Appendix V

Passive acoustic monitoring in tidal channels and high flow environments

Passive Acoustic Monitoring in Tidal Channels and High Flow Environments

Report for OERA/FORCE, The Pathway Program

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I. Introduction

This report provides an overview of methods, data processing techniques, and equipment used to make passive acoustic measurements in tidal channels. The acoustic field is measured in these energetic environments to characterize the natural noise field, quantify contributions by tidal energy and other human deployed devices, and to detect and localize vocalizing marine animals, the latter being the primary objective of interest in this report. No commercially available, purpose built acoustic monitoring systems have been designed for operation in turbulent tidal channels, estuaries, or rivers, despite a growing body of underwater acoustic field work being carried out in the context of environmental impact assessment of tidal energy extraction. However, a number of technologies designed for more benign oceanographic conditions have been experimentally deployed in high flow environments, including conventional cabled or autonomous hydrophone and analogue-to-digital instrument packages, internally recording hydrophones with digital interfaces, autonomous and cabled hydrophone or vector sensor arrays, and integrated hydrophone and data processing systems for marine animal detection. Flow noise, natural ambient noise, sensor size and geometry, and deployment method all have an effect on the detection efficiency of passive acoustic systems. Experimental results and system performances are compared across all instrument package types, deployment methods, and study areas.

The primary scientific and engineering challenge while working in a turbulent flow environment is the identification and mitigation, either through mechanical or signal conditioning means, of the pseudo-sound (flow noise) generated by pressure fluctuations due to turbulent flow on the surface of the hydrophone. The magnitude, spectral shape, and bandwidth of the flow noise depends on the flow speed and effective shape of the hydrophone. Mechanical solutions are proposed, such as the deployment of sensors on Lagrangian drifting floats in place of fixed moorings, and the use of flow shields, baffles, and vibration isolation mounts to minimize the flow noise generated. Coherent processing of acoustic signals recorded on multiple sensors has also been demonstrated as a method to reduce incoherent flow noise while providing gain to acoustic signals propagating in the water.

In tidal channels and rivers, flow noise can potentially mask true propagating sound into the 10's of kilohertz band, with increasing intensity with decreasing frequency. This makes the characterization of ambient noise and quantification of turbine and industrial noise challenging to measure and reduces the effective range of detection of vocalizing marine animals.

The similarity between the deployment of passive acoustic systems in tidal channels and from moving vessels is suggested, the latter being the subject of several decades of research while the former is still in relative infancy. Novel uses of autonomous vehicles may also present a solution to the large field effort required for sustained, flow noise free, passive acoustic monitoring in high flow environments.

Tidal turbines could become an important source of ambient noise in tidal channels through cavitation and motor or mechanical noise (Wang, 2007). Turbine anthropophony could affect animal navigation, communication, predator-prey detections (Lombardi, 2016), and marine life cycles (Pine, 2012). Moreover, turbine-generated sound could be damaging to fish tissue (Halvorsen, 2011). If substantive, these effects would threaten near-field and far-field ecosystem health, stressing the need for rigorous environmental impact assessments in the tidal power sector.

The report is organized as follows: Section II discusses the physics of flow noise and potential methods of identification and mitigation; Section III surveys studies in passive acoustic monitoring in high flow environments that have been previously carried out and compares the two primary methods of deployment (fixed and drifting sensors); Section IV describes marine animals of interest and compares the methods and instruments for detecting, classifying, and localizing them; Section V provides a summary, recommendations, and conclusions.

II. Flow noise and self-noise identification and mitigation

A. Flow noise

Turbulent flows occupy a wide range of frequencies and wavenumber domains, with broad spatial and temporal variability. The advective nonlinearity of turbulent flows, combined with the variety of effective shapes that a sensor and instrument housing may present, makes them unpredictable in space and time and contributes to their complex nature (M. Van Dyke, 1982) (Finger, 1979). As such, it is difficult to reliably model flow noise.

Bassett (Bassett, 2013), applied the findings from three Strasberg papers on hydrodynamic flow noise and wind screen noise (Strasberg, 1979, 1984, 1988) to predict the upper frequency limit for flow noise, noting that it is related to the wavelengths of the spatial velocity fluctuations and the mean velocity of the flow, u, by $f = |u|\ \eta^{-1}$, where η is the Kolmorgorov microscale. The microscale describes the length scale at which viscosity overcomes the turbulent fluctuations, and is practically related to the dissipation rate, ε, and the kinematic viscosity, ν, by $\eta = (\nu^3/\varepsilon)^{0.25}$. While the viscosity difference between sea water and fresh water is small (~ 90%), the dissipation rate has large variability, with reported peak dissipation rate of $2\text{x}10^{-3}$ m^2 s^{-3} at Admiralty Inlet, Washington (Thomson 2012), and order $1\text{x}10^{-3}$ m^2 s^{-3} measured in Grand Passage, Nova Scotia (Guerra-Paris, 2019), both several orders of magnitude greater than typical rates in the open ocean. For the particular case of Admiralty Inlet, WA, the maximum theoretical frequency at which flow-noise is expected was 10 kHz. In practice, the scale of the sensor itself plays an important role in lowering that upper frequency limit.

In the idealized circumstance of an infinitesimally small sensor, flow noise would follow a spectral slope of $f^{-5/3}$, behaviour that is analogous by Kolmogorov's turbulence theory. This flow noise is not to be confused with wind-generated noise that produces $f^{-5/3}$ spectral slopes at higher frequencies (Knudsen, 1948). Bassett et al. (Bassett, 2014) identifies $f^{-5/3}$ flow noise below 20 Hz and describes steepened spectral slopes, f^{-m} where $m > 5/3$, at low-to-mid frequencies. Lombardi (Lombardi, 2016) identifies these steep spectral slopes in measurements from the Grand Passage tidal channel. The flow noise that produces f^{-m} is a result of small-scale turbulence being averaged out across the surface of a finite sized hydrophone, typically several orders of magnitude larger than the microscale, which dampens (or reduces) the measured flow noise as frequency increases.

B. Identification of flow noise

Flow noise is always 'red' (decreasing in intensity with increasing frequency), so the upper limit of the flow noise bandwidth, or the critical frequency where the intensity of the flow noise is equal to the intensity of the true sound or noise, is of primary interest. Below the critical frequency, flow noise masks the true sound that would otherwise be measured by the sensor, while above the critical frequency the measurement can be considered to be uncontaminated by flow noise. Flow noise and natural, wave driven noise in the ocean have spectra that obey power laws, where the former depends on the length scale of the sensor. To determine the critical frequency, a break in the slope of the spectrum can be found computationally, or by inspection. This method is generally employed and carries with it some level of uncertainty.

When measurements are made with two or more sensors, the spatial coherence between them may be used to identify the critical frequency with high accuracy (Auvinen, 2019). Propagating ambient noise is highly correlated between two hydrophones placed less than a few wavelengths away. Additionally, propagating noise at wavelengths sufficiently large relative to sensor spacing produces very high coherence at low frequencies, since the hydrophones become effectively co-located. Conversely, flow noise is a source of incoherence, as pseudo-sound is uncorrelated between sensor, thus flow noise is marked by low coherence while ambient noise is marked by high coherence (Barclay, 2013). At low frequencies (below frequencies corresponding to half the sensor separation) the transit of this coherence boundary, from flow noise (incoherent) to ambient noise (coherent) provides a precise metric for describing the upper extent of the flow noise bandwidth.

In some instances, co-located measurements of static and Lagrangian (drifting) hydrophones have been made to determine the upper bandwidth limit of flow noise on the static device, assuming the free drifting sensor is flow noise free.

C. *Mitigation strategies for flow noise*

The dampening effect associated with sensor size can be exploited by choosing a cut-off frequency above which true sound must be measured and designing the receiver's surface to have an area on the order of the corresponding acoustic wavelength in the fluid. In the case of recording turbine noise over a bandwidth of interest with respect to fish and other low-frequency sensing marine life (~10 - 100's of Hz), the scale of such a sensor becomes impracticable. However, this mechanism has been theoretically developed and proposed for underwater surveillance applications. Ko demonstrated, for the particular case of flush mounted hydrophones as you might find on the hull of a submersible, that a careful choice of sensor shape, the application of an elastomer layer, and the combination of single hydrophones into an array can further reduce the effects of noise induced by a turbulent boundary layer flow (Ko, 1992, 1993). He further claims that the arrangement of array elements, including interelement spacing has little effect on the performance of the flow noise suppression.

For the case of tidal turbine monitoring, Auvinen (Auvinen, 2019) and Worthington (Worthington, 2014) demonstrated that linear arrays can be used to reduce flow noise in open channel turbulent flow. As the flow noise is generated locally on each sensor, it is independent from one sensor to the next, while true propagating sound will appear coherent across the array. By coherently averaging the received signals across the array, the flow noise is suppressed while the true sound is amplified.

Another method to reduce the impact of flow noise is to use a flow shield and isolation system where the hydrophone is encased in a larger structure, either semi-permeable with a very low hydraulic conductivity, or impermeable and oil-filled. These types of systems should have three purely mechanical effects on the reduction of pseudo-sound. Firstly, the flow of water over the hydrophone is eliminated by the shield acting as a baffle, along with any flow noise normally generated on the surface of the hydrophone. Vibrational noise will be generated on the shield, but as it is larger than the hydrophone, the upper frequency limit of flow noise is effectively lowered. Lastly, the hydrophone is suspended inside the shield using an isolation system that aims to minimize the vibrational energy transferred from the shield to the sensor. Without isolation, the flow shield may be wholly ineffective (Porskamp, 2015). These types of systems are extremely effective for in-air flow noise reduction, are commercially available, and seen in use by professional recording studios, and television news-people reporting in adverse weather conditions. It should be noted that conventional dynamic in-air microphones are not as sensitive as a ceramic hydrophone to vibrational energy propagating through the housing of the sensor, so an isolation system is usually not required and a fuzzy wind-sock attached directly fixed to the microphone can be quite effective. This is not the case with ribbon microphones or ceramic sensors, that should always employ suspension systems.

The spring constant needed for an effective isolation and suspension system is dictated by the wavelength. The resonance of the isolation system must be half the lowest desired resolvable (flow noise free) frequency. For frequencies on the order of 10^2 Hz, in water, where wavelengths are 5 times larger than in air, the suspension system becomes unreasonably large, as does the flow shield that encases it. As the size of the flow shield increases, so does the drag on the entire system and the problem is only practically tenable with careful engineering (e.g. dashpot suspension, hydrodynamic flow bodies). Additionally, the use of flow shields lowers the sensitivity of the hydrophone, requiring re-calibration, and reducing the effective listening range of a receiver (Malinka, 2015).

A simple method to minimize flow noise is to place the recording system in a region where flow speeds are minimized, such as very near the seabed, or out of the flow channel. In both cases, transmission loss between the turbine, animal, or source of interest must be well understood in order to determine a source level, or detection efficiency, as the study may require. As previous reports have identified (Environmental Effects Monitoring Programs, Fundy Ocean Research Center for Energy, March 2016), transmission loss in turbulent shallow water environments with high tidal flow is not well understood and must be further investigated. In the case of the depth-dependence of background (turbine-less) noise in Minas Passage, a comparison of median pressure spectral densities between a bottom-mounted recording with a steel and neoprene flow shield, a free-drifting near surface hydrophone with a simple suspension system, and two static mid-water column mounted hydrophones with no-shields or suspension was made (Martin, 2018). The measurements between the drifter and bottom mounted system were the most in agreement. The upper frequency limit of flow noise on the bottom mounted system was 60 Hz, while the un-shielded mid-water column phones had an upper frequency flow noise contamination limit of, optimistically, 600 Hz. Most importantly, the agreement between the drifter and the bottom mounted system suggests that the depth-dependence of ambient noise is minimal over the band of 60 Hz – 1 kHz.

To better understand the sound propagation loss in a turbulent tidal channel and thus the effective horizontal ranges of sources such as turbines, marine animals, active sonars, and passive acoustic monitoring systems, one experiment has been carried out in Admiralty Inlet, Washington, and two experiments were carried out in in Grand Passage, Nova Scotia. The Admiralty Inlet experiment showed reduced transmission loss during slack tide and compared the results to geometric spreading laws. In Grand Passage, 2015, a drifting source was deployed near moored hydrophones to determine the effective listening radius under different flow conditions and baffling arrangements, for that particular arrangement of recievers. In 2018, an active source and set of three receivers at distances between 100 m and 1.1 km were moored in Grand Passage. Linear frequency modulated sweeps, and pure tones were played every 30 minutes in an effort to quantify the effects of tidal state and mean and turbulent flow speed on transmission loss (Wilson, 2019). The analysis of the collected data is underway, along with the development of a validated transmission loss model for turbulent high mean flows.

D. Self-noise

Other forms of self-noise should also be taken into consideration when designing an experiment in a high flow environment. Systems suspended from surface floats will experience wave induced noise caused by vertical motion in the water column, unless an adequate isolation and suspension system is employed. Additionally, though drifting systems do an adequate job of removing the effects of the mean flow noise, the finite size of the drifting system may be subject to flow noise created by system motion due to turbulent flow and vertical sheer. One method employed to avoid this flow noise, or instrument motion noise, is to deploy the sensor inside of a drogue (Wilson, 2014). Moored systems with subsurface floats will suffer from cable strum, and noise induced by mooring knock down unless vortex shedding fairings, hydrophone isolation and suspension systems, and hydrodynamic floats are used. Bottom-mounted systems near the seabed are susceptible to turbidity currents. In high flow environments, sands and gravel have been observed to generate noise through contact directly on the instrument housing (Martin, 2018).

E. Conclusions

A review of the basic physics of flow noise, identification, and mitigation techniques for passive acoustic measurement methods in tidal channels has the following conclusions:

1) Due to high dissipation rates in tidal channels, flow noise can potentially mask sound over a very large bandwidth (0 – 10 kHz).
2) The bandwidth of flow noise contamination can be generally identified by looking for regions of changing slope in the noise spectrum, or more accurately by investigating the frequency dependent spatial coherence between adjacent sensors in an array. Comparisons between drifting measurements and static measurements can also be used to identify flow noise bandwidth
3) Increasing the size of a sensor lowers the upper frequency limit at which flow noise masks a measurement.
4) Measuring sound with a coherently averaged array of sensors lowers the upper frequency limit at which flow noise masks a measurement.
5) Placing shielded sensors near the bottom boundary where flow speeds are reduced mitigates flow noise.
6) The depth-dependence of ambient noise in a shallow water tidal channel (Minas Passage) is negligible over the band 100 Hz – 1 kHz. Transmission loss modelling in turbulent media is poorly understood.

III. Sensor deployment configurations

In 2013, two review papers were written covering all published acoustic environmental monitoring activity, the first by Robinson and Lepper based in the United Kingdom (Robinson, 2013) and the second by Copping et al., based in the United States of America (Copping, 2013). The latter study resulted in the Tethys database, an online resource collecting papers in the peer-reviewed and grey literature on the topic of marine energy extraction, and environmental monitoring and impacts. Both surveys discuss wave energy and tidal energy conversion devices, system source levels, installation noise levels including pile driving, and methods used for passive acoustic monitoring.

For this report, the work of Robinson & Lepper and Copping is updated and expanded, summarizing the various passive acoustic monitoring efforts in tidal channels, consisting of ambient noise baseline measurements, turbine operational noise, construction and installation noise, and planned transmissions, presented in Table 1. The configuration of equipment employed for each measurement campaign is classified generally as 1) boat drifting, 2) buoy drifting, 3) bottom moored or mounted, or 4) turbine mounted single hydrophones, pairs, or larger (vertical, horizontal, or two dimensional) arrays. The objectives of the ensemble of studies at each site are described as either background, construction, or operational noise measurements, along with some selected publications describing the results. In certain cases, detection of marine animals or planned transmissions from user deployed sources are described. This table attempts to be exhaustive and up-to-date.

Table 1. Summary of deployment locations, passive acoustic monitoring equipment configurations employed, acoustic measurement type, and associated references.

Tidal Energy Noise Monitoring Campaigns			
Location	Methodology used	Measurements	References
Lynmouth, UK	Drifting boat hydrophone	Operational noise	(Parvin et al 2005) (Richards et al 2007) (Faber Maunsell & Metoc 2007).
Strangford Lough, UK	Drifting boat hydrophone	Operational noise	(Nedwell and Brooker, 2008) (Kongsberg, 2010) (Götz et al, 2011)
Fall of Warness, Orkney, UK	Drifting boat hydrophone Drifting buoy hydrophone	Background noise, Construction noise, Operational noise.	(Wilson et al, 2010) (Aquatera 2010, 2011) (Wilson, 2014) (Beharie and Side, 2011)
Cobscook Bay, Maine, USA	Drifting buoy with pair of vertically separated hydrophones	Operational noise.	(CBTEP, 2012)
Kvalsund, Western Finnmark, Norway	Drifting boat hydrophone	Operational noise	(Akvaplan-niva, 2009)
East River, New York, USA	Towed hydrophones	Operational noise	(OES, 2013)

Admiralty Inlet, Puget Sound, USA	Bottom mounted hydrophone, Drifting buoy with vertical pair of hydrophones, Drifting boat hydrophone, Drifting vertical line array.	Background noise, Operational noise, Planned transmissions	(Bassett, 2010, 2013, 2014) (Polagye, 2012) (Copping et al 2013) (Xu, 2012)
Minas Passage, Bay of Fundy, Canada	Drifting buoy hydrophone, Bottom moored system, Turbine mounted system, Moored subsurface float, Boat deployed horizontal array.	Background noise, Free spinning turbine noise.	(Martin, 2012) (Martin, 2018) (Tollit, 2013) (Auvinen, 2019)
Schottel, Queen's University Belfast Tidal Test Site in Portaferry, Northern Ireland	Drifting buoy hydrophone	Background noise, Operational noise including free spinning and braking.	(Schmitt, 2015)
River Turbine, Iguigig, Alaska, USA	Drifting spar buoy hydrophone	Operational noise	(Polagye, 2015)
Site Expérimental Estuarien National pour l'Essai et l'Optimisation Hydrolienne (SEENOH), Bordeaux, France	Drifting boat hydrophone	Background noise, Installation noise, Operational noise	(Bald, 2015) (Giry, 2018)
Cook Inlet, Alaska, USA	Moored directional array, Moored hydrophone	Background noise, Beluga whale monitoring	(Worthington, 2014)
Ramsey Sound, UK	Boat deployed partial drifting hydrophone with subsurface float and weight, 12 element turbine mounted array	Background noise, Cetacean detection and localization	(Broudic, 2012a, 2012b) (Willis, 2012) (Malinka, 2018)
Grand Passage, Canada	Bottom moored hydrophone, Drifting buoy hydrophone Turbine mounted hydrophone	Background noise, Planned transmissions	(Malinka, 2015) (Wilson, 2019)
West Scotland (Sound of Islay, Scarba, the Great Race, Gulf of Corryvreckan, Kyle Rhea, the Sound of Sleat)	Moored C-PODs Drifting C-PODs Moored vertical line array Bottom mounted hydrophone, Towed hydrophone array, Drifting hydrophone.	Porpoise detection and localisation Baseline noise, Construction noise, Operational noise	(Wilson, 2013) (Macaulay, 2017) (Benjamins, 2016) (EMEC, 2012) (Benjamins, 2017)
Mississippi River, Memphis, Tennessee, USA	Moored hydrophone Drifting hydrophone	Background noise, Operational noise.	(Bevelhimer, 2016)
Sequim Bay, Washington, USA	Bottom mounted vector sensor array	Test tones	(Raghukumar, 2019)

At the 17 study sites presented, each representing a larger number of individual experiments, measurement campaigns and studies, seven studies employed moored or bottom mounted systems, 14 used drifting buoy or boat measurement, and six have used drifting and moored hydrophones, in some cases simultaneously as a means of quantifying flow noise. Six sites have been studied using directional arrays or pairs of hydrophones to incorporate directional information of the noise field, perform localization of marine animals, or to supress flow noise.

Many early studies used drifting boat deployed hydrophones, though self-noise generated by surface motion and boat noise such as lapping of waves against the hull and topside activity were identified as significant contaminants in the acoustic records. Hydrophones deployed under drifting buoys with isolation and suspension systems, drogues, or catenary sections were employed in later studies to improve the reduction of surface motion noise, and the associated turbulent flow noise. In general, these types of measurements are described as having the highest fidelity to the true sound field and this claim is often substantiated by the demonstration of relatively reduced flow noise and motion induced noise levels on subsequently collected sets of data.

In a subset of cases, comparisons between moored recorders and drifting recorders are used to quantify the performance of flow noise suppression on static systems. Operationally, bottom mounted systems provide the ability to monitor a single point in space for a long period of time (even indefinite), while drifting systems measure a snapshot (typically on the order of minutes) of the noise field over wider area. The advantages and disadvantages of these two methods must be put in context of the monitoring program being designed.

For example, in quantifying turbine generated noise, flow noise suffered by a static system tends to mask the frequencies (10's - 100's of Hz) of interest, therefore favouring a labour intensive and carefully executed drift measurement campaign. For the detection and localization of marine animals such as porpoise and Beluga, the band of interest is outside of the flow noise contaminated acoustic regime and moored or even turbine mounted sensors are adequate. For monitoring harbor porpoises and other odontocetes, C-PODs (autonomous echolocation loggers), were popularly employed as both drifters and moored units, and found to be reasonably effective in both configurations.

In the case of continuous real-time monitoring, a cabled moored or mounted system is the only option, thus methods of flow noise suppression must be employed if the objective is to record turbine generated noise. No standard flow shield design has been proposed, and results from flow shield experiments are mixed, sometimes reducing flow noise (Raghukumar 2019, Bassett 2013), sometimes reducing sensitivity with no effect on flow noise over the band of interest (Malinka 2015, Porskamp 2015). A number of custom-built arrays were deployed in tidal channels with various motivations; however, the use of large diameter horizontal arrays has not been well investigated. A significant body of literature and expertise concerning ship towed passive sonar systems has been developed over the last century, including analytical theories for the prediction of flow noise for sensors placed in oil filled elastomeric tubes (e.g. Corocos, 1963, Knight, 1996). A study of towed array design knowledge could lead to significant advances in flow noise suppression from stationary hydrophone systems in tidal channels, through both improved isolation, and signal processing.

Digital hydrophones, which are now manufactured by a number of North American and international companies, are preferable for permanently cabled static observation systems because of their ability to optically transfer data at high speeds and with little signal attenuation, though this was only demonstrated in a single report. Digital hydrophones, particularly the OceanSonics icListen, were a popular choice for deployment in tidal channels, likely because of their compact form factor.

The field intensive requirement of drifter deployments is seen as a major drawback from an otherwise ideal technology. One proposed solution is the autonomation of drifting passive acoustic monitoring systems. Research is underway using Unmanned Arial Vehicles (UAVs) to make underwater noise measurements using dip sonars (Lloyd, 2017). The use of a station-keeping autonomous hovercraft with a deployable acoustic sensor has also been proposed (Barclay, 2019). Both technologies could potentially provide duty cycled long term monitoring of tidal energy sites, without the interference of flow noise.

Polagye (2014) and Lepper (2016) mention the importance of particle motion (as opposed to pressure) measurements due to the physiological sensitivity of some marine animals to particle velocity as opposed to pressure. An array of vector sensors, capable of resolving particle motion and pressure, was deployed in a single study (Raghukumar, 2018, 2019), demonstrating the ability to resolve directional information in the sound field while identifying flow noise contamination. However, this system operated with a limited acoustic bandwidth of 50 Hz - 5 kHz, reducing its ability to resolve vocalizing animals of interest, particularly echolocation clicks.

IV. Detection, classification, and localization of marine animals

Several scientific objectives were met in the studies listed in Section III, Table 1. The objectives of interest for this report are the detection, classification, and localization of vocalizing marine animals. In order to understand which passive acoustic instruments are best suited to these tasks, and future work on animal presence, population density estimate, and animal-turbine interaction, the published studies were surveyed to determine which marine animals were detected in the study area, the passive acoustic instrument used to make the detection, and the relative performances of these instruments. In these comparisons, an effort is made to understand factors that will influence the detection efficiency of the instrument, such as flow noise (or current flow speeds), ambient noise with special attention paid to sediment generated noise on the seafloor, reverberation, the propagation environment, sensor placement, and sensor deployment methodology. In considering these factors, and by estimating their relative effects, the performance of the sensors can be compared more directly.

A. Marine animals of interest

In order to best understand detection performance, the bandwidth of the marine animal vocalizations must be known. Over the ensemble of study sites, the known presence by acoustic detection of marine animals is summarized in Table 2, along with the relevant bandwidth of interest for each animal and instrument used to make the detection.

Table 2. Survey of acoustically detected marine animals in tidal channels, characteristics of sounds produced, and instrument packages used for detection.

Marine animals detect at tidal energy sites			
Marine animal	Study site(s) present	Characteristics of vocalizations	Instrument used
Dolphins (bottlenose, Risso's, short-beaked common, Atlantic white-sided and white-beaked dolphin)	Ramsay Sound, Minas Passage	Clicks: with root mean square bandwidths of 23−54 kHz, centred at ~ 90kHz Whistles, varying bandwidth: low 10's of kHz	C-POD Turbine mounted hydrophones
Harbour porpoise	Great Race, Scarba, Sound of Islay, Minas Passage, Admiralty Inlet, Kyle Rhea	Clicks: centred at 130 kHz with 16kHz bandwidth. Highly directional (beam pattern 9.5 to 16 degrees).	C-POD (bottom mounted, SUB moored, drifting) Boat drifting vertical line array Drifting hydrophones
Beluga Whale	Cook Inlet	Clicks with bandwidths of 40 – 120 kHz Non-echolocation calls: 2.0 to 5.9 kHz	EAR C-POD DASAR

It should be noted that animals such as the harbour and grey seals, and humpback, fin, and minke whales have been visually observed in Minas Passage but have never been acoustically detected, despite acoustic monitoring with some regularity. In most cases, the presence of these animals is rare, their calls are sporadic and infrequent, and simply may not have coincided with a passive acoustic survey. However, these animals produce sound mostly below 1 kHz, and always below 5 kHz where masking from flow noise may also be contributing to the absence of detections. It is difficult to conclude which factor is playing the limiting role in the lack of acoustic observations of these animals.

Over the band of 5 kHz – 10's of kHz, beluga non-echolocation calls and dolphin whistles should be detected in tidal channels where these animals are present. The limited number of studies on these animals do not report many detections of these types of calls, though it is difficult to conclude if that is due to the limited presence and call rates coupled with the sparsity of data sets, or the frequency band and potential masking of the calls.

The endangered Southern Resident killer whale are frequently visually observed in Admiralty inlet, WA (Snohomish PUD, 2012). These animals produce echolocation clicks centered at 60 kHz with bandwidths of 50 kHz, as well as social vocalizations in the band 1 – 6 kHz. A modelling study found that passive acoustic detection range of the whales in the tidal channel reduces by 90% during flood and ebb tides strong enough for turbine operation, relative to slack tide (Bassett, 2013). This proposed mechanism of the reduction of this range is masking by sediment generated noise. No published acoustic observations of the killer whales at this site have been reported.

Passive acoustics monitoring may also be used to detect fish (Luczkovich, 2008). However, in all cases the combination of low source levels (typically around 130 dB re 1 μPa) and their frequency band (100's of Hz) makes the detection of fish in high flow environments very unlikely due to flow noise masking. No passive acoustic observations of fish have been reported in the studies listed in Table 1.

The majority of passive acoustic monitoring studies of marine animals in tidal channels are centered on the detection, classification, and localization of harbour porpoises, dolphins, and belugas using their echolocation clicks. These short duration signals have reasonably wide bands (10 – 50 kHz) and are centered at relatively high frequencies (90 – 130 kHz).

B. Instrument and detection rates comparison studies

A limited number of passive acoustic instrument packages have been used to detect marine animals in tidal channels. Since the primary signals of interest are echolocation clicks, the data recording packages suitable for detection must have high sampling rates, above 250 kHz, and thus large memory capacity for storing the raw pressure time series. Acoustic data collected as raw pressure time series must be processed for detection, classification, and localization using either commercially available software or using custom detection algorithms. A popular choice amongst researchers was the use of PAMGUARD, an open source software managed by Sea Mammal Research Unit at the University of St Andrews in Scotland. The software allows automated detection and classification of marine animals sounds in the time series, and recently, localization modules have been added to its library.

One established alternative to these separate hardware (recording) and software (detection and classification) systems is the development of stand-alone instruments, where the pressure time series is analyzed in real-time given some prescribed criteria which provides classification of clicks, and then discarded, while the meta-data is stored. Chelonia Ltd. has manufactured three generations of this class of instrument called the POrpoise Detector (POD): the T-POD, the digital C-POD, and most recently the C-POD-F, which allows storage of the full wave form of each detection. In the case of the C-POD, the instrument used in the majority of studies surveyed here, the time and duration of each detected click are recorded. Clicks are detected using a proprietary algorithm and classified using the KERNO classifier (also proprietary) which identifies the echolocating species.

These two classes of systems have been deployed in drifting, moored, bottom mounted and turbine mounted configurations, and used to detect, classify, and located porpoises, dolphins, and belugas in tidal channels and have been shown to have very different performances.

A study in the relatively benign environment of the Baltic Sea found that a co-located C-POD detected between 21 – 94% of the click trains detected by PAMGUARD applied to broadband recordings made on a SoundTrap, a conventional pressure time series recorder produced by Ocean Instruments (Sarnocinska, 2016). The reduced rate of detection was due to many factors, but the primary one was that PAMGUARD detects individual clicks, while C-POD detects trains of clicks using patterns in the inter-click intervals as well as characteristics of the clicks; a more restrictive and discerning detection algorithm. All trains of four clicks or less are ignored by the C-POD, for example, which greatly reduces false positives. PAMGUARD's click detection algorithm compares energy in narrow-band filters whereas the C-POD employs a zero-crossing algorithm.

The large spread in the detection ratio of the two systems was the result of very poor correlation between the detection rates in time. In the research paper, one proposed explanation is that the signal excess required for a positive detection on the C-POD is larger than that of PAMGUARD's algorithm. Although this would impact the detection ratio between instruments and provide a non-zero intercept when calculating the linear regression between relative performance, this would not cause poor correlation at higher signal excess levels than the minimum detection threshold, shown as the large spread in the scatter plot presented in Fig. 2 of (Sarnocinska, 2016). The study also observed that when only a few animals were in the study area, the C-POD tends to report a detection rate of zero as compared to a non-zero rate reported by PAMGUARD, which suggests either that hydrophone sensitivity (detection range) is higher on the SoundTrap, or that the rate of false positives could be very high (order 10^3 clicks per minute) on the SoundTrap, although this seems unlikely.

The lack of a consistent linear relationship between the detection rate in clicks-per-minute of the C-POD and SoundTrap-PAMGUARD highlights the fact that data collected on these two classes of systems cannot be directly compared. Instead, the difference between acoustic sensitivities and detection efficiencies must be understood. By accounting for the effective listening range and detection efficiencies, it is conceivable that a method for inter-data comparison may be developed.

Another study in a non-tidal environment comparing a co-located C-POD and a Digital acoustic MONitoring (DMON) recorder (Woods Hole Oceanographic Institute) found that C-PODs reported a small number of false detections, with false positive rates ranging between 1% and 4% for individual units (Roberts, 2015). In this case, the researchers compared recorders using 'detection positive minutes', per unit time. With this metric, it was found that C-PODs performed with a high accuracy and low spread in detection ratio relative to the time series recorder (72%–91%) over a period of ~ 8 hours. The authors also show that this performance ratio depends on the unit time over which detection positive minutes are computed.

A study in Monterey Bay, California found very good agreement between the number of echolocation-clicks per hour detected on a co-located SoundTrap and C-POD (Jacobson, 2017). In this case, the pressure time series data were analyzed using an in-house built detector and filtering scheme and found 13% more echolocations than the C-POD.

A comparative study of harbour porpoise detection rates between a C-POD housed within streamlined SUB buoy suspended 3 m above the seafloor, two bottom platform mounted C-PODs, and a co-located conventional passive acoustic recorder, the icListen (OceanSonics) was carried out in 2014 in the Minas Passage (Porskamp, 2015). High-flow induced noise in the caused the C-POD's maximum recordable clicks per minute to be exceeded, resulting in 'lost time', and thus under-detected porpoise click trains. This effect was greater on the SUB buoy C-POD than the bottom mounted units. This may be due to flow noise, sediment generated noise, mooring noise (including noise generated by the mooring being blown down against the bottom). The latter is the most likely since it is expected that sediment generated noise would be greater or equal in intensity near the bottom so would contribute equally to lost time on both recorders, and, while flow increases with decreasing depth, it is not likely to be significant at frequencies above 10 kHz.

Reports of saturation of the C-POD detection buffer due to sediment generated noise have been made by researchers in Admiralty Inlet and previously in Minas Passage (Tollit, 2013).

The bottom mounted C-PODs detected roughly 10 times more detection minutes per day than the subs mounted C-POD, while the icListen detected five times more detection minutes per day than the co-located C-PODs. Another comparison experiment in Minas Passage also observed a factor of 10 increase in the number of detection minutes on an icListen as compared to the C-POD (Tollit, 2013). This is either due to the software analysis technique applied to the icListen time series (i.e., the detection algorithm), or greater flow and/or electronic noise present in the C-POD recording. The flow noise generated on both instruments is likely similar, as the physical dimensions of the two co-located instruments are similar. The receiving sensitivity of the C-POD is -211 dB re 1V/μPa and the icListen is -169 dB re 1V/μPa. Though these reported sensitivities are significant, the detection stage of each package also contributes to the disparity between measurements.

A study in Kyle Rhea was carried out with deployments of C-PODs moored 5 m from the bottom along the edge of the channel (in an effort to protect the instruments from the full force of the flow) and drifters comprised of a surface float and a C-POD mounted on a Lagrangian drogue 5 m below the surface (Wilson, 2013). Additionally, a pair of HS150 (Sonar Research & Development) hydrophones were towed 100 m behind a boat through the study area in a separate acoustic and visual survey. The hydrophone data was analyzed using PAMGUARD to detect clicks, which were classified manually. The moored C-PODs suffered from lost time due to high background noise, while the co-incident drifting C-PODs did not, suggesting that flow noise is causing the buffer saturation on the moored units, or that the moored units were placed in areas of high background (sediment generated) noise. Comparisons with the towed array are limited in this study, but generally it was found that the drifting C-PODs had the highest detection rates.

Comparisons of the ability of a C-POD, duty cycled Ecological Acoustic Recorders (EAR, Oceanwide Science Institute), and the Directional Autonomous Seafloor Acoustic Recorder (DASAR, Greenridge Scientific) to detect Beluga whales in the tidal energy site in Cook Inlet, Alaska were made (Worthington, 2014). Detections from the raw acoustic data were found using an in-house developed whistle detector, with a human verification step to eliminate false positives. In order to reduce the complication of recorder specific detection efficiency comparison, the meta-data were decimated to detections per hour across all three devices and presented in the final report as detections per month, and detection days per month. Even with this further data processing step, the agreement between devices was poor, with the C-POD outperforming the DASAR and EAR by a factor of two in December, March, and April, while the reverse is true in November and January. To further cloud data interpretation, the C-POD only detected echolocation clicks, while the DASAR and EAR only detected social Beluga vocalizations since their sampling frequency was too low to detect the echolocation signals.

A drifting pair of icListen recorders and a pair of C-PODs were deployed in Minas Passage on a single float spanning the upper 20 m of the water column (Adams, 2018). The drifting C-PODs suffered no lost time due to buffer filling, which supports a hypothesis that flow noise or mooring generated noise is responsible for triggering false detections. Sediment generated noise was not reported on in the study, but the acoustic time series data could be analyzed to investigate the depth-dependence and spatial variability of such noise. The detection minutes on the icListen were between 4-5 times greater than on the C-PODs. In this case, an in-house developed software package ‘Coda’ was used to detect clicks in the raw time series data. Again, it is difficult to determine if the relatively poor detection performance of the C-POD is due to hardware (lower hydrophone sensitivity) or software (more stringent detection algorithm) since the instrument is effectively a closed system.

In general, the standard C-POD detection limit of 4096 clicks min^{-1} can be easily exceeded during deployment in tidal channels. This has been extensively reported in the above described studies that employ moored and bottom mounted C-PODs, as well as several drifter deployments (Benjamins, 2016, Wilson, 2013). This may be due to sediment generated noise, mooring noise, or flow noise, though the physics of the latter seems unlikely. More work is needed to determine the primary cause of lost time for both deployment configurations of C-PODs in the different areas of study.

C. Detection Range Estimation

A direct comparison of detection range between an icListen and a C-POD in a low-noise, shallow water environment at 69 kHz showed that the combined sensitivity of the C-POD hydrophone and click-detection algorithm is lower than the icListen (Tollit, 2013, Porskamp, 2013). It is not possible to determine if this is due to hardware or software as the C-POD is a closed system. The range test described in the text lacks sufficient detail to describe a generalized detection efficiency ratio, but for this particular case the icListen was able to detect the signal to the maximum tested range of 500 m, while the C-POD’s maximum detection range was 375 m.

It was reported that a C-POD could detect echolocations in 5 m water depths, in a calm estuary, at a distance of 933 +/- 75 m (Roberts, 2015). This was demonstrated with little consistency in the study, with the C-POD reliably demonstrated a detection range of 300 m. Detection ranges of T-PODs and C-PODs in similar benign environments have been reported as ~ 200 – 300 m (Kyhn et al. 2008, 2012).

Using a mean empirically derived porpoise click source level and a high-frequency transmission loss model, receive levels can be used to estimate source-receiver distance and thus a detection range. This method was used to conclude that the detection range of an icListen deployed in the Minas Passage FORCE site had a mean of ~275 m and a typical daily maximum of 500 m (Porskamp, 2013). Detection ranges of C-PODs at the EMEC site were reported to be < 150 m (Benjamins, 2017). Deployment of a C-POD in Admiralty Inlet showed detections of ‘landmark’ click trains (where the C-POD itself is the target of the echolocation) at a distance of 90 m (Polagye, 2012).

The theoretical maximum on-axis detection range for these vocalisations is proposed to be less than 500 m under the assumptions of a relatively modest maximum source level (Villadsgaard et al., 2007), spherical spreading, and a detection threshold of 120 dB re 1 μPa. This range is dictated by the high sea water absorption coefficient at 130 kHz, which varies as f^2 (i.e., at 13 kHz, the absorption is 2 orders of magnitude weaker!). However, in tidal channels attenuation due to bubble scattering and turbulent mixing may decrease detection ranges further, though more research is needed to quantify this effect.

Improving the understanding of high frequency sound transmission in tidal environments will allow better estimates of detection ranges of any passive acoustic sensor and provide clarity to past date and future studies. For example, Tollit (2013) reported that the deeper the C-POD unit, the higher the number of porpoise detections in the Minas Passage, based on a data set of 7 SUB buoy mounted C-PODs. This may be due to the larger effective listening volume of the sensor deployed in deeper water, lower background noise level with increasing depth at 10’s and 100’s kHz (Moore, 2016), or by porpoise usage of the passage.

D. Localization

Only two three-dimensional (3D) localization studies have been carried out to date. A 3D distribution of seven hydrophones mounted to a turbine was used to detect and localize porpoises and dolphins (Malkina, 2018). The estimated the range of the system was between 20 - 200 m for sound sources with source level 178 – 205 dB re 1 μPa_{p-p} respectively, where an 8 dB signal excess (SE) level was assumed for the detector. It was further estimated that the probability of detection and localization was below 50% for ranges of greater than 20 m, and 10% at 50 m. A large aperture vertical array of eight hydrophones deployed from a drifting ship was combined with a small quad array to localize in 3D and gave a detection range of 200 m (Macaulay, 2017).

E. Performance summary and recommendations

Results from the few passive acoustic instrument comparison tests for the detection of marine animals in tidal channels provide a basis for some recommendations. Hydrophones with greater sensitivity have larger detection ranges, which lead to higher detection rates. Additionally, instruments that record the pressure time series which is then analyzed by a click detector (PAMGUARD, Coda) have much higher click-per-minute detection rates, and generally higher detection positive minutes per unit time, regardless of environment or deployment configuration. In some cases, the detection positive minutes time-base can confound comparison results between C-PODs and other devices. Direct comparison of detector performance is difficult to impossible, since the C-POD performance is the result of a coupled hardware (hydrophone sensitivity, electronic noise floor) and software (detector efficiency, false positive filter) system.

C-PODs are typically programmed to limit the number of detections per minute, causing ‘lost time’ when that limit is reached before a minute is through. In tidal channels, lost time can be above 90%.

Masking by flow noise and mooring noise decreases detection rates on bottom moored C-PODs, while masking by sediment generated noise and mooring noise decreases detection rates on bottom moored, SUB moored, and drifting C-PODs. The inability to distinguish between these masking sources confounds the performance comparison between drifting and bottom mounted sensors. In general, drifting C-PODs were found to have the least lost time, followed by bottom mounted C-PODs, with mooring deployed C-PODs performing the worst.

The C-POD-F may be able to reduce lost time – this claim is made by promotional material (C-POD & C-POD-F.ppt retrieved from the Chelonia website) but is not clearly explained. C-POD-F will be able to record wave forms (or pressure time series) at sampling rates up to 1 MHz, when detections are made. This will help solve the uncertainty behind masking noise processes.

The detection range of a C-POD or a hydrophone system at relevant frequencies in a tidal channel has not been directly measured. Measurements in benign environments showed that both the icListen (at 69 kHz) and the DMON (using porpoise clicks) outperformed the C-POD. A typical value for a hydrophone detection ranges of porpoise clicks in a tidal channel is between 100 and 300 m. 3D localizing arrays were only able to operate successfully out to 90 m for a 7-element volumetric array, and 200 m for an 8-element linear array.

Considering these findings, the recommended approach for passive monitoring of porpoise in a tidal channel is to use a bottom mounted or drifting compact hydrophone with an acoustic bandwidth of at least 150 kHz, such as the icListen HF or SoundTrap 300, to collect pressure time series. PAMGUARD has been shown to perform well as a detector and classifier. The acoustic bandwidths of the DASAR and EAR are too small to be effective. As shown in Section III, there are many other hydrophone and data acquisition systems that are capable of making these measurements, but we have so far limited the discussion to instruments that have been demonstrated in these environments. Potentially suitable commercially available systems for animal detection in tidal environments are the Reson TC4014-5, Magrec HPO3 hydrophones, though those would need to be connected to a data acquisition system. Suitable complete systems include the AMAR G4 (JASCO), the ORCA Acoustic Recorder (Seiche), and the TR-ORCA or TR-Porpoise (Turbulent Research). Some of these systems, as well as the SoundTrap and icListen, allow multiple sensors to be configurated into arrays, demonstrably useful for studies where localization is needed.

The choice between drifting and bottom mounted deployments depends on available survey effort, and observational objectives. For the detection of high frequency echolocation clicks, flow noise should be minimized by all means available, though the icListen and SoundTrap have demonstrated their ability to detect clicks without flow noise mitigation from bottom mounted platforms. For the detection of animals that vocalize at lower frequency, flow noise reduction strategies must be developed.

V. Conclusions

Overall, a wide assortment of hydrophone and data acquisition systems were used in the studies listed in Table 1. A small number of systems have demonstrated detections of animals (harbour porpoise, dolphins, beluga) in tidal channels. By surveying the ensemble of studies that describe the performance of these systems in tidal channels and in other ocean environments where comparison studies have been made, some conclusions are reached. The ideal system has the highest sensitivity, best mitigation of flow noise, and records the entire pressure time series. Practically speaking, these systems can be bottom deployed for long term monitoring without flow noise reduction, and they will be able to detect animals at ranges of 150 – 300 m in tidal channels. Compact hydrophone and data acquisition systems that record the pressure time series outperform C-PODs and provide higher data analysis capability. The C-POD-F may reduce the technological gap between these two classes of instruments, but this has not yet been demonstrated.

Additionally, it was found that the deployment configuration is the most important factor to consider when pairing passive acoustic technology with monitoring objectives. Drifting buoy suspended systems with appropriate vibration isolation and an underwater drogue provide the least contaminated measurement, while requiring a large field effort. Fixed systems provide continuous monitoring, but methods in flow noise suppression, both mechanical and signal processing, must be advanced. It is suggested that the towed array literature be consulted to improve flow shield and static system design. The current best performing static system appears to be the bottom mounted, shielded hydrophones, though they are susceptible to noise generated by mobile sediments colliding with the instrument body. Autonomous vehicles may also propose a solution for long-term high-fidelity monitoring programs, though considerable technological development is needed.

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