



Assessment of Risk to Marine Mammals from Underwater Marine Renewable Devices in Welsh waters

Phase 2 - Studies of Marine Mammals in Welsh High Tidal Waters

On Behalf of

Welsh Assembly Government




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Executive Summary

- S.1 Current driven tidal turbines are a promising source of renewable electrical power for those countries, such as Wales, that have suitable high tidal energy areas off their coasts. To ensure that such developments occur with as little adverse environmental impact as possible it is important to better understand the ecology of the animals that make use of tidal rapid habitats. Cetaceans, which are European Protected Species (EPS) and seals, for which Special Areas of Conservation (SAC) have been designated close to and encompassing areas of tidal rapid in Wales,, are groups of particular interest, and for both there are concerns that they may suffer collisions with rotating turbine blades. In addition, turbines may act as barriers to movement, especially if many devices are deployed together in arrays. Marine mammals are often seen within tidal rapids and there are some observations that suggest that these can be important areas for them. However, our understanding of marine mammal distributions and behaviours within high tidal energy areas is actually very poor for two reasons. In the first place, tidal rapids are an extremely difficult environment in which to conduct research, especially when currents are running strongly, which is exactly the time when the potential risk of collision with turbines is greatest. Consequently, very little relevant quantitative data has been collected from these habitats. The second consideration is that these areas are a very small part of the range of any marine mammal species and are so unusual, that it is not possible to extrapolate from observations of densities or behaviour made on a much larger spatial scale outside these areas. The purpose of the project reported here was to undertake directed research on marine mammals at tidal rapid sites in Wales and to collect data relevant to assessing risks if tidal turbines were installed at these sites. As this was very much a new area of investigation a variety of research approaches were trialled and some new techniques were developed and tested.
- S.2 Cetacean research was conducted using a range of approaches: visual and towed hydrophone acoustic surveys from a dedicated research vessel, passive acoustic monitoring using static acoustic data loggers and visual observations from the shore. In addition, a new system for measuring dive behaviour using a vertical hydrophone array was developed and tested. Cetacean fieldwork took place in July and August of 2009 in the tidal rapids around the Skerries and North and South Stacks in Anglesey and tidal rapids in Ramsey Sound and off the Bishops and Clerks to the west of Pembrokeshire. Fieldwork is always heavily dependent on weather conditions. July and August 2009 were exceptionally windy and this had a particularly deleterious effect on visual data.

Seal behaviour was measured using high resolution GPS/GSM tags attached to newly weaned pups at breeding beaches close to tidal rapid sites with tags being attached in the autumn of 2009 and 2010.

- S.3 A survey design was devised for boat based visual and acoustic surveys which reduced the impact of tidal current on survey effort while ensuring that the survey areas were covered evenly at all states of the tide. Towed acoustic surveys showed that porpoise densities were high in both study areas. This was particularly the case off Pembrokeshire where rates of acoustic detection were higher than have been reported from any other locations so far. Calculated densities for both sites were also amongst the highest so far reported. The data also indicated variation in porpoise densities and distributions across the area which correlated with depth but was also related to tidal height and current flow and their temporal variations. Static acoustic loggers (tPODs) which were deployed at the Skerries and Ramsey Sound, were particularly effective in revealing tidal and diurnal patterns. In most cases more acoustic detections were made at night than during the day. Strong tidal patterns were also observed, but these were typically quite different at different sites within each study area. In some cases sites within a kilometre showed contrasting tidal and diurnal patterns. One pattern that seemed to hold in both the POD and the towed hydrophone data was that porpoise densities were higher in "flushing out" areas, areas of more turbulent waters "down stream" from the area of strongest flow. In some cases, the location of these higher density areas moved to the "other side" of the highest current areas when the tidal stream reversed. These findings show that there are patterns of differential area use within these sites which may affect collision risk and could also potentially be used to reduce it.
- S.4 Substantial numbers of common dolphins were also detected visually and acoustically in the study area off the Bishops and Clerks west of Pembrokeshire. However, there were insufficient independent encounters to model patterns of density and distribution.
- S.5 The towed hydrophone data also provided interesting information on levels of high frequency background noise at different locations and different states of the tide. Overall, background noise correlated with current speed, increasing markedly once currents rose above 1.5 m.s¹. There were also discrete areas of extremely high noise which may be caused by areas of moving sediment. This has implications for the use of acoustic monitoring to detect marine mammals and the ability of marine animals to detect and avoid tidal turbine devices acoustically.

- S.6 The use of the water column by animals in tidal rapid areas has important implications for collision risk but this is extremely difficult data to obtain from cetaceans. We developed and tested a system for measuring the depth at which porpoise vocalisations were made using a vertical hydrophone array deployed from a drifting vessel. This was very much a feasibility study but also provided useful data showing that in the study areas off Anglesey, porpoises appeared to be diving to the sea bed and making full use of the water column. Trials conducted after the end of this study have shown that the method provides accurate measures of depth and range and development of improved analysis techniques are continuing.
- S.7 Although a great deal of effort was expended on conducting visual surveys, both on the vessel and from shore, very poor weather conditions meant that they yielded very little additional useful data. However, the opportunity was taken to develop a photogrammetric localisation technique better suited to the task of localising marine mammals during shore observations.
- S.8 With the exception of a few visual sightings made during cetacean surveys, all the information on seal movements and behaviour has been collected using high resolution fastloc GPS and depth tags which relay data back via the GSM mobile phone network. These were attached to newly weaned seal pups at breeding beaches close to high tidal current sites at the Skerries, Bardsey Island and Ramsey Sound in late October of 2009 and 2010. As the data from the second deployment of tags is still being collected, a complete analysis has not yet been completed. However, some preliminary observations are highly relevant. Typically, pups spent the first month or so in waters close to their breeding beaches, spending most of this time in tidal rapid areas, apparently drifting with the current and repeatedly diving to the bottom in a pattern characteristic of foraging dives. With time, animals travelled more widely, one ranging as far as the west of Brittany. In several cases however, seals found other high tidal current areas and appeared to drift and forage within these in a similar way. It is thus clear that during the first few months of life, when individuals might be expected to be most vulnerable, young seals are making extensive use of high tidal current areas.
- S.9 This has been one of the largest concerted attempts to study marine mammals in high tidal current areas. It has provided the first quantitative information on densities, distributions of marine mammals at potential tidal current sites and new information on temporal patterns, movements and dive behaviour. The project has also made progress in developing the tools and techniques required for studying marine mammals in such challenging environments and in particular have highlighted the utility of passive acoustic

techniques. Its limitations should also be acknowledged however, cetacean field work was restricted to a few months in the summer of one year, effort was focused on only one species, the harbour porpoise, and important tools (such as the vertical array) were developed but there was insufficient time to use them to collect extensive data. Seal telemetry work has so far been restricted to only a subset of the population, newly weaned pups. We hope therefore that this will serve as a spring board to more extensive and long term studies.

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1 Introduction

1.1 Background

- 1.1.1 Renewable power generation is an important part of long-term plans for sustainable, low carbon energy production. One technology that promises significant potential for some coastal regions, including areas around the Welsh coast, is tidal power. Electrical power would be generated by placing rotating turbines driving generators within areas of high tidal current. While there could be long term environmental benefits from these devices in terms of reduced emissions and improved sustainability, immediate local environmental impacts from the construction and operation of tidal turbine plants must also be considered. Areas with high tidal currents that have been identified as preferred sites for tidal turbines are usually frequented by marine mammals; indeed there are indications that such areas may be preferred habitats (e.g. Johnston *et al.*, 2005a; Johnston *et al.*, 2005b; Pierpoint, 2008).
- 1.1.2 One of the most significant potential threats from tidal turbines has been identified as the risk of collision between marine mammals and turbine blades (Wilson *et al.* 2007). The extent to which this will prove a problem will be highly dependent on the degree to which marine mammals are able to detect and avoid turbine blades, and this information will only become available once observations can be made at operating devices. However, it is a reasonable assumption that the probability of collisions will depend quite directly on the amount of time that animals spend in the proximity of turbine blades, which equates to a fine scale density distribution of marine mammals in high tidal current areas. Because different turbines can be deployed at different depths and marine mammals spend significant time underwater, the diving behaviour of marine mammals and the proportion of time they spend at different depths are important parameters affecting collision risk. What we need to know, in effect, are the three dimensional distributions and densities of marine mammals and relate these to the potential site choices for tidal turbines.
- 1.1.3 Another area of concern is the extent to which operating turbines might disturb marine mammals, potentially excluding them from important habitats. In addition, arrays of tidal turbines may act as barriers restricting animal's movements between important areas.
- 1.1.4 High tidal current areas are a small and unusual part of the range of any marine mammal species. While there is a general belief that they may be important and

preferred areas, there is little understanding of the densities of animals in these areas, or how they use these remarkable habitats. In part, this is because the strong tidal currents and the rough sea conditions that they give rise to make these very difficult areas in which to conduct standardised surveys. In fact they would normally be avoided. A further complication is that it is expected, and has been reported, that the use of these areas by marine mammals varies with the state of the tide. Thus any survey work needs to cover the areas through all stages of the tides.

- 1.1.5 For these reasons, this project focused on fine scale and detailed surveys of cetaceans in high tidal current areas including investigations of dive depth and underwater behaviour, while attempting to gain an understanding of how these animals use high tidal current systems and their significance as habitat for local populations. This type of work poses severe challenges for conventional survey methods and there are no existing agreed procedures to apply. For this reason we planned to use a number of different and complementary approaches, allowing an assessment of methodologies to be made, while providing the required data to provide us with an understanding of the use of high tidal areas in Welsh waters.
- 1.1.6 The surveys undertaken and reported in the subsequent sections were not specifically designed as species-specific harbour porpoise surveys e.g. visual surveys and acoustic systems, and records of all species have been included in the report where appropriate. However, due to the relatively high abundance of harbour porpoises compared to other species within the study areas, most records (and consequently potential encounters with marine renewable devices are likely to involve) harbour porpoises.

1.2 Existing knowledge of porpoise distributions in study areas

- 1.2.1 Two areas of high tidal energy for which there are already plans to install tidal turbines were identified. The first was off the Skerries and South Stack in Anglesey and the second in waters to the west of Pembrokeshire, including Ramsey Sound.

North Anglesey

- 1.2.2 Harbour porpoise are present year round off the coast of Anglesey, North Wales, principally along the northern coast from Point Lynas in the east to South Stack in the west, with an increase in sightings over the summer months (Calderan, 2003; Shucksmith *et al.*, 2009). The northern coastline of Anglesey is characterised by many overlaying rocks, and a broken and uneven seabed of pinnacles and gullies with rapid changes in bottom relief. The topography, in conjunction with the area's strong currents

results in the presence of a range of fine-scale oceanographic tidal features with which harbour porpoises are often associated (Shucksmith *et al.*, 2009).

- 1.2.3 Lack of systematic survey work carried out on the northern coasts of Wales means that harbour porpoise distribution and abundance in these areas is relatively poorly known (Calderan 2003; Shucksmith *et al.* 2009; Reid *et al.*, 2003b). However, some land-based monitoring has been carried out, in particular by Marine Awareness North Wales. This group also conducted boat-based visual line-transect surveys between 2002 and 2004. These vessel surveys estimated an absolute abundance of 309 animals along the northern coast of Anglesey over the summer months. 65% of all porpoise detections were in waters between 30 and 45 m deep, and 75% of sightings were made within 5 km of land (Shucksmith *et al.*, 2009).
- 1.2.4 Shucksmith *et al.* (2009) found the highest porpoise densities along the Anglesey north coast to be at Point Lynas and South Stack, both of which the authors suggested as foraging grounds for porpoises, with animals taking advantage of the tidal features which are assumed to aggregate prey. Calderan (2003) also found regular harbour porpoise presence in the waters around Middle Mouse (Ynys Badrig). Presence, absence and apparent foraging behaviour at the site were strongly dependent on the state of tide, with the highest densities and levels of activity being during the flood phase.

Pembrokeshire

- 1.2.5 The harbour porpoise is the most commonly encountered cetacean on the Pembrokeshire coast (Reid *et al.*, 2003a, Baines and Evans, 2009). The species is present throughout the year (Evans *et al.*, 2003, Pierpoint, 2001). A region-wide acoustic and visual survey (Pierpoint, 2001) located concentrations of animals off the estuary of the River Teifi, at Strumble Head and close to the Pembrokeshire Islands. The species is believed to breed locally (Penrose and Pierpoint, 1999); approximately 24% of schools observed in July included neonate calves. There is very little information on the local movements of individual animals, or that identifies the factors that cause porpoises to regularly occupy specific locations. The region however, has been identified as being of particular importance for harbour porpoises within the UK (Evans and Wang, 2002).
- 1.2.6 A number of studies have been carried out at near-shore sites with good vantage points that regularly attract aggregations of porpoises. Highest numbers of animals (< 100 at any one time) have been recorded at Strumble Head (Pierpoint *et al.*, 1994). Strumble Head is a prominent headland about which extensive tidal races form. Harbour porpoises are often observed within the tidal rips, upwellings and overfalls surfacing

amongst feeding seabirds. Land-based observations have been carried out at Ramsey Sound since 1992 (Pierpoint, 1993; Barradell, 2009). Tidal races form in Ramsey Sound where the tidal stream is constricted by coastal and seabed topography, between Ramsey Island and the mainland. Pierpoint (2009) speculates that harbour porpoise exploit a regular occurrence and accessibility of prey in Ramsey Sound. Porpoises appear to occupy this site awaiting prey that is carried to them and concentrated by the tide. This site supports groups of 1-18 animals. Newport Bay on the north Pembrokeshire coast is an embayment without strong tidal features. A study using passive acoustic data-loggers however, found that porpoise detection rates were far higher at night than during daylight hours (Pierpoint *et al.*, 2000). The nocturnal peak in activity was again believed to be associated with the accessibility of prey, particularly in the early winter when herring visit the bay to spawn.

1.3 Existing knowledge of grey seal distribution in study areas

Numbers of seals at haul-out sites

- 1.3.1 Data on the number of grey seals at haul-out sites around the Irish Sea are sparse. For the analysis here (Chapter 7), data were taken from several sources:
- Scotland and Northern Ireland: data from SMRU aerial surveys in 1996-2008 (SCOS 2009);
 - Irish Republic: data from aerial surveys and ground counts in 2003 (Cronin *et al.* 2004); and
 - Wales: ground count data (Wescott and Stringell, 2004; Keily *et al.*, 2000).
- 1.3.2 Numbers of seals associated with all known haul-out sites are grouped together, based on the telemetry data, to give a single figure for each of seven haul-out regions.

Telemetry data analysis and space use modelling

- 1.3.3 In previous tag deployments in Welsh waters, Argos location data were filtered to smooth the tracks and minimise the error associated with the locations before being included in the model. The high resolution GPS data provided by the current tags means that this stage can be omitted from this study (see Section 7). Tracks for each animal were split into individual trips, defined as beginning when an animal first dived to over 10 m after a haul-out period and ending when the animal hauled out again. Each trip was assigned to one of the seven haul-out regions.

- 1.3.4 Data on seal movement (speed, trip duration, locations of haul-outs, and obstacles to movement) were used to calculate the accessibility of points at sea as a function of distance from the centre of a haul-out region (Matthiopoulos, 2003a). Maps of accessibility were used to inform estimation of space use by each seal. Estimates of uncertainty were calculated through combining estimates of usage for all tagged individuals. Usage maps were weighted for the number of seals within each haul-out region.
- 1.3.5 The main product from this analysis was a seal usage map, equivalent to a density contour plot for the estimated distribution of seal activity at sea. The usage map generated from deployment of 19 Argos satellite transmitters is shown in Figure 1-1 for illustration.

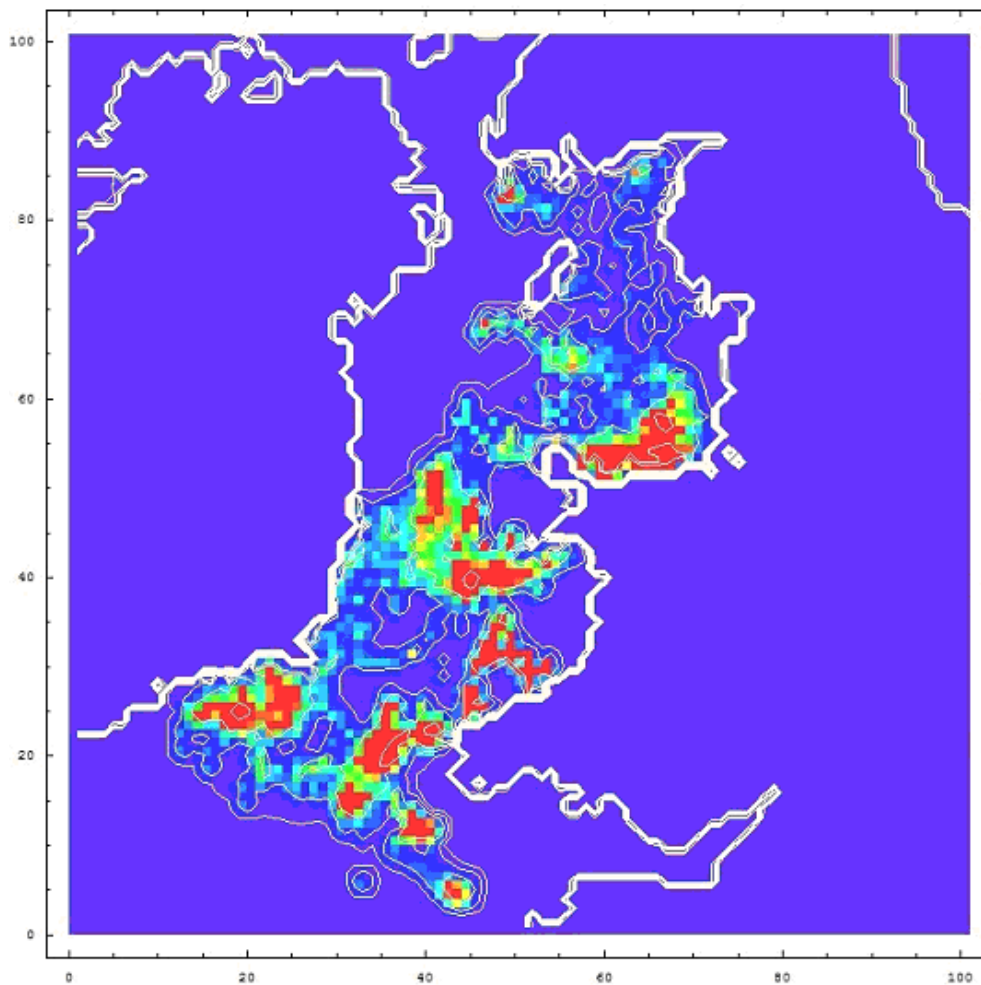


Figure 1-1 The modelled at-sea usage for grey seals in the Irish Sea based on data from 19 satellite transmitters attached to adult grey seals in 2004.

1.4 Report structure

1.4.1 This report is divided into the following chapters: Chapter 2 provides an overview of the harbour porpoise work schedule and survey effort; Chapter 3 provides details and discussion on the boat based visual and towed acoustic surveys; Chapter 4 on the use of TPODs to describe aspects of harbour porpoise ecology in high tidal habitats; Chapter 5 on the use of vertical array for recording harbour porpoise activity; Chapter 6 provides a brief overview of shore based observation of marine mammal activity; and Chapter 7 on the preliminary results the grey seal tagging trial. Chapter 8 provides a general discussion and conclusions based on an overview of all of the surveys undertaken as part of this project, and recommendation for future work in this field.

2 Harbour Porpoise Work Schedule and Survey Effort

- 2.1.1 There have been relatively few attempts to survey cetaceans in high tidal current areas. The habitat poses some substantive challenges and there are no universally recognised methods for conducting quantitative surveys. Thus, we started by adopting a broad approach including methods utilising land and boat based visual observation as well as towed and static acoustic monitoring for harbour porpoises. This would allow us to gauge the potential and problems of different approaches and focus effort on the most promising ones once identified.
- 2.1.2 Published studies have suggested that areas characterised by both the highest tidal streams, and the areas of outflow and disturbed water either side, are particularly important for marine mammals (Pierpoint, 2008, Johnston *et al.*, 2005). These observations were used to set the scale of our study areas, covering “tidal systems” rather than simply small areas with the highest stream rates.
- 2.1.3 Off Anglesey, survey blocks were delineated for two areas, one based around the channel between the Skerries and the mainland and the second in the area between North and South Stacks (Figure 2-1). Off Pembrokeshire, the principal survey block was an area to the west of the Bishops and Clerks islands, an area which, unlike Ramsey Sound, cannot be observed from land and is comparatively poorly known in term of cetacean densities, yet holds substantial potential interest as a site for tidal turbine installations (Figure 2-2).

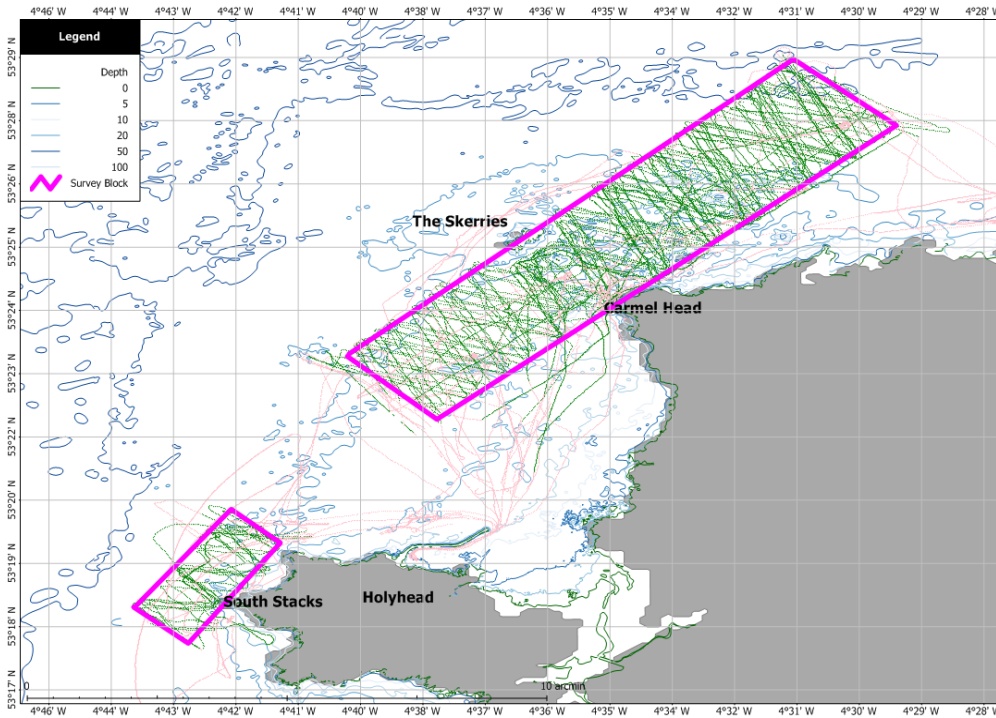


Figure 2-1 Study sites off the Skerries and South Stacks in northwest Anglesey. Green lines show survey tracks on designed survey effort, light pink lines show tracks collecting acoustic data but off designed survey effort.

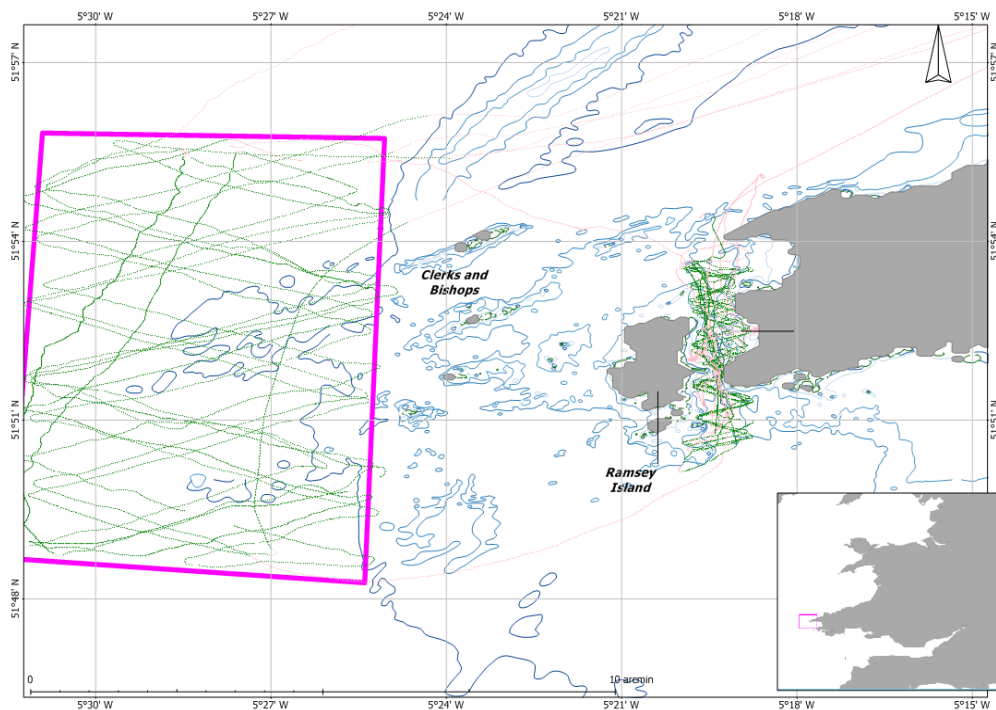


Figure 2-2 Map of Pembrokeshire study sites. Green lines show survey tracks on designed survey effort, light pink lines show tracks collecting acoustic data but off designed survey effort. See Figure 2-1 for bathymetric contour key.

- 2.1.4 Vessel based work was undertaken in the Skerries field site between 20th July 2009 and 13th August 2009 and at the Pembrokeshire site between 14th August 2009 and 28th August 2009 (a daily summary of boat based activities is provided in Appendix 1). Static passive acoustic detection devices were also deployed at both sites between 21st July 2009 and 12th August 2009 in the Skerries and 17th August 2009 and 25th September 2009 at Ramsey Sound. Shore-based observations were conducted from Carmel Head in the Skerries survey areas between 25th July 2009 and 11th August 2009 and in Ramsey Sound between 2nd September 2009 and 18th September 2009. The success of porpoise fieldwork, especially that involving visual observation, is highly dependent on good weather conditions. Analysis of visual sighting survey data for harbour porpoises shows that sighting rates fall off rapidly once sea state rises above Beaufort 1 (Palka, 1996). Conditions might be considered “fair” up to Beaufort 2 and any pretence at conducting productive visual surveys is typically abandoned above Beaufort 3. Areas of high tidal current with tidal features such as standing waves result in “sea states” that diminish detectability even in the lowest wind speeds, and also exacerbate the effect of wind speed on sea state and sighting conditions.
- 2.1.5 Figure 2-3 and Figure 2-4 show the daily average wind speeds for the periods of boat-based field work off Anglesey and Pembrokeshire respectively, based on data from the closest oceanographic data recording buoys. On these plots, the orange and red lines show the thresholds for “fair” and “possible” conditions respectively for visual porpoise surveys. It is clear that, although the survey periods were chosen to maximise the probability of experiencing calm conditions, the weather was extremely poor, and much worse than would be expected at this time of year in these locations. In fact, over the entire study period, we experienced just two half days of good porpoise sighting weather while we were working off Anglesey, and none at all off Pembrokeshire. This inevitably seriously impacted field work, especially that which involved visual survey.

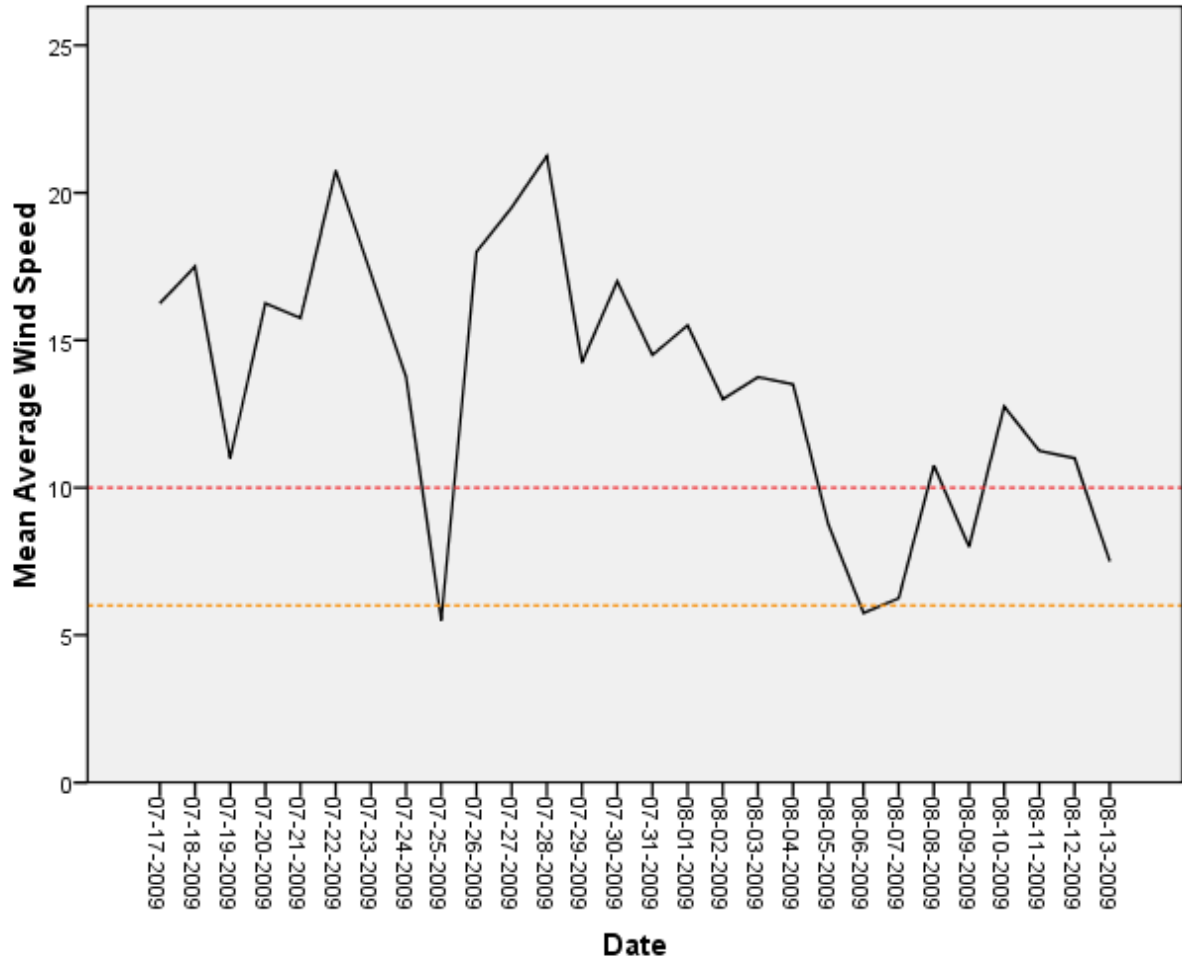


Figure 2-3 Mean daily wind speed during field work off Anglesey region based on data from Liverpool Bay oceanographic data buoy (#62125 53.80°N 3.5°W). Orange line shows threshold between force two and three which might represent the upper limit of “fair” visual conditions for visually based porpoise research, red line shows boundary of force three and four which is the upper limit for “possible” conditions for porpoise visual observations

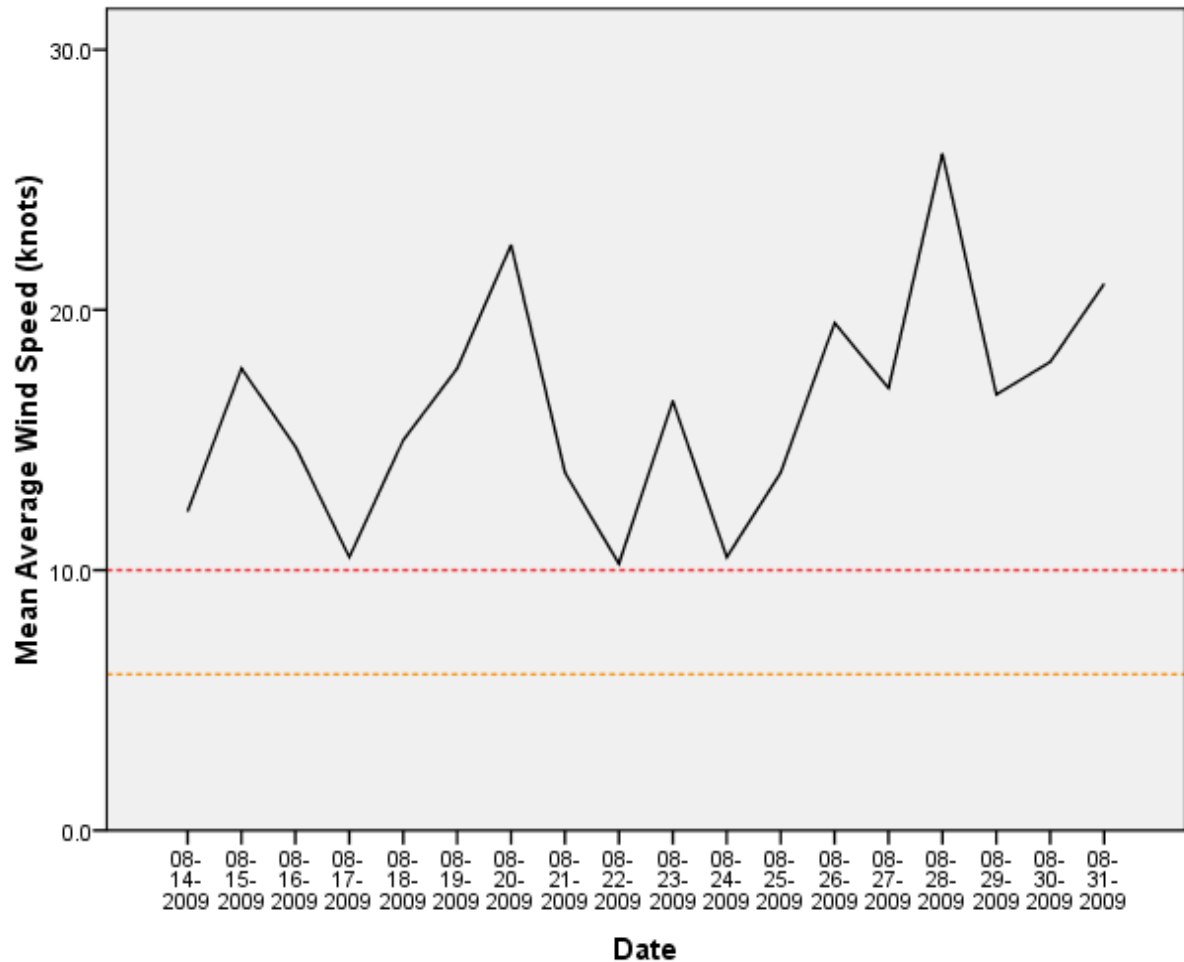


Figure 2-4 Mean daily wind speed off Pembrokeshire region during period of fieldwork based on data from Pembrokeshire Bay oceanographic data buoy (#62303 51.603°N, 5.1°W). Orange line shows threshold between force two and three which might represent the upper limit of “fair” visual conditions for visually based porpoise research, red line shows boundary of force three and four which is the upper limit for “possible” conditions for porpoise visual observations.

3 Visual and Acoustic Boat Based Surveys for Harbour Porpoise and other Marine Mammals in High Tidal Areas

3.1 Introduction

3.1.1 Boat based visual line transect survey is probably the commonest approach employed for making population estimates of cetaceans, including harbour porpoise, and a substantial amount of work has gone into developing methods to analyse data from such surveys (Thomas *et al.*, 2010). Large scale population surveys in both Europe, (Hammond and Macleod, 2003; Hammond *et al.*, 1995) and North America (Palka, 2000; Barlow and Hanan, 1995) have relied on data collected from ship board surveys to calculate abundance and population estimates for harbour porpoises. In recent years towed acoustic survey equipment has increasingly been used alongside visual techniques on ship board line transect surveys and these have proven particularly useful on harbour porpoise surveys (Gillespie *et al.* In review; Chappell *et al.*, 1996; Gillespie and Chappell, 2002; Gillespie *et al.*, 2005).

3.2 Methods

Survey design

- 3.2.1 Marine mammal surveys have rarely been carried out in areas of high tidal current and there is as yet no consensus on the most appropriate methodologies to apply. High tidal currents pose several survey design problems as discussed in the next few paragraphs.
- 3.2.2 When surveying from a vessel within a water mass that is moving at significant speeds, there is a substantial difference between the vessel's tracks and consequent survey effort through the water and those over the seabed. Thus, a researcher needs to decide at an early stage whether the survey is of a water mass or of a geographical space. In some cases, which of these is appropriate will be clear. For instance, if surveying passive plankton, one would design a survey of a water mass, whereas if the target were a sessile benthic organism, such as a coral, one would survey geographical space. The appropriate perspective is less clear-cut when surveying actively swimming animals, such as marine mammals, that may or may not maintain station within currents. Design is further complicated by the fact that the strength of current will vary both spatially and temporally.

- 3.2.3 For this project, it was decided to consider the survey to be of a geographical space rather than a moving water mass, principally because tidal turbines are certainly fixed in space as, to a lesser extent, are tidal features in the water column, such as overfalls and rips. Furthermore, some observations of marine mammals in high tidal stream areas report individuals maintaining station in currents (e.g. Pierpoint, 2008).
- 3.2.4 A zig-zag survey design across and in the direction of the current was selected. The angles of the survey tracks made in relation to the current direction were chosen such that for a constant vessel speed through the water the speed over the bottom would be the same at both zero current and at the maximum expected tidal current, and between these extremes bottom speed would not vary by more than 7%. Maintaining constant boat speed through the water was particularly important for the consistency of the acoustic data since boat speed is a major factor determining noise. A number of survey legs with turning angles of 44 degrees and different starting locations were laid out for each survey block with a range of different starting points. For each survey run available (i.e. not previously completed), tracks were chosen in a non-systematic manner.
- 3.2.5 To achieve these tracks it was necessary to adjust the vessel's heading more or less continuously over the course of each leg to allow for the effects of current. This required constant attention from the helmsman but was certainly a more practical approach than alternatives such as adjusting boat speed. Even so, maintaining the designed survey tracks was challenging in areas with strong and variable tidal currents and with numerous navigation hazards to avoid.
- 3.2.6 Because, by design, survey tracks would only be conducted in the direction of the current, the vessel would often have to motor directly against the current between consecutive survey routes, often on tracks that avoided the strongest currents. During such "passages" full acoustic effort was maintained but often visual effort was reduced to allow visual teams to rest or attend to other tasks. These data will not be treated as part of the main survey but may provide useful additional distribution data (see Figure 2-1 and Figure 2-2).
- 3.2.7 Another important consideration when designing surveys in high tidal current areas is that it is expected that the spatial distribution of animals will vary temporally in these areas, in particular with the tidal state. Thus, in addition to attaining an even spatial coverage (as one would seek to do in a standard survey) one would also like each area to receive equal coverage during each state of the tide. To address this, the spatial extent of the survey effort during different tidal states was computed and noted and,

where possible, the timing of surveys was adjusted to attempt to achieve near-even spatial coverage over different tide states.

- 3.2.8 A final concern is the fact that the tidal flow affects the ease at which animals can be detected. For instance, at the surface, tidal features such as standing waves, rough patches and overfalls will all make animals harder to detect visually. In addition, levels of underwater background noise can be affected by tidal currents, probably as a result of water turbulence and the movements of sediments. This will affect acoustic detection. These factors complicate conventional survey analyses and need to be taken into account at the design stage. To partially address these issues, we employed two completely different detection methods, visual and acoustic, which are likely to be affected differently by such features. We also updated information on sighting conditions within the sightings database frequently, whilst background noise was logged continuously.
- 3.2.9 Some of these design and methodology issues were discussed at a workshop that participants in this study were involved in organising. This was held at the University of St Andrews Centre for Research in Ecology and Ecological Modelling (CREEM) in June 2009.

Research vessel

- 3.2.10 The vessel used as the survey platform for this project was “Boy Brendan”, a 55’ displacement motor vessel operated by Sea Wide Surveys, Falmouth. It was selected as it had a number of features that suited it for this work. These included: (a) being equipped with a capable crane and winches and a crew with extensive experience of deploying and retrieving gear over the side; (b) mounts for depth sounders and sonar on the bow and the beam; and (c) the ability to accommodate four scientists on board. A scaffolding tower was constructed on the foredeck to provide a secure lookout location for up to three observers with a height of eye of ~5m (Figure 3-1).



Figure 3-1 Left panel: *Boy Brendan*, showing sonar bow mount on starboard bow and the scaffolding viewing platform.

Visual data collection

3.2.11 Visual data were collected using the highly automated system developed for the SCANSII survey (Gillespie *et al.* in press) (see Figure 3-2). This is based on the Logger data collection program originally supported and made available by IFAW (the International Fund for Animal Welfare). The Logger software stores data in a single integrated Microsoft Access database. Data validation and error checking were performed, usually at the end of each working day, with the help of dedicated software developed for the SCANSII survey in 2005.

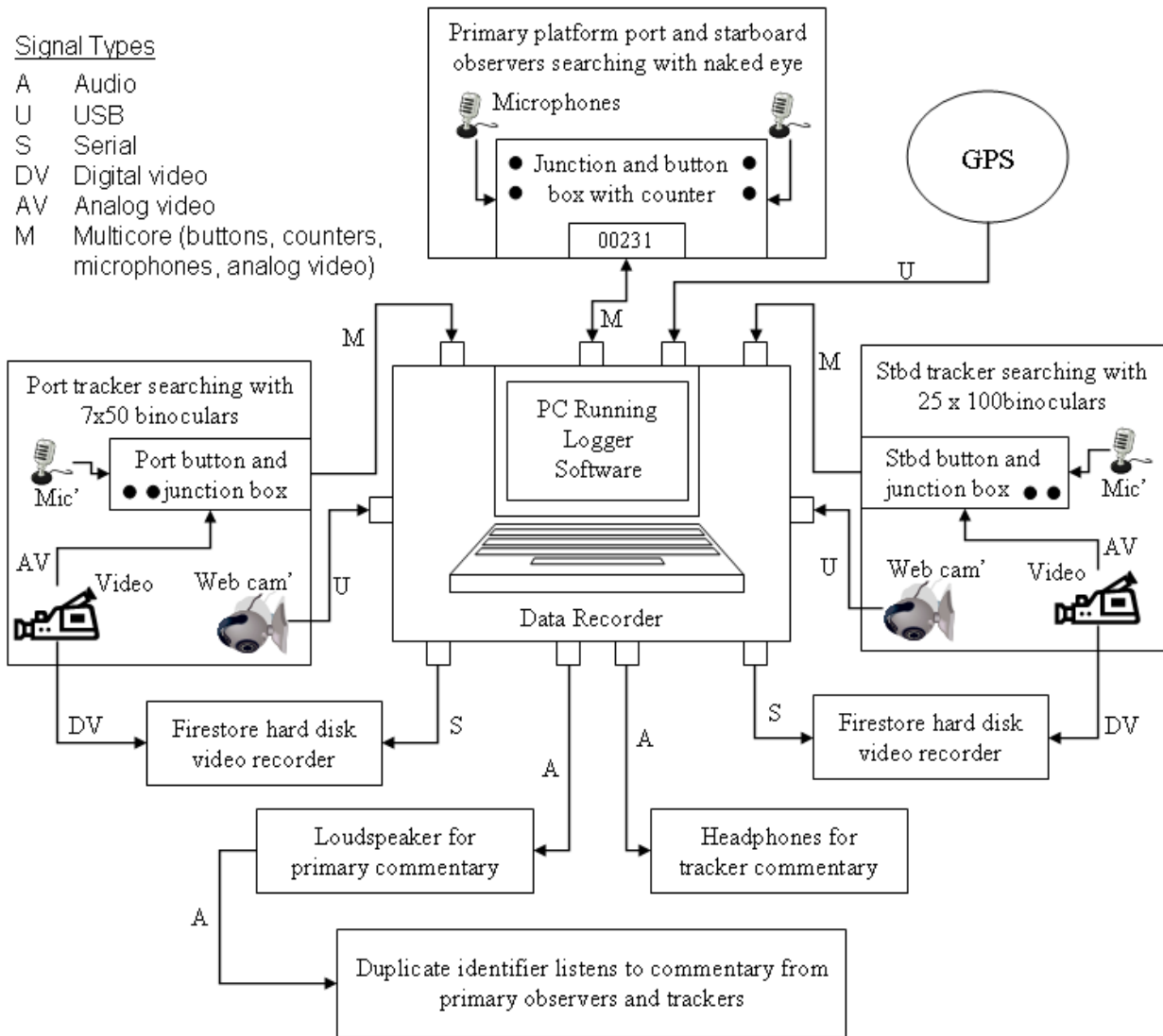


Figure 3-2 Schematic of data collections system developed for SCANSII survey. This system was used for this survey but with only a single tracking station (the Port Tracker in the scheme above).

3.2.12 When conditions allowed, visual data were collected from the sightings platform by a team of three observers. Two primary observers, one to port, the other starboard, searched from the track line to the beam with the naked eye. These observers are referred to as “primary” observers. Marine (7x50) binoculars were used as required to investigate sightings further. A third observer, the “tracker”, was stationed between them and searched a more restricted sector (approximately 60 degrees either side of the trackline) using 7x50 binoculars coaligned with a high definition video-based range measuring system. The three observers worked as a single team as, with only one small platform, it was not feasible to use methods requiring independent observers.

- 3.2.13 A data recording station was established on the vessel's bridge. Here a fourth researcher, the data recorder, entered data into customised forms in the Logger program which ran continuously on a laptop computer. Logger also automatically recorded data on the vessel's position from the ship's Hemisphere Vector GPS unit. In addition to providing data on the vessel's location, speed and heading over ground, the Hemisphere GPS system gave a continuous accurate measure of the vessel's heading (in such high currents this was often quite different to the direction of movement provided by a standard GPS). The data recorder used headphones to listen to voice channels from all three observers and could communicate with them using handheld radios.
- 3.2.14 When primary observers made a sighting they pressed their "sighting" button. This triggered Logger to open a time-stamped sighting form and to initiate an audio recording. These recordings were time buffered so that several seconds of sound before the button press were also captured. They were intended to be used during data validation to check the details of any sighting. The data recorder filled in as many details as possible on the forms opened by sighting button key presses. Subsequent sightings believed to be resightings of the same animal were marked by pressing a different "resighting" button. The bearing to animals and their headings were assessed with the help of angle boards mounted on the platform. Ranges were estimated by eye or measured using the reticules in the binoculars or with a sighting stick held at arm's length¹.
- 3.2.15 The "tracker" had a third set of sighting and resighting buttons. In addition to opening the appropriate time-stamped forms and initiating audio recording, pressing the tracker buttons caused Logger to start recording video from a camcorder mounted on a frame so that it was coaligned with the tracker's binoculars with the same field of view. These recordings were made using a Focus Enhancements FS4 Firestore hard disk recorder, a device that incorporates a six second video buffer, so that the six seconds of video before the key press (which would thus include the cues that initiated the sighting) were also recorded. This feature has proven extremely useful when attempting to record range video from animals such as harbour porpoises which are only fleetingly visible at the surface. Frames from video sequences that showed both the horizon and the object

¹ Several bespoke sighting sticks were made to match individual observer's eye height on the platform and their arm length.

of interest were captured and analysed during validation to provide an accurate measure of range.

3.2.16 The video/binocular frame also held a downward facing webcam. The angle in which the binoculars were pointing at any time could be determined by measuring the angle of lines marked on the floor of the observation tower running across ship on captured webcam frames. Pressing the tracker buttons triggered Logger to capture ten frames from the webcam. Angles relative to the vessel were measured during validation to determine the bearing to the sightings.

3.2.17 In addition to information on marine mammal sightings, data were also collected for all feeding seabird groups observed within 100 m and for all vessels within 1 km. Tidal features passing within 50 m of the vessel's track were also noted. Tidal feature types included:

- Tidal race: main body of fast moving water;
- Tidal boil: a circular area of smooth water where a small upwelling is occurring;
- Standing wave: waves induced by current. Often confused they may appear to be stationary;
- Front: the boundary between two different water masses; and
- Whirlpool: a swirling body of water, usually with a central downwelling.

Towed passive acoustic monitoring

3.2.18 Porpoises can be detected acoustically using hydrophones to pick up their underwater vocalisations and specialist software to detect them. Harbour porpoise use narrow band ultrasonic (115-135 kHz) pulses for echolocation (Verfuss *et al.*, 2009). Because these vocalisations are well above the human auditory range, special equipment and digital signal processing is required to detect them. Effective detection range is typically in the order of 200 m (Chappell *et al.*, 1996; Gillespie and Chappell, 2002). Acoustic detection is generally less affected by weather conditions than visual detection and can continue in poor sighting conditions and at night, which are both highly significant practical advantages.

3.2.19 Towed hydrophone survey equipment, similar to the system developed for the SCANSII surveys (Gillespie *et al.* In review) was deployed and operated whenever the vessel was at sea. The towed hydrophones consisted of pairs of Magrec HP03 hydrophone units separated by 25 cm mounted in a 5 m long 35 mm diameter oil-filled polyurethane tube

towed on 100 m of strengthened cable. Each HP03 is made up of a 12.7 mm piezoelectric ceramic sphere connected to a 35 dB preamplifier which incorporates a 2 kHz low cut filter to reduce lower frequency background noise. The nominal bandwidth of the element and preamplifier is 2 – 150 kHz. Signals from the hydrophone pairs were conditioned and further amplified using a Magrec HP27ST amplifier filter box. Signals to be used for porpoise detection passed through a 20 kHz high-pass filter before being sampled by a National Instruments USB-6251 high speed digital acquisition card controlled by an Asus Boxer 12v computer. The maximum sampling rate of the NI 6251 is 1.2 MHz. For survey, two channels were each digitised at 500 kHz, providing a sampled acoustic bandwidth of 250 kHz. The accuracy of depth measures with the vertical array were confirmed using an artificial ‘porpoise’ sound source.

3.2.20 Data were processed onboard in real time using the IFAW “Rainbow Click” click detection and classification program with detectors optimised for harbour porpoise to provide real time information on acoustic detections (Gillespie *et al.* In review). Although porpoise detections were often seen on the program’s display in real time, this information was never relayed to visual observers. Rainbow Click files were analysed every few days to provide preliminary quick look information on porpoise detections.

3.2.21 In addition, full bandwidth digitised data were recorded continuously. These data were reanalysed carefully after the survey by a single researcher (SC) to provide a consistent high quality dataset of detections and estimated ranges from the track line. The recordings were also processed to provide a measure of the acoustic energy every second in the frequency band processed by the click detector in Rainbow Click. The filter exactly matched that used by Rainbow Click with a passband of 110-150 kHz and a decaying average time constant of 0.2 seconds. This provided a measure of background noise that was most likely to directly affect the program’s ability to detect porpoise clicks.

3.2.22 These full bandwidth recordings also provide information on spatial and temporal patterns of high frequency (>20 kHz) noise fields in the area. Medium frequency acoustic signals (2-22 kHz) were also recorded continuously through an Edirol sound card with a 48 kHz sampling rate².

² Analysis of these recordings could be very useful in predicting how the background noise could affect the ability of animals to detect tidal turbines either passively, by detecting the noise the turbines themselves or actively, using echolocation.

Modelling of spatial and temporal distribution patterns of harbour porpoise

3.2.23 An investigation of the factors that affect porpoise abundance within an area requires an absolute or relative index of density across a representative range of values for potential spatial and temporal covariates. The simplest models utilise data from directly comparable designed surveys, but more complex models could integrate from different survey types alongside other information from static sources such as TPODs. For the initial modelling, the acoustic survey data provided the largest and most consistent data set. Acoustic data provided locations of porpoise groups that were detected but interpreting group size was problematic. Therefore, for this analysis the group size was taken from the visual data.

3.2.24 Acoustic data within the two designed survey blocks (Carmel Head/Skerries and Bishops and Clerks) were divided into 250 m segments of track line and an average value for each covariate was derived for each segment. Porpoise presence was modelled as binary data with either porpoises detected or not.

3.2.25 For each segment i , the probability that a group of porpoises will be present was modelled as a Logit link function:

$$p_i = \frac{e^{\varphi_i}}{1 + e^{\varphi_i}} + \alpha_i$$

3.2.26 Where α_i is an error term and φ_i is a linear function of environmental covariates:

$$\varphi_i = f_1(x_{1i}) + f_2(x_{2i}) + \dots$$

3.2.27 With each f_j a smooth function of environmental covariate x_j . Terms involving more than one environmental covariate may also be included e.g. the smooth function may be expressed in terms of an interaction between covariates x_n and x_m as $f_k(x_n; x_m)$.

3.2.28 Models were fitted using the mgcv library within R (Wood, 2006). Model selection was based on minimising the Un-biased Risk Estimator (UBRE) value for the model. This is equivalent to the Akaike Information Criteria re-scaled to the known scale parameter of 1 used in a binary model (Wood, 2006). We were not able to conduct an exhaustive set of all possible models as done by Isojunno (2008). Instead we used combinations of covariates where there was some prior reason to expect an effect. However, inevitably some slightly arbitrary choices were made and there would be further scope for additional model development. Thin plate smoothing splines were used in all cases

based on the properties described in Wood (2006) with the smoothing parameter λ fixed at 1.4. Noise level measurements which are known to affect acoustic detection rates were included in all models.

3.2.29 A specific interest for this study was the relationship between porpoise distribution and covariates related to state of the tide and tidal flow. Thus these covariates were included in exploratory models.

3.2.30 A variety of data from a range of sources (see Table 3-1) were collated using Manifold GIS and Microsoft Access for potential use as covariates. The models that seemed most informative in terms of being able to explain spatial and temporal variation in density were used to make predictions of densities for the two study areas for particular times in the tidal cycle and these were plotted as surfaces using Manifold.

Table 3-1 Summary of covariates used in the modelling process

Value	Units	Source
Location	Latitude Longitude	GPS
Noise	Relative Sound Pressure Level dB	Analysis of recordings
Tidal time	Relative position in daily tidal cycle	Calculations based on Belfield Tide Plotter
Tidal Range	Tidal range in m of current tide	Calculations based on Belfield Tide Plotter
Tidal Cycle	Relative position in the lunar tidal cycle	Calculations based on Belfield Tide Plotter
Predicted Tidal Current Speed and direction	Speed m.s^{-1} Direction N/S and E/W vectors	Polpred software. Proudman Laboratory
Predicted Maximum Spring Flood and Spring Ebb Currents (Skerries Only)	Fine scale prediction of current speed m.s^{-1} for Skerries region only	GIS processing of image provided by Marine Current Turbines Ltd
Bathymetry Depth	m	Gridded data on (1/10 th minute) resolution. SeaZone Hydrospatial dataset
Bathymetry Aspect	degrees	Derived from bathymetry using GIS
Bathymetry Slope	degrees	Derived from bathymetry using GIS

Value	Units	Source
Marine Habitat Type	EUNIS Habitat Codes	Mesh website http://www.searchmesh.net/
Bottom Type		Derived from BGS SeaZone data using GIS analysis
Range from closest high noise "sediment" patch	Nautical miles	GIS analysis of collected data
Range from closest tidal features of each type	Nautical miles	GIS analysis of collected data

3.3 Results

Survey effort by tidal Cycle for the Skerries

3.3.1 Figure 3-3 provides an indication of how survey effort was distributed with state of tide in the Skerries survey block. The tracks themselves indicate that overall the survey coverage was even and intensive. From the plots showing coverage by tidal hour for different two minutes of latitude (two nautical mile) sections it can be seen that, although the distribution of effort was not completely uniform across the tidal cycle in each block, the core areas were well-covered on all tidal states. There were insufficient data from other surveyed areas (South Stacks, Ramsey Sound and the Bishops and Clerks block) to conduct this type of analysis.

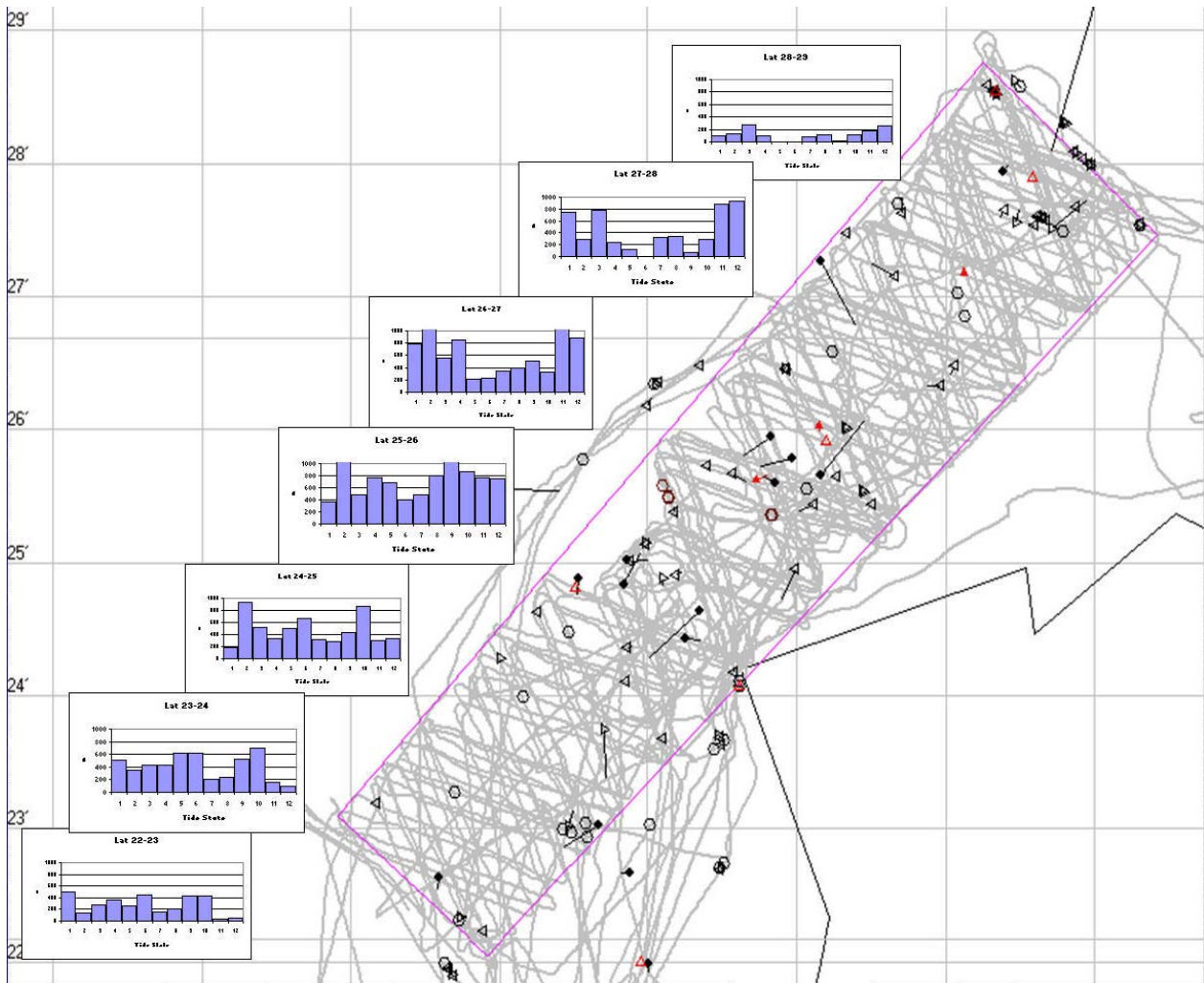


Figure 3-3 The distribution of effort spatially and temporally within the Skerries Survey Block. Bar charts show distribution of effort by tidal hour for two minutes (2 nautical miles) of latitude sectors.

Visual sightings data

Marine mammals

3.3.2 The very poor weather conditions, discussed above, greatly limited the quality of the visual data that were collected and for this reason we have based most quantitative analysis on acoustic rather than visual detections. Figure 3-4 and Figure 3-5 show all marine mammal sightings made in the two study areas. Off Anglesey the vast majority of cetacean sightings were of harbour porpoises with a single encounter with a bottlenose dolphin. There was also a sighting of bottlenose dolphins off Carmel Head by the shore based observers during this time. Sightings of grey seals were mainly to the north and east of Carmel Head. Off Pembrokeshire the majority of sightings were of common dolphins in the western part of the Bishops and Clerks survey blocks (one small group of

common dolphins was also observed passing through Ramsey Sound while the survey vessel was at anchor). Grey seals were sighted in the eastern part of the Bishops and Clerks study area.

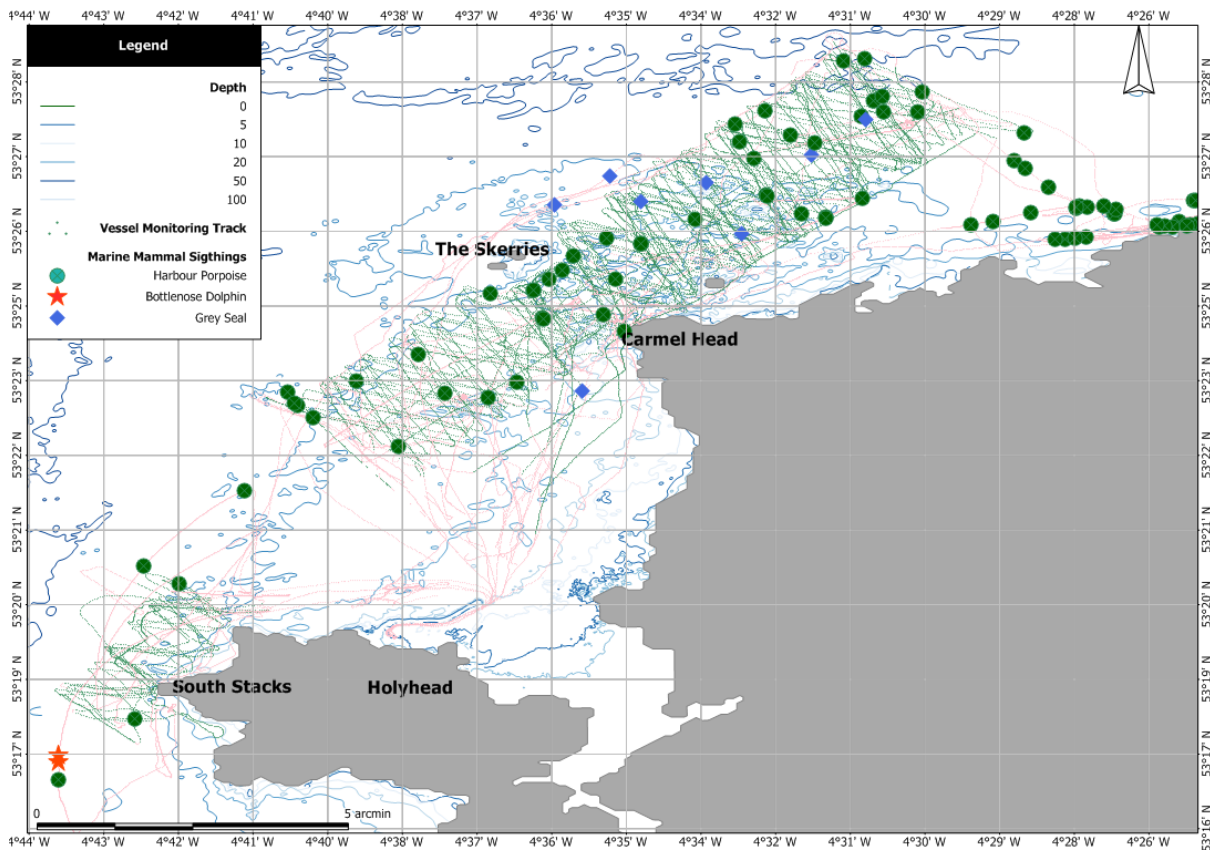


Figure 3-4 *Distribution of all marine mammal species made off Anglesey during the summer of 2009. All survey tracks are shown- Green designed effort, pink non designed effort.*

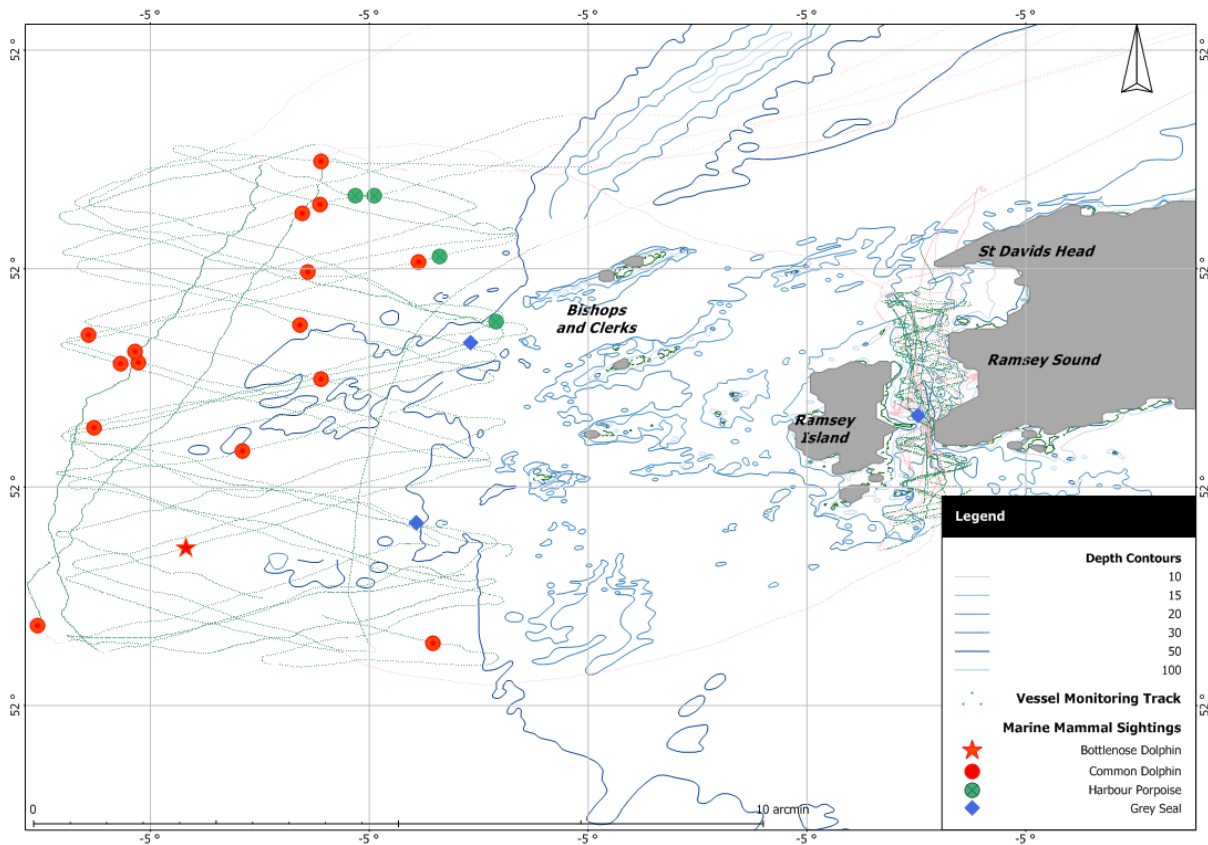


Figure 3-5 *Distribution of all marine mammal species made in Ramsey Sound and off the Bishops and Clerks islands, Pembrokeshire during the summer of 2009. All survey tracks are shown- Green tracks show designed effort, pink non designed effort.*

Seabirds

3.3.3 Groups of seabirds that appeared to be feeding and passed within 100 m of the vessel were recorded during surveys and these are plotted in Figure 3-6. The group most often seen “feeding” (diving down to the surface) were terns. The generic grouping “Other Birds” included herring gulls, kittiwakes and auks.

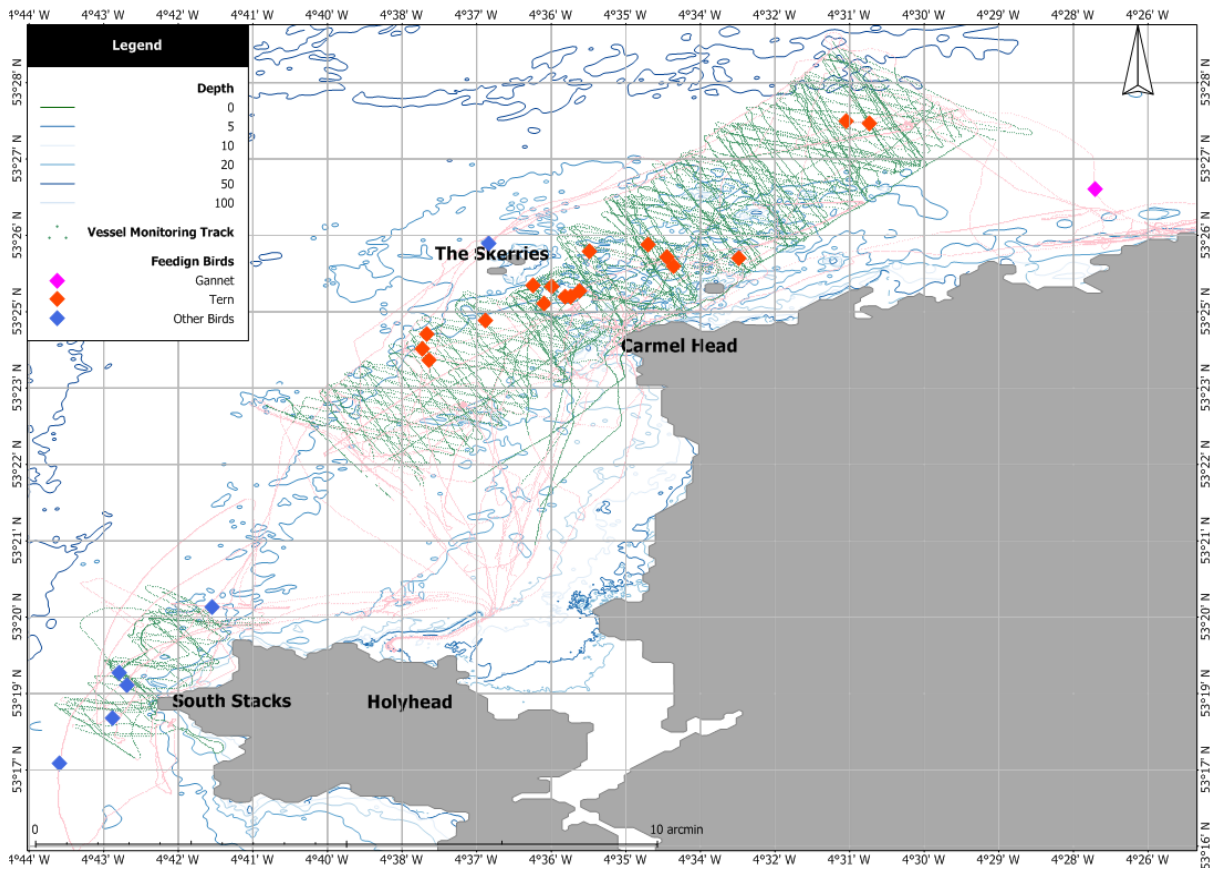


Figure 3-6 Locations at which groups of feeding seabirds were noted within 100 m of the track line off Anglesey in summer 2009.

Porpoise group size from visual observations

- 3.3.4 Porpoise group size is difficult to determine acoustically. We have used visual data to estimate this and these data are summarised in Table 3-2.
- 3.3.5 Although the mean group size for the Ramsey area was higher, this was largely as a result of a single observation of six individuals. The differences were not significant between areas of between Primary and Tracker observations (ANOVA, $df=88$, $f=2.8$, $p=0.07$). Therefore all data were combined to give a mean group size of 1.51 (SD 0.85).

Table 3-2 Porpoise group sizes estimated by Primary and Tracker observers from the Skerries/Carmel Head and Bishops and Clerks surveys sites (number of groups, mean group size and SD – standard deviation)³.

	Primary				Tracker			
	Number of groups	Mean Group Size	SD	Max	Number of groups	Mean Group Size	SD	Max
Carmel Head Skerries, off Anglesey	48	1.38	0.61	3	33	1.55	0.83	4
Bishops and Clerks, off Pembrokeshire	8	2.13	1.73	6	0	n/a	n/a	n/a

Acoustic monitoring

3.3.6 Acoustic survey effort completed in the two study sites is summaries in Table 3-3.

³ See Section 3.2.12 for definition of primary and tracker observers.

Table 3-3 Summary of acoustic monitoring effort and marine mammal detections in the Skerries/Carmel Head and Bishops and Clerks surveys sites⁴.

	Designed survey completed (nm)	Single Tracks Porpoise Encounter	Multiple Tracks Porpoise Encounter	Events Porpoise Encounter	On Axis Porpoise Encounter	Click Porpoise Encounter	Dolphin Acoustic Encounter
Carmel Head Skerries, off Anglesey	607	30		27	1	14	
Bishops and Clerks, off Pembrokeshire	232	37	1	36		13	6

Background noise

3.3.7 Distinct areas with very high levels of background noise were noted during the acoustic surveys. These were apparent as dense concentrations of "unidentified clicks" in the Rainbow Click analysis program and usually these could be seen to be localised and discreet. Typically they were shown with clear acoustic bearings which could be tracked from bearings ahead of the vessel to bearings astern as the vessel moved by them. Our assumption was that these noise events were due to sediment moving in the tidal flow, possibly from gravel beds. The location of all such "sediment noise" events identified during offline acoustic analysis for harbour porpoise (see Acoustic Detections) are shown in Figure 3-7. Often the locations of these events were consistent between different surveys and in some case they seem to be grouped into bands running along the axis of the current (as might be expected if they were indeed associated with particular sediment beds). Sedimentologists have used passive acoustic monitoring to measure movement of marine sediments in currents. Levels of noise correlate with sediment transport weights, while spectral analysis of signals can provide information on the size of particles in the moving sediment (Mason et al., 2007; Thorne, 1985; Thorne, 1986; Voulgaris *et al.*, 1995).

⁴ See Section 3.3.9 for explanation of different porpoise acoustic encounter types.

3.3.8 Figure 3-8 is a plot of noise against predicted tidal current. A sharp increase in noise levels is evident as current increases from 1 to 2 m.s⁻¹ this could be indicative of the current speeds at which substantial amount of sediment starts to move. Its likely that sediments of different sizes will become mobile at different current speeds. The fall in noise at current speeds over 2.5 m s⁻¹ is surprising. This may be a sampling effect in that there are relatively few records at these high current speeds, note too the very high confidence intervals. It will also be the case that these high currents are only experienced in a subset of spatial locations, and these may be less likely to have sediment beds, perhaps because they have been "swept clean".

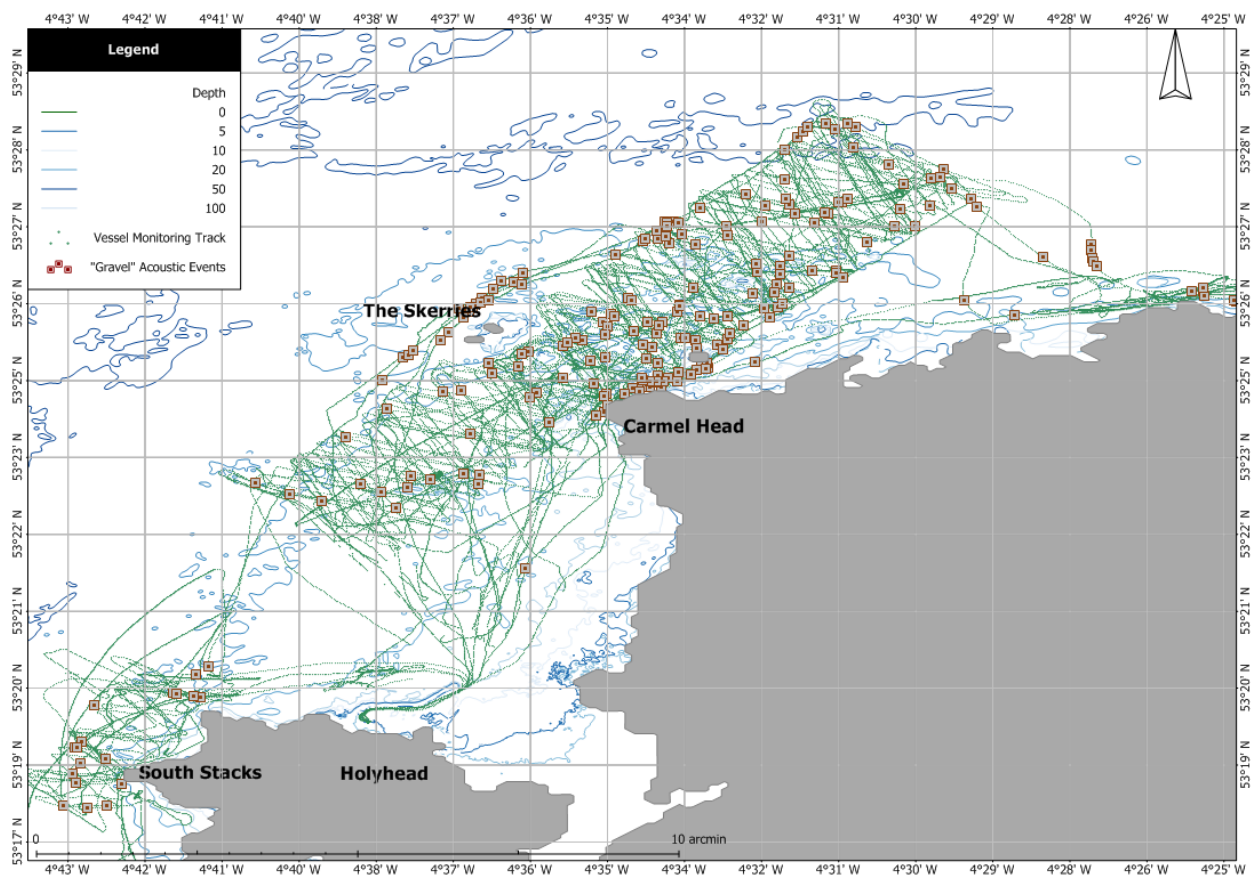


Figure 3-7 Location of areas of high noise when currents were running – thought to be due to moving sediment.

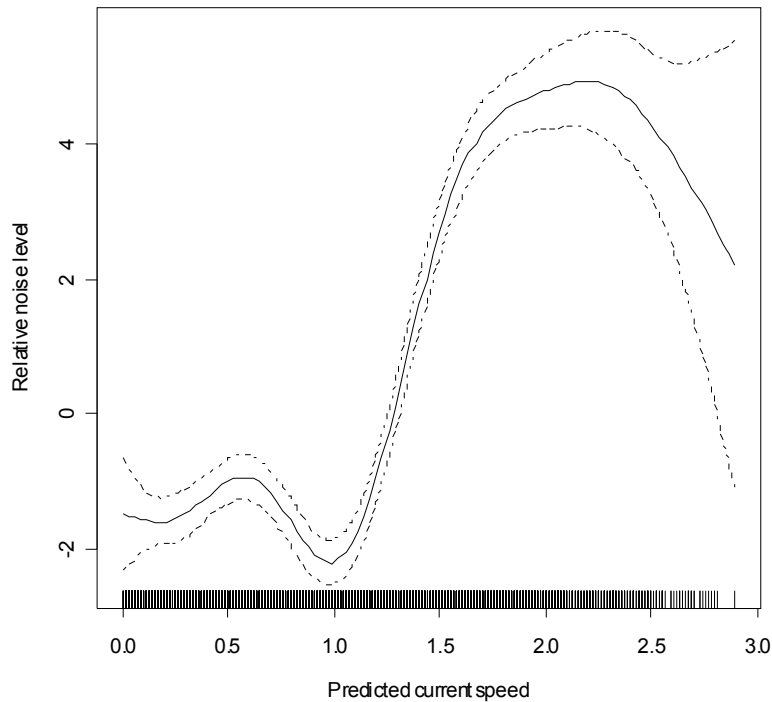


Figure 3-8 Plot of noise against current speed. The drop in noise level at higher current speeds may be sampling artefacts due to lower number of samples for these faster currents and/or the fact that such high currents were only encountered in a subset of areas, which may have been "swept clean" of sediments.

Acoustic detections

3.3.9 Analysis of the full bandwidth recordings that were made continuously during surveys resulted in the porpoise detections summarised in Table 3-3. Several different types of acoustic encounter were identified, following the methods outlined in Gillespie *et al.*, (in review, b).

3.3.10 "**Single tracks**" were encounters consisting of a single distinct track of clicks on bearings altering regularly from ahead to astern. "**Multiple Tracks**" were similar but involved more than one distinct track. "**Events**" were instances which involved many click detections which were not on distinct tracks. "**On axis porpoise acoustic events**" were similar to "**Events**" but the bearings were all at 90 degrees. "**Clicks**" were single strong clicks that had the spectral and temporal characteristics of porpoise clicks but occurred on their own. Locations of porpoise acoustic encounters in the two study sites are shown in Figure 3-9 and Figure 3-10.

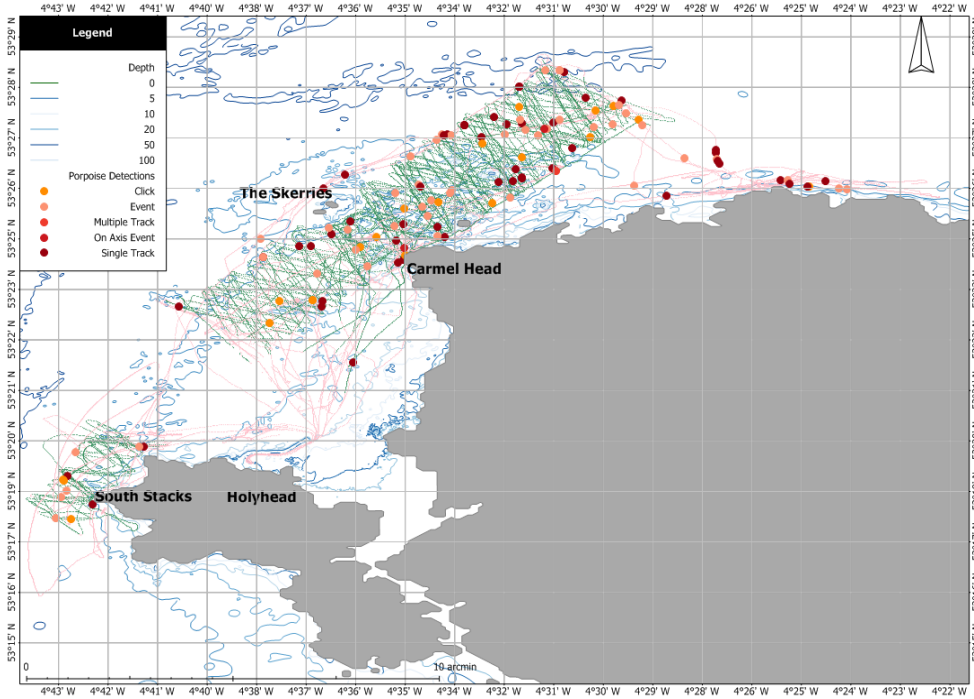


Figure 3-9 Locations of all porpoise acoustic encounters in the study area; Carmel Head and South Stacks, off Anglesey. See text for description of event types. Survey tracks are shown- green is designed survey, pink is non-designed survey.

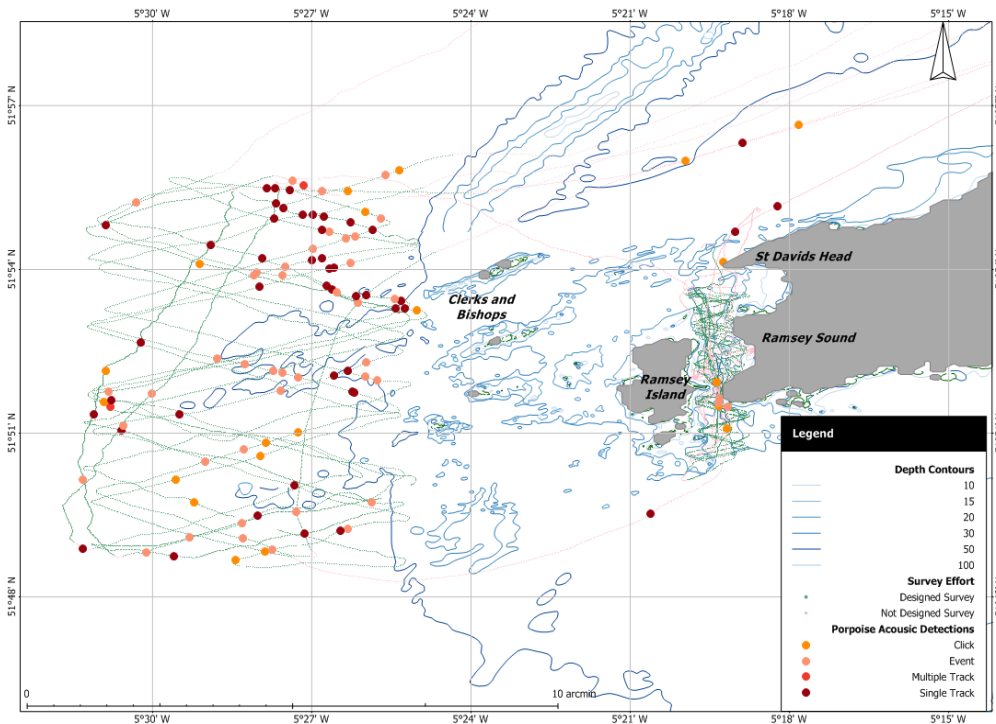


Figure 3-10 Locations of all porpoise acoustic encounters in the study area; Bishops and Clerks, off Pembrokeshire. See text for description of event types. Survey tracks are shown- green is designed survey, pink is non-designed survey.

Acoustic detection function

3.3.11 In the case of single and multiple track encounters it is possible to fit a function to the pattern of click bearings as the vessel passes the vocalising animals to come up with the animal's most likely location in respect to the track line and to calculate a perpendicular distance (Gillespie *et al.*, In Review). A complication in this case was that, because of the strong currents, the vessel's track over ground was not necessarily a good indicator of the orientation of the hydrophone. In this case we used the vessel's true heading, as provided by a vector GPS module on the vessel, one hydrophone length earlier, to provide the hydrophone's actual orientation at the time of each detection. We used the Distance program (Version 6.0) (Thomas *et al.*, 2010) to calculate an acoustic detection function using perpendicular distances from 88 good quality single track encounters. These data and the best fitting model are shown in Figure 3-11. A half normal model with 2 cosine parameters gave the best fit (Akaike information criterion = 1035). This indicated an effective strip half-width of 186 m with 95% CI between 157-222 m. (The effective strip half-width is the distance either side of the trackline at which as many animals are detected further away than are estimated to be missed closer to the trackline).

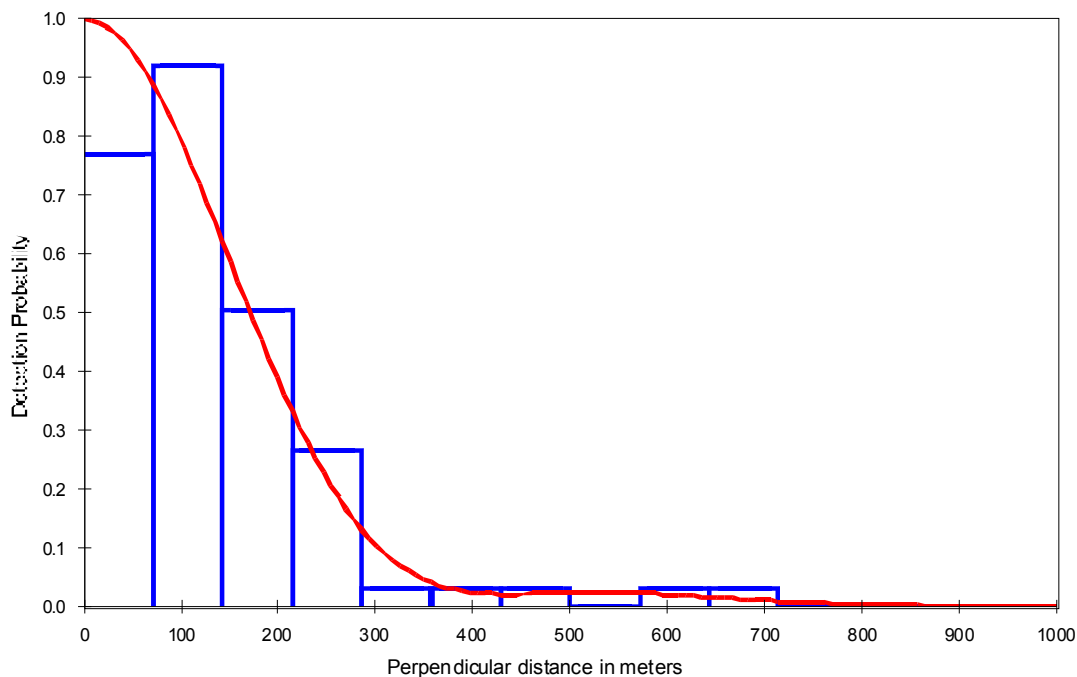


Figure 3-11 Plot of perpendicular distance from the trackline for 88 good quality tracked acoustic detections. The best fitting model, shown in red, was a half normal model with 2 cosine parameters. Akaike information criterion = 1035. Effective strip width 186 m 95% CI 157-222 m.

3.3.12 To investigate the percentage of animals that were detected acoustically we calculated the time at which all porpoise sighted during surveys would be expected to come abeam of the hydrophone, based on the tow length of the hydrophone, the distance ahead of the vessel that the animals were seen and the vessel speed. On 33 occasions, porpoises were seen during surveys at a perpendicular distance from the trackline of less than the effective strip width (186 m). There was an acoustic detection within 200 seconds of the calculated passing time on 34.4% of these occasions. The expectation from the acoustic detection function (Figure 3-11) is that 50% of all potential detections within the effective strip width would be made. The difference between this value and the 34.4% of visual detections linked to an acoustic detection could be taken as a measure of the proportion of available animals that were detected acoustically. Thus, based on this rather ad hoc calculation, our expectation for $g(0)$, the proportion of animals on the trackline that were detected acoustically is 0.68.

Models of temporal and spatial covariates

3.3.13 Within the two survey boxes (Carmel Head and South Stack, the Skerries, off Anglesey and Bishops and Clerks, off Pembrokeshire) surveys were carried out along pre-determined transects designed to achieve even coverage probability. Only data collected on these zig-zag tracks were used for the models. However, some examination of the full dataset including passages through the study areas was thought to be informative, particularly with respect to the relationship between detection rates and noise levels on the hydrophone. Figure 3-12 shows the overall relationship between detection rates and noise. As is expected, detection rate decreases with increasing noise levels. The slight dip at low noise levels can be explained by very few data (and no detections) at these values.

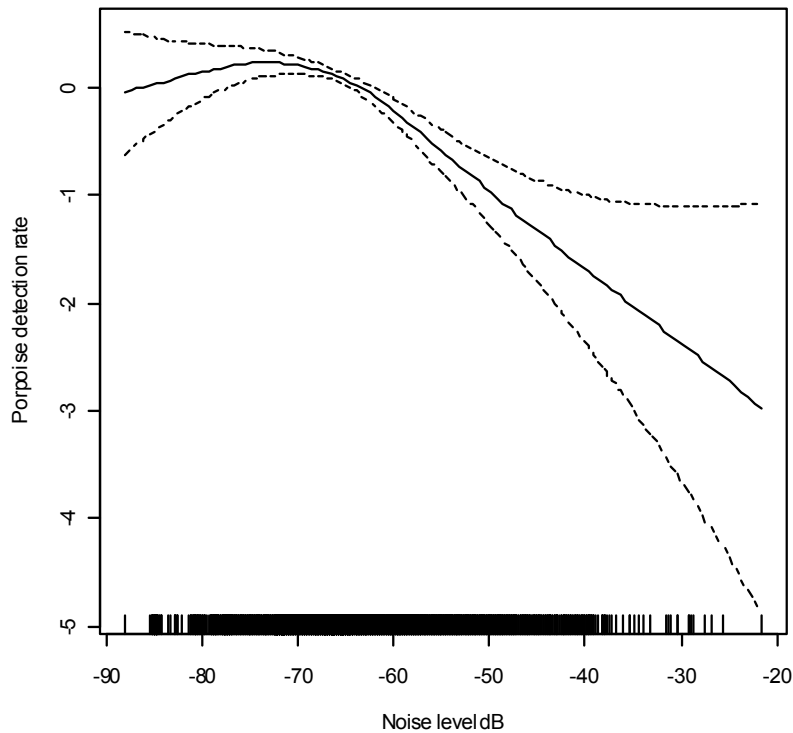


Figure 3-12 *Relative detection rate with received noise level at the hydrophone in porpoise click frequency band for all data combined.*

Measured noise levels

3.3.14 Noise levels will affect the performance of the porpoise detection programs used here (PAMGUARD and Rainbow Click). By making noise measurements using spectral and temporal filters that exactly matched those used in the triggering routines in the program we have endeavoured to make acoustic measurements of noise which should most closely correlate with detection probability (in this case this is of course all the noise on the recordings, this will include background environmental noise, vessel noise, flow noise and any electrical noise).

3.3.15 Much of the noise received at the hydrophone will be due to flow noise and engine noise from the survey vessel. However, other noise sources were noted, particularly what sounded like movement of gravel on the seabed (see Section 3.3.7). Exploratory models to investigate the relationship between received noise and environmental factors showed that depth, current speed, slope and distance from places where high gravel noise had been observed were all significant factors. The best model fit was obtained with an interaction between distance to sediment noise patches (for which geographical locations are shown in Figure 3-7) and current flow and between depth and slope (Figure 3-13 and Figure 3-14). Overall, noise increased sharply when current flow

reached about 1m.s^{-1} (Figure 2-15), but particularly when close to assumed gravel patches. The depth and slope effect shows noise increasing with steeper slopes. This may be related to more biological activity with complex bottom types, the reflection of noise from the research vessel or the prevalence of moving sediments at different locations.

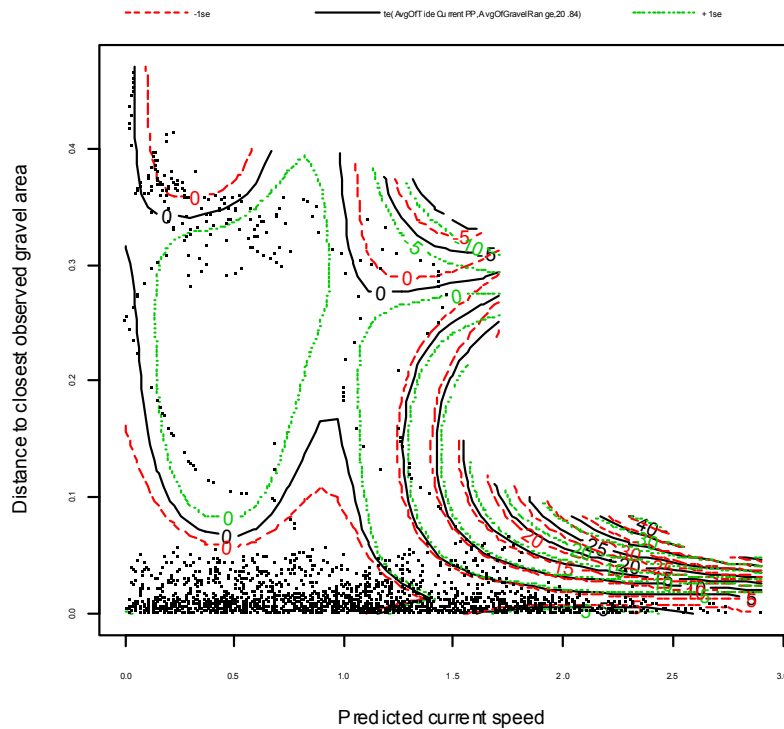


Figure 3-13 Contour plot of noise levels as a function of predicted current speed and distance to the closest observed gravel patches. Black lines show average levels, green and red are plus and minus one standard error respectively.

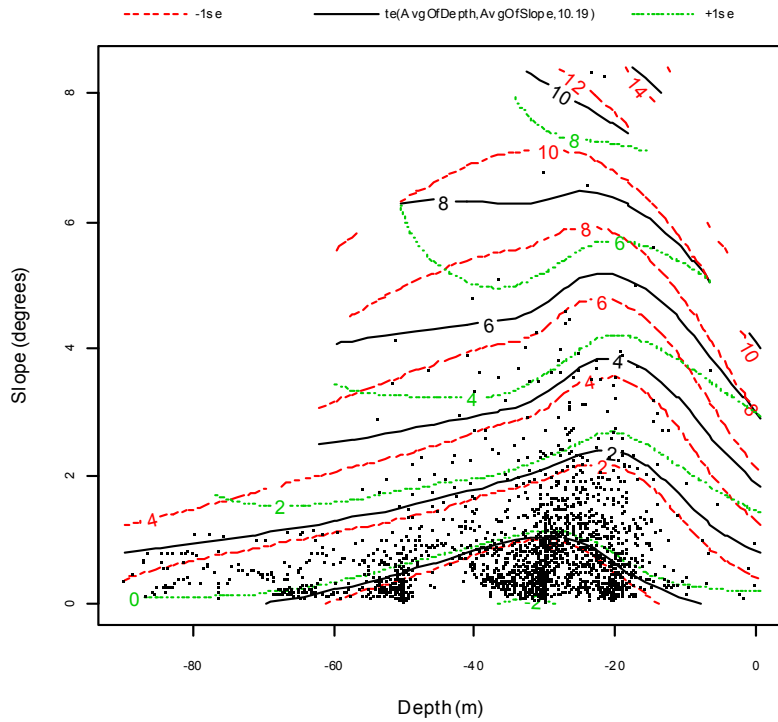


Figure 3-14 Contour plot of relative noise levels as a function of depth and slope. Blacks lines show average levels, green and red are plus and minus one standard error respectively.

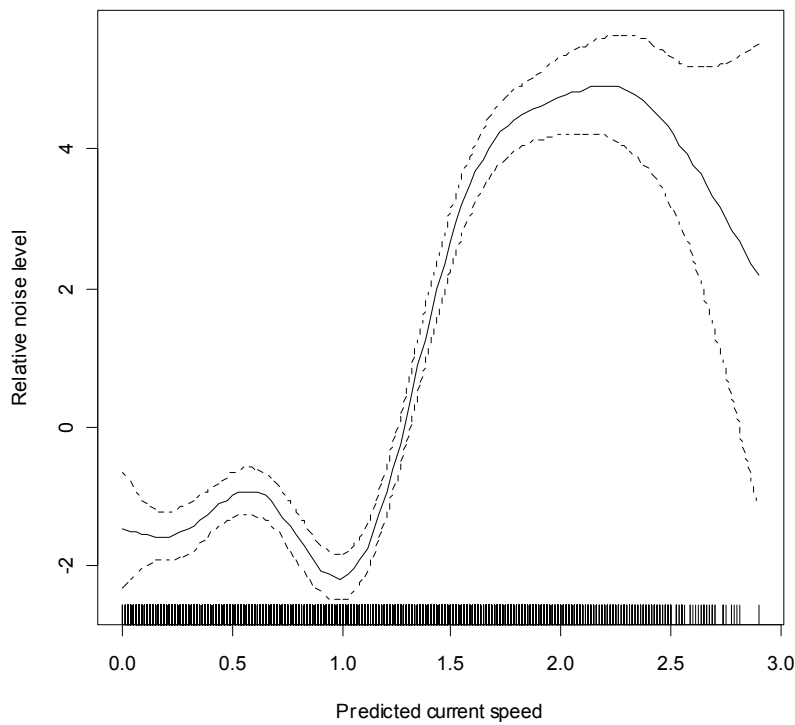


Figure 3-15 Relative noise levels as a function of predicted current speed and distance to closest observed gravel patch.

Depth

3.3.16 Previous studies off west Wales (Isojunno, 2008) have found a relationship between porpoise density and bathymetry with a linear decline from 50 m to 10 m. In our data, the overall relationship with depth is consistent with this but suggests a peak in density at water depth of around 70 m (Figure 3-16). Goodwin and Speedie (2008) found a peak in porpoise distribution in waters of around 100 m depth for areas along the west coast of the UK from the southwest to Scotland including some data from the coast of Wales. However, their survey effort generally extended further offshore than in this study.

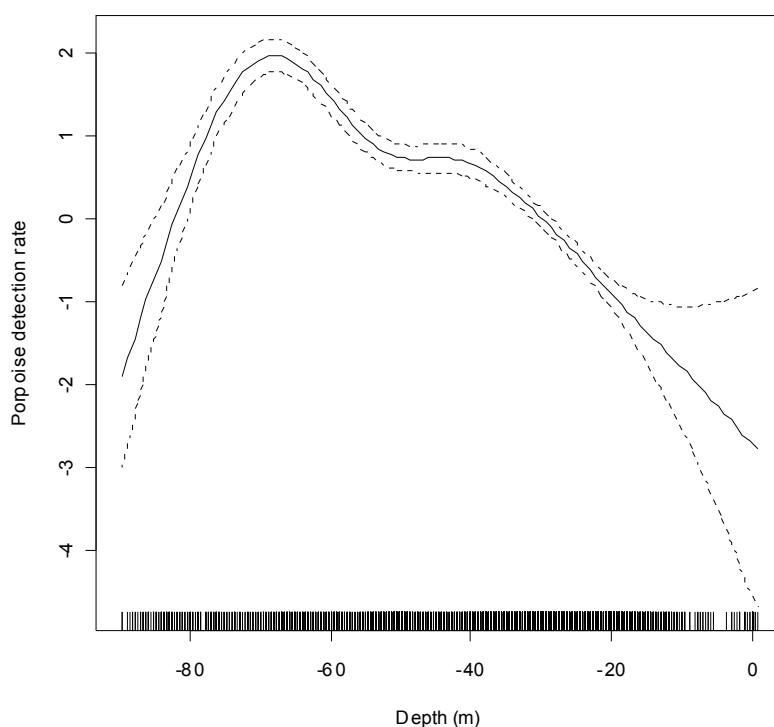


Figure 3-16 *Relative detection rate with depth. All data combined.*

Bishops and Clerks offshore survey block, off Pembrokeshire

3.3.17 The best fit GAM (generalised additive model) involved noise, time of day, depth, distance from all tidal features and an interaction between latitude and tidal height. However, the best fit model only explained 12.7% of the deviance and so none of the observed effects would be considered to have high explanatory power. No significant relationships were found between porpoise distribution and covariates related to current velocity.

3.3.18 In this model, noise affected detection rates as would be expected from the analysis of all data combined over the range of noise values recorded. Time of day was a significant

effect with detection rates dropping through the day; localised diurnal patterns in movements would not be surprising. The relationship with depth shows lower detection rates in deeper water (greater than 70 m) but otherwise little effect.

3.3.19 Tidal height was a significant term when interacting with latitude (Figure 3-17).

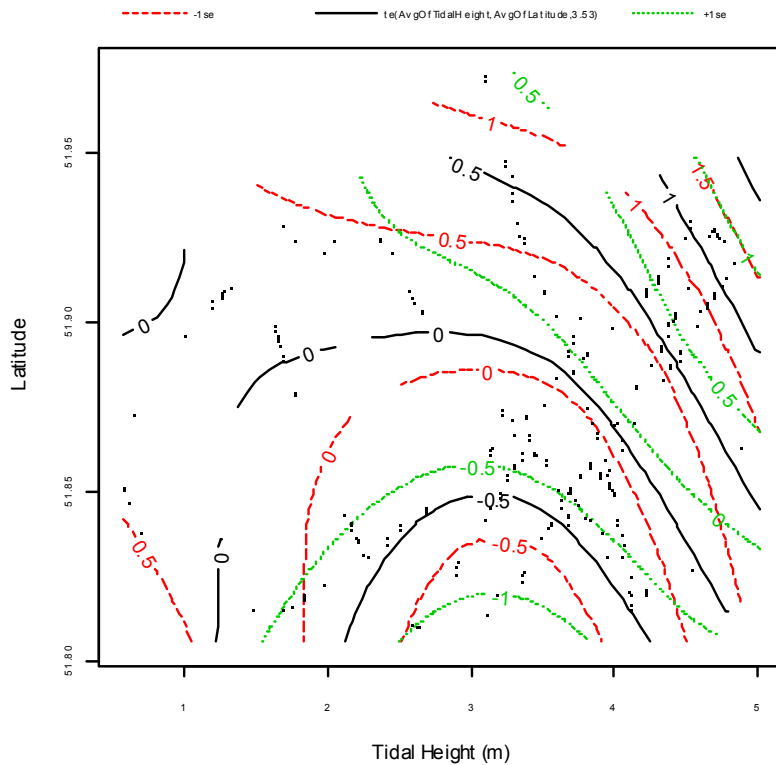


Figure 3-17 *Interaction between Latitude and Tidal Height for best fit model for Bishops and Clerks. Highest detection rates were in the north of the block with high tidal heights. Detection rates decreased towards the south with the lowest in the south at half tide. Black lines show average levels, green and red are plus and minus one standard error respectively.*

3.3.20 Longitude was not a significant factor but some spatial information is also captured in the distance from observed tidal features (Figure 3-18). Detection rates decreased with distance from tidal features with areas of tidal features towards the northeast of the survey block.

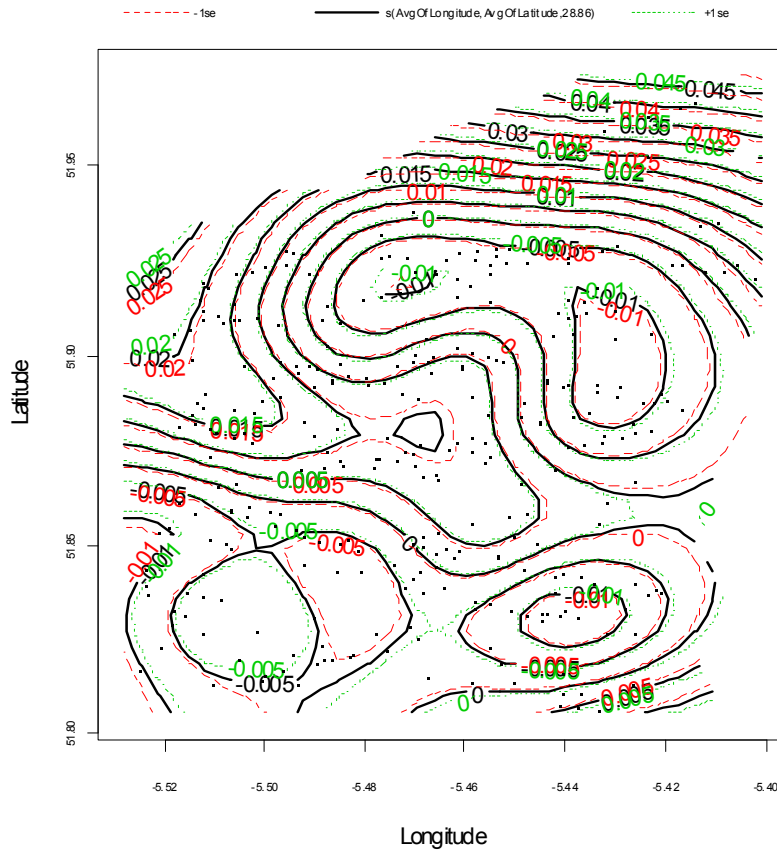


Figure 3-18 Contour plot of distances to all tidal features as used in the best fit model in Bishops and Clerks study area. Black lines show average levels, green and red are plus and minus one standard error respectively.

3.3.21 Predicted surfaces based on the best fit model for three tidal heights, means high water springs (HMWS), mean sea level (MSL) and mean low water springs (MLWS), are shown in Figure 3-19, Figure 3-20 and Figure 3-21 respectively. There is a slight tendency for densities to be further north at MHWS and to the south at MLWS. However, we would caution against over interpretation of these data.



Figure 3-19 Predicted porpoise density surface for Bishops and Clerks survey areas at mean high water springs. (Note: prediction becomes increasingly unreliable outside the surveyed area).

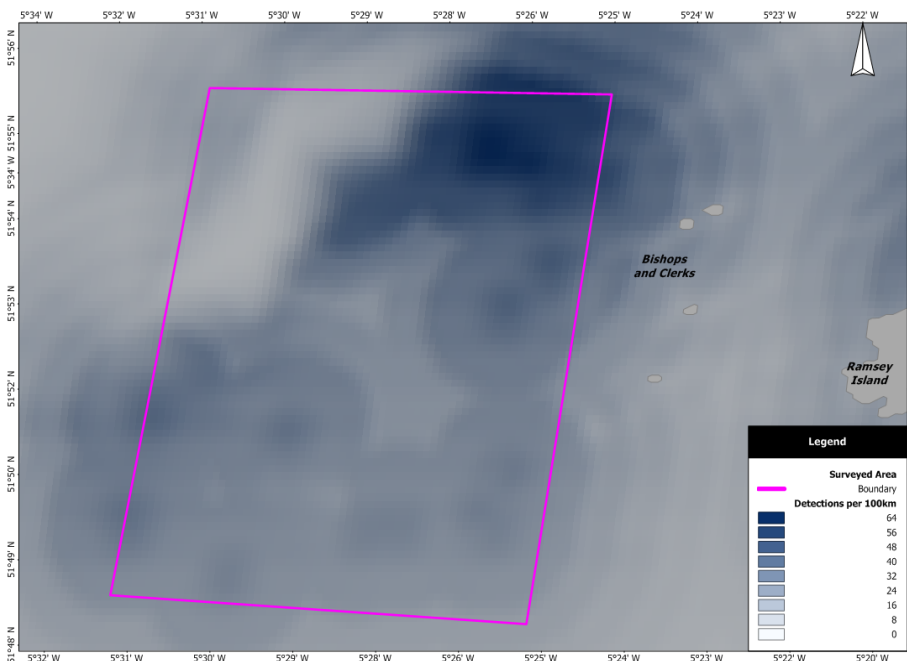


Figure 3-20 Predicted porpoise density surface for Bishops and Clerks survey areas at mean sea level. (Note: prediction becomes increasingly unreliable outside the surveyed area).

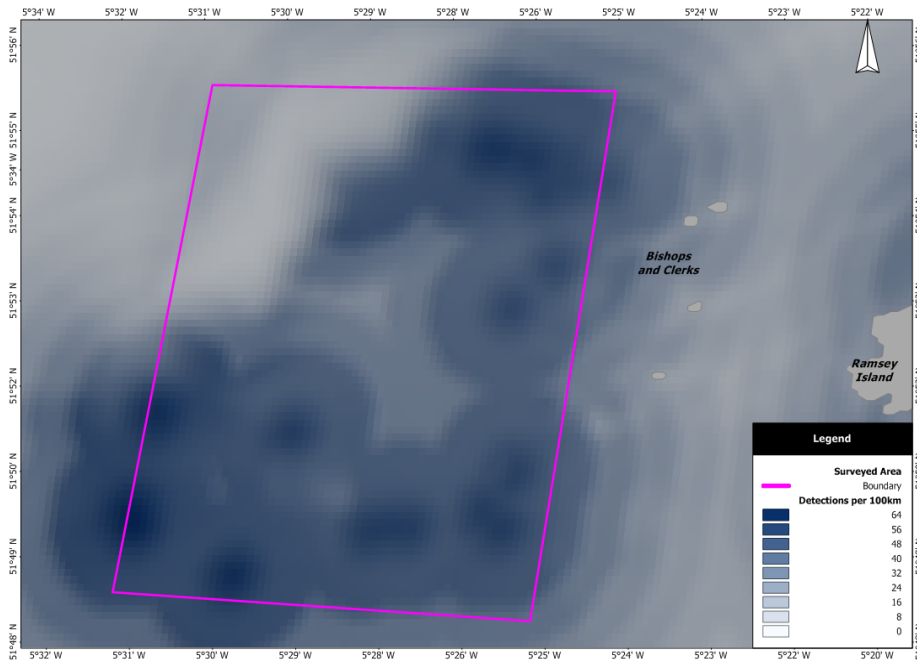


Figure 3-21 Predicted porpoise density surface for Bishops and Clerks survey areas at mean low water springs. (Note: predictions become increasingly unreliable outside the surveyed area).

Skerries (Carmel Head and South Stacks) survey block, off Anglesey

3.3.22 The best fit model involved noise, longitude, an interaction between depth and the maximum tidal rate on the flood (Figure 3-22) and an interaction between distance from tidal races and tidal height (Figure 3-23). However, the best fit model only explained 5.5% of the deviance and so none of the observed effects would be considered to have substantial explanatory power. Overall, densities increased from west to east, but also with the distance from the tidal race which occurs across the centre of the box (Figure 3-24) also contains spatial information. No significant relationships were found between porpoise distribution and current velocity at the time.

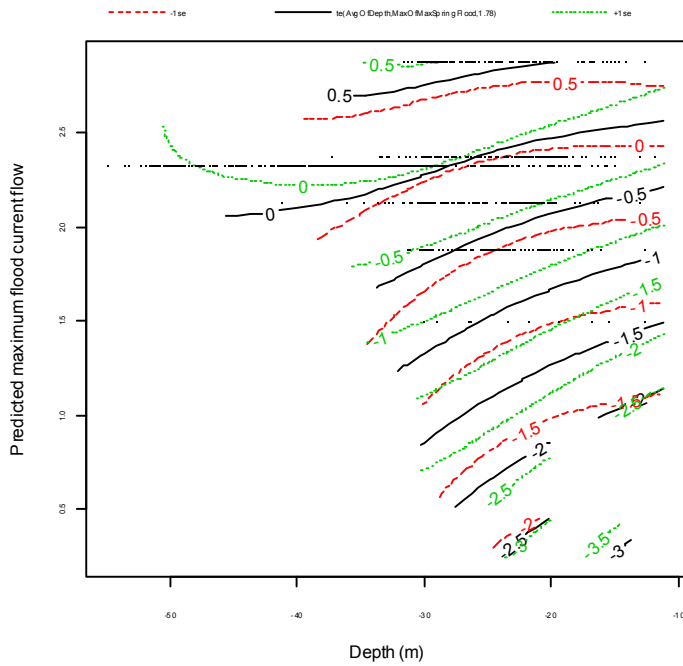


Figure 3-22 Contour plot of detection rates in relation to depth and maximum predicted current flow on the flood tide in the Skerries (off Anglesey) survey area. Detection rates were lowest in shallow, low energy areas and increased with depth and maximum current flow.

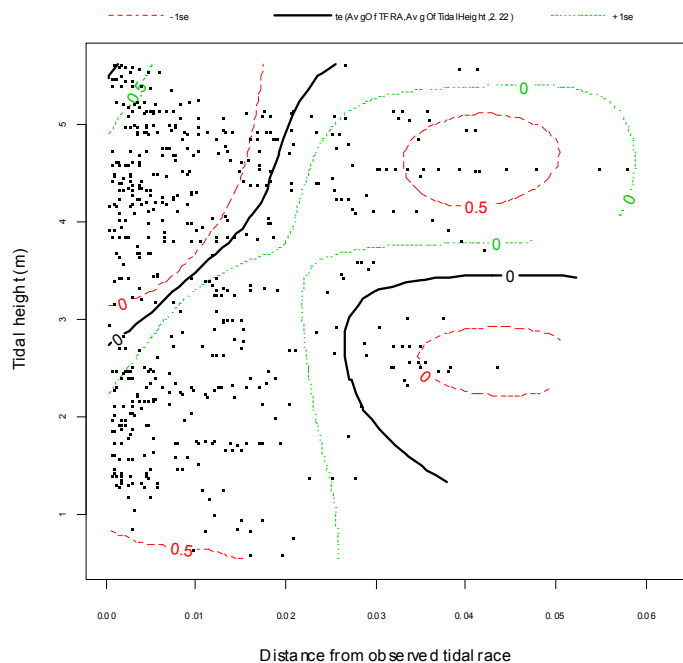


Figure 3-23 Contour plot of detection rates in relation to distance from observed tidal races and tidal height. Although a significant term in the best fit model, the plot is fairly flat but with higher detection rates at low tidal heights close to tidal races or at high tidal heights furthest away.

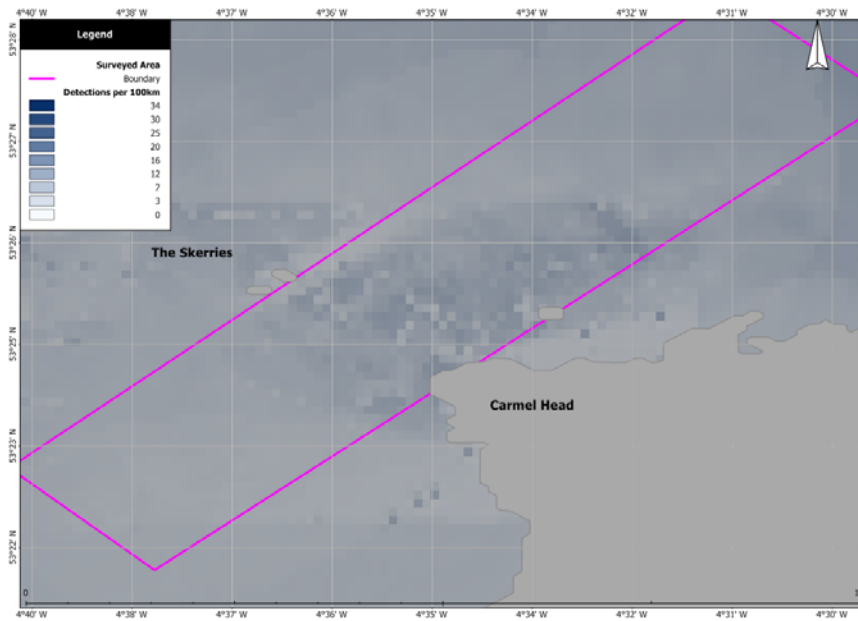


Figure 3-25 Predicted porpoise density surface for Carmel Head/Skerries (off Anglesey) survey areas at mean high water springs. (Note: prediction becomes increasingly unreliable outside the surveyed area).

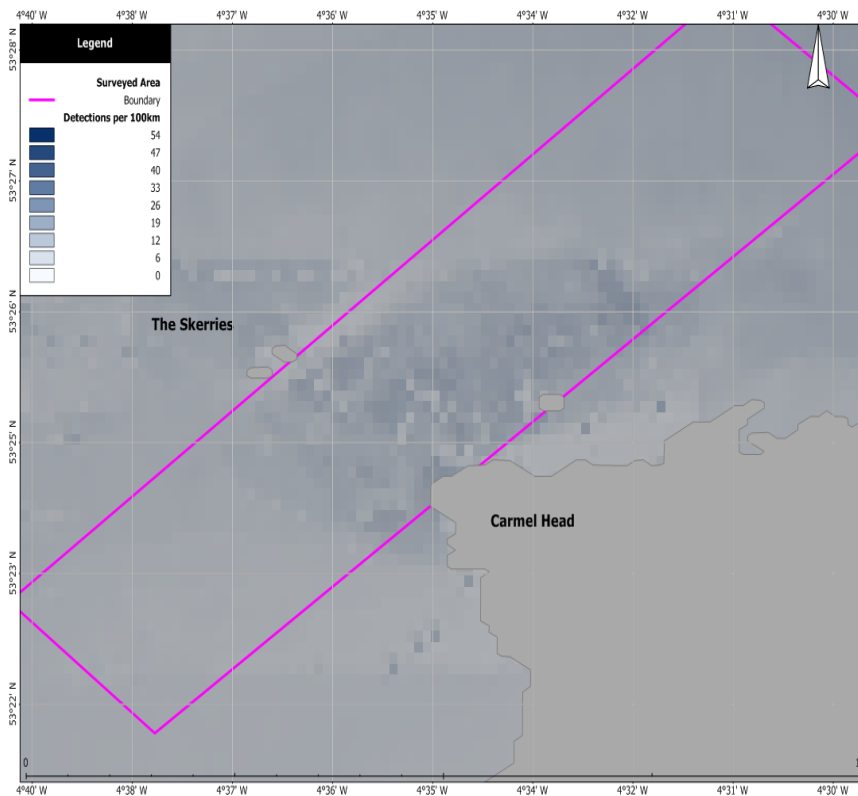


Figure 3-26 Predicted porpoise density surface for Carmel Head/Skerries (off Anglesey) survey areas at mean sea level. (Note: prediction becomes increasingly unreliable outside the surveyed area).

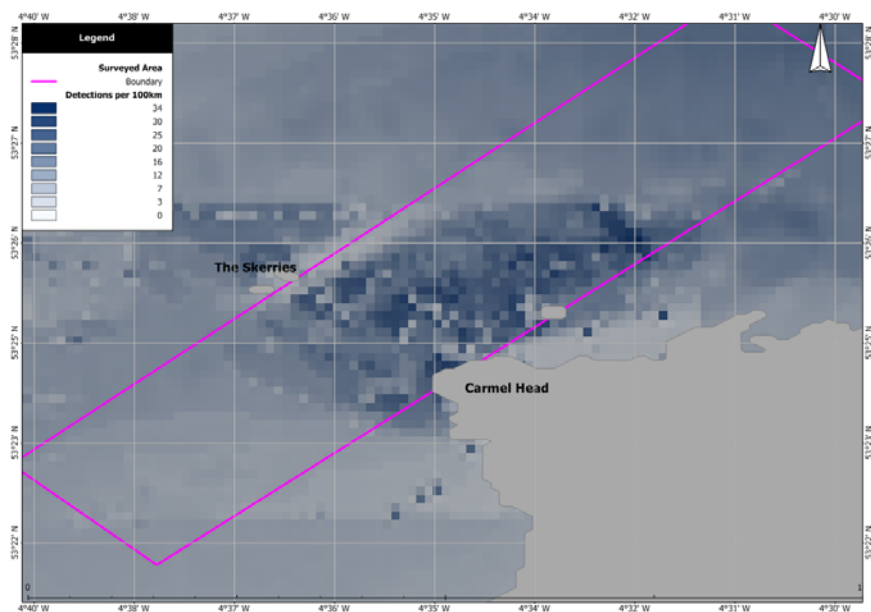


Figure 3-27 Predicted porpoise density surface for Carmel Head/Skerries (off Anglesey) survey areas at mean low water springs. (Note: prediction becomes increasingly unreliable outside the surveyed area).

3.4 Discussion

- 3.4.1 The very poor weather conditions that prevailed throughout the survey period greatly reduced the quality of the visual data collected. However, sightings have provided some useful information on marine mammal species other than harbour porpoises, in particular showing substantial numbers of common dolphins in the western section of the Bishops and Clerks study area and also on the distributions of grey seals in the Skerries region. In addition, data were collected showing the distribution of feeding seabirds in the Skerries region. For porpoises, visual data have provided valuable information on group size and an indication of the approximate proportion of available animals detected acoustically.
- 3.4.2 Quantitative analysis of porpoise distributions and densities has relied on the passive acoustic data collected using towed hydrophone systems.
- 3.4.3 It has been widely suggested that high tidal current areas are preferred habitat for harbour porpoises. However, as far as we are aware, no quantitative assessments of densities have been made within these areas to allow comparison with other areas. In no small part this is because these are very difficult environments in which to conduct surveys, especially during periods when tidal streams are running at their highest rates. In Table 3-4 we compare detection rates and densities measured in this study with those

reported in other areas by other authors. We make two comparisons, between raw acoustic detection rates per 100 km from different areas, and for an assessment of density (uncorrected for $g(0)$ ⁵) based on acoustic detection rates, the observed group size of 1.5 and an effective strip width (eshw) of 186 m and densities derived using visual methods in other areas.

Table 3-4 comparison between detection rates and estimated densities measured from the two study areas during this study and those reported from other areas.

Detection rate and density comparison						
Site/Area	N (number of detections)	Effort (km trackline)	n/100 km (detections per km)	Density (assuming group size =1.5, esw=186 m)	Survey type	Source
Bishops and Clerks, off Pembrokeshire	82	232	35.3	1.43	Acoustic	This study
The Skerries (Carmel Head and South Stacks), off Anglesey	57	607	9.4	0.38	Acoustic	This study
Kiel Bight	52	494	10.5		Acoustic	Gillespie <i>et al.</i> , 2005
Little Belt	49	291	16.8		Acoustic	Gillespie <i>et al.</i> , 2005
Southern North Sea 2001	81	1267	6.4		Acoustic	Gillespie <i>et al.</i> , 2003
Southern North Sea 2002	9	598	1.5		Acoustic	Gillespie <i>et al.</i> , 2003
English Channel 2001	9	433	2.1		Acoustic	Gillespie <i>et al.</i> , 2003
SCANSII - Irish Sea				0.34	Aerial	Hammond and Macleod, 2006.

⁵ $g(0)$ is the probability of detecting an animal on track line during the survey. If all animals were detected then $g(0)$ would be 1. If half the animals were missing then $g(0)$ would be 0.5

Detection rate and density comparison						
Site/Area	N <small>(number of detections)</small>	Effort <small>(km trackline)</small>	n/100 km <small>(detections per km)</small>	Density <small>(assuming group size =1.5, esw=186 m)</small>	Survey type	Source
SCANSII - W coast of Scotland				0.39	Aerial	Hammond and Macleod, 2006.
SCANSII - English Channel				0.33	Aerial	Hammond and Macleod, 2006.
SCANSII – Southern North Sea				0.51	Visual ship	Hammond and Macleod, 2006.

3.4.4 These measures indicate relatively high densities within our two study areas. The acoustic detection rates in the Bishops and Clerks study area are over twice as high as those reported from any other area, while those from the Skerries are exceeded only by rates in well known porpoise high density areas in the western Baltic which were collected from a quiet vessel. Comparing density estimates, we find that those in the Bishops and Clerks are the highest recorded while the estimates for the Skerries survey block are only exceeded by estimates from the west coast of Scotland and the southern North Sea. Our density estimates do not allow for $g(0)$ and are thus negatively biased. If the value for $g(0)$ of 0.68 estimated in this study was applied, then density estimates at the Skerries would only be exceeded by our own from those at Bishops and Clerks.

3.4.5 Within the relatively small study areas spatial modelling indicated substantial variability in predicted densities, especially at the Bishops and Clerks site. We would caution against over interpretation of these data, and further analysis and ideally a longer data series are required to explore the robustness of these predictions. However, they do suggest that there could be scope in this approach for using such information when siting tidal turbines to reduce risks of encounters (and potential collisions) between turbines and harbour porpoises.

3.4.6 There are some indications of interactions between covariates related to the tidal cycle and spatial covariates. This indicates changes in spatial distribution through the tidal cycle, as has been observed elsewhere.

4 The Use of TPOD, Static Acoustic Loggers, to Describe Aspects of Harbour Porpoise Ecology in High Tidal Areas

4.1 Introduction

- 4.1.1 This section of the report describes the use of autonomous, acoustic data-loggers, TPODs, to make a continuous record of harbour porpoise acoustic activity at the two sites described in the previous section. TPODs are passive devices, which identify and log the echolocation click trains produced by porpoise when foraging, during social interaction, and to otherwise ‘illuminate’ their immediate underwater environment (Tregenza *et al.*, 2001). Harbour porpoises make characteristic narrow band, ultrasonic clicks that are distinct in frequency from the sounds of other European marine mammal species.
- 4.1.2 TPODs are able to detect harbour porpoise echolocation clicks within a radius of approximately 300 m; a preliminary analysis of data collected using earlier versions of the TPOD, suggests that the likelihood of detecting harbour porpoises within 100 m radius is 80-90% (Tougaard *et al.*, 2006). The data collected provides limited spatial coverage unless very large numbers are deployed. However, because they log continuously and can be deployed for periods of months at time they can provide excellent temporal coverage. These characteristics make TPODs a suitable method by which to investigate porpoise activity at specific sites of interest. TPODs have been used extensively for harbour porpoise baseline assessments and environmental impact studies (e.g. Tougaard *et al.*, 2005; Pierpoint, 2008; Todd *et al.*, 2009). The present study used TPODs to describe habitat use by harbour porpoises at potential locations for tidal energy device development.
- 4.1.3 TPODs were deployed first within The Skerries/Carmel Head study site off Anglesey and then at Ramsey Sound near St. David’s (Pembrokeshire). The study objectives were to document and compare day-to-day levels of porpoise activity between the study sites, and between mooring locations at each site. TPOD data was also used to investigate whether porpoises followed patterns of behaviour that are related to the semi-diurnal (flood-ebb) tidal cycle. In addition, data were examined to assess whether porpoise occurrence varied between the day and night, as this behaviour would affect site assessments carried out by visual observation.

4.2 Methods

TPOD

4.2.1 TPODs are self-contained acoustic monitoring devices designed and manufactured by Chelonia Ltd., UK. Each TPOD consists of a hydrophone, two battery packs and analogue circuitry housed in a robust, tubular housing. When deployed with twelve alkaline batteries and set to log click trains every minute, TPODs are able to operate unattended for up to 60-80 days. Data are stored on a 128 Mb memory chip. TPODs record the precise times at which ultrasonic pulses (clicks) are detected and pulse duration, both to 10 μ s resolution. Click types attributable to different species or sources are identified using user-defined filter and threshold settings. Offline, TPOD software scans the data searching for regular sequences of clicks – click trains. A full description of the TPOD is available at <http://www.chelonia.co.uk/index.html>.

TPOD settings

4.2.2 The TPOD settings used are shown in Table 4-1. TPODs carry out a series of six successive scans in each 1 minute logging period. Detection parameters may be set independently for each scan. Five of the six scans were dedicated for harbour porpoise detection. The sixth scan was set to detect the broadband vocalisations of dolphin species reported from these study sites. Bottlenose dolphin for example, may occasionally produce similar sounds to harbour porpoise clicks, alongside their more typical broadband click trains. This scan was used as a control to identify and reject porpoise-type click trains that occurred within encounters with other species.

Table 4-1 TPOD deployment & logging effort.

TPOD	The Skerries	Ramsey Sound
T438	21 st Jul – 7 th Aug (18 days)	17 th Aug – 25 th Sep (40 days)
T439	21 st Jul – 12 th Aug (23 days)	lost
T440	no data	16 th Aug – 25 th Sep (41 days)
T462	21 st Jul – 6 th Aug (17 days)	16 th Aug – 25 th Sep (41 days)
T465	21 st Jul – 5 th Aug (16 days)	lost
T468	21 st Jul – 7 th Aug (18 days)	17 th Aug – 25 th Sep (40 days)

Data Treatment

4.2.3 TPOD data were downloaded using the software TPOD.exe (version 8.24; train filter 4.1). This program scanned the data for sequences of porpoise-type clicks with consistent frequency and click length characteristics that formed click trains. Click trains were identified as regular sequences of increasing or decreasing inter-pulse intervals. The software classified click trains as either:

- Cet Hi: Click trains with a high probability of cetacean origin;
- Cet Lo: Lower probability of cetacean origin;
- Cet All: Pooled Cet Hi and Cet Lo click trains;
- Doubtful: Often cetacean source, but a less reliable indicator;
- Very Doubtful: Sometimes cetacean origin (particularly delphinids) but often boat sonar; and
- Fixed Rate: Usually boat sonar, but some slow, very regular delphinid trains also.

4.2.4 For the analyses presented here, we used the combined class of high and lower probability cetacean click trains (“cet all”) that were classified as harbour porpoise in scans 1-5. Click trains were rejected if other “cet all” clicks were recorded during the same period on scan 6 (Table 4-2).

4.2.5 We used the measure Detection Positive Minutes (DPM) as a robust indicator of porpoise presence and the level of porpoise echolocation activity (Tregenza and Pierpoint, 2007). DPM was the proportion of TPOD logging minutes in which harbour porpoise click trains were recorded and expressed as a percentage. DPM were derived for over a range of time intervals from 30 minutes to a day depending on the analysis being undertaken.

Table 4-2 *Version 4 TPOD scan settings.*

Settings	Scans 1-5	Scan 6
Target Filter A (centre)	130 kHz	50 kHz
Reference Filter B (centre)	92 kHz	70 kHz
Click Bandwidth	4	5
Noise Adaptation	++	++
Sensitivity	10	6
Scan Limit (max clicks logged)	None	240

Deployment

4.2.6 Six TPODs (v4) were deployed at Carmel Head, Anglesey in July and August 2009. After a period of approximately three weeks, these TPODs were retrieved and re-deployed at Ramsey Sound. The seabed moorings consisted of a primary chain clump weight (~100 kg), which was buoyed, with a TPOD secured to the riser. The TPODs were set to float 5 m above the seabed. Two sub-sea buoys were attached to the riser above each TPOD to help keep it near vertical in the water column. The locations of the TPOD moorings are shown in Figure 4-1.

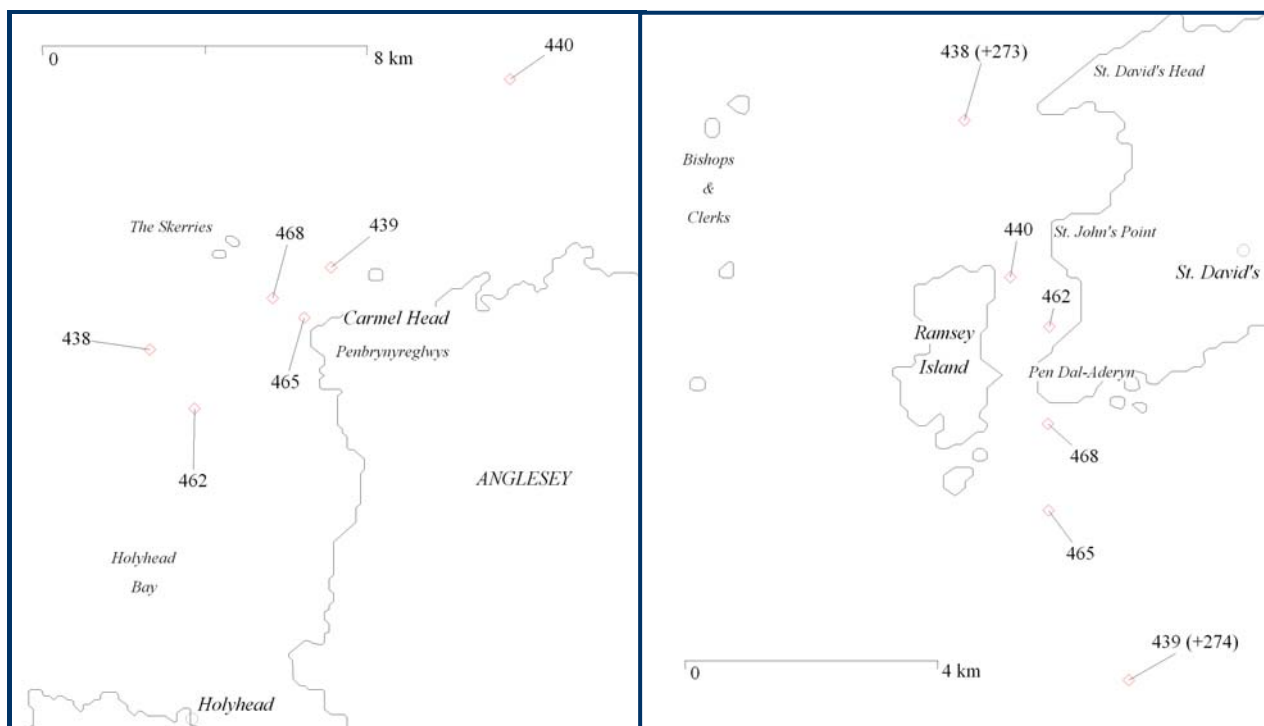


Figure 4-1 The location of TPOD moorings at Skerries/Carmel Head (Anglesey) (left) and the Ramsey Sound (Pembrokeshire) (right) in 2009

4.2.7 The deployment sites were chosen with some care. As far as possible deployment sites with similar water depths were selected. Based on observations made by Pierpoint (2008) and others at Ramsey Sound the authors had some reason to expect that sites at either end of restricted channels might be important and might be used differently at different states of the tide. At the Skerries, TPODs T465, T468 and T439 were placed in areas of strongest flow, which are likely and/or are sites of interest for tidal turbine development. These areas could also be easily monitored from the shore lookout station at Carmel Head, enabling a comparison of the datasets collected by each method. T440, T438 and T462 were deployed to provide data from areas immediately outside the areas of highest tidal flow.

4.2.8 In Ramsey Sound, T440 was placed on the site of the planned deployment of the Delta stream experimental turbine. T462 provided additional coverage to the north of the areas of fastest flow at a spot which could be independently monitored from one of the shore stations. T468 and T465 were sited close to the tidal rapid area to the south of the Sound which Pierpoint (2008) had identified as being a favoured foraging site during ebb tides. These two sites could also be readily observed from an established shore station. T438 and T439 provided coverage well to the north and to the south of the Sound respectively.

- 4.2.9 Two TPODs (v3) were also attached to two of the moorings. These units failed to record data consistently however, and their results are not discussed further in this report.

TPOD calibration

- 4.2.10 The TPODs used during this project had previously been deployed together during an in-sea calibration test. The calibration test was carried out in Newport Bay (Pembrokeshire) in August and September 2006. The test was 63 days in duration during which all TPODs were attached vertically, side by side, on a 1 m² seabed frame. The aim of the test was to check that the units functioned correctly and that they displayed similar sensitivity, i.e. rates of harbour porpoise detection. The results of the calibration test showed that although all TPODs tracked very similar day-to-day variation in DPM, some statistical differences were found in their detection rates (Pierpoint, 2006). To address this, scale factors were developed that adjusted daily DPM values towards the common mean of all six TPODs. The scale factor (SF) was calculated as the proportional difference (PD) between total DPM recorded by each TPOD ($\sum DPM$) and the summed daily average DMP of all six TPODs ($(\sum DPM)$):

$$PD = \text{abs} (\sum DPM - \sum DPM) / \sum DPM$$

$$SF = 1 - PD$$

- 4.2.11 A scale factor was calculated for each TPOD and was applied as a multiplier to daily DPM values. Scale factors were applied to DPM values whenever detection rates were compared between different TPOD locations, to remove effects of differences in sensitivity between different TPOD units.

Data analysis

- 4.2.12 Each minute of logged time was scored as being either detection positive or detection negative depending on whether or not at least one porpoise click train had been detected during that interval. Daily DPM (the proportion of total, daily logging minutes with porpoise click train detections, adjusted with a TPOD-specific scale factor) was used to compare levels of harbour porpoise activity recorded at TPOD locations within each study site and between the Ramsey Sound and Skerries sites.
- 4.2.13 At individual TPOD locations, non-parametric statistical methods were used to test null hypotheses that no differences existed between time-of-day and tidal phase classes.

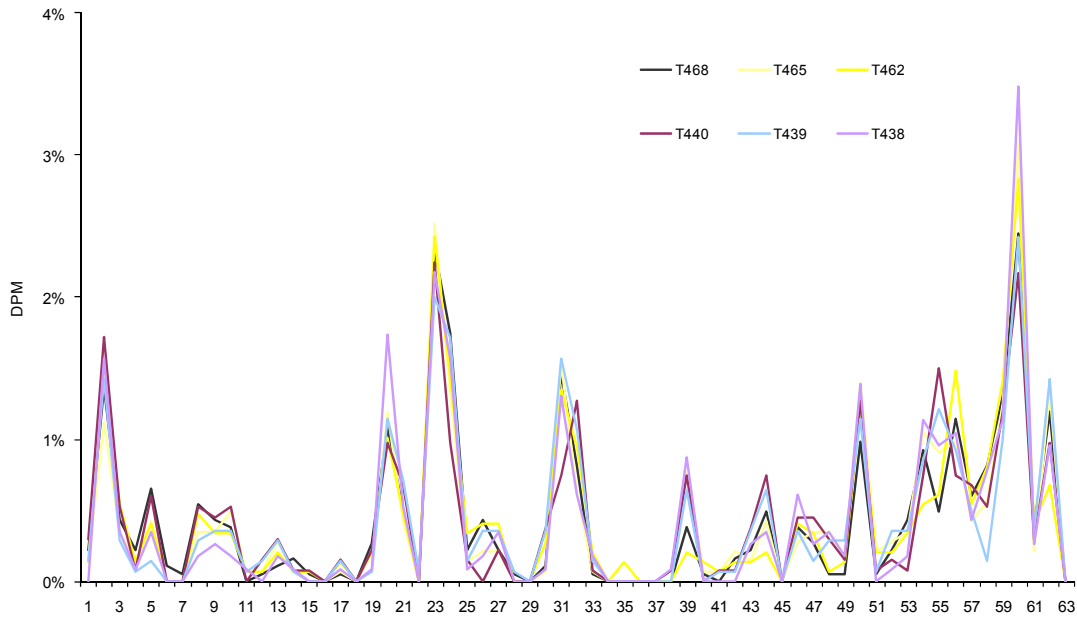
Wilcoxon's signed ranks test (Conover, 1999) was used to compare daytime and night-time detection rate. TPOD data were assigned to "day" or "night" categories each day based on published local times (standard transit) of sunrise and sunset (UKHO, 2009).

4.2.14 To examine porpoise activity patterns relative to the tidal cycle, detection minutes were also grouped into ½ hour tidal intervals and assigned to ebb and flood categories based on the time at which the tidal stream was predicted to slacken and reverse direction (UKHO, 2006); Figure 4-2 and Table 4-3). Detection rates were compared statistically in four classes: day-ebb, day-flood, night-ebb and night-flood. In reality, the precise timing of slack tide is likely to have varied due to lunar phase, weather conditions and to some degree between different locations at each study site. For this study, day-night, and ebb-flood classes were assessed using Friedman tests, which is a non-parametric equivalent of 2-way ANOVA (Iman and Davenport, 1980). In cases where the test gave a significant result (at alpha = 0.05), pairwise comparisons were made (Conover, 1999).

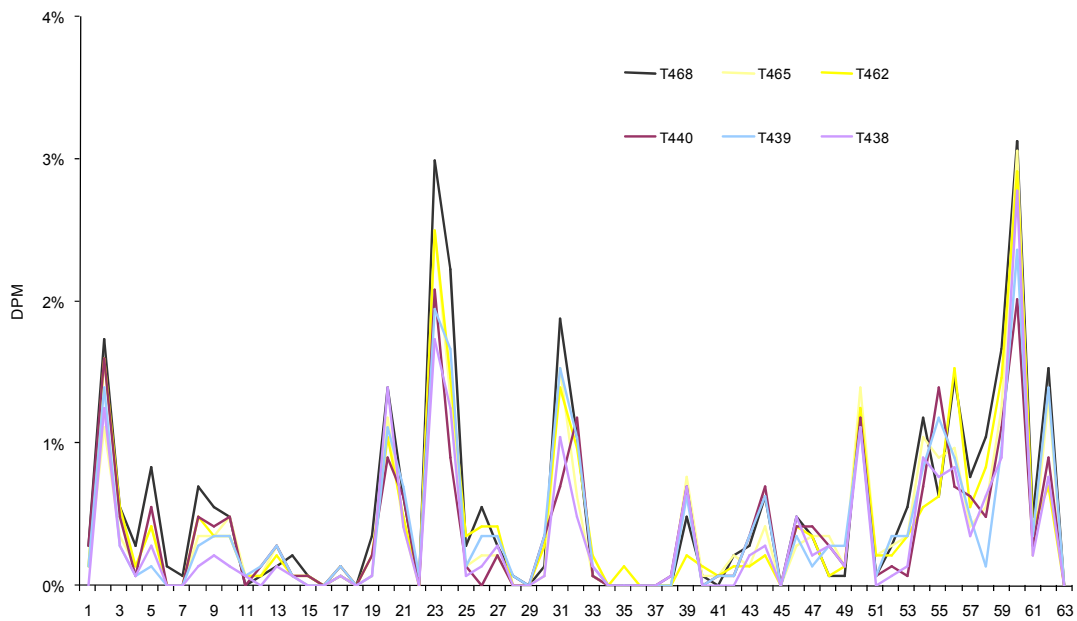
4.3 Results

TPOD calibration

- 4.3.1 The raw and scaled data from the calibration test are shown in Figure 4-2. All six TPODs tracked similar daily DPM values during the 63-day co-deployment. Two or more TPODs tended to yield statistically different detection rates (Friedman test: $T_2 = 10.34$, 5 df, $P < 0.001$). Scale factors (SF) were applied to adjust individual daily DPM values toward the common mean of all six TPODs (Table 4-3). Once these were applied, no significant differences in DPM between TPODs remained (Friedman test: $T_2 = 1.41$, 5 df, $P = 0.222$).
- 4.3.2 As SF incorporated differences due to random sampling error as well as TPOD sensitivity, they were likely to overcompensate to some degree, i.e. the DPM values of the most sensitive and least sensitive TPODs would be reduced and increased by a greater amount respectively, than was warranted by the difference in sensitivity alone.



a) Raw daily DPM % values.



b) Scaled daily DPM % values

Figure 4-2 TPOD calibration: a) raw and b) scaled Detection Positive Minutes (DPM) during a 63 day deployment in Welsh waters.

Table 4-3 *DPM from the 63-day in-sea calibration test, mean ranks and scale factors applied when comparing daily DPM values of two or more TPODs.*

TPOD	Raw		Scale Factor	Scaled	
	DPM %	Mean Rank		DPM	Mean Rank
T438	0.35	2.49	1.254	0.44	3.10
T439	0.43	3.50	1.026	0.44	3.53
T440	0.40	3.48	1.077	0.44	3.83
T462	0.45	3.71	0.970	0.44	3.51
T465	0.43	3.41	1.008	0.44	3.37
T468	0.56	4.40	0.783	0.44	3.67

Duration of TPOD deployment

4.3.3 In total, 254 TPOD-days of data were gathered from the two study sites (4873 h) (Table 4-1). At the Skerries, all six TPODs deployed were recovered, but only five provided data; T440 failed to operate correctly. A total of 1691 TPOD-hours of data were collected at this site, the TPODs operating for between 16 and 23 days. At Ramsey Sound, four out of six TPODs were recovered. Two moorings and TPODs (T439 and T465) were lost. The remaining TPODs operated successfully for 40-41 days and recorded a total of 3182 TPOD-hours of data.

Daily levels of harbour porpoise activity

4.3.4 Harbour porpoise occurrence was high at both study sites. Porpoises were recorded by a minimum of one TPOD, and usually all TPODs, every day at the Skerries and in Ramsey Sound. At the majority of locations for both sites, porpoises were recorded at least once on 85-100% of days. The lowest rate of daily occurrence at any TPOD location was 56% (TPOD T440 at a site in the north of Ramsey Sound). At the Skerries, harbour porpoise click trains were recorded in 1334 of 101,455 logging minutes, and at Ramsey Sound in 2525 of 190,898 logging minutes: this yielded an identical % DPM value of 1.3% overall, for the duration of TPOD deployment at each site.

4.3.5 Within each site, certain TPOD locations recorded higher levels of porpoise activity than others. The total DPM for the duration of deployment, varied from 0.2% to 4.1% at the five Skerries TPOD locations, and from 0.2% to 3.4% at the four Ramsey Sound locations. Maximum daily DPM recorded at a Skerries location was 7.9% (T468), and 10% at Ramsey Sound (T468) (Table 4-4).

4.3.6 The sites with the highest rates of harbour porpoise detection were T468 and T438 at the Skerries and T468 and T462 at Ramsey Sound (Table 4-4). At the Skerries T468 was located mid-way between Carmel Head and the Skerries; T438 was located approximately 3 km southwest of T468 while at Ramsey Sound, T468 and T462 were located just 1.5 km apart, on the south and north sides of the Pen Dal-Aderyn Headland respectively (Figure 4-1).

Table 4-4 Summary of % DPM values, an index of harbour porpoise activity levels. Detection Positive Days (% DPD) is given as a measure of daily occurrence: the percentage of days on which porpoises were recorded at each location. Locations have been ranked within each study site by median daily % DPM.

Site	TPOD	% DPD	Total % DPM	Median Daily % DPM	Daily DPM% Range	Rank
The Skerries	T438	100	1.4	1.25	0.35 – 4.43	2
	T439	100	0.3	0.28	0.07 – 1.11	4
	T462	71	0.2	0.07	0.00 – 0.56	5
	T465	94	0.6	0.60	0.00 – 1.32	3
	T468	100	4.1	4.24	1.11 – 7.92	1
Ramsey Sound	T438	95	0.4	0.21	0.00 – 2.08	3
	T440	56	0.2	0.07	0.00 – 2.36	4
	T462	85	1.3	0.49	0.00 – 4.65	2
	T468	85	3.4	2.81	0.00 – 10.00	1

4.3.7 Although porpoise activity was higher at some locations than others, daily levels of activity did not appear to vary consistently between locations at the same site. Whilst there were some periods in which activity increased or fell concurrently at two or more TPOD locations on consecutive days (e.g. Ramsey Sound: 27th August to 3rd September), more often peaks in activity would occur independently at adjacent TPOD locations (e.g. the Skerries: 24th to 29th July) (Figure 4-3 and Figure 4-4).

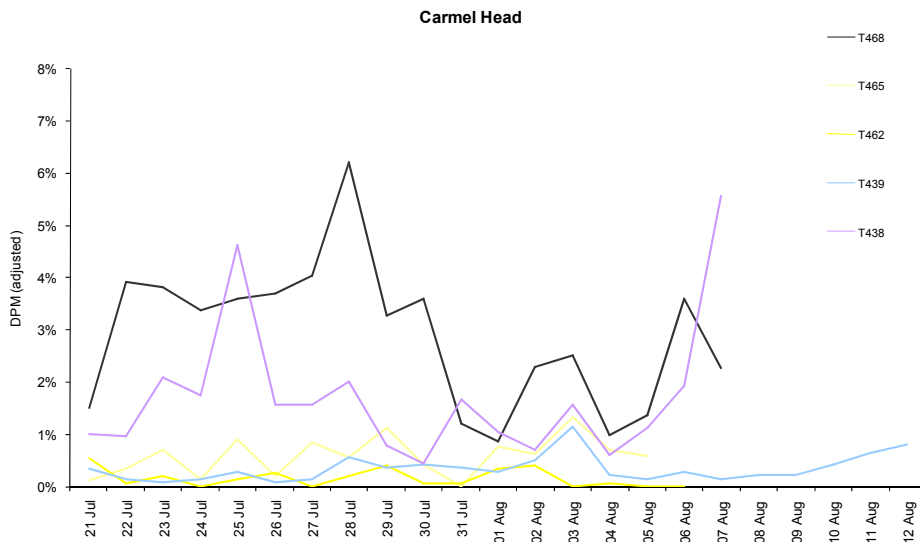


Figure 4-3 Daily detection positive minutes during deployments at five sites in the Skerries/Carmel Head study area.

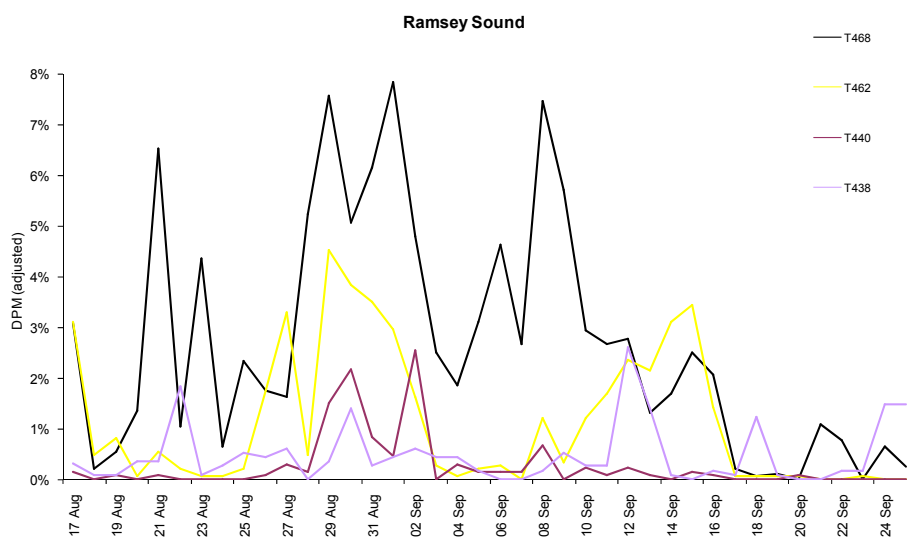


Figure 4-4 Daily detection positive minutes during deployments at four sites in the Ramsey Sound study area.

Daytime / night-time variation in porpoise activity

4.3.8 DPM during the day and night at each TPOD location were also compared. Average DPM values are shown in Table 4-5. These data were used to test two hypotheses:

- H_0 : there was no significant difference in the level of porpoise activity recorded during daylight hours and during the hours of darkness each day; and
- H_1 : higher levels of porpoise activity tended to be recorded either during the day or during the night.

Table 4-5 Comparison of median daily DPM values recorded during the day and night. The P-values are the results of Wilcoxon's signed ranks test (two-sided).

Site	TPOD	Median Day % DPM	Median Night % DPM	n Days	P-value	Significance Level $\alpha = 0.05$
The Skerries	T438	0.74	1.82	18	0.0010	**
	T439	0.21	0.38	23	0.2226	ns
	T462	0.10	0.00	17	0.7910	ns
	T465	0.26	0.94	16	0.0020	**
	T468	4.95	1.68	18	0.0077	**
Ramsey Sound	T438	0.00	0.47	40	<0.0001	***
	T440	0.00	0.00	41	0.0002	***
	T462	0.00	0.98	41	<0.0001	***
	T468	0.64	4.02	40	0.0001	***

4.3.9 At the Skerries, detection rates were relatively low at one TPOD location, T462, and at this site there was no clear day-night pattern. Three of the other four sites however, showed higher levels of echolocation activity at night than during the day (Figure 4.5: T438, T439, T465). The diel variation was statistically significant at two of these sites: at T438 and T465 significantly more porpoise activity was recorded at night; and in 16 of 18 and 14 of 16 twenty-four hour periods respectively. One site however, T468, showed a reverse pattern with significantly higher detection rates recorded during the day than during the night ($P = 0.008$). Daytime levels were higher than night-time levels on 15 of

18 days. This was the only location in this study where significantly more diurnal than nocturnal harbour porpoise activity was recorded.

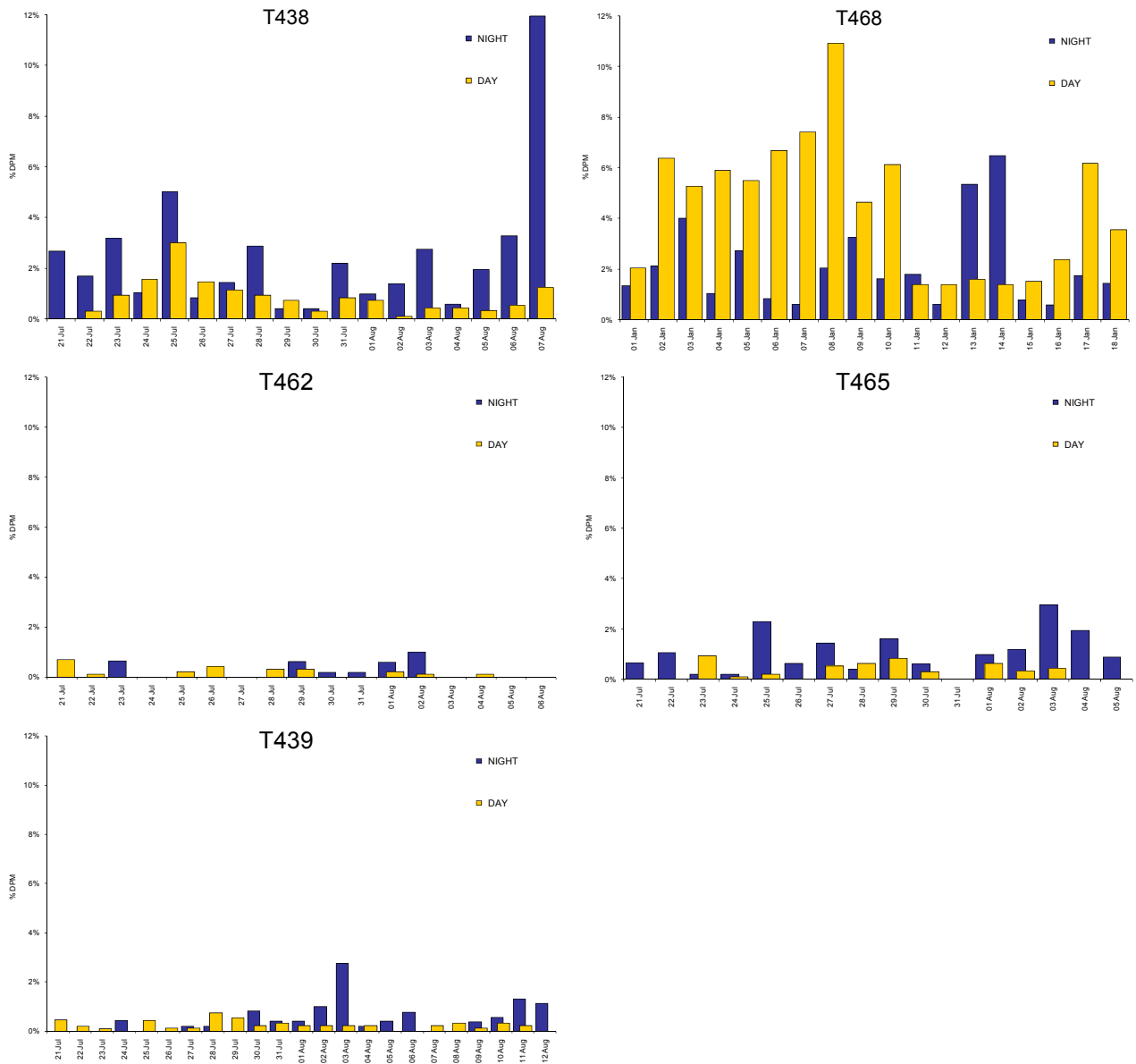


Figure 4-5 The Skerries / Carmel Head: day – night variation in porpoise acoustic detection rates at each POD location

4.3.10 At Ramsey Sound there was significantly more night-time than daytime porpoise activity at all four locations (T438, T440, T462, T468; $P < 0.001$ in each case). Relatively high levels of activity were recorded during daylight at one location only (T468). Here, DPM exceeded 1% on 18 of 40 daytime periods compared to 28 of 40 night-time periods (Figure 4-6).

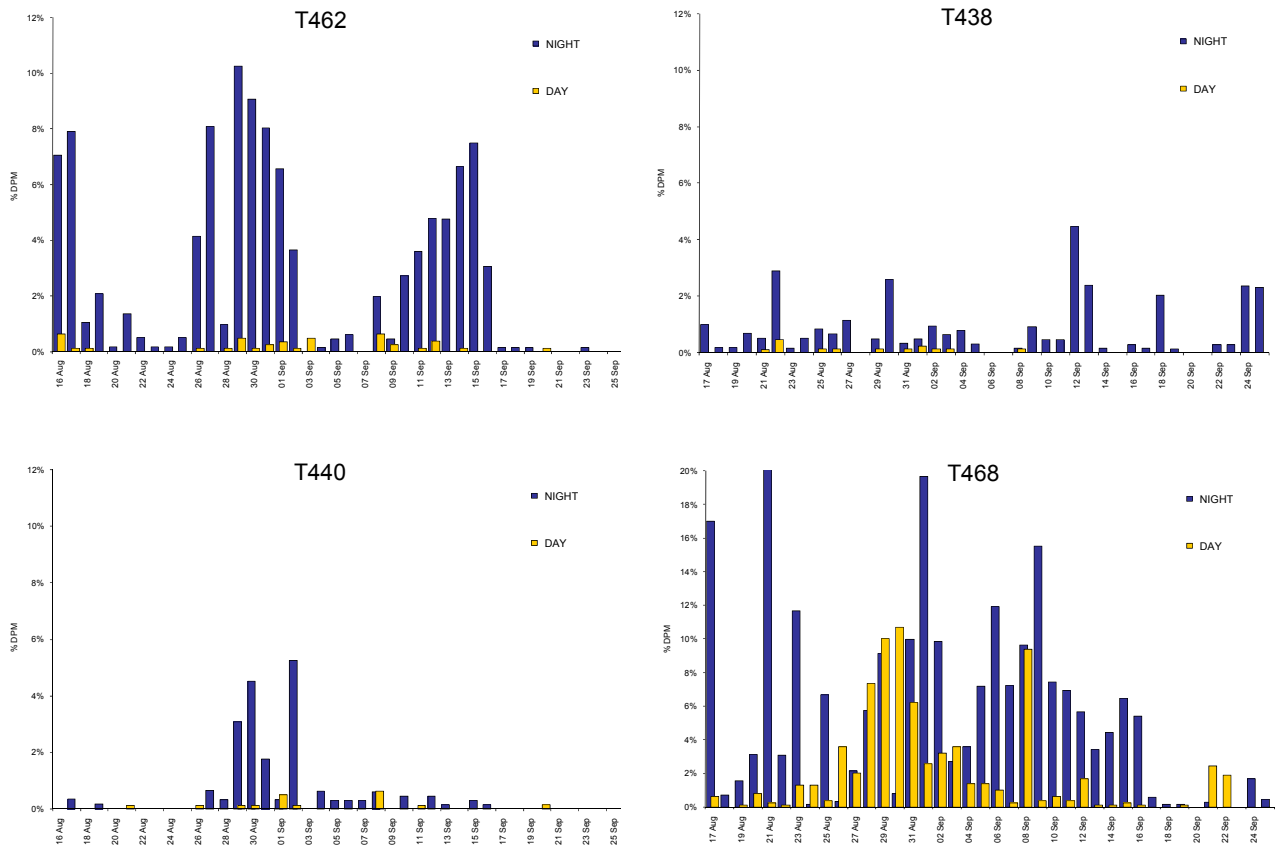


Figure 4-6 Ramsey Sound: day – night variation in porpoise acoustic detection rates at each POD location.

4.3.11 In general therefore, there was a tendency for more harbour porpoise echolocation activity to be recorded at night than during the day. There was comparatively little daytime activity at most locations. Daylight detections were most frequent, both at the Skerries and in Ramsey Sound, at the locations with the highest rates of usage by porpoises overall. The TPOD data recorded harbour porpoise occurrence at all locations in Ramsey Sound and at the Skerries both in the day and at night. If however, we assume that sustained rates of echolocation activity reflect the relative importance of different locations for foraging, then those locations at which porpoises spent most time foraging at night were the only locations at which foraging also appeared profitable during the day.

Variation in porpoise activity over the ebb-flood tidal cycle

4.3.12 Porpoise detection rates at the Skerries and Ramsey Sound are plotted in Figure 4-7 and Figure 4-8 for ½ hour intervals within each tidal cycle and the data are summarised

on maps showing TPOD locations in Figure 4-9. At some locations, particularly within Ramsey Sound, there was a clear tidal pattern.

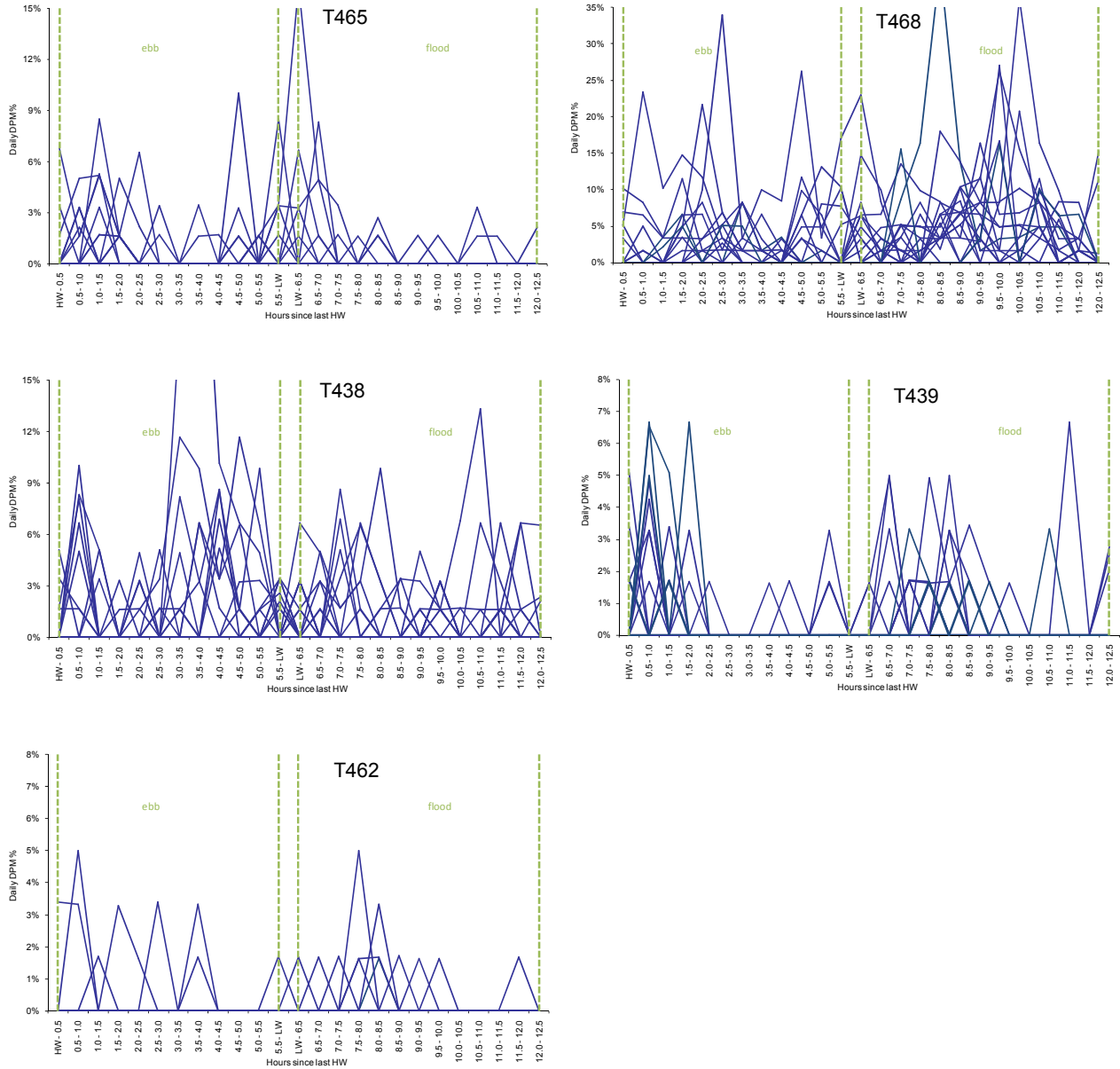


Figure 4-7 The Skerries / Carmel Head: distribution of porpoise detections in relation to the time of last HW.

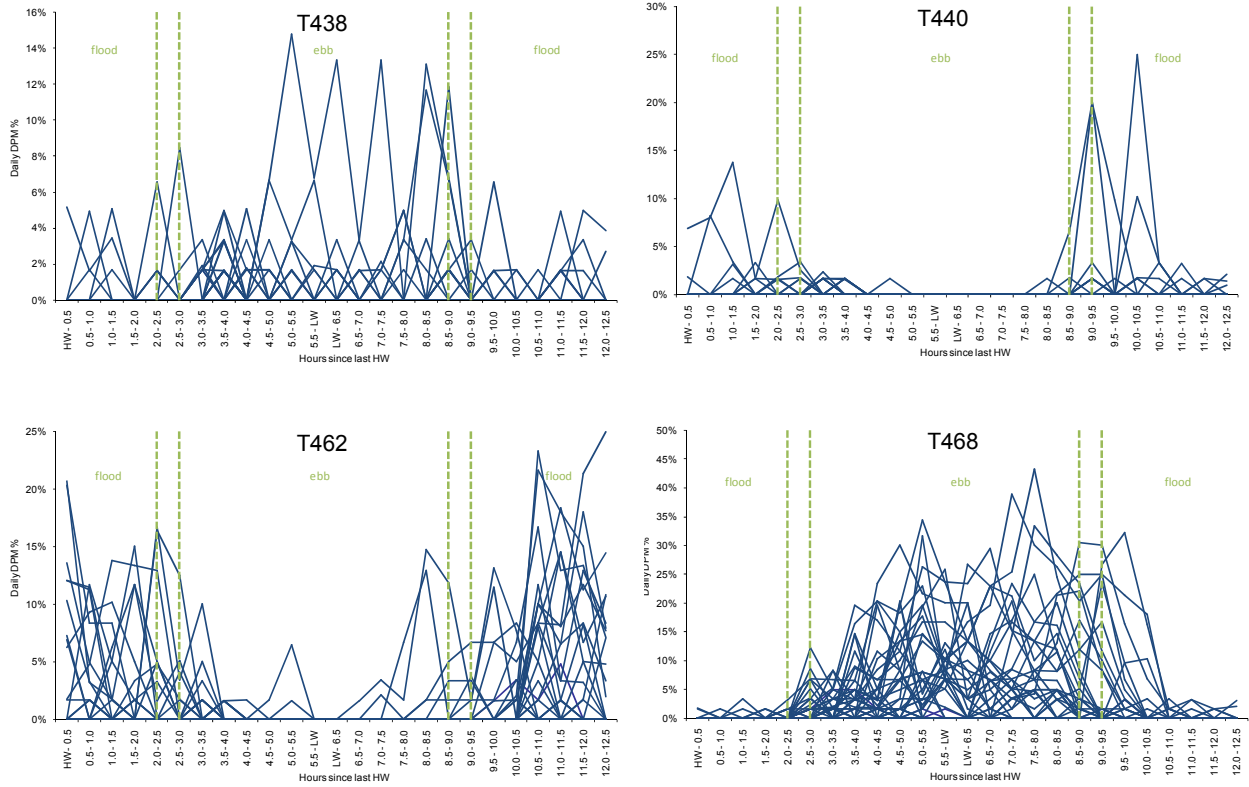


Figure 4-8 Ramsey Sound: distribution of porpoise detections in relation to the time of last HW.

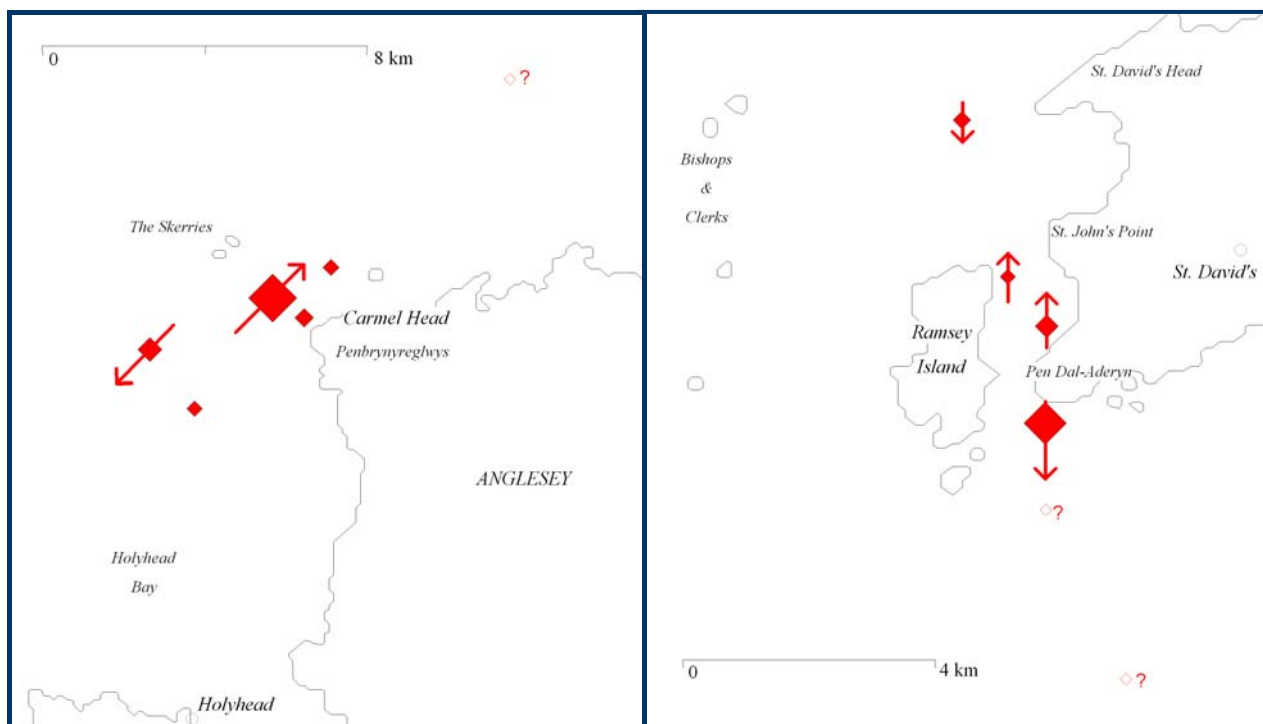


Figure 4-9 An illustration of relative levels and dominant tidal phase of harbour porpoise activity recorded at each POD location for (a) the Skerries (left) and (b) Ramsey Sound sites (right). Symbol size is proportional to total DPM %. Arrows indicate the direction of the tidal stream when peak detections were recorded. At both sites the flood tide has a north going current and the ebb a south going current.

4.3.13 At the Skerries activity in at least three locations appeared to occur at a similar level throughout the ebb-flood cycle. At the two locations with high usage however, there was evidence of contrasting patterns of activity. At T468, although porpoises were recorded at all stages of tide, there was a higher rate of detection during the northwest-setting flood phase than during the ebb. At T465 however, there was more porpoise activity during the south-westerly ebb phase and around the time of low water. The authors therefore speculate that individual animals may move between foraging locations at different stages of tide.

4.3.14 Clearer patterns of porpoise behaviour emerged at Ramsey Sound, perhaps because tide race habitat at Ramsey Sound was more constricted by coastal and seabed topography than at the more open headland locations at the Skerries/Carmel Head. Consistently at T468 in Ramsey Sound, to the south of the narrows and strongest tidal rapids, porpoise activity was concentrated during the ebb tide. An increase in activity was recorded from shortly after the onset of the ebb, until shortly after the tide reversed direction after LW slack. There were then relatively few porpoise detections during the

flood phase. (This pattern is consistent with visual observations made from the shore Pierpoint, 2008) By contrast, at sites T462 and T440 (just north of the narrows) this pattern was reversed. Here there was relatively little porpoise activity during the ebb phase with the majority of detections occurring when the tide was flooding northwards. At T438 to the north of Ramsey Sound, porpoises were present throughout all stages of the tide, but intense periods of activity occurred on several different days during the ebb tide.

Investigation of interactive effects of time-of-day and the tidal cycle

4.3.15 In an attempt to separate the effects of these potentially confounding factors, the activity rates for daytime and night-time, during both ebb and flood tidal phases were compared. Hence, porpoise detections were assigned to one of four classes: day-ebb (DE), day-flood (DF), night-ebb (NE) and night-flood (NF). Average DPM values in each class are shown in Table 4-6. These data were then used to test the following hypotheses:

- H_0 : there was no significant difference in the level of porpoise activity recorded during day-night, ebb-flood phases each day; and
- H_1 : higher levels of porpoise activity tended to be recorded in one or more of these phases.

Table 4-6 Comparison of median daily DPM values recorded during the day and night, flood and ebb phases of the tide. The P-values are the results of Friedman tests. In cases where a significant difference is indicated, all significant pair wise comparisons are shown.

Site	TPOD	Median daily % DPM				P-value $\alpha = 0.05$	Significant pairwise comparisons $\alpha = 0.05$
		Day Ebb	Day Flood	Night Ebb	Night Flood		
The Skerries	T438	0.48%	0.78%	0.98%	1.29%	0.241 ns	-
	T439	0.00%	0.20%	0.00%	0.00%	0.947 ns	-
	T462	0.00%	0.00%	0.00%	0.00%	0.808 ns	-
	T465	0.26%	0.09%	0.94%	0.37%	0.037 *	NE > DE (P = 0.048) NE > NF (P = 0.033)
	T468	1.48%	5.44%	1.75%	1.56%	0.003 **	DF > DE (P = 0.002)

Site	TPOD	Median daily % DPM				P-value $\alpha = 0.05$	Significant pairwise comparisons $\alpha = 0.05$
		Day Ebb	Day Flood	Night Ebb	Night Flood		
							DF > NF (P = 0.001)
Ramsey Sound	T438	0.00%	0.00%	0.40%	0.00%	< 0.001 ***	NE > DE (P < 0.0001) NE > NF (P = 0.001) NF > DF (P < 0.0001)
	T440	0.00%	0.00%	0.00%	0.00%	< 0.001 ***	NF > DF (P < 0.0001) NF > NE (P < 0.0001)
	T462	0.00%	0.00%	0.00%	1.85%	< 0.001 ***	NF > DF (P < 0.0001) NF > NE (P < 0.0001)
	T468	1.50%	0.00%	6.95%	0.00%	< 0.001 ***	DE > DF (P < 0.0001) NE > DE (P = 0.0002) NE > NF (P < 0.0001)

4.3.16 The null hypothesis was rejected at two locations at the Skerries, which showed differences between day-night, ebb-flood classes. At T468 most activity was recorded during the flood phase, and there was more activity during the daytime flood tide than at night (P = 0.001). This was the only location at which significantly greater level of activity was recorded during the day than at night. At T465, which is located in the south-western part of the site, porpoise activity during the ebb tide was higher than during the flood, particularly at night (P = 0.048). There were no significant tendencies at the other three locations.

4.3.17 At Ramsey Sound, there were significant differences in day-night ebb-flood phases at all four locations. In the southern part of the site, T468 recorded significantly more porpoise detections during the south-setting ebb tide than during the north-setting flood tide, but there was more activity during the ebb tide at night than during the day (P = 0.0002).

4.3.18 In contrast, the two locations in the northern half of Ramsey Sound, T440 and T462, recorded significantly more porpoise activity during the flood tide than the ebb tide. In both cases there was also more activity during the flood tide at night than during the day (P < 0.0001). To the north of Ramsey Sound at T438, porpoises were most often

detected at night and during the ebb tide ($P < 0.0001$). There was also however, significantly more activity during the flood tide at night, than on the flood tide during the day ($P < 0.0001$).

4.4 Discussion

- 4.4.1 TPODs have been used to establish baseline information for harbour porpoise activity patterns at two high tidal energy sites on the Welsh coast. Over a two-month period, these autonomous devices logged 4900 h of monitoring effort and measured porpoise occurrence and levels of echolocation activity at nine locations.
- 4.4.2 TPODs have a number of advantages over visual assessment methods, including that the detection process is automated and not susceptible to bias due to variation in observer skill and weather conditions. A further advantage of an automated detection system is that it is possible to log the presence of porpoises continuously, throughout 24 h. Comparisons between data collected by different TPODs do however, assume that each TPOD is equally sensitive and likely to record porpoises under the same circumstances, at the same rate. In previous calibration tests the authors found that this assumption was not necessarily true. To address this calibration test results were used to develop scale factors, which compensated for sensitivity differences between TPODs. The scale factors were subsequently applied to daily DPM values to mitigate for potential sensitivity bias when comparing detection rates at different locations. For a full baseline assessment of these sites the authors recommend that TPODs be randomly assigned to mooring locations, and that they are systematically rotated through all locations through the course of an assessment. This would enable a TPOD identification code to be incorporated as a covariant when modelling variation in detection rate.
- 4.4.3 Daily occurrence of harbour porpoise at the two Welsh study sites was high; porpoises were recorded at the Skerries and Ramsey Sound on every day (and night) of the study. Overall, porpoises were present at each site least 1-2% of the time, but occurrence varied markedly between adjacent TPOD locations. Daily DPM values of up to 10% were recorded at the most highly used locations. From the levels of porpoise activity that were recorded, it was concluded that both study sites included important habitat for harbour porpoise as well as locations that were consistently used less often by this species.
- 4.4.4 At both sites TPODs were placed in the exact locations suggested for possible tidal turbine deployments. At the Skerries, the TPODs closest to the proposed turbine sites, T468 and T465, showed some of the highest detection rates. In contrast, at Ramsey

Sound T440, located directly in the vicinity of a site proposed for a tidal turbine, the lowest frequency of detection for harbour porpoises was recorded on 56% of the days over a 41-day deployment, and porpoises were recorded on average, in less than 0.1% of effort minutes per day. The present data therefore indicate that the likelihood of direct encounter risk for harbour porpoises would probably be less here, than at the four other locations monitored in Ramsey Sound.

- 4.4.5 The levels of nocturnal activity at most locations were substantially higher than they were during daylight hours. Visual assessment would therefore have considerably underestimated the relative importance of some locations. It was unclear why porpoise echolocation activity was generally higher at night. This may have reflected a greater abundance of animals, elevated click rates associated with intense periods of feeding, or both these factors. DPM is however, relatively insensitive to changes in echolocation click rate; a single animal or click train is sufficient to trigger a DPM. This indicator more closely reflects porpoise occurrence therefore, than the total number of echolocation clicks produced; higher DPM values indicating that porpoises were present in the vicinity of the TPOD for a greater proportion of the monitoring period. Harbour porpoise echolocate habitually and almost continuously (Verfuß *et al.*, 2005). Prolonged periods of silence by porpoises at these locations during daylight would therefore have been an unlikely cause of the observed difference in diel detection rates.
- 4.4.6 In conclusion, it was apparent from these studies that harbour porpoises tended to visit and occupy certain locations far more frequently at night than during the day, although the cause of this is unclear. A possible explanation may be that foraging intensified at these locations at night, either because a higher density of prey were present or because there was more opportunity for prey capture (e.g. if prey emerged from refuges to feed at night). This pattern was not seen universally however. The location at which the highest levels of porpoise detection were recorded at the Skerries, T468 showed the opposite pattern. It was the only location where DPM was significantly higher during the day than at night. This inconsistency between locations may illustrate that harbour porpoise exploit diverse locations throughout 24 h, in response to changing concentrations of prey.
- 4.4.7 Little is known about prey species or prey density at either of our study sites, but the availability of some known prey species (e.g. herring or sandeel; Santos and Pierce, 2003; Santos *et al.*, 2004) may increase at night, either because they shelter from predators during the day or because they respond to their own planktonic or nektonic prey, which rise in the water column at night (Blaxter and Holliday, 1969; Blaxter and

Batty, 1987; Cardinale *et al.*, 2003). Pierpoint *et al.* (2000) speculated that the onset of high levels of porpoise activity in Newport Bay (Pembrokeshire) at night late in the year coincided with the arrival of a local spawning stock of herring. Similarly, Todd *et al.* (2009) reported that most porpoise encounters within a complex of North Sea gas exploration and production platforms occurred at night, when an increase in the rate at which feeding “buzzes” were recorded, suggested that porpoises approached the platforms to feed.

- 4.4.8 Alternatively, porpoises may have avoided the study sites during the day, having been displaced for example, by high levels of boat disturbance. Levels of tourist boat traffic in Ramsey Sound are relatively high during the summer and a code of conduct for boat users has been established specifically to reduce the risk of colliding with or disturbing harbour porpoises (<http://www.pembrokeshiremarinecode.org.uk/code%20conduct.htm>). Raised levels of nocturnal activity have been noted elsewhere however, at sites that experience relatively little boat traffic during the day (Pierpoint *et al.*, 2000). In the present study, two open water and relatively quiet sites at the Skerries also attracted higher levels of porpoise activity during the night than during the day. Clearly, further study is required to determine whether prey availability is greater at these locations at night, and/or whether boat traffic is a contributory factor that explains the difference in levels of porpoise activity at some locations during the night and day.
- 4.4.9 Regular patterns of activity that correlated with the state of tide or the direction of tidal currents were also noted. Tidally-related behavioural patterns at Ramsey Sound were in accordance with previous studies that monitored porpoises by visual observation (Pierpoint, 2009; Barradell, 2009). The use of automated data-loggers enabled us to determine that these tidal patterns extended into and throughout the night also, and were superimposed upon tendencies for day-night differences in activity at some sites. Again, the study results showed marked variation between different locations within each study site however, at some locations porpoise activity was evenly distributed throughout all states of tide. Elsewhere, some locations only appeared to represent important habitat for harbour porpoise at certain stages of tide. It was evident that the most distinct diel and tidal patterns of activity were recorded at the locations used most by porpoises overall, arguably their most important locations. This may lend support to the concept that coastal tidal race habitat is often important for harbour porpoises because of physical factors that cause a consistent and periodic concentration of resources. Pierpoint (2009) hypothesised that the striking periodicity of harbour porpoise occurrence in the southern part of Ramsey Sound was due to the exploitation of prey

that was concentrated by the south-setting ebb tide on steep, seabed and coastal topography.

4.4.10 These data facilitate our interpretation of land-based or ship-based counts of harbour porpoise. Specific locations may provide important habitat for harbour porpoise and support numbers of foraging animals only at certain stages of tide. At locations with strong tidally-related patterns of activity, harbour porpoise activity is likely to be higher at peak periods during the night than is recorded by sighting surveys during the day. It is clear that for site assessment purposes, harbour porpoises should be monitored throughout the day and night, and throughout the ebb-flood tidal cycle. Longer-term TPOD deployments would be a suitable method of addressing spring-neap, seasonal and inter-annual variation. Currently, static acoustic data-loggers including the TPOD, that provide the ability to monitor harbour porpoise activity automatically and continuously for extended periods, are fundamental to the thorough assessment of specific sites. The data they yield however invariably raise a host of additional questions regarding the ecology of the UK's most common species of marine mammal.

5 Using a Vertical Array to Investigate use of the Water Column by Harbour Porpoise in High Tidal Areas

5.1 Introduction

- 5.1.1 Knowledge of the distribution of marine mammals in three dimensions is crucial to assessing and minimising collision risk. In recent years, understanding of the underwater behaviour of cetaceans has increased, mainly as a result of studies using telemetry. Telemetry studies of harbour porpoises have typically involved animals that were released after becoming entrapped in fishing structures such as herring weirs (Otani *et al.*, 2000; Read and Westgate, 1997; Westgate *et al.*, 1995; Sveegaard and Teilmann, 2007). Consequently, these studies have been limited to areas where these types of fishing devices are employed, chiefly the Bay of Fundy in Canada and Danish Baltic waters. Telemetry studies have provided some information on the diving behaviour of porpoises. On occasion they can make very deep dives, for example, Westgate *et al.* (2007) reported dives of over 200 m. However, few if any of these data have come from high tidal energy areas. Because these areas are such a small part of the available habitat for marine mammals it is unlikely that any tagged animal will spend a substantial proportion of its time in them. In addition, because these habitats are so extreme and unusual, there is no basis for inferring behaviour in tidal rapids by extrapolation using data recorded elsewhere.
- 5.1.2 What is therefore required is a method that has the potential for providing data on the underwater behaviour of harbour porpoises that can be taken to and operated in areas of high tidal energy at times of peak current. The relative time of arrival of sounds, such as porpoise clicks, at an array of hydrophones can provide information on the location of the sound source. A linear array of hydrophones suspended vertically in the water is both relatively easy to deploy in the field and able to provide information on the range and depth of vocalising animals (Cato, 1998). This technique has been used before to investigate the diving behaviour of cetaceans. For example, Hastie *et al.* (2006) measured the dive behaviour of bottlenose dolphins using a vertical array. The particular challenge that needed to be overcome in this study was to apply the techniques in extreme tidal currents; maintaining the vertical alignment of the array and making multichannel recordings and measurements at the high ultrasonic frequencies produced by harbour porpoises.

- 5.1.3 Note: We were able to conduct additional work carrying out a calibration trial to show accuracy of depth and range measurement and developing an improved analysis approach after the main report was completed. This work is presented as Appendix 2.

5.2 Methods

Equipment

- 5.2.1 The vertical array used in this project comprised two stereo pairs of hydrophones (sub array) that could be deployed at different depths along a heavily weighted steel crane cable (Figure 5-1). Hydrophones in each sub array were separated by 25 cm and each pair was mounted in a weighted rigid plastic tube suspended within a larger (200 mm diameter) free-flooding polythene pipe. These polythene pipes were attached to the crane cable at the desired depths. This arrangement allowed each sub array to hang like a pendulum within the polythene tube. As the larger tube isolated the hydrophones from water movement each sub array hung perfectly vertically. Inclometers at the top and the bottom of the steel cable were used to measure the cable's deflection. The inclinometers' output (x and y angles relative to vertical) were transmitted as RS232 sentences which were read continuously and stored using a Labview program written by one of the team (JM).

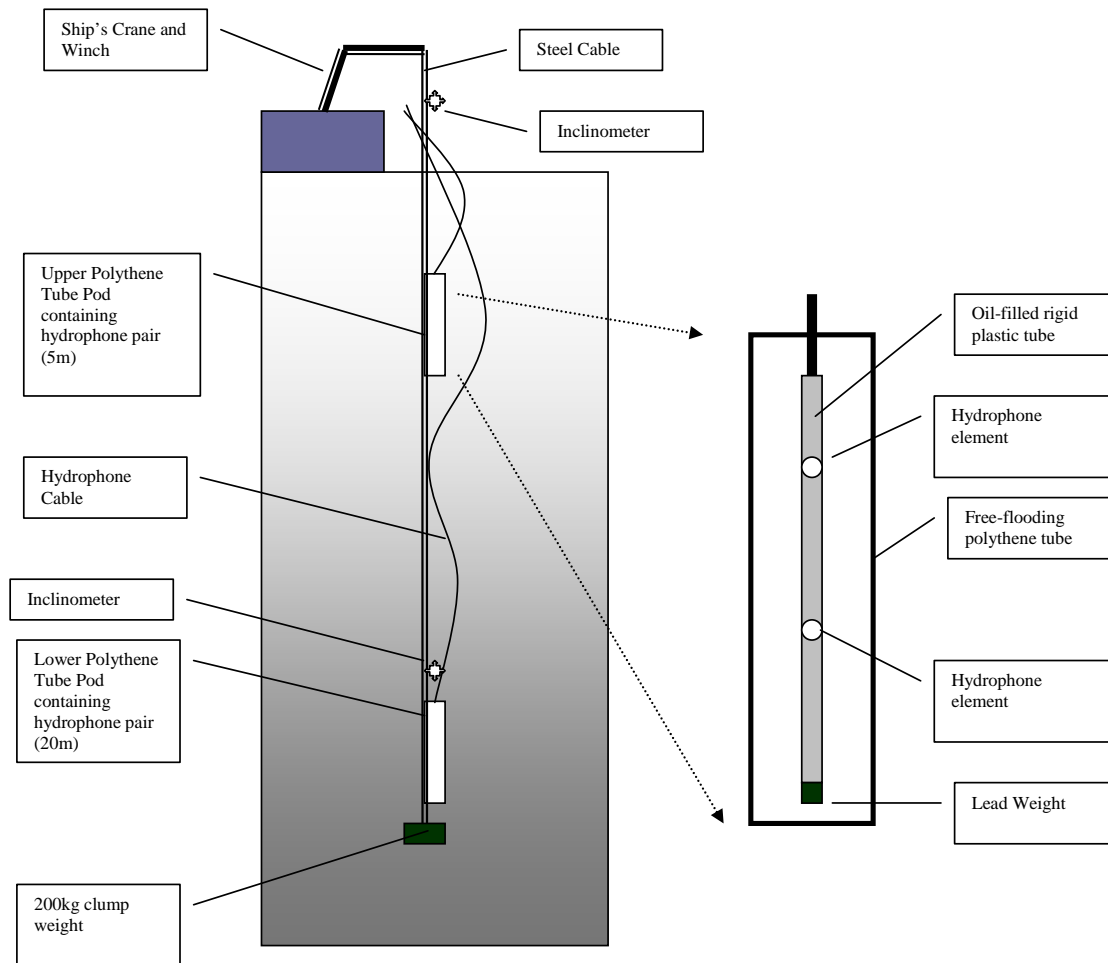


Figure 5-1 Diagram of a four element vertical array for determining the depth of porpoise vocalisations.

5.2.2 Signals from each sub array were amplified and processed by a Magrec HP27 ST amplifier/conditioner unit and filtered with a 20 kHz high pass filter before being digitised. Capturing porpoise signals from this array required digitisation of four channels at 500 kHz each. This was achieved by using two synchronised National Instruments 6251 USB DAQ devices. Software to achieve this synchronisation was written specifically for this project by Douglas Gillespie and implemented in the PAMGUARD acoustic monitoring program⁶ where it is now universally available.

⁶ PAMGUARD is an open source software suite freely available at <http://www.pamguard.org/home.shtml>

Data analysis

- 5.2.3 These recordings were then analysed with PAMGUARD with each “pendulum” pair in the hydrophone array being treated as a pair of channels. The click detection algorithm in PAMGUARD is identical to that in the RainbowClick software used to detect porpoise clicks during towed hydrophone surveys. Short sections of the wav files (around each candidate porpoise click detection) were extracted and used for further analysis using Matlab.
- 5.2.4 Sections where porpoise clicks were detected on all four channels within the travel time for sound between the two most distant hydrophones (~19 m at 1500 m/sec) were selected for further locational analysis. (Clicks detected on channels with a greater time separation than this could not have arrived directly from the same source).
- 5.2.5 Time delays were calculated between the clicks detected on all channels (six possible time delays in total) using cross correlation of the click waveforms which had been band pass filtered between 100 to 150 kHz to reduce noise.
- 5.2.6 The array was assumed to be vertical in the water column and the location of the hydrophones was taken from field notes.
- 5.2.7 A two dimensional (range and depth) fit of the location of the source for each click was determined using a maximum likelihood estimator $\arg\max \hat{\lambda}(R, D | d_i)$ where

$$\hat{\lambda}(R, D | d_i) = \prod_{i \neq j} 0.5 \left(\frac{d_{i,j} - t_{i,j}}{\delta t_{i,j}} \right)^2$$

- 5.2.8 Where R and D are the range and depth of the animal clicking, d_i are the measured time delays, t_i are the calculated time delays for the given array geometry and the position (R, D) and δt are the estimates of the errors on the calculated time delays based on estimates of the accuracy of the hydrophone elements’ positions within the array and the accuracy of the speed of sound measurement.

Array position errors

- 5.2.9 The most significant source of acoustic positioning error is likely to be from errors in the position of the individual hydrophones within the array. The boat was drifting freely with the current while recordings were being made but movement of the vessel relative to the water, due to the effects of wind for example, would have occurred and the cable may also have been deflected by the influence of differential current speeds at different

depths in the water column. Such errors are currently estimated based on likely construction tolerances, observations of how much the array seemed to be off vertical in the field and a preliminary examination of inclinometer data (e.g. see Figure 5-3).

5.2.10 Clearly, errors between elements within each sub array are likely to be a lot smaller than the errors between elements in different sub arrays. Two sets of errors are therefore used (each in x,y,z coordinates). Firstly an error on element coordinates within each sub array, and secondly errors on the overall alignment of each sub array. When estimating time delay for elements in the same sub array, only the first errors are used. For errors between elements in different sub arrays the two types of error are added in quadrature.

5.2.11 For this analysis, standard errors within each sub array were assumed to be ± 1 cm in each coordinate. Based on inclinometer data and an estimate of depth accuracy, between sub arrays, errors were assumed to be ± 2 m in the x and y (horizontal) coordinates and ± 0.5 m in depth. The error in the speed of sound was taken as ± 2 m.s⁻¹.

Timing error estimation

5.2.12 If the position of each hydrophone element is represented by vectors a_i and a_j between two hydrophone elements i and j , and b is the position of the vocalising animal, then the

expected time delay $\delta t_{i,j}$ is simply $\delta t_{i,j} = \frac{|\vec{b} - \vec{a}_j| - |\vec{b} - \vec{a}_i|}{c}$ where c is the speed of sound

in seawater.

5.2.13 To estimate the error on the time delay measurement, it is first assessed whether or not the elements i and j are in the same sub array. If they are not, then the three error components for the element are added in quadrature to the three error components for the sub array containing each element. The magnitude of these three error components along the unit vector $b-a$, is then taken and the three error components added in quadrature and divided by the speed of sound to generate an overall error for the propagation time from the animal to each element. The total error due to inaccuracies in element position is then the sum in quadrature of the time errors to each element.

5.2.14 An additional timing error due to uncertainties in the speed of sound is then taken as

$\delta t_{i,j} \frac{\delta c}{c}$ and this is in turn added in quadrature to the timing error due to array alignment.

Position estimation

5.2.15 Positions were estimated using the Matlab function `lsqnonlin` to obtain the position (R,D) from the maximum of equation 1. Position errors were then estimated from the curvature of the likelihood function to either side of the maximum value. A typical likelihood surface is shown in Figure 5-2, showing detections with a depth estimate of 9 m and a range of 150 m.

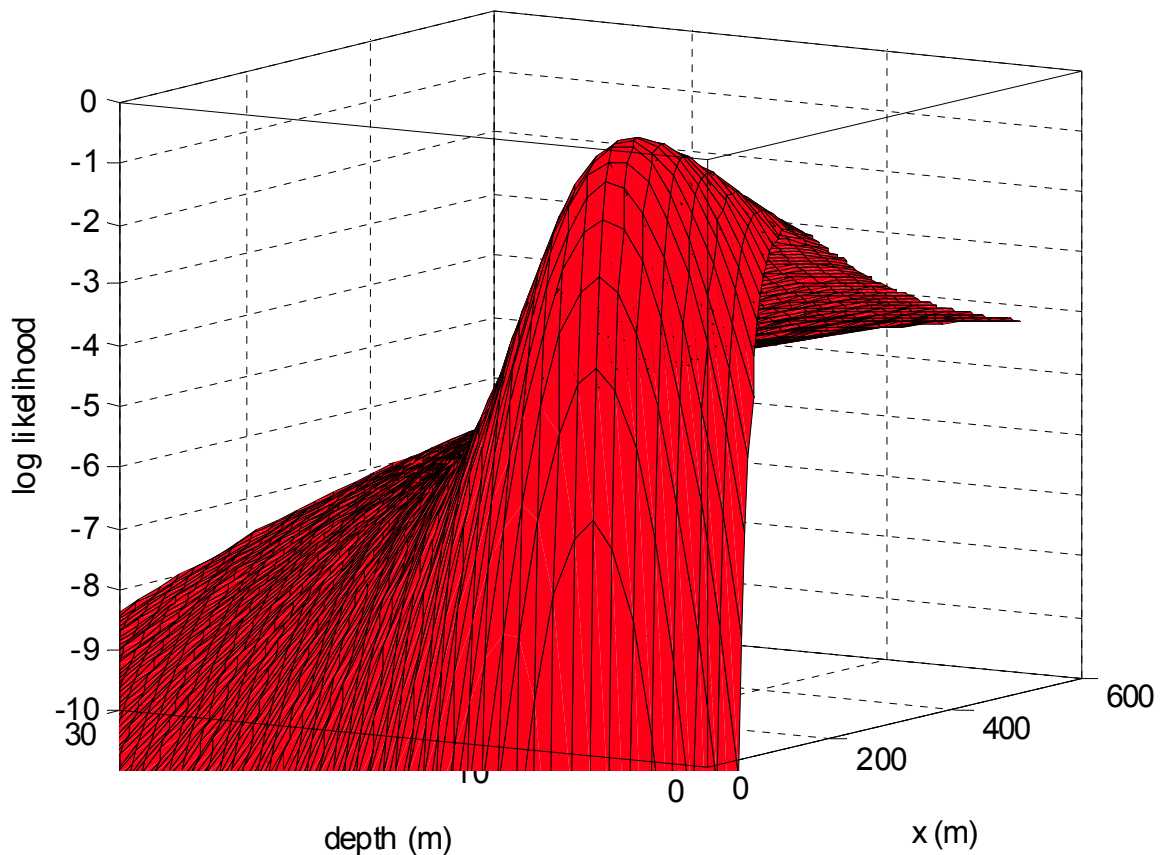


Figure 5-2 *Example plot of likelihood against depth and range (x) for a porpoise click recorded on the vertical array.*

5.3 Results

5.3.1 After some preliminary experimentation and trouble-shooting an effective system for deploying the vertical array from the vessel while drifting in strong tidal currents was devised. Drifts often had to be terminated to reposition the vessel into deep water or to avoid obstacles but some long drifts were also achieved. During drifts, a full complement

of visual observers was maintained and the location of any porpoises observed recorded. Inclinometer data indicated that the weighted cable was usually within 5° of the vertical during drift recordings (Figure 5-3).

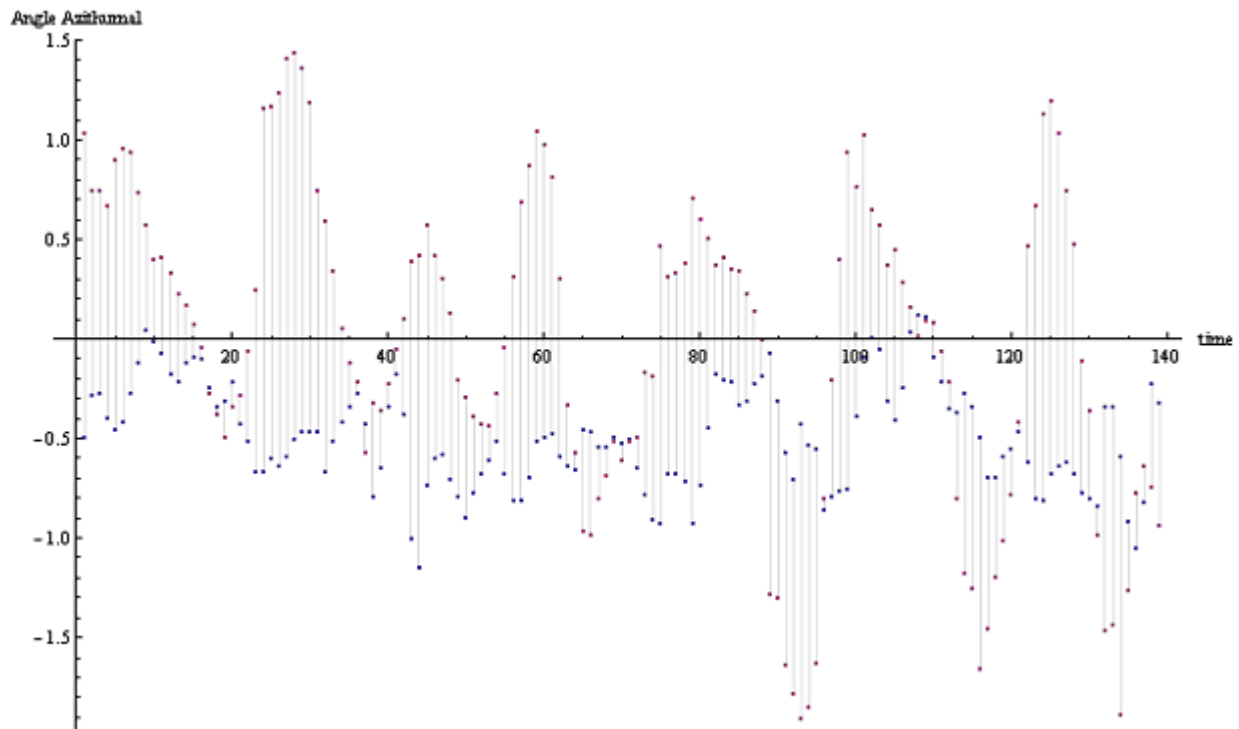


Figure 5-3 Plot of typical inclinometer data showing angle from vertical in degrees of the crane wire at the location of the bottom hydrophone pair (red dots) and the top of the cable above water (blue dots). Samples are 0.2 seconds apart.

5.3.2 Figure 5-4 shows vessel tracks during drift recordings with the vertical array at both Skerries and Ramsey Sound. Some 213 GB of recordings (approximately 15 h) were collected.

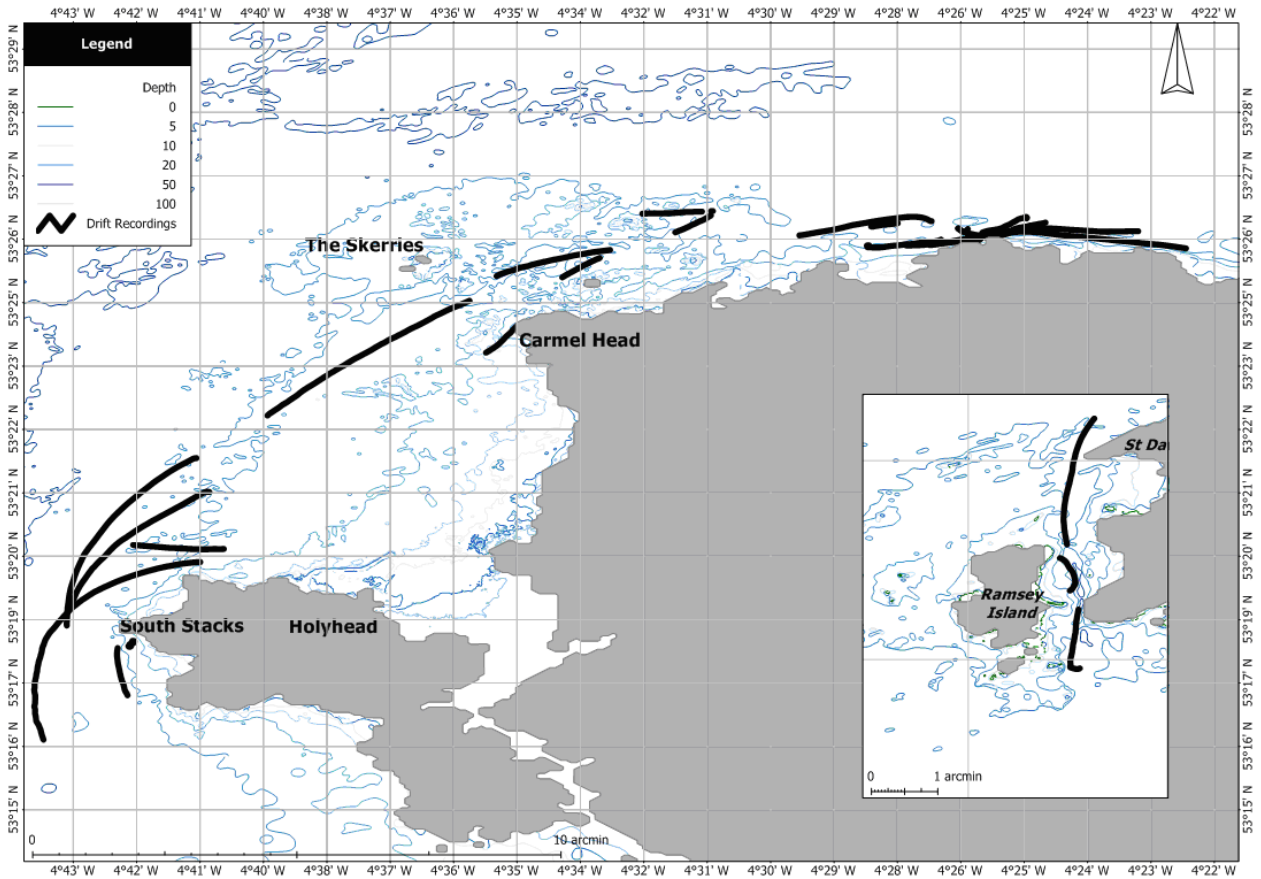


Figure 5-4 Tracks of vessel while making drift recordings with vertical line array. Inset shows tracks in Ramsey Sound.

5.3.3 A total of 1048 click pairs, identified as harbour porpoise close enough in time on the two channel pairs to constitute a possible match (e.g. Figure 5-5) were identified. Of these, a solution was found and a location calculated in 635 cases.

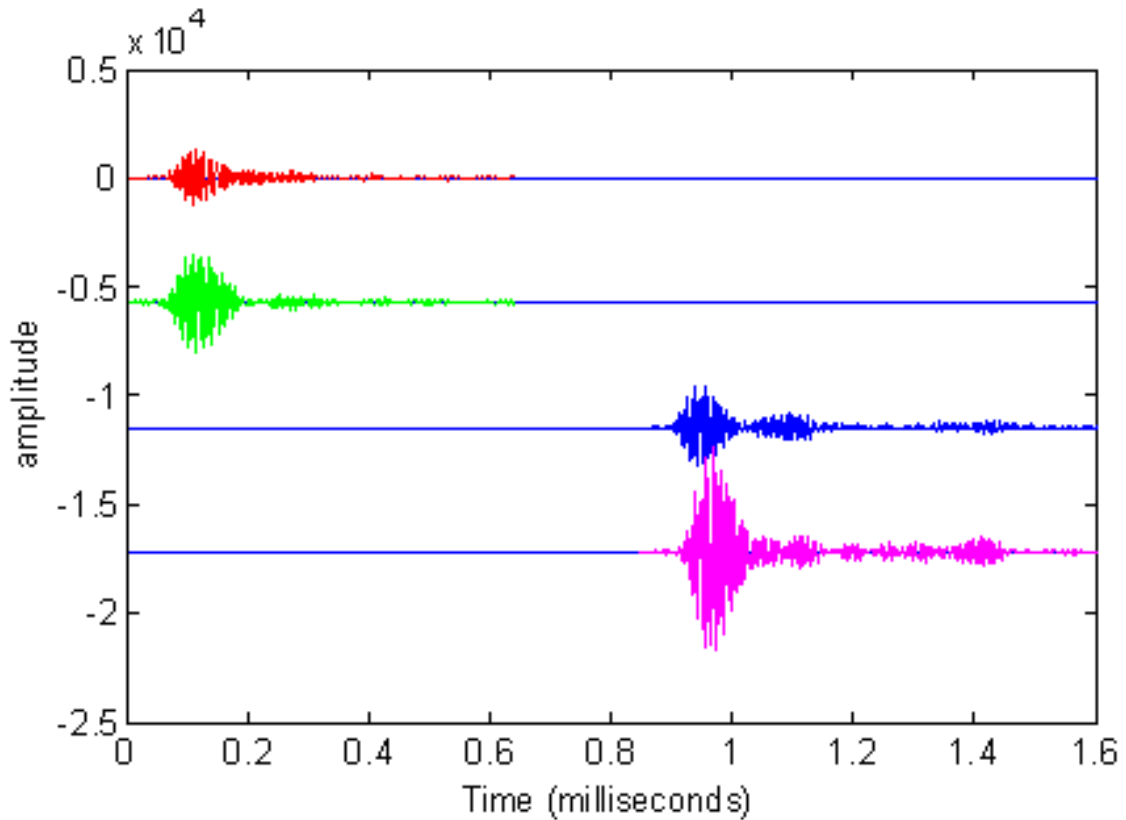


Figure 5-5 *Porpoise click waveforms recorded on four channels from the vertical array.*

5.3.4 Positional accuracy varied greatly and as would be expected, accuracy decreased rapidly further from the array (Figure 5-6). As a general rule, it is unrealistic to track animals which at a distance of more than about 5 times the array dimension. The array dimension in this study was about 15 m. We have therefore restricted depth data to that from animals localised to within 100 m of the array.

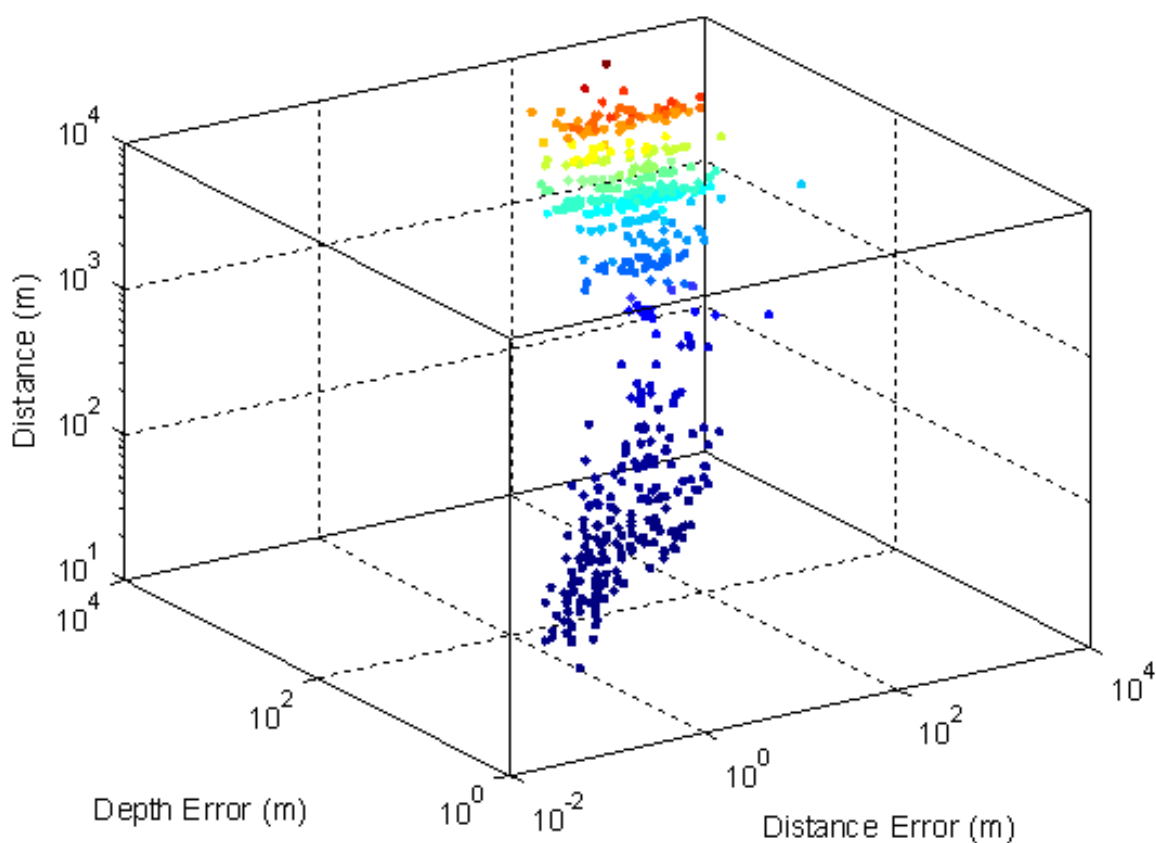


Figure 5-6 Errors on range and depth measurements as a function of range. It can be seen that the error on the range estimation is considerably greater than the error on the depth estimation. This is a direct result of the vertical array geometry employed.

5.3.5 Figure 5.7 shows the depth and range to clicks that were localised within 100 m of the array. Blue vertical lines are drawn between clicks separated by > 60 seconds (indicating that clicks between blue lines may be from the same animal). In many cases, sequences of depths and ranges are roughly aligned forming gradually changing “tracks”, as one would expect to see from a vocalising animal moving through the water column. It is noteworthy, and encouraging, that no locations placed porpoises above the water’s surface.

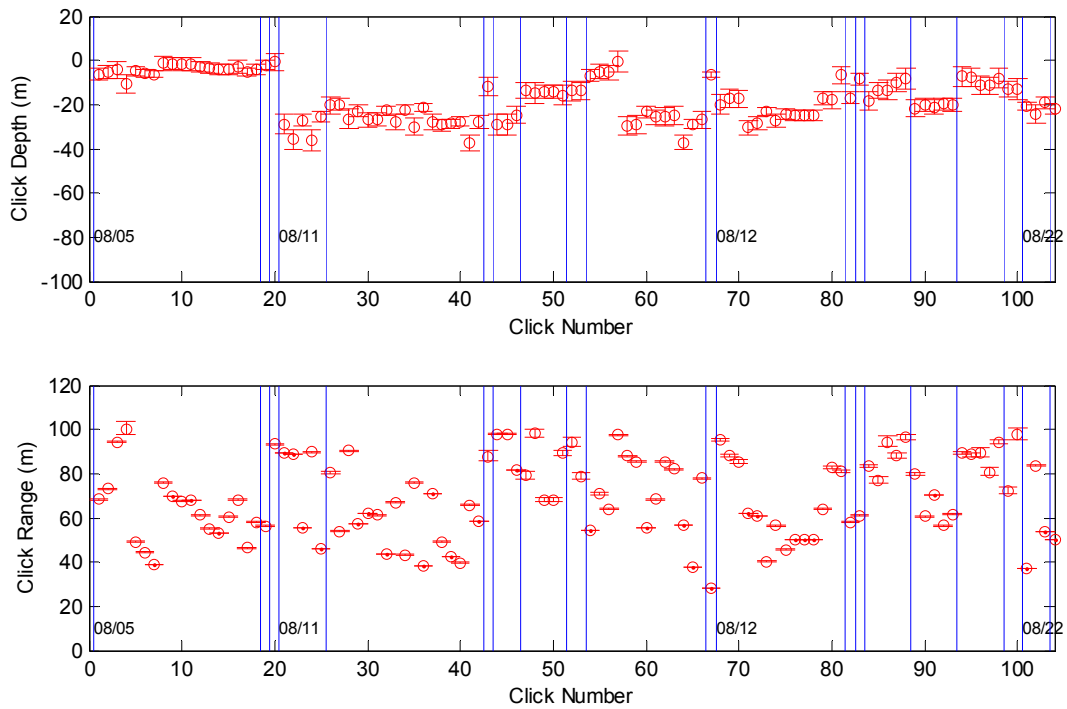


Figure 5-7 Depth(top panel) and range (bottom panel) for clicks localised within 100m of the array. Vertical blue lines show breaks between clicks separated by >60 seconds. Clicks between lines are likely to be from the same individual or group.

5.3.6 Figure 5-8 shows the distribution of clicks with depth shown as histograms for all clicks closer than 100 m and for clicks closer than 50 m (the closer clicks being more accurately tracked). It can be seen that click locations are distributed between 0 and 45 m depth in the water column. The higher number of clicks at depths between 20 and 35 m may be indicative of porpoises spending time foraging at the bottom, as has been reported by other studies. The small number of clicks between 50 and 100 m from the array which were tracked to small negative depths is consistent with the estimated error on these locations.

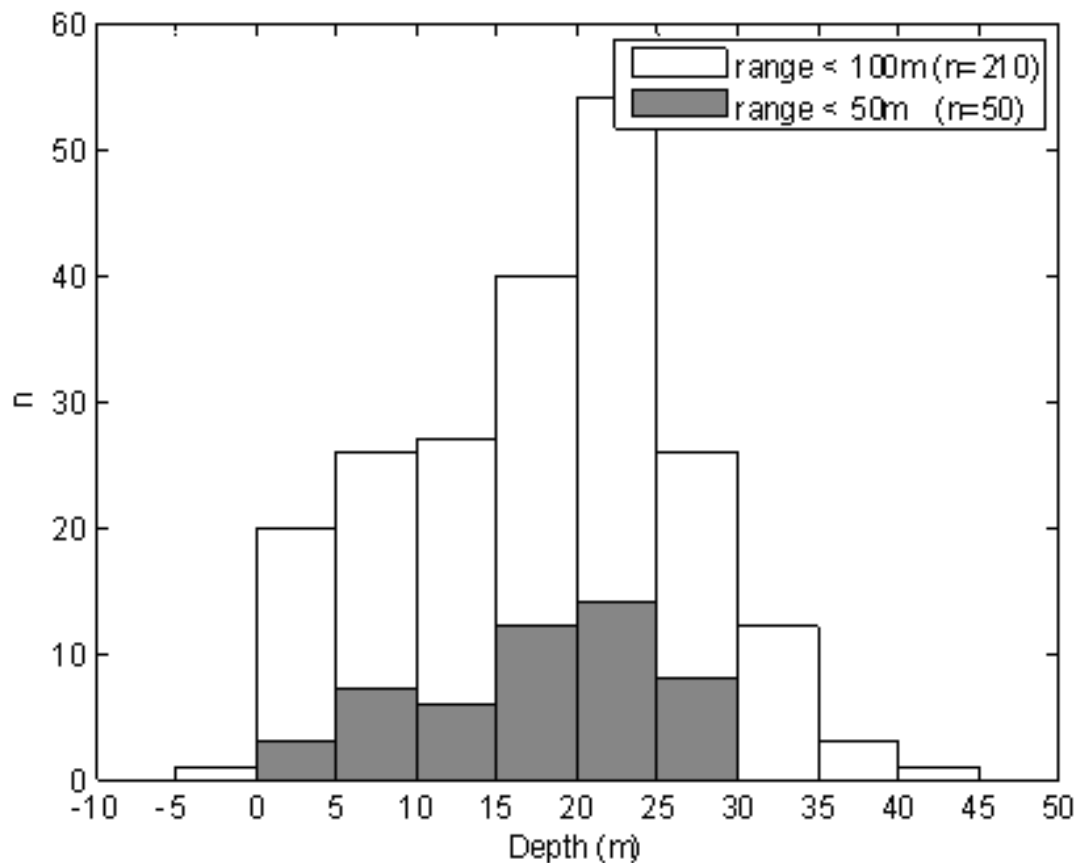


Figure 5-8 *Distribution of depths at which porpoise clicks were located.*

5.4 Discussion

5.4.1 This is a new and somewhat novel technique and consequently a substantial amount of development and new programming has been required. At the instigation of this project this method seemed to be one of the few capable of delivering information on use of the water column, which is very important in assessing and minimising collision. Consequently, although it was technically risky, the authors believed it was worth developing and exploring, but, as there could have no confidence that the method would be successful and yield useful data, it was not appropriate to budget large amounts of time for analysis or to collect a very extensive field dataset. Thus, at this stage an assessment of the technique's potential and accuracy is provided, together with some preliminary results.

5.4.2 This method can provide information on the distribution of depths at which porpoises vocalise in areas of high tidal current. The location of single clicks can be measured with a useful accuracy even when array configuration errors towards the upper end of those

measured are assumed. It is likely that location accuracy can be improved if inclinometer data are used to provide better information on the location of hydrophones. It is also possible that precision can be improved by fitting tracks to sequences of clicks likely to come from the same individual animal. Animals can only be located with this method when they produce sound, thus these data really show the depths at which they vocalise rather than the probability that they are at a particular depth. Porpoises seem to vocalise frequently during normal swimming behaviour (Akamatsu *et al.*, 2005). However, some biases could result. More representative and complete data on dives might be derived by fitting a movement model to patterns of acoustically derived locations to reconstruct likely dive behaviour. The characteristics of echolocation vocalisations can provide information on other aspects of an animal's behaviour underwater. For example, rapid "buzz" locations are often made when animals are foraging (Kyhn *et al.*, 2009). Putting these insights together with an ability to track the location of animals underwater should provide more detailed information on the use porpoises are making of these areas.

5.5 Further research

- 5.5.1 Given the available time during this study for this experimental technique, it is considered that some useful progress has been made, on what was in effect a feasibility study. Additional analysis could be undertaken with the existing recordings, mainly to explore methodological issues, including making better use of the inclinometer data. Initial further data analysis has been undertaken since this report was initially drafted, and this information is included in Appendix 2 of this report.
- 5.5.2 Given the encouraging results reported here, we feel confident that using this approach to collect additional field data would yield a more complete and useful dataset showing the depth distributions of porpoises in areas with high tidal currents.

6 Shore Based Observations to Investigate Aspects of Harbour Porpoise Ecology in High Tidal Areas

6.1 Introduction

6.1.1 Areas of water close to shore can be observed by land based observers. Because no dedicated platform is involved this can be a cost effective data collection method and there should be no concerns about responsive movements and disturbance. The technique has often been used to monitor high tidal current areas but it is not without its issues. Clearly, only areas close to shore can be monitored in this way. There are also severe methodological difficulties in determining effective ranges, sightings functions and detection probabilities and as in many visual methods, fixing the location of sightings accurately and efficiently is a challenge. Our intention in this part of the project was to both collect useful field data and to explore some methodological improvements.

6.2 Methods

Estimating detection probability in relation to distance from observer

- 6.2.1 Line transect surveys from vessels usually estimate the change in detection probability with perpendicular distance from the vessel track. In the absence of any response to the vessel it can be assumed that the density of animals will be independent of distance from the trackline. Thus the frequency distribution of detections as a function of perpendicular distance also indicates the relative detection probability. Estimating the absolute detection probability usually involves calculating this relative detection function from the distribution of observed distances and scaling this according to the estimated detection probability for an animal directly on the trackline (often called $g(0)$).
- 6.2.2 Shore based observations from a fixed point are more similar to point transects but the assumption that animal density is independent of distance from the observation point is unlikely to be met. Thus, it is generally not possible to derive a detection function based on observed radial distances. However, knowing the way in which detection probability varies with distance is critical for interpreting observed distribution patterns. The probability that an animal will be detected is also a function of the length of time that it spends within the area.

- 6.2.3 An alternative method for estimating detection probability from shore based observations is to use two independent observers in a similar way to independent observer experiments on vessel surveys to estimate $g(0)$. This method on vessels uses the proportion of detections that are made by one or both observers to estimate detection probability directly on the track line. For this project we adapted the method to try and estimate detection probability from a fixed observation point. For vessel based surveys the aim is usually to estimate the detection probability for an animal that may make multiple surfacings as it passes the vessel at a certain perpendicular distance. For shore based observations of harbour porpoise it is often difficult to know whether successive surfacings are from the same individual. Hence estimating a detection probability for an animal is problematic. In addition this will depend on how long the animal spends in the area. A more straightforward approach is to use cue counting type methods where the number of porpoise surfacings in a given area in a given time is used as the index of density and the probability of detecting an individual surfacing is estimated.
- 6.2.4 The visual boat based methods used in this study were based on those developed for the SCANSII survey used independent 'Primary' and 'Tracker' observers to conduct Mark-Recapture Distance Sampling. For shore based observations this study used a modification of this approach to try and estimate detection probability for porpoise surfacings as a function of radial distance.

Methods for two independent shore-based observers

- 6.2.5 Accurate time and location information for porpoise surfacings from both observers is critical for assigning whether these are duplicates sightings of the same individual. When several animals are in the area, surfacings will occur at a rate that is not practicable to write down or enter directly into a computer. Data entry would also require an additional observer or for the observers to stop watching in order to enter data. Video systems can overcome these problems by recording a full audio commentary alongside video images that can be used to measure location.
- 6.2.6 For this study, both observers were equipped with the same video system and a downward facing still digital camera was used to measure bearings. Instead of using reference marks on the deck of the vessel, a reference stick was placed by each observer's feet and fixed to the ground. The observer's location was recorded using a GPS and remained the same each day within the study area. The video camera was then pointed at a landmark at a known location and bearing images of the reference mark taken in order to provide a correction relative to True North. An additional

reference mark was selected as a calibration target. This was chosen such that it filled the frame with the lens on full zoom. The video camera had previously been calibrated to measure the angle per pixel on the image with the lens at full zoom. Whenever the zoom settings were changed in order to track animals closer to the observer the lens was recalibrated against the target by recording images that could then be measured using the analysis software.

- 6.2.7 For each observation session one observer was designated as the 'Tracker' and the other as a 'Scanner'. The role of the Tracker was to search for individuals or groups and then track these for as long as possible recording each surfacing. This would create a set of trials of surfacing events that either would or would not be detected by the Scanner. The Scanner was instructed to scan steadily using binoculars across the whole area of interest. A complete scan was designed to take 15 minutes and a beeper was set to go off every two minutes to give the Scanner a reference to try and maintain an even scan rate. When the Scanner detected an animal they remained looking at it for long enough to capture the location of the surfacing, species identification and assess group size but resumed the systematic scanning as soon as possible.
- 6.2.8 In addition to examining distribution patterns, one of the objectives of the study was to examine movement patterns of porpoises as potential input to risk models in the vicinity of turbines. The Tracker data was designed to also fulfil this role by obtaining tracks for as long as possible of movements of individuals and groups.

Field work

Carmel Head, Anglesey

- 6.2.9 Land-based surveys were conducted from a fixed-point on the cliffs at Carmel Head, Anglesey, opposite the Skerries (Figure 6-1) during the period 25th July 2009 to 11th August 2009. In total, eight surveying sessions were completed here, some of which had to be curtailed due to adverse weather conditions. These are summarised in Table 6-1.

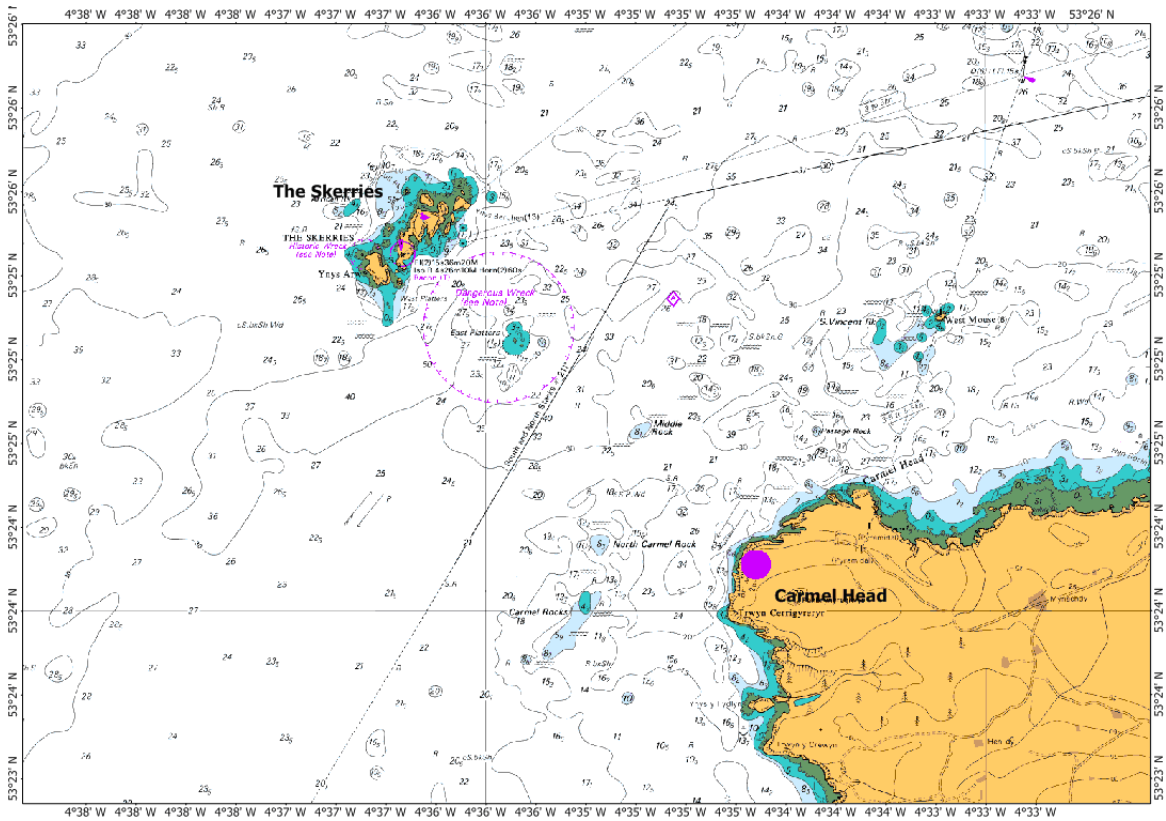


Figure 6-1 Location of shore station on Carmel Head, Anglesey in July/August 2009.

Table 6-1 Summary of land based survey effort at Carmel Head, Anglesey in July and August 2009.

Date	Hours of Survey Effort
25-Jul-09	5 ½ hrs
29-Jul-09	4 ½ hrs
01-Aug-09	5 ½ hrs
02-Aug-09	3 hrs (abandoned due to bad weather)
06-Aug-09	5 ½ hrs
07-Aug-09	7 hrs
08-Aug-09	1 hr (abandoned due to bad weather)
11-Aug-09	1 hr (abandoned due to bad weather)

Ramsey Sound, Pembrokeshire

6.2.10 Dedicated shore-based visual surveys were conducted in Ramsey Sound between 3rd September 2009 and 18th September 2009 by the same observers that had completed most of the effort in Anglesey. Two shore stations overlooking the Sound were utilised and these are shown in Figure 6-2. Survey effort is summarised in Table 6-2.

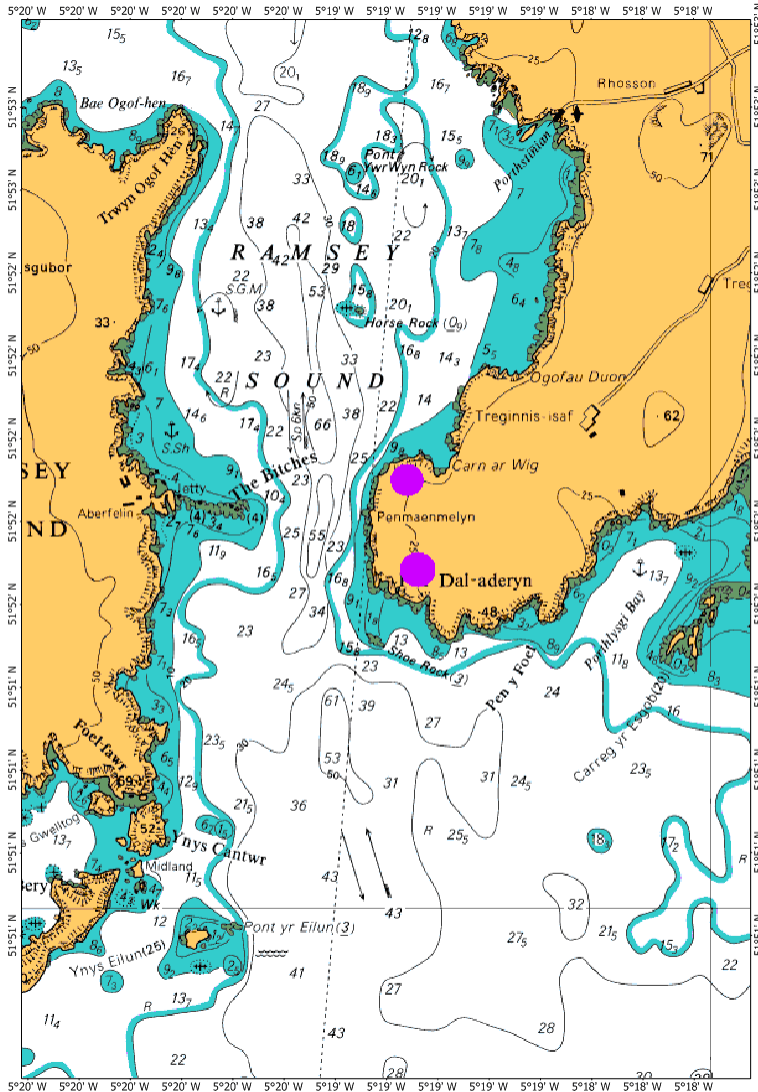


Figure 6-2 Locations of two shore stations overlooking Ramsey Sound used in September 2009.

Table 6-2 *Summary of survey effort expended in Ramsey Sound in September 2009.*

Date	Hours of Survey Effort
03-Sep-09	2.9
05-Sep-09	8.2
07-Sep-09	6.9
09-Sep-09	6.8
10-Sep-09	4.1
11-Sep-09	7.3
12-Sep-09	4.6
13-Sep-09	5.3
15-Sep-09	3.6
16-Sep-09	5.1
17-Sep-09	6.2
18-Sep-09	2.4

6.3 Results

6.3.1 Shore based observations were severely hampered by the weather to the extent that insufficient sightings data were obtained to attempt the type of analyses that had been intended. Sufficient data were collected to demonstrate that the technique could be used to collect accurate range and bearing information to fix the location of porpoises using land based observations.

6.4 Discussion

6.4.1 As with other visually based research components of this project, shore based work was severely impacted by the weather. Shore based visual observation can be a useful and cost effective techniques for study sites which are close to shore and can be observed from an elevated vantage point. It is unfortunate that the new methods which the authors had intended to trial, which could have allowed visual observers to collect quantitative data on densities and distributions, were not adequately tested. Work that was done suggested that the method should be effective in favourable weather conditions (<

Beaufort 2). Some methodological issues were raised and these were addressed by a short development project which is presented in following section.

6.5 Further research

Experimental shore based movement tracking using a digital SLR camera

Methods

- 6.5.1 The video tracking systems was originally developed for use on ships where the observation height is relatively low (typically 10-12 m) resulting in a small angle of dip between the animal and the horizon. This allowed the use of long focal length lenses to improve image quality while still capturing both the animal and the horizon in the image. This becomes more difficult from higher observation positions where a wider field of view is required, resulting in animals being very difficult to detect on video images. Alternative trials were conducted with a digital SLR camera (Canon EOS 400D equipped with a 55-250 mm lens). The advantage of this camera is the much higher resolution of the images (3888x2592 pixels) resulting in approximately 5 times more information in each image than high resolution video. Another advantage of the stills camera is that the focal length of the lens was recorded for each image within the image file details. The main disadvantage is that there is no image buffer so the photographer has to capture the porpoise surfacing event. The system is unlikely to work for surveys where capturing the initial sighting is crucial but was tested for shore based tracking during periods of weather which were too poor for the vessel to leave harbour. Provided that it is possible to capture images containing the surfacing animal, the horizon and some fixed feature such as distant land, rocks or buoys at the surface, then the only equipment required for tracking is a digital SLR and hand-held GPS. Measurements are taken from still images using the angle of dip to the horizon and horizontal angle to a known reference point (Figure 6-3). A calibration test was performed on a fixed target to check that the focal lengths recorded in the images Exif data were accurate. These results are shown Figure 6-4 and would appear adequate for the type of measurements being made.

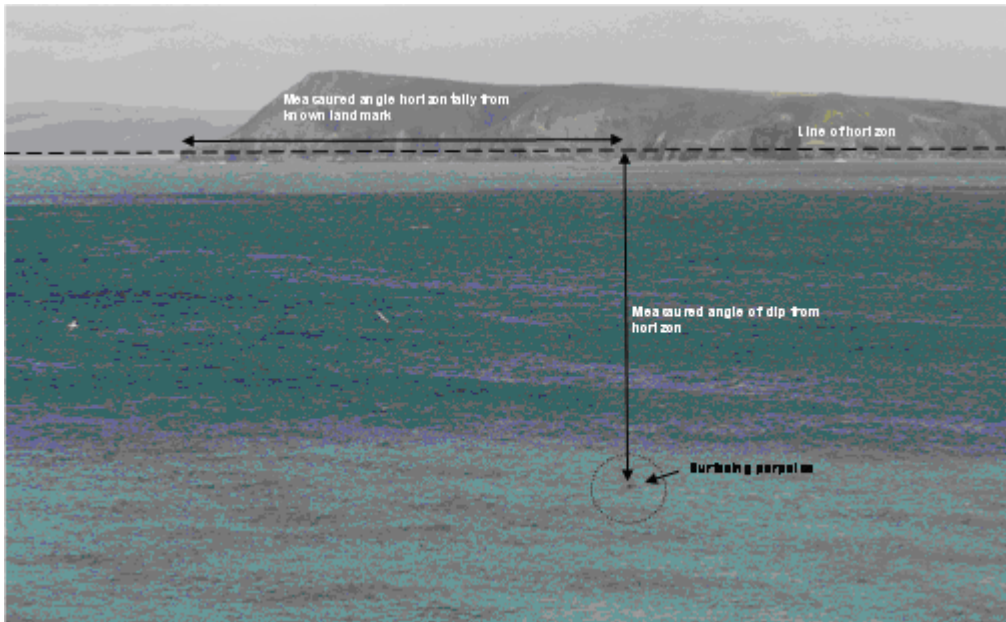


Figure 6-3 Measurements taken from a still image to locate a surfacing harbour porpoise.

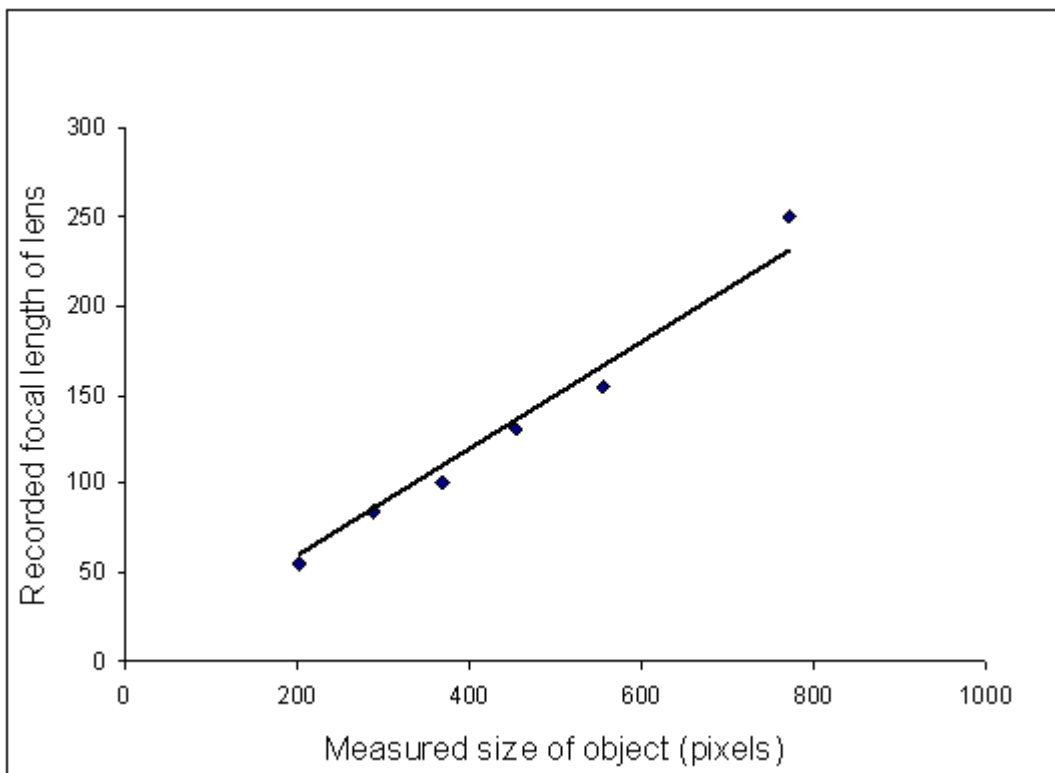


Figure 6-4 Recorded focal length of Canon EF-S 55-250 mm zoom lens against measured size of a fixed object in pixels on image.

6.5.2 Porpoises were sighted regularly off Pen Anglas which is close to Fishguard Harbour (where the vessel sheltered in poor weather) and is also well sheltered from south-south westerly winds. It is an area of strong tidal currents producing a substantial tidal race at certain times of the tide. An observation point was chosen at a height of 27 m above sea level at looking north towards distant land marks which could also be captured on the images. Where the land was closer than the horizon a correction was made based on the distance to the land and the observation height. The observation height was measured as the median height over a two hour period from a hand-held GPS (Garmin 76) above mean sea level with a correction for predicted tidal height.

Results

6.5.3 Porpoises were observed in suitable locations for tracking for around one and a half hours on 20th August 2009. During this period 32 images were captured with adequate information to determine surfacing locations. In general, it proved possible to photograph most surfacings once a porpoise had been observed for a few minutes. However, it was never possible to capture the initial sighting. The distribution of radial distances is shown in Figure 6-5 and all surfacing locations are plotted in Figure 6-6.

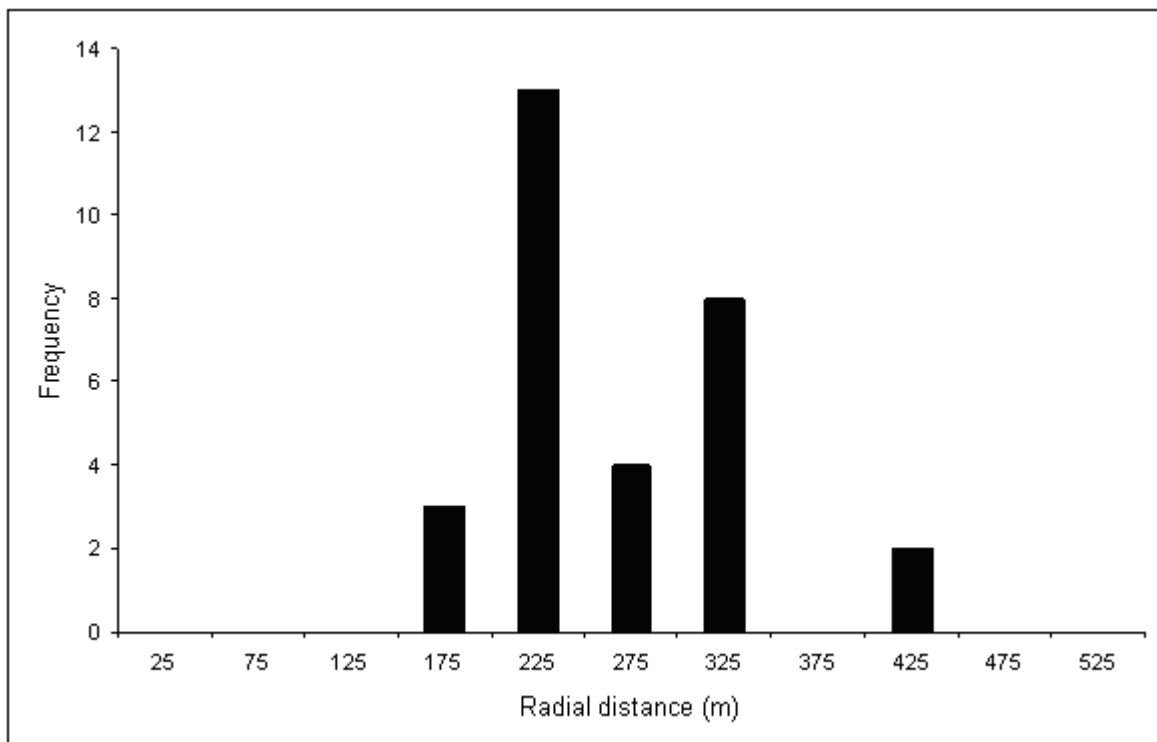


Figure 6-5 Frequency of observed distances to surfacing porpoises from Pen Anglas (Fishguard) observation height 27 m.

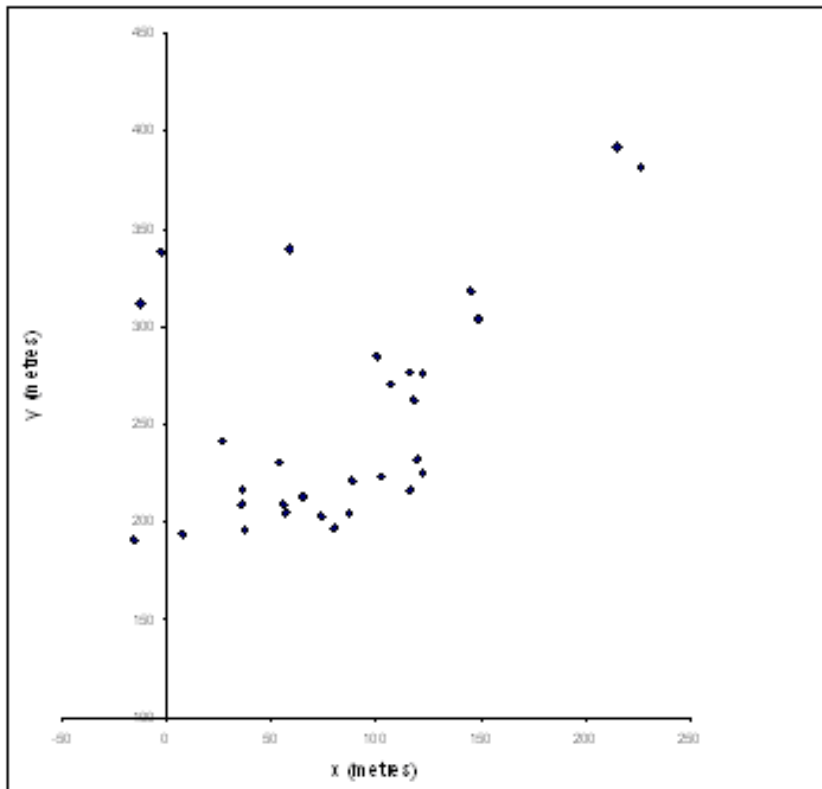


Figure 6-6 Locations of all surfacings of porpoises captured on still images, (x,y) coordinates are relative to observation position.

6.5.4 The longest track for which the observer was confident of following a single individual involved 8 surfacings over a period of 187 seconds. The average of the travel speeds between successive locations was 0.92m.s^{-1} (SD 0.42). A total of 18 successive locations were suitable for calculating travel speeds with an overall mean travel speed of 0.97m.s^{-1} (SD 0.43).

Discussion

6.5.5 The use of a digital SLR camera proved to be a simple way of obtaining tracks of porpoises with minimal equipment. The system is only useable under certain situations where porpoises can be photographed against a suitable background. Where relative locations are obtained these are potentially very accurate (to within a fraction of one degree) because bearing information is measured directly from fixed points on the same image as the animal. By contrast the narrower field of view of the video system generally relies on measuring bearings using a separate still camera and reference marks, with more scope for bearing error.

6.5.6 While an SLR camera cannot replace the full video and bearing camera set-up for survey work there are situations where useful data can be obtained and the authors would recommend shore teams being equipped with a suitable still camera to use as opportunities arise.

7 Grey Seal Telemetry Study

7.1 Introduction

7.1.1 The Sea Mammal Research Unit (SMRU) was contracted to carry out a telemetry-based study of the behaviour of grey seals at sea. The basic aims of the study were to track the movements and record the diving and swimming behaviour of individual grey seals, tagged at sites in Wales, and relate the observed behaviours to the potential for interaction with future tidal turbine installations in Welsh coastal waters. Data collection is ongoing, and only a brief summary is presented here. A further seven transmitters were made available in 2010 and combined with five tags remaining from the 10 commissioned in 2009 and three refurbished tags retrieved during 2010. This allowed 10 tags to be deployed at Ramsey Sound and 5 tags at the Skerries in October/November 2010. A complete analysis of the results from the combined 2009-2011 data together with a re-analysis of the results from an earlier deployment of 19 ARGOS satellite transmitters on adult grey seals in 2004 will be presented in a final report in summer 2011.

7.2 Methods

Telemetry system

7.2.1 An investigation of the scale of possible interactions with tidal turbine devices requires information on the 3D movements of marine mammals. Seals are extremely hard to see in open water, spend the majority of their time (>85%) submerged. They are effectively silent for most of the time and therefore cannot be accurately tracked using either visual or acoustic monitoring techniques (as used for harbour porpoise discussed in the previous chapters). In addition, grey seals are known to make wide ranging movements between distant foraging and haul-out areas making it impossible to study individuals using any boat or land based monitoring method. In order to study the movement and dive patterns of seals at an appropriately fine scale, we used recently developed GPS Phone Tags, which combine GPS quality locations with efficient data transfer using the international GSM mobile phone network (see Figure 7-1).



Figure 7-1 *GPS Phone Tag*

- 7.2.2 These tags provide GPS quality (usually better than 10 m accuracy) locations at a user-controlled rate, together with complete and detailed individual dive and haul-out records. They are small, weighing 370 g which is <1% of an average seal pup mass. Data are relayed via a quad-band GSM mobile phone module when the animal is within GSM coverage. This results in relatively low cost, high energy efficiency, high data bandwidth and International roaming capability (including Ireland and France).
- 7.2.3 They incorporate a Fastloc GPS sensor that offers either the possibility of attempting a location at every surfacing or as frequently as required. Less than a second is needed to acquire the information required for a location. The tag also uses precision wet/dry, pressure and temperature sensors to form detailed individual dive (max depth, shape, time at depth, etc) and haul-out records along with temperature profiles and more synoptic summary records. Both location and behavioural data are then stored in memory for transmission when within GSM coverage.
- 7.2.4 For species such as grey seals that periodically come near shore – within GSM coverage – the entire set of data records stored in the memory can be relayed via the GSM mobile phone system. Visits ashore may be infrequent, so up to six months of data can be stored on-board the tag and these data can also be downloaded directly if the tag is retrieved.
- 7.2.5 A detailed description of the parameter settings in the data handling software is attached as Appendix 3.

Timing of tagging and choice of study animals

- 7.2.6 Two age classes of seal had been initially identified as being of prime interest, newly weaned pups and adult females. However, the project start date meant that there was no opportunity to catch adult females before September. At this time females are generally returning to their breeding sites and do not range widely. In addition, the period of haul-out for breeding would mean that tags would not provide useful information for around a month, during which time they would be subject to additional problems of abrasion before being moulted off approximately one month later.
- 7.2.7 Grey seal pups are abandoned on land and therefore enter the water as completely naïve animals with no experience of foraging and no established movement patterns. Breeding sites in North Wales are either in caves or on small islands which are often associated with strong tidal currents. Grey seal pups are therefore likely to be in areas of potential interaction with tidal generators during what is likely to be a vulnerable phase of their lives. After consultation with CCW, it was decided that the best strategy would be to concentrate the tagging effort on pups during their initial time at sea, with no tags fitted to adult females. For practical and logistical reasons, it was further decided that the tagging effort in 2009 should be concentrated in the vicinity of the Skerries, off Anglesey. In 2010 tags were also applied in Ramsey Sound.
- 7.2.8 For comparison, there is an existing dataset of tracking data from older grey seals collected in 2004-2005, which is described in Section 1.3.

Analysis of movement data

- 7.2.9 In 2009, only five out of the eventual total of twenty seals were tagged. One seal died after 13 days at sea and one was 'rescued' after coming ashore in Cornwall after 62 days at sea. The three remaining devices continued to send location and dive data until the time at which their batteries should have been exhausted in late spring. An additional 10 more tags have been deployed at Ramsey Sound and 5 tags at the Skerries in October/November 2010. A comprehensive analysis of the movements, habitat use and dive behaviour patterns with respect to location and tidal energy will be carried out following the retrieval of data from these more recently deployed tags and data from them is not discussed here (although initial outputs are from some of the tags).
- 7.2.10 Here we describe the analysis methods that will be applied to the complete datasets. We then provide a brief, preliminary description of the movements of the first five pups in the initial deployment and describe the initial results from the deployments in 2010.

- 7.2.11 Two levels of analysis will be applied to the movement and dive behaviour data. The tracks of all seals will be examined in relation to locations of potential tidal turbine sites to estimate the length of time spent within specified distances of sites and in areas of strongest tidal energy. Dive behaviour data will provide a 3D picture of space use throughout the tracking periods. At a wider population scale, we will generate space use maps for juvenile grey seals for comparison with earlier adult seal space use analysis. To date there are not sufficient data to allow us to estimate space use by juvenile grey seals in Welsh waters. This analysis will be completed in 2011 when data from the deployment of an additional fifteen devices in October/November 2010 will have provided enough coverage to generate a space use map for juvenile seals in Welsh waters. The methods used will be similar to those employed in producing space use maps for older grey seals in 2004-05 described below.
- 7.2.12 Briefly, the space usage analysis will comprise two stages, described in Matthiopoulos (2003a, b) and Matthiopoulos *et al.* (2004). The method uses telemetry data (in this study from high resolution SMRU GPS transmitters; in 2004-05 using ARGOS system locations from SMRU Satellite Relay Data Loggers), and estimates of the relative numbers of animals using haul-out sites in the areas of interest. For previous deployments the population data relate to counts at haul-out sites (as briefly described in Section 1.3).

7.3 Results

Tagging

- 7.3.1 Based on observations of pup age classes during CCW field trips in early October, and previous experience of the duration of lactation and post weaning fasting periods, a joint SMRU and CCW team mobilised into the field in late October 2009. Far fewer seal pups were present than had been expected, possibly as a consequence of the severe weather throughout mid and late October. Known breeding sites between Anglesey and Hells Mouth Bay were searched, including cave sites. In the event, just five pups of the correct developmental stage and condition were located, i.e. pups that were fully moulted (at least over the front half of the body), assumed to be weaned, greater than 37kg in mass and with no significant injuries. Of these five, three were found on the Skerries off Holyhead. The search area was extended and the two additional pups of suitable age and condition were found on Bardsey Island. All five pups were tagged on 22nd and 23rd October 2009.

7.3.2 All animal handling and tagging methods are approved under SMRU's Home Office Licence. Standard transmitter attachment techniques were used. Briefly, seals were caught on land and physically restrained. No anaesthesia was required and tags were glued to cleaned, dried fur on the back of the neck using quickset Epoxy resin. Seals were released and left at their capture site. One animal went briefly into the shallows next to the beach, but hauled out again within a few minutes.

Preliminary tag data

7.3.3 Highly detailed movement and dive behaviour records have been received from all five tagged seals. Almost complete records of location, diving depths and durations were received from all five seals. Tracking periods lasted 234, 216, 183, 63 and 14 days. The two shorter deployments were terminated when one of the seals died and one was rescued. Continuous dive data were received for all five seals.

7.3.4 In order to receive data the tagged animals must spend some time in the vicinity of a mobile phone receiver. As a result the data delivery is sporadic. However, when data transmissions occur, a large amount of stored information may be sent. Figure 7-2 and Figure 7-3 show the track data from all five tagged animals.

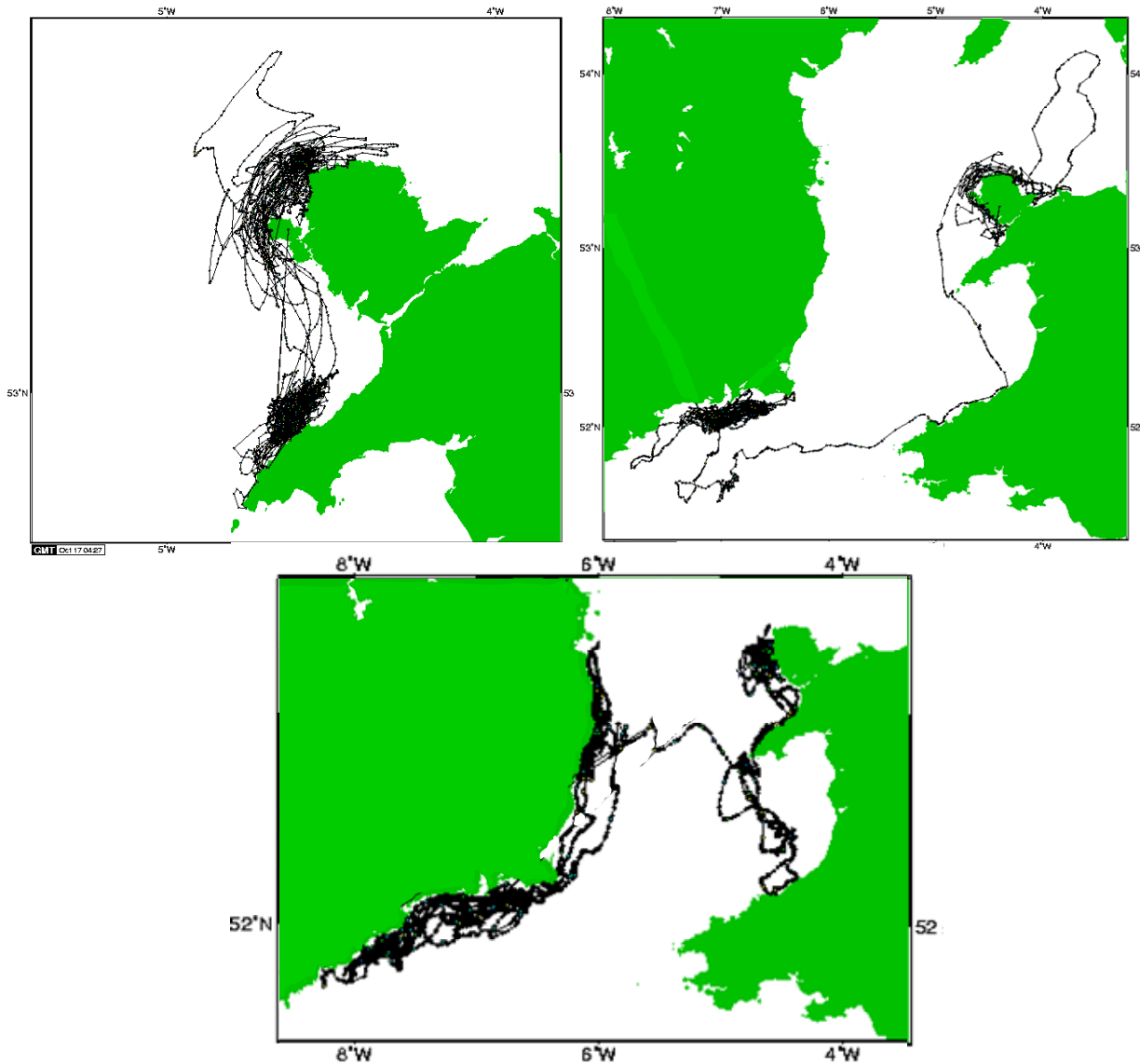


Figure 7-2 GPS tracks of three grey seal pups tagged on Skerries, Anglesey. All three seals spent an initial period foraging in the high tidal flow areas around Anglesey before moving away. One remained in the area, using a haul-out site on the Llyn Peninsula for 10 weeks before moving back to the Skerries. The others moved to haul-out sites in the Saltees, Ireland.

7.3.5 The three pups tagged on the Skerries (Figure 7-2) spent 26-39 days foraging close inshore around Anglesey before moving away. One moved to a haul-out site on the Llyn Peninsula where it spent 10 weeks foraging in a small area stretching approximately 15 km to the north east. It then returned to the Skerries haul-out site and foraged in the inshore waters around the north of Anglesey and Great Saltee Island, south east Ireland. In all three cases foraging has been almost entirely restricted to

waters within 10 km of the shore within 30 km of their haul-out sites. All three pups were apparently foraging successfully into May.

- 7.3.6 Both Bardsey pups spent the first two to three weeks foraging close to their pupping site, again apparently in high tidal energy areas (Figure 7-3). One seal pup was subsequently found dead on shore, 13 days after leaving the pupping site. Initial inspection indicated that the seal was apparently in good condition and showed no signs of injury associated with the transmitter. Results of a formal post mortem will be available for the final report. The other Bardsey Island pup initially spent 28 days foraging within 30 km of its tagging site. It then began a period of continuous movement, to Anglesey, then to the coast near Rosslaire in Ireland, west Cornwall and the Scilly Isles. It did not appear to develop a fixed foraging pattern at any site and after a final swim from the Scilly Isles to an area 40 km west of Brittany it returned to Cornwall and was caught onshore and taken to a seal sanctuary. This seal had lost approximately 30% of its weaning mass by the time of capture. Had it not been caught, it would probably not have survived the winter.

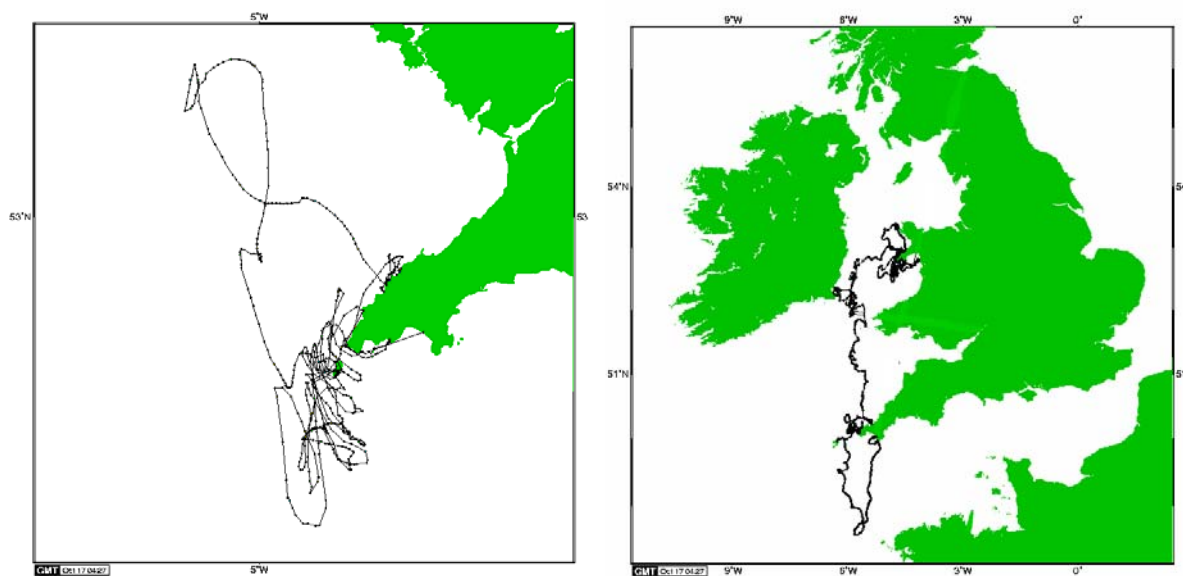


Figure 7-3 *GPS tracks of grey seal pups tagged on Bardsey Island. Both spent an initial period of two weeks foraging in the vicinity of Bardsey Island. One was subsequently found dead on the Llyn Peninsula. The other spent short periods foraging near Rosslaire in Ireland, Scilly Isles and Lands End and made one extended but apparently unsuccessful foraging trip to the west of Brittany. The seal was re-captured on 26/12/09 and taken to a rehabilitation centre in Cornwall.*

Preliminary dive behaviour data

7.3.7 Figure 7-4 shows an example of the summary data from the dive depth and haul-out sensors. The data presented are simple two hour summaries of maximum depth and time spent dry at the surface or on land. Similar data are available for all five pups for which records have been received so far. The raw dive data, i.e. detailed depth time profiles and accurate surface times are available for all animals.

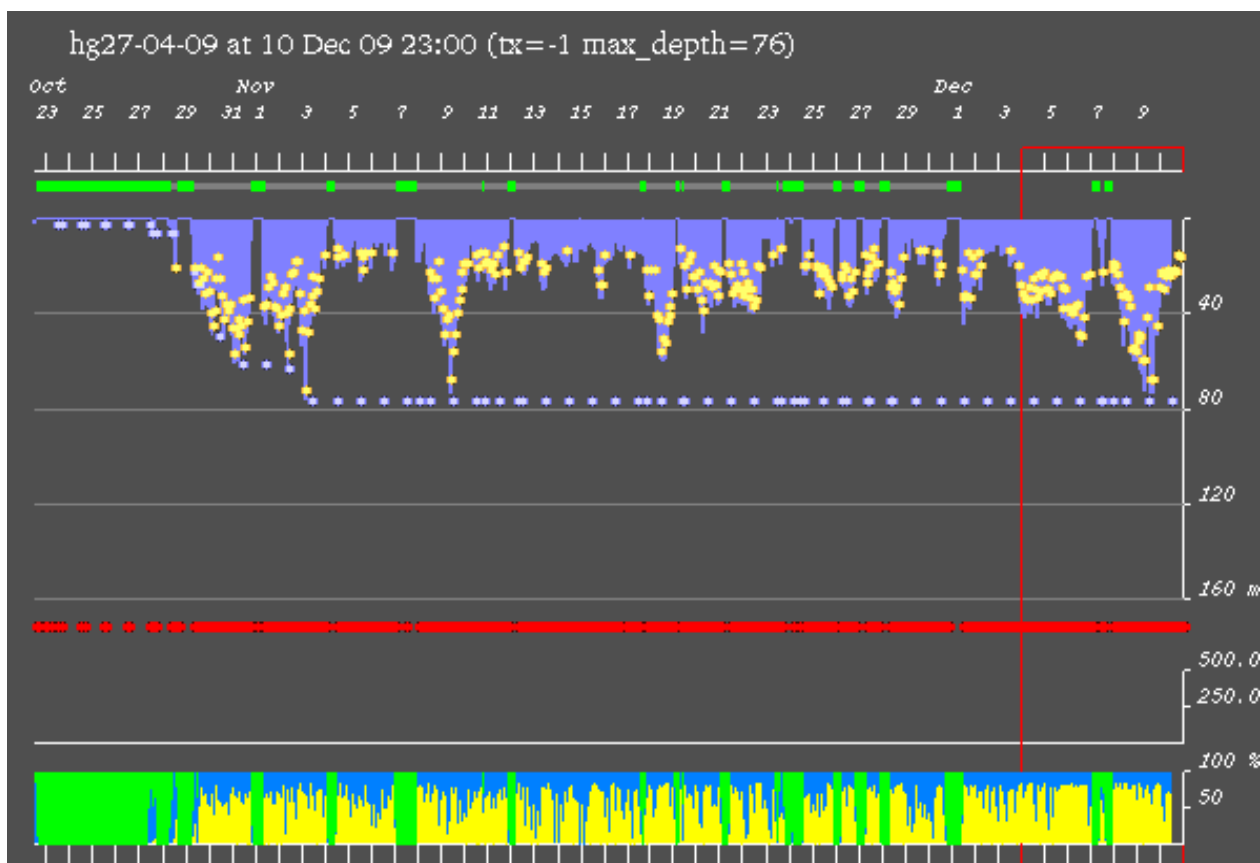


Figure 7-4 Example of the summary data transmitted by one of the grey seal pups tagged on the Skerries. Blue bar graph at the top represents the summary dive behaviour, showing maximum dive depth in two hr bins. Yellow dots indicate where full depth temperature profiles were recorded. Depth profiles of all individual dives are transmitted and will be used in analysis of 3D space usage.

7.3.8 Figure 7-5 shows dive profiles of a seal swimming in the high tidal current area around the Skerries. Depth records indicated typical patterns of diving behaviour for grey seals in both datasets. While at sea, the pups spent the majority of their time diving, spending 76% of their time submerged similar to the adults 75% (Section 1.3). Figure 7-5 (a and b) show typical flat bottomed foraging dives (Thompson *et al.*, 1991; 1993) in areas with relatively flat sea bed, where the maximum depth is close to the estimated water depth.

Figure 7-5 (c) shows examples of typical travelling dives with more variable profiles. The complexity of the bottom topography in this area and the error inherent in the interpolating between GPS fixes makes it impossible to accurately assign an estimate of the depth of the water column to each dive. However, in previous studies dive patterns suggest that the seals swam down to or close to the seabed on the majority of dives during travel phases (McConnell *et al.*, 1997; Thompson *et al.*, 1991; 1993).

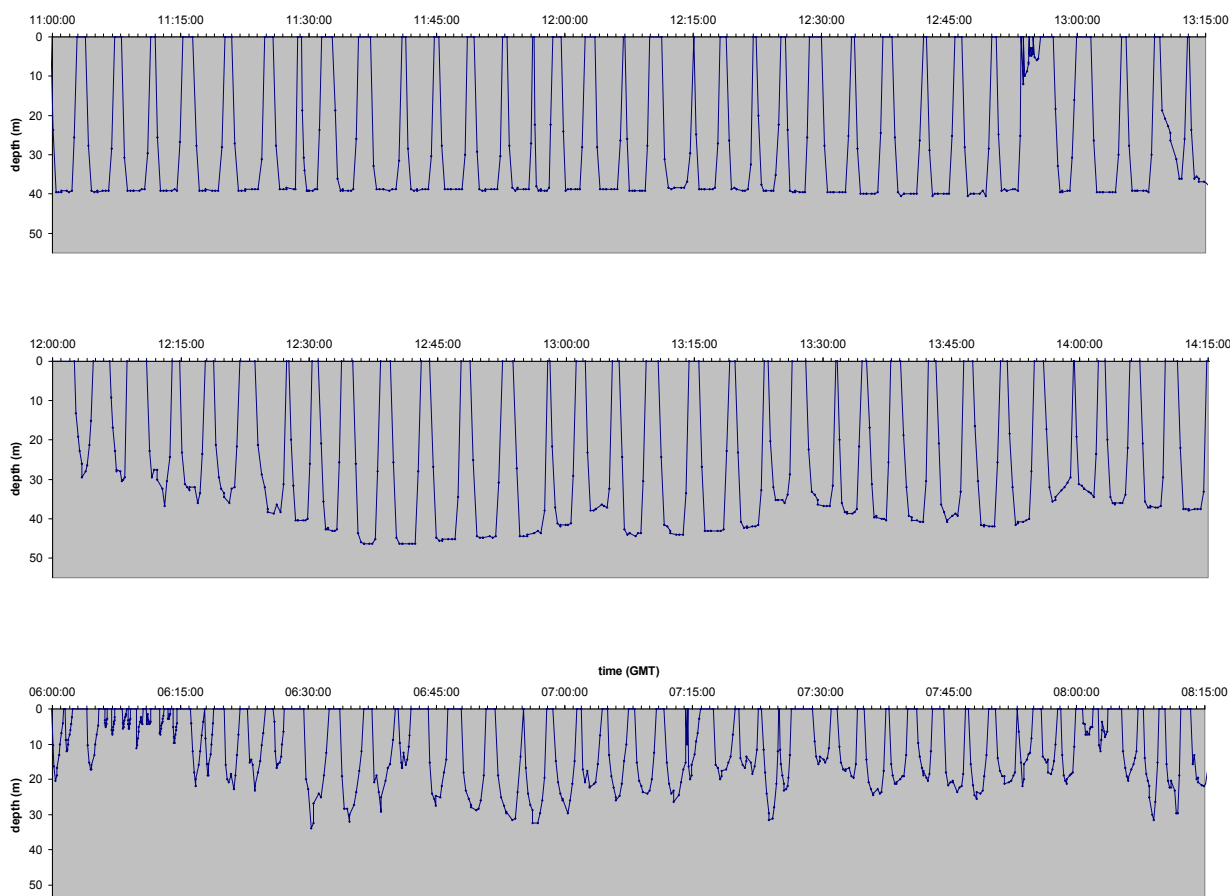


Figure 7-5 Dive profiles of a juvenile grey seal swimming in high tidal current areas around the Skerries off Anglesey, North Wales. of distances from shore at which seals crossed an arbitrarily defined line stretching 8km from Carmel head passing through the Skerries. Periods of typical flat bottomed foraging dives to the sea bed (a and b) were interspersed with typical travelling dives (c).

7.3.9 As with all previous grey seal studies, the dives comprised a rapid descent phase followed by either a rapid ascent or a protracted bottom phase followed by a rapid ascent. While at the surface grey seals typically do not swim actively (Thompson *et al.*, 1993), simply resting at the surface for short periods to load oxygen and dump carbon

dioxide before diving again. The seals therefore spent a limited amount of time in mid water depths.

7.3.10 Figure 7-6 shows the proportion of time spent at different depths, expressed as a proportion of the maximum depth, within individual dives. This clearly demonstrates that the majority of time is spent at the bottom of the dive or at the surface. However, the complexity of the topography and the interpolation errors in location of each dive makes it impossible to determine what proportion of these dives reached the seabed and it is therefore not possible to say where exactly in the water column the dive activity occurred.

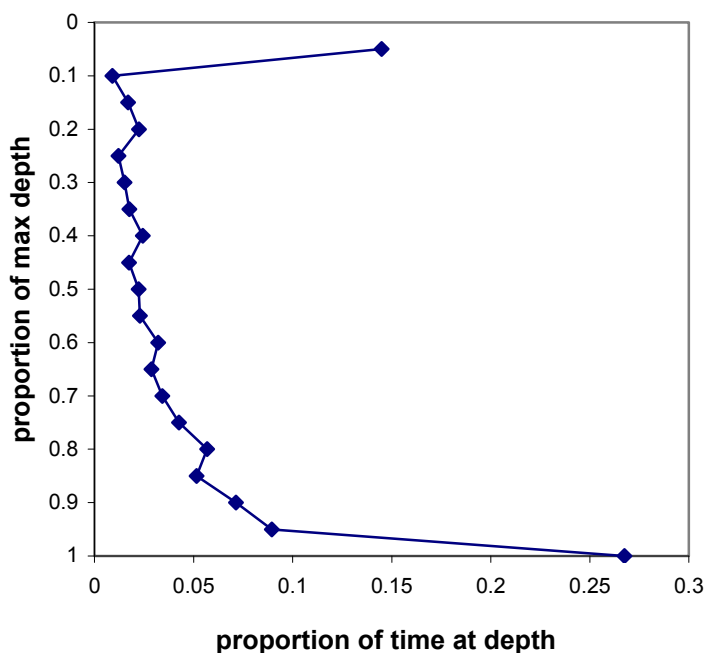


Figure 7-6 *Proportion of time spent at different depths, expressed as a proportion of the maximum depth, within individual dives (n=17000) by seal 07 while swimming within 15km of the Skerries.*

7.3.11 The rate at which seals pass through the area swept by the blades of a tidal turbine is an important parameter which sets the upper limit on the potential for direct physical interactions with the device. The GPS position fixes accurately indicate the seals' XY positions at approximately 15 minute intervals. The pressure sensor data provide a 10 point depth profile for each dive. Although these data do not provide sufficient spatial resolution to identify direct passage through a small window equivalent to a turbine, they can be used to estimate the general pattern of transits through a specified area.

- 7.3.12 As an example of the type of data available we estimated the number of times and the depths at which the tagged seals crossed an arbitrary 8 km long line drawn from Carmel Head to the Skerries and extending approximately 4 km further offshore. Pairs of consecutive locations were used to estimate the seal's swimming track assuming that it swam in a straight line between the location fixes. The time at which the seal crossed the line was estimated assuming constant swimming speed between locations. Swimming depth at that point was estimated by linearly interpolating between the pair of depth estimates immediately before and after the crossing point.
- 7.3.13 As previously stated, this is a preliminary analysis of a small sample of seals. Only two of the tagged seals crossed this line. It appears that the crossing points are approximately uniformly distributed across the area both in terms of distance from shore (Figure 7-7) and swimming depth (Figure 7-8). The difference between the proportion of time spent in the mid water depth shown in Figure 7-6 and the more even spread of depth usage implied by Figure 7-8 is problematical. It appears to be a result of the increased horizontal movement between locations due to tidal currents and the fact that a higher proportion of dives crossing the arbitrary line were V shaped transit dives (Figure 7-5c).

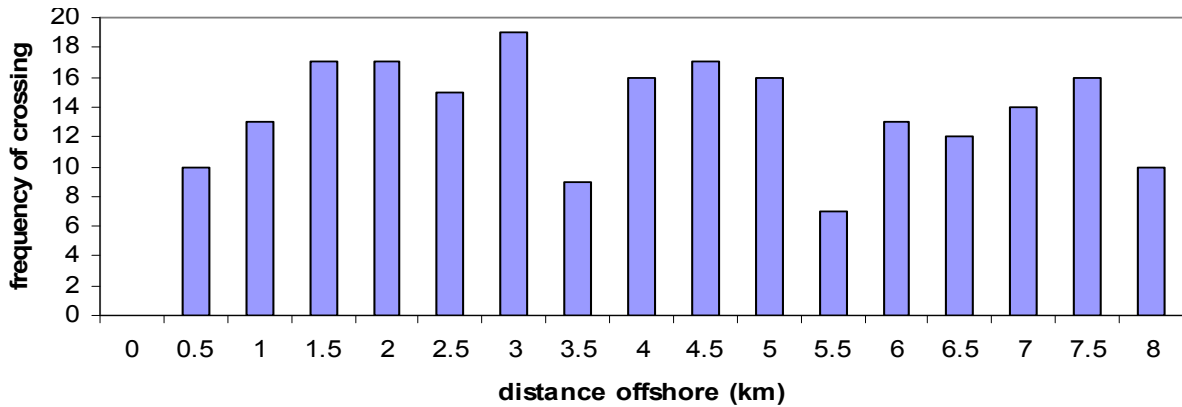


Figure 7-7 Distribution of distances from shore at which seals crossed an arbitrarily defined line stretching 8km from Carmel head passing through the Skerries.

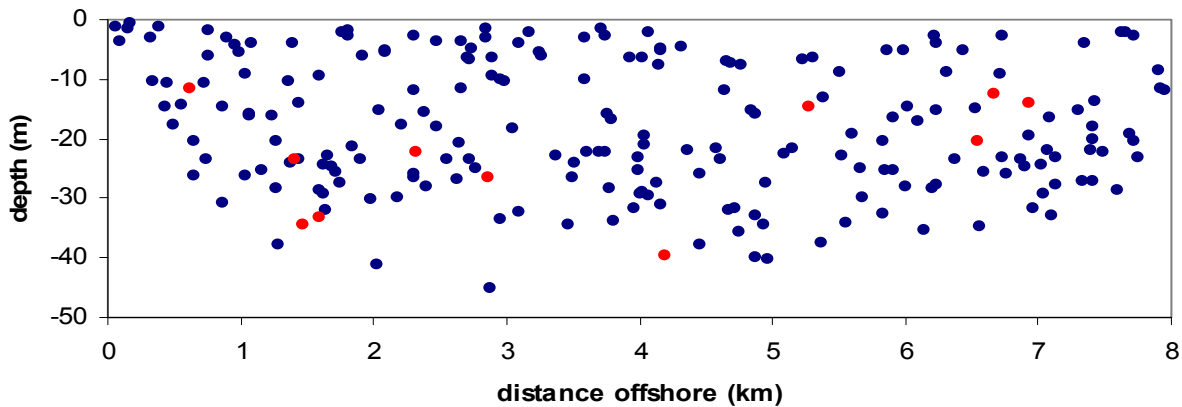


Figure 7-8 Depth and distance from shore of seals crossing an arbitrarily defined line stretching 8km from Carmel head passing through the Skerries.

7.3.14 As the data represent only two seals and in fact >90% of the crossings were by one seal, it is too early to say if this is representative of the behaviour of grey seal pups at this site. The much larger sample size that we expect to have available in spring 2011 will include data from an additional 15 grey seal pups from Anglesey and Ramsay. This will allow us to investigate the intensity of seal activity in these high tidal current areas in more detail. In addition, track smoothing methods will be applied to archived, lower-resolution ARGOS satellite telemetry tracks from adult grey seals in an attempt to provide the same information for older animals.

Future deployments

7.3.15 Due to lack of suitable, accessible seal pups for the study we were only able to deploy half of the initial batch of transmitters. We therefore ended the 2009 deployment with five unused transmitters and three transmitters that were refurbished and rebatteried after

being retrieved from dead and rescued pups. In addition, funds were provided by Welsh Assembly Government for seven additional tags.

7.3.16 These have now been deployed in two batches; ten on grey seal pups at Ramsey Island and five on pups at the Skerries off Anglesey. At the time of writing preliminary location and dive data have been received from two Anglesey seals and six Ramsey seals. Maps of these initial swimming tracks are presented in Figure 7-10.

7.3.17 Results from these deployments will be combined with the initial deployment results reported here. The data should be sufficient to allow a full habitat usage map to be generated for the Welsh grey seal population (adults based on information provided in Section 1.3 and for seal pups from this study).

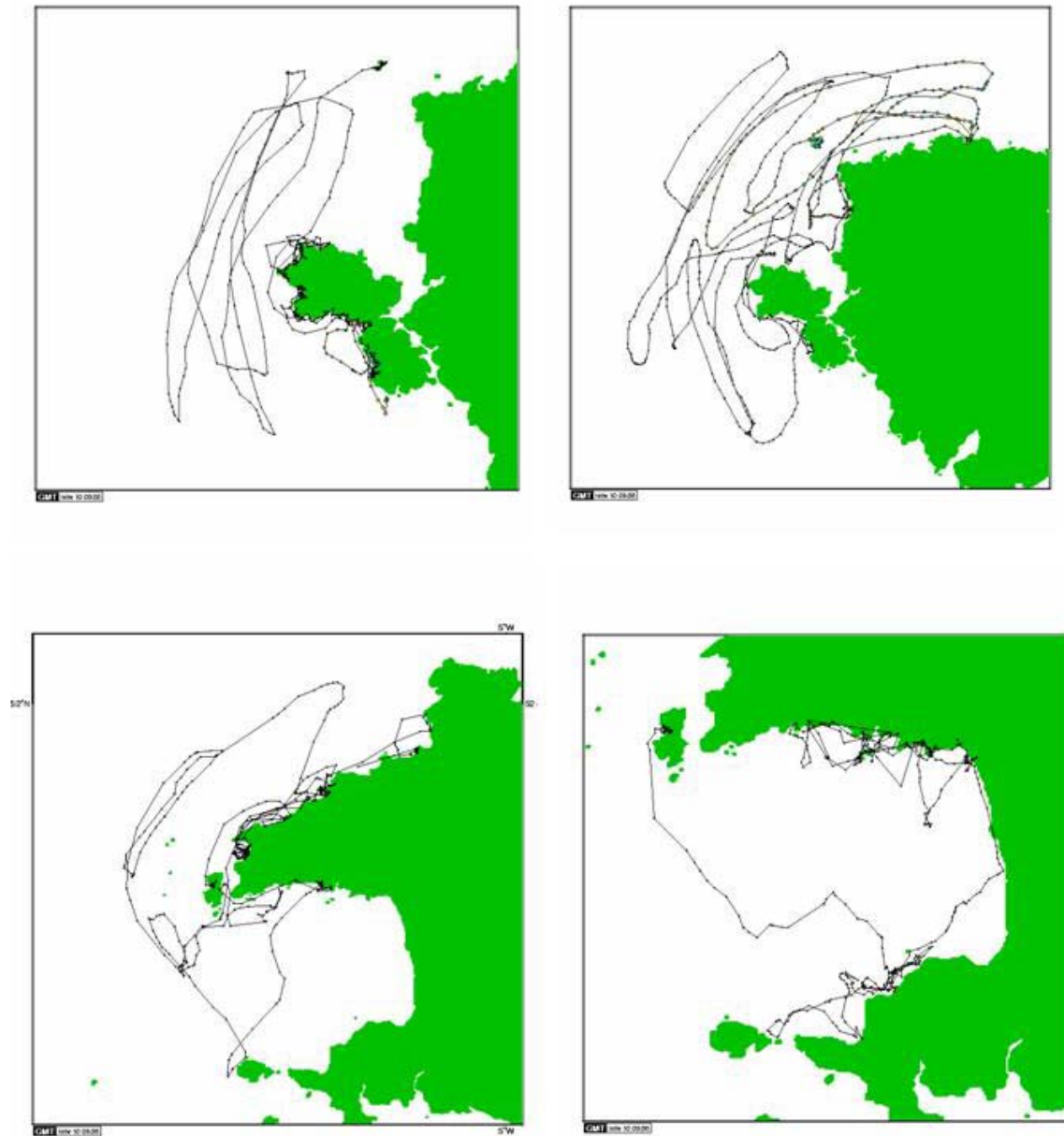


Figure 7-9 GPS tracks of grey seal pups tagged on Ramsey Island and the Skerries, Anglesey in October/November 2010. Tracks represent the first foraging trips by naïve weaned grey seal pups. The tracks of Skerries seals are similar to the early foraging trips of the 2009 sample (see Figure 7-2 and Figure 7-3).

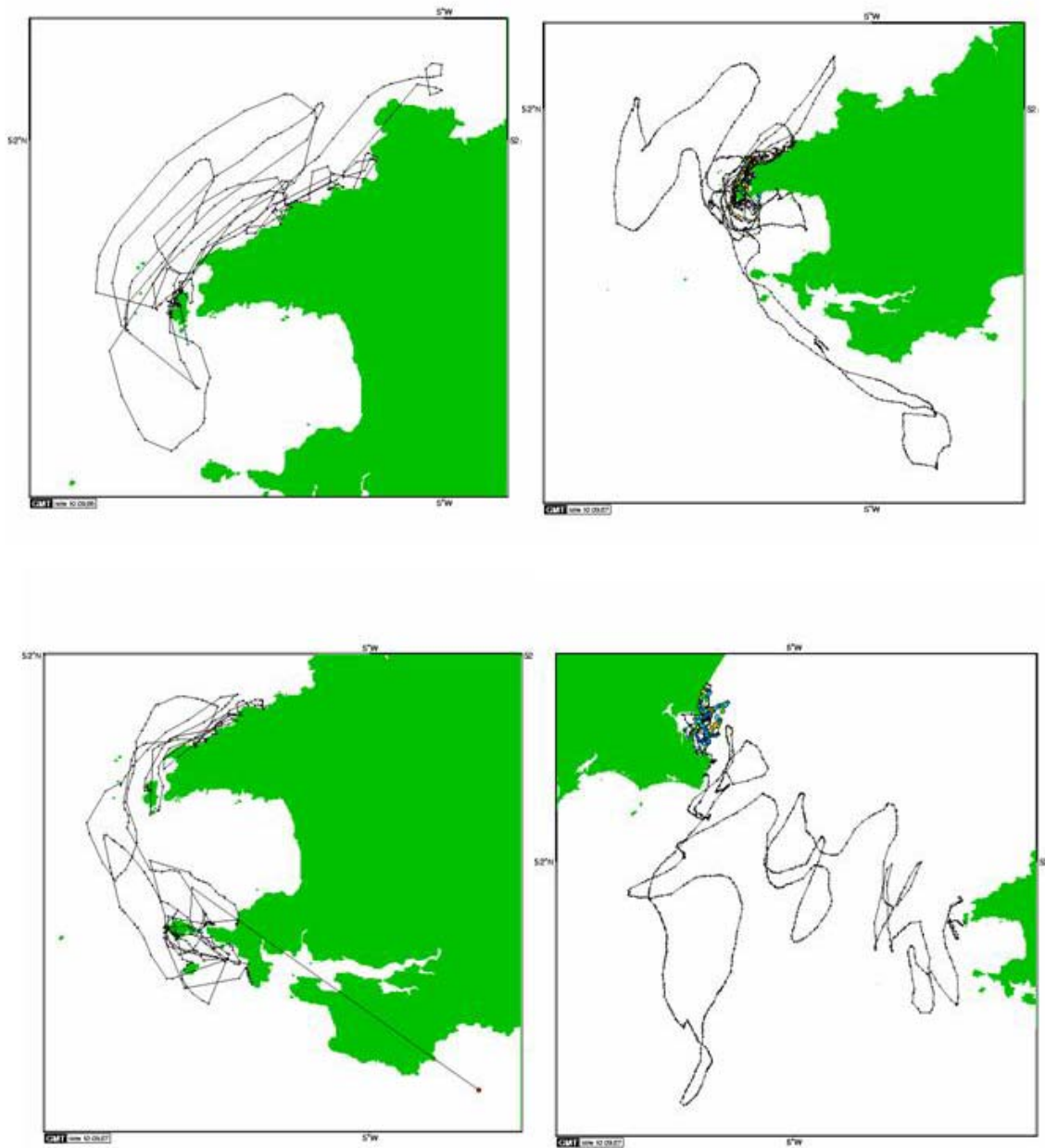


Figure 7-10 (continued) GPS tracks of grey seal pups tagged on Ramsey Island and the Skerries, Anglesey in October/November 2010. Tracks represent the first foraging trips by naïve weaned grey seal pups. The tracks of Skerries seals are similar to the early foraging trips of the 2009 sample (see Figure 7-2 and Figure 7-3).

8 General Discussion, Conclusions and Recommendations

8.1 Tidal rapids as habitats for marine mammals

Densities and distributions

- 8.1.1 This work has confirmed and, we believe for the first time, provided quantitative support for, the widely held view that tidal rapid systems are important habitats for marine mammals supporting higher densities than other areas. For porpoises, the acoustic detection rates in the Bishops and Clerks study area off Pembrokeshire were higher than any previously reported, while those at the Skerries, Anglesey, were exceeded only on surveys in the western Baltic, which had been conducted off a vessel that was very quiet and thus likely had a higher strip width. Similarly, the assessments of density for the Bishops and Clerks block were higher than any recorded during the SCANS survey. The Skerries block were exceeded by estimates for the west coast of Scotland and the southern North Sea. However, the densities estimated for this project were not adjusted for $g(0)$ and thus were likely to be negatively biased. If the $g(0)$ estimate calculated during this project was applied then the Skerries densities would also exceed those from other areas.
- 8.1.2 It is also clear that within these areas there is considerable variability in local densities and frequency of occurrence both spatially and temporally. Data from PODs in particular, indicated a very high level of spatial and temporal variability. At both study sites there were indications that patterns of distributions within tidal rapid systems varied with the state of the tide, and in several cases it seemed to be the case that “flushing out” areas, either side of the most restricted regions with the highest flows, might be preferred during the tidal phase when they were downstream of the main restriction. However, there was also much fine scale and as yet unexplained variability within the POD data. In some cases, PODs deployed close to each other showed both very different overall detection rates and quite different diurnal and tidal temporal patterns. For example, in the Skerries study site, PODs 468 and 465 showed over an order of magnitude difference in detection rates and the opposite diurnal patterns of occurrence in spite of being only 1.2 km apart.
- 8.1.3 Towed hydrophone data generally showed less pronounced spatial and temporal variability than POD records. This difference very probably reflects the differences in the

amount and distribution of sampling effort provided by these two methods. PODs sample intensively over restrictive spatial scales and individually provide a very restricted coverage. Towed hydrophones provide a good coverage of area, but the overall amount of effort in terms of monitoring hours was much lower than achieved by the aggregate of all the PODs. Thus, one method, the PODs, can detect fine scale differences between point locations but provides a poor coverage of the area. While the second method, the towed hydrophone surveys, provides a good and near-even coverage, but because the amount of data collected in any restricted location is small, it has less power showing these small scale spatial and temporal differences. An interpretation of the two somewhat different pictures from the POD and towed hydrophone datasets is that there are fine scale differences, perhaps on scales of a hundred metres or less, in the way that animals use the habitat.

- 8.1.4 The POD data also showed that more animals were detected at night than during the day. This could reflect a real diurnal change in distribution but it is equally plausible that it reflects a change in behaviour, with animals echolocating more at night, perhaps because visual cues are more restricted in the dark.
- 8.1.5 Locations of vocalising porpoises from the vertical hydrophone has provided the first data on the dive depths of harbour porpoises in high tidal energy areas at times when tidal currents are greatest and collision risks most severe. Because this is a newly developed method, data collected and analysed thus far are few, but they indicate animals may be making full use of the water column and may be spending more time on the bottom (possibly benthic foraging).
- 8.1.6 Fine scale telemetry data has been collected from newly weaned grey seals during the critical period after they leave their natal beaches; establish themselves independently and into their first year. These animals made extensive (in some cases almost exclusive) use of tidal race areas, seeming to move forwards and backwards with the tide and repeatedly diving to the bottom. These dive patterns suggest that they were foraging. It is interesting that in some cases, after animals left the tidal rapid area next to their natal beaches, that they subsequently seemed to preferentially use other high tidal current areas. The extent to which these animals continue to use these areas in later life is not yet clear but additional information will be collected as the current tag deployments continues and new ones are added. Preliminary analysis of dive data suggests that seals generally dive directly to the seabed and are therefore spending little time in midwater.

- 8.1.7 It is important to note that the seal telemetry data presented represents only a small sample of five seal pups and is a small subset of the data that will be available by spring 2011. The descriptions of dive and movement patterns must be regarded as preliminary and any interpretation must be treated with caution.

Significance for marine mammals

- 8.1.8 Most authors have assumed that tidal rapid areas are favoured foraging sites for marine mammals, though there is no clear evidence as to why this should be the case. It could be that encounter rates with prey are high, this may be because marine mammals' prey species are aggregated in the area by water movements and topography or they may actively move there, perhaps to utilise plankton that might have been aggregated there. Encounter rates may also be increased if prey are carried to marine mammal predators by strong currents. To benefit from this, marine mammals would have to be able to sense prey within the main current while keeping out of it themselves. In this way they could increase encounter rate without having to swim at high speed. Alternatively, fast currents might make prey more accessible perhaps because they are disoriented or disadvantaged by turbulence associated with strong currents. There is little in the literature that explores these ideas in detail and we have been able to shed little new light on the topic, in large part due to the effects that poor weather had on planned detailed visual tracking work.

Implications for encounter and other risks from tidal turbines

- 8.1.9 The high densities of porpoise in these areas means that encounter risks are likely to be higher than those predicated using density estimates derived from larger scale surveys such as SCANS. Similarly, there is potentially a higher risk of collision for naive newly weaned pups that appear to make extensive use of these areas after they leave the breeding beaches.
- 8.1.10 In the course of towed hydrophone acoustic surveys we noted both areas of very high background noise and a pronounced tidal variation in noise with levels being higher when current exceeded rates of around 1.5 m.s^{-1} . This could affect an animal's ability to detect turbines both because it could mask the turbine's self noise and the signals of any active acoustic warning devices deployed and because it could interfere with the echolocation signals of small odontocetes. If active acoustic devices were to be used then they may avoid some of these masking effects by operating at a frequency outside the bands of strongest noise. (If the high noise patches are indeed caused by moving

sediments, as we hypothesised, their locations might be of significance for engineers as well).

- 8.1.11 High tidal energy areas seem to represent important habitats for porpoises, and it may be the case that sub sets of local populations specialise in foraging within these small areas. Thus, if turbine installations cause animals to be excluded from these areas, either directly, or perhaps through the use of aversive acoustic signals as a mitigation procedure, this could have a potential impact on local sub populations, especially if there are groups that specialise in utilising these special habitats. In addition, there is a high level of public awareness of marine mammals in these areas, particularly in the Ramsey Sound area where they are important attractions for thriving wildlife tourism enterprises.
- 8.1.12 Understanding the high level of spatial and temporal variability that was evident in both study sites is particularly relevant in the context of a tidal turbine development for several reasons. In the first case because it will affect the likelihood of encounters between porpoises and turbines. Secondly, this information could be used to determine the fine scale location of turbines to reduce encounter probability. In addition, the way that marine mammals use this habitat will have implications for the significance of disturbance, habitat exclusion and any barrier effects. While the data indicates that heterogeneity exists, further work would need to be done to quantify it and determine if this is predictable in the longer term.
- 8.1.13 A preliminary examination of the fine scale movements of two seals in the vicinity of the proposed turbine array in Anglesey suggests that when passing through such an area seals are roughly evenly distributed with respect to both depth and distance. However, again this must be treated with caution as it is based on preliminary results from only two seals. A similar analysis will be presented in 2011 based on a much larger sample set.

8.2 Additional analysis of data collected on this project

- 8.2.1 The project was successful in collecting a wide range of data and an exhaustive analysis of these has not been possible with the resources available. One area in which additional work might be done is in spatial and temporal modelling of the towed hydrophone data, especially if improved predictor datasets (for example, from detailed tidal flow models, detailed bottom type or satellite telemetry) were available. Only limited work has been done to test the reliability of the predictions. In the Skerries block, towed hydrophone data and POD data overlap in space and time. An analysis to compare the two datasets and develop a methodology that could combine their

complementary strengths would be useful generally, as well as in this specific context. The vertical array has provided encouraging results. Most effort has so far been expended on development and programming and on analysing the most straightforward datasets. Promising results from some additional work undertaken after the main body of this report was completed are presented in Appendix 2. As this method seems able to provide data that is very relevant for studies related to tidal turbines consideration should be given to making the software more accessible by rewriting the Matlab routines in a user friendly and freely available software package such as PAMGUARD.

- 8.2.2 Audio recordings in two frequency bands between 100 Hz and 250 kHz were made continuously during acoustic surveys and so far these have only been used in models of porpoise acoustic detection. These would be available to any researchers wanting to map noise levels in these areas.

8.3 Lessons for future work

- 8.3.1 This has been one of the first substantial and dedicated efforts to conduct surveys for marine mammals in areas with high tidal currents. It would be unwise to be proscriptive in recommending methodologies for survey in these areas at this stage and it is important that further innovation should be encouraged. It will also be the case that the most appropriate methodologies for any particular survey should be assessed in the light of the survey objectives, target species, expected weather conditions and the physical characteristics of the site (Berggren *et al.*, 2008; SMRU Ltd, 2010). However, there are certainly lessons to be learnt from the techniques that were more and less successful in this case.

Surveys

- 8.3.2 These are exceptionally challenging areas in which to conduct marine mammal surveys. It is particularly important therefore that surveys should be carefully targeted at answering the questions of highest value for management. We developed a survey design which addresses some of the problems inherent in work in these areas and seems to be practical in the field. We hope that this will be used as a starting point for others to review and work towards an accepted methodology. The efficacy of visual surveys will always be highly affected by the rough sea conditions that pertain in these areas when currents are running. Thus, it is extremely useful to conduct towed hydrophone surveys in addition to visual monitoring. In some cases and with some

species it might make sense to rely on passive acoustics as the primary survey methodology.

- 8.3.3 Static acoustic monitoring can provide indices of presence over extended periods of time. There are some problems with using them in these locations however. In the first place there are practical issues related to providing adequate moorings in such energetic environments. More fundamentally, the very high levels of spatial heterogeneity in these areas, means that very large numbers of devices will need to be deployed. PODS do not provide a measure of detection range or of background noise, and this is a particular problem in areas like these where background noise has been shown to vary substantially both spatially and temporally. Some major technical developments will be required to overcome these issues.
- 8.3.4 Shore based monitoring can be a cost effective way of monitoring areas close to shore. However, the technique suffers from some fundamental problems which make it difficult to derive robust indices of abundance from the data it provides. In addition, as typically implemented, it may not provide sufficient spatial precision to capture fine scale variability in densities that may occur in these areas. As part of this project we worked on some technical solutions for these problems but poor weather conditions prevented us from fully applying or testing these methodologies.
- 8.3.5 Marine mammals operate in a three dimensional world and for surveys, such as this, where a goal is to provide data that can inform assessments of collision risk, it is important to provide information on animals' probability of occurrence with depth. The approach pioneered here, of using drifting vertical arrays is one of the few ways that these data could be obtained for porpoises. It seems to have been successful and practical, but the requirement to use a drifting boat to deploy the array increases field costs. When turbines are installed it may be possible to use their structures to support a static vertical array which would provide long term three dimensional location data within the vicinity of turbines.
- 8.3.6 For seals, which are difficult to spot at sea or to detect acoustically, and to which telemetry devices can be readily applied, tagging represents a promising method for measuring the movements and distribution of individuals.
- 8.3.7 Pros and cons of different survey approaches in high tidal current area are summarised in Table 8.1

Table 8-1 Summary of some pros and cons of different methodologies for monitoring marine mammals at high tidal current sites

Pros	Cons
Static Acoustic Monitoring Devices such as PODs	
<ul style="list-style-type: none"> • Can provide extended fine scale temporal coverage • Day and night coverage • Low running costs • Relatively unaffected by surface sea state 	<ul style="list-style-type: none"> • Do not provide data on detection range • Difficult to maintain moorings in high tidal currents • Mooring close to turbines often prohibited • Onerous licensing requirements for long term moorings • High risk of loss in some areas. Not compatible with some fishing practices • Will be affected by varying levels of noise, between locations and over tidal cycle • PODs do not measure noise levels directly • Analysis techniques not well developed • Very limited spatial coverage • Only effective with as subset of species (some odontocetes)
Land Based Visual (point) Survey	
<ul style="list-style-type: none"> • No platform required, low cost • No influence from observers on subjects • All species can be detected 	<ul style="list-style-type: none"> • Limited spatial coverage (effective detection range for porpoises ~2km) • Detection function difficult to determine limited scope for quantitative survey • Affected by sea state due to current and weather • Affected by visibility- e.g. mist, rain, fog • Survey not possible at night
Boat Based Visual Survey	
<ul style="list-style-type: none"> • Considered a standard technique • Accepted analysis methodology • All species can be detected • Good spatial coverage • Compatible with towed and vertical array 	<ul style="list-style-type: none"> • Detection probability affected by sea state due to current and weather also by visibility- e.g. mist, rain, fog • Monitoring not possible at night • Platform affected by tidal current

Pros	Cons
surveys	<ul style="list-style-type: none"> Temporal coverage limited by platform cost Requires a substantial experienced field team Typically requires larger (more expensive) stable vessel
Visual Aerial Survey	
<ul style="list-style-type: none"> Large areas can be covered quickly, potential for good spatial coverage Standard technique with established methodology All species can be detected Platform and survey tracks not affected by current Practical in areas of complex topography 	<ul style="list-style-type: none"> Temporal coverage limited by platform cost Detection probability highly affected by sea state due to current and weather and by visibility- e.g. mist, rain, fog Survey not possible at night Practicality dependent on distance from airports Topography, e.g. high hills, may affect safe operation Not compatible with vertical array deployments
Towed Hydrophone Surveys	
<ul style="list-style-type: none"> Less affected by weather, sea conditions and current than visual methods Monitoring at night possible Provides good spatial coverage High level of automation allowing for minimal field teams and high levels of consistency Compatible with other boat based surveys Smaller (cheaper) vessels preferable and platform of opportunity possible 	<ul style="list-style-type: none"> Not effective with all species Equipment required Analysis methodologies less well established than for visual Temporal coverage limited by platform costs
Vertical Hydrophone Array	
<ul style="list-style-type: none"> Provides data on depth of vocalisation from the relevant and required location 	<ul style="list-style-type: none"> Analysis methodologies being developed Requires dedicated vessel Only suitable for odontocetes
Telemetry	
<ul style="list-style-type: none"> Provides long term, information rich datasets Good data on movements and dive depths No human influence on behaviour once subjects have recovered from tagging 	<ul style="list-style-type: none"> Not a practical prospect for small cetaceans in UK waters Spatial coverage of data depends on the movements of individuals - which may rarely enter area

Pros	Cons
	<p>of interest</p> <ul style="list-style-type: none"> • Tagging of large number of individuals may be required to provide representative data • Determining densities from telemetry data is not straight forward • An invasive technique with some risk to animals

Behavioural studies

- 8.3.8 Potentially, studies of the behaviour of individual animals within high tidal energy areas could provide several types of useful data. Fine scale tracking of the movements of individuals would provide very detailed information on habitat use complimenting the broader scale data provided by survey. Detailed information on animals' behaviour within these areas would also provide improved insights into the use they make of these areas for foraging and other important activities. Finally, behavioural studies will be important for studies of the effects and impacts of tidal turbines themselves, and in particular whether and how animals are able to reduce collision risk by avoiding them.
- 8.3.9 For seals, as has been shown in this study, fine scale telemetry provides detailed data on many relevant aspects of behaviour. Telemetry is not a viable option for harbour porpoises. A practical methodology might be detailed tracking from a small manoeuvrable boat (and in some locations from land), potentially combined with passive and active acoustic monitoring. The poor weather conditions prevented us attempting any of this type of work on this project. However, the shore based tracking methods described in Section 6 should make shore based tracking more useful for this application.
- 8.3.10 For animals like harbour porpoises, which are highly vocal, passive acoustic tracking using arrays of hydrophones could be an effective option for providing detailed location and movement data in areas close to the arrays. Such arrays would probably need to be bottom mounted with cables bringing signals from multiple hydrophones back to a single point for storage and analysis. Software development would certainly be required to allow streamlined processing of the large datasets that would ensue, however, our experience with the vertical array data from this project would suggest that this could be undertaken with little technical risk. Installing such an array from scratch in such a challenging environment would be a substantial and costly engineering task unless it

was possible to make use of structures and cable runs installed as part of the turbine installation process.

- 8.3.11 For seals in addition to completing the original planned deployment of 10 transmitters (only 5 were eventually deployed), an additional 10 transmitters have been deployed, plus the 5 previously not deployed, allowing for an evenly matched sample of 10 pups at both the Anglesey and Ramsey sites. Data from these sites will be combined with results from earlier satellite telemetry studies of adult grey seals from the same areas, In addition, the data will be combined with results from a similar scale deployment on grey seal pups in Orkney in 2010 and compared to earlier deployments on tags on seal pups in the central North Sea (based on older satellite telemetry devices).

8.4 Impact and mitigation studies

- 8.4.1 Tidal turbines are a new technology and we still have limited understanding of the risks that different models might pose to marine mammals, the extent to which animals will adapt to reduce these risks and the type of mitigation that might be required to reduce impacts to an acceptable level. It is clear, however, that this process will involve a combination of population assessment and behavioural studies of marine mammals within the challenging environment of high tidal current area using the methods outlined above (and others).
- 8.4.2 One important observation, which can only be made once tidal turbines are in place and operational, is the extent to which different species can detect and avoid them. Detailed active sonar observations as well as passive acoustic tracking in combination with visual tracking, are methods likely to be applied to this for research purposes. It has been suggested that acoustic devices might be attached to turbines to alert animals to their presence. Such an approach would need to consider aspects such as habitat exclusion and potential for habitation and learning. In addition, information on levels of background noise in these areas and how this varies in time and space, similar to the data we collected on this project, would also be relevant in assessing the detectability of different device types.
- 8.4.3 Installation of turbines is likely to go ahead in conjunction with long term monitoring schemes. As with any research, it is important that the objectives and goals for this are very clearly defined so that an effective program to address them can be carefully designed. For porpoises, and other highly vocal cetaceans, passive acoustic monitoring promises to provide the most cost effective methods for monitoring. A mixture of mobile

towed hydrophone survey and the use of static monitoring devices would probably be required. Technological development in both of these areas would be helpful. For towed hydrophones multi element arrays that would allow immediate range measurement would be an important advance. For static monitoring, devices that measure noise levels and (ideally) range, are necessary, especially for monitoring in the highly variable habitat of high tidal current areas.

8.5 Further works at these sites

- 8.5.1 This project has provided a substantial amount of new data from two tidal current areas that are likely candidates as sites for tidal turbine installations. However, these should be seen as generic proof of concept studies that were conducted within these sites rather than comprehensive studies of the sites themselves and were not designed for assessments of specific planned developments. A particular limitation of the cetacean surveys is that each study took place over periods limited to several weeks in the summer at each site. We strongly recommend that, based on an assessment of the methods employed here, a long term program of monitoring, capable of revealing seasonal and inter-annual variation at these sites should be initiated.

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Glossary

ARGOS A worldwide tracking and environmental monitoring service utilising orbiting satellites that pick up signals from tags. Location is determined by measuring Doppler shifts in the tag's signals. Tags can send short data messages.

Clicks Single strong clicks that have the spectral and temporal characteristics of porpoise clicks but occur on their own.

CPOD The latest variant of the POD porpoise detection device- see POD

Detection Function A function describing how detection rate decreases with distance. For example, how relative probability of visual detection falls with distance from the trackline. Detection functions are normally determined empirically by fitting a function to data collected during surveys. The DISTANCE software includes routines for fitting several different families of function.

Detection Positive Days (DPD) The number days within a time period when at least one porpoise detection was made.

Detection Positive Minutes (DPM) The number of minute intervals in a time period in which at least one porpoise detection was made. This is a measure often used to summarise detections of porpoises by PODs- see PODS. This is a measure often used to summarise detections of porpoises by PODs- see PODS.

DISTANCE The standard software for analysis of distance based survey data, for example line transect data. DISTANCE is freeware maintained by the Centre for Research into Ecological & Environmental Modelling (CREEM) at the University of St Andrews.

Effective Strip Width (ESW) The strip width centred on the trackline in a line transect survey within which as many animals are missed as are detected outside the ESW. Thus, a line transect survey can be considered to be equivalent to a strip transect survey with a strip width equal to the ESW.

European Protected Species (EPS) A species, listed on Annex IV of the European Habitats Directive, that is accorded strict protection by member states from various human activities, including protection from disturbance. All cetacean species are EPS.

Events Instances which involve many click detections which are not on distinct tracks.

g(0) The proportion of animals on the trackline that are not detected during a line transect survey.

GPS (Global Positioning System) An accurate real time worldwide positioning system which utilises signals from a constellation of satellites maintained by the US military.

GSM (Global System for Mobile Communication) A widely used international standard for mobile phones.

GSM/GPS Tag A telemetry device in which location is determined using the GPS system and data (on location and other parameters) are transmitted using the GSM mobile phone network. Typically, with marine mammals, data are archived and only downloaded when animals come within range of mobile phone networks.

Logger A software program for collecting marine mammal survey and research data in the field. Logger was written by Douglas Gillespie with support from the International Fund for Animal Welfare (IFAW) and is freely available for projects generally aligned with IFAW's goals.

Multiple Tracks Similar to “**Single Tracks**” but involve more than one distinct track.

Odontocete The toothed whales, including all species of dolphin and porpoises.

On axis porpoise acoustic events Similar to “**Events**” but the bearings are all at 90 degrees.

PAMGUARD A suite of programs for detecting, characterising and localising cetacean vocalisations in real time. PAMGUARD, which is currently funded by the Joint Industry Project E&P Sound and Marine Life program, is maintained by the Sea Mammal Research Unit at the University of St Andrews and is freely available for non commercial use.

Passive Acoustic Monitoring (PAM) A term applied to the process of detecting marine mammals by detecting, classifying and localising (DCL) their vocalisations using a combination of hydrophone equipment and software and human monitoring.

POD A commercially available automated, static acoustic monitoring device produced by Chelonia Ltd. PODs are the most widely used autonomous acoustic monitoring device for marine mammals in Europe. Although optimised for detecting and classifying porpoises, the clicks of most other odontocetes can be detected on PODs.

Primary Observers The principal observers on a survey responsible for collecting the primary sighting data from which population density estimates will be calculated.

Rainbow Click A program for detecting, classifying and localising transient sounds optimised for odontocete clicks. Initially developed for detecting sperm whales, advances in digitisation hardware and computer processing power mean that Rainbow click can now be used for porpoises. Rainbow Click was written by Douglas Gillespie with support from the International Fund for Animal Welfare. Rainbow click is freely available for research aligned with the objectives of IFAW.

Satellite Relay Data Logger A type of telemetry device which archives data and relays it through satellites. The SMRU SRDL tag, widely used with seals, sends short data messages using the ARGOS system.

SCANS, SCANSII SCANS stands for Small Cetacean Abundance in the North Sea and Adjacent waters. These were two large scale surveys conducted on the Northern European Continental Shelf in July 1994 and July 2005. Harbour porpoise were a particular target for these surveys and an important aim was to determine whether levels of by catch in the area could be sustained by the population. The SCANS surveys provided opportunities for improving methods for visual and towed hydrophone survey.

Special Area of Conservation (SAC) These are protected areas established under the EU Habitats Directive to provide protection for species on Annex I. Bottlenose dolphins, harbour porpoises and both grey and common seals are Annex I species.

Single Tracks Are encounters consisting of a single distinct track of clicks on bearings altering regularly from ahead to astern.

Tidal Rapid An area where tidal currents flow at a particularly high rate. Often these coincide with restrictions between two pieces of land or are found at headlands.

Towed Hydrophone A hydrophone that is towed behind a vessel. Elements are mounted within a streamlined housing to reduce flow noise. A long tow cable distances the hydrophones from vessel noise

TPOD The TPOD was the second generation of POD design. see POD.

Trackline The course of the survey platform during a line transect survey

Tracker Observer A visual observer whose task is to locate and track animals observed during a survey. Often the intention is to measure the probability of detection of the primary observers by recording the proportion of tracked animals detected.

Vertical Hydrophone Array An array of hydrophones deployed in a straight line near vertically. A vertical array is the simplest configuration for calculation of the depth of a sound source.

Appendices

Appendix 1

Table summarising vessel based survey activities using Boy Brendan during the Welsh Tidal Turbine Project in July/August 2009. Lowest and highest recorded sea states and survey effort (in terms of both hours and track-line covered) are shown for several types of survey activity-

- Acoustic only, towed acoustic data collected but no visual effort,
- Single platform- two visual observers on the sighting tower but no tracker.
- Dual platform, two visual observers and tracker on sighting platform.
- Passage, boat transiting off track-lines, acoustic and visual data may be collected but will not contribute to primary survey effort.

See main body of report for additional details.

Date	Survey Type	Effort	Sea State From - To	Distance (nm)	Survey Hours	Notes and Observations
Wednesday, July 15, 2009						Boy Brendan leaves Falmouth 11.30
Thursday, July 16, 2009						Boy Brendan arrives Fishguard 14:50
Friday, July 17, 2009						Gales - boat confined to harbour, fitting equipment
Saturday, July 18, 2009						Gales - boat confined to harbour, fitting equipment, establishing protocols
Sunday, July 19, 2009						Poor weather - building POD moorings. Decide to move operations to Holyhead
Monday, July 20, 2009						Vessel makes passage to Holyhead. Research team travel by road and liase with shore team in Bangor
Tuesday, July 21, 2009						Poor weather - deploy 6 pods in the Skerries survey block
Wednesday, July 22, 2009						Gales. Vessel confined to harbour. Work on vertical array

Date	Survey Type	Effort		Sea State From - To	Distance (nm)	Survey Hours	Notes and Observations
Thursday, July 23, 2009	Single Plat Effort	4	4	23.2	6.8		Surveys in Skerries block attempted in poor weather. Tracking (dual platform) impossible.
Friday, July 24, 2009	Dual Plat Effort	2.5	4	15.0	2.6		Surveys in Skerries block. Dual platform visual surveys attempted for short period
	Single Plat Effort	3	5	23.1	5.0		
Saturday, July 25, 2009	Dual Plat Effort	2	4	50.0	8.9		Surveys in the Skerries block. Worsening sea conditions force early abandonment of survey
	Passage	2	4	15.0	2.5		
Sunday, July 26, 2009							Gales - boat in harbour, work on vertical array
Monday, July 27, 2009	Acoustic effort only	2.5	5	58.0	8.2		Weather too poor for visual survey. Towed acoustic monitoring only
	Passage	2.5	5	23.5	3.4		
Tuesday, July 28, 2009	Acoustic effort only	3	5	4.0	0.6		Poor weather forces surveys to be abandoned in rough seas
	Passage	3	4	5.0	0.7		
Wednesday, July 29, 2009	Acoustic effort only	4	5	4.6	0.7		Mixed weather conditions. Level of effort and type of survey adapted to make the most of changing conditions
	Dual Plat Effort	1	5	45.0	5.8		
	Off Effort	4	4	1.7	0.2		
	Passage	2	5	17.1	2.8		
	Single Plat Effort	2	2.5	7.1	1.0		

Date	Survey Type	Effort	Sea State From - To	Distance (nm)	Survey Hours	Notes and Observations
Thursday, July 30, 2009						Poor weather forces early abandonment of surveys
Tuesday, July 31, 2007						Gales boat in harbour, fixing equipment etc
Saturday, August 01, 2009	Acoustic effort only	3	5	40.0	4.5	Weather poor but improving through the day allowing some visual effort
	Dual Plat Effort	2	4	16.6	2.2	
	Single Plat Effort	2.5	5	9.2	1.9	
Sunday, August 02, 2009	Acoustic effort only	2	2	3.5	0.6	Mandy McMath of CCW on board. Poor weather and developing mechanical problems on the vessel precipitate shortened survey.
	Dual Plat Effort	2	4	11.2	1.6	
	Off Effort	2	5	4.7	2.2	
	Single Plat Effort	2	4	8.5	1.5	
Monday, August 03, 2009						Poor weather and engine problems keep boat in harbour
Tuesday, August 04, 2009						Poor weather and engine problems keep boat in harbour
Wednesday, August 05, 2009	Acoustic effort only	2.5	3	11.4	2.9	Survey in Skerries block and first trials of vertical array
	Dual Plat Effort	2	5	22.2	3.8	
	Drifting	2	4	4.1	2.9	
	Off Effort	2	3	7.9	2.3	
	Single Plat Effort	2.5	4	3.7	0.9	
Thursday, August 06, 2009	Acoustic effort only	2	3	3.5	0.8	Improving weather conditions. Completed survey work and drifting surveys with vertical

Date	Survey Type	Effort		Sea State From - To	Distance (nm)	Survey Hours	Notes and Observations
	Drifting	2	4	8.6	4.1	array.	
	Off Effort	2	3	12.2	4.5	Recovered first pod	
	Passage	3	3	1.6	0.5		
Friday, August 07, 2009	Dual Plat Effort	1.5	4	44.0	6.4	Reasonable weather conditions. Recovered 4 pods	
	Off Effort	2	3	11.7	3.4		
	Passage	2	2.5	2.4	0.4		
	Single Plat Effort	2.5	3	6.1	1.0		
Saturday, August 08, 2009	Acoustic effort only	4	4	11.2	2.6	Very windy. Attempted survey work at South Stacks, later in Skerries	
	Dual Plat Effort	3	3	1.4	0.3		
	Passage	3	5	13.6	2.4		
	Single Plat Effort	3	5	23.6	3.9		
Sunday, August 09, 2009	Dual Plat Effort	2	5	33.7	4.9	Windy but completed surveys in Skerries and South Stacks	
	Off Effort	3	4	2.0	0.3		
	Passage	3	5	13.0	2.3		
	Single Plat Effort	1	3	17.5	2.4		
Monday, August 10, 2009						Gales. Vessel in harbour	
Tuesday, August 11, 2009	Dual Plat Effort	2	3	10.4	1.5	Surveys and vertical array drift recordings around South Stacks	

Date	Survey Type	Effort	Sea State		Distance (nm)	Survey Hours	Notes and Observations
			From	To			
	Drifting	2	2	5	12.3	4.3	
	Off Effort	2.5	2.5	5	13.6	3.2	
	Passage	2	2	4	9.0	2.0	
Wednesday, August 12, 2009	Dual Plat Effort	1	1	2	9.8	1.2	Weather improving after a rainy start. Survey work and vertical array drift recordings in Skerries and Middle mouse (Ynys Badrig). Last day working in Anglesey
	Drifting	1	1	2.5	7.8	4.2	
	End of Day	2.5	2.5	2.5	1.8	0.3	
	Off Effort	2	2	2	0.7	0.2	
	Passage	0.5	0.5	3	18.6	3.2	
Thursday, August 13, 2009							Vessel refuelled and leaves harbour en route to Fishguard. Team tidy up and drive down
Friday, August 14, 2009							Gales. Vessel confined to harbour in Fishguard
Saturday, August 15, 2009							Gales. Vessel confined to harbour in Fishguard
Sunday, August 16, 2009	Off Effort	2	2	2	1.3	0.2	Vessel moved down to Ramsey in heavy weather. Laid first two PODs
	Passage	2	2	5	48.3	8.2	
Monday, August 17, 2009	Acoustic effort only	3	3	3	1.6	0.2	Deployed remaining PODs and surveyed in Ramsey Sound.
	Dual Plat Effort	1	1	3	29.4	3.8	
	Off Effort	2	2	3	10.2	3.0	
	Passage	2	2	2.5	6.4	1.1	
	Single Plat Effort	2	2	4	3.6	0.6	

Date	Survey Type	Effort	Sea State		Distance (nm)	Survey Hours	Notes and Observations
			From	To			
Tuesday, August 18, 2009	Drifting		2	3	3.2	1.2	Continued survey in Ramey sound in worsening weather. Some VA drift surveys. Vessel ran for shelter in Fishguard overnight
	Off Effort		2	3	2.1	1.3	
	Passage		2	4	9.8	2.0	
	Single Plat Effort		2	5	14.6	2.1	
Wednesday, August 19, 2009							Storm bound Fishguard
Thursday, August 20, 2009							Storm bound Fishguard
Friday, August 21, 2009	Acoustic effort only		3	5	72.5	10.4	Attempted survey Clerks and Bishops box off Ramsay
	Off Effort		3	3	9.2	2.3	
Saturday, August 22, 2009	Drifting		2	2	1.4	0.6	Strong winds. Attempted vertical array drift surveys and shore tracking in shelter under cliffs at Fishguard
	Off Effort		2	3	11.0	4.6	
	Passage		2	2.5	5.5	1.9	
Sunday, August 23, 2009							Storm bound Fishguard
Monday, August 24, 2009	Acoustic effort only		2	4	8.6	1.1	Weather improving. Survey effort in Bishops and Clerks box. Short drift survey in Ramsay sound. Anchored Ramsay Sound
	Drifting		2	2.5	1.0	0.2	
	Off Effort		2	4	8.1	2.0	
	Passage		2	4	38.8	5.7	

Date	Survey Type	Sea State		Distance (nm)	Survey Hours	Notes and Observations
		Effort	From - To			
	Single Plat Effort	2	4	20.9	2.9	
Tuesday, August 25, 2009	Acoustic effort only	3	4	18.0	2.4	Survey work in Bishops and Clerks box. Return to Fishguard in worsening weather
	Off Effort	2	2.5	1.7	0.3	
	Passage	2.5	4	26.7	3.0	
Wednesday, August 26, 2009						Storm bound Fishguard
Thursday, August 27, 2009	Acoustic effort only	2.5	4	38.8	4.9	Short survey in Bishops and Clerks box to utilise weather window. Return Fishguard ahead of worsening weather
	Off Effort	2.5	2.5	6.3	0.9	
	Passage	2.5	5	57.4	7.1	
Friday, August 28, 2009						Break down ship and pack up equipment to ship back to lab. Vessel departs

Appendix 2



Appendix 2 to the Phase 2 - Studies of Marine Mammals in Welsh High Tidal Energy Waters

On Behalf of

Welsh Assembly Government




Date: 28th March 2011
Our Ref: JER3688


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1 Introduction

1.1.1 The subproject to measure the dive depth and underwater behaviour of harbour porpoise in tidal rapids using a vertical array (Chapter 5) involved the development of completely new methodology and hardware and involved some technical risk. It was therefore appropriate that we treated this as a proof of concept study and invested rather limited field and analysis resource to the work while we were still unsure of its performance. However, the encouraging results from our initial analysis of vertical array data (Chapter 5) encouraged us to undertake additional work to explore an alternative analysis method using Markov Chain Monte Carlo methods, and to use these to conduct more detailed analysis of acoustic encounters to provide information on dive profiles. We also carried out and analysed some additional field trials using a synthetic porpoise sound generation device to provide ground truth data in realistic field conditions.

2 Software Development

2.1 Markov Chain Monte Carlo localisation

Background

- 2.1.1 An array of four or more hydrophones can localise in three-dimensional space. In this case practical considerations related to maintaining an array configuration in strong tidal currents led us to use a vertical array consisting of two hydrophone pairs. Although the required number of hydrophones for three-dimensional localisation was met, the linearity of the array results in degeneracy of position after localisation so that only range and depth information were provided. Consider a click incident on a single pair of hydrophones; the only information that can be extracted is the bearing to the sound source (porpoise). Because of the broadly omni-directional nature of hydrophones this bearing is resolved in three-dimensional space as a cone of possible locations. The porpoise can be located anywhere on the surface of this cone; however, the length of the cone is unknown. When a second pair of hydrophones is introduced a second cone results. Where the surfaces of these two cones cross indicates the position of the porpoise. For a three-dimensional array of four hydrophones there are six possible cones and there will generally be only one crossing point, providing three-dimensional point localisation. However, because of the symmetry of the vertical array the cones always cross each other in perfect alignment, resulting in a ring of possible locations centred on the array (Figure 2-1). Therefore both depth and range can be accurately determined.

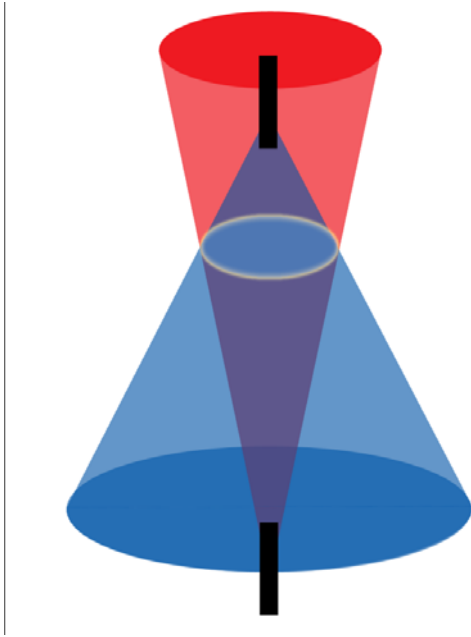


Figure 2-1 A vertical array of four hydrophones shows the far field approximation of 3D cones symmetric around the vertical axis. Each rectangle represents a hydrophone pair. The yellow circle represents the points at which the cones cross.

2.1.2 Time of arrival delays were calculated for each hydrophone using a combination of PAMGUARD and custom Java script (see later) and a Markov Chain Monte Carlo Algorithm was then utilised to localise each click.

2.1.3 Markov Chain Monte Carlo is a common statistical method widely used in physics and astronomy. Figure 2-2 shows multiple hydrophones represented by black dots in three-dimensional space. $r(i)$ and s represent the vectors from the origin to hydrophone i and the source respectively. Considering distance= speed x time this leads to the equation

$$(r_x(i) - s_x)^2 + (r_y(i) - s_y)^2 + (r_z(i) - s_z)^2 = c^2 * T(i)^2$$

where c is the speed of sound, $T(i)$ is the total time from the source to hydrophone i with $r_x/y/z$ and $s_x/y/z$ the Cartesian components of r and s . Rearranging this yields.

$$T(i) = \frac{((r_x(i) - s_x)^2 + (r_y(i) - s_y)^2 + (r_z(i) - s_z)^2)}{c^2}$$

- 2.1.4 The significance of this equation is that it allows the calculation of time delays between elements in a hydrophone array for a source located at any point in three-dimensional space.
- 2.1.5 Although trivial, this forms the basis of Markov Chain Monte Carlo localisation, from now on referred to as MCMC. MCMC localisation works by taking a random point in space and calculating the χ^2 for that location using.

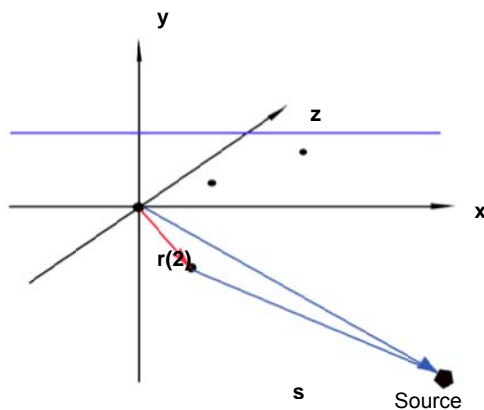


Figure 2-2 Vector diagram showing distance from source to hydrophone 2 in 3D space.

- 2.1.6 The significance of this equation is that it allows the calculation of time delays between elements in a hydrophone array for a source located at any point in three-dimensional space.
- 2.1.7 Although trivial this forms the basis of Markov Chain Monte Carlo Localisation- from now on referred to as MCMC. MCMC localisation works by taking a random point in space and calculating the χ^2 for that location using.

$$\chi^2 = \sum \frac{(\tau_{obs}(ij) - \tau_{calc}(ij))^2}{\epsilon^2}$$

- 2.1.8 Where $\tau_{obs}(ij)$ is the actual observed time delay between hydrophones i and j and $\tau_{calc}(ij)$ is the calculated time delay between hydrophones i and j from an acoustic source if it was at the assumed location. ϵ represents the expected error in observed data. For a four hydrophone array $i=1,1,1,2,2,3$ and $j=2,3,4,3,4,4$.

2.1.9 The algorithm then executes a small random "jump" in space using a cylindrical co-ordinate system and the χ^2 for this new location is calculated using the same formula.

2.1.10 If χ^2 is lower at the new location the jump is deemed successful, the new location is adopted. If χ^2 is not lower then the jump is only accepted with a probability of

$$p = e^{-\left(\frac{\Delta\chi^2}{2}\right)}$$

2.1.11 Where $\Delta\chi^2$ represents the difference in χ^2 values between the previous and new jump point. If still unsuccessful the new location is discarded and another random jump calculated from the previous location. If successful then the jump is instigated from the new location. In this way a chain of successful jumps results, converging quickly to the likely porpoise location. Once close to this location the chain then jumps around it creating a cloud of points, the density of which represents a probability distribution of the porpoise's position.

2.1.12 The power of this technique is that it provides a reliable measure of the probability distribution of location and it can also easily incorporate other unknown parameters, in addition to the location of the porpoise. In the case of the vertical array for example it is possible to allow the chain to search for unknowns in the position of the array.

Compensating for cable angle

2.1.13 Inclinerometers were included in the array but they provided incomplete information on the array position. The inclinometer located on the top of the array was kept in line with the bow of the survey vessel and thus provides exact information on the orientation of the top of the cable. However, due to the twist in the cable the orientation of the bottom inclinometer was not known and therefore only provided limited information. The orientation of the cable connecting both hydrophones is completely unknown. If one assumes inclination angles of Θ and azimuthal angles of Φ (Figure 2-3) then there are three unknowns, Θ_2, Φ_2 and Φ_3 .

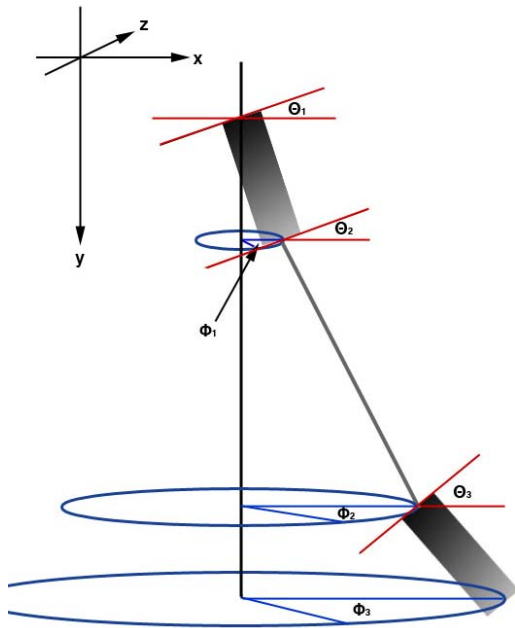


Figure 2-3 *Diagram of the vertical array. The shaded rectangles each represent a hydrophone pair. The red lines indicate the inclination angles Θ_1 , Θ_2 , Θ_3 and circles represent the resultant possible azimuthal components due to unknown direction and inclination of the cable. The co-ordinate axis represented the Cartesian co-ordinate system used throughout the project.*

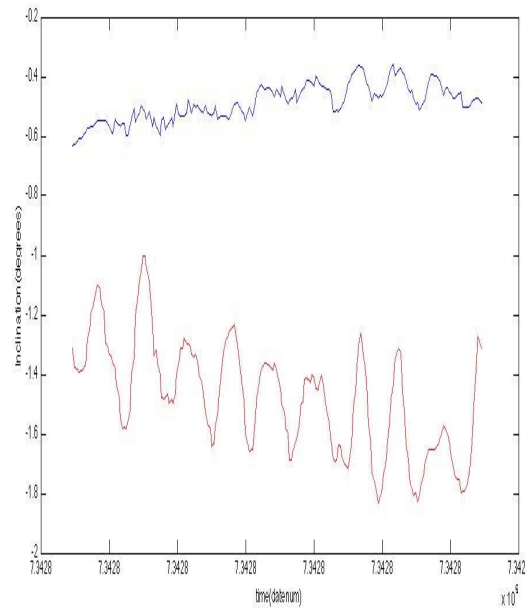


Figure 2-4 *Inclination angles of the array over time May18 2010. Red represents to top inclinometer and blue represents the bottom inclinometer. Time is in matlab datum format which converts date/time in a single number starting at 0 on Jan 0000 00:00:00.*

2.1.14 Plotting the inclination angles, Θ_1 and Θ_3 it is evident that a periodic variation in angle occurred. This periodic motion is attributed to the roll of the ship and therefore it can be assumed that movement in the array is mostly in one plane. Thus the unknowns, Φ_1 and Φ_2 , can be eliminated leaving Θ_2 , the inclination of the cable, as the last unknown parameter. The Markov Chain therefore calculates a random position in space and a random value for Θ_2 on every jump.

Implementation

2.1.15 The method was implemented as a Java program and run on all the data collected during the initial field work (Chapter 5) and additional trials conducted in May 2010. The test for a successful MCMC localisation is to determine whether several (in our case we used ten) different Markov chains all converge to the same probability distribution. The first 65% of each chain was discarded to prevent any bias from the initial starting locations and the mean and standard deviation of the depth and range of the remaining jumps calculated.

2.1.16 For the Welsh and west coast May 2010 data the test of convergence was successful if all chain depths were within 1.5 m of each other.

2.1.17 Final data was output to a spreadsheet showing time, depth and range along with errors for each localised click.

Improved interpretation and measurement of time of arrival delays between hydrophones

2.1.18 The recorded wav files from each hydrophone were run through PAMGUARD to detect likely porpoise clicks and a specially written Java program was then used to identify probable corresponding clicks on different hydrophones and localise using the MCMC techniques discussed above.

2.1.19 First attempts at analysis (Chapter 5) simply selected a "primary hydrophone" and then detected all clicks on that hydrophone. For each of these "primary" clicks a time window was determined on the acoustic data channel from every other hydrophone based on the acoustic travel time to that hydrophone from the primary hydrophone. Clicks outside these time windows could not possibly match the primary click. If only one click was detected within each of the time windows a localisation attempt occurred. If more than one click was detected within any of the time windows the data was considered "ambiguous" and discarded. This is a wasteful procedure because echoes and other clicks in rapid click trains often occur within the same time windows on the other channels and, as a consequence, many localisation attempts being abandoned. Routines were therefore developed for recognising and appropriately processing echoes and other "supernumerary" clicks would allow a greater number of localisations to be performed, especially in recordings made in reverberant conditions.

2.1.20 The first procedure developed involved retaining the clicks within any time window with more than one click that resulted in the shortest time delay. This was based on a simple assumption that a click echo will have a greater travel time than the click itself. Application of this procedure more than doubled the number of successful localisations from the records demonstrating the value of this relatively simple method.

2.1.21 A more developed algorithm was then created to further reduce the amount of data discarded. Again a primary hydrophone was designated and time windows created on the other hydrophone channels. However, in this case time delays between all possible combinations of clicks within the windows were calculated and localised. The Markov Chain Monte Carlo method will generally discard inconsistent time delays and those that are successfully localised can be easily rated in terms of their quality by determining the average chi value of each chain. In this way localisations based on echoes or aliased

clicks can be discarded and the 'true' localisations retained. When this procedure was implemented the number of successful localisations was increased 3.5 times.

- 2.1.22 Although this second more complex approach produced a further improvement i it comes with some overheads because localising every possible combination of clicks is computationally time consuming.
- 2.1.23 A choice of which method to apply for a particular analysis can be made based on the amount of data that needs to be analysed and the importance of being able to locate as many clicks as possible.
- 2.1.24 One related problems remains. Given the highly directional nature of porpoise clicks, in large arrays of hydrophones, it could often be the case that a click would not occur on the primary hydrophone but would occur on sufficient of the others to allow a localisation. For example, if a six hydrophone array has incident clicks on every hydrophone bar the primary hydrophone the five clicks on the other channels would be discarded even though five hydrophones are perfectly capable of producing a localisation in three dimensions.
- 2.1.25 Future development will explore refining the criteria for interpreting click combinations using waveform analysis (echoes tend to have a less well-defined wave envelope than directly received clicks) and working on a method to ensure click combinations on hydrophones other than the primary hydrophone are not discarded.

3 Calibration Trials

- 3.1.1 A porpoise click generator comprising of a hydrophone connected to the output of a large Sony XPLOD CM-2200GTX 12v amplifier receiving signals from an NI 6251 DAQ card was assembled and used as a source to measure the performance of the vertical array. (We are grateful to Jay Barlow, NOAA SWFC for suggesting this configuration of equipment). A wav file comprising of a wave train of twenty simulated porpoise clicks over two one second was created in MATLAB and output to the National Instruments card using the LabView Program. The equipment was deployed from a floating inflatable dinghy at a series of ranges between 50 m and 250 m from the research vessel which was also drifting. At each "station" the transmission hydrophone was deployed at four different depths. (Table 3-1). Range was measured using laser range finding binoculars accurate to 0.5 m and depth of the transmitting hydrophone was recorded using a UWATEC Aladin prime dive computer accurate to 0.1 m.
- 3.1.2 The vertical array was configured with hydrophones at water depths of 4.77, 5.13, 18.13 and 18.38 m and kept taut with a 100 kg weight.

Table 3-1 *Range and depth of the sound source at different times during calibration trials to measure the accuracy of localisation calculations.*

Time	Distance from Boat (m)	Depth of Hydrophone (m)
18:57:32	82	10
18:58:43	92	10
18:59:28	98	7.5
19:00:24	113	5
19:01:01	127	2.5
19:08:03	241	10
19:09:24	245	7.5
19:10:32	248	5
19:11:24	247	2.5
19:17:12	350	10
19:18:20	350	7.5
19:19:04	351	5

Time	Distance from Boat (m)	Depth of Hydrophone (m)
19:20:16	349	2.5
19:25:51	62	10
19:25:52	62	10
19:26:54	61	7.5
19:27:23	59	5
19:27:45	58	5
19:28:20	58	2.5

3.2 Calibration results

- 3.2.1 Calibration trials were conducted in very calm conditions with a smooth sea surface. The transmission hydrophone broadcasts sound omni-directionally and in these reverberant conditions surface echoes were a prominent feature on recordings complicating analysis. Generally however, the results of the calibration are encouraging. Figure 3-1 to Figure 4-1 show all the successful depth and range localisations obtained over the course of the calibration trial as red triangles. The majority of successful localisations occurred between ranges of 58 and 127 m; there were five localisations at 241 m. Only transmissions at depth of 10 m, 7.5 m and 5 m were correctly determined by the localisation algorithm. Those at 2 m could not be successfully localised. At a range of 241 m only the 10 m ping was localised. This was probably due to surface reflections which were more pronounced with smaller surface reflection angles that occur with shallower sound sources and greater ranges.
- 3.2.2 A systematic error of -2 m was present in all the depth localisations. This is thought to be due to a measurement error of the array location. Because the error is consistent throughout all localisations it has been compensated for in Figure 3-2.
- 3.2.3 Figure 3-3 shows the calculated range and Figure 4-1 shows the mean calculated range for each station. At ranges of ~60 and ~125 m there is a good agreement between mean acoustically measured ranges and actual ranges. However, there seem to be a distinct class of erroneous localizations with very short measured ranges. Why these occur is currently not understood but it is likely that in a sequence of localisations such anomalies could be recognised and discarded. At 241 m the acoustically measured and

actual ranges are not in good agreement. However, all five acoustic localisations are quite consistent. This surprising result requires more attention.

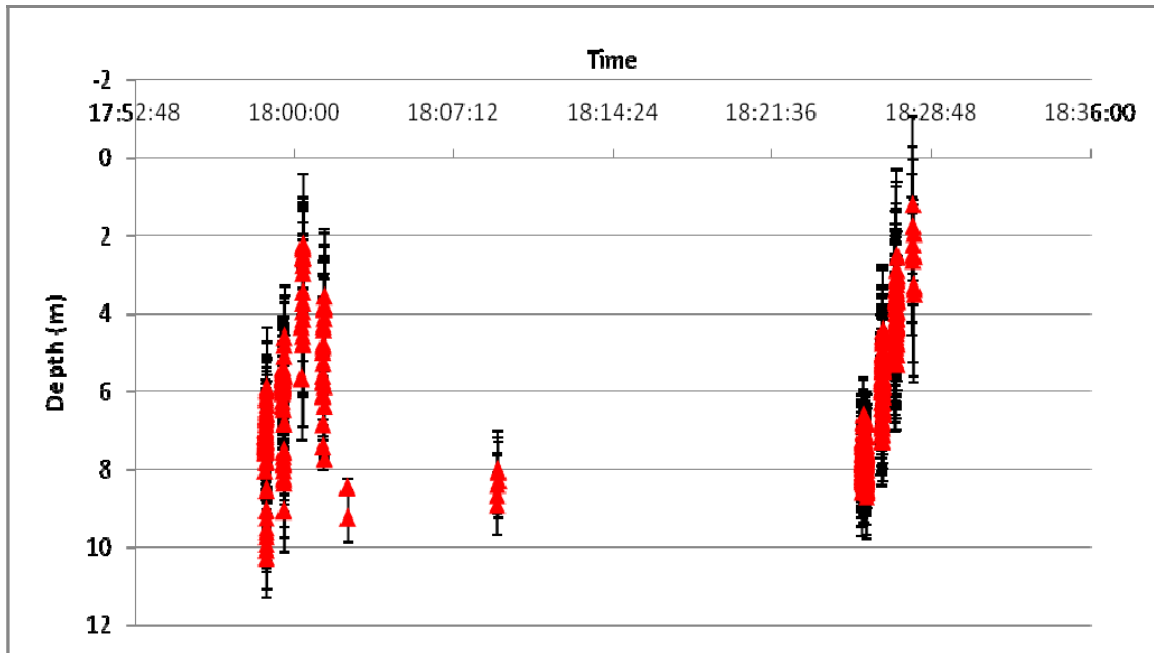


Figure 3-1 Depth of successful localisations. Red triangles represent the mean depth value of all MCMC chains and error bars represent the standard deviation of the MCMC probability density cloud.

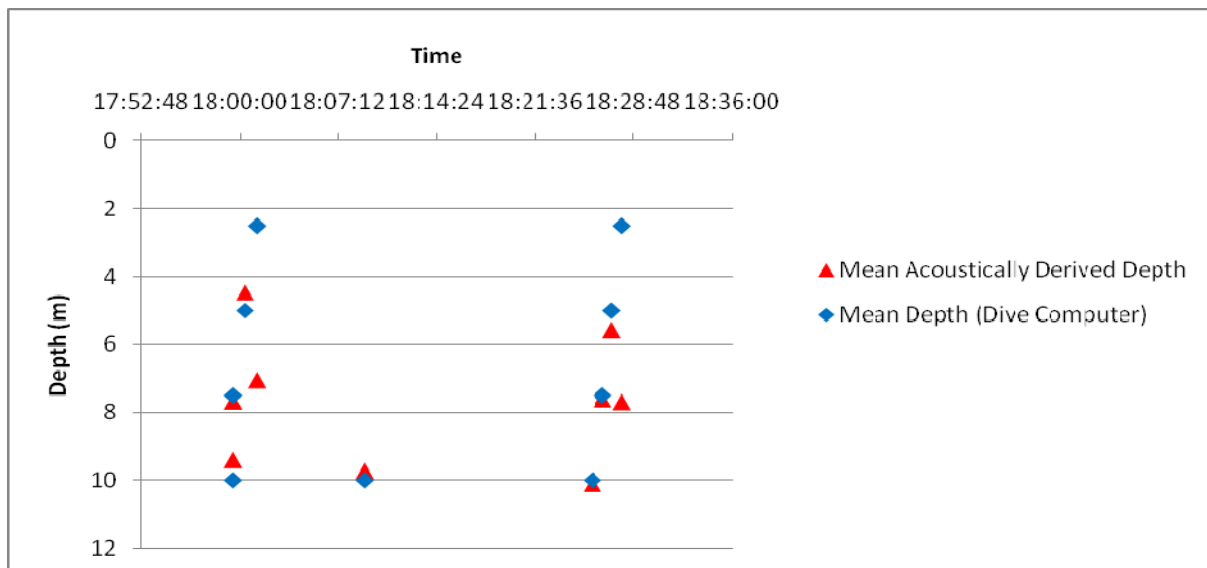


Figure 3-2 Mean depth values of localisations. Red triangles represent the mean depth value of all localisations for each ping. The blue diamonds represent the actual depth of the hydrophone upon output of each simulated porpoise click train. The positions of the hydrophone for pings which were not successfully localised have been discarded. A systemic error of -2 m has been compensated for.

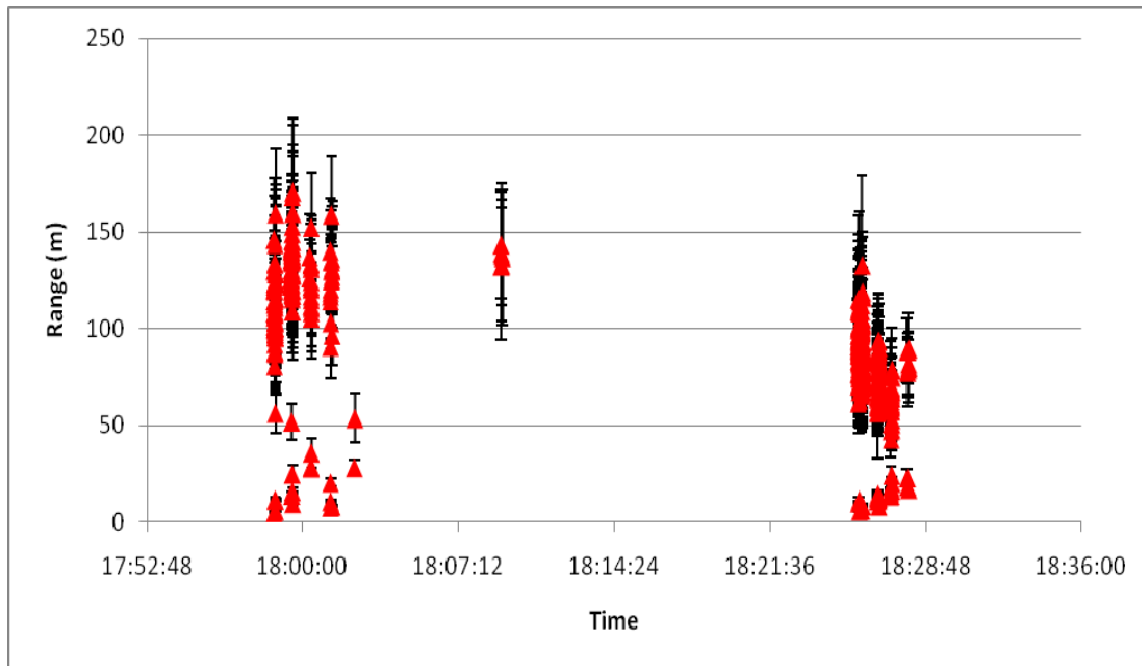


Figure 3-3 Range of successful localisations. Red triangles represent the mean range value of all MCMC chains and error bars represent the standard deviation of the MCMC probability density cloud.

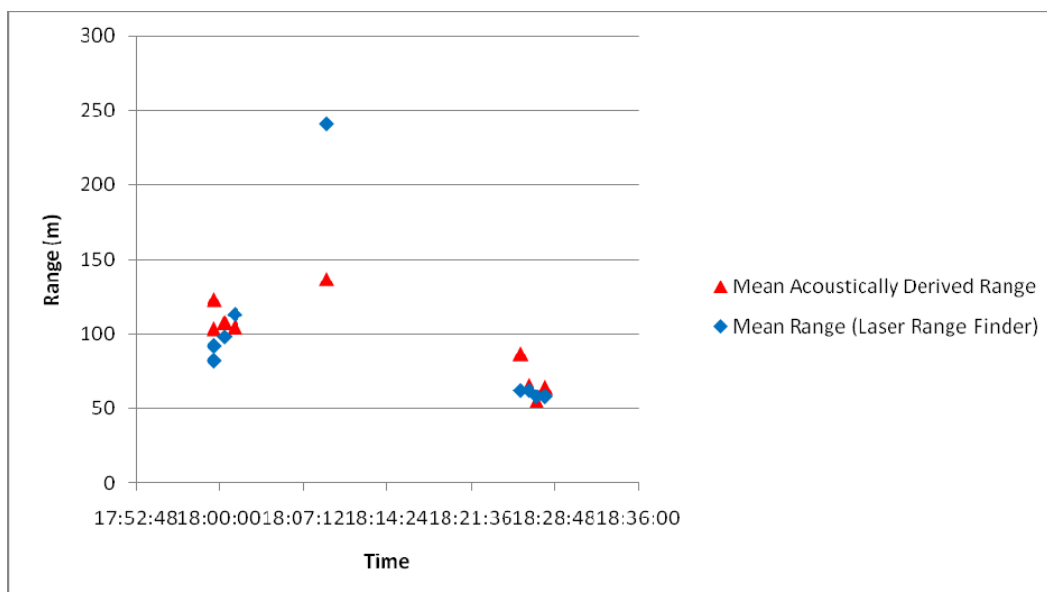
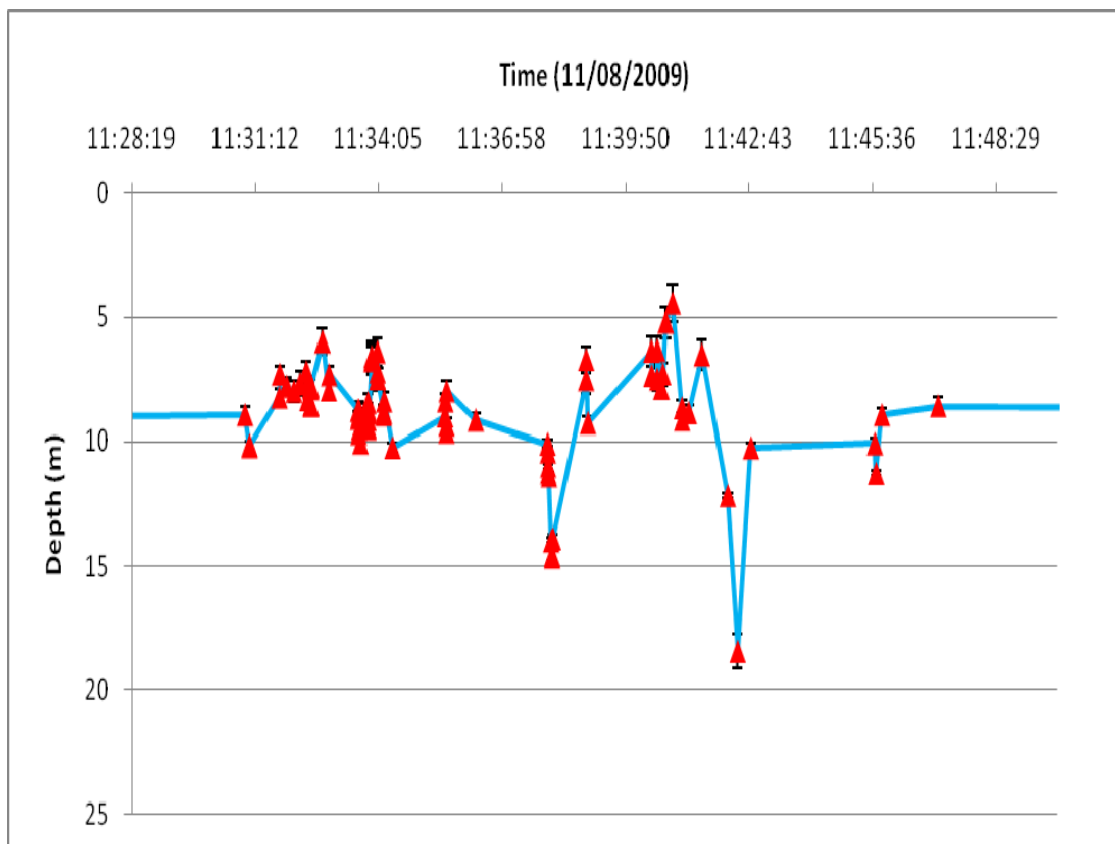
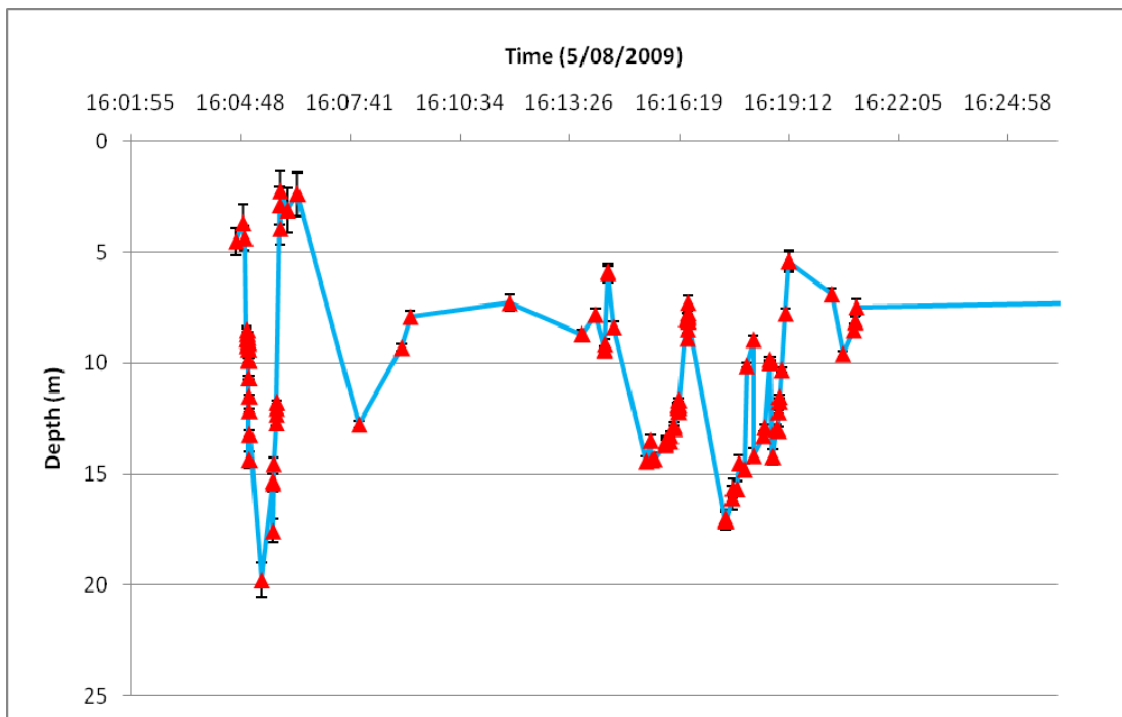
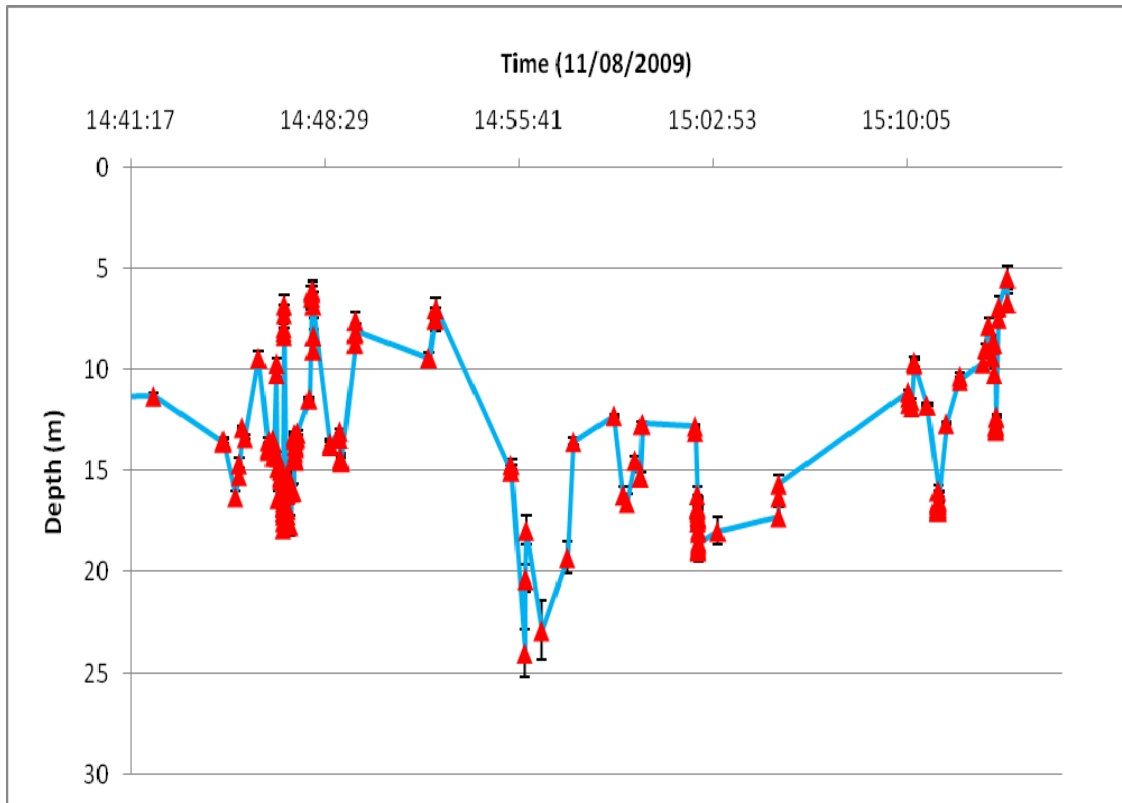


Figure 3-4 Mean range values of localisations. Red triangles represent the mean range value of all localisations for each ping. The blue diamonds represent the actual range of the hydrophone upon output of each simulated porpoise click train. The positions of the hydrophone for pings which were not successfully localised have been discarded.

4 Dive Profiles

4.1.1 Fine scale plots of depth and time were produced using the improved analysis techniques described above to provide depictions of dive profiles. Clearly, depths can only be calculated when an animal vocalises so these profiles will inevitably be patchy and incomplete. A small number of stray localisations were often present. These have been removed by passing the data through a standard deviation filter- this simply discards points which stray from the moving average by more than a standard deviation of the 5 previous and 5 following points. In general this removed <10% of localisations.





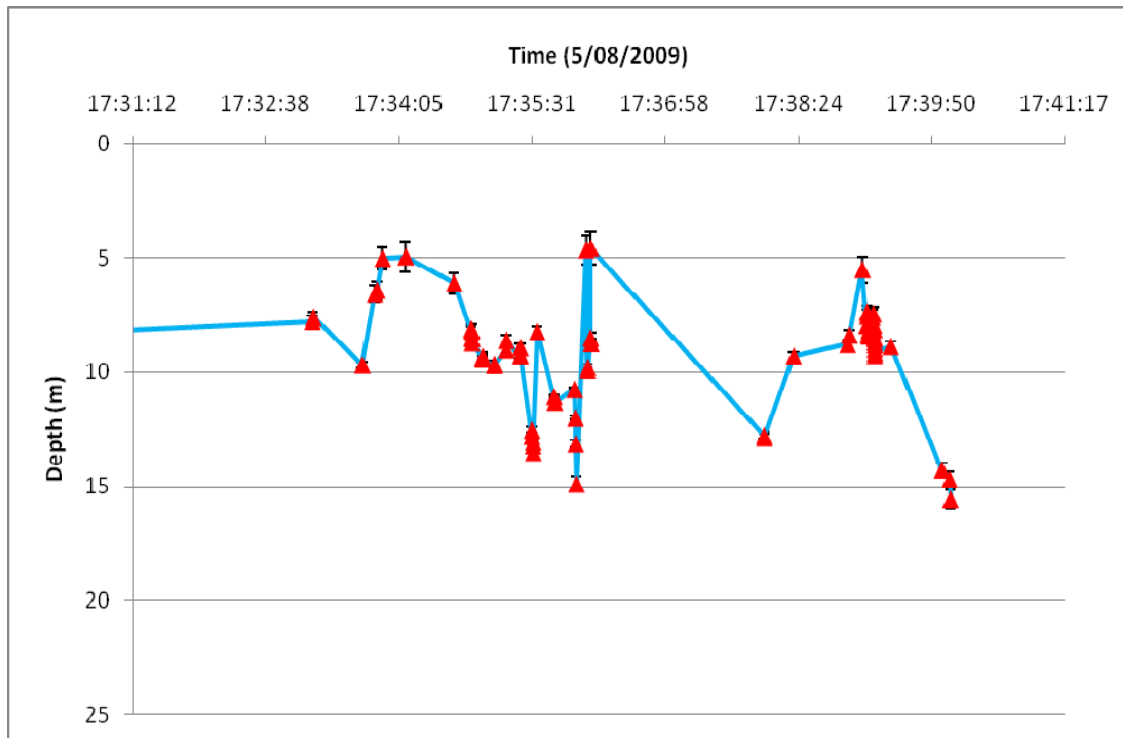


Figure 4-1 Fine scale plots of porpoise depth (calculated from vertical array recordings) against time showing depth profiles for diving harbour porpoises.

5 Conclusion

- 5.1.1 Further development of analysis algorithms implemented as Java programs has allowed a greater number of good locations to be calculated from vertical array data and also yield more complete information about these locations.
- 5.1.2 The calibration results show that the vertical array can accurately localise the depth and range of a porpoise-like sound source. A high click repetition rate, omni directional transmit hydrophone and very low sea state resulted in multiple echoes and interference effects providing difficult data for localisation during the trial and this may have contributed to inconsistent results at 2 m depth and 240 m ranges. Given this, our success in determining the position of the hydrophone at ranges out to 125 m and at depths of 5 m and greater is particularly encouraging. The directional nature of real porpoise clicks should result in fewer surface echoes than the omni directional hydrophone used in the trials. We are therefore hopeful that some aspects of performance of the system will be improved when detecting real animals. The method can be employed to determine dive profiles of porpoise and very probably other high frequency echo locating cetaceans.
- 5.1.3 These new developments make us confident that this vertical array methodology can provide essential data on the use of the water column in tidal rapids by harbour porpoises and other odontocetes which will lead to a better assessment of exposure risk and might also facilitate mitigation measures to minimise this hazard.

Appendix 3

The following pages give a detailed description of the parameter settings for data logging and data summarizing sections of the transmitters on board software. Stored Pages are sent only when a transmitter makes a good contact with a cell phone transmitter mast. In lower quality contacts, only a single (most recent) GPS location point is sent, together with some diagnostic data.

**Software specification for GSM_08A deployment
(Generic GPS/GSM)**

Valid for dates in years 2008 to 2011

Transmitting via GSM

Page transmission sequences:

Until day 1464: 0 1 2 3 0 1 using 1 PTT numbers

Airtest for first 12 hours:

Attempt a call every 1 hour

GSM call settings:

Transfer messages to postbox every 1 hour 30 mins

Call every 6 hours

Abort call if submerged for 8 secs or connected for 10 mins

Service provider is 'auto'

Check sensors every 4 secs

When near surface (shallower than 4m), check wet/dry every 2/4 secs

Consider wet/dry sensor failed if wet for 2 days or dry for 99 days

Dives start when wet and below 1.5m for 8 secs

and end when above 1.5m for 0, or dry at any time

No separation of 'Deep' dives

No cruises

A haulout begins when dry for 10 mins

and ends when wet for 40 secs

Dive shape (normal dives):

9 equally-spaced points (no characterisation) per dive

Dive shape (deep dives):

none

CTD profiles: max 500 dbar up to 4 dbar in 1 dbar bins.

Temperature: Collected, Stored.

Conductivity: Not collected.

Salinity: Not collected.

Fluorescence: Not collected.

Send the deepest 1 upcasts in each 2-hour period.

Minimum depth to trigger collection of cast:

20m in hour 1

20m in hour 2

or 20% greater than current maximum.

Sample CTD sensor every 4 seconds.

Each profile contains 12 cut points

consisting of 0 fixed points, minimum depth, maximum depth, 10 broken-stick

points

GPS fix: attempt a fix every 30 mins

Discard results with fewer than 5 satellites

Make a single attempt each time

Processing timeout: 32 secs

Inhibit GPS after first success in haulout

TRANSMISSION BUFFERS (in RAM):

Dive in groups of 8 (77.7778 days @ 10mins/dive): 1400 = 5600 bytes

No 'deep' dives

Haulout: 50 = 200 bytes

2-hour summaries in groups of 12 (60 days): 60 = 240 bytes

No berniegrams

No timelines

No cruises

No diving periods

No spot depths

No emergence records

No Duration histograms

No Max depth histograms

CTD casts (25 days): 300 = 1200 bytes

GPS fixes (62.5 days): 3000 = 12000 bytes

No spot CTD's

TOTAL 19240 bytes (of about 21000 available)

MAIN BUFFERS (in 8 Mb Flash):
 Dive in groups of 8 (500 days @ 10mins/dive): 9000 x 408 bytes = 3672000 bytes
 No 'deep' dives
 Haulout: 2000 x 16 bytes = 32000 bytes
 2-hour summaries in groups of 12 (360 days): 360 x 248 bytes = 89280 bytes
 No berniegrams
 No timelines
 No cruises
 No diving periods
 No spot depths
 No emergence records
 No Duration histograms
 No Max depth histograms
 CTD casts (166.667 days): 2000 x 68 bytes = 136000 bytes
 GPS fixes (416.667 days): 20000 x 120 bytes = 2400000 bytes
 No spot CTD's
 TOTAL 6180 kb (from 8445 kb available)

PAGE CONTENTS (1024 bits - 40 overhead):

PAGE 0:

PTT NUMBER OVERHEAD (32-bit code) -----[32 bits: 0 - 31]
 PAGE NUMBER -----[3 bits: 32 - 34]

GPS in format 0:

Record could be in buffer for 62 days 12 hours
 Timestamp: max 90 days 12 hours @ 1 sec= 7819200
 tx as raw 23 bits in units of 1 (range: 0 to 8.38861e+06)
 (recommended sell-by 90 days 11 hours)
 Sell-by range: 90 days
 n_sats: raw 3 bits in units of 1 (range: 5 to 12)
 GPS mode: -- not transmitted --
 Best 8 satellites:
 Sat ID's: raw 5 bits in units of 1 (range: 0 to 31)
 Pseudorange: raw 15 bits in units of 1 (range: 0 to 32767)
 Signal strength: -- not transmitted --
 Doppler: -- not transmitted --
 Max signal strength: -- not transmitted --
 Noisefloor: -- not transmitted --
 Max CSN (x10): raw 3 bits in units of 20 (range: 350 to 490)
 -----[189 bits: 35 - 223]

GPS in format 0:

Record could be in buffer for 62 days 12 hours
 Timestamp: max 90 days 12 hours @ 1 sec= 7819200
 tx as raw 23 bits in units of 1 (range: 0 to 8.38861e+06)
 (recommended sell-by 90 days 11 hours)
 Sell-by range: 90 days
 n_sats: raw 3 bits in units of 1 (range: 5 to 12)
 GPS mode: -- not transmitted --
 Best 8 satellites:
 Sat ID's: raw 5 bits in units of 1 (range: 0 to 31)
 Pseudorange: raw 15 bits in units of 1 (range: 0 to 32767)
 Signal strength: -- not transmitted --
 Doppler: -- not transmitted --
 Max signal strength: -- not transmitted --
 Noisefloor: -- not transmitted --
 Max CSN (x10): raw 3 bits in units of 20 (range: 350 to 490)
 -----[189 bits: 224 - 412]

GPS in format 0:

Record could be in buffer for 62 days 12 hours
 Timestamp: max 90 days 12 hours @ 1 sec= 7819200
 tx as raw 23 bits in units of 1 (range: 0 to 8.38861e+06)
 (recommended sell-by 90 days 11 hours)
 Sell-by range: 90 days
 n_sats: raw 3 bits in units of 1 (range: 5 to 12)
 GPS mode: -- not transmitted --
 Best 8 satellites:
 Sat ID's: raw 5 bits in units of 1 (range: 0 to 31)
 Pseudorange: raw 15 bits in units of 1 (range: 0 to 32767)
 Signal strength: -- not transmitted --
 Doppler: -- not transmitted --
 Max signal strength: -- not transmitted --
 Noisefloor: -- not transmitted --
 Max CSN (x10): raw 3 bits in units of 20 (range: 350 to 490)
 -----[189 bits: 413 - 601]

GPS in format 0:

Record could be in buffer for 62 days 12 hours
 Timestamp: max 90 days 12 hours @ 1 sec= 7819200


```

tx as raw 23 bits in units of 1 (range: 0 to 8.38861e+06 )
(recommended sell-by 90 days 11 hours)
Sell-by range: 90 days
n_sats: raw 3 bits in units of 1 (range: 5 to 12 )
GPS mode: -- not transmitted --
Best 8 satellites:
  Sat ID's: raw 5 bits in units of 1 (range: 0 to 31 )
  Pseudorange: raw 15 bits in units of 1 (range: 0 to 32767 )
  Signal strength: -- not transmitted --
  Doppler: -- not transmitted --
Max signal strength: -- not transmitted --
Noisefloor: -- not transmitted --
Max CSN (x10): raw 3 bits in units of 20 (range: 350 to 490 )
-----[189 bits: 602 - 790]

```

```

GPS in format 0:
Record could be in buffer for 62 days 12 hours
Timestamp: max 90 days 12 hours @ 1 sec= 7819200
tx as raw 23 bits in units of 1 (range: 0 to 8.38861e+06 )
(recommended sell-by 90 days 11 hours)
Sell-by range: 90 days
n_sats: raw 3 bits in units of 1 (range: 5 to 12 )
GPS mode: -- not transmitted --
Best 8 satellites:
  Sat ID's: raw 5 bits in units of 1 (range: 0 to 31 )
  Pseudorange: raw 15 bits in units of 1 (range: 0 to 32767 )
  Signal strength: -- not transmitted --
  Doppler: -- not transmitted --
Max signal strength: -- not transmitted --
Noisefloor: -- not transmitted --
Max CSN (x10): raw 3 bits in units of 20 (range: 350 to 490 )
-----[189 bits: 791 - 979]

```

```

DIAGNOSTICS in format 0:

Wet/dry status: raw 2 bits in units of 1 (range: 0 to 3 )
Number of resets: wraparound 2 bits in units of 1 (range: 0 to 3 )
-----[4 bits: 980 - 983]

```

Available bits used exactly
=== End of page 0 ===

PAGE 1:

```

PTT NUMBER OVERHEAD (32-bit code) -----[32 bits: 0 - 31]
PAGE NUMBER -----[3 bits: 32 - 34]
DIVE group in format 0:
Normal dives transmitted in groups of 8
Time of start of last dive: max 91 days @ 4 secs= 1965600
tx as raw 21 bits in units of 1 (range: 0 to 2.09715e+06 )
(recommended sell-by 90 days 23 hours)
Sell-by range: 90 days
Number of records: raw 4 bits in units of 1 (range: 0 to 15 )
Reason for end: -- not transmitted --
Group number: wraparound 7 bits in units of 1 (range: 0 to 127 )
Max depth: odlog 2/7 in units of 4 dm (range: 0 to 7662 dm)
Dive duration: odlog 1/7 in units of 4 s (range: 0 to 1530 s)
Mean speed: -- not transmitted --
Profile data (9 depths/times, 0 speeds):
  Depth profile: odlog 2/7 in units of 4 dm (range: 0 to 7662 dm)
  Profile times: -- not transmitted --
  Speed profile: -- not transmitted --
  Residual: -- not transmitted --
  Calculation time: -- not transmitted --
Surface duration: odlog 2/7 in units of 4 s (range: 0 to 7662 s)
Dive area: raw 7 bits in units of 7.87402 permille (range: 0 to 1000 permille)
-----[944 bits: 35 - 978]

```

```

DIAGNOSTICS in format 1:
Wet/dry status: raw 2 bits in units of 1 (range: 0 to 3 )
Wet/dry fail count: wraparound 3 bits in units of 1 (range: 0 to 7 )
-----[5 bits: 979 - 983]

```

Available bits used exactly
=== End of page 1 ===

PAGE 2:

```

PTT NUMBER OVERHEAD (32-bit code) -----[32 bits: 0 - 31]

PAGE NUMBER -----[3 bits: 32 - 34]

```

SUMMARY group in format 0:
 Transmitted in groups of 12
 Record could be in buffer for 60 days
 End time: max 60 days 8 hours @ 2 hours= 724
 tx as raw 10 bits in units of 1 (range: 0 to 1023)
 (recommended sell-by 60 days 5 hours)
 Sell-by range: 60 days
 Number of records: raw 1 bits in units of 1 (range: 0 to 1)
 Cruising time: -- not transmitted --
 Haulout time: raw 6 bits in units of 15.873 permille (range: 0 to 1000 permille)
 Dive time: raw 6 bits in units of 15.873 permille (range: 0 to 1000 permille)
 Deep Dive time: -- not transmitted --
 Normal dives:
 Avg max dive depth: odlog 2/7 in units of 4 dm (range: 0 to 7662 dm)
 SD max dive depth: odlog 2/7 in units of 4 dm (range: 0 to 7662 dm)
 Max max dive depth: odlog 2/7 in units of 4 dm (range: 0 to 7662 dm)
 Avg dive duration: raw 5 bits in units of 30 s (range: 0 to 930 s)
 SD dive duration: raw 5 bits in units of 10 s (range: 0 to 310 s)
 Max dive duration: raw 5 bits in units of 30 s (range: 0 to 930 s)
 Avg speed in dive: -- not transmitted --
 Number of dives: raw 7 bits in units of 1 (range: 0 to 127)
 Deep dives:
 Avg max dive depth: -- not transmitted --
 SD max dive depth: -- not transmitted --
 Max max dive depth: -- not transmitted --
 Avg dive duration: -- not transmitted --
 SD dive duration: -- not transmitted --
 Max dive duration: -- not transmitted --
 Avg speed in dive: -- not transmitted --
 Number of dives: -- not transmitted --
 Avg SST: -- not transmitted --
 -----[743 bits: 35 - 777]

HAULOUT in format 0:
 Number of records: raw 1 bits in units of 1 (range: 0 to 1)
 Haulout number: wraparound 8 bits in units of 1 (range: 0 to 255)
 Start time: -- not transmitted --
 End time: max 91 days @ 1 min= 131040
 tx as raw 17 bits in units of 1 (range: 0 to 131071)
 (recommended sell-by 90 days 23 hours)
 Sell-by range: 90 days
 Duration: odlog 2/6 in units of 90 s (range: 0 to 85995 s)
 cf. Max duration is 1 day
 Reason for end: -- not transmitted --
 Contiguous: -- not transmitted --
 -----[34 bits: 778 - 811]

HAULOUT in format 0:
 Number of records: raw 1 bits in units of 1 (range: 0 to 1)
 Haulout number: wraparound 8 bits in units of 1 (range: 0 to 255)
 Start time: -- not transmitted --
 End time: max 91 days @ 1 min= 131040
 tx as raw 17 bits in units of 1 (range: 0 to 131071)
 (recommended sell-by 90 days 23 hours)
 Sell-by range: 90 days
 Duration: odlog 2/6 in units of 90 s (range: 0 to 85995 s)
 cf. Max duration is 1 day
 Reason for end: -- not transmitted --
 Contiguous: -- not transmitted -- -----[34 bits: 812 - 845]

HAULOUT in format 0:
 Number of records: raw 1 bits in units of 1 (range: 0 to 1)
 Haulout number: wraparound 8 bits in units of 1 (range: 0 to 255)
 Start time: -- not transmitted --
 End time: max 91 days @ 1 min= 131040
 tx as raw 17 bits in units of 1 (range: 0 to 131071)
 (recommended sell-by 90 days 23 hours)
 Sell-by range: 90 days
 Duration: odlog 2/6 in units of 90 s (range: 0 to 85995 s)
 cf. Max duration is 1 day
 Reason for end: -- not transmitted --
 Contiguous: -- not transmitted --
 -----[34 bits: 846 - 879]

HAULOUT in format 0:
 Number of records: raw 1 bits in units of 1 (range: 0 to 1)
 Haulout number: wraparound 8 bits in units of 1 (range: 0 to 255)
 Start time: -- not transmitted --
 End time: max 91 days @ 1 min= 131040
 tx as raw 17 bits in units of 1 (range: 0 to 131071)
 (recommended sell-by 90 days 23 hours)

Sell-by range: 90 days
 Duration: odlog 2/6 in units of 90 s (range: 0 to 85995 s)
 cf. Max duration is 1 day
 Reason for end: -- not transmitted --
 Contiguous: -- not transmitted --
 -----[34 bits: 880 - 913]

DIAGNOSTICS in format 2:

ADC offset: raw 11 bits in units of 1 A/D units (range: 0 to 2047 A/D units)
 Wet/dry fail count: wraparound 3 bits in units of 1 (range: 0 to 7)
 Max depth ever: raw 9 bits in units of 10 dm (range: 0 to 5110 dm)
 Number of resets: wraparound 2 bits in units of 1 (range: 0 to 3)
 GPS no satellites: raw 14 bits in units of 1 (range: 0 to 16383)
 GPS <5 satellites: raw 14 bits in units of 1 (range: 0 to 16383)
 GPS >= 5 satellites: raw 14 bits in units of 1 (range: 0 to 16383)
 GPS reboots: wraparound 3 bits in units of 1 (range: 0 to 7)
 -----[70 bits: 914 - 983]

Available bits used exactly
 === End of page 2 ===

PAGE 3:

PTT NUMBER OVERHEAD (32-bit code) -----[32 bits: 0 - 31]
 PAGE NUMBER -----[3 bits: 32 - 34]

CTD profile in format 0:

End time: max 81 days @ 2 hours= 972
 tx as raw 10 bits in units of 1 (range: 0 to 1023)
 (recommended sell-by 80 days 21 hours)
 Sell-by range: 80 days
 CTD cast number: wraparound 7 bits in units of 1 (range: 0 to 127)
 Min pressure: raw 6 bits in units of 1 dbar (range: 4 to 67 dbar)
 Max pressure: raw 9 bits in units of 1 dbar (range: 4 to 515 dbar)
 Min temperature: raw 12 bits in units of 10 (range: 0 to 40950 = -5 to 35.95 °C in
 steps of 0.01 °C)
 Max temperature: raw 12 bits in units of 10 (range: 0 to 40950 = -5 to 35.95 °C in
 steps of 0.01 °C)
 Number of samples: -- not transmitted --
 12 profile points 0 to 11 (from total of 12 cut points):
 Pressures 0 to 0 are fixed
 Min pressure is fixed
 Max pressure is sent separately
 bin) 10 broken stick pressure bins: raw 8 bits in units of 1 bin (range: 0 to 255
 permille) 12 x Temperature: raw 8 bits in units of 3.92157 permille (range: 0 to 1000
 permille) Temperature residual: -- not transmitted --
 Temperature bounds : -- not transmitted --
 Conductivity bounds : -- not transmitted --
 Salinity bounds : -- not transmitted --
 Min fluoro: -- not transmitted --
 Max fluoro: -- not transmitted --
 -----[232 bits: 35 - 266]

CTD profile in format 0:

End time: max 81 days @ 2 hours= 972
 tx as raw 10 bits in units of 1 (range: 0 to 1023)
 (recommended sell-by 80 days 21 hours)
 Sell-by range: 80 days
 CTD cast number: wraparound 7 bits in units of 1 (range: 0 to 127)
 Min pressure: raw 6 bits in units of 1 dbar (range: 4 to 67 dbar)
 Max pressure: raw 9 bits in units of 1 dbar (range: 4 to 515 dbar)
 Min temperature: raw 12 bits in units of 10 (range: 0 to 40950 = -5 to 35.95 °C in
 steps of 0.01 °C)
 Max temperature: raw 12 bits in units of 10 (range: 0 to 40950 = -5 to 35.95 °C in
 steps of 0.01 °C)
 Number of samples: -- not transmitted --
 12 profile points 0 to 11 (from total of 12 cut points):
 Pressures 0 to 0 are fixed
 Min pressure is fixed
 Max pressure is sent separately
 bin) 10 broken stick pressure bins: raw 8 bits in units of 1 bin (range: 0 to 255
 permille) 12 x Temperature: raw 8 bits in units of 3.92157 permille (range: 0 to 1000
 permille) Temperature residual: -- not transmitted --
 Temperature bounds : -- not transmitted --
 Conductivity bounds : -- not transmitted --
 Salinity bounds : -- not transmitted --

```

Min fluoro:  -- not transmitted --
Max fluoro:  -- not transmitted --
-----[232 bits: 267 - 498]

CTD profile in format 0:

End time:  max 81 days @ 2 hours= 972
           tx as raw 10 bits in units of 1  (range: 0 to 1023 )
           (recommended sell-by 80 days 21 hours)
Sell-by range:  80 days
CTD cast number:  wraparound 7 bits in units of 1  (range: 0 to 127 )
Min pressure:  raw 6 bits in units of 1 dbar (range: 4 to 67 dbar)
Max pressure:  raw 9 bits in units of 1 dbar (range: 4 to 515 dbar)
Min temperature:  raw 12 bits in units of 10  (range: 0 to 40950 = -5 to 35.95 °C in
steps of 0.01 °C)
Max temperature:  raw 12 bits in units of 10  (range: 0 to 40950 = -5 to 35.95 °C in
steps of 0.01 °C)
Number of samples:  -- not transmitted --
12 profile points 0 to 11 (from total of 12 cut points):
    Pressures 0 to 0 are fixed
    Min pressure is fixed
    Max pressure is sent separately
    10 broken stick pressure bins:  raw 8 bits in units of 1 bin (range: 0 to 255
bin)
    12 x Temperature:  raw 8 bits in units of 3.92157 permille (range: 0 to 1000
permille)
Temperature residual:  -- not transmitted --
Temperature bounds :  -- not transmitted --
Conductivity bounds :  -- not transmitted --
Salinity bounds :  -- not transmitted --
Min fluoro:  -- not transmitted --
Max fluoro:  -- not transmitted --
-----[232 bits: 499 - 730]

CTD profile in format 0:

End time:  max 81 days @ 2 hours= 972
           tx as raw 10 bits in units of 1  (range: 0 to 1023 )
           (recommended sell-by 80 days 21 hours)
Sell-by range:  80 days
CTD cast number:  wraparound 7 bits in units of 1  (range: 0 to 127 )
Min pressure:  raw 6 bits in units of 1 dbar (range: 4 to 67 dbar)
Max pressure:  raw 9 bits in units of 1 dbar (range: 4 to 515 dbar)
Min temperature:  raw 12 bits in units of 10  (range: 0 to 40950 = -5 to 35.95 °C in
steps of 0.01 °C)
Max temperature:  raw 12 bits in units of 10  (range: 0 to 40950 = -5 to 35.95 °C in
steps of 0.01 °C)
Number of samples:  -- not transmitted --
12 profile points 0 to 11 (from total of 12 cut points):
    Pressures 0 to 0 are fixed
    Min pressure is fixed
    Max pressure is sent separately
    10 broken stick pressure bins:  raw 8 bits in units of 1 bin (range: 0 to 255
bin)
    12 x Temperature:  raw 8 bits in units of 3.92157 permille (range: 0 to 1000
permille)
Temperature residual:  -- not transmitted --
Temperature bounds :  -- not transmitted --
Conductivity bounds :  -- not transmitted --
Salinity bounds :  -- not transmitted --
Min fluoro:  -- not transmitted --
Max fluoro:  -- not transmitted --
-----[232 bits: 731 - 962]

DIAGNOSTICS in format 3:

Number of resets:  wraparound 2 bits in units of 1  (range: 0 to 3 )
Wet conductivity:  raw 8 bits in units of 1  (range: 0 to 255 )
Dry conductivity:  raw 8 bits in units of 1  (range: 0 to 255 )
GPS reboots:  wraparound 3 bits in units of 1  (range: 0 to 7 )
-----[21 bits: 963 - 983]

Available bits used exactly
=== End of page 3 ===

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