Summary of workshop: Passive acoustic monitoring in high flow environments

May 15, 2020

Prepared by:
European Marine Energy Centre (EMEC) Ltd

Prepared for:
Offshore Energy Research Association (OERA)
Fundy Ocean Research Center for Energy (FORCE)

Summary of workshop: Passive acoustic monitoring in high flow environments

1. BACKGROUND

The Offshore Energy Research Association (OERA) has a mandate to enable sustainable development of Nova Scotia's energy resources by facilitating and funding collaborative research and development. It has supported numerous tidal energy R&D projects over the years and is now leading the Pathway Program in collaboration with the Fundy Ocean Research Center for Energy (FORCE) with funding from Natural Resources Canada (NRCan) and Nova Scotia Department of Energy and Mines (DEM). The Pathway Program is a coordinated R&D program that will define, test, and validate environmental effects monitoring (EEM) solutions for the instream tidal energy industry to meet regulatory requirements. The program will increase the understanding of environmental impacts from instream tidal energy projects in the Bay of Fundy and improve the understanding of fish and marine mammal interaction with instream tidal energy devices. The program will also improve data processing and analyses, so that results can be reported to regulators and disseminated to the public in a timely manner.

The main objectives of the program are to:

i) define a Department of Fisheries and Oceans Canada (DFO) approved solution for the tidal energy industry,
ii) apply machine learning to data analysis to reduce reporting time and compliance costs,
iii) minimize initial capital costs to developers,
iv) develop regional capability to manage, process, analyze and report EEM data, and
v) develop intellectual property that regional companies can exploit commercially in multiple marine industries, both regionally and globally.

To conduct this program successfully, OERA and FORCE are assessing different types of monitoring technology that can gather robust data to inform regulatory requirements. To complete this assessment, OERA and FORCE are consulting with experts through a series of workshops to gather information on the effectiveness of different technology in high-flow environments to collect the required monitoring data.

The third workshop under the Pathway Program was focused on "Passive acoustic monitoring in high flow environments" and was the first international workshop within the program. The Pathway Program contracted the European Marine Energy Centre (EMEC) to facilitate the workshop development, delivery, and information-gathering. This report summarizes the outcomes of the workshop discussion and any insights gathered during the workshop that will support the successful delivery of the Pathway Program. The workshop was held as a virtual workshop on April 30, 2020.

2. WORKSHOP FOCUS

Instream tidal turbine projects, in Nova Scotia and elsewhere, have an environmental stewardship obligation to both the local community and regulatory bodies to gain an understanding of the potential environmental impacts associated with deploying and operating their novel technology. This is achieved by undertaking environmental monitoring activities around projects to further understanding of potential interactions and behavioural effects on marine mammals and fish or the potential for permanent alteration to habitats. This is critically important in ecologically sensitive and culturally significant areas like the Bay of Fundy.

Passive acoustic monitoring (PAM) plays a vital role in the suite of environmental monitoring options available to researchers, developers and regulators. PAM provides the capacity to monitor the vocal activity of a range of species, as well as to measure the levels of anthropogenic noise introduced into the marine environment in association with the installation, operation and decommissioning of tidal turbine projects. Many of the vocalising species (in particular certain marine mammals) which PAM can be used to detect are protected under various legislation[1] and are therefore both a concern to regulators, and a potential roadblock to permitting for developers.

Unfortunately, there are difficulties associated with the use of PAM for environmental monitoring in high flow environments, as well as those which are inherent to the use of PAM technology in any setting, which must be overcome. The difficulties associated with PAM around instream tidal turbines have been well described, and include issues resulting from flow noise and high ambient noise levels (e.g. from sediment transport and turbulence). This can result in a reduction in signal-to-noise ratios and potentially overwhelm automated detectors. The high data densities associated with full bandwidth recordings, which increase demands on data storage and processing times, are common to all PAM applications.

Additional challenges are posed when deploying PAM instrumentation alongside other environmental monitoring equipment (e.g. echosounders, imaging sonars, ADCPs). This can result in the contamination of recordings with the sounds produced by other acoustic devices which can mask, or be mistaken for, biological signals of interest. The introduction of unwanted noise (i.e. any noise other than from the turbine itself or the background ambient) into recordings for the measurement of turbine noise can also make accurate noise characterisation problematic. In recognition of these issues, due consideration must be given to, for example, appropriate duty cycling schedules and the suitability of automated triggers for event detection.

The purpose of the workshop was to present recent work involving the use of PAM in tidal stream environments, to stimulate discussions and knowledge sharing regarding the key issues relating

[1] For example, harbor porpoises are protected under the Marine Mammal Protection Act in the United States, the Species at Risk Act and Fisheries Act in Canada, and the Habitats Directive and Marine Strategy Framework Directive in Europe.

to PAM capabilities when deployed in high energy environments, and relating to deployment of PAM on integrated monitoring platforms.

Presentations were provided by speakers from a variety of universities and research institutions, describing their most recent advances and applications of PAM methods in a range of tidal stream environments, followed by questions and a short discussion. The primary objective of the workshop was to share information about the work being conducted on PAM as part of the Pathway Program and elsewhere in the world, and to facilitate the formation of future collaborations and knowledge sharing between researchers and other key stakeholders.

3. WORKSHOP FORMAT

The workshop was originally planned to be held as a side event at the Environmental Interactions of Marine Renewables (EIMR) 2020 conference in Oban, Scotland and attended in person. Due to the global coronavirus pandemic, the workshop was held as an online 'virtual' workshop on 30 April 2020, using the Microsoft Teams platform. The workshop was facilitated by EMEC (specifically Elaine Buck, Technical Manager, and Joshua Lawrence, Acoustic Engineer), on behalf of OERA and the Pathway Program. It was a closed workshop, with invitations issued to individuals from a diverse range of backgrounds, including academic institutions, regulatory and advisory bodies, tidal energy developers, independent research centers, and environmental consultancies. Following introductions to the workshop from EMEC and to the Pathway Program from Dan Hasselman (FORCE) and Luiz Faria (OERA), five invited speakers presented their work on the applications of PAM in high energy tidal flow environments. The presenters were:

- Jason Wood (SMRU Consulting North America)
- Michael Adams and Brian Sanderson (both of Acadia University)
- Joanna Sarnocinska (University of Southern Denmark)
- Chloe Malinka (Aarhus University)
- Douglas Gillespie (University of St Andrews)

Presentations were followed by questions, when time permitted, and, following the final presentation, a more general discussion regarding broader points and concepts that had been covered during the presentations took place. In total, 44 people attended the workshop. A list of participants can be found in Appendix A.

4. SUMMARY OF DISCUSSION

4.1 Introduction to the Pathway Program (Dan Hasselman, FORCE, and Luiz Faria, OERA)

OERA is an independent, non-profit organization working to promote the sustainable development of the energy sector in Nova Scotia. FORCE, established in 2009, is Canada's leading research centre for the demonstration of tidal power, fulfilling a role of environmental stewardship by running monitoring programmes for fish, birds, lobster, marine sound, and marine mammals, and primarily, serving as a host site for developing tidal energy technologies. Together, OERA and FORCE are leading the Pathway Program, a coordinated program which has been developed to define, test and validate a monitoring solution for tidal energy developments with the approval and acceptance of the local regulatory body, the Department of Fisheries and Oceans Canada (DFO) (Figure 1). The overarching goal of the program is to reduce operating expenses and to provide expedited and timely reporting to regulators.

The Pathway Program has three clearly defined phases:

1) Global capability assessment: this phase involves the process of reaching out to subject matter experts to gain an understanding of the breadth of the expertise across the network, and to provide a series of reports and webinars with recommendations regarding appropriate sensor technology. In addition, this phase includes the continuing engagement with global experts and regulators through consultations, as well as through a series of workshops (of which this workshop is a part) to foster ongoing collaborations and knowledge sharing.
2) Data processing and analysis: the second phase of the program will aim to reduce the time taken from the collection of environmental data to the production of reports for regulators and other relevant stakeholders, primarily through advances in the automation of data processing and reporting. Dalhousie University and the DeepSense team have made good progress on the automation of the processing of echosounder data, and is in the process of automating the reporting process. There has also been progress towards the development of automated detectors and classifiers for PAM data, and the automation of analyses and report generation. Future work is planned for a similar process for imaging sonar datasets, building on the methods developed at the University of Washington and the University of the Highlands and Islands.
3) Technology validation phase: the final phase of the program will be a series of experimental deployments of a range of environmental monitoring instruments (e.g. PAM devices and echosounders). Using an iterative approach, alongside ongoing consultation with international experts and feedback from regulators, a robust study design will be developed. Ultimately, this final phase of the project will conclude with the integration of the various technologies into a single, regulator-approved, environmental monitoring platform.

Figure 1. A Gantt chart summarising the activities associated with each stage of the Pathway Program

4.2 Harbor porpoise monitoring at FORCE (Jason Wood, SMRU Consulting North America)

As part of FORCE's environmental effects monitoring plan (EEMP), passive acoustic monitoring has been conducted at the FORCE site in Minas Passage, Nova Scotia, since 2011. The aims of these deployments were to understand the use of this area by harbor porpoises, and to establish the impacts of the operational Open Hydro tidal turbine on porpoise distributions. Primarily, the aim was to detect a permanent avoidance of the mid-field (100-1000 m) or a major change in the distribution or activity of porpoises across the site, if present.

Since 2011, between three and eight Chelonia C-PODs were deployed using a gradient survey design to collect baseline data on porpoise distributions and space use. In addition, since 2016, five C-PODs have been deployed as part of the FORCE EEMP around installed turbines, two of which were within 203 m of the deployed turbine location. Data was collected over a total of 6519 C-PODs monitoring days, with more than 2350 of those days collected prior to the turbine installation, with varying but improving spatiotemporal coverage (although the winter period received the lowest coverage).

Harbor porpoises were detected on 98.8% of days, with a mean of eight detection positive minutes per day, and a 7% probability of a porpoise detection occurring in any given 10 minutes monitoring period. When used to account for issues with autocorrelation within the data, a GAM-GEE modelling framework revealed that there were clear trends associated with the annual, lunar, tidal, and diel cycles, with peaks in porpoise detection rates occurring in June and

November, during neap tides, at low current speeds particularly on the ebb tide, and at night (Figure 2).

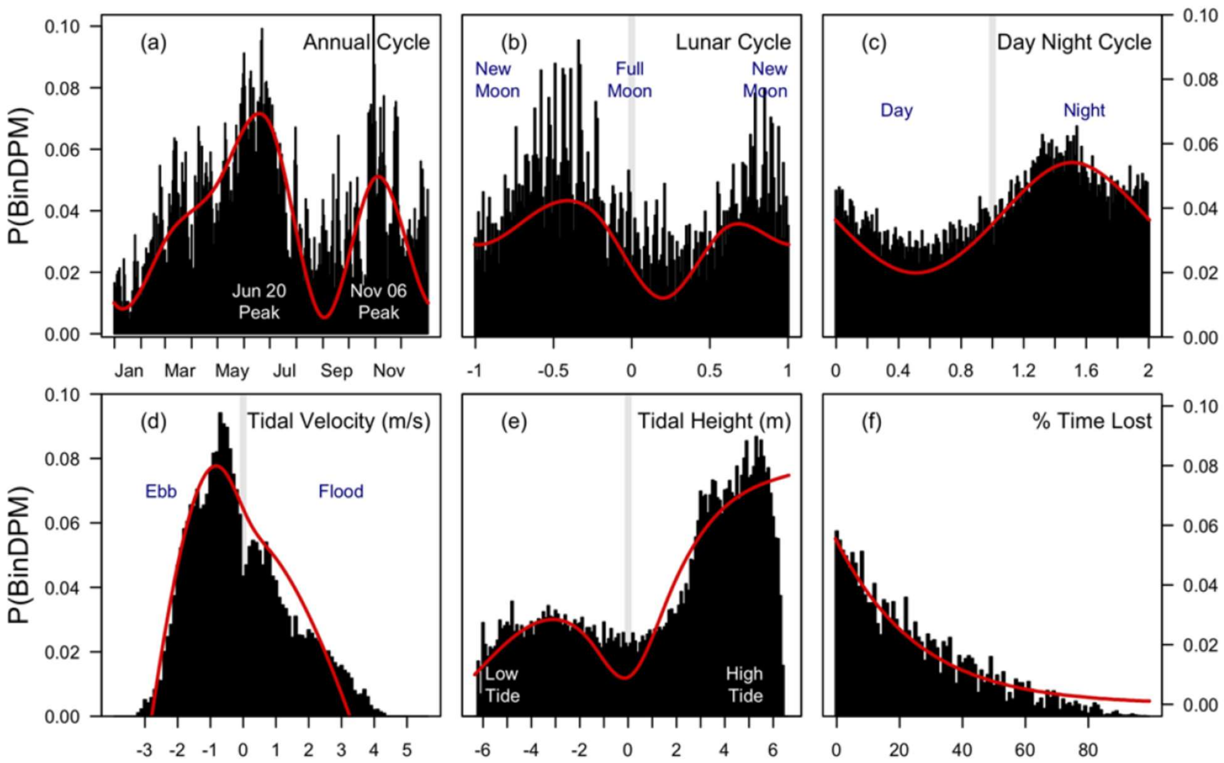


Figure 2. Fitted trends from GAM-GEE modelling of predicted porpoise detection positive minutes (DPM) vs temporal and tidal covariates (a-e) and proportion monitoring time lost (f).

One consideration that must be given to the use of C-PODs in high flow environments is that the relatively high ambient noise levels impose certain limitations on their effectiveness. High ambient noise levels mean detection ranges will be relatively small, and as flow speeds (and the associated ambient noise) increases, the amount of monitoring time lost also increases due to the inundation of the systems rolling memory buffer.

Despite the test dataset (the monitoring time when the turbines were operational) being small relative to the baseline, the study revealed a significant reduction in porpoise click activity at both monitoring sites within 230 m of the turbines, when the turbines were operational. It was also found that porpoise click activity levels at these sites returned quickly to the pre-installation baseline when the turbine was non-operational (but present), and post-decommissioning. It was noted, however, that a larger dataset with longer-term monitoring during turbine operations would provide more certainty around the nature of the observed avoidance behaviour.

A second study occurring at the FORCE site was the comparison of PAM devices deployed simultaneously on a seabed monitoring platform. The devices included on the platform (otherwise known as lander) were:

- a JASCO AMAR G4,
- an Ocean Sonics icListen HF,
- an Ocean Instruments SoundTrap ST300 HF, and
- a Chelonia C-POD and F-POD.

These were used to record artificial porpoise echolocation clicks, transmitted from an Ocean Sonics icTalk, as well as real clicks from any opportunistic encounters with actual harbor porpoises, so that the relative detection rates of the each system, along with other metrics (false positives), could be compared. It was highlighted that the differences in orientation on the lander, as well as the protection from flow noise each unit offers (various hydrophones on the AMAR G4 were installed with different styles of flow shields; differing densities of foam, a 'sock'), may have an impact on the detection rates of each sensor. An additional issue which complicated the analysis of these datasets was that the low source level of the icTalk-generated clicks (130 cf. 165-170 dB re. 1 µPa for the biological equivalent (Villadsgaard *et al*., 2007)[2]) necessitating the use of a low detection threshold (6 dB), and detection range was relatively low (median ~50 m).

The 'gold standard' human annotated detections from the AMAR dataset yielded ~7000 artificial porpoise clicks. Of the recorder units and detectors used, the icListen recorded the highest number of true positives (~3000), but this came at the cost of an overwhelming number of false positives (~17000). The data processing and analysis of detections of real porpoises (recorded as detection positive minutes) is ongoing; however, it has been found that although the number of detections made by the C-PODs and F-PODs were lower, the number of false positives they generated was lower, by approximately two orders of magnitude, than the number produced by the AMAR dataset.

As such, a characteristic of C-PODs, which has sometimes been heralded as a limitation (their lower detection sensitivities/rates), could be taken as an advantage in a situation where controlling the number of false positives is important. There are, however, genuine limitations with the use of C-PODs, including the lack of ambient noise level monitoring, limited detection range, lost time due to the memory buffer, and the 'black-box' nature of the detectors and classifiers used. The alternative, therefore, is to use full bandwidth continuous recordings. This is a more expensive option however, in terms of both equipment and analysis, and is still limited by the range over which detections can be made. Drifting units can be used to overcome the latter issue to provide broader spatial coverage, and to better understand the limitations of a static system.

[2] Villadsgaard, A., Wahlberg, M. and Tougaard, J., 2007. Echolocation signals of wild harbour porpoises, *Phocoena phocoena*. *Journal of Experimental Biology*, 210(1), pp.56-64.

4.3 Harbor porpoise monitoring in Minas Passage using moored and drifting hydrophones (CPODs and icListenHF) & discussion of 'Coda' and Lucy software (Mike Adams and Brian Sanderson, Acadia University)

Passive acoustic monitoring surveys were conducted in Minas Passage using a custom drifter design to minimise the influence of flow noise (due to relative motion between the hydrophone element and the water surrounding it) on recordings. These consisted of a pole float and GPS logger on the water surface (with low cross sectional buoyancy to minimise heave), supporting a line carrying two C-PODs, two icListenHF recorders, and two Vemco VR2W receivers, terminated with lead weight to keep the system vertical and to maintain inertial stability (Figure 3). Drifters were released to drift passively through Minas Passage past the FORCE tidal test site on both flood and ebb tides, both collecting records of porpoise encounters (via C-PODs) and making full bandwidth recordings (using the icListenHFs). Full recordings were processed using 'Coda', a new matched filter-based detector classifier, to identify porpoise clicks and encounters.

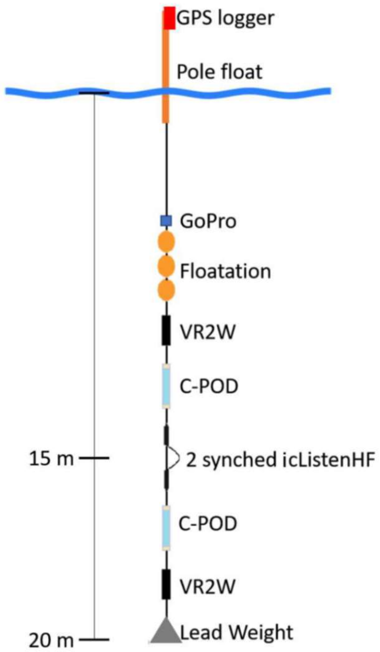


Figure 3. Schematic of drifter design

The drifter design is used to minimise pseudo-sound; C-PODs deployed in subsea floats are known to be vulnerable to losing monitoring time, due to the increases in ambient sound levels, signal distortion, and pseudo-sound associated with increasing current speeds. The latter being linked to mooring designs which are inappropriate for high flow environments. Indeed, even when deployed on a stable drifter, C-PODs were subject to 'lost time' when current speeds exceeded 1.5 ms^{-1}, although the mitigation offered by the drifter meant that less than 50% of monitoring minutes experienced 'lost time' when current speeds were 3-3.5 ms^{-1}. This was a large reduction relative to moored C-PODs. This highlighted the importance of addressing mooring instability and the selection of an appropriate deployment configuration prior to the commencement of monitoring.

The Coda detector applied to the icListenHF recordings identified many more detection positive minutes (DPM) than the C-PODs, even following the use of additional more stringent filters (Table 1). These filters were deemed effective following a semi-automated review of the clicks they identified, during which some clicks were added/discarded but DPM was unaffected. There was, however, good overlap between the C-POD and the Coda DPM data, although the C-POD detectors occasionally produced false positives from the misidentification of signals such as an echosounder or fish tags. Therefore, C-PODs could be considered an effective means of monitoring over large spatiotemporal scales.

Symbol	Detection Method	# DPM
C_{POD}	C-POD	81
—	icListenHF	—
D_{CI}	icListenHF & Coda	1269
F_{CI}	Filter & icListenHF & Coda	354
A_{CI}	Alternate-Filter & icListenHF & Coda	586

Table 1. Detection positive minutes (DPM) from different detection hardware/algorithm combinations.

Porpoise clicks identified with a Coda-like detector-classifier from acoustic data collected by multiple synchronised icListenHF units deployed on the same drifter were used, along with a custom localisation suite, to produce an estimate of range and bearing (and estimates of associated error) to the source of the click, i.e. the echolocating animal. This served to demonstrate that a synchronised hydrophone array, along with effective processing and localisation software, could provide data on near-turbine movement tracks and behaviours of harbor porpoises in high energy tidal environments.

In conclusion, it is essential that the overall context in which PAM is utilised is considered. PAM is never deployed in a vacuum; the environments in which it is used (particularly in tidal energy applications) are noisy, and often other devices, e.g. ADCPs, which are present provide additional challenges. It can also be difficult to assess the differences between a selection of data processing and analysis packages (e.g. Coda vs Lucy vs PAMGuard), because of variations in their implementation rendering like-for-like comparisons impossible. It can be noted however, that in all applications the instruments, deployment methodology, and the hydrodynamic environment must be considered. There also must be caution in the drive towards fully-automated data processing using machine learning algorithms and other artificial intelligence applications; they should not be seen as a replacement for more traditional methods, such as matched filtering, or other manual or semi-automated methods.

4.4 Relative performance of different PAM technologies and click detectors/classifiers (Joanna Sarnocinska, University of Southern Denmark)

A study was conducted comparing the relative performances of Chelonia C-PODs and Ocean Instruments SoundTraps, the latter producing full bandwidth recordings which were analysed in post-processing using PAMGuard click detector and classifier modules. Both devices were deployed on the same moorings, anchored to the seabed and retrieved using an acoustic release. Two study sites were used - the Great Belt and Little Belt areas of water on either side of the Danish island, Funen. Great Belt is a major shipping channel linking the North and Baltic Seas and therefore experiences relatively high ambient noise in comparison to Little Belt which has far lower levels of vessel traffic. Seven deployments were carried out between the two sites, each lasting between 11 and 70 hours, with the recorders using standard settings (and C-PODs using 'high', 'high and moderate' and 'high, moderate and low' filters'). The common unit produced by both recorder/detection systems, used in the comparative analyses, was the number of porpoise clicks detected per minute (CPM).

Correlation between the C-POD and PAMGuard CPM was positive and significant at the Little Belt site, although fewer clicks were detected by the C-PODs. The best correlations, and more similar CPM data were obtained using the 'high, moderate and low' filter settings on the C-PODs. At the Great Belt site, with high ambient noise, correlations between the PAMGuard and C-POD CPM data, averaged over 10 minute bins, were much weaker (Figure 4). Considering the percentage of detection positive minutes per hour it became apparent that the C-PODs had no detections in minutes that the SoundTrap/PAMGuard system had positive porpoise detections, i.e. in high noise environments, the C-PODs were prone to generating false-negatives.

In summary, the advantages of C-PODs are: they can be used for long deployments (5-6 months at a time); they are straightforward to use and deploy; standard guidelines exist for the validation and scrutiny of the data products they output; and, they have a low false-positive rate. They are, however, conservative and have a relatively high false-negative rate, particularly in high noise environments, and their detector/classifiers are 'black box' software, offering the user no opportunity to customise the algorithms use. Systems which use full bandwidth recordings and post-processing software (e.g. PAMGuard), however, offer users full control of the settings and thresholds used for detectors/classifiers (and, indeed, the ability to re-process data multiple times using different combinations of settings). Although there is a tendency for a higher false-positive rate which may require additional manual scrutiny to account for, and there are no standardised classification guidelines to ensure comparability between studies.

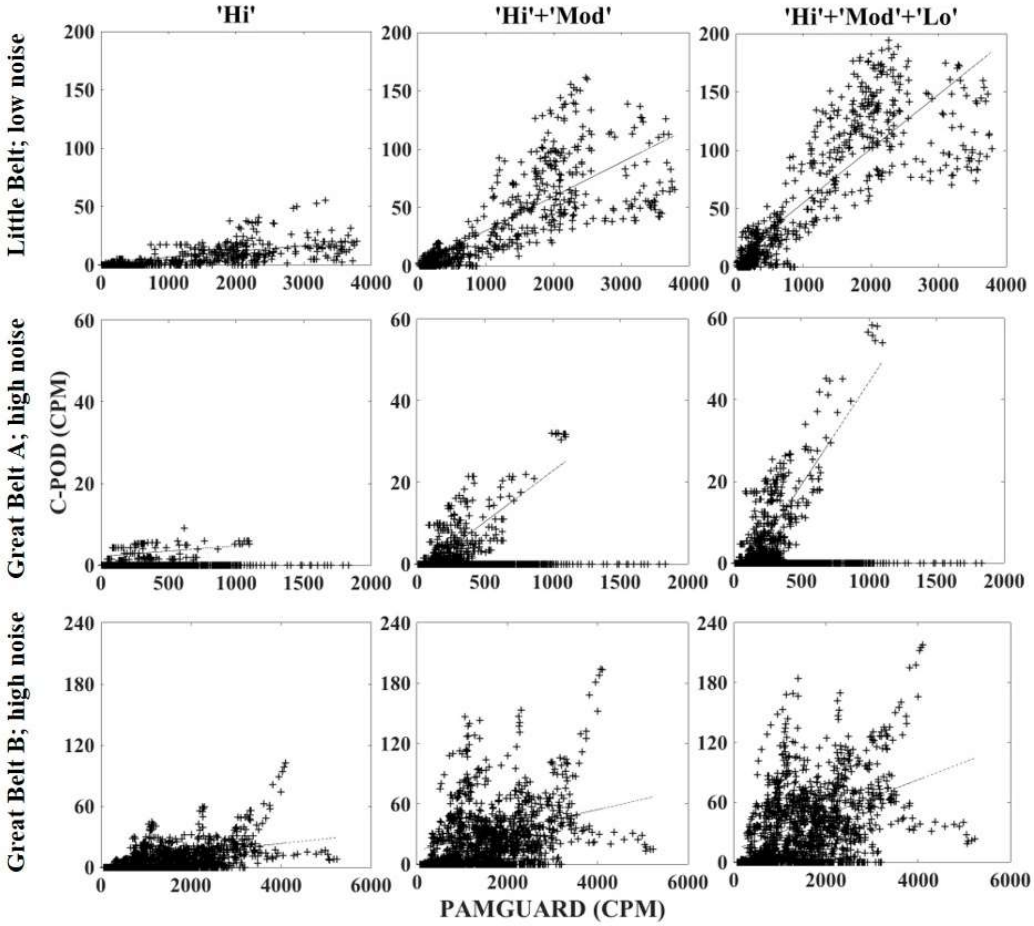


Figure 4. Counts of clicks per minute (CPM) recorded by PAMGuard and C-PODs at the different sites and using different C-POD filter settings.

4.5 Environmental monitoring in high flow conditions (Chloe Malinka, Aarhus University)

In order for effective passive acoustic monitoring to be carried out, it is important to understand the soundscape of the environment being monitored. Ambient noise in high flow environments (e.g. tidal races) vary temporally and spatially, and so, consequentially, effects the ability to detect signals of interest. For example, in Kyle Rhea, Scotland, fluctuations in ambient noise levels were found to cause the range at which a drifting hydrophone could theoretically detect a harbor porpoise echolocation click to fluctuate between ~50-500 m (Figure 5). These high levels of variability in detection ranges have significant implications for the interpretation of passive acoustic data, and for the equipment that is selected for use in given monitoring applications. C-PODs use proprietary software to generate counts of clicks detected to give an indication of animal presence/absence, whereas full bandwidth recorders, e.g. SoundTraps or icListens, allow the user to analyse the data as they choose to extract echolocation clicks as well as whistles, any unexpected sounds recorded, and, essentially, noise levels. The latter recording systems provide, as well as animal presence/absence data, a measure of acoustic detectability and contextual information that may help in understanding any recorded changes in animal behaviour (acoustic or otherwise).

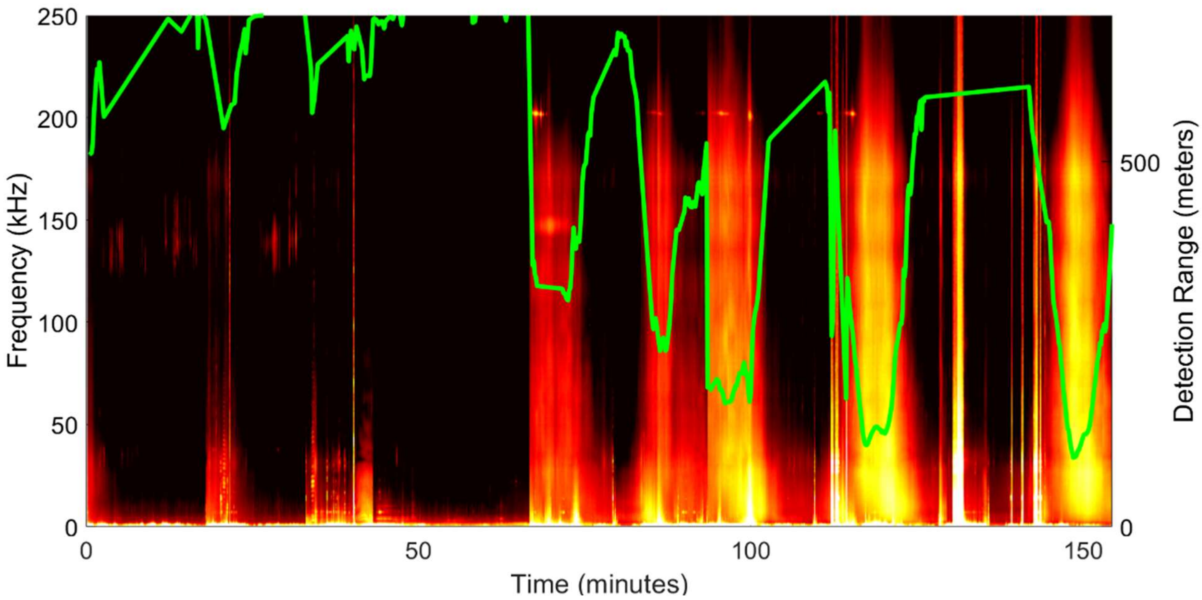


Figure 5. Spectrogram of ambient noise levels (black-white low-high scale), with estimated range for porpoise click detection overlayed (green line, secondary Y-axis)

When studying the impacts of the installation and operation of a tidal turbine on marine mammals, pre-installation surveys using a single channel recording can provide a measure of animal presence/absence along with site specific encounter rates, and any temporal patterns (diurnal, tidal, seasonal trends) which might be present. Using multiple channels extends this ability to include a degree of localisation of the source of a series of received clicks; the use of four or more channels will allow the calculation of a source location in three dimensions, and the linking of sequential clicks' locations can therefore provide a reconstructed track for a given animal. This would allow a comparison of much finer scale behaviour before and after turbine installation than is possible when relying on single channel recordings.

For pre-installation surveys, a drifting vertical multi-channel hydrophone array can provide geo-referenced detections and reconstructed animal tracks of harbor porpoises moving through a tidal energy site. Following installation, the turbine structure itself can provide a useful platform on which PAM equipment can be securely mounted. A study was conducted using PAM devices deployed on the structure at the DeltaStream turbine developed by Tidal Energy Ltd which was installed in Ramsey Sound, Pembrokeshire, Wales. A 12-hydrophone array was deployed, with hydrophones arranged in triplets. Three months of passive acoustic data was collected while the turbine was operational. Acoustically transparent polyethylene cowlings were placed over the hydrophone triplets for protection, and a National Instruments DAQ chassis mounted on the turbine base was used to digitise the data prior to being relayed to shore via fibre optic cable. This raw data was compressed by 99%, only saving short clips of the data which were triggered by an automated detector, prior to a supervised validation procedure. This system effectively monitored porpoise movements in three dimensions around an installed tidal turbine (Malinka *et al*. 2018)[3], although the time in which the turbine was operational was limited.

In conclusion, to facilitate the collection of fine-scale animal movement data, recent advances in the design of drifting multi-channel arrays have made their production and deployment significantly less complex than previous iterations. Arrays can be built using off-the-shelf components (e.g. SoundTraps), and, using a time-synchronisation pulse to synchronise recordings across channels, for localisation of echolocating animals. Furthermore, they are autonomous, capable of recording at high samples rates, and are sufficiently portable to be deployed by hand from a small vessel.

4.6 Passive acoustic monitoring at the MeyGen tidal turbine array, Scotland (Douglas Gillespie, University of St Andrews)

The goals of the PAM deployment at MeyGen were to monitor small cetaceans (specifically harbor porpoises) at an operational turbine in the Pentland Firth; a site which experiences currents of up to 10 knots. The system to be used was designed taking into account a series of lessons that were learnt during a similar deployment in Ramsey Sound (discussed in Section 4.5). Successfully integrating monitoring systems into turbine hardware allows for long deployments, however in order to achieve successful integration, early discussions with turbine engineers are imperative. In addition, hydrophones require additional mechanical protection, a reliable DAQ system, and that the inclusion of redundancy, particularly when systems are to be deployed with no opportunities for ongoing maintenance.

The system consisted of clusters of four bespoke hydrophones and pre-amplifiers mounted in a tetrahedral arrangement on a polyethylene base and covered with a polyethylene 'hard hat' to protect the elements against mechanical damage (Figure 6). This base and attached hardware were mounted to the turbine structure with a plywood 'under-base' providing protection from reflections from the solid turbine components. A newly designed data acquisition system using National Instruments Compact RIO controllers included a 30 second buffer in the outgoing datastream to ensure that brief interruptions to the network connection did not result in data loss, and therefore successfully operated to collect data from 12 hydrophones at 500 kSs^{-1} with 100% reliability. Essential to the success of this monitoring programme was the cooperation of the MeyGen engineering team, beginning two years prior to deployment. The project had costs

[3] Malinka, C.E., Gillespie, D.M., Macaulay, J.D., Joy, R. and Sparling, C.E., 2018. First in situ passive acoustic monitoring for marine mammals during operation of a tidal turbine in Ramsey Sound, Wales. *Marine Ecology Progress Series*, 590, pp.247-266.

to MeyGen including time, one wet mate connector, and the costs of the mechanical integration of the PAM system into the turbine hardware and electronics.

The data processing chain involved a desktop that controlled the data acquisition on the turbine that was running PAMGuard (and PAMDog, a watchdog programme to ensure PAMGuard runs consistently), and received approximately 1 TB of raw data per day via optical fibre. Automated event detection compressed the raw data to ~3 GB of detection data per day, which was written to external hard drives. A remote desktop was used to monitor the data gathering PC, and hard drives with detection data were posted to St Andrews for storage, backup and analysis.

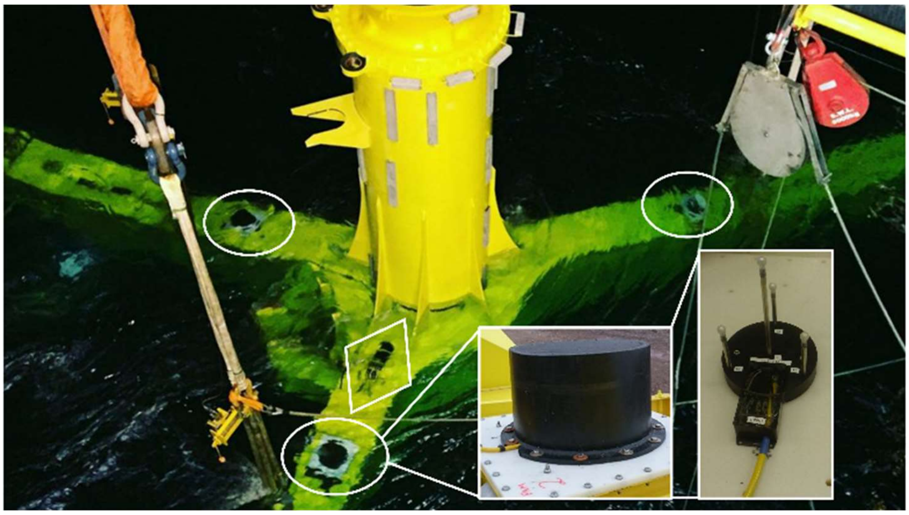


Figure 6. Images showing hydrophone cluster placement on the turbine structure, plastic 'hard hat' cowling (inset) and tetrahedral hydrophone configuration (inset).

An issue which must be considered in PAM deployments, especially those in such close proximity to an operational turbine, is the noise levels and the issues (either saturation or too low sensitivity) that can arise from inappropriate gain and filter selection. In this case, a 4 kHz high-pass filter was used to remove the high amplitude, low frequency noise produced by the turbine (Risch *et al*. 2020)[4]. The noise experienced by the PAM system was dominated by tidal flow, with the majority of turbine noise occurring below 20 kHz, while the PAM system detection range was >40 kHz. This meant, however, that the capability of the system to detect harbor porpoises was affected by flow speed, which resulted in a need to distinguish between periods of low detections due to low animal presence, and periods of low detections due to a reduction in the detection capacity of the system. The solution to overcome this issue was to use a constant, relatively high, absolute detection threshold, which effectively discarded all quiet clicks recorded during periods of low noise, and so controlled for the variation in detectability across the tidal cycle. Another issue which must be considered in the processing of these data is the potential for a reduction of efficiency in making detections due to biofouling. It is worth noting, harbor porpoise detections

[4] Risch, D., van Geel, N., Gillespie, D. and Wilson, B., 2020. Characterisation of underwater operational sound of a tidal stream turbine. *The Journal of the Acoustical Society of America*, 147(4), pp.2547-2555.

are still being made at the site three years after deployment; but there is significant biofouling on the 'hard hat' coverings of the hydrophones and, as yet, there has been no quantification of the effects this will have on system performance. One final issue that was experienced with the analysis of this dataset was that it is labour intensive; it took approximately 2 days' of work per week to sort through the data and confirm detections made by the automated system. It will likely be possible to use this large dataset to train the automatic detectors for use in future projects, but there is also a risk of overtraining the software and losing the capacity to record unexpected sounds and signals.

From the data collected at the MeyGen site, three main insights into the behaviour of harbor porpoises (at a range of scales) have been gained. On the largest scale, harbor porpoises were found to display strong seasonal and diurnal variations in the presence at the site, highlighting the limitations of summertime daylight hour visual surveys in accurately characterising porpoise distributions. At a medium scale, evidence was found of avoidance of the turbine by porpoises over several 10s of metres during operation, and at the finest scale, ongoing analyses suggest that there is active avoidance of the rotors at ranges less than the diameter of the rotor swept area.

The key lesson learned from this deployment is that the system proved highly reliable in a hostile environment with 11 out of 12 hydrophones still operating three years after deployment and 99% uptime when power from the turbine was available. The 'hard hat' cowlings worked to protect the hydrophone elements from mechanical damage and wet-mate connectors potentially provide a valuable solution to issues of corrosion (other sensors failed due to corrosion but could not be retrieved and re-deployed due to the use of dry-mate connections). These solutions are being applied to a new monitoring platform currently being designed. This platform includes two multibeam imagining sonar and one PAM cluster of a similar configuration to those used in the MeyGen array, and should therefore be capable of monitoring seals and small cetaceans in the vicinity of tidal turbine, and is due for deployment towards the end of 2020.

4.7 Points arising in the general discussion or received following the workshop

Protection from flow noise, and thus lowering the noise floor of the recording system to allow the detection of lower amplitude signals, is essential for maximising the performance of PAM systems. Various options have been tested, including: the 'hard hats' described in Section 4.6, several different types of open-cell foam, and flow socks, which have had varying degrees of success. Although they potentially come with compromises to other aspects of acoustic performance (e.g. open-cell foam was found to reduce both flow noise and the detection range of signals of interest).

A question was asked about the requirements placed on project developers and partners for environmental effects monitoring, and how regulators view the role of PAM in characterising effects on marine mammals around operational turbines. Caroline Carter of Scottish Natural Heritage, submitted the following in response, after the workshop:

"I think what you are asking is whether we will be looking at requiring all tidal stream developers to monitor turbines using PAM. The answer there is more nuanced than a yes or no. There is still much we do not understand regarding animal behaviour in these areas, and our advice will always be on a case-by–case basis, will reflect what we've learned, what we think the impacts are, and what we think we might need to know. MeyGen for example, is being developed using a 'deploy and monitor' approach. The work Doug presented is an output of this approach. Funding for the project came from the Scottish Government as well as the developer, and the work is ongoing. MeyGen was consented with a phased deployment plan and the subsequent phases will be dependent on the results so far. For other developments in different locations, there may be different requirements depending on the circumstances and the species of concern. PAM is likely to be a component of our monitoring toolbox, but there are other species of interest that do not vocalise (e.g. harbor seal) and so different means may be required (see SMRU work with active sonar). Given the level of understanding at the moment, we expect developers to be required to monitor, but the methods of monitoring may vary. I think what has worked is the collaborative approach we have taken so far, with Scottish Government, the developers and academia brought together to agree/develop monitoring approaches that fit the circumstances."

It was noted that caution should be applied when using C-PODs in tidal stream environments, where their inability to record noise levels leaves a vital contextual variable unquantified, and where high ambient noise levels frequently overwhelm the buffer of the automated detection leading to a high proportion of 'lost time'. The use of full bandwidth recorders should be encouraged as industry best-practice.

There is definite room for improvement in the technology involved in both the hardware and software aspects of PAM, and so it is expected that the development and tuning of deployment configurations and detector algorithms will continue. However, it is also evident that the technology is at a level of development where very useable data can be collected for answering important ecological questions about the behaviour of small cetaceans and the potential impacts induced by tidal turbines in tidal stream environments. It is important that the configurations and settings of detector-classifiers are adjusted to suit each specific environment in which they are used – it is rare that a 'standard configuration' can be used and be maximally effective. It is important to note, that a detector trained (and potentially over-fitted) at a given site may not be as effective at a different location.

The discussions noted that an important question remains unanswered, and may be up to regulators to answer: when is the technology/methodologies to be used ‘good enough’, i.e. they are capable of answering the specific questions being asked in a given case?

The Pathway Program is aiming to satisfy Canadian regulators, for whom the focus of monitoring is to understand the frequency of detections and provide an estimate of abundance of harbor porpoises in Canadian waters, specifically around the development of tidal energy projects in the Bay of Fundy. While it might be the case that a monitoring platform may not be directly transferrable to all other sites globally, the deployment methods, hardware, and analytical tools developed under the program should provide Canadian regulators with the tools and information to make educated decisions as the industry moves forward. It is also essential that regulators base their questions and requirements on the advice of the scientific community, with a degree of understanding about what is feasible from this type of monitoring. This highlights the importance and value of involving regulators directly in projects such as the Pathway Program.

5. Summary of key points and takeaways

- The limitations of C-PODs when deployed in tidal stream environments are significant (e.g. lack of noise measurements, loss of monitoring time due to saturation of the detector), and the use of full bandwidth recorders should be encouraged.
- Drifting acoustic measurements can provide a reliable platform for the collection of PAM data in tidal streams, reducing flow noise and other pseudo-sound which affects static deployments. Flow protection for static PAM arrays should be further investigated.
- Hydrophone arrays are capable of tracking harbor porpoises in three dimensions in tidal streams, either deployed from GPS-tracked drifters or mounted on turbine structures. This can provide valuable insight into the fine scale movements of porpoises around these sites.
- A one-size fits all monitoring solution will be difficult to achieve. There will necessarily need to be tuning of the deployment methodologies and data processing algorithms, based on the specifics of a given site or application, and on the regulatory requirements faced. The key goal is to develop a toolbox of methods which can be applied, with fine tuning, to as wide a range of applications as possible.
- Regulator involvement at all stages of the monitoring process is essential to the success of projects which aim to provide information on which regulators can base decisions. There must be a dialogue between regulators and the scientific community and other relevant stakeholders about what PAM is able to achieve, and what regulatory requirements can be met.

Appendix A. List of participants

Name	Institution
Chloe Malinka	Aarhus University
Anna Redden	Acadia University
Brian Sanderson	Acadia University
Michael Adams	Acadia University
Gemma Veneruso	Bangor University
Lucy Quayle	British Columbia Institute of Technology and Simon Fraser University
Gavin Feiel	Dalhousie University
Clair Evers	Department of Fisheries and Oceans Canada
Hilary Moors-Murphy	Department of Fisheries and Oceans Canada
Matthew Baker	Department of Fisheries and Oceans Canada
Jinshan Xu	Department of Fisheries and Oceans Canada
Sarah Thomas	DP Energy
Ana Couto	EMEC
Caitlin Long	EMEC
Donald Leaver	EMEC
Elaine Buck	EMEC
Joshua Lawrence	EMEC
Erica Mathers	EMEC
Benjamin Williamson	Environmental Research Institute
Dan Hasselman	FORCE
Jessica Douglas	FORCE
Shannon McNeil	FORCE
Tyler Boucher	FORCE
Bruce Martin	JASCO Applied Sciences
Luiz Faria	OERA
David Mellinger	Oregon State University
Selene Fregosi	Oregon State University
Denise Risch	Scottish Association for Marine Science
Nienke Van Geel	Scottish Association for Marine Science
Steven Benjamins	Scottish Association for Marine Science
Caroline Carter	Scottish Natural Heritage
Carol Sparling	SMRU St Andrews
Douglas Gillespie	SMRU St Andrews
Gordon Hastie	SMRU St Andrews
Jamie MacAulay	SMRU St Andrews

Laura Palmer	SMRU St Andrews
Jason Wood	SMRU USA
Greg Trowse	SOAR
Patrick Butler	Sustainable Marine Energy
Ray Pieroway	Sustainable Marine Energy
Virginia Iorio	University of Aberdeen
Anthony Bicknell	University of Exeter
Joanna Sarnocinska	University of Southern Denmark
Chris Bassett	University of Washington

Appendix B. Speaker presentations

The slides from the presentations delivered at the workshop are provided below. The pages on which each set of slides begin are as follows:

Partially Funded by Natural Resources Canada | Financé partiellement par Ressources naturelles Canada

Canada

OERA

force | Fundy Ocean Research Centre for Energy

The Pathway Program: An Overview

Luiz Faria, OERA Project Manager

Daniel J. Hasselman, FORCE Science Director

Partially Funded by Natural Resources Canada | Financé partiellement par Ressources naturelles Canada

Canada

OERA

Leading collaborative petroleum and renewable energy research

Partially Funded by Natural Resources Canada | Financé partiellement par Ressources naturelles Canada | Canada

THE PATHWAY PROGRAM

- The Pathway Program is a coordinated effort that will define, test and validate an Environmental-Effects Monitoring (EEM) solution for the tidal energy industry that will be accepted by DFO

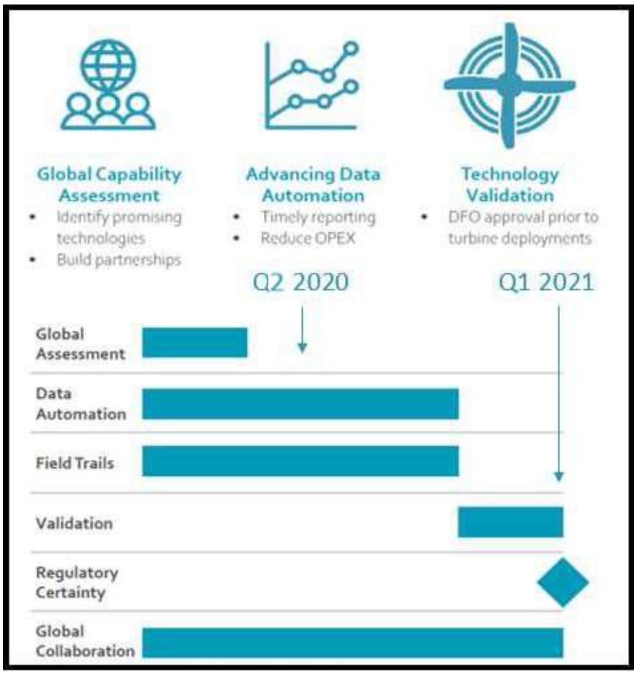
- **Benefits:**
  - DFO approval of monitoring solution before 1st tidal turbine deployments
  - Minimize operating time before 2nd tidal turbine deployment
  - Faster authorizations for future deployments

- **Additional goals:**
  - Apply machine learning to data analysis to reduce reporting time and compliance costs
  - Minimize initial capital costs to developers
  - Develop regional capability to manage, process, analyze and report EEM data
  - Develop intellectual property that regional companies can exploit commercially in multiple marine industries, both regionally and globally

Partially Funded by Natural Resources Canada | Financé partiellement par Ressources naturelles Canada | Canada

PATHWAY PROGRAM – PHASES

1. Global capability assessment
2. Advancing data processing and analysis
3. Technology validation



Partially Funded by Natural Resources Canada | Financé partiellement par Ressources naturelles Canada | Canada

1. GLOBAL CAPABILITY ASSESSMENT

- Tidal power development is a global issue that requires international expertise
  - subject matter experts (different classes of monitoring technologies)
    - reports and webinars with sensor recommendations (OERA website)
    - ongoing consultation - project methodology development
  - Continual engagement with international experts and regulators
  - Workshops - ongoing collaborations and knowledge exchange (reports generated/distributed)
    - i. Cabling and platform development (Halifax; 12/10/2019)
    - ii. Data automation and data management (Halifax; 03/04/2020)
    - iii. Passive Acoustic Monitoring (webinar; 4/30/2020)
    - iv. Echosounders (Halifax; TBD)
    - v. Imaging sonars (Seattle; TBD)
    - vi. Sensor integration (Halifax; TBD)

2. ADVANCING DATA PROCESSING AND ANALYSIS

- Reduce time from data collection to report generation for regulators

- Echosounders - DeepSense (Dalhousie University)
  - development of machine learning algorithms to reduce data post-processing time
  - automated analyses and report generation

- Passive Acoustic Monitoring technology
  - development of detector/classifier algorithm for automation of *.wav files
  - automate analyses and report generation

- Imaging Sonars
  - explore utility of algorithms developed by UW and UHI
  - distribute RFP if required

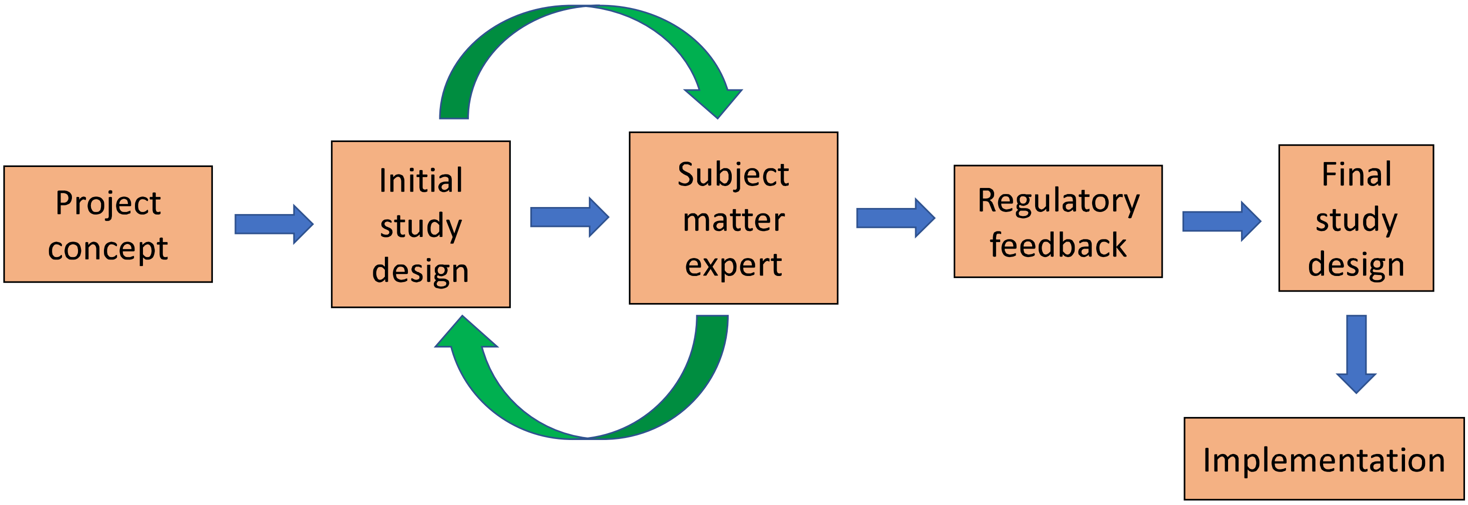
3. TECHNOLOGY VALIDATION

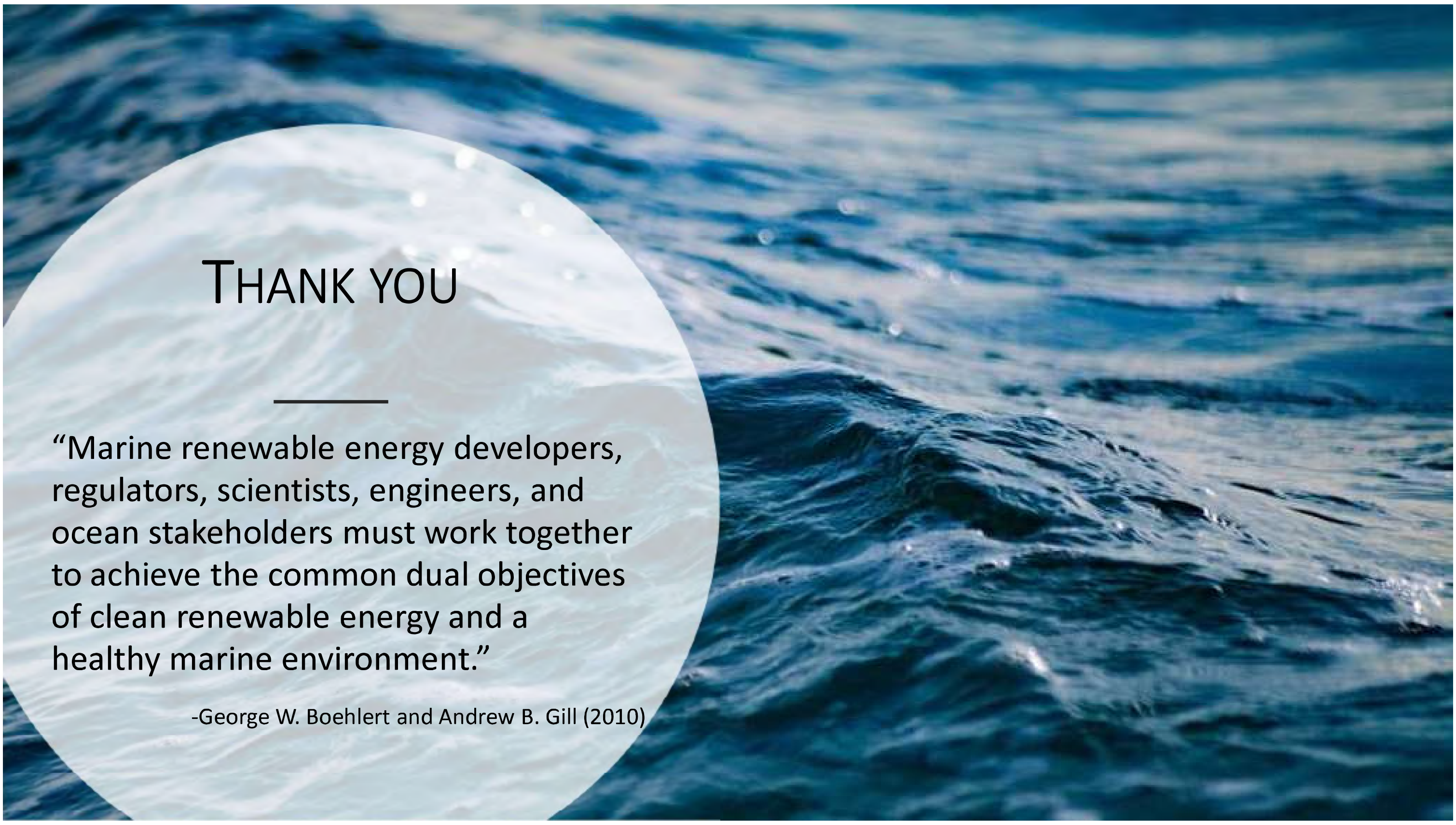
- Staged approach to sensor utility demonstration in high-flow environments:
  - echosounders
  - Passive Acoustic Monitoring technology
  - imaging sonars
  - sensor integration

Partially Funded by Natural Resources Canada | Financé partiellement par Ressources naturelles Canada | Canada

3. Technology validation – a standardized approach

- An iterative process to develop a robust study design in consultation with international experts and review by regulators



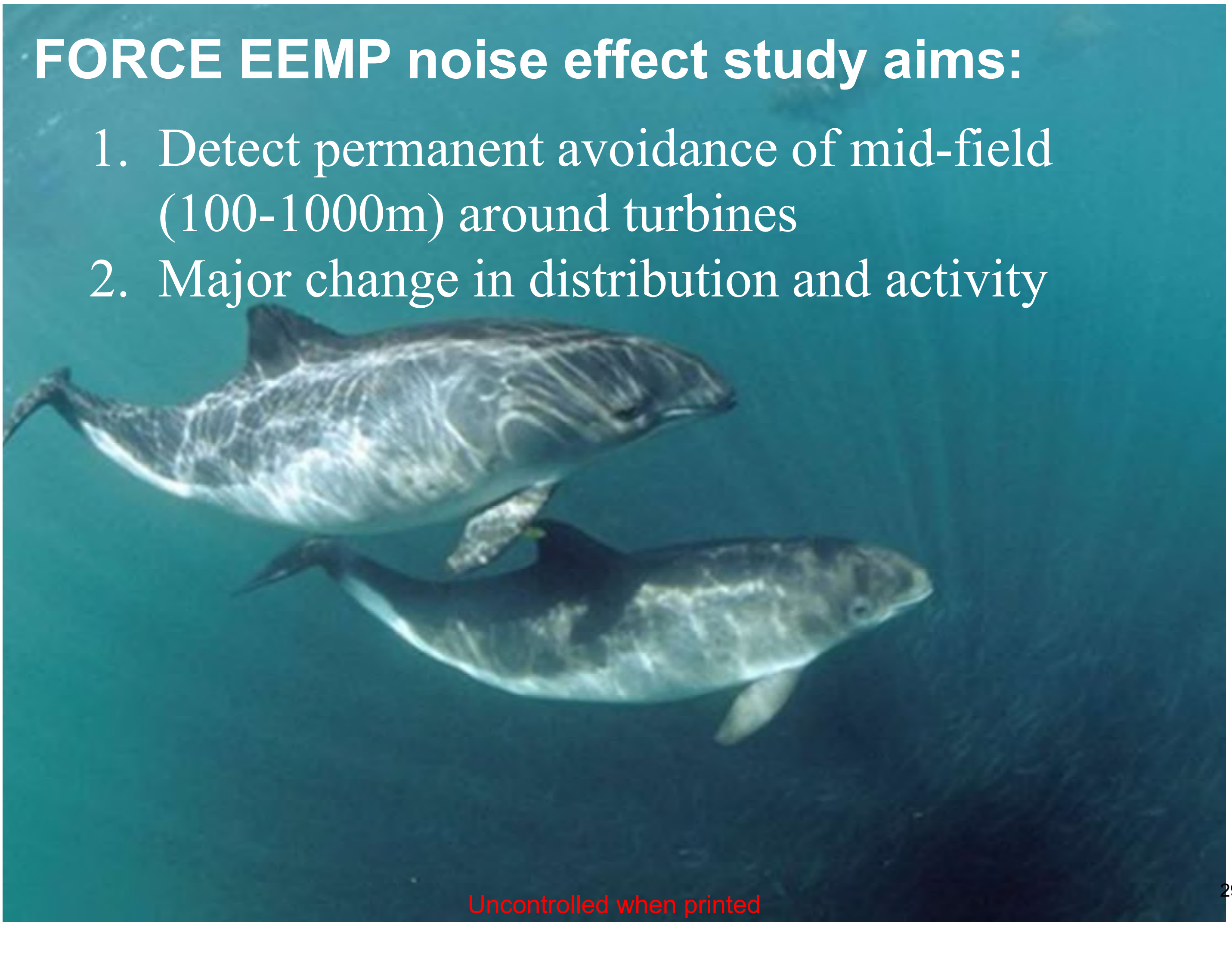


HARBOUR PORPOISE MONITORING AT FORCE

Jason Wood
30 April 2020
PAM Virtual Workshop

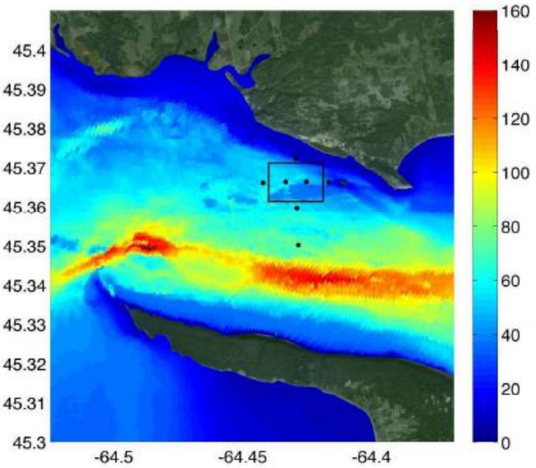
Focus of Talk
1) FORCE EEMP
2) Comparison of PAM Devices

SMRU Consulting
North America

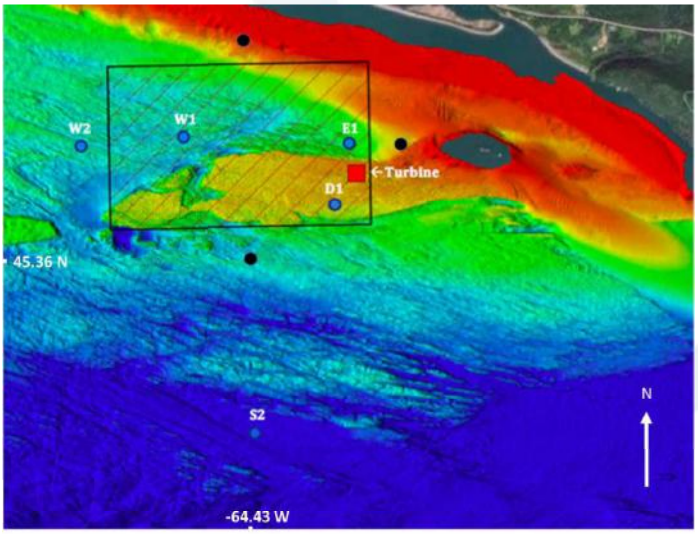


Study Design: C-POD monitoring

- Use of 3-8 C-PODs (Chelonia) with SUB-B3 buoys
- Gradient design with baseline since 2011
- FORCE EEMP (since 2016) uses 5 C-PODS (2 within 230 m of Open Hydro turbine site)



SMRU Consulting
North America

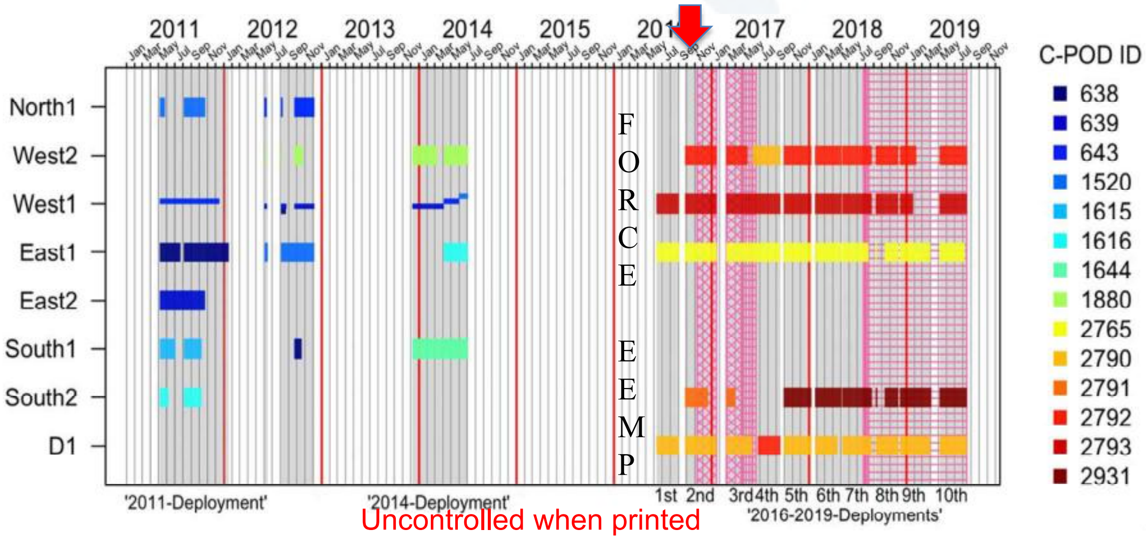


Blue dots represent 5 EEMP monitoring sites

Study Results: Data collection

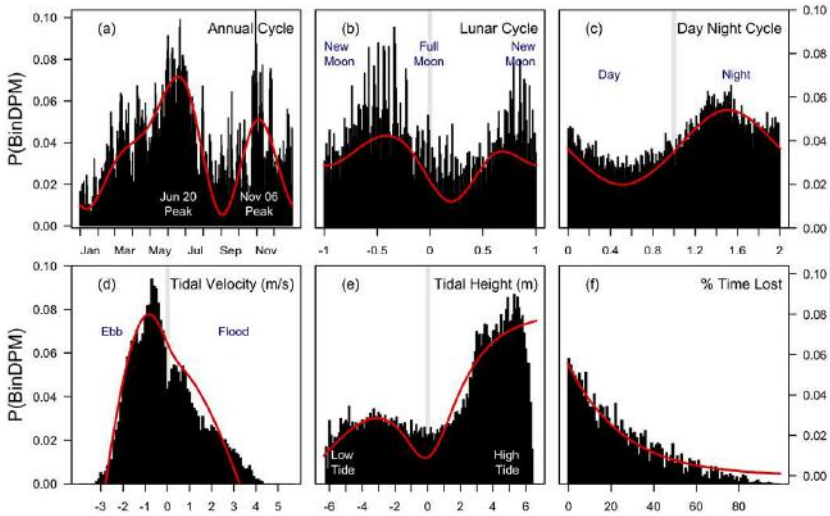
- 6,519 C-POD monitoring days collected with >2,350 prior to the installation of 1st turbine (pink cross hatch operational). 1,626 days of monitoring.
- Temporal and spatial coverage improving, least in winter period (D1 was new EEMP near-turbine monitoring site)

Turbine



Study Results: Overall summary

- Porpoise detected on 98.8% of days, median 8 min/day (IQR=3-17 min/day).
- Minimum probability of presence 7% per 10 min. period
- GLM-GEE predicted higher click detection rates in late spring and fall, at low (0-2.5 m/s) current velocities esp. on ebb tide, at night and higher tidal heights.



Probability of porpoise detection per 10-min period

SMRU Consulting North America

Study Limitations:

- Highly dynamic and very complex tidal environment
- Detection range small
- % Time Lost due to memory buffer at high tidal flows. Some early monitoring sites excluded due to very high rates.
- Movement of Sub-buoy in strong currents and % Time lost results in click detection estimates that are likely "minimum estimates"
- C-POD monitoring of 'operational turbines' totals only 130 days (turbine 1) and 18 days (turbine 2)

SMRU Consulting North America

Study Results: Tidal turbine effects

- No overall avoidance of mid-field range during turbine deployment and operations, but GAM-GEE shows significant reduction in porpoise click activity for both C-POD sites within 230 m of turbine and increase at furthest site (1,690 m away).
- Porpoise vocal activity returned to pre-installation baseline rates when turbine was non-operational (but present) and when turbine was removed.
- A longer time series is believed required before robust conclusions can be drawn on turbine effects.

SMRU Consulting North America

BASELINE PRESENCE AND EFFECTS OF TIDAL TURBINE INSTALLATION AND OPERATIONS ON HARBOR PORPOISE IN MINAS PASSSAGE, BAY OF FUNDY

DOMINIC TOLLIT[1], RUTH JOY[1], JASON WOOD[1], ANNA REDDEN[2], CORMAC BOOTH[1], TYLER BOUCHER[3], PETER PORSKAMP[2] and MELISSA OLDREIVE[3]

1. SMRU Consulting North America, 604-55 Water street, Vancouver, B.C., V6B 1A1, Canada.
2. Acadia Centre for Estuarine Research, Acadia University, Box 115, 23 Westwood Avenue, Wolfville, NS, B4P 2R6, Canada.
3 Fundy Ocean Research Center for Energy (FORCE), PO Box 2573, Halifax, NS, B3J 1V7, Canada.

SMRU Consulting North America

Comparison of PAM Devices

- AMAR
- icListen
- SoundTrap
- CPOD
- FPOD

- icTalk
- Opportunistic porpoise

SMRU Consulting North America

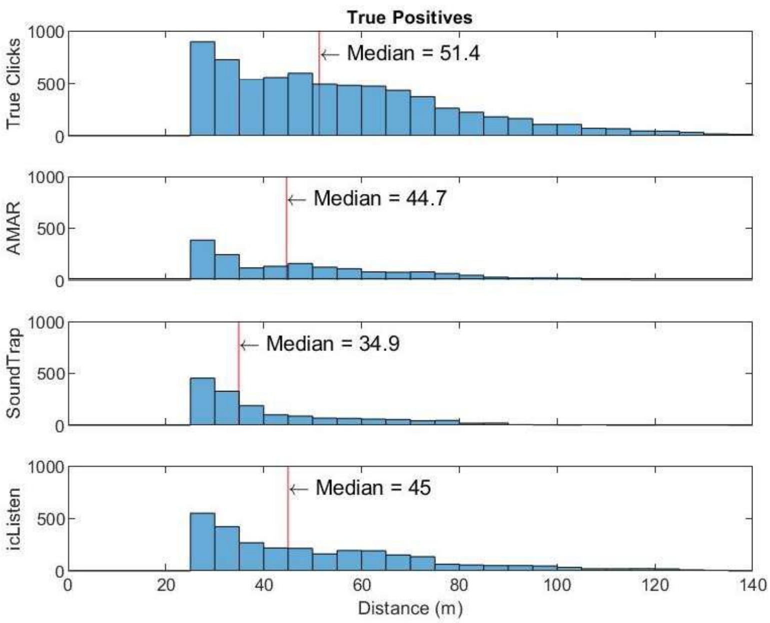
Detection Range for icTalk

Hardware	Threshold	Deployment	Annotated clicks	TP	FP	FN	Precision	Recall
AMAR	6	2	6893	1780	2484	5113	0.42	0.26
SoundTrap	6	2	6893	1576	12940	5317	0.11	0.23
icListen	6	2	6893	3078	16758	3815	0.16	0.45
CPOD	NA	2	6893	46	15811	6847	0.00	0.01
FPOD	NA	2	6893	65	186314	6828	0.00	0.01

- icTalk Source Level 130 dB re 1μPa
- Porpoise Source Level 165-170 dB re 1μPa[1]

[1] Villadsgaard et al. 2007

SMRU Consulting North America



Uncontrolled when printed

Porpoise Detections

- Work is ongoing

Hardware	Threshold	Deployment	Annotated DPM	TP	FP	FN	Precision	Recall
AMAR	6	2	10	10	5682	0	0.00	1.00
SoundTrap								
icListen								
CPOD	NA	2	10	6	62	4	0.09	0.60
FPOD		2	10	4	72	6	0.05	0.40

SMRU Consulting
North America

C-PODs - Lessons learnt

- Advantages of C-PODs: Low cost and easy for multiple month deployments, standardized detection methodology which focuses on controlling false positives, unit reliability good. Control of FP is not a bug but a feature.
- Disadvantages of C-PODs: Do not provide ambient noise levels, only detect cetacean clicks, memory buffer can lead to lost monitoring time, black box detection and classification, and smaller detection range due to control of false positives. Performance varies depending on deployment method.

SMRU Consulting
North America

Discussion points

- Use of PAM hardware and software depends on the QUESTIONS asked and BUDGET available.
- A high-quality hydrophone recording continuously is the best option, providing data to run multiple detectors and determine ambient noise levels. However, cost of units and analysis far higher.
- High frequency clicks and noise from water flow leads to hydrophones monitoring only a small volume of water – drifting hydrophones therefore useful for understanding spatial use and limitations.
- Platform sensor integration hugely important (& challenging).

SMRU Consulting
North America

Thanks for listening

Contact:
jw@smruconsulting.com

Acknowledgements

- FORCE and OERA for funding
- Murray Scotney, Tyler Boucher and FORCE team for fieldwork logistics
- Brian Sanderson for current speed predictions

SMRU Consulting
North America

Harbour porpoise monitoring in Minas Passage using moored and drifting hydrophones (CPODs and icListenHF)

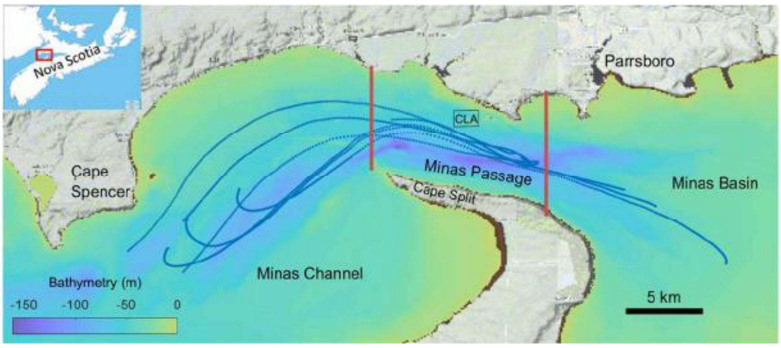
Mike Adams and Brian Sanderson

Acadia University

30 April 2020

ACADIA UNIVERSITY

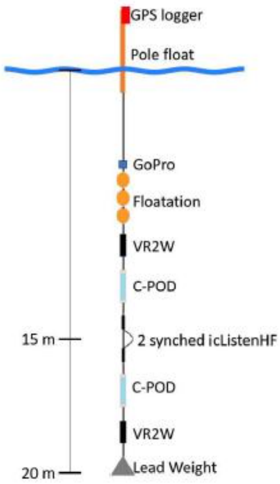
1) FORCE CLA; Tidal Energy Location



Drifter tracks, flood/ebb asymmetry **Ref 1**

Ebb flow is a turbulent jet into Minas Channel

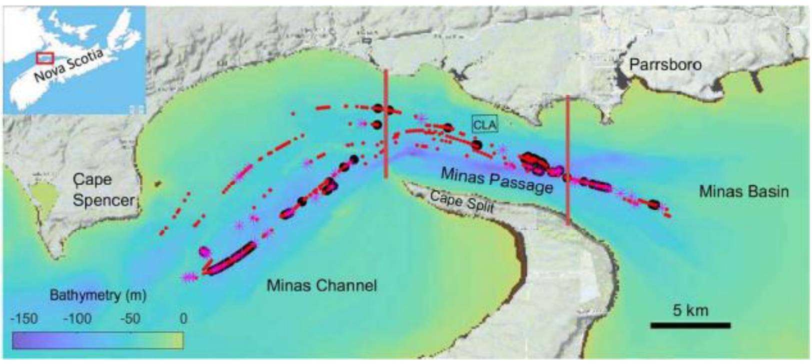
2) Drifter and Instrument Layout



- Pole float
  & subsurface
  floats/mass
- ⇒Inertial stability
- ↓pseudo-sound
- ↓signal disruption
- ↑Tension, ↓drag,
  ↑vertical orientation
- C-POD records
  events
- icListenHF records
  broadband, 512 kS/s

Ref 1,2,3,4

3) Click Detection

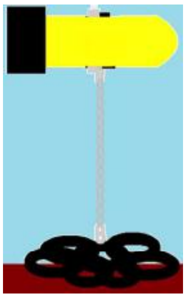


- Visual sightings
- C-POD few detections in the ebb-tide jet (Minas Channel)
- Coda obtains porpoise clicks from broadband time series

4) The Issues with Hydrophones in Turbulent Waters

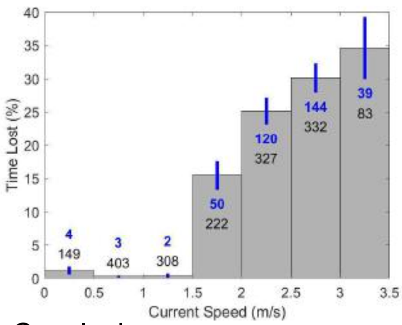
- Ambient sound level $\uparrow$ current
- Signal distortion $\uparrow$ current
- Pseudo-sound $\uparrow$ bad design

C-POD vulnerable to 'lost time'



5) C-POD Lost Time vs Ambient &/or Pseudo-Sound

C-PODs on a very stable drifter **Ref 1,2**



C-PODs Lost Time (LT)

- LT $\uparrow$ if current $>$ 1.5 m/s
- Still, LT $<$ 50% of minutes at 3-3.5 m/s
- **C-PODs on moored SUBs floats had $\gg$ LT**

Ref 1,5

Conclusions:

- SUBs float instability $\uparrow$ pseudo-sound.
- Pseudo-sound $\uparrow$ lost time.
- **Need to address mooring instability** **Ref 1,6,7,8**

6) C-POD and icListenHF-&-Coda

Symbol	Detection Method	# DPM
C_{POD}	C-POD	81
—	icListenHF	—
D_{CI}	icListenHF & Coda	1269
F_{CI}	Filter & icListenHF & Coda	354
A_{CI}	Alternate-Filter & icListenHF & Coda	586

Semi-automated review of F_{CI} and A_{CI}:

- Second-by-second, window moves through trains.
- Matched filter.
- Regression fits, click frequency, click envelope.
- Spectrograms

F_{CI} and A_{CI} were largely correct: $\pm$ clicks, DPM unchanged.

Ref 1,4

7) C-POD and icListenHF-&-Coda-&-Review

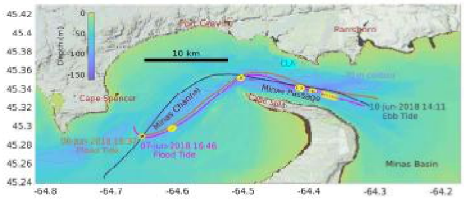
	DPM		DPM		DPM
$C_{POD} \wedge D_{CI}$	**70**	$C_{POD} \wedge \neg D_{CI}$	11	$D_{CI} \wedge \neg C_{POD}$	1199
$C_{POD} \wedge F_{CI}$	53	$C_{POD} \wedge \neg F_{CI}$	28	$F_{CI} \wedge \neg C_{POD}$	301

Conclusions:

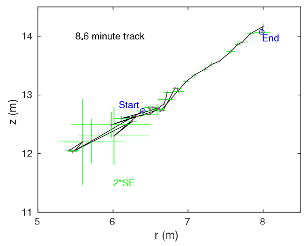
- **Good degree of overlap**
- C_{POD} fooled by echo sounder and acoustic fish tag
- F_{CI} excludes some weak D_{CI} that C_{POD} keeps; SNR
- All methods are incomplete; signal distortion $\Rightarrow$ ambiguity
- **Use C-POD for monitoring large spatiotemporal scales**

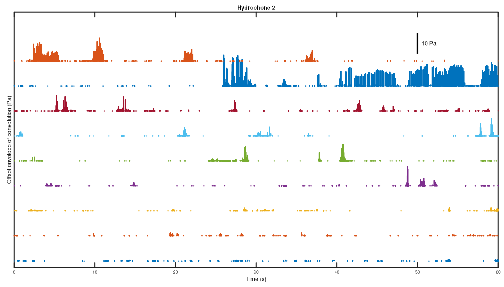
Ref 1,4

8) Localization relative to drifter



Drifter, 4 sync hydrophones
Coda^{like} & semi-auto-review
(matched filter)
Localization suite
8 minute track, behaviour
Ref 1,3,4

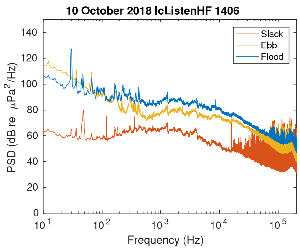


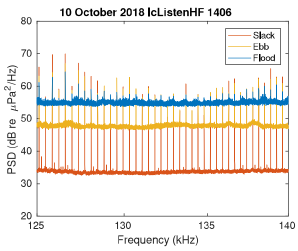


- Conclusion: **Use synchronized hydrophone array & Coda-like processing & localization suite for near-turbine porpoise tracks and behaviour**

9) Working in very noisy conditions:

Ref 9,10





- 'Coda' ≡ coded to run in an icListenHF, ID likely porpoise clicks →store parts of time series
- **Methods and context matter**
  - Instruments
  - Moorings
  - Current environment
  - Biology, Mathematics

Seeking known signal ⇒ matched filter
(Sanderson et al, in prep)
Don't quite know ⇒ add other methods
Only AFTER all of the above ⇒ AI

Uncontrolled when printed

10) References

1. Adams, M. J. (2018). Application of a multi-hydrophone drifter and porpoise detection software for monitoring Atlantic Harbour Porpoise (*Phocoena phocoena*) activity in and near Minas Passage. Honours Thesis, Biology, Acadia University.
2. Adams, M., Sanderson, B., Porskamp, P., and Redden, A. (2019). Comparison of co-deployed drifting passive acoustic monitoring tools at a high flow tidal site: C-PODs and icListenHF hydrophones. The Journal of Ocean Technology, Vol. 14, pp 61-83, Special Edition
3. Sanderson, B., Adams, M., and Redden, A. (2019). Using reflected clicks to monitor range and depth of Atlantic harbour porpoises. The Journal of Ocean Technology, Vol. 14, pp 85-100, Special Edition.
4. Adams, M.J. (2020). Using a drifting hydrophone array to obtain positions of Atlantic harbour porpoise (Phocoena Phocoena) and analyze their vocalizations and swimming behaviour. MSc Thesis, Biology, Acadia University.
5. Tollit, D., Joy, R., Wood, J., Redden, A., Booth, C., Boucher, T., Porskamp, P., and Oldreive, M. (2019). Baseline presence of and effects of tidal turbine installation and operations on harbor porpoise in Minas Passage, Bay of Fundy, Canada. Journal of Ocean Technology, Vol. 14, pp. 24-48, Special Issue.
6. Wood, J., D. Tollit, A. Redden, P. Porskamp, J. Broome, L. Fogarty, C. Booth, and R. Karsten, Passive acoustic monitoring of cetacean activity patterns and movements in Minas Passage: Pre-turbine baseline conditions (2011/2012). Final Report for FORCE and OERA, 2013.
7. Porskamp, P.H.J., J.E. Broome, B.G. Sanderson, A.M. Redden. 2015. Assessing the performance of two passive acoustic monitoring technologies for porpoise detection in a high flow tidal site. Canadian Acoustics Association. Vol. 43, No. 3, 44-45.
8. Sanderson, B., C. Buhariwalla, M. Adams, J. Broome, M. Stokesbury, A. Redden. 2017. Quantifying detection range of acoustic tags for probability of fish encountering MHK devices. Proceedings of the 12th European Wave and Tidal Energy Conference, 27 Aug-1st Sept 2017, Cork, Ireland.
9. ISEM (2019). Integrated Active and Passive Acoustic System for Environmental Monitoring of Fish and Marine Mammals in Tidal Energy Sites (ISEM), Final Report to Offshore Energy Research Association. OERA project reference: 300-173-2.
10. Sanderson, B., Adams, M., and Redden, A. (2019). Sensor Testing Research for Environmental Effects Monitoring (STREEM). Final Report to the Offshore Energy Research Association of Nova Scotia. ACER Technical Report, No. 127, pp. 68. Acadia University, Wolfville, NS, Canada.

11) Thanks!

Relative performance of different PAM technologies and click detectors/classifiers

Comparing the performance of C-PODs and SoundTrap/PAMGUARD in detecting the acoustic activity of harbor porpoises (Phocoena phocoena).

Sarnocinska, Joanna; Tougaard, Jakob; Johnson, Mark; Madsen, Peter T.; Wahlberg, Magnus

Published in:
Meetings on Acoustics. Proceedings

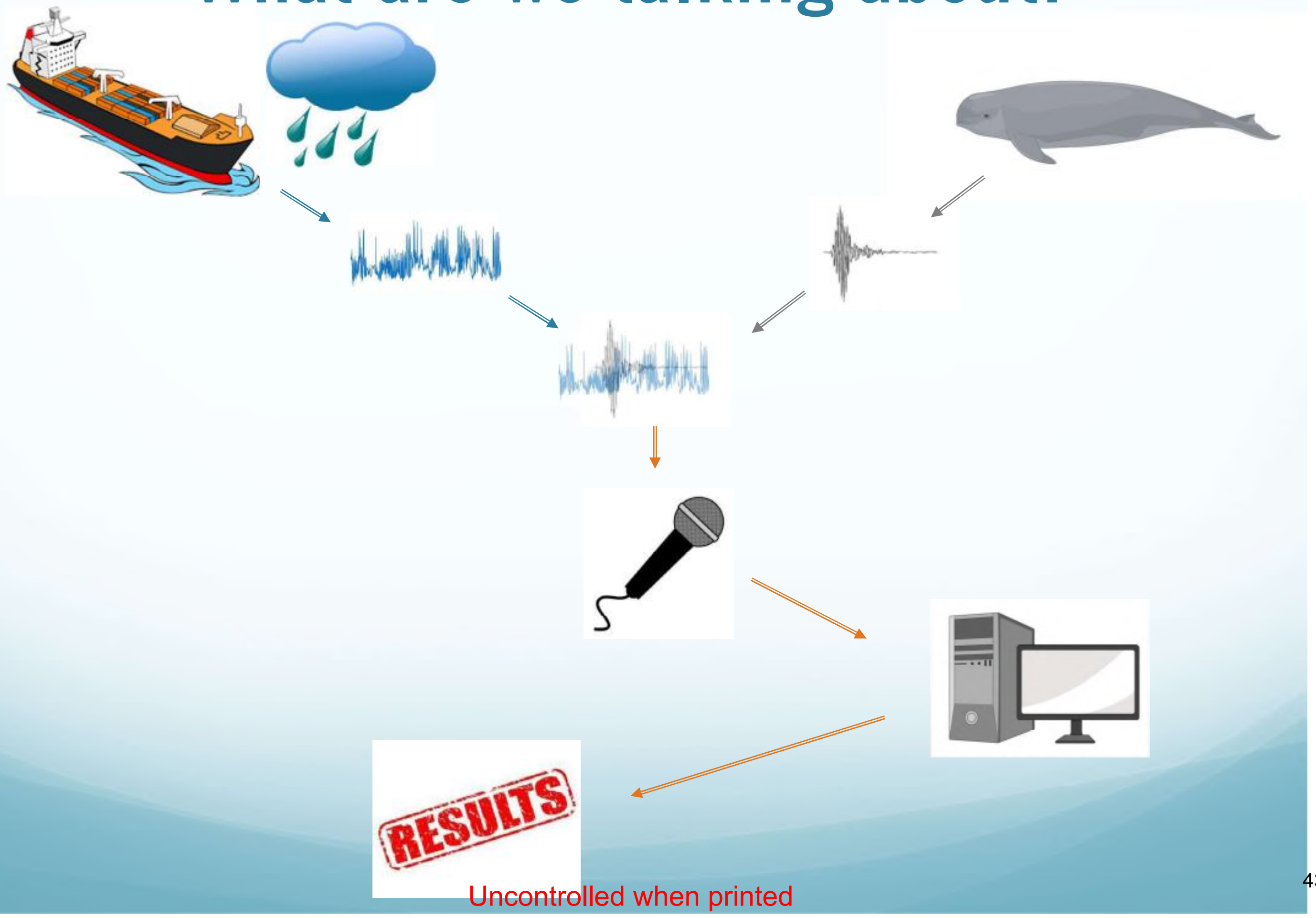
MARENCO Marine Environmental Consulting

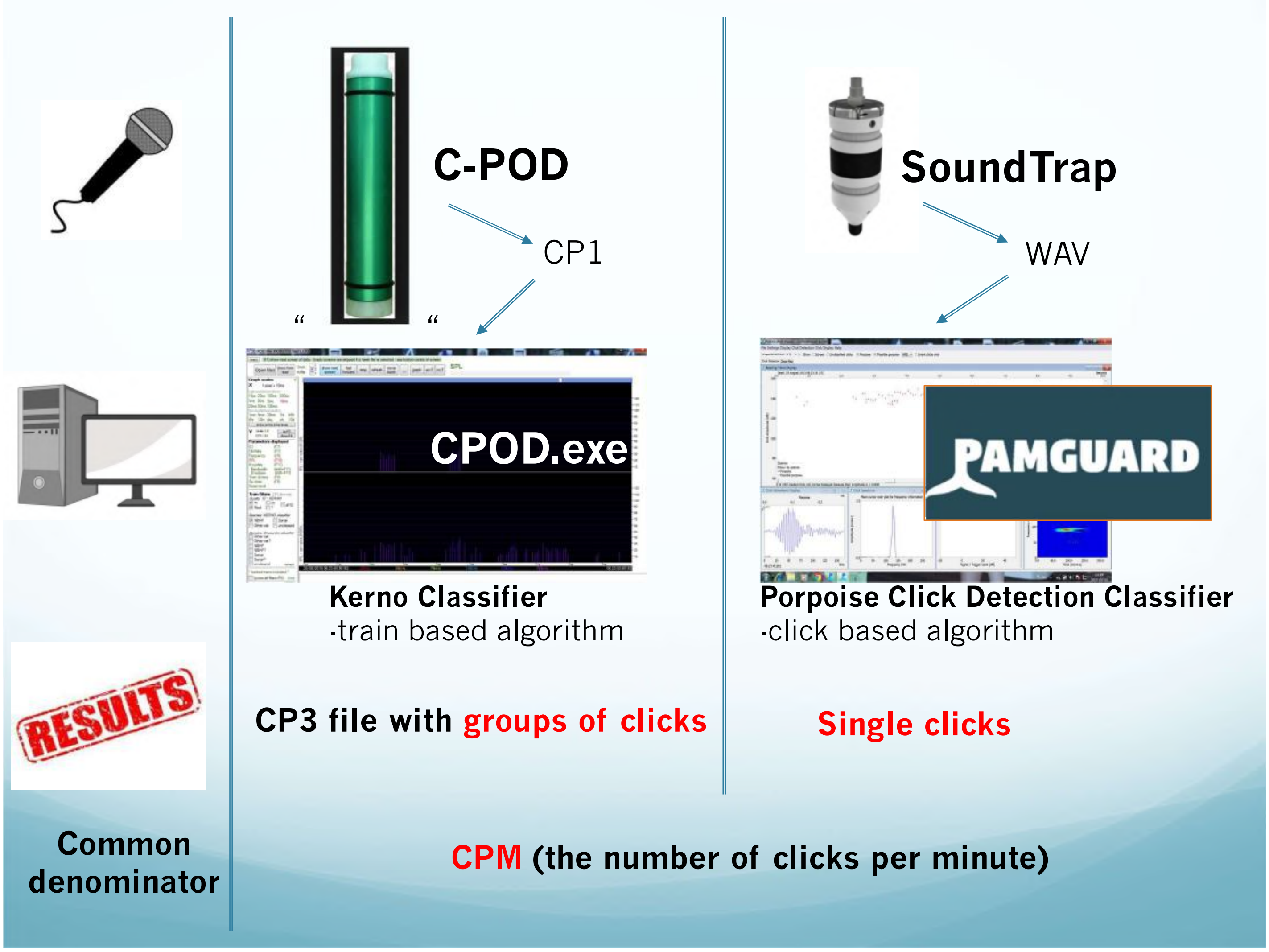
Agenda

- Brief introduction to the 2 systems
- Methodology used in this study
- Results
- Conclusion: pro and cons of C-POD and PAMGuard
- Summary

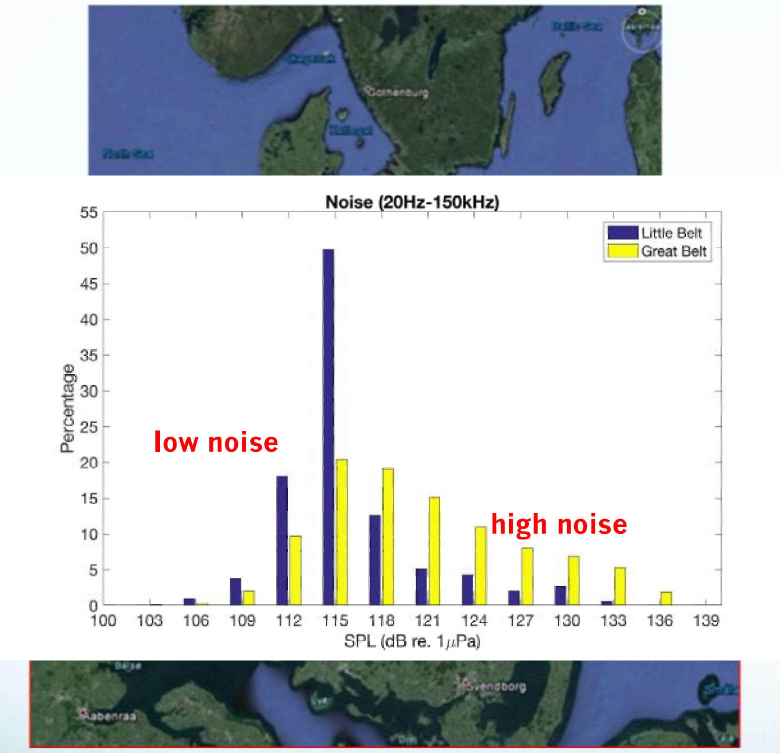
Introduction

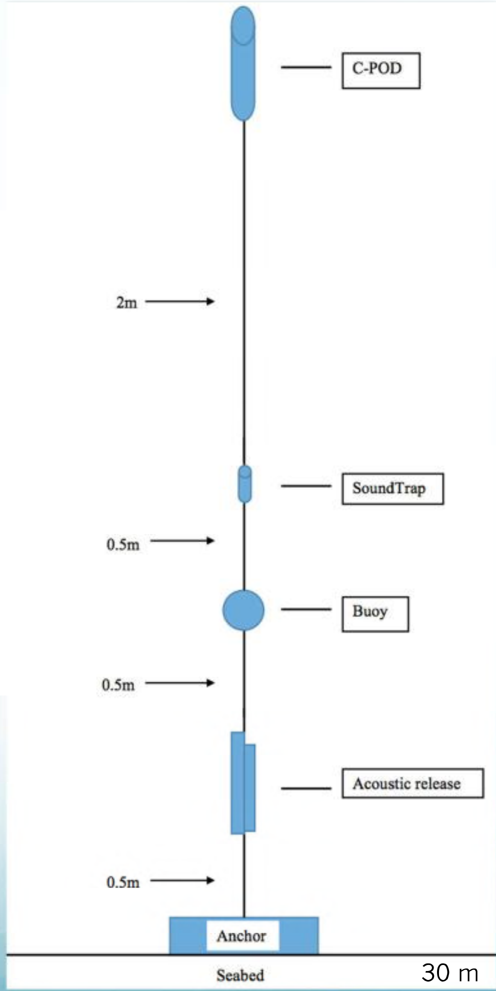
What are we talking about?





Methodology





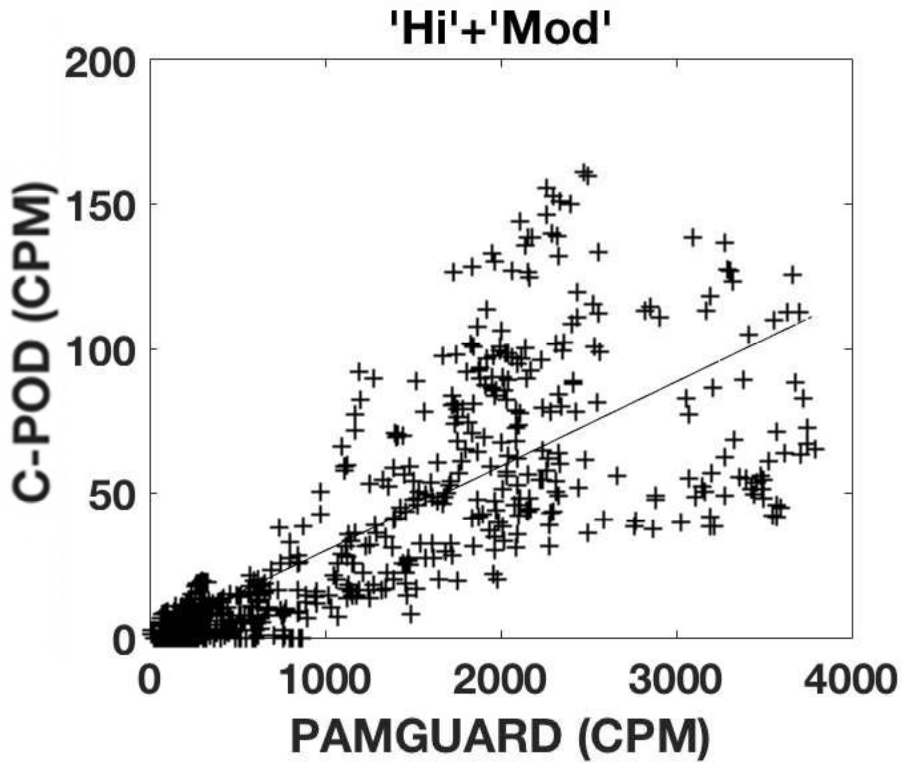
Standard settings:

- C-POD: quality 'Hi', 'Hi'+'Mod', 'Hi'+'Mod'+'Lo'
- PAMGuard: Porpoise Click Detection

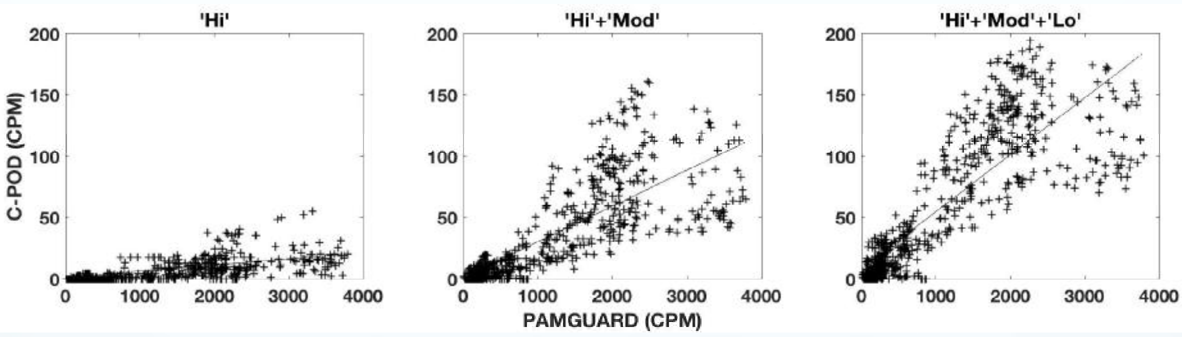
clicks per minute (CPM)

Results

Comparison of clicks per minute detected by C-POD and PAMGuard

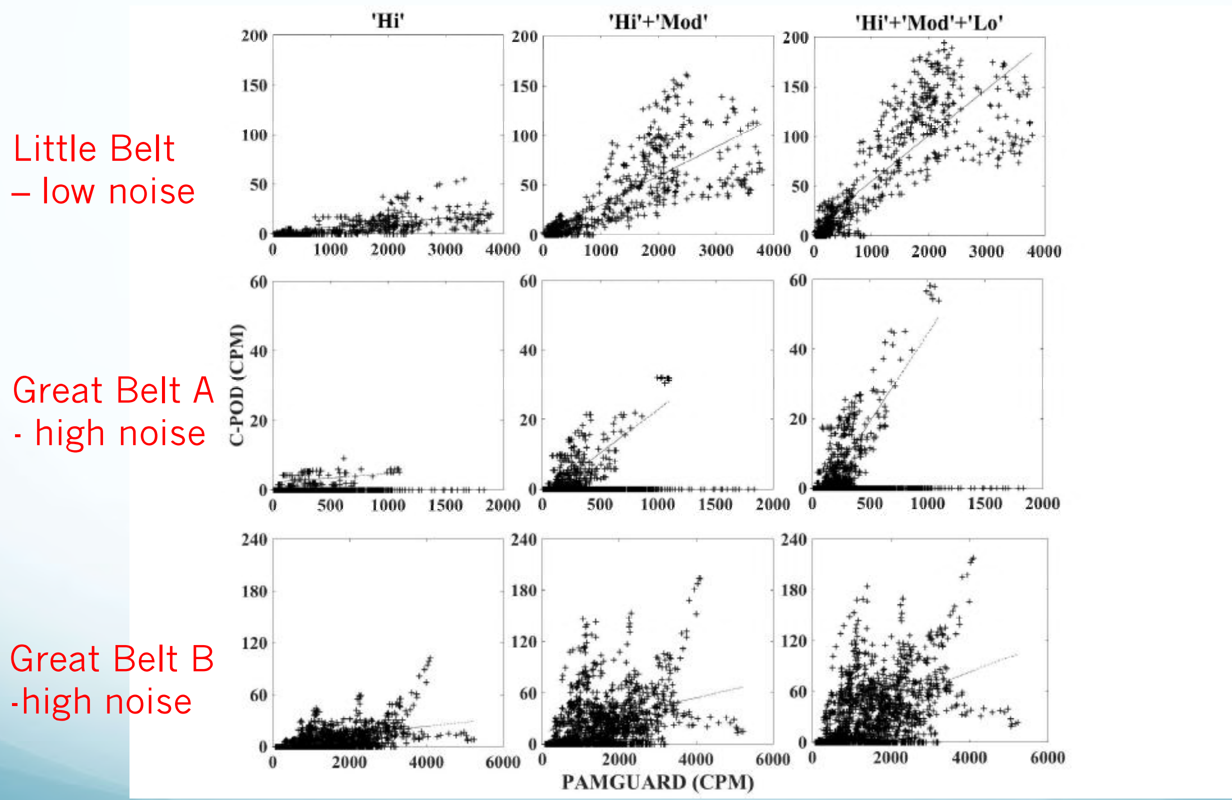


Comparison of clicks per minute detected by C-POD and PAMGuard from Little Belt. Clicks per minute were averaged over 10 minutes

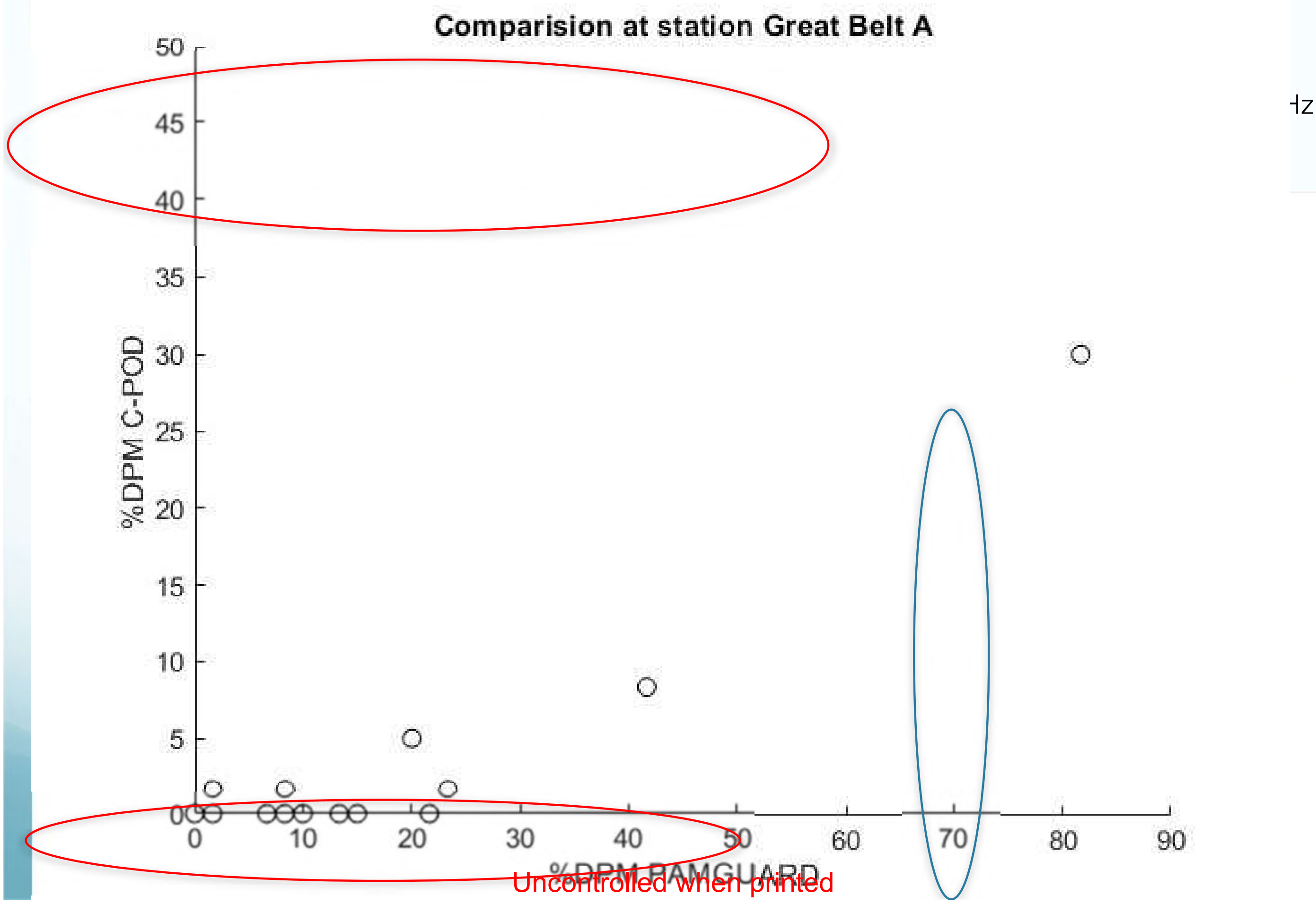


Uncontrolled when printed

Comparison of clicks per minute detected by C-POD and PAMGuard within three representative deployments. Clicks per minute were averaged over 10 minutes



Great Belt A, %DPM Detection positive minutes per hour (at least 5 clicks in the minute)



Conclusions

C-POD vs PAMGuard

C-POD

- + running time: continously 5 – 6 months
- + easy to use, automated
- + standard guideline for visual validation of click trains available online
- + low false detection rate
- - all C-POD filters are conservative and miss a lot of clicks
- - not possible to adjust Kerno classifier for different ambient noise levels
- - classifier is a black box thus difficult to validate results

PAMGuard

- + full control by the user
- + possible to adjust porpoise's detector relative to the ambient noise
- + possible to view analysis in Pamguard Viewer Mode, readjust settings and reanalyze clicks
- + high probability of detection
- - more difficult to use
- - bigger risk of false positives (based on single clicks)
- - no standard guideline for visual validation available online

Summary

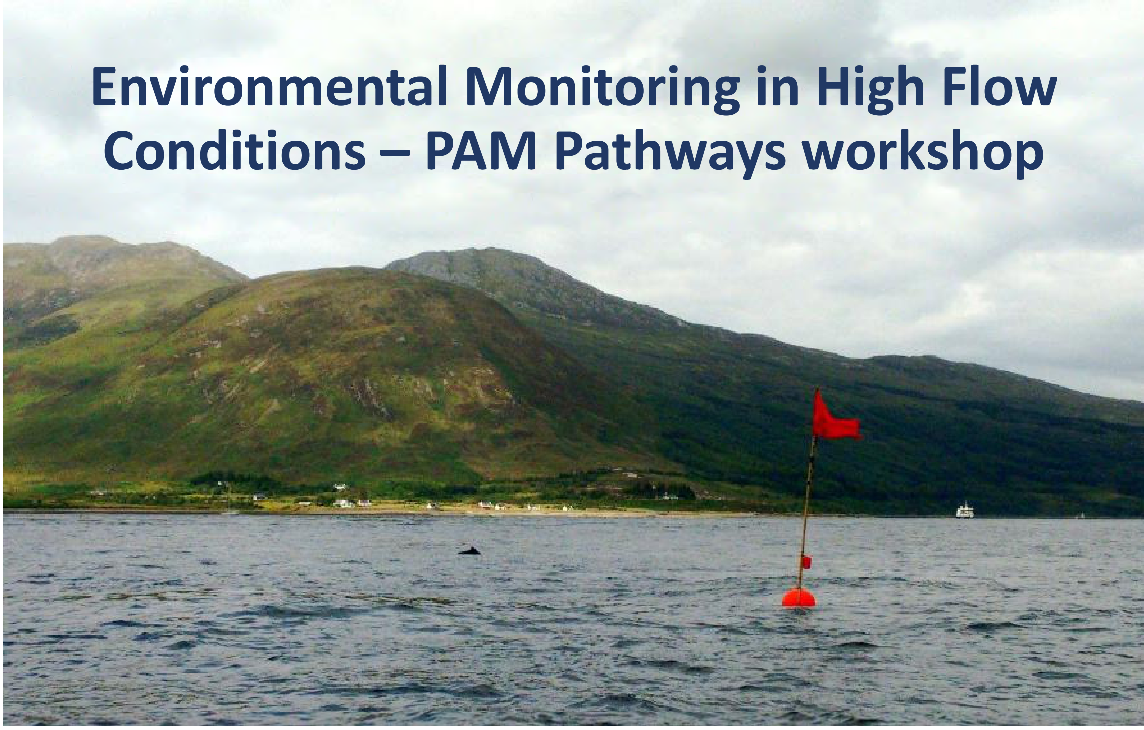
- The two systems correlated well under low noise conditions (Little Belt), but not in high noise conditions (Great Belt).
- Any detector's performance is affected by the background noise level and it will never be 100% accurate
- Both systems have pros and cons

Thank You for listening!

MARENCO
Marine Environmental Consulting

Uncontrolled when printed

Environmental Monitoring in High Flow Conditions – PAM Pathways workshop



@c_malinka
Chloe.e.malinka@gmail.com

EMEC/OERA PAM Pathways online workshop

Chloe Malinka
30/04/2020

Chloe Malinka 30/04/2020

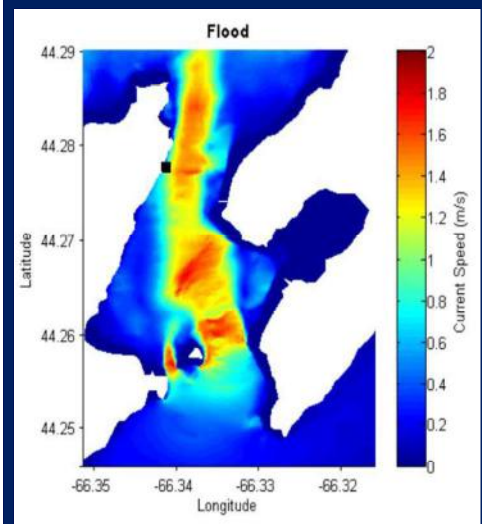
Passive
Acoustic
Monitoring

2

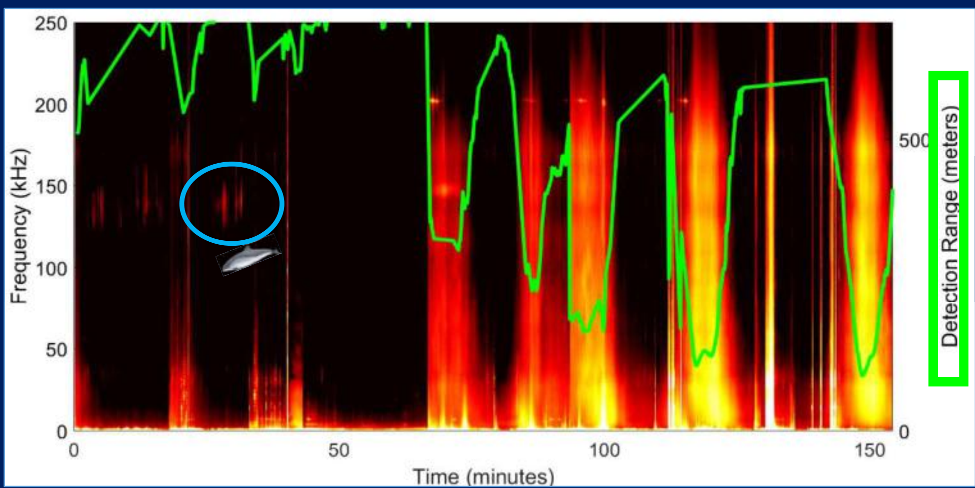
Relevant projects involved with in past:

- Noise & baseline MM surveys, **Fundy Tidal Inc.**
- Drifting vertical arrays in tidal races (**NERC Porpoise Localising Array Buoy**)
- PAM (*Passive Acoustic Monitoring*) analysis from moored **HiCUPs**, **SGDS** project
- PAM analysis from operational DeltaStream turbine, **Tidal Energy Ltd.**, Ramsey Sound, Pembrokeshire

To do PAM effectively, we need to know the soundscape… The soundscape of a tidal rapid is complex.



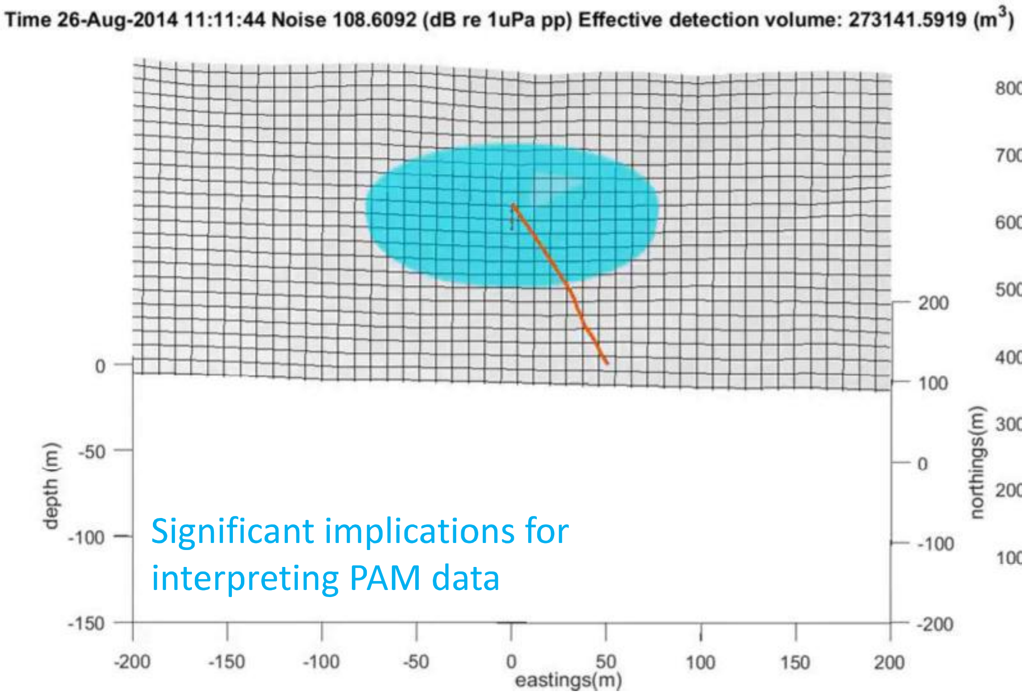
Malinka *et al.* 2015. Grand Passage, NS.
Figure by Justine McMillan.
Shout out to Greg Trowse's drifter work in GP.



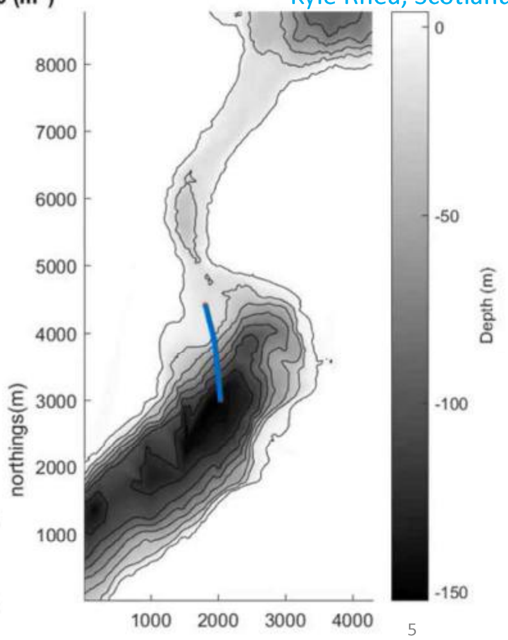
Macaulay *et al.* 2017. Kyle Rhea, Scotland.

Chloe Malinka 30/04/2020

Consequences of complex soundscapes for PAM



Kyle Rhea, Scotland.



Significant implications for interpreting PAM data

Chloe Malinka 30/04/2020

Methodological implications of complex soundscape for PAM

Click Logger vs. *Full Bandwidth Recorders*

E.g. CPOD (*Chelonia Ltd.*)

↓

Proprietary software

↓

Click counts

↓

Animal presence/ absence

Max 1 yr

E.g. SoundTrap (*Ocean Instruments NZ*), icListen (*Ocean Sonics*)

↓

Analyse however you like (*e.g.* open source toolbox such as PAMGuard*)

Dolphin/Porpoise clicks, buzzes
Dolphin whistles
Unexpected sounds
Noise

Animal presence/ absence
Acoustic detectability
Animal density
Other factors impacting behaviour

Max 6 mo

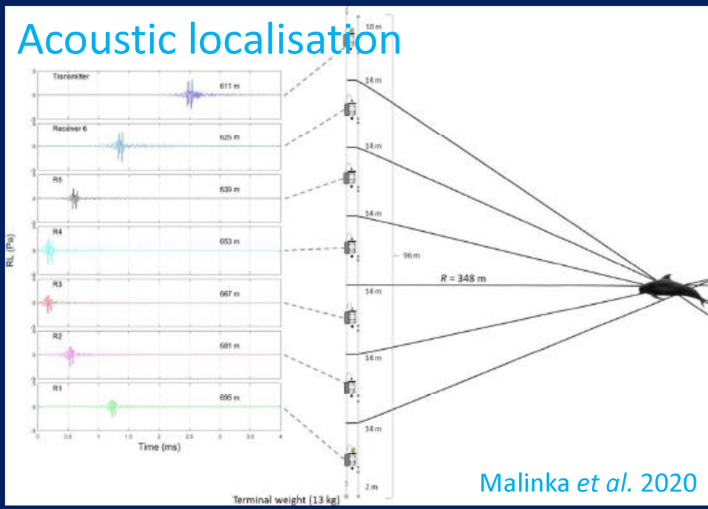
PAMGUARD

- (Gillespie *et al.* 2008)
- www.pamguard.org
- Real-time operation
- Automatic Detection, Classification, Localisation

Chloe Malinka 30/04/2020

Single hydrophone vs. multiple hydrophones

- Pre-turbine single-channel recordings
  - Animals presence/ absence;
  - Site-specific encounter rates at seasonal and diurnal scales
    - → for exemplar of this, see upcoming Palmer *et al.*



Malinka *et al.* 2020

- Can use PAM to explore *more than* just presence/absence
  - 2 [time-synchronised] hydrophones → bearing to animal
  - 4 … …→ 3D coordinate of animal

- → Could use PAM to explore behavioural impacts of turbines (before & after) with arrays (multiple time-synchronised hydrophones)

7

Chloe Malinka 30/04/2020

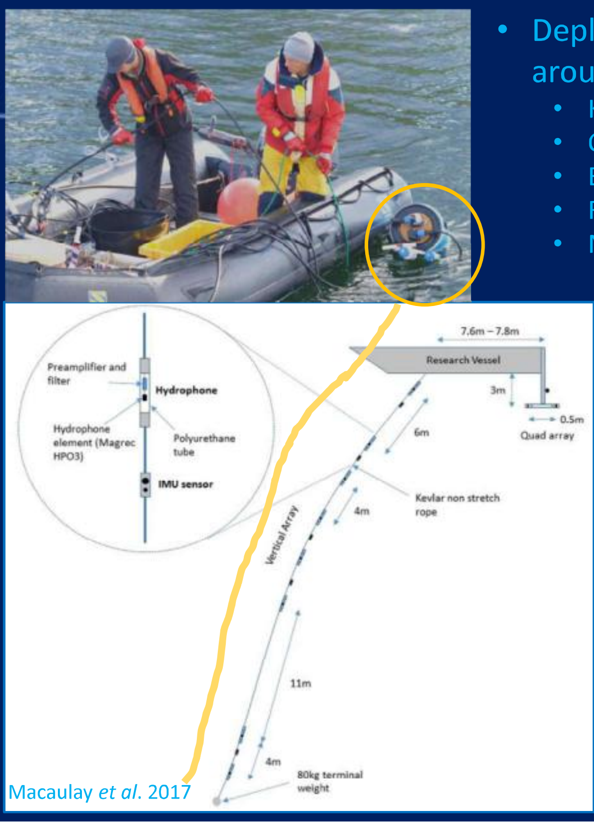
Pre-Turbine Monitoring

"Vertical array"

= series of multiple time-synchronised hydrophones

→ allows for acoustic localisation

- Drifting configuration reduces flow noise artefacts



Macaulay *et al.* 2017

- Deployed at tidal races around UK, pre-turbine
  - Kyle Rhea
  - Corryvreckan
  - Eynehallow Sound
  - Falls of Warness
  - Near Holyhead, Wales

- ☺ Fine-scale 3D geo-referenced localisations & animal behaviours

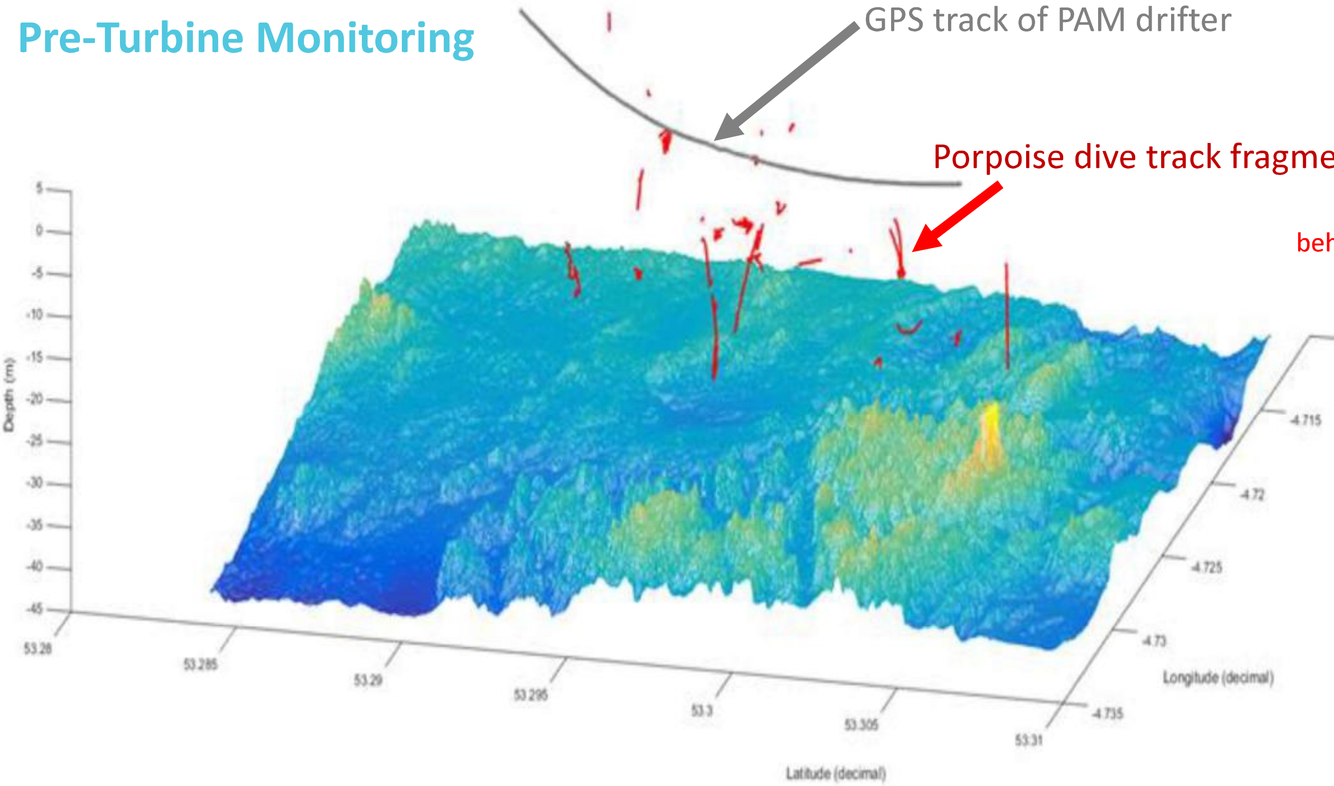
- ☹ Difficult tech, required experts to assemble

8

Uncontrolled when printed

Chloe Malinka 30/04/2020

Pre-Turbine Monitoring



Acoustic behaviours too (*e.g.* "buzz" used in foraging contexts)

From data collected with Gemma Veneruso (Bangor University) in Welsh waters

9

Chloe Malinka 30/04/2020

Monitoring once turbine in water

What a handy PAM platform!

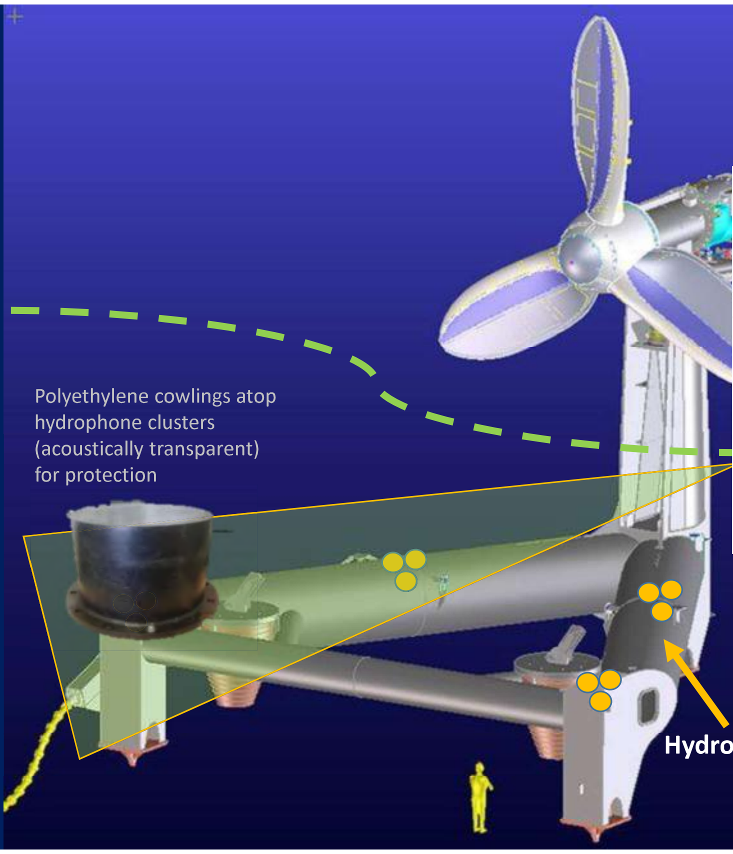
- *DeltaStream* turbine, Tidal Energy Ltd.
- Ramsey Sound, Pembrokeshire, Wales
- Deployed: Dec 2015
- Moored 12-hphone PAM system
- 3 months of acoustic data

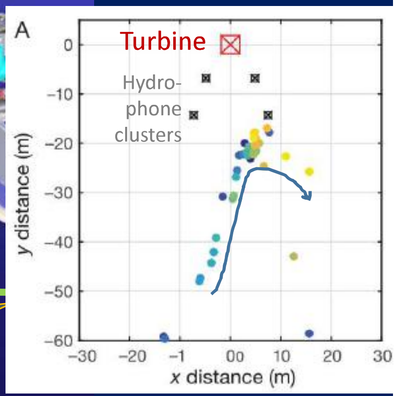
✶ PAM array at operational turbine

10

Chloe Malinka 30/04/2020

- Data digitised on NI DAQ chassis on turbine base
- Sent via fibre optic cable to shore
- Raw acoustic data compressed 99%
- Supervised acoustic validation





Malinka *et al.* 2018 (prototype project)

(MeyGen: see upcoming Gillespie *et al*. for more behaviours from larger dataset)

11

Chloe Malinka 30/04/2020

AARHUS UNIVERSITY

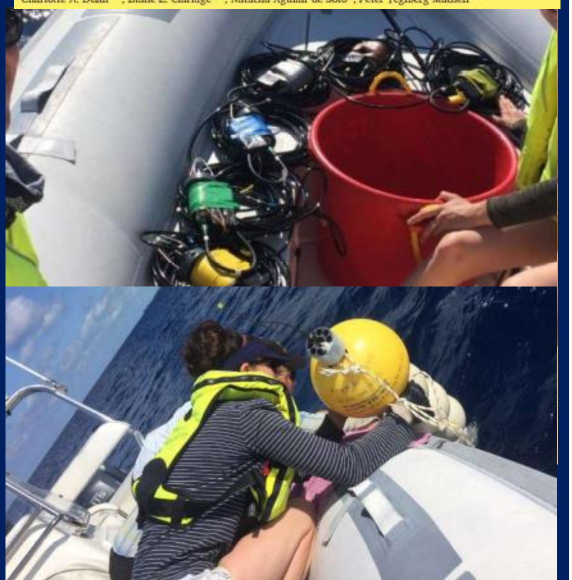
Tech advancements

- Build your own vertical array using off-the-shelf components
- Time-syncing with sync pulse in cable
- Benefits
  - Autonomous, deep-friendly
  - High sample rate (up to 576 kHz)
  - Highly portable: Can fit in laundry basket

Deep-Sea Research Part I

An autonomous hydrophone array to study the acoustic ecology of deep-water toothed whales

Chloe E. Malinka, John Atkins, Mark P. Johnson, Pernille Tønnesen, Charlotte A. Dunn, Diane E. Claridge, Natacha Aguilar de Soto, Peter Teglberg Madsen



12

With thanks to:

Chloe.e.Malinka@gmail.com
@c_malinka

Colleagues

- NS-based work
  - Prof Alex Hay
  - Greg Trowse
  - Richard Cheel
  - Dr Justine McMillan
- UK-based work
  - Dr Doug Gillespie
  - Dr Carol Sparling
  - Dr Jamie Macaulay
  - Dr Jonathan Gordon
  - Dr Simon Northridge
  - Alex Coram
  - Dr Gordon Hastie
  - Dr Ruth Joy
  - Laura Palmer
  - Gemma Veneruso
- DK-based work
  - Prof Peter Madsen
  - Dr Mark Johnson
  - John Atkins

*** Check out **EIMR** conference (online last week) for more talks:*

www.uhi.ac.uk/en/research-enterprise/events-and-seminars/eimr/eimr-2020/

Institutions, Collaborators, Funders

Sea Mammal Research Unit
University of St Andrews
Dalhousie University
Aarhus University
SFU
Pamguard
Danish Acoustical Society
Oticon Fonden
SMRU Consulting
Tidal Energy
OceanInstruments NZ Acoustic Monitoring Systems
ERDF – Welsh Government – Europe & Wales: Investing in your future – European Regional Development Fund
OERA Offshore Energy Research Association
EMEC The European Marine Energy Centre Ltd
Fundy Tidal Inc.
force
Ocean Sonics
Carbon Trust
Department of Energy & Climate Change
NERC Science of the Environment
The Scottish Government

Chloe.e.Malinka@gmail.com
@c_malinka

References

Gillespie, D., Mellinger, D.K., Gordon, J.C.D., Mclaren, D., Redmond, P., Mchugh, R., Trinder, P., Deng, X.Y., Thode, A., 2008. PAMGUARD: Semiautomated, open source software for real-time acoustic detection and localisation of cetaceans. Journal of the Acoustical Society of America 30 (5), 54-62. doi: http://dx.doi.org/10.1121/1.4808713

Macaulay, J.D.J., Gordon, J.C.D., Gillespie, D., Malinka, C.E., Johnson, M.P., Northridge, S., (**2015**). Tracking harbor porpoises in tidal rapids: a low cost autonomous platform to track the movement of harbor porpoises in tidal rapids. Sea Mammal Research Unit, NERC Knowledge Exchange Report., p. 32. https://risweb.st-andrews.ac.uk/portal/en/researchoutput/tracking-harbor-porpoises-in-tidal-rapids(59db2edc-84f2-4060-98e3-c207b78ca008)/export.html

Macaulay, J.D.J., Gordon, J.C.D., Gillespie, D., Malinka, C.E., Northridge, S., (**2017**). Passive acoustic methods for fine-scale tracking of harbour porpoises in tidal rapids. Journal of the Acoustical Society of America 141 (2), 1120-1132doi: http://dx.doi.org/10.1121/1.4976077

Macaulay, J., Malinka, C., Coram, A., Gordon, J. & Northridge, S., (**2015**). MR7-1-2. The density and behaviour of marine mammals intidal rapids. Report by Sea Mammal Research Unit (SMRU), p. 53. doi: 10.13140/RG.2.2.26623.82089 http://www.smru.st-andrews.ac.uk/documents/scotgov/MR7-1-2_porpoise_in_tidal_rapids_VF1.pdf

Malinka, C.E., Atkins, J., Johnson, M.P., Tønnesen, P., Dunn, C.A., Claridge, D.E., de Soto, N.A., Madsen, P.T., (2020). An autonomous hydrophone array to study the acoustic ecology of deep-water toothed whales. Deep Sea Research Part I: Oceanographic Research Papers 158C, 103233doi: https://doi.org/10.1016/j.dsr.2020.103233

Malinka, C., Cheel, R., Hay, A.E., (**2015**). Towards Acoustic Monitoring of Marine Mammals at a Tidal Turbine Site: Grand Passage, NS, Canada. European Wave and Tidal Energy Conference (EWTEC), Nantes, France, p. 10. doi: 10.13140/RG.2.1.1991.3365

Risch, D., Geel, N.v., Gillespie, D., Wilson, B., 2020. Characterisation of underwater operational sound of a tidal stream turbine. The Journal of the Acoustical Society of America 147 (4), 2547-2555•doi: 10.1121/10.0001124

Sparling C, Gillespie D, Hastie G, Gordon J, Macaulay J, Malinka C, Wu M, McConnell B, (**2016**). Scottish Government Demonstration Strategy: Trialling Methods for Tracking the Fine Scale Underwater Movements of Marine Mammals in Areas of Marine Renewable Energy Development In: Science, M.S. (Ed.), Scottish Marine and Freshwater Science. Sea Mammal Research Unit, p. 114. doi: 10.7489/1759-1

Passive acoustic monitoring at the Meygen tidal turbine array, Scotland Lessons Learned

Douglas Gillespie (1*), Laura Palmer (1), Jamie Macaulay (1), Carol Sparling (2), Gordon Hastie (1)

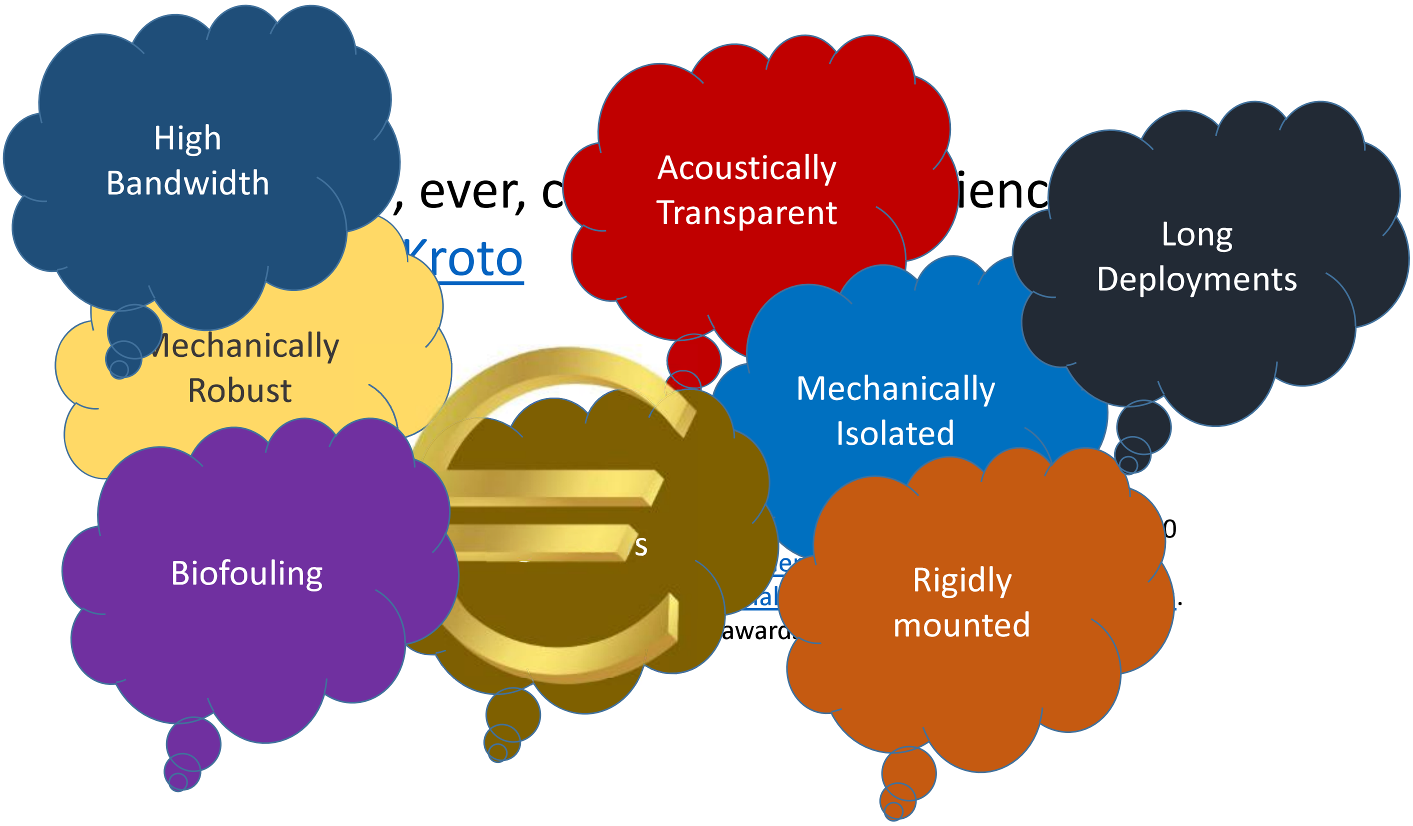
(1) Sea Mammal Research Unit, Scottish Oceans Institute, University of St Andrews, KY16 8LB, Scotland

(2) SMRU Consulting, Scottish Oceans Institute, University of St Andrews, KY16 8LB, Scotland

Never, ever, compromise on science.

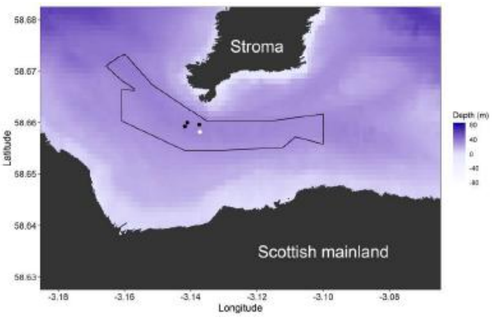
Harry Kroto

Sir Harold Walter Kroto FRS[3][4] (born **Harold Walter Krotoschiner**; 7 October 1939 – 30 April 2016), known as **Harry Kroto**, was an English chemist. He shared the 1996 Nobel Prize in Chemistry with Robert Curl and Richard Smalley for their discovery of fullerenes. He was the recipient of many other honors and awards.



The Mission …

- To monitor small cetaceans at an operational turbine in the Pentland Firth for a minimum one year
  - 10 knot current, Far from shore
  - High frequency species (harbour porpoise)
  - Monitoring system integrated into turbine for power and comms
- Lessons learned from TEL / Ramsey Sound deployment
  - Integrating systems into turbine infrastructure works and allows for long deployments
  - Early discussions with turbine engineers essential
  - Hydrophones needed greater mechanical protection
  - Off shelf DAQ system wasn't entirely reliable (part due to shared Ethernet)
  - Redundancy important
  - More redundancy better!



Funding Scottish government MMSS/002/15

marinescotland Scottish Government gov.scot

Sea Mammal Research Unit

SIMEC ATLANTIS ENERGY

University of St Andrews

Uncontrolled when printed

University of St Andrews

Our Hydrophones…

- Made our own with ceramics from China
- Potted and mounted on tetrahedral mounts
- In house preamps (Mark Johnson)
- Solid potted to power and signal cable
- Bolted to 10mm polyethylene bases
- Polyethylene hard hats for mechanical protection
- Plywood ‘under-base’ to reduce reflections from structure

3 years later: still detecting!

Sea Mammal Research Unit

University of St Andrews

Sea Mammal Research Unit

Acquisition System

- TEL used Compact DAQ

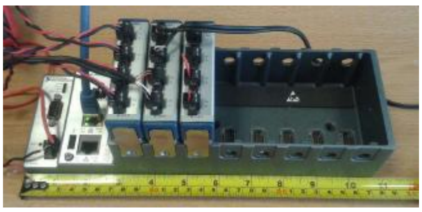
Plug n Play out of the box

Plug n Play into even old versions of PAMGuard

Unstable ‘off the bench’ and fell over with the slightest network delay.

Could only handle 8 channels maximum

- Meygen system used Compact RIO



Extensive programming of FPGA front end, c/c++ code of on-board ARM processor to pack data and stream to network socket

New module in PAMGuard to receive and unpack data + control the Linux shell on the CRIO

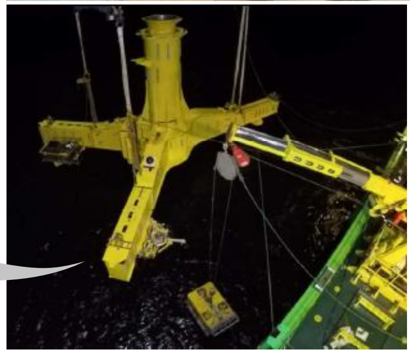
30s buffer built into to the C code, so didn’t care about brief network ‘glitches’

12 Channels. 100% reliability

SOURCEFORGE

Installation and Deployment

- PAM (and other components) dry-mate cabled to turbine prior to installation
- Extensive cooperation from Meygen engineers
- Costs to Meygen:
  - Time
  - One wet mate connector
  - Mechanical integration costs
- One way trip to the bottom
- No option for maintenance



SIMEC ATLANTIS ENERGY

Sea Mammal Research Unit

University of St Andrews

Data processing chain …

Crio
FPGA code
C++ Code

PAMGuard control of CRio

Raw data (1 Terabytes/day)

Desktop in Substation
PAMGuard
PAMDog

Detection data 3 Gigabyte/day

Regular checks

PC's in St Andrews
PAMGuard
Matlab / R

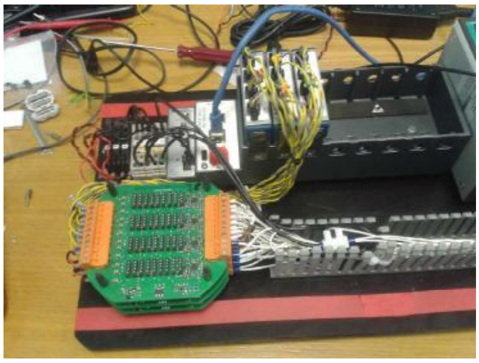
PC's in St Andrews
Google remote desktop

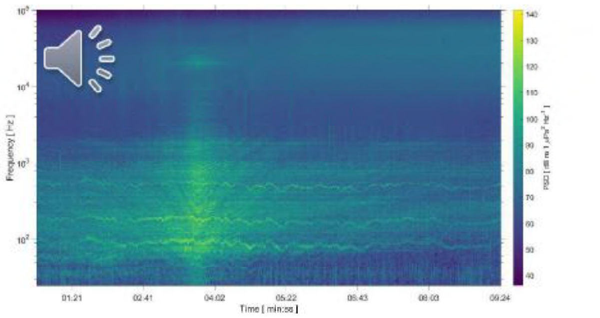
Cloud storage

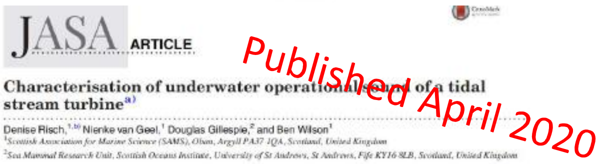
Noise Noise Noise

- Filter and Gain settings
  - Too high = saturation
  - Too low = less sensitivity
  - Little data on expected noise => Lost sleep

Etec variable gain preamplifiers






JASA ARTICLE

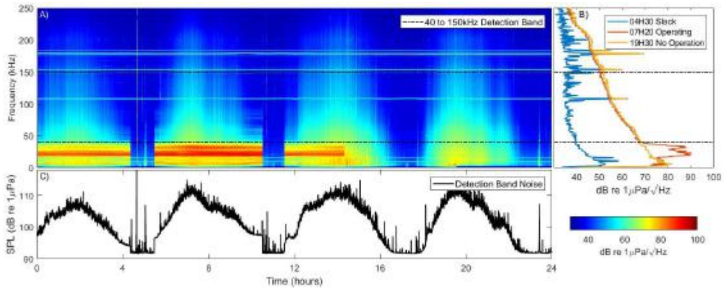
Characterisation of underwater operational sound of a tidal stream turbine[a)]

Denise Risch,[1,b)] Nienke van Geel,[1] Douglas Gillespie,[2] and Ben Wilson[1]

[1]Scottish Association for Marine Science (SAMS), Oban, Argyll PA37 1QA, Scotland, United Kingdom

[2]Sea Mammal Research Unit, Scottish Oceans Institute, University of St Andrews, St Andrews, Fife KY16 8LB, Scotland, United Kingdom

Published April 2020



- High Frequency noise from turbine
- Noise dominated by tidal flow

Analytical Challenges

- Noise
  - Untangle reduced detections from high noise and reduced detections from there being fewer animals.
  - See Laura Palmer EIMR presentation: Threw away all quiet clicks, to provide constant absolute detection threshold
- Biofouling ?
  - Still detecting after 3 years, but with what efficiency ?
- Processing Time
  - Still labour intensive
  - Can use current data to build better automation
  - Beware of over automation – overtraining and missing the unexpected.

Sea Mammal Research Unit

University of St Andrews

Results

- See EIMR presentations by Laura Palmer, Doug Gillespie and Denise Risch
- Search EIMR 2020, find online presentations
- Session 3: Presence and behaviour around devices (George Lees, SNH: “The session was to have been the highlight of the conference”)

1. Strong seasonal and diurnal variation in presence
2. Evidence of avoidance when turbine operates
3. Evidence of fine scale evasion of rotors

Sorry !

Plots redacted pending publication

Sea Mammal Research Unit

University of St Andrews

Project Outputs

Two technical papers describing system

Douglas Gillespie and Jamie Macaulay: JASA Express Letters https://doi.org/10.1121/1.5129678 Published Online 23 October 2019

Time of arrival difference estimation for narrow band high frequency echolocation clicks

Douglas Gillespie and Jamie Macaulay
Sea Mammal Research Unit, Scottish Oceans Institute, University of St Andrews, St Andrews, KY16 8LB, Scotland

Abstract: Algorithms are presented for the accurate time of arrival difference estimation of high frequency narrow band echolocation clicks from Harbor Porpoise. These clicks typically have a center frequency of around 130 kHz (wavelength ~1.2 cm) and duration of <0.1 ms. When using hydrophones spaced centimeters apart, spatial aliasing can cause large errors on inter-hydrophone timing measurements due to the incor-

Published

Passive acoustic methods for tracking the 3D movements of small cetaceans around marine structures

Douglas Gillespie, Laura Palmer, Jamie Macaulay, Carol Sparling, Gordon Hastie
doi: https://doi.org/10.1101/2020.01.30.926659

This article is a preprint and has not been certified by peer review [what does this mean?].

Abstract | Full Text | Info/History | Metrics | Preview PDF

Abstract

A wide range of anthropogenic structures exist in the marine environment with the extent of these set to increase as the global offshore renewable energy industry grows. Many of these pose acute risks to marine wildlife, for example, tidal energy generators have the potential to injure or kill seals and small cetaceans through collisions with moving turbine parts. Information on fine scale behaviour of animals close to operational turbines is required to understand the likely impact of these new technologies. There are inherent challenges associated with measuring the underwater movements of marine animals which have, so far, limited data collection. Here, we describe the development and application of a system for monitoring the three-

In review

Coming Soon

Laura Palmer et al. **Harbour porpoises (*Phocoena phocoena*) avoid operational tidal turbines**

Fine Scale results …

Harbour porpoises exhibit localised evasion of tidal turbines
Douglas Gillespie, Laura Palmer, Jamie Macaulay, Carol Sparling , Gordon Hastie

JASA ARTICLE

Published

Characterisation of underwater operational sound of a tidal stream turbine[a)]

Denise Risch,[1,b)] Nienke van Geel,[1] Douglas Gillespie,[2] and Ben Wilson[1]
[1]*Scottish Association for Marine Science (SAMS), Oban, Argyll PA37 1QA, Scotland, United Kingdom*
[2]*Sea Mammal Research Unit, Scottish Oceans Institute, University of St Andrews, St Andrews, Fife KY16 8LB, Scotland, United Kingdom*

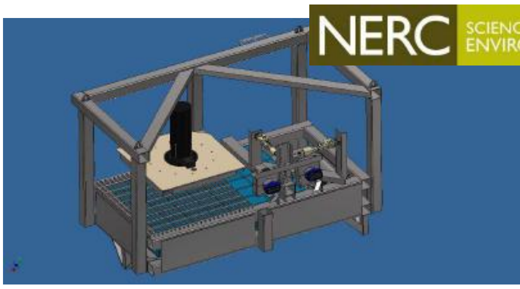
University of St Andrews

Lessons Learned & Next Steps

- The PAM system operated very successfully
  - Two years of data
  - 11 out of 12 hydrophones still operating
  - 99% uptime when auxiliary power available from the turbine
- Hard Hat cowlings?
  - Acoustic data show some reflections
  - Still collecting good data nearly three years after deployment
- Other sensors (Multibeam sonar and cameras) failed due to corrosion
  - Unable to maintain equipment
  - Super expensive wet mates would have been a good idea

- Current system now decommissioned
- New NERC funded platform
- Two Tritech multi-beam sonar (for seals)
- One PAM cluster
- Deploying late 2020

NERC SCIENCE OF THE ENVIRONMENT



Sea Mammal Research Unit

Scottish Government gov.scot

University of St Andrews

Thanks …

- The Scottish Government for funding for the environmental monitoring
- Many co workers at the Sea Mammal Research Unit (Carol Sparling, Gordon Hastie, Joe Onoufriou, Laura Palmer, Jamie Macaulay, Sophie Smout, Debbie Russell, Simon Moss, Steve Balfour, and Matt Bivins (among others)
- The engineering team at Simec Atlantis who enabled the project and integrated the environmental monitoring system into their turbine (Lorna slater, Bruce Mackay and many others)
- Scot. Gov. steering group: Elaine Tait (MSPaP), Paul Thompson (UoA), Kelly Macleod (JNCC), Janelle Braithwaite (MSPaP), Roger May (MSLOT), Ian Davies (MSS), Ross Culloch (MSS), John Armstrong (MSS), Jared Wilson (MSS), Ewan Edwards (MSS), Denise Risch (SAMS), George Lees (SNH), Erica Knott (SNH), Chris Eastham (SNH), Karen Hall (SNH), Cara Donovan (Atlantis), and Lily Burke (MSPaP)

Sea Mammal Research Unit

SOURCEFORGE
The Complete Open-Source Software Platform