Marine Mammal Scientific Support Research Programme MMSS/002/15

Marine Renewable Energy MRE1

Annual Report

Marine Mammals and Tidal Energy

Sea Mammal Research Unit
Report to
Marine Scotland, Scottish Government

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V5

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Editorial Trail			
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Executive Summary

The work presented under the Marine Renewable Energy (MRE) theme falls in to three tasks;

MRE 1.1 – Fine scale marine mammal behaviour around tidal energy devices.

MRE 1.2 – Harbour seal movement modelling.

MRE 1.3 – Estimating collision risk using available information.

As MRE 1.2 has been delivered and the deliverables for MRE1.3 were amalgamated into the Marine Scotland This annual report only considers MRE 1.1 as MRE 1.2 and 1.3 have been completed and are available here: http://www.smru.st-andrews.ac.uk/reports/.

MRE 1.1

- This task aims to monitor the behaviour of marine mammals in the vicinity of an operational tidal turbine. A monitoring system utilising a combination of Passive Acoustic Monitoring (PAM), Active Acoustic Monitoring (AAM) and video cameras was deployed to identify marine mammal species using the areas around the turbine and to construct 3D tracks of their movements.
- The environmental monitoring system was successfully installed on the Turbine Support Structure (TSS) at Nigg on 3 October 2016 with deployment of the TSS at the site on 24 October 2016. Following the installation of the Atlantis Turbine in February 2017, initial commissioning of the monitoring system revealed a communications failure with all of the sensors. This was corrected during shore-based maintenance of the turbine in the summer of 2017.
- The Atlantis turbine was successfully re-deployed in mid-October 2017 and a second period of monitoring system commissioning was conducted. Power to the monitoring system turbine became available on 18 October and initial communications tests established that the PAM system was fully functional. However, no communications could be established with the video camera systems or the Gemini multibeam sonars. Plans to recover the platform with the sonars are currently being developed.
- Since commissioning, the PAM system has been operating stably for 95.7 % of the time. From the start of data collection up to the end of 31 December 2017 (~ ten weeks) a total of 11 dolphin and 199 porpoise encounters were made. This equates to a mean of 2.8 porpoise encounters and 0.2 dolphin encounters per day.
- A key output from the PAM data analyses will be the 3D locations of echolocation clicks in relation to the turbine. Echolocation click localisation techniques are currently being refined using the data collected. An important aspect of 3D localisation is to calibrate the array by pinging it with a sound source from a known location; trials to do this are being planned and will be used to improve localisation accuracy.
- To examine fine scale movement of seals in a wider spatial context, 24 harbour seals were caught and tagged in the Inner Sound during two field efforts between 26 September and 3 October 2016, and between 2 and 13 April 2017. These data aim to provide real time locations of seals to base stations on shore each time a seal surfaces, providing supporting evidence to determine if a collision occurs between a seal and a turbine.
- In total 115,100 locations were recorded from the tagged seals during the two tagging deployments. Seals spent a total of 16 % of their time in the Inner Sound, with a relatively low number of locations (195) recorded within the MeyGen lease area. Only three seals were recorded at the surface within 100 m of any of the turbines; the closest surface location to any of the turbines was 35.15 m.

Contents

1 Marine Renewable Energy (MRE) Theme

Concerns about the impacts of tidal energy devices on marine mammals derive primarily from the potential for injury or mortality as a result of direct interactions (collisions) between animals and moving rotors of tidal devices. However, the true risks posed by these devices remain uncertain due to a paucity of information on a) how marine mammals behave in close proximity to operating tidal turbines, b) how marine mammals use tidally energetic areas proposed for development, and c) the individual consequences of turbine interactions with marine mammals.

The MRE 1 work package comprises three linked tasks. Together, these will be used to derive parameters required to populate improved collision risk models and to directly measure potential interactions on instrumented tidal turbines.

2 MRE1.1 - Fine scale marine mammal behaviour around tidal energy devices

2.1 Introduction

This task aims to monitor the behaviour of harbour seals and other marine mammals in the vicinity of an operational tidal turbine. It is based on the technology that was developed under the Scottish Government contract 'Demonstration strategy: Trialling methods for tracking the fine scale underwater movements of marine mammals in areas of marine renewable energy development' (Sparling *et al*., 2016). This previous work developed a combination of Active Acoustic Monitoring (AAM) and Passive Acoustic Monitoring (PAM) techniques for deployment on the turbine and on a seabed mounted platform to detect and track marine mammals at a high resolution (at a scale of metres). The work described here builds on the development phase by designing, manufacturing, and deploying a combination of an AAM sensor platform and turbine-based PAM and video at an operating tidal turbine. This aims to provide data on the movements of marine mammals around the operating turbine that will form the basis of an analysis of close range encounter rates and marine mammal behavioural responses to the turbine.

This task uses a suite of AAM/PAM/video sensors deployed alongside an operating tidal turbine for a one year period. This is being carried out at the MeyGen Inner Sound development in the Pentland Firth, which is an array of four tidal turbines (three Andritz Hydro Hammerfest HS1000 turbines and one Atlantis Resources Ltd AR1500 turbine; http://www.meygen.com/technology/); the sensor system has been integrated into the Atlantis AR1500 turbine. The Atlantis AR1500 turbine is a 1.5MW horizontal axis turbine with active pitch and yaw capability. It has 18 m diameter rotors that rotate at a nominal speed of 14 rpm; the total height of the turbine above the seabed is 24 m. All four turbines have been deployed and are operational.

Information on the movement tracks of animals will be matched with rotational information from the turbine developer as well as tidal phase and speed of current information to allow analyses of close range avoidance responses of marine mammals to the tidal turbine. Overall, the analyses aim to provide the information required to reduce uncertainty in current collision risk models.

2.2 Deliverables

<u>Deliverable 1</u>: Sensor platform commissioning and deployment at turbine.

<u>Deliverable 2</u>: Investigation of frequency of fine scale interactions between marine mammals and operational tidal turbine (initial findings report after one month of turbine operation).

<u>Deliverable 3</u>: Monthly reports of detections of marine mammals from AAM and PAM installed on the MeyGen tidal turbine (for 12 months from end of turbine commissioning).

<u>Deliverable 4</u>: A final report detailing the frequency and nature of the fine scale interactions between marine mammals and an operational tidal turbine, the broader scale movements of seals in relation to operating tidal turbines, and recommendations on monitoring equipment and protocols for the detection and tracking of marine mammals around tidal turbines.

<u>Deliverable 5</u>: A PhD thesis on the fine scale movements of top predators around a tidal turbine.

2.3 Progress and results

2.3.1 Deliverable 1: Sensor platform commissioning and deployment at turbine.

The overall design of the Environmental Monitoring System is a combination of Passive Acoustic Monitoring (PAM) and Active Acoustic Monitoring (AAM) to construct (where possible) 3D tracks of animals within several tens of metres from the Atlantis AR1500 tidal turbine. Furthermore, where possible, species identification will be validated using underwater video deployed on the turbine. Detailed specifications of the system were provided in previous annual reports. Broadly, the system includes:

- A PAM system consisting of three clusters each of which contain four hydrophones. The hydrophones of each cluster are arranged in a tetrahedral pattern and are enclosed within a strong polythene housing to prevent the risk of damage from moving objects in the water. A cluster is mounted on each of the three Turbine Support Structure (TSS) legs and can provide an unambiguous pointing vector to detected sounds but no range information. Sounds detected on multiple clusters can be fully localised to provide locations of vocalising cetaceans in three dimensions. Details of the PAM system are described in Appendix A.
- Dual multibeam Gemini sonars mounted on a custom designed High Current Underwater Platform (HiCUP) to detect and track seals (and potentially other species). This was designed to be deployed on the seabed approximately 30 m from the TSS. This would allow targets to be tracked accurately in the X and Y plane both upstream and downstream of the turbine. Further, the utilisation of dual sonars can also be used to effectively localise and track marine mammals in the depth (Z) plane.
- Two underwater videos cameras deployed on two of the TSS legs. These are high-end video surveillance camera that have an all-round view over a full hemisphere, oriented to face upwards through the rotor-swept area of the turbine.

The AAM/PAM/video environmental monitoring system was successfully installed on the TSS at Nigg on 3 October 2016, and deployed at the MeyGen site on 24 October 2016. Following the installation of the Atlantis Turbine in February 2017, initial commissioning of the monitoring system revealed a communications failure with all of the sensors. This included the 12 Passive Acoustic Monitoring (PAM) hydrophones and two video cameras mounted on the TSS, and the dual Gemini multibeam sonars mounted on the HiCUP which is cabled to the turbine. Fault diagnosis was conducted by a team of MeyGen-Atlantis and SMRU personnel, and indicated that the most likely cause was a fault in the 48 V DC power supply from the turbine nacelle. When the turbine was recovered for routine maintenance in June 2017, tests of the power system in the nacelle confirmed this diagnosis, with the fault being caused by an incorrectly terminated connector. This was corrected by replacing the connector and shore-side tests confirmed power to the wet-mate connectors on the bottom of the turbine. These connect to the Lower Connection Management System (LCMS), which had remained in the water mounted on the TSS.

The Atlantis turbine was successfully re-deployed on the TSS in mid-October 2017 and a second period of monitoring system commissioning was conducted. Power to the monitoring system turbine became available on 18 October and initial communications tests were conducted; these established that:

- communication with a Smart Ethernet Switch (SES) in the TSS-JB was successful;
- the PAM system (digital electronics are all contained within the TSS-JB) was fully functional;
- no communications could be established with the video camera systems mounted on the TSS;
- no communications could be established with the Gemini multibeam sonars or their associated pitch/roll control systems.

An assessment of the likely failure mechanisms associated with the video cameras and sonars, together with the results of the formal commissioning tests and an assessment of the data quality, the efficiency of the analytical processes, and a recommendation of the reporting content and scheduling, and are provided in detail in an Environmental Monitoring System Commissioning Report (Gillespie *et al*., 2017). At present, the PAM system is fully operational but the two video cameras and the Gemini sonars remain non-operational. MeyGen are currently making plans to recover the platform with the Gemini sonars.

2.3.2 Deliverable 2: Investigation of frequency of fine scale interactions between marine mammals and operational tidal turbine

Since environmental monitoring commissioning, the PAM system has been operating stably except for brief periods due to power outages, for system maintenance, or to test other turbine monitoring systems with the

PAM system powered off. Between system commissioning and 20 February 2018, the PAM system was operational for 95.7% of the time. Acoustic data were initially received on all 12 hydrophones with no evidence of any damage to any hydrophones. Since 7 November 2017 a tonal noise at a frequency of 108 kHz has been present on one hydrophone channel; however, it is not affecting the ability to detect and localise animals using the other 11 hydrophones, all of which are fully operational (Figure 1).

Recording all raw data from 12 hydrophones sampling at 500 kHz per channel would be impractical, generating approximately one terabyte of raw data per day. Instead, the PAMGuard software (Gillespie *et al*., 2008) is used to detect sounds of interest in real time, saving only short sound files likely to contain animal vocalisations with significant energy in the 40 to 150 kHz frequency band (covering the vocalisations of small cetacean species likely to be encountered in these waters). The system also records noise measurements and raw acoustic data decimated (sub sampled) to a lower frequency of 48 kHz so that more detailed analysis of lower frequency vocalisations can be made as required. A full description of the PAMGuard software configuration is provided in Appendix A.

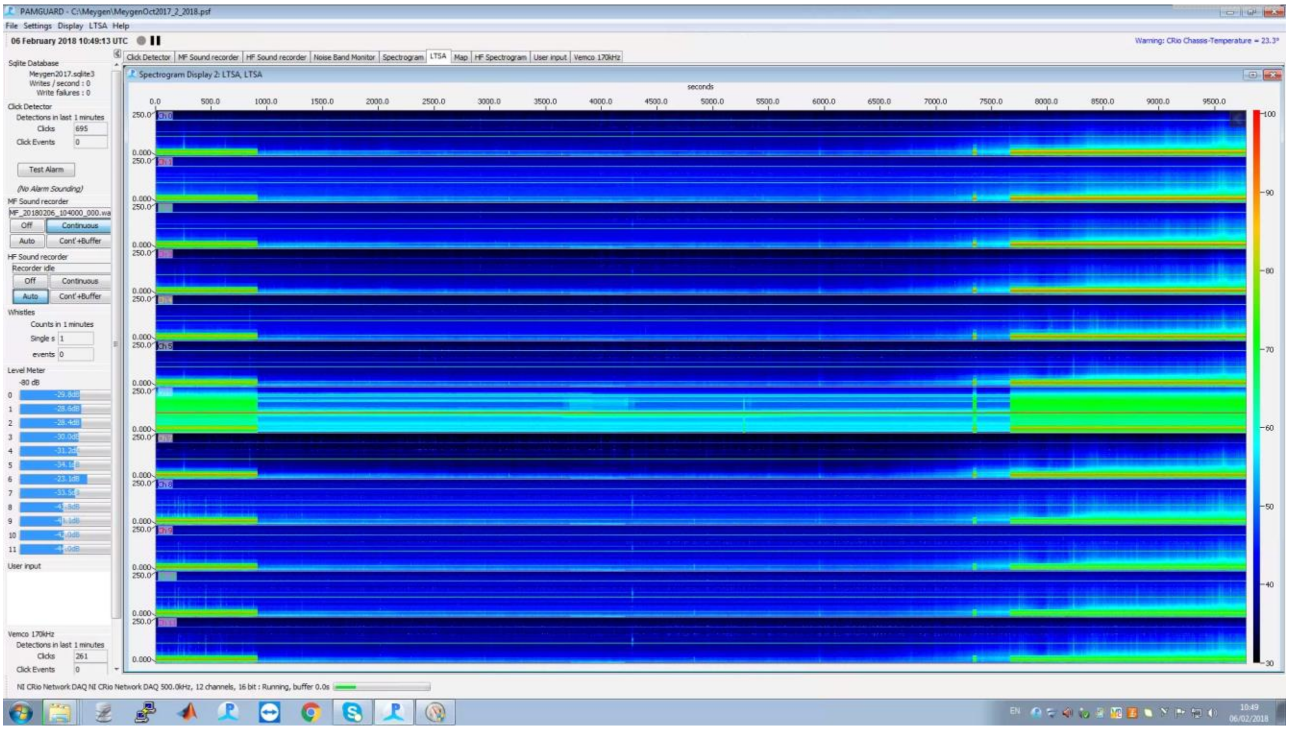

Figure 1. Screenshot of the PAMGuard data collection software showing a long term (approximately 3 hours) spectral average output from each of the 12 hydrophones. The spectral average is colour coded to show periods of relatively low (blue) to high (red) noise. Periods of tidal flow and turbine operating are apparent at the start and end of the display with a relatively low noise period in the middle. Note that a constant tonal noise at a frequency of 108 kHz is apparent on hydrophone 7.

Once recovered to SMRU, data are securely backed up to the university network storage facility and to additional USB hard drives. Click detector data are further automatically processed to a) re-estimate bearings to sounds without using the noisy channel seven hydrophone and b) run a click classification algorithm for the detection of porpoise clicks. An analyst then visually scans the data for sequences of clicks appearing on consistent slowly varying bearings from each cluster, which are indicative of dolphin or porpoise echolocation click sequences (Figure 2). These are marked on the PAMGuard display and the details of each encounter are added to the PAMGuard database. Clicks from marked encounters are then localised using the 3D localisation algorithms described in Macaulay *et al*. (2017). Details of this stage of the analysis are given in Appendix B.

Currently, data have been analysed up to the end of December 2017 (~ ten weeks); during this period 11 dolphin and 199 porpoise encounters (events with at least 30 echolocation clicks on a consistent bearing and close together in time, i.e. < 10 minute gap, or a clearly different bearing to the sounds indicating a different animal) have been made (Table 1). This equates to a mean of 2.8 porpoise and 0.2 dolphin encounters per day.

Table 1. Summary of the numbers of detections by species and month. In total, there were 210 cetacean detections between 19 October and 31 December 2017.

Month	Days of monitoring	Porpoise encounters (daily mean)	Dolphin encounters (daily mean)
Oct 2017	12.3	27 (2.2)	5 (0.4)
Nov 2017	26.9	76 (2.5)	3 (0.1)
Dec 2017	31.0	96 (3.1)	3 (0.1)
Total	70.2	199 (2.8)	11 (0.2)

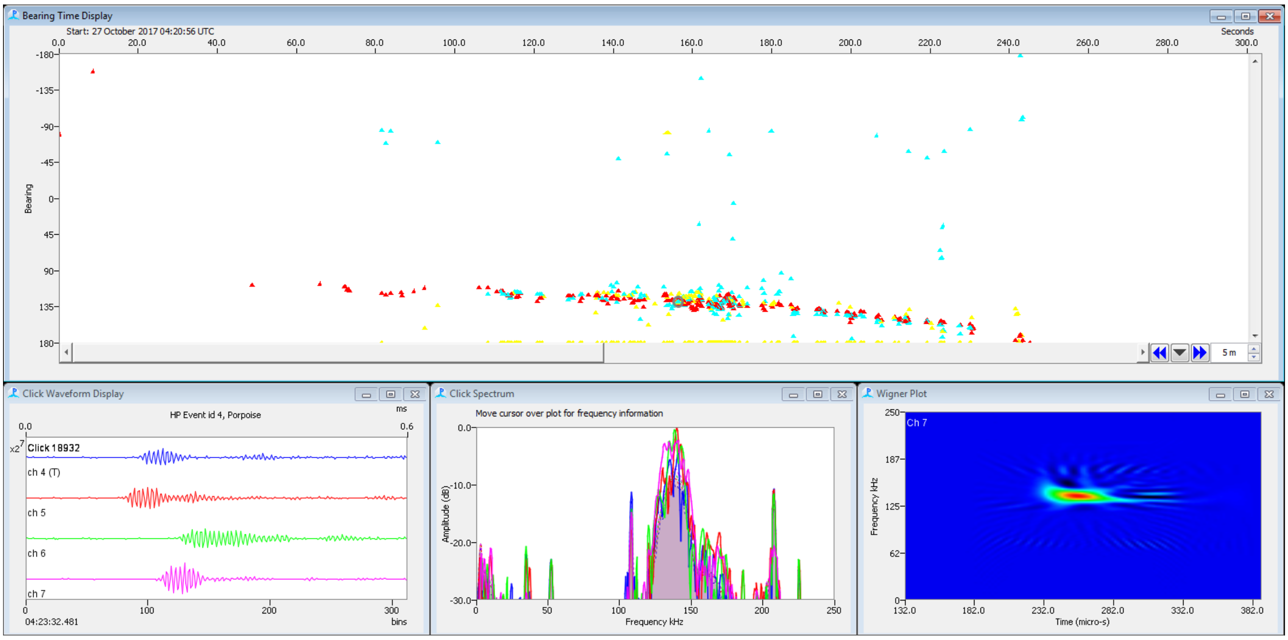

Figure 2. PAMGuard display during a porpoise encounter on 27 October. The top panel of the display shows bearings to clicks from each hydrophone cluster (each cluster being represented by a different colour). The bottom panels show the waveform, spectrum and Wigner (time-frequency) plot for a single selected click.

The primary purpose of this study is to measure changes in the behaviour of animals in response to the operational turbine. Animal presence and behaviour at the site may also be affected by a number of other factors (co-variates). These may include the state of the tide, the lunar phase, time of day, and other human activities such as shipping, etc. The probability of detecting and tracking animals will also be affected by noise which is itself a function of tidal flow, turbine operations and other anthropogenic activities. Behaviour with respect to turbine operations will therefore be examined by fitting multivariate statistical models to the data in a similar fashion to the analysis described in Malinka *et al*. (2018).

Turbine rotational data is provided by MeyGen, who is also providing tidal flow metrics at the site with 0.5m.s^{-1} resolution at one minute intervals. Tidal information has also been extracted from the POLPRED database (National Oceanography Centre, 2010) for a location relatively close to the turbine site, although it should be noted that POLPRED predictions may not be accurate close to coastlines. Peak tidal flows in each cycle vary by a factor of approximately two over a spring/neap cycle. As such, individual flow measurements viewed in isolation do not give a good indication of when they occur within a tidal cycle. Consequently, the inclusion of “percentage peak flow” in the models is being explored. This is calculated by taking each instantaneous flow measurement and dividing it by the maximum flow encountered up to three hours either side of that measurement (which will capture a peak flow in one direction or the other). For analysis, flood tides (flowing from West to East) are considered positive and ebb tides (flowing from East to West) negative.

Figure 3 shows distributions of tidal flow and percentage tidal flow for the period October to December 2017, overlaid with numbers of encounters with porpoise and dolphin click events. While the figure shows that animals are detected at all states of the tide, no further inferences should be made from these data until the modelling work has been completed. For example, although the plots appear to show higher numbers of animals during the flood tide, relative noise levels during ebb and flood tides that would affect detectability have not been fully quantified. Initial investigation suggests that noise levels are higher at high flow rates (Figures 4 and 5), which will reduce detectability at these times.

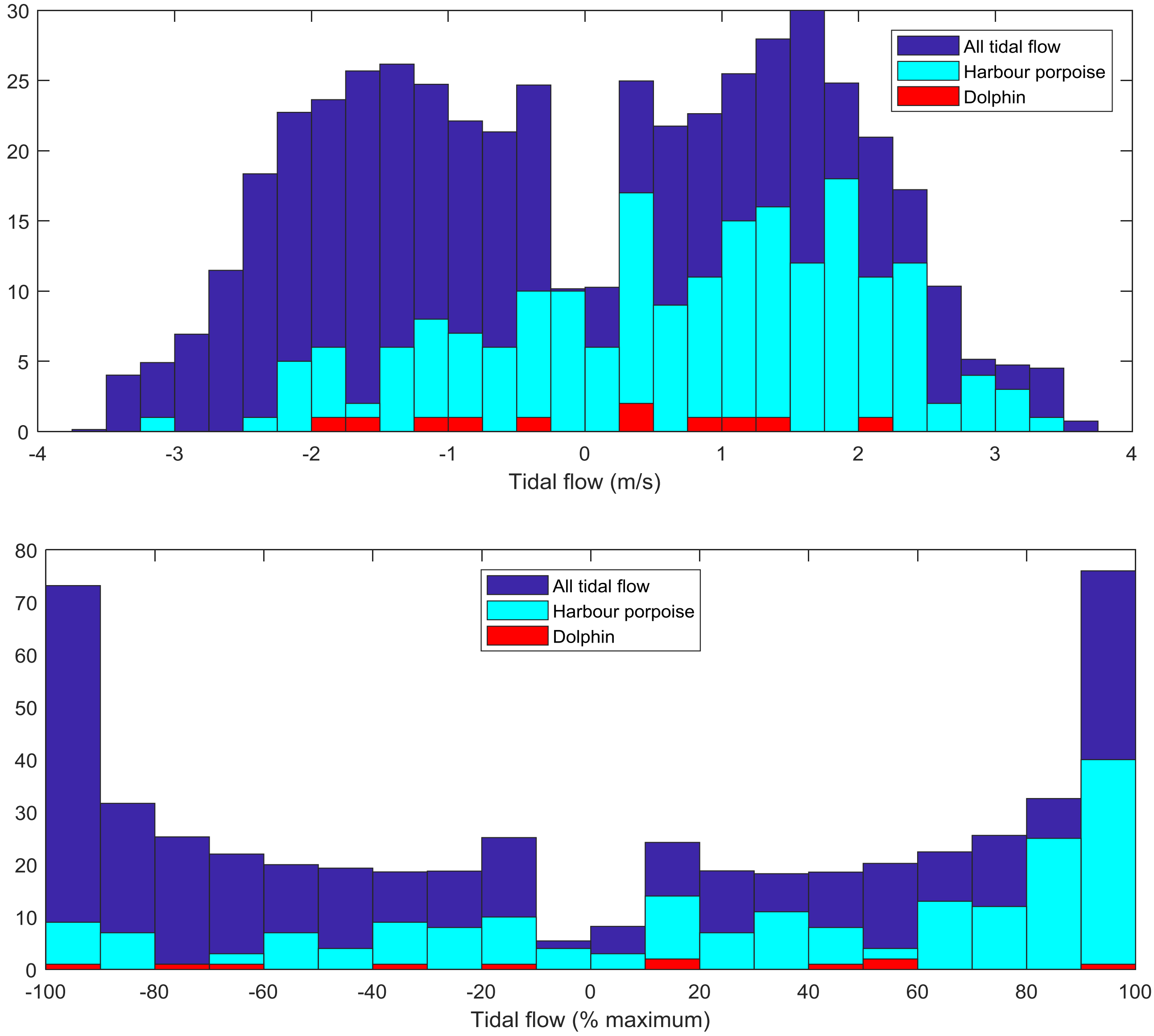

Figure 3. Summary of all cetacean encounters by tidal flow (POLPRED Data). The figure shows the numbers of encounters (colour coded by species/species group) as a function of absolute tidal flow speed (upper panel) and by percentage tidal flow (lower panel: the instantaneous flow as a percentage of the highest flow in a 3-hour window either side of that instant).

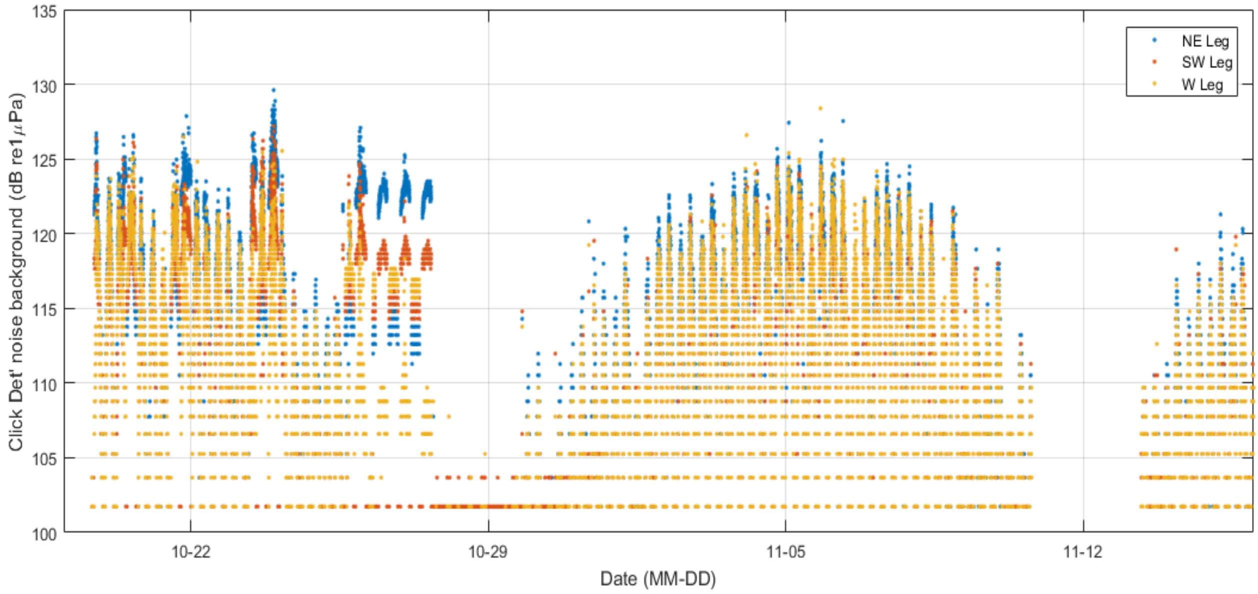

Figure 4. Data showing noise in the click detector frequency band from each hydrophone cluster. There are changes by up to 20dB over a tidal cycle and between neap-spring tides. Such changes significantly impact the range at which harbour porpoises and dolphins can be detected.

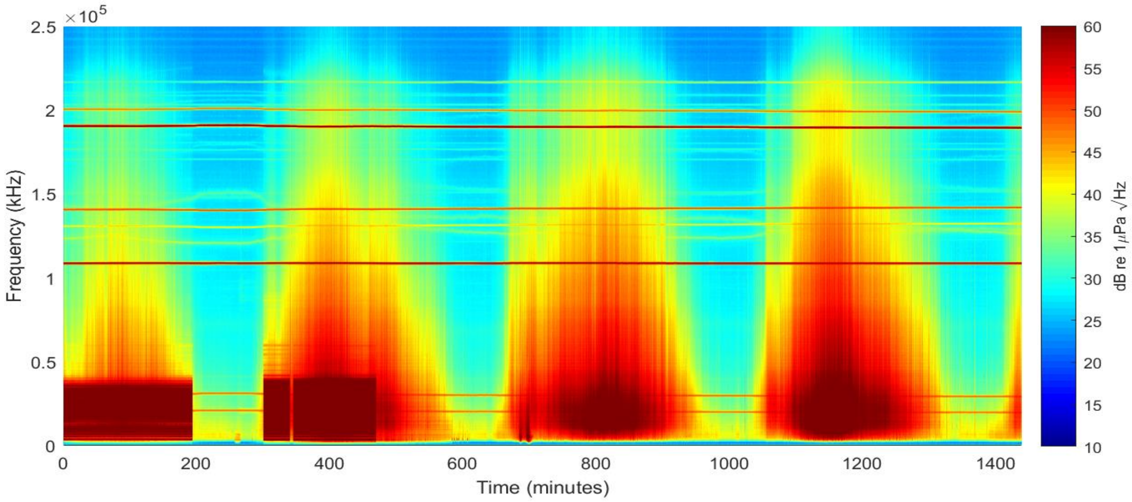

Figure 5. A long term spectral average of four tidal cycles. In the first two cycles the turbine is operational and high levels of low frequency noise below 50 kHz is clearly visible. In the last two tidal cycles the turbine is not operational and noise in the lower frequency band is reduced.

A key output from the PAM data analyses will be the 3D locations of echolocation clicks in relation to the turbine. Echolocation click localisation using the PAMGuard 3D localisers are currently being refined using the data collected and it is expected that 3D locations and tracks of animals will be available for the next annual report. An important aspect of 3D localisation is to calibrate the array by pinging it with a sound source from a known location. Trials to do this will take place in summer 2018 and will improve localisation accuracy.

2.3.2.1 Harbour seal telemetry

Twenty-four harbour seals (Table 1) were caught in the Inner Sound during two field efforts between 26 September and 3 October 2016, and between 2 and 13 April 2017. Capture and handling procedures for the tag attachment are outlined by Sharples *et al*. (2012). Each seal was fitted with a high-resolution UHF/GPS tag so that fine scale movement in relation to the tidal turbines could be interpreted within a wider spatial context providing supporting evidence of potential collision events between the turbines and seals.

UHF/GPS tags attempt record locations whenever a seal surfaced (maximum resolution of every three minutes), and used the Fastloc algorithm (Hazel, 2009) to process and store the GPS data on-board. Each time a seal surfaced, it also attempted to transmit location data from the tag to a series of autonomous archival base stations on shore, using UHF telemetry, when in line-of-sight. Data were manually downloaded from the base stations several times a month. Location data from the seals were cleaned to remove erroneous locations using thresholds of residual error (<25) and the number of satellites (>4) as per Russell *et al*. (2015). Additionally, speed over the ground was calculated between pairs of locations and the second location was removed when the estimated speed over the ground was greater than $7 m.s^{-1}$ (a conservative estimate, given a constant transit speed above this was unlikely when coupled with maximum expected tidal flow rates in the region).

The duration that each GPS tag transmitted data ranged from 19.8 and 146 days (mean = 91.8; SD 40.6) during the first deployment and from 11 and 92 days (mean = 32; SD = 17) during the second deployment. Sampling frequency for the GPS tags remained high throughout the deployment periods with a modal, binned range of time between locations of 3 - 3.5 minutes (Figure 6).

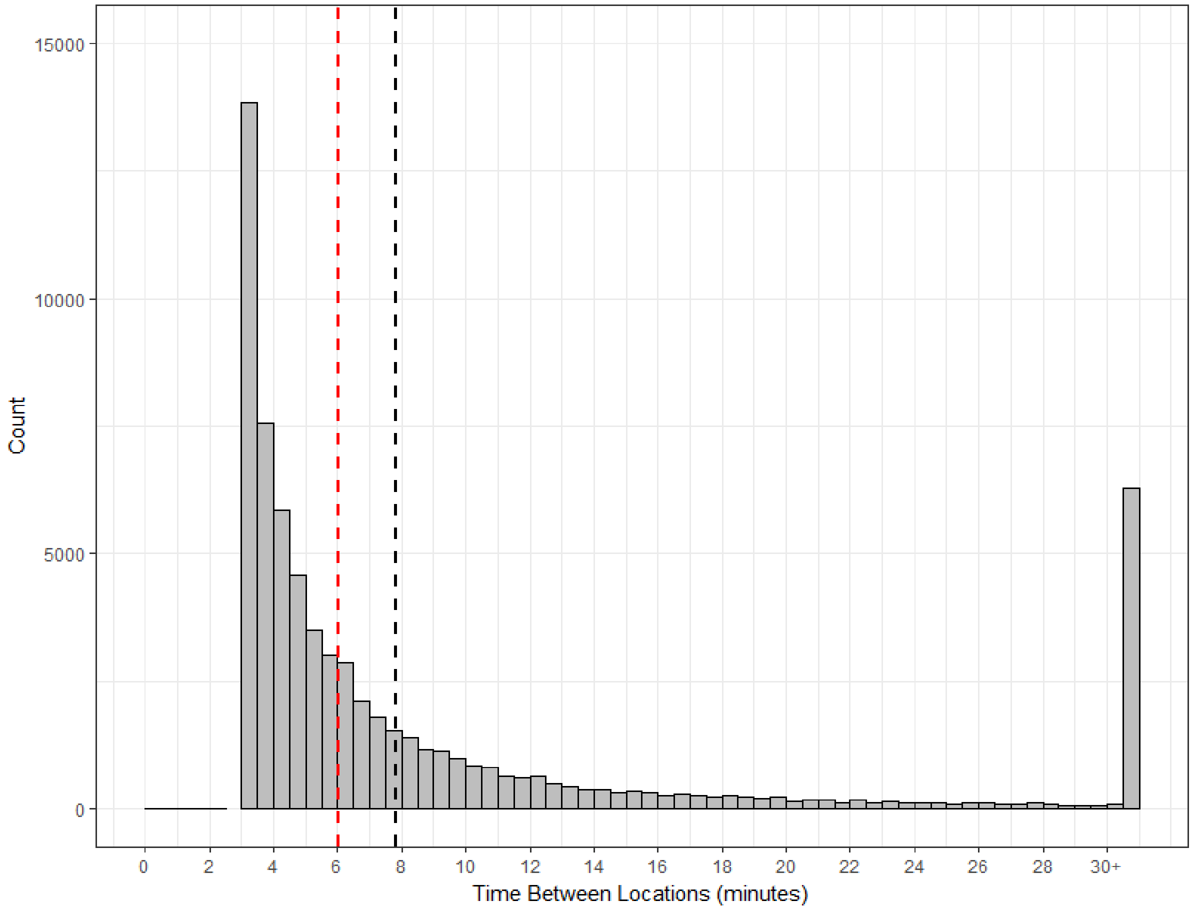

Figure 6. Frequency of time difference between location fixes. The black, dashed, vertical line indicates the mean time between all locations (7.8 minutes). The red, dashed, vertical line indicates the median time between all locations (6 minutes).

Results of the locations of seals in relation to the turbines are summarised for each seal in terms of closest distances between seals and turbines and numbers of locations within 100m of the turbines. Individual movement is reported in terms of the proportion of time spent within the Inner Sound and the MeyGen Lease area using locations regularised to 5-minute intervals.

Further, UHF dive loggers were deployed on each seal to provide high-resolution dive depth information (at 10 second intervals) during each dive. These data are currently being analysed.

Table 2. Capture metrics for all seals tagged in the Pentland Firth in September/October 2016 and April 2017. Note that tags that failed to transmit any data are shown by an asterisk in the UHF/GPS Body Number column.

Tagging Date	Capture Location	Sex	Flipper Tag ID	UHF/GPS tag #	UHF/TDR tag #	Length (cm)	Axial Girth (cm)	Mass (Kg)
28-Sep-16	Brough Bay	M	00593	65254	51031	153	110	89.2
29-Sep-16	Brough Bay	F	00594	65231	51019	110	80	33.6
30-Sep-16	Gills Bay	F	00595	65199	51025	148	110	91.6
30-Sep-16	Scotland's Haven	M	00596	65191	51011	144	110	92.6
01-Oct-16	Scotland's Haven	M	00599	65201	51009	115	104	85.0
01-Oct-16	Scotland's Haven	M	00598	65334	51020	165	116	106.2
01-Oct-16	Scotland's Haven	M	00597	65246	51030	155	96	75.4
01-Oct-16	Scotland's Haven	M	D006	65242	51026	147	116	100.2
02-Oct-16	Scotland's Haven	M	D008	65446	51022	154	115	93.0
02-Oct-16	Scotland's Haven	M	D007	65239	51029	153	114	102.0
02-Apr-17	Ham	M	D112	65257 *	51104	149	108	87.0
02-Apr-17	Ham	M	D113	65500	51120	147	101	81.4
02-Apr-17	Ham	M	D111	65243	51105	151	110	92.6
03-Apr-17	Harrow Harbour	F	D115	65507	51109	147	112	103.4
03-Apr-17	Harrow Harbour	M	D114	65513	51111	137	99	73.6
07-Apr-17	Harrow Harbour	M	00598	65504	51100	159	116	112.0
07-Apr-17	Harrow Harbour	F	D116	65195 *	51101	142	115	103.2
07-Apr-17	Ham	M	D117	65499	51112	156	112	108.0
07-Apr-17	Brough Bay	F	D118	65502	51119	143	121	110.7
08-Apr-17	Harrow Harbour	F	D120	65506	51114	146	109	86.4
08-Apr-17	Ham	M	D119	65505	51116	148	99	74.6
09-Apr-17	Harrow Harbour	F	D121	65496	51115	142	105	88.4
13-Apr-17	Gills Bay	F	D122	65503	51108	146	106	97.6
13-Apr-17	Gills Bay	F	D123	65512 *	51117	135	103	76.0

Of the 24 tags deployed, 21 successfully transmitted data to base stations (Table 2). In total, 115,100 locations were recorded for the tagged seals throughout the two tagging deployments (Figure 7); seals spent a total of 16% (13,783 locations; Table 3) of their time in the Inner Sound (Figure 8). However, a relatively low number of locations (195) were recorded within the MeyGen lease area and only three of the seals were recorded at the surface within 100 m of any of the turbines (Figure 9); the closest surface location to any of the turbines was 35.15 m (Table 3). At present, no information on the operational status of the three Andritz Hydro Hammerfest HS1000 turbines (e.g. pre-installation/post-installation and not rotating/post-installation and rotating) has been made available. Once obtained, this will form the basis of a full analysis of potential distribution changes of seals in response to the turbine array; discussions with MeyGen to get access to these data are on-going.

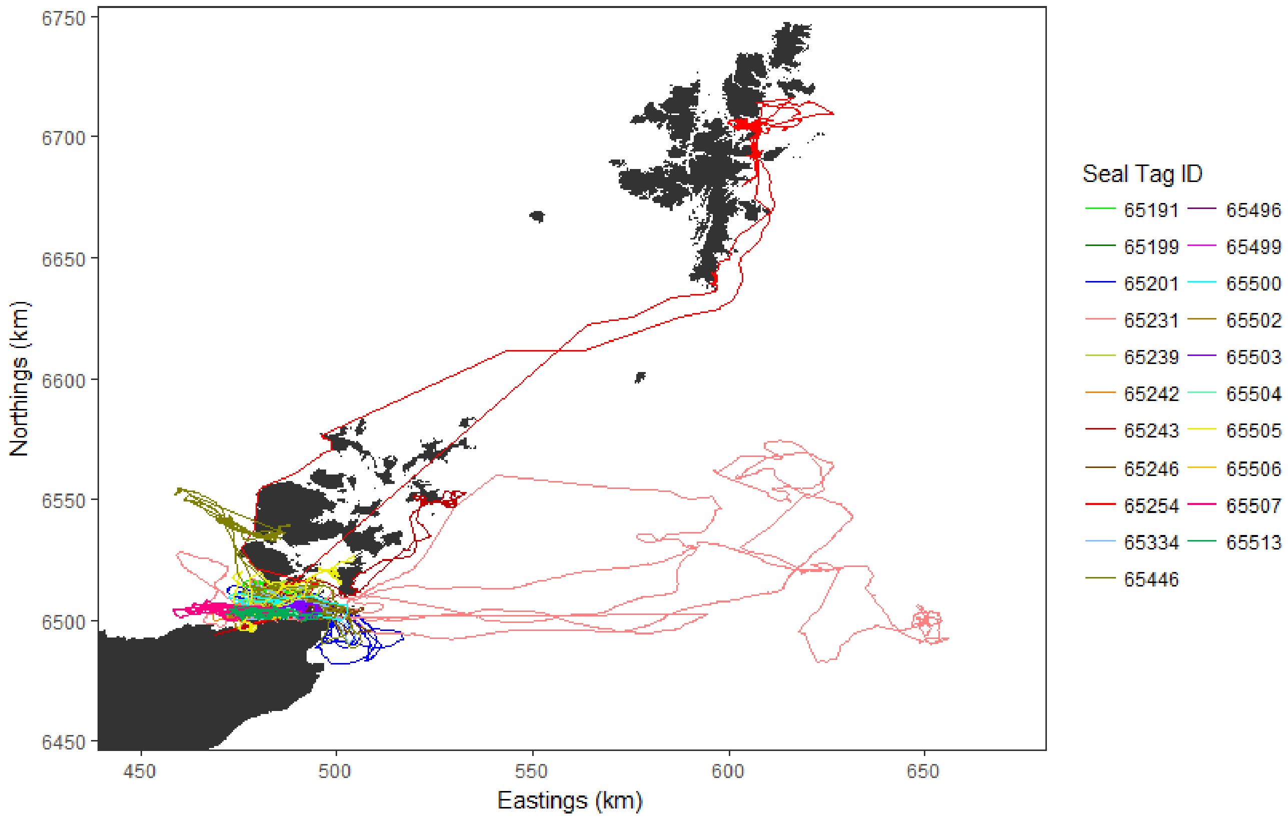

Figure 7. Tracks of 21 seals (14 male, 7 female) tagged with UHF/GPS tags in the Pentland Firth between September 2016 and June 2017; individual tracks have been colour-coded by tag ID. Tracks were linearly interpolated between locations therefore interpretation of fine scale movement should be treated with caution.

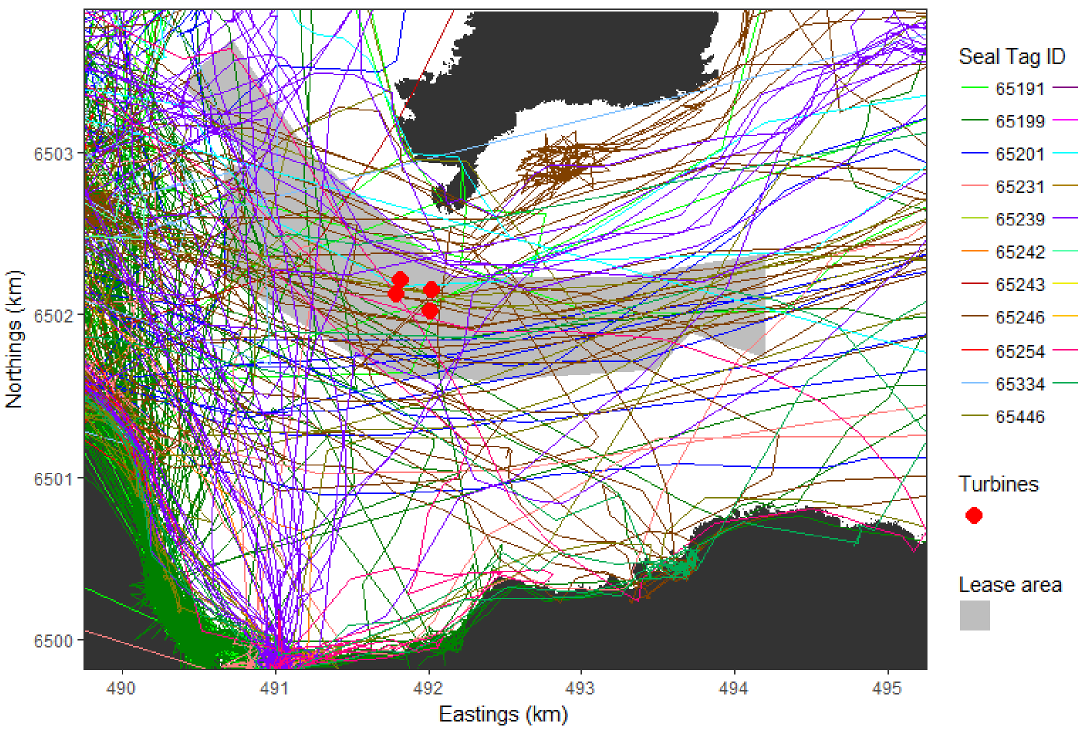

Figure 8. Tracks of 21 seals (14 male, 7 female) tagged with UHF/GPS tags in the Pentland Firth between September 2016 and June 2017 with focus on the Inner Sound with the MeyGen lease area; individual tracks have been colour-coded by tag ID. Tracks were linearly interpolated between locations therefore the ability to determine fine scale movement is limited.

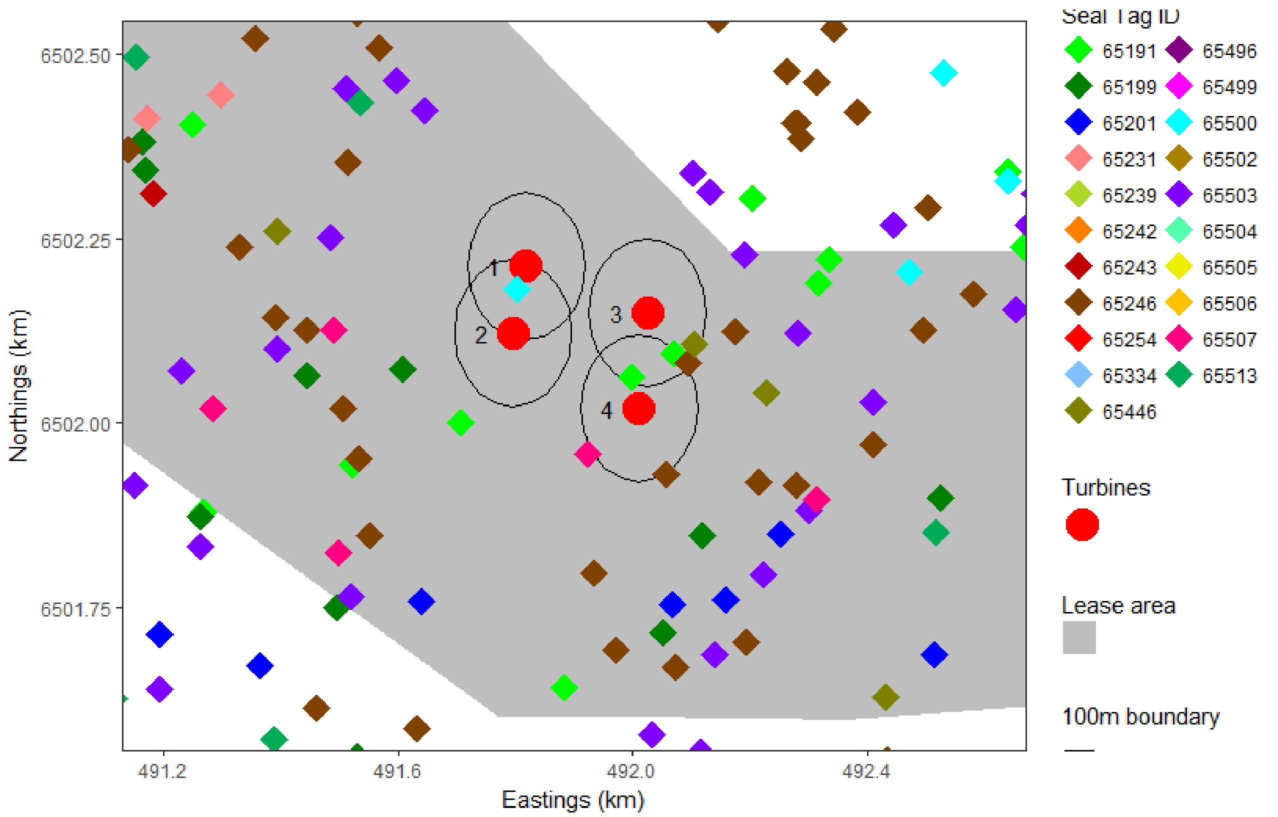

Figure 9. Locations of individual seals from UHF/GPS data collected around the turbine array; individual locations have been colour-coded by tag ID.

Table 3. Summary of the data from 21 seals (14 male, 7 female) tagged with UHF/GPS tags in the Pentland Firth between September 2016 and June 2017.

	Data Summary: UHF/GPS
Number of tagged seals:	21
Total number of locations for all tags:	115100
Number of locations in the Inner Sound for all tags	13783
Percentage of time spent in the Inner Sound for all tags:	16
Number of locations in the lease site for all tags:	195
Percentage of time spent in the lease site for all tags:	<0.01
Number of locations within 100m boundary of each turbine:	4
Number of tagged seals within 100m of each turbine:	3
Closest location distance (m) to the turbines:	35.15
Date/time (GMT) of closest location distance in the report period:	11/04/2017 20:11

Use of acoustic pinger tags (VEMCO V9: 180 kHz; https://vemco.com/products/v9-180-khz/) that can potentially be detected and tracked by the PAM system are currently being considered for deployment as they could allow the construction of 3D tracks of tagged seals around the turbine. These tags have a reported source level of 143 dB re 1µPa @1m and the results of a series of simulations based on the measured background noise levels at the pinger frequency (180 kHz) at the turbine using the PAM system indicates that detection ranges would be relatively low (~20 m) during peak tidal flow. However, field measurements of detection range will be carried out at the Atlantis turbine as part of the PAM tracking validation in summer 2018. Further, potential overlap with the hearing ranges of harbour seals (Cunningham and Reichmuth, 2016) mean that it would be prudent to carry out behavioural response tests to the pinger tags prior to deployment. Should the results of the pinger field tests during the PAM validation tracking show that the pingers can be effectively detected and tracked past the turbine, pinger tests with seals in the captive facility to quantify behavioural responses will be carried out during autumn 2018 to inform their potential future tag deployments.

2.3.3 Deliverable 3: Monthly reports of detections of marine mammals

Routine access to the PAM PC using remote desktop software is carried out at least twice a week to make system operational checks; this includes a check of the software stability, disk space, and that data are being stored to the correct location. Data are also remotely backed up to USB hard drives connected to the PAM PC as required. The critical data collected are binary output files from PAMGuard, which contain information on detected echolocation clicks and whistles, noise level measurements and other diagnostic information. The volume of data varies depending to noise levels, but is generally in the region of two to four Gbytes per day. These data are currently backed up to secure network storage managed by the University of St Andrews and two additional copies are being kept at SMRU on large external hard drives. This work is ongoing and, to date, monthly PAM reports for the period October to December 2017 have been delivered. Further, monthly seal telemetry reports summarising the GPS tag data have been provided for the periods between September 2016 and June 2017.

2.3.4 Deliverable 4: A final report detailing the frequency and nature of the fine scale interactions between marine mammals and an operational tidal turbine

This work will commence after data collection and analysis carried out as part of Deliverables 2 and 3.

2.3.5 Deliverable 5: PhD thesis on the fine scale movements of top predators around a tidal turbine

A PhD studentship (partly funded by Scottish Natural Heritage through the Marine Alliance for Science and Technology Scotland) will utilise data from the sensors to track non-vocal species (e.g. seals and diving birds) to investigate: a) how these animals utilise tidal areas, and b) how they behave in relation to an operating tidal turbine. The studentship also utilises data from the animal-borne GPS tags deployed on harbour seals to measure the movements of seals around a tidal turbine at a broad spatial scale (tens – hundreds of metres). High-resolution 3D tracks of seals in close vicinity to an operating turbine will be constructed using information from animal-borne UHF/dive loggers and, potentially, acoustic tags in combination with the passive and active acoustic sensors. Data on the interactions of seabirds underwater may also be available from the active sonar sensors, as well as from telemetry.

The project will build on previous research on the movements of seabirds in relation to marine renewable energy installations, and will investigate how seabirds use a high velocity current tidal channel. The research will also include shore-based observations as background to any high-resolution tracking information for seabirds.

2.4 Future tasks

- A number of field trials are required to validate 3D localisation accuracy of the PAM system for dolphin and porpoise clicks. It is proposed that a drifting experiment is carried out at the turbine location to ping the PAM system with porpoise and dolphin like sounds. This could be done from a small work vessel drifting past the turbine at a series of ranges during different operational states. This activity is currently being planned in close consultation with Atlantis/MeyGen.
- Development of a final report detailing the analysis of up to 12 months of data on the frequency and nature of the fine scale interactions between marine mammals and an operational tidal turbine, including recommendations on monitoring equipment and protocols for the future detection and tracking of marine mammals around tidal turbines.
- A third harbour seal tagging trip is planned for April 2018 during which up to 20 seals will be tagged with UHF/GPS and UHF dive loggers as described above.

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4 Appendix A: MeyGen PAM data collection system

The Passive Acoustic Monitoring (PAM) data collection system installed on the Atlantis turbine comprises twelve high frequency hydrophones installed in three tetrahedral clusters, one on each leg of the Turbine Support Structure (TSS). These are connected via analog data cables to the TSS Junction box (TSSJB) which contains signal conditioning amplifiers, digitizing electronics and network connection to shore. On shore, the digitized signals are processed in real time using the PAMGuard software (Gillespie *et al*., 2008; www.pamguard.org) which automatically detects sounds of interest and makes diagnostic noise measurements before discarding the raw data that would be impractical to store, requiring approximate one terabyte of storage per day.

Here, the hardware and software configurations are described up to the point that data are delivered to St Andrews for detailed final analysis.

4.1 Hardware

4.1.1 Hydrophones

The hydrophones are comprised of a 10 mm spherical ceramic (ST HF SR10 from Shenzhen Yujie Electronics Co, http://www.szyujie.com/en/). These were potted in polyurethane (ALH-Systems NP14-80) and mounted on a stainless steel/machined plastic mounting so that each cluster of four hydrophones was in a tetrahedral configuration with 15 cm spacing between hydrophone centres. The 15 cm spacing is equivalent to an inter-hydrophone travel time of approximately 0.1 ms with a nominal sound speed of 1500 m/s. Individual ceramics were calibrated against a Reson TC4013 reference hydrophone and determined to have sensitivities of -210 dB re 1V/Pa. Each ceramic was connected via a short coaxial cable to a custom preamplifier with a gain of 30 dB, mounted and potted in clear epoxy (Robnoe Resisns RX771C), in a box close to the ceramics. Data cables to the TSS JB were also potted into the same box to avoid the need for additional underwater connectors (Figure 10 a).

Each hydrophone cluster was mounted on a flat polythene base and covered with a 50 cm diameter polythene cowling in order to protect the hydrophone elements from damage in the harsh environment of a highly turbulent tidal flow. The polythene bases were bolted to mounting plates clamped to the TSS (Figure 10 b).

a 

b 

Figure 10. a. Assembled hydrophone clusters with potted hydrophones and data cables, b. the hydrophone cowling and mounting plate attached to a leg of the TSS.

Analog data cables from the three hydrophone clusters connected to a sealed junction box (the TSSJB), also permanently mounted to the TSS. The junction box is connected to the turbine infrastructure via an ROV mateable connector from where it receives 48 V DC power from a power supply in the turbine Nacelle. The cable also carries copper gigabit ethernet that converts to optical fibre within the turbine structure and connects the system to shore.

Inside the TSSJB, additional signal conditioning amplifiers (model 150410A, Etec aps. Denmark) high pass filter the data (second order 5 kHz) and provide an additional gain of 20 dB before the signals are digitised using three National Instruments NI222 modules in a CRio 9067 chassis. Custom software developed for the CRio simultaneously sample all twelve channels at a rate of 500 kHz, compress the data using lossless compression algorithms described in Johnson *et al*. (2013) and used the TCP network transfer protocol to transmit the data to a computer installed in the onshore control station.

4.2 Onshore Processing

The shore side PC runs the PAMGuard software (Beta version 2.00.11) configured to detect a wide variety of marine mammal sounds, and also to make diagnostic noise measurements and some sound recordings. In particular, the software was configured with the modules described below.

4.2.1 Sound Acquisition

A custom sound acquisition module was developed which communicates with and controls the NI CRio chassis in the TSSJB. As data arrive they are uncompressed and passed on to downstream PAMGuard modules. The acquisition module timestamps data based on the PC clock, which is configured to update regularly from a time server, and keeps a count of the total number of samples acquired from the Crio system. These times and sample numbers are stored every minute into a database.

4.2.2 Click Detector

The click detector was configured to detect high frequency echolocation clicks from porpoises and dolphins. Harbour porpoises produce only narrow band clicks with energy between 100 and 150 kHz (e.g. Møhl and Andersen, 1973; Goodson and Sturtivant, 1996). Dolphins produce broadband clicks with energy between 10's of kHz to over 100 kHz (Au, 1993). Due to significant tonal noise interference from the turbine at a frequency of 20 kHz, the click detector was initially configured to only trigger on sounds with significant energy between 40 and 150 kHz. From Commissioning in October 2017 until 31 January 2018, the trigger filter used a second order Butterworth filter. From 31 January 2018 this was changed to a fourth order filter to further reduce the interfering effects of the 20 kHz noise. To reduce processing load, the detection algorithm only uses data from the topmost hydrophone in each cluster for triggering. When a trigger event occurs, data from all four hydrophones are read and stored from 0.2 ms before to 0.2 ms after the trigger to ensure that the signal was captured on all four hydrophone channels in each cluster. Time delays between the arrival of each signal on each of the hydrophones are then calculated and a pointing vector to the sound source calculated. As well as detected clicks, the click detector also outputs the signal level within the trigger system every second to provide an assessment of background noise levels within the click detection system.

4.2.3 High Frequency Spectrum and Long Term Spectral Average

For diagnostic purposes, a high frequency spectrogram is calculated on a sub sample of the 500 kHz data. A 1024 sample (2 ms) block of data is taken every 20480 samples (41 ms) and a scrolling spectrogram of these data displayed. A Long Term Spectral Average (LTSA), which is the average power over multiple samples of the high frequency spectrum, was calculated and stored every 6 s.

4.2.4 Octave Band Noise Measurement

Root Mean Square (RMS) noise measurements were calculated and stored every 10 s for Octave wide frequency bands centred at 2, 4, 8, 16, 32, 64 and 128 kHz. Filters for each octave band were fifth order Butterworth which is compliant with the ANSI Specification for octave-band and fractional-octave band analog and digital filters (ANSI, 2004). Noise levels were only computed for the topmost hydrophone in each cluster.

4.2.5 High Frequency sound Recorder

The high frequency sound recorder can store data continuously or on a pre-programmed cycle into 12 channel wav files. New files are started automatically when they reach a predetermined size. For the first month of operation, recordings were made continuously for fine-tuning of the automatic detectors. It was then changed to make a 10 s long recording every hour.

4.2.6 User Input

A simple module which allows the operator to type in time stamped comments.

4.2.7 Decimator

A decimator is used to sub sample the high frequency data to a lower sample rate of 48 kHz to allow processing for whistles, audio output and recording of lower frequency data. High frequency data are filtered with a 6 pole Butterworth filter with a cut off frequency of 24 kHz prior to sub sampling.

4.2.8 Mid Frequency Spectrogram

A spectrogram was calculated for all 12 channels of the 48 kHz decimated data using an FFT length of 512 samples (10.7 ms) with a 50 % overlap and a Hann window function.

4.2.9 Whistle and Moan Detector

The whistle and moan detector takes output from the mid Frequency Spectrogram and searches for whistles using the algorithms described in Gillespie *et al*. (2013). Detection takes place only on the topmost hydrophone in each cluster. When whistles are detected, phase information from all four hydrophones in each cluster is used to estimate time of arrival differences of the signal on each hydrophone and to calculate a pointing vector towards the sound source.

4.2.10 Mid Frequency Sound Recorder

The mid frequency sound recorder takes output from the decimator and makes 12 channel WAV file recordings to disk. This has been operating continuously since continuous recording of high frequency ended after the first month of operation.

4.2.11 Binary File Storage

Output from the click detector (both detected clicks and noise measurements), the whistle and moan detector, the LTSA and octave noise band measurements are written to binary storage files. A new file for each output data stream is started each hour or if files exceed 30 Mbytes in size.

4.2.12 Database

An SQLite database stores data from comments typed into the PAMGuard user interface by operators and timing information from the Sound Acquisition Module.

4.2.13 Displays

PAMGuard was configured with a number of displays, which during data collection are primarily for diagnostic and quality control purposes. The click detector shows a display of estimated bearings to detected clicks and the waveforms and power spectra of individual detected clicks as well as an indication of noise within the trigger system. Outputs of the mid and high frequency spectrograms and the LTSA are displayed in scrolling 12 channel spectrogram displays. The noise band monitor also displays levels on a scrolling display and the two sound recorders and user input all have display panels for operational status and data input.

4.3 Monitoring

Watchdog software (known as PAMDog) runs on the PC to ensure continuous PAMGuard operation. The PC is configured to boot automatically when powered and will start the watchdog software automatically. The watchdog software attempts to communicate with PAMGuard and if it cannot, it automatically launches PAMGuard and starts data acquisition. Once running, every few seconds the watchdog checks PAMGuard status and resets it if necessary.

The system is monitored remotely via the Internet using Goggle Remote Desktop software. Generally, the system is checked three times a week. Data, which are initially written to internal hard drives are regularly (at least twice a week) copied to external hard drives which are posted back to St Andrews every few weeks since there is insufficient Internet bandwidth for direct downloading of the data. Once securely backed up in St Andrews data can be deleted from the data acquisition PC.

5 Appendix B: Offline Data Processing

Data returned to St Andrews are processed in order to classify individual porpoise like clicks and to search for sequences of dolphin and porpoise clicks representative of animals moving close to the turbine.

5.1 Automatic Processing

Data are first processed automatically to re-estimate pointing vectors (bearings) and to detected sounds without using the noisy channel 6 data.

A species classifier is then run on the click data to identify candidate porpoise clicks. A number of measurements are taken from the click waveforms and power spectra and clicks are defined as porpoise if they satisfy the following criteria:

1. A length between 20 and 220 ms.
2. Energy in a 100 – 150 kHz frequency band that is ≥ 6 dB more than the energy in two control bands (40 – 90 kHz and 160 – 190 kHz).
3. A peak frequency between 100 and 150 Hz.

No attempt has been made so far to automatically detect dolphin clicks since at present these are too easily confused with impulsive noises from the turbine.

5.2 Manual Processing

Once the automatic processing has been completed, data are manually audited to pick out porpoise and dolphin events.

The operator scrolls through the data, generally viewing two minutes of data at a time with one display showing click bearing vs time and another showing click amplitude vs. time. Each click is represented by a small circle for unclassified clicks or as a triangle for porpoise clicks. The operator can chose to colour the clicks by hydrophone cluster or by classification type. If individual clicks are selected on either of the time displays, the waveform, power spectra and Wigner (frequency-time) plot of the individual click is displayed (Figure 11).

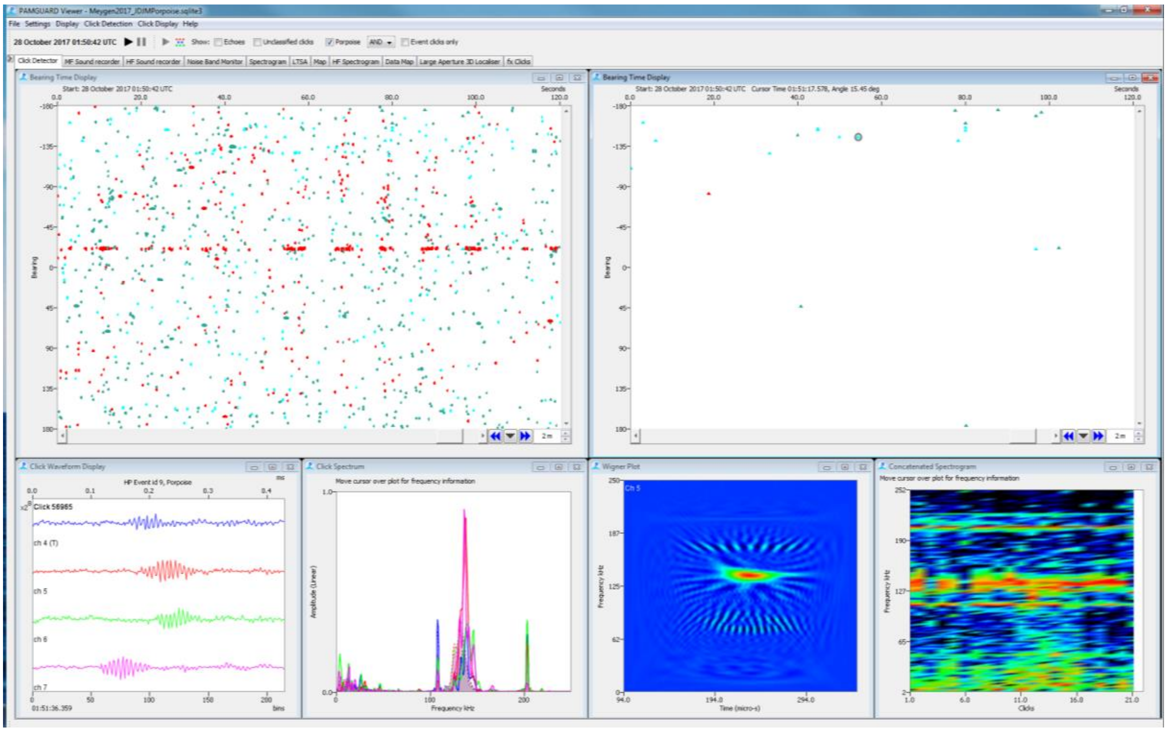

Figure 11. PAMGuard analysis display. The two larger top windows show the bearing and amplitude of clicks plotted against time over a 2 minute period. The smaller lower plots show the waveform, power spectrum and Wigner plot of individual clicks and a concatenated spectrum of all clicks manually assigned to an "event".

The operator identifies porpoise and dolphin events by visually searching for sequences of clicks on a consistent bearing. Click sequences are marked by the operator and the details of individual clicks in a sequence are written to the database. The operator assigns a species based on the classification of individual clicks within the event and their view of the clicks waveforms and spectra.

5.3 Localisation and track parameterisation

Clicks within identified events are localised using the 3D localisation algorithms described in (Macaulay *et al.*, 2017). Assessing the accuracy of these localisations and developing methods to link the localisations of individual clicks into tracks that can be geo-referenced to the position of the turbine are underway.

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