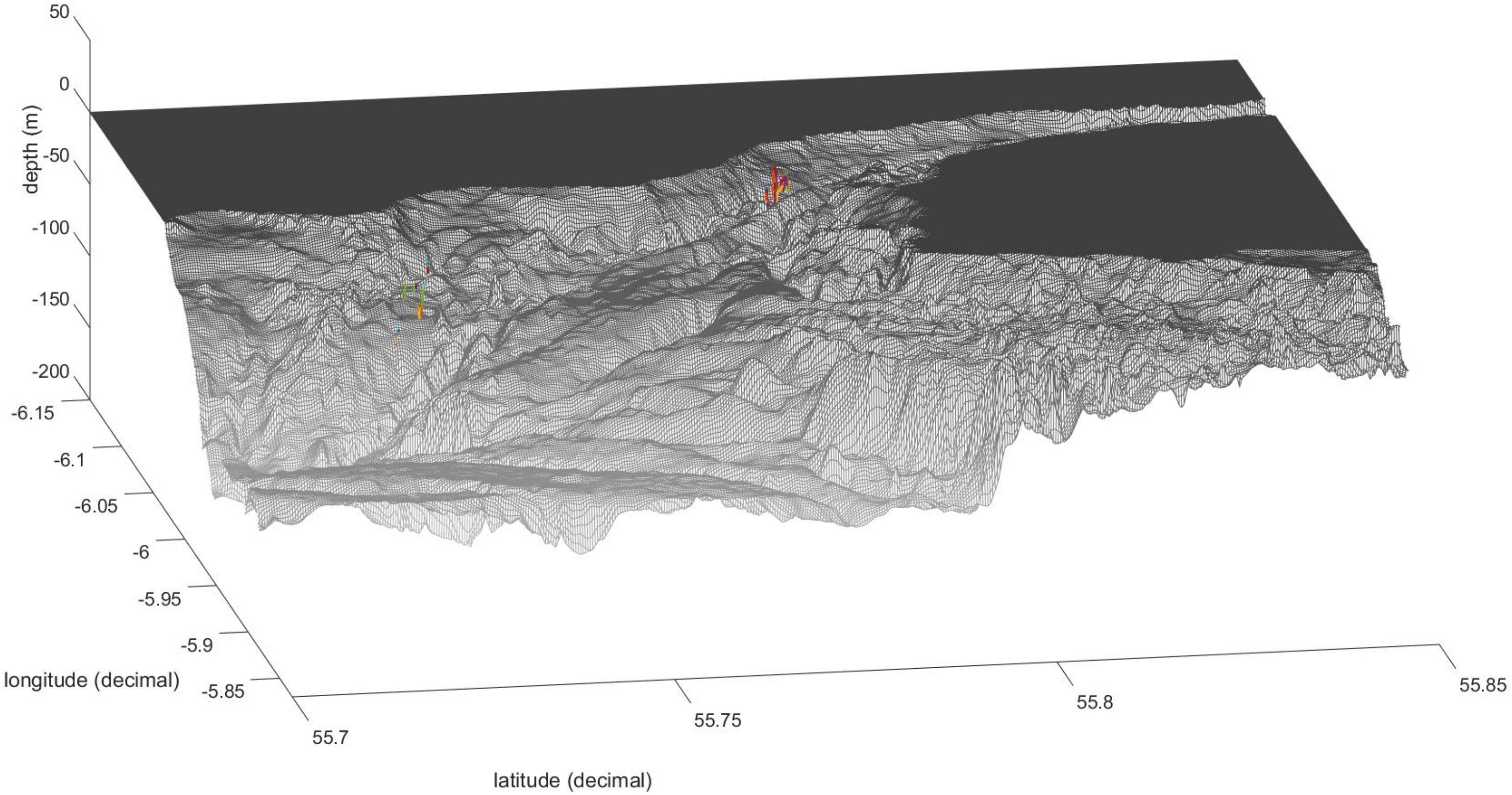

Figure 40. All porpoise tracks detected in the Sound of Islay during the 2013 survey. The Sound of Islay is a fast flowing and, in the narrow channel between Islay and Jura, a relatively shallow tidal area. As such the vertical array was deployed in a shallower configuration decreasing accuracy. In addition high frequency noise levels in this area could be significant decreasing detectability. Due to these factors less survey effort was devoted to this site and few tracks detected.

5.5.6 Kyle Rhea

Kyle Rhea entire site

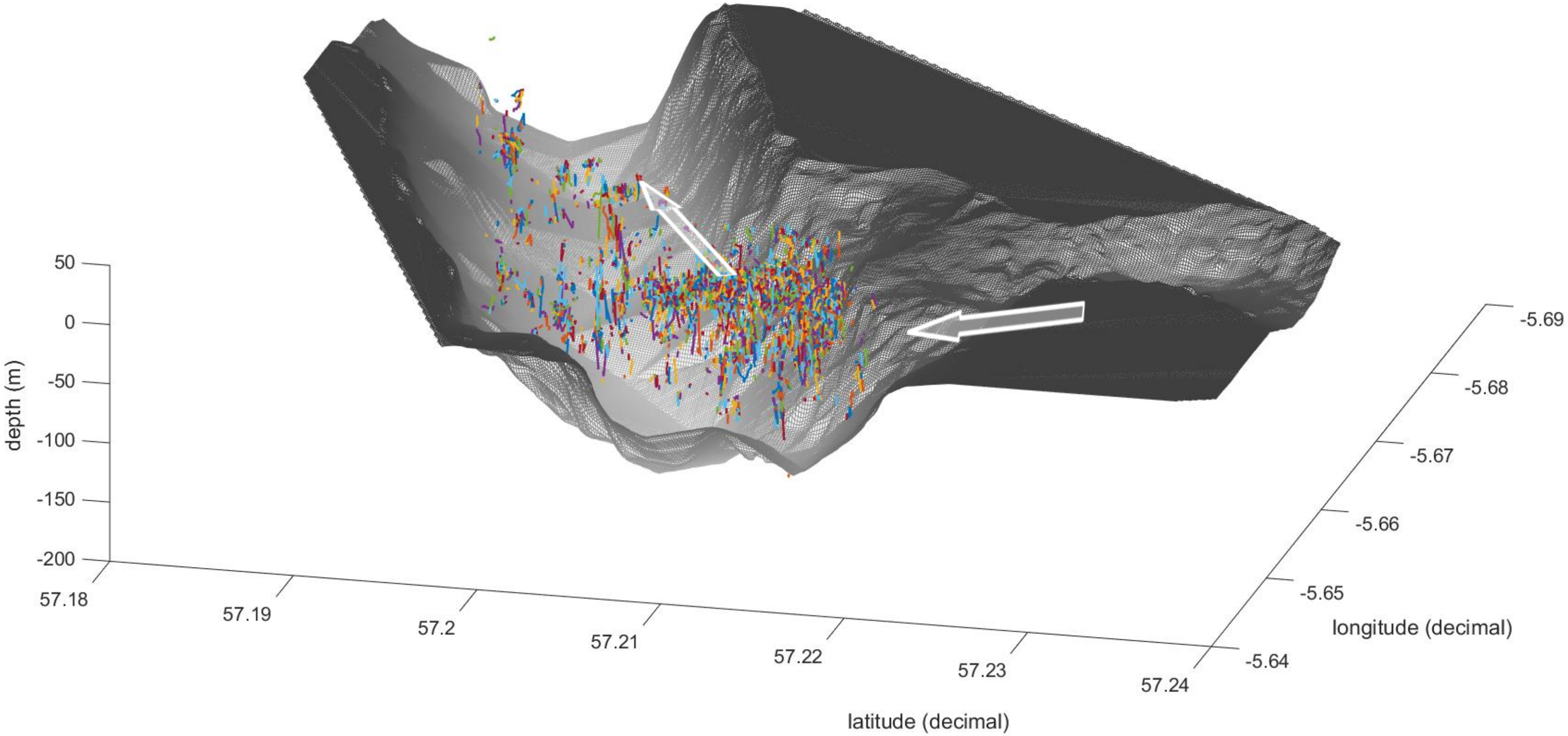

Figure 41. All results from data collected near Kyle Rhea during the 2014 survey. Kyle Rhea consists of a narrow and shallow channel between Skye and the mainland which open up into a much deeper and wider area. The shallow channel has a fast moving tidal rip up to 6 knots whilst in the deeper area current flows are up to 2.5 knots (Caroline, 2013). The number of porpoise detections per hour and visual sightings at this site were significantly higher than Corryvreckan and the Great Race and an order of magnitude greater than Orkney, suggesting this could be, at least during the time of the survey, an important habitat for harbour porpoises. The arrows show the direction of the current during the ebb tide.

Kyle Rhea magnified

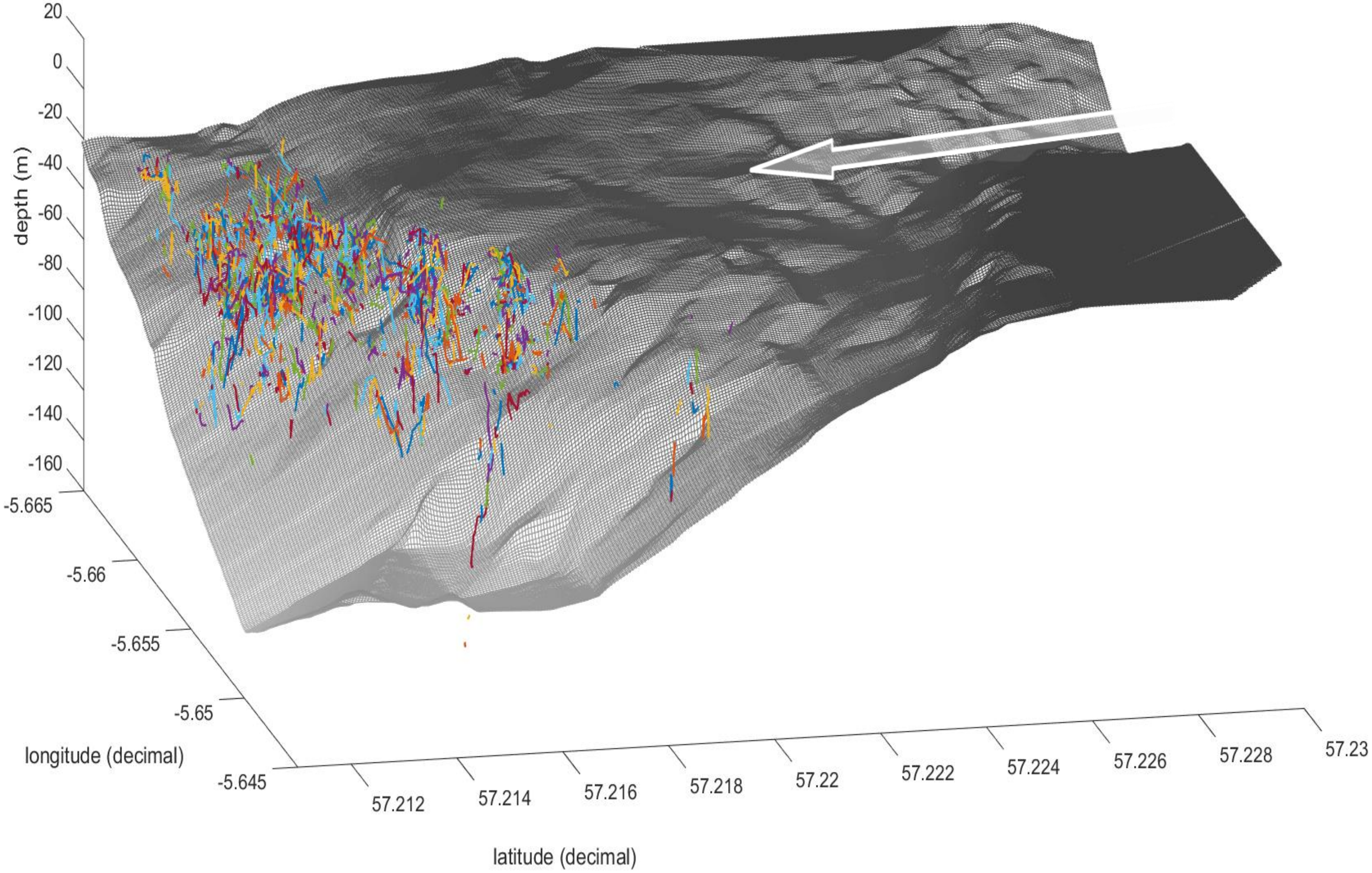

Figure 42. Magnified example of data collected Kyle Rhea. The area where the shallow channel opens into the deeper channel contained amongst the highest number of clicks per minute, suggesting a high density of porpoises. The arrow shows the direction of the current during the ebb tide.

5.6 Diurnal patterns

During 2014 a significant portion of the survey took place at night, allowing diurnal patterns in depth distributions to be explored, as shown in Figures 43 and Figure 44. There appears to be a trend for animals to spend more time diving to deeper depths during daylight hours than at night.

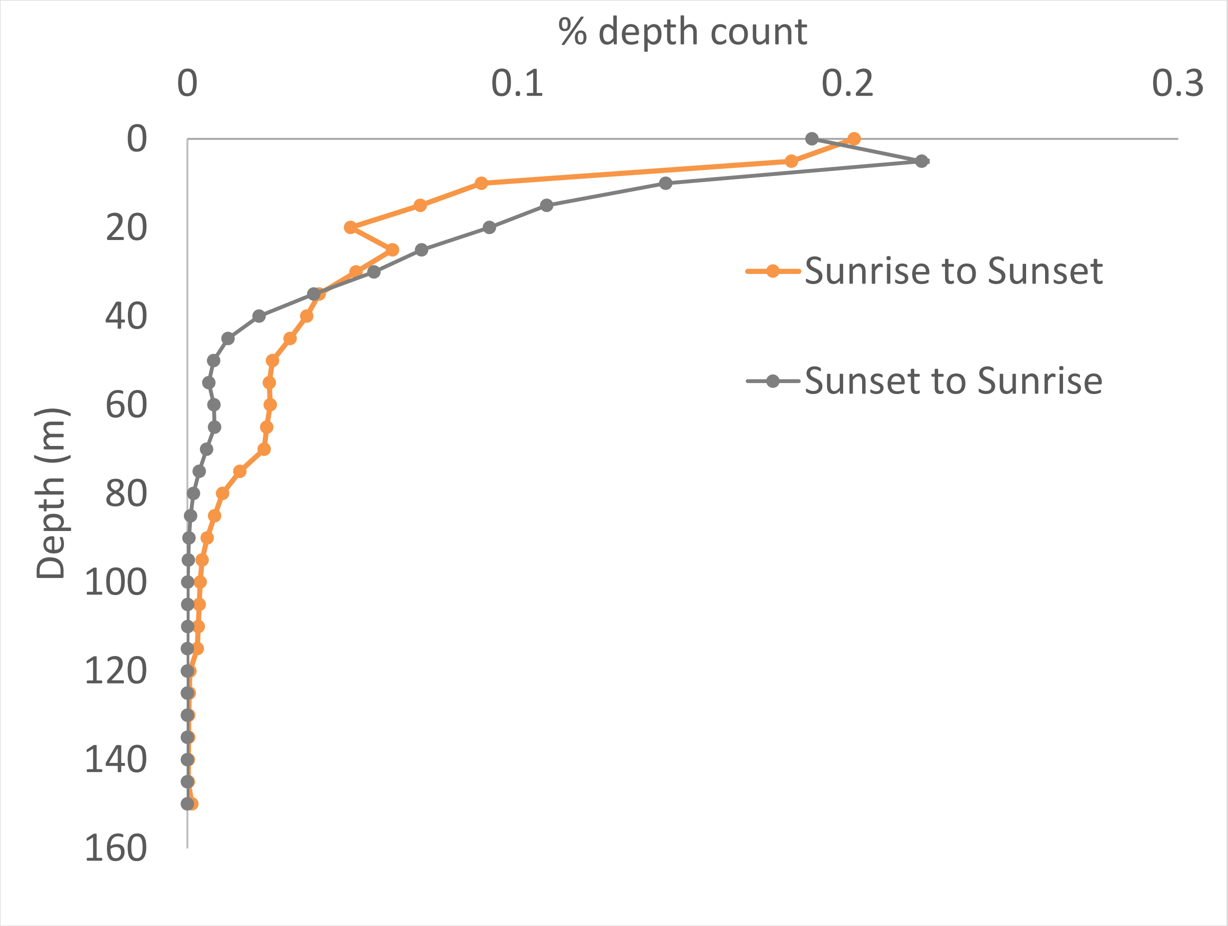

Figure 43. Depth distribution during daytime (orange) and night-time (grey) hours.

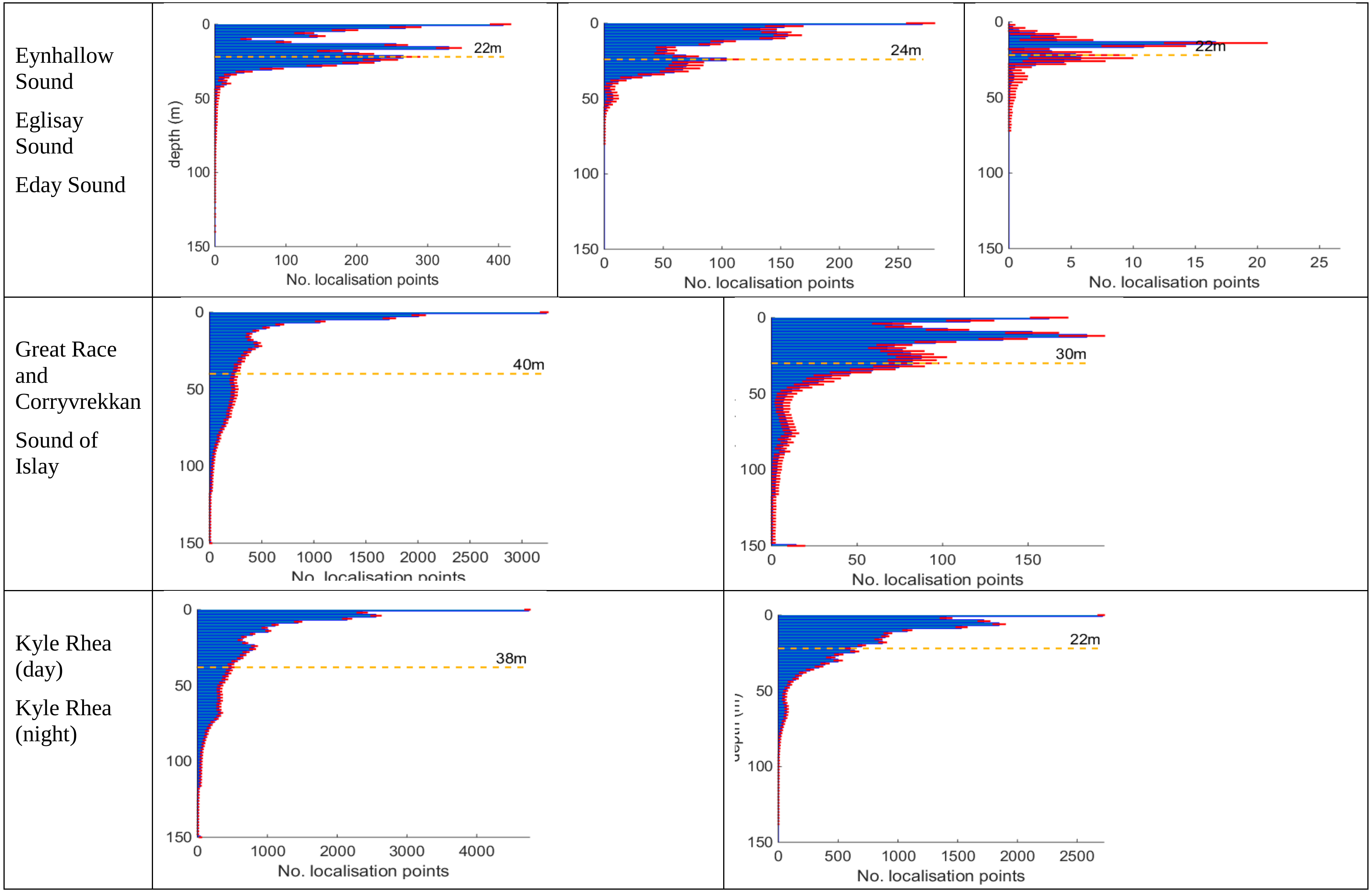

Figure 44. Depth distributions for all six tidal sites. The dashed orange line and label represents the surface to depth interval at which animals spend 75% of their time. Red lines show errors in depth bins. Each bin consists of 0.5 second interpolated points from tracks generated by the multi-track Kalman. The total number of points for each bin is representative of the relative number of detected tracks in that bin at different tidal sites. Kyle Rhea is split between daytime surveys and night time surveys. All other surveys took place during daylight hours.

6 Conclusions

Over four years, the Scottish Government has funded the development of vertical hydrophones arrays to localise the positions of porpoises underwater, in tidal rapids, providing essential data on depth distribution required to model collision risk. No equivalent system existed when this work was started although a feasibly study in 2009 suggested its potential (Gordon *et al*., 2012). A significant amount of effort has necessarily been spent on developing and refining hardware and software. The array was extensively tested using a pinger to simulate porpoise clicks and errors in depth and range were shown to be sufficiently small to allow this system to provide fine scale information on the movements of animals underwater, with ranges of up to approximately 200m. Through this work a reliable methodology, backed up by a significant software infrastructure within an open source framework, now exists to facilitate studies into porpoise dive behaviour in tidal areas.

The main advantage of using drifting large aperture hydrophone arrays is that they can track multiple animals in a particular area, rather than relying on tagged animals to enter a location of interest. No large sea bed structures are required to collect data and hence this system is a cost effective solution to investigate animal behaviour at pre-consenting stages for tidal turbines or other developments. Once turbines are installed, many of the methodologies used here can be applied to static hydrophone arrays located on or around the turbines.

However, there are disadvantages to using a drifting system and PAM in general. Any drifting system is unlikely to remain in one location for any significant length of time and so collecting data from small specific areas (e.g. the sites of tidal turbines) may be time consuming. The fact that both the drifting tracks of the array and most probably animal distribution are highly correlated with the tide means that absolute density estimation is difficult/impossible, even with multiple drifting units, and therefore any comprehensive study of a tidal area would have to be complemented with a visual/acoustic line transect survey.

In relation to tracking animals, weaknesses remain in the fact that, due to both highly directional vocalisations and harbour porpoises occasionally not vocalising (Linnenschmidt *et al*., 2013), only sections or fragments of animal tracks are detected during a dive. The development of automatic tracking algorithms has somewhat mitigated this, with multi-track Kalman filters able to fill in smaller gaps between animal tracks and distinguish between different animals, but the ideal situation of being able to record entire dives is very rare. For the purposes of determining depth distributions this is acceptable due to the volume of data collected, however, for detailed analysis of porpoise behaviour, extracting the most from dive fragments requires further work (examples given in Figures 45 and 46).

Three field seasons were carried out at a variety of different types of tidal sites. As mentioned above, methods to determine absolute abundance from drifting PAM system currently do not, and are perhaps unlikely to ever, exist,. However, assuming that an area is adequately covered and that noise conditions and vocalisation behaviour remain relatively constant, the number of clicks detected per hour gives an indication of the *relative* abundance of harbour porpoises. For areas such as the Sound of Islay noise is a significant issue causing large numbers of false detections and reducing the effective detection range of the array. However, for all other sites noise was broadly similar. The number of detected clicks per hour in Kyle Rhea was ~7000, almost three times as many as the GreatRace/Corrvreckan and over ten times that of any site in Orkney, providing some indication of the relative importance of these sites for harbour porpoises.

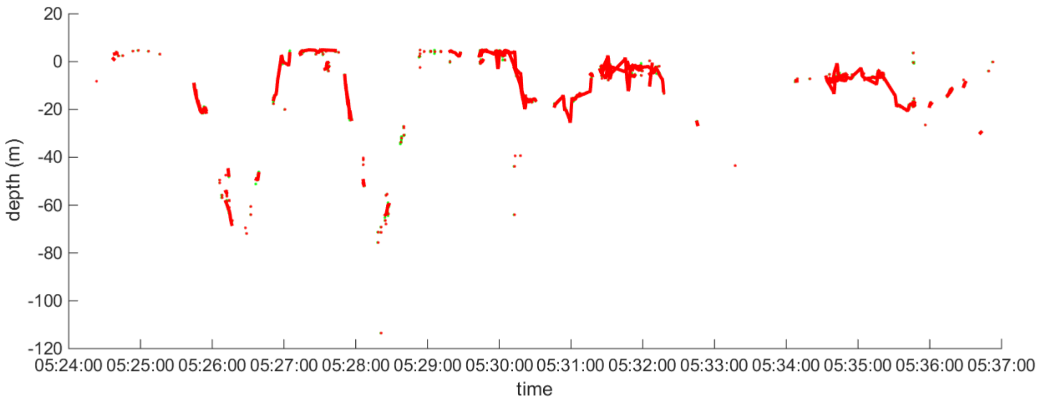

Figure 45. Dive fragments of animals. Here the algorithm has not interpolated two obvious dives between 05:24 and 05:28. Allowing the multi-track algorithm too much freedom to join up tracks can result in spurious results whilst too little freedom means dive fragments remain very small. There is thus a trade-off to be made. Manually analysing data should allow for a greater number of full dives to be extracted.

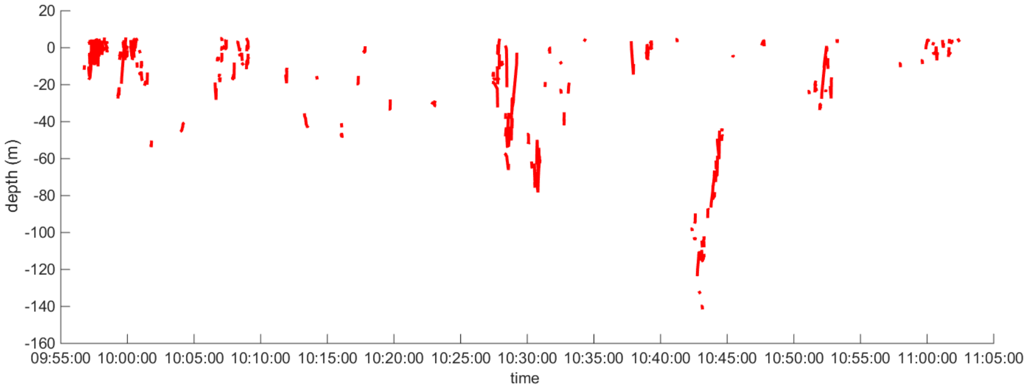

Figure 46. An example of dive fragments near 150m deep. The depth distributions in both Kyle Rhea and the Great Race, the two sites with comparatively deep water and those with the most detected animals, show harbour porpoises spending 75% of their time in the first 40m and 38m of the water column respectively. It is intriguing that both these depth distributions have similar shapes with a maxima between 0-5m and smaller maxima at 22/24m, suggesting that behaviour may be similar in both areas. The maxima at 22-24m, which only occurs during daytime, is particular interesting, indicating that there may be some significance to that depth, perhaps relating to prey distribution or social interactions. Porpoises were more likely to be located near the sea surface at night in Kyle Rhea, indicating that it will be important to collect data during nocturnal period for collision risk assessments. Analysis of acoustic behaviour at these depths and times, in particular looking for feeding patterns and social communication would provide further insights into what drives these distributions.

In addition to similar maxima in the depth distribution, harbour porpoises in both Kyle Rhea and Great Race/Corryvreckan occasionally perform much deeper dives with small fragments detected near 150m, well beyond the anticipated operational detection depth for the array. Further investigation of deeper tidal areas should therefore focus on the true extent of deeper dives and on the tail end of depth distributions. For this, a longer array is needed; this was partly the reasoning behind a deeper water extension to the array in the 2014 survey, however, due to time and budget constraints this was still only a 45m array in a 150m channel. The reduced probability of detection for deeper diving animals was compensated with a POL function generated as described above. However, this will break down with the scarcity of data at depth and indeed the tail end of the function, beginning at about 70m, is likely to be an artefact due to this. Thus it should be assumed that the depth distributions become more unreliable beyond 70m in this case. It should be noted that the probability of localisation is the focus of further work however, the results suggest that, if possible, future measurements should be made with an array which "fills" the water column (i.e. extends close to the bottom) then only a small compensation will need to be made for likely changes in detection probability with depth.

The depth distributions in Orkney and Sound of Islay are bimodal, with porpoises likely to be located either at the sea surface or 22/24m. However, in this case, the maxima at 22-24m is likely to be an artefact of the average sea bed depth, as all tidal sites in Orkney were significantly shallower than Kyle Rhea and the Great Race/ Corryvreckan. Figures 34-42 show the detailed geo-referenced dive behaviour of harbour porpoises which can be collected with this system. The potential insights it is possible to gain from this dataset are enormous. Information on foraging habits can be collected by cross referencing acoustic behaviour that indicates prey capture with an animal's position in the water column. Movement and orientation in relation to tidal flow could be determined, showing whether animals drift with or swim against currents, prefer areas with eddies or fast moving tidal races or a combination of both. Source levels of clicks can be determined and detailed noise analysis performed for different areas, with implications for how detectable animals might be when acoustic sensors are placed on or near tidal turbines.

Although all of the above issues are of scientific and commercial interest, the analysis presented here focuses on the primary driver for this work: the collection of information on the proportion of time that porpoises spend at different depths for particular tidal energy sites to inform collision risk models. It has been possible to demonstrate the proportion of time spent at depth in each of the six study sites, and a comparison between daytime and night-time dive profiles was made at one site. Whereas such data could now be used to parameterise crude collision risk models for any one of these sites, further work should ideally be undertaken to examine porpoise density flux (number of animals passing a particular point in a given time frame). This analysis was not planned for the current project but could be undertaken with these existing data.

The data summarised here provides the first substantial general dataset on porpoise depth distributions and underwater behaviour in tidal rapids. Given that virtually no data existed before, the data can be used as an initial reference to better inform collision risk estimates. However, less than one and a half weeks of continuous data have been collected, all during the summer and mostly during daylight hours. This, combined with the variation between sites evident in this dataset, emphasises the importance of collecting data on a site by site basis. Therefore, the recommendation is that this approach should be used at potential tidal sites with a survey spread over at least a full year to determine both seasonal and diurnal patterns in dive behaviour A focus for further development should be 'enabling technologies' such as user friendly software and hardware, in order to make this technology more available for consultancies and other researchers. In addition, collision risk models will need an associated estimate of absolute density of animals, something which currently cannot be determined from drifting systems. As such a combined visual/ PAM line transect survey to estimate animal numbers should be used alongside a drifting system to examine dive profiles. A new towed hydrophone array system has also been designed and tested, which could enable absolute density estimates to be made using a towed array alone (Macaulay *et al., 2015*), though some further work would be needed to achieve this.

6.1 Future work

It has been shown that using drifting large aperture hydrophone arrays can be an effective methodology to determine fine scale movement of porpoises underwater, however, the technical expertise required to build and operate such a system means that, without further development, this is likely to stay in the academic realm. In 2014, SMRU won a Knowledge Exchange grant to develop the autonomous buoy-based vertical array that can be easily deployed from a small vessel. The system consists of a buoy with a vertical array and integrated cluster attached, which should have the ability to collect the same quality of data as the current system deployed from a research ship. This will make future studies more practical and reduce field costs

Joining clicks into track segments and segments into more complete tracks is an important step in the analysis that warrants further development. Joining track fragments represents a classic pattern recognition problem, something that computers are generally less adept at than an average human (Basu & Ho, 2006). Thus, as well as investigating ways to improve multi-track Kalman filter algorithms, tools should also be developed to enable a person to quickly scroll through raw localisation points and manually create 3D tracks from the data, allowing the maximum information to be extracted for studies on behaviour.

The extent to which detection probability varies with depth and the extent to which this might affect estimates of the proportion of time spent at depth should be a priority area for future study.

This is currently the most comprehensive dataset ever collected on porpoises in tidal rapids. As discussed above this report only represents a small portion of the potential insights these data can provide on how porpoises utilise tidal habitats. In particular techniques need to be further developed to detect, classify and sort click trains into different behaviour types and to cross reference these data to localised porpoise positions.

In a broader context, meaningful methodologies need to be developed to combine data from vertical arrays with other survey types, such as acoustic (or visual) line transect surveys, that can determine density, and with static data loggers, that can record long term temporal patterns. By using these different approaches it should be possible to obtain a comprehensive overview on how porpoises utilise tidal habitats, thus helping further inform models of collision risk and habitat exclusion.

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8 External data sources

INIS Hydro survey

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Digimap Bathymetry

Digimap bathymetry.Hydrospatial gridded bathymetry [ASCII geospatial data, 1 arcsecond]. Tiles: nw55900035, nw55900030, nw55850035, nw5585003 (2012); nw55600060, nw55600065, nw55550060, nw55550065 (2013); nw55700060 (2014). Updated 2008, SeaZone Solution Ltd., Using: EDINA Marine Digimap Service, <http://edina.ac.uk/digimap>, downloaded October 2014.

GSHHG coastline data.

A Global Self-consistant, Hierarchical, High-resolution Geography Database. Grid version 20140701. <http://www.gebo.net>. Distributed under the GNU Lesser General Public license. Original version of dataset available from <http://www.ngdc.noaa.gov/mgg/shorelines/gshhs.html>. Downloaded July 2014.

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