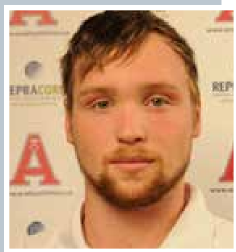
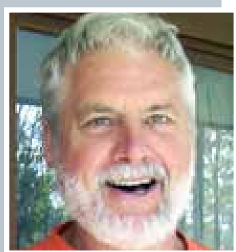
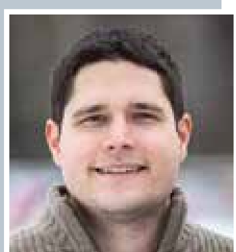
Listen up



Mike Adams



Brian Sanderson



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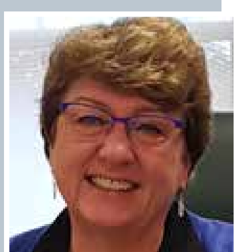

Anna Redden

Adams, Sanderson, Porskamp, and Redden examine the convenient and widely used porpoise click detector (C-POD) event-logger with a particular view towards better understanding its performance for monitoring harbour porpoise in a fast-flowing tidal environment.

Who should read this paper?

This work is of interest to anyone who is concerned with detecting porpoises at high flow sites that are under consideration for tidal power installations. Tidal power developers, marine ecologists and engineers, and environmental regulators may find it useful.

Why is it important?

C-POD is a tool that is widely used by the oceans community but it is difficult to confirm its performance in strong tidal flows where harbour porpoise are found and tidal power is under development. Comparisons are made with detections of harbour porpoise vocalizations obtained by applying the Coda algorithm to broadband hydrophone measurements. The idea is to identify segments in the time series so detections can be reviewed in many ways and comparisons made across synchronized measurements.

Results show limitations and usefulness of C-PODs for monitoring porpoise activity in strong tidal flow. This benefits the ocean community by illustrating how the technology can be reliably used as well as its limitations. Comparison with Coda and broadband hydrophones indicates circumstances best suited for each method.

About the authors

Mike Adams completed his B.Sc. (Hons.) in Biology (2018) at Acadia University, Canada. He is currently enrolled in graduate studies at Acadia and his project involves the use of drifting hydrophone arrays and advances in methodology to monitor Atlantic harbour porpoise in high current environments. He has expertise with marine animal monitoring technology and has undertaken field programs to study both fish and marine mammals. His passion is for marine mammals and finding ways to effectively research their behaviour in their natural environment.

Brian Sanderson is a physical oceanographer with interests in drifter trajectories, ocean mixing, and computational fluid modelling. He has also published on a variety of marine ecology topics and has most recently turned his attention to the detection of vocalizations by harbour porpoises and obtaining source location. His objective is to be able to conveniently measure abundance of porpoises relative to distance from a turbine installation in order to inform responsible development of tidal power.

Peter Porskamp completed his B.Sc. (Hons., 2013) and M.Sc. (2015) in Biology at Acadia University, Canada. The primary focus of his studies at Acadia involved using passive acoustic monitoring tools to study patterns in harbour porpoise distribution and behaviour at the FORCE tidal turbine test site in Minas Passage. After his time at Acadia, he pursued an Advanced Diploma in Marine Geomatics (2016) at the Centre of Geographic Sciences. Currently, he is a PhD Candidate at Deakin University using remote sensing technologies to create benthic habitat maps.

Dr. Anna Redden is a marine ecologist and professor at Acadia University and has significant marine life monitoring expertise and experience in the upper Bay of Fundy. She has authored or co-authored over 90 primary publications, technical reports, and review papers. Since 2010, her research with colleagues and research students includes acoustic tracking of several fish species through the Minas Passage and studies (in collaboration with SMRU Ltd.) involving moored hydrophones to assess year-round marine mammal activity in the Minas Passage and FORCE demonstration area.

COMPARISON OF CO-DEPLOYED DRIFTING PASSIVE ACOUSTIC MONITORING TOOLS AT A HIGH FLOW TIDAL SITE: C-PODS AND ICLISTENHF HYDROPHONES

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ABSTRACT

Porpoise click detectors (C-PODs) and icListenHF hydrophones that record with a high sample rate were deployed on a drifter in fast tidal currents in Minas Passage, Bay of Fundy, on six days during June 2017. Harbour porpoise vocalizations were detected within the icListenHF records by using the Coda algorithm and subsequent processing which included a detailed manual review of each click in each click train. The proportion of harbour porpoise detection positive minutes (DPM) was only 0.04 C-PODs compared to 0.19 for the icListenHF hydrophones. Nevertheless, both methods are an incomplete measure of porpoise vocalizations. DPM obtained by the C-PODs had a 65% likelihood of also being classified a DPM from the analysis of icListenHF measurements. Both methods measure some fraction of porpoise vocalization activity so long-term environmental monitoring with either C-PODs or icListenHF hydrophones should serve to discover any substantial change in patterns of porpoise echolocation activity. Nearby active acoustic devices were associated with 38% of the false-positive DPM obtained by C-PODs but Coda did not register such signals as harbour porpoise vocalizations.

It is convenient to deploy C-PODs on bottom-moored subsurface-floats in order to monitor porpoise in fast currents at sites where in-stream tidal turbines are tested. However, C-POD performance degrades when non-target noise quickly fills the memory buffer, resulting in lost detection time. The drifter measurements demonstrated increases in memory loss as current speed increases above 1.5 m/s. Additional lost time might be caused when a C-POD is moored using an unstable tethered subsurface float. The type of mooring may matter because an icListenHF hydrophone attached to a stable bottom platform gave very similar DPM results to those on the drifter.

KEYWORDS

Harbour porpoise; Bioacoustics; Passive acoustic monitoring; Minas Passage; Drifters

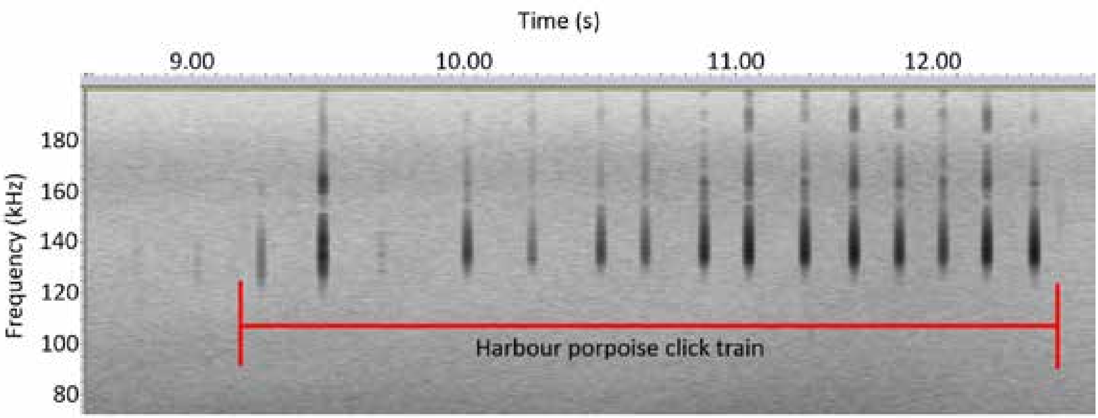


Figure 1: Example spectrogram generated using Audacity [2017]. Porpoise echolocation data was collected with an icListenHF hydrophone mounted on a drifter in Minas Passage, October 7, 2016. A harbour porpoise click train is evident at 130-150 kHz from 9.20 to 12.50 seconds.

INTRODUCTION

Tidal energy represents a predictable and renewable power source and is presently being examined as an option for harvesting marine energy as the global interest in, and need for, renewable energy grows. Tidal energy development involves installation of turbines in fast tidal currents. Such sites are also used by migrant and/or resident fish and marine mammals which may interact with in-stream tidal devices. In Canada, tidal energy development is in the demonstration phase at the Fundy Ocean Research Center for Energy (FORCE) in Minas Passage, Bay of Fundy. In addition to testing turbine technologies, FORCE also monitors the distribution of fish and other marine life towards understanding the environmental effects of in-stream turbines.

Atlantic harbour porpoise, *Phocoena phocoena* [Linnaeus, 1758], is the most commonly observed marine mammal in Minas Passage [Wood et al., 2013] and is designated as a species of "Special Concern" by the Committee on the Status of Endangered Wildlife in Canada [COSEWIC, 2006]. Atlantic harbour porpoise is listed as "Threatened (Schedule 2)" under Canada's Species at Risk Act and is also protected from disturbance in Canadian waters by Marine Mammal Regulations 2018 [Fisheries Act, 2018]. To address concerns about potential turbine-marine mammal interactions, an array of porpoise detectors (C-PODs) have been used to monitor harbour porpoise activity at and near the FORCE test site since 2010 [Tollit et al., 2011; 2019].

Harbour porpoises use echolocation for navigation and for locating and capturing prey. Their echolocation clicks are short duration, ranging from 75-150 µs, with a frequency of ~130 kHz and a source level of 178-205 dB re 1 µPa @ 1 m [Villadsgaard et al., 2007]. A sequence of clicks generated by the same animal over a relatively short interval is a click train (Figure 1).

Two common methods for monitoring porpoise activity in and around tidal energy developments are visual observations and passive acoustic monitoring (PAM) of echolocation click activity. Visual observations have the advantage of making it possible to confirm, to within a reasonable doubt, the presence of individuals belonging to a particular species, but they have the disadvantage of being labour intensive and are impeded by darkness, rough seas, rain, and fog. Gulf of Maine / Bay of Fundy harbour porpoise visual surveys in 1991 and 1992 noted that data collected during Beaufort Sea state greater than 2 could be negatively biased [Palka, 1996].

Passive acoustic monitoring involves the use of hydrophones to collect acoustic recordings, including sounds produced by animals [Zimmer, 2011]. Generally, two types of hydrophones are used: broadband recorders and automated event loggers. The C-POD (Chelonia Ltd.) event logger, used in this study, detects and logs echolocation clicks, is low-moderate in cost per unit, and can be deployed autonomously with internal batteries for up to four months. C-PODs use a closed source program and classifier (C-POD.exe; KERNO classifier) to process raw C-POD data into porpoise echolocation detections [Chelonia Ltd., 2014]. C-PODs are convenient to use and have been the primary method for monitoring harbour porpoises from fixed stations at and near the FORCE test site [Tollit et al., 2019].

The C-POD and its precursor (T-POD) have been used extensively around the world for monitoring the behaviour and presence of harbour porpoises, including at tidal energy development sites [Wood et al., 2013; Benjamins et al., 2016; Tollit et al., 2019]. Other studies have focused on porpoise response behaviours to marine construction at offshore wind farms [Brandt et al., 2011, Scheidat et al., 2011], porpoise avoidance of acoustic deterrents used to reduce harbour porpoise by-catch in the fishing industry [Carström et al. 2009], porpoise activity around offshore gas installations [Todd et al., 2009], and the seasonal and spatial distributions of endangered porpoise populations [Carlén et al., 2018]. C-PODs have also been used to monitor and study other odontocete species including Indo-Pacific bottlenose dolphin (*Tursiops aduncus*), Indian Ocean humpback dolphin (*Sousa plumbea*) [Temple et al., 2016], and the beluga whale (*Delphinapterus leucas*) [Castellote et al., 2013].

The icListenHF hydrophone (Ocean Sonics Ltd.) is an example of a broadband hydrophone. Broadband hydrophones collect a large amount of acoustic data, so the limitations of onboard storage can make them inconvenient for long-term deployment in circumstances where measurements cannot be transmitted to shore by either cable or WiFi. A major advantage, however, is that the user can process data collected by broadband hydrophones using any number of algorithms to detect porpoise echolocation clicks. Having complete access to the raw data allows detection algorithms to be thoroughly scrutinized. This advantage is central to the present comparative study of PAM technologies.

To date, there have been several reports detailing comparisons of C-PODs with other hydrophone technologies. Sarnocinska et al. [2016] compared harbour porpoise detections by a C-POD with detections obtained by a co-deployed SoundTrap ST202HF (Ocean

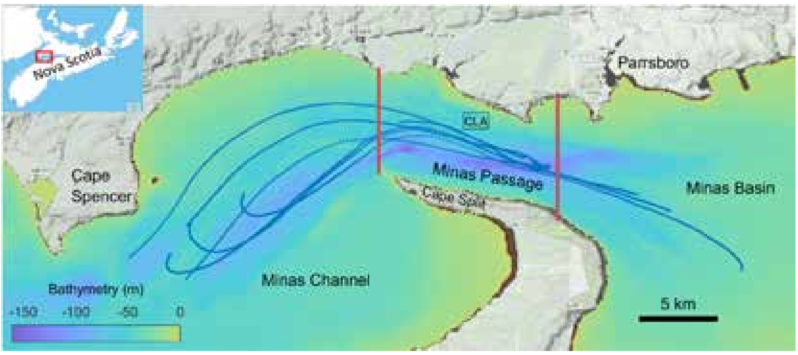


Figure 2: Map of study area, showing six tracks (blue lines) of the drifting hydrophone array during June 12, 14, 15, 16, 26, and 27, 2017. Porpoise detection is evaluated for three spatial regions that are separated by the two vertical orange lines: Minas Channel, Minas Passage, and Minas Basin. The FORCE test site (CLA) is represented by the black box (1 km x 1.6 km) in Minas Passage, which is about 5.5 km wide.

Instruments, New Zealand), with data processed using marine mammal detection software (PAMGUARD) developed by the Scottish Oceans Institute. The C-POD consistently detected fewer echolocation clicks than SoundTrap/PAMGUARD, with highly variable correlations between the two sets of detections. Jacobson et al. [2017] and Clausen et al. [2018] also found C-PODs to have lower detection efficiency than a co-deployed broadband hydrophone, SoundTrap 202HF (Wildlife Acoustics). And, two studies of bottlenose dolphins found that C-PODs consistently underperformed when compared to a full bandwidth counterpart (DMON) [Hansen, 2011; Roberts and Read, 2014].

Flow noise and noise associated with tethered moorings and mobile sediments have been flagged as major issues for the passive acoustic detection of porpoises at the FORCE tidal energy test site in Minas Passage [Wood et al., 2013]. As passive acoustic monitoring of harbour porpoises in this test site has included both C-PODs and icListenHF hydrophones, the primary objective of this study was to compare detection efficiency of the instruments using a drifting platform which serves to mitigate the confounding effects of flow noise. An additional objective was to compare the contemporaneous visual observations with the acoustic detections to validate both acoustic techniques.

Multi-year C-POD measurements at the FORCE test site indicate daily presence of porpoise vocalizations with more detections near high tide and an annual peak in June [Wood et al., 2013; Porskamp, 2015; Tollit et al., 2019]. The FORCE test site is a small area (1 km x 1.6 km) compared to the 30-40 km tidal excursion (Figure 2) so measurements in the drifting framework provide a different perspective from measurements fixed to a small area that a large volume of water rushes through [Benjamins et al., 2016; Adams, 2018; Tollit et al., 2019].

METHODS

Site Description

The Inner Bay of Fundy is a semi-diurnal, hyper-tidal system with a tidal range of 11-17 m. The 5.5 km wide and 14 km long Minas Passage connects Minas Channel to Minas Basin (Figure 2) and features current speeds up to 6 m/s [Karsten et al., 2008]. Maximum depth within Minas Passage is approximately 170 m [Fader, 2009].

The FORCE test facility for demonstrating new Tidal In-Stream Energy Conversion

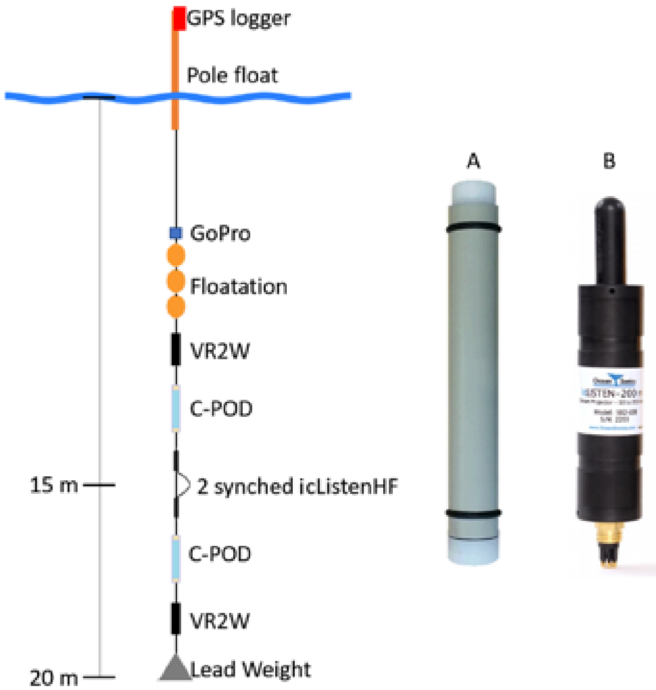


Figure 3: Schematic of the custom-built drifter with full instrumentation load-out. Drifter was deployed in Minas Passage and adjacent areas in June 2017. Pictured right: A) C-POD, B) icListenHF.

technologies is located in the northern region of Minas Passage (Figure 2), which features a basalt platform [Fader, 2009]. During our field studies, a 16 m diameter OpenHydro tidal turbine, which had been operational at FORCE since its deployment in November 2016, was recovered with the aid of several tugboats and a barge.

Drifter Design and Instrumentation

The custom-made drifter used in this study comprised a high visibility pole float equipped with a GPS logger (Garmin GPSmap 62s) tethered to a subsurface inertia unit with three 20 cm spherical floats and a lead weight (~11.5 kg) (Figure 3). Various acoustic sensors were mounted at 1-2 m intervals on the 12 m section of rope between the flotation units and the weight. Total length of the drifter was approximately 20 m. Equipment load-out consisted of two synchronized icListenHF hydrophones, two Chelonia C-PODs to log detections of porpoise clicks, and two Vemco VR2Ws (69 kHz) which were included for the opportunistic detection of acoustically tagged fish. On five of six drifts, a waterproof action camera (GoPro Hero3 White Edition) was mounted above the flotation unit, 6-7 m below the surface, to observe harbour porpoises should they approach the drifter.

The icListenHF is a high frequency (512,000 samples/second) smart hydrophone developed and manufactured by Ocean Sonics Ltd. (Figure 3). An onboard computer, along with internal battery and data storage, allows the icListenHF to be deployed as an autonomous unit for about seven hours. The two hydrophones used in this study were synchronized to +/- 122 nanoseconds using a sync cable. The differences in detection rates of the two icListenHF hydrophones were explored and found to be nonsignificant [Adams, 2018].

The C-POD (Chelonia Porpoise Detector) is an autonomous passive acoustic click logger (Figure 3). C-PODs record the detection of high-frequency click trains produced by harbour porpoises and other odontocetes. Although they serve as a hydrophone, the C-PODs do not store time series data but rather log click trains by saving details such as sound pressure amplitudes, frequencies, and click envelope to minimize data storage space. C-PODs are designed for autonomous, long-term deployment, with batteries (10 alkaline D-cells) and data storage (4 GB SD card) capable of about four months of continuous recording [Chelonia Ltd., 2014]. Compared to the icListenHF hydrophone technology, C-PODs cannot be synchronized, and they exhibit lost time in noisy, high current sites [Tollit et al., 2011]. Lost time happens when the C-POD memory buffer fills with largely non-target events (e.g., noise from mobilized sediment, anthropogenic activity, mooring hardware) before the end of a minute, causing the C-POD to cease recording until the start of the next minute. The C-PODs used for this study were set to allow the memory buffer to log up to 4,096 events in each minute of recording time. This setting is the same as that used in the multi-year, environmental monitoring program at FORCE [Tollit et al., 2019].

Drifter Deployment

Six drifts of five to seven hours each were conducted in Minas Passage and adjacent areas during daylight hours on June 12, 14, 15, 16, 26, and 27, 2017. The first four drifts (one ebb followed by three flood) were on or near a neap tide. The remaining two drifts (ebb tide) were completed near the following spring tide. The OpenHydro tidal turbine installed at FORCE was retrieved on the June 15, 2017, while the drifter was in Minas Channel, approaching Minas Passage.

The two icListenHF hydrophones were powered up for each drift and data downloaded at the end of each drift. The C-PODs were activated the day before the start of the study, then soaked in water for full wetting of the transducer housing to ensure full sensitivity. C-POD battery capacity (three to four months) allowed the C-PODs to be operational continuously with data downloaded at the end of the study.

The drifter was manually deployed from the side of a small (5.5 m) rigid hull inflatable boat (RHIB). After deployment, the RHIB drifted with the engine off except when the engine was briefly used to reposition the RHIB whenever it drifted more than about 800 m from the drifter. The RHIB's 118 kHz echo sounder was turned on for a total of 10 minutes (~0.5% total drift time) to momentarily check water depth. A 69 kHz Vemco fish tag was submerged from the side of the RHIB for ~5 minutes at the start of each drift to provide a landmark sequence of a known signal to act as a validation that the synchronization of the hydrophones was successfully achieved. Garmin GPSmap 62s devices logged the positions of the drifter and the boat, at 5-second intervals, with an accuracy of ± 5 m [Garmin Ltd., 2011].

The field crew made visual observations throughout all drifts. Harbour porpoise sightings (Figure 4) were recorded in the field logbook, noting time, number of individuals, estimated bearing, and distance from the RHIB. Porpoises were not detected by the GoPro camera (Secchi depth was 4.5 m), which was installed on the drifter for possible images of porpoises interacting with the drifter. Sources and times of anthropogenic noise (RHIB movements, fishing vessels, tidal turbine recovery operations) were also recorded but no relationship was found with detected vocalizations of porpoises [Adams, 2018].

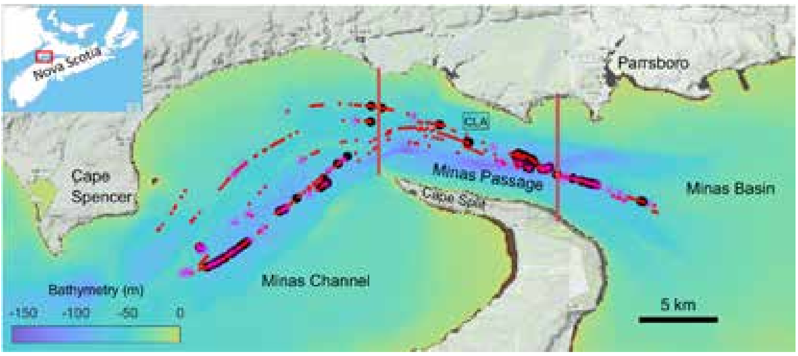


Figure 4: Map of study area, showing positions at which harbour porpoises were detected during the six drifts in June 2017. Vocalizations detected with the icListenHF hydrophones are shown by red points. Vocalizations detected with the C-PODs are shown by filled black circles. Visual detections are shown by the magenta asterisks.

icListenHF Data Processing

Coda, a C program developed by Brian Sanderson in partnership with Ocean Sonics Ltd., was used to detect harbour porpoise clicks within icListenHF records. A broadband filter (100-150 kHz) was applied to the raw acoustic data (.wav files). Coda then used a matched filter with the template based on an ensemble of porpoise clicks measured from prior studies. When a click is located, the energy (Pa2) in the frequency band used by porpoises (124-138 kHz) is compared to the energy in the neighbouring bands to eliminate false-positives caused by broadband noise. Hood et al. [2016] compare neighbouring bands for the same purpose. Detections obtained directly from Coda applied to icListenHF measurements will be referred to as DCI-detections, noting that 50% of the minutes sampled had at least four DCI-detections by one icListenHF or the other. It must be emphasized that Coda was developed for onboard application within an icListenHF which constrains computational cost and requires that each application of the Coda algorithm, which tests for a click, is applied in isolation to a sequence of 1,024 samples. Thus, the goal is for Coda to identify segments of data which may be stored and further investigated in order to reduce the uncertainty in the detection of porpoise vocalisations.

DCI-detections were further investigated in two stages. An automated application of a more stringent filter on the click level and its ratio to broadband noise was followed by filtering out DCI-detections that did not belong to a click train. Filtered detections all belong to click trains and will be denoted FCI-detections so that an FCI-DPM is a detection positive minute that contains FCI-detections. Thus, the 50% detection positive minutes above is reduced to 19% FCI-DPM. It should be noted that detection positive minutes increased to 31% with an alternative approach (ACI-DPM) that selected first for trains and then tested the strongest click in the train relative to broadband noise. Results that follow will focus upon the first method of selecting DCI-detections. There are, however, defensible arguments for many methods.

The second stage used semi-automated manual review software to review portions of the time series that contained FCI-detections. The review included examination of spectrograms, application of the matched filter to 1s intervals, calculation of click envelopes and regression fits to standard forms, regression fits to obtain click frequency, and consideration of how these characteristics vary within a train of clicks along with evaluations of each click relative to the properties of other types of signal. This manual review did not cause any of the FCI-DPM to be downgraded to detection negative status, so it does not change the present analysis. However, the manual review did enable us to remove a few questionable clicks and identify others that seemed, on balance and given context, to belong to one of the click trains within FCI-detections. The ACI-DPM were not subject to a complete manual review but results from hydrophone icListenHF 1211 were reviewed for the first drift. Manual review confirmed that ACI added 30 DPM to the 56 FCI-DPM for the first drift.

The above method was also used to reanalyze icListenHF measurements that were previously reported by Porskamp [2015]. That experiment included icListenHFs and C-PODs that were mounted to a rigid frame (Lander Platform) that was heavily weighted to be stable on the bottom. The Lander Platform was deployed within the FORCE test site for 28 days during June 2014.

C-POD Data Processing

C-POD data were processed using the Chelonia C-POD.exe program. The click logger's data file (CP1 file) is read into the C-POD.exe program, where the click trains are filtered to remove chance trains from non-cetacean sources (rain, crustaceans, and mobilized sediment particles). A quality value of either High, Moderate or Low is assigned. Due to the high false-positive rate of the Low quality click trains, only Moderate and High-quality trains were included for further analysis. Secondarily, the clicks are classified by type of click, which is determined by an assessment of the inter-click interval, frequency, and length/amplitude of the click trains. Narrow band high frequency trains are classified as harbour porpoise click trains. The resulting file (CP3 file) is then exported in terms of detection positive minutes, DPM [Chelonia Ltd., 2014]. A minute is designated C-POD detection positive (C-DPM) if either of the two C-PODs registered a DPM. We do this, for both icListenHFs and C-PODs, in order to average the effects of any variation in instrument performance and vertical position on the drifter assembly (Figure 1).

Comparison of C-POD, icListenHF/Coda, and Visual Observation Data

Comparing visual observations of porpoises with passive acoustic detection of porpoise vocalization is made difficult by the differences in the observation and data processing procedures. Visual observations represent the instant of time when an animal is observed, by observers who were some distance from the animal and the drifting platform. It is assumed that there is a considerable chance that a porpoise observed in the vicinity of the drifting platform will be detected by the passive acoustic recorders some short time before or after the visual observation. Therefore, we will expand the duration of a visual observation with respect to time so that if t is the time that a visual observation was recorded then the porpoise will have been presumed present from $t - \tau$ to $t + \tau$. The value of τ is arbitrary but must relate in some physical way to how long a porpoise will be reasonably close to the drifting platform. At a typical swimming speed of 1 m/s [Otani et al., 2000], a harbour porpoise will travel $2\times \tau$ m during the extended interval of time. With $\tau = 5$ minutes, this amounts to travelling 600 m which seems reasonable.

Analyses with different values of τ did not change conclusions in any fundamental way.

This procedure allowed us to define each minute of the drifting platform's track as a visual positive minute or a visual negative minute and will be denoted V5-DPM. Redefining the visual observations in this way allowed them to be expressed in the same manner as the C-DPM and FCI-DPM, as a sequence of logical values for each minute within a total of 1,903 minutes measured over the six drifter tracks with a true element of each sequence representing a detection positive minute and a false otherwise.

For mathematical clarity, the sequences of DPM were assigned the following symbols:

- *I* for FCI-DPM that were obtained from icListenHF measurements
- *C* for C-DPM that were obtained from C-POD measurements
- *V* for V5-DPM that were obtained from visual observations

The proportion of sampled minutes that are detection positive can also be considered a probability and thus subject to the rules of logic. The probability p of a C-DPM is denoted by $p(C)$ and is calculated as the number of true values in C divided by the number of minutes sampled. Similarly, for $p(I)$ and $p(V)$. Probabilities calculated for I and C being true rely solely on the presence or absence of detected harbour porpoise echolocation activity within any sampled minute, while the probability of V being true depends on both observations and τ.
Consider two sequences of events called A and B. The probability that both A and B are both true is denoted as $p(A \cap B)$. If A is independent of B, then $p(A \cap B) = p(A) \cdot p(B)$ but if A and B depend on one another, then $p(A \cap B) > p(A) \cdot p(B)$. It is convenient to define the ratio:

$$R = \frac{p(A \cap B)}{p(A) \cdot p(B)} \tag{1}$$

so R > 1 when A and B are dependent.

It is of interest to know how the probability of A is conditioned by selecting only those events when B is true. This is called the conditional probability and is denoted by $p(A \mid B)$. Thus, $p(I \mid V)$ is the probability that I is true for those minutes where V is true. Application of the negation operator $\neg$ A turns true values of A false and false values of A true.

Investigating C-POD Lost Time

Investigating the lost detection time with the two C-PODs was undertaken by first binning minutes into three groups: no lost time, under 50% time lost, and over 50% time lost. By recording which minutes belonged to each of the lost time bins, the C-DPM, FCI-DPM and V5-DPM could be similarly binned for comparison. Local current speed was obtained by differencing the drifter tracks and then compared to lost time. Lost time was also compared to Environment Canada hourly meteorological records at Parrsboro and Greenwood, Nova Scotia.

RESULTS

C-POD, IcListenHF/Coda, and Visual Detection Comparison

There were ~16 times more DCI-DPM than

Detector Method (Instrument)	# DPM
C-DPM (C-POD)	81
DCI-DPM (icListenHF)	1,269
FCI-DPM (icListenHF)	354
ACI-DPM (icListenHF)	586

Table 1: Harbour porpoise DPM for C-PODs (C-DPM) and icListenHF hydrophones, with (FCI-DPM) and without (DCI-DPM) stringent Coda filters. An alternate detection algorithm was also explored (ACI-DPM). 1,903 minutes of acoustic data were recorded and processed.

Detected by both C-POD and icListenHF	# DPM	Undetected by icListenHF	# DPM	Undetected by C-POD	# DPM
C ∩ DCI	70	C ∩ ¬ DCI	11	DCI ∩ ¬ C	1,199
C ∩ FCI	53	C ∩ ¬ FCI	28	FCI ∩ ¬ C	301
C ∩ ACI	58	C ∩ ¬ ACI	23	ACI ∩ ¬ C	528

Table 2: Harbour porpoise DPM for C-PODs and from analyses of icListenHF hydrophones. 1,903 minutes of acoustic data were recorded and processed. A∩B is detection positive if and only if both A and B are detection positive. The negation operator is ¬.

there were C-DPM obtained from the C-PODs (Table 1). Eleven of the C-DPM that were logged by the C-PODs were not DCI-DPM (Table 2). The icListenHF time series from both instruments were inspected for each of these 11 minutes; three contained very weak porpoise clicks that were rejected by the Coda software. None of the remaining eight minutes appeared to have porpoise clicks when closely examined; three contained broadband frequency spikes, two contained 69 kHz fish tag signals, one contained a 118 kHz echo sounder signal, and two contained no identifiable signals. A harmonic of the 69 kHz Vemco tag was evident in the spectrogram of icListenHF measurements and it was probably this harmonic that the C-PODs registered as porpoise clicks. The Coda software does not mistake such signals for porpoise clicks.

Automated filtering of the 1,269 DCI-DPM reduced the number to 354 FCI-DPM and 586 ACI-DPM (Table 1). Of the 354 FCI-DPM, only 53 were obtained by the C-PODs and there were 28 C-DPM that were not FCI-DPM (Table 2). Of the 586 ACI-DPM, only 58 were C-DPM, leaving 528 that were not obtained by the C-PODs, and 23 C-DPM that were not ACI-DPM. Of these 23 C-POD detections, 11 can be explained as above, and inspection of icListenHF measurements for the remaining 12 minutes indicate the following: seven appeared to contain porpoise clicks that were rejected by the automated filtering of Coda detections because the clicks were either too weak or had inter-click intervals that were too long, one with broadband spikes, two without explanation, and two with strong 69 kHz tag signals.

In order to visually compare porpoise detections by the different methods, we begin by concatenating DPM over the six experiments. Thus, the FCI-DPM give a sequence of true and false values for each of the 1,903 minutes measured by the icListenHF hydrophones. Similarly, the C-DPM for C-POD measurements and V5-DPM for visual observations of surfacing porpoises. In Figure 5, true values within each

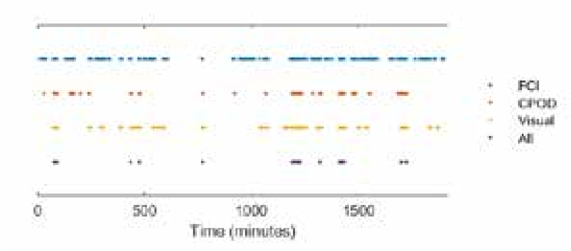


Figure 5: DPM recorded by each observation technique: FCI (Filtered Coda icListenHF), C-POD, Visual observation. Coloured points representing a minute with a porpoise detection. Minutes without detection are left blank. The bottom sequence (All) shows minutes when all three monitoring techniques detect a porpoise.

A	B	p(A) ± SE	p(B) ± SE	p(A ∩ B) ± SE	p(A)·p(B) ± SE	R $\frac{p(AB)}{p(A)\cdot p(B)}$ ± SE
I	*C*	0.19 ± 0.009	0.043 ± 0.005	0.028 ± 0.004	0.008 ± 0.001	3.5 ± 0.6
I	*V*	0.19 ± 0.009	0.20 ± 0.009	0.064 ± 0.006	0.036 ± 0.002	1.7 ± 0.2
C	*V*	0.043 ± 0.005	0.20 ± 0.009	0.026 ± 0.004	0.008 ± 0.001	3.1 ± 0.6

Table 3: Probability of detection p by different combinations of detection sequences: C-DPM (C), FCI-DPM (I), and V5-DPM (V). N = 1903 minutes sampled.

DPM sequence are plotted with a dot, false values are not plotted. All three methods showed a similar pattern (Figure 5). Broadly, visual observations give V5-DPM that look like a subset of FCI-DPM obtained from icListenHF measurements. The C-POD observations give C-DPM that appear to be a somewhat smaller subset of FCI-DPM. It is difficult to fully resolve so many minutes on a small plot, so we have also plotted points where all methods give detections and that turns out to be quite sparse. Obviously, the different methods obtain similar results but often not exactly aligned by the minute.

Coda/icListenHF obtains more detections, $p(I) = 0.19 \pm 0.009$, than C-POD $p(C) = 0.043 \pm 0.005$ (Table 3). The probability that both Coda/icListenHF and C-POD obtain detections for the same minute, $p(I \cap C) = 0.028 \pm 0.004$, is low and the probability of all three methods obtaining a porpoise detection is very low, $p(I \cap C \cap V) = 0.017 \pm 0.003$, as evident in Figure 7. Ideally, each detection method would give identical results, but clearly they do not. Nevertheless, we would hope that their detections are not entirely independent of one another. Dependency of the different methods can be evaluated using Table 3. All rows in the table show $p(A \cap B)$ is substantially greater than the product $p(A)\cdot p(B)$ so we can conclude that I, C, and V are dependent on one another. The ratio R suggests that the dependency is most evident between I and C whereas it is least evident between I and V.

Analysis of the conditional probabilities of each detection sequence demonstrated that both acoustic methods had a higher probability of detecting a porpoise in minutes where a visual detection occurred (Table 4). Additionally, the probability of the C-POD detecting a porpoise was 10x higher when there was an FCI-DPM compared to when there was no FCI-DPM (Table 4). A similar trend was observed when looking at the probability of an FCI-DPM when a C-POD DPM occurred to when one did not (Table 4). Finally, the probability of a visual DPM was higher if either acoustic method recorded a DPM compared to when the acoustic methods detected nothing (Table 4).

Conditional Probability	p ± SE	Conditional Probability	p ± SE
$p(I \mid V)$	0.33 ± 0.02	$p(I \mid \neg V)$	0.15 ± 0.009
$p(V \mid I)$	0.34 ± 0.03	$p(V \mid \neg I)$	0.16 ± 0.009
$p(C \mid I)$	0.15 ± 0.02	$p(C \mid \neg I)$	0.018 ± 0.003
$p(I \mid C)$	0.65 ± 0.05	$p(I \mid \neg C)$	0.17 ± 0.009
$p(C \mid V)$	0.13 ± 0.02	$p(C \mid \neg V)$	0.021 ± 0.003
$p(V \mid C)$	0.60 ± 0.05	$p(V \mid \neg C)$	0.18 ± 0.009
$p(\mathrm{A} \mid \mathrm{I})$	0.96 ± 0.01	$p(\mathrm{A} \mid \neg \mathrm{I})$	0.16 ± 0.009
$p(\mathrm{I} \mid \mathrm{A})$	0.58 ± 0.02	$p(\mathrm{I} \mid \neg \mathrm{A})$	0.01 ± 0.003

* Conditional probability p(A | B) is the probability of an event (A), given that another event (B) has already occurred.

Table 4: Conditional probabilities* for detection sequences: C-DPM (C), FCI-DPM (I), and V5-DPM (V). Conditional probabilities are given at the bottom for ACI-DPM (A) and FCI-DPM (I).

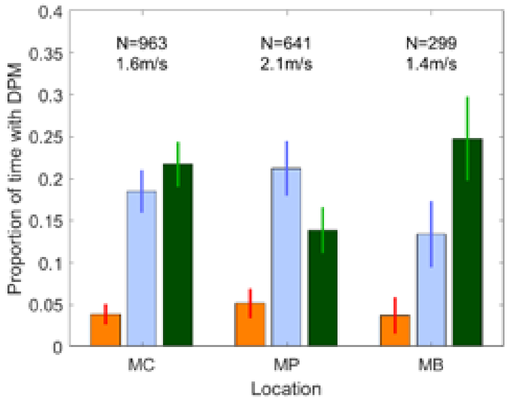
icListenHF SN#	Platform	Proportion FCI-DPM ± SE	# click trains per DPM
1211	Drifter, June 2017	0.139 ± 0.008	3.99
1239	Drifter, June 2017	0.157 ± 0.008	4.15
1239	Lander, June 2014	0.137 ± 0.018	1.67

Table 5: Comparison of porpoise vocalizations detected by each icListenHF on a drifting platform relative to a stationary sensor platform (Lander) deployed on the seafloor within the FORCE test site.

Conditional probabilities between FCI-DPM and ACI-DPM (bottom of Table 4) support the notion that FCI is an incomplete measure of DPM and that ACI moves us a little closer to completeness.

Porpoise vocalizations detected by each icListenHF on the present drifter had very similar proportion of DPM to that obtained from an icListenHF that was mounted to a rigid platform (Lander Platform) resting on the seafloor at the FORCE test site (Table 5). It is notable that the average number of click trains per DPM was substantially higher when measured from a platform that drifts with the water than when measured from a platform moored on the seafloor. A drifter moves with the volume of water being sampled and porpoises typically swim slowly [Otani et al., 2000] compared to current speed in Minas Passage, so few porpoises are detected for long time intervals. Fast currents sweep large volumes past a moored instrument, so more animals will pass by, but they will pass by quickly with fewer detected click trains per DPM.

Harbour porpoise click trains were detected by both icListenHFs and C-PODs across all drift locations (Minas Channel, Minas Passage, and western Minas Basin) and at low to high current speeds. The left panel of Figure 6 shows the proportion of time with DPM for the three locations as obtained from C-PODs, FCI (filtered Coda / icListenHF), and V5 (porpoise sightings). Care was taken to examine the lagged auto-correlation function for FCI-DPM. The integral time-scale [Hinze, 1975] of the auto-correlation function was four minutes. Thus, when calculating standard error for Chi-square tests, the number of degrees of freedom is one-quarter of the number of samples (N).



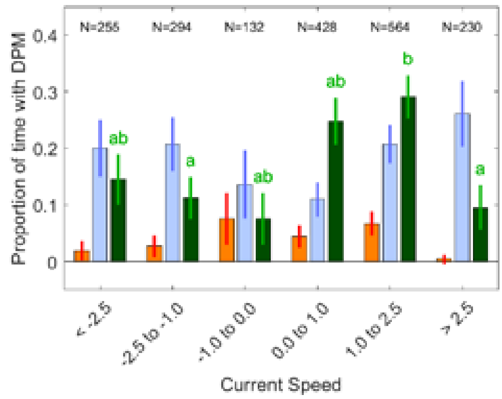


Figure 6: Proportion of C-DPM (orange), FCI-DPM (blue), and V5-DPM (green) (mean ± 1 standard error) at three locations (left panel) and six ranges of current speed (right panel). In the right panel, signed current speed is positive for flood tide and negative for ebb tide. In the left panel, we indicate average current speed for measurements at each location. N equals the number of minutes sampled. Locations: Minas Channel (MC), Minas Passage (MP), and Minas Basin (MB). Green letters above the bars (a,b) show post-hoc analysis results (Pairwise Nominal Independence) of Chi-Squared tests for the V5-DPM. All other tests resulted in a nonsignificant difference or too small a sample size to test for significant difference.

The Chi-square test showed that FCI-DPM and V5-DPM did not vary across locations but there were not enough C-POD detections for a reliable Chi-square test. Qualitatively, the standard errors in the left panel of Figure 6 suggest C-POD detections did not vary with location in any substantive way.

The left panel in Figure 6 shows proportion DPM binned according to current speed (positive for flood and negative for ebb). The Chi-square test showed that FCI-DPM did not vary with current speed. For the visual observations, the Chi-squared test showed that V5-DPM was only different for the 1.0-2.5 m/s speed interval. C-PODs obtained too few DPM for the Chi-squared test to be reliable. Qualitatively, Figure 6 gives the appearance that there are more C-POD DPM at low current speeds which would be consistent with the analysis of lost time that follows.

C-POD Lost Time

The two C-PODs recorded without lost time for 81% of all the minutes sampled during the six hydrophone array drifts (Table 6). Almost 5% of the recorded minutes featured lost time less than 50%, while approximately 15% of the minutes recorded had greater than 50% lost time (Table 6). The probability of a minute being detection positive was calculated for each acoustic technique in relation to the percentage of lost time within each minute. The C-PODs experienced a precipitous decrease in detection efficiency with time lost, with the probability of a detection decreasing from 4% to practically 0% (Table 6). On the other hand, the FCI-DPM did not show meaningful changes in detection probability during minutes when C-PODs suffered lost time (Table 6). V5-DPM appeared to decline somewhat when conditions caused lost time.

The question arises as to whether the two co-deployed C-PODs (serial numbers 1520 and 1616) were losing recording time during the same minutes. Any attempt to address this question must begin by acknowledging that C-PODs are not perfectly synchronized, so the beginning and end of a sampling minute might

C-POD Time Lost Category	Probability ± SE	N (minutes)	Fraction of total minutes sampled
TL = 0%	C-DPM: 0.038 ± 0.005 FCI-DPM: 0.146 ± 0.009 V5-DPM: 0.21 ± 0.01	3,061	0.808
0% > TL ≤ 50%	C-DPM: 0.006 ± 0.008 FCI-DPM: 0.170 ± 0.040 V5-DPM: 0.15 ± 0.04	171	0.045
TL ≥ 50%	C-DPM: 0 ± 0 FCI-DPM: 0.144 ± 0.020 V5-DPM: 0.11 ± 0.02	556	0.147

Table 6: Probabilities of a C-DPM (C-POD) and FCI-DPM (icListenHF) for different C-POD lost time categories. N equals the number of C-POD sampling minutes in each time lost category.

differ by a few seconds from one instrument to the other. Nevertheless, the instruments are largely contemporaneous. Thus, we can examine whether time lost is similarly contemporaneous by examining conditional probabilities. The probability of C-POD 1520 having lost time if C-POD 1616 had lost time was 0.91 ± 0.15, while the probability of C-POD 1616 having lost time if C-POD 1520 had lost time was 0.93 ± 0.13. This suggests that both instruments might be suffering lost time for the same reason.

It might be expected that lost time will be related to things that cause ambient sounds. Lost time was not related to records of hourly wind speed at either Parrsboro or Greenwood meteorological stations nor to rain. This is not a conclusive negative finding because wind and rain have local variability. Current speed obtained from drifter tracks has the advantage of being determined local to the C-PODs. Current speed was found to have no obvious effect on the C-POD lost time so long as surface currents were less than 1.5 m/s. At 1.5-2 m/s there was an abrupt jump in percentage of time lost with time lost further increasing for still faster currents (Figure 7).

DISCUSSION

Lost Time

Limits placed on storage allocation of detected clicks for each minute of sampling are sometimes exceeded before a C-POD can measure over the entire minute. This results in lost time for sampling by the C-POD when ambient noise is high. Rainfall, wind, and wind waves are well known to change ambient sound level [Hildebrand, 2009] and might, in general, cause lost time. However, the present measurements were inadequate to evaluate any influence that these potential factors might have for the water mass flowing through Minas Passage. The present study found lost time increasing as current speed increased above 1.5 m/s. Lost time would not be an issue if the memory buffer was being

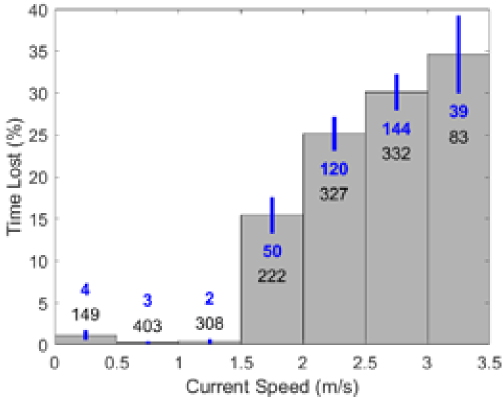


Figure 7: Histogram of C-POD lost time as a function of current speed. Flood and ebb drift data combined. Dark blue bars are standard error. Blue numbers are the number of minutes with time lost for each current speed bin. Black numbers are the number of minutes sampled for each current speed bin.

filled with reliable detections of porpoise vocalizations but the C-POD almost always fails to register a reliable detection during any minute when there is lost time, whereas the FCI is just as likely to classify such minutes as detection positive as at any other time. About 19% of the minutes measured by C-PODs suffered lost time but even when current speed was 2.5-3.5 m/s there were at least as many minutes for which there was no lost time as minutes with lost time. Thus, the proportion of DPM might be corrected by extrapolating from neighbouring minutes without lost time, given that lost time is not associated with high rates of false detections. Visual detections may be weakly associated with C-POD lost time, perhaps because the water surface is more disturbed by strong "boils" when current speed is high.

Previous studies in Minas Passage [Wood et al., 2013; Porskamp et al., 2015; Tollit et al., 2019] have observed that C-PODs suffer lost sampling time. Those previous studies used moored instruments and so it is conceivable that flow noise [Strasberg, 1979] might have contributed to lost time. Tollit et al. [2019] finds that there was at least some lost time for about 85% of the 10-minute detection intervals in the long-term monitoring dataset collected by bottom-tethered C-PODs at the FORCE test site. The present measurements found lost time for only 33% of the 10-minute intervals measured by C-PODs mounted on the drifter. Lost time in the present experiments appears to be attributable to ambient sound level increasing with current speed. Clearly, flow noise is minimized for drifter-mounted instruments that move with the current.

It is possible that flow noise contributes to higher lost time by bottom-tethered C-PODs at the FORCE test site but there are other factors that may also be important. Sanderson et al. [2017] reported that the FORCE test site had higher ambient sound levels in the frequency range used by harbour porpoise vocalizations than the areas tracked by the drifter, so that may cause additional lost time. Another cause might be sounds and vibrations caused by tethered mooring instability. The mooring used at the FORCE test site consisted of a C-POD mounted inside a SUB streamlined instrument float (Open Seas Instrumentation) with an acoustic release and 2 m riser chain attached to a steel weight. Sanderson et al. [2017] observed that this type of mooring was unstable at high flows and that sometimes the floats are scuffed and damaged by collision with the bottom. Bottom collisions, and vibration of the riser line and other mooring hardware, might also make it more difficult to detect porpoise vocalizations. From time to time, the ballasting of SUB-floats has been modified in various ways, so insight might be obtained if

C-POD measurements were compared for those different configurations.

Proportion FCI-DPM (obtained using Coda to analyze icListenHF measurements) was seemingly unaffected at times when C-POD experienced lost time (Table 1), but we note that C-POD time will not exactly match icListenHF time, although it is expected that the clocks had not drifted relative to one another by more than a small fraction of a minute during the deployment period. Furthermore, the proportion of FCI-DPM does not decline in fast currents (Figure 6), consistent with them being unaffected at times when C-PODs experienced lost time.

C-POD, IcListenHF/Coda, and Visual Detection Comparison

C-POD and icListenHF hydrophones were co-located on the drifter within 1-3 m of each other so, in principle, a porpoise vocalization that is detected by an icListenHF should have a very good chance of also being detected by a neighbouring C-POD. Thus, the C-POD and icListenHF hydrophone can be said to measure the same quantity so comparison of their measurements is straightforward and can be expected to give insight into the relative performance of hardware and algorithms used for detecting harbour porpoise vocalizations. Visual observations of a harbour porpoise briefly surfacing, on the other hand, do not measure the same signal as the hydrophones, and the porpoise is almost always sighted at a position far from the hydrophones. There can be no expectation that a porpoise will be acoustically detected at the same time of it being visually sighted. Nevertheless, we have used a balance of probabilities argument that if a porpoise is sighted near the drifter at some time then there is a good chance that its vocalization might be detected by a hydrophone during some surrounding interval. For our measurement methods, setting that interval to five minutes either side of the visual sighting gave a very similar proportion of detection positive minutes as obtained from applying the Coda algorithm to the icListenHF measurements (FCI-DPM). Thus, the surrounding time interval can be thought of as an aid that also normalizes visual sightings to acoustic detection of harbour porpoise vocalizations.

Proportion of DPM did not vary significantly with respect to locations along the drifter path, regardless of whether DPM were obtained from C-POD, icListenHF, or visual observations. This is hardly surprising given that the drifter moves with the water mass and given that the typical swimming speed of a porpoise is only about 1 m/s [Otani et al., 2000]. On the other hand, Wood et al. [2013] and Porskamp [2015] report that C-PODs moored at the FORCE test site detected more vocalizations near high tide than near low tide. The most obvious interpretation for this result is a spatial gradient of porpoise abundance along the length of the water mass that passes through Minas Passage in a tidal cycle, with higher abundance to the western end. Obviously, in future, this hypothesis could be tested by deploying two hydrophone-bearing drifters near the different ends of that water mass.

Figure 6 indicates that different current speeds cause no significant difference in detections by either C-PODs or icListenHF hydrophones (notwithstanding C-POD detections being fewer relative to detections from icListenHF measurements). Visual detections did seem to be compromised by fast flood currents (Figure 6) and we noted fewer harbour porpoise sightings near Cape Split (Figure 4). Drifter trajectories passed close to Cape Split on the flood tide. We observed fast currents and rough waters at that location and time which may explain reduced visual detections [Palka, 1996].

As mentioned above, C-POD detection of porpoise vocalizations is compromised in fast currents due to lost time, if nothing else. More generally, however, we are interested to know which methods detect most reliably, how well are detections by one method related to detections by another, and which methods are most practicable for environmental monitoring. Even more relevant to measuring effects of in-stream tidal energy development on porpoise: What should we make of the differences?

Overall, using the drifter as a platform, the proportion of DPM obtained using the icListenHF hydrophones (FCI-DPM) was about four times that obtained from the C-PODs (C-DPM). Decreased C-POD detection efficiency when comparing C-PODs and broadband recorders has been reported previously [Wood et al., 2013; Porskamp et al., 2015; Sarnocinska et al., 2016; Jacobson et al., 2017; and Clausen et al., 2018]. C-PODs and FCI-DPM (icListenHF) are more comparable in slower moving waters. Reduced proportion DPM when C-PODs are in fast currents is consistent with increased lost time in such circumstances.
Time series measurements by the icListenHF, and semi-automated software, enabled each FCI click train to be manually reviewed in context of objective metrics. We consider such review to bestow some measure of reliability although, ultimately, a human decision was made for every single click. Vocalizations detected by a C-POD cannot be similarly reviewed. Most of the vocalizations that were detected by the icListenHF (FCI) were totally missed by the C-POD. Perhaps we might say that the C-POD has a false-negative bias. But a slightly adjusted click detection algorithm (ACI) would seem to suggest that FCI suffers the same problem, albeit to a lesser extent.

On the other hand, the C-POD does sometimes report an apparent porpoise vocalization which is not obtained from the icListenHF measurements. In all, the C-PODs obtained 23 DPM that were not also ACI-DPM. Does ACI also suffer a false-negative problem? After careful review of those 23 minutes of icListenHF recordings, in a sense, assuredly it does. Ten of those 23 DPM did contain clicks that could be discerned in a spectrogram and resolved by a matched filter, but they were weak signals and sometimes widely spaced, so they were rejected by either Coda or the subsequent filtering. This underscores a seemingly unavoidable difficulty; all our detection methods involve arbitrary criteria, so we will not be dogmatic about defending or promoting any of them. Five of those 23 DPM were false-positive detections of nearby active acoustic devices (an acoustic fish tag and an echo sounder). More generally, active acoustic devices certainly can interfere with one another and also with passive acoustic methods. This may be problematic for environmental monitoring at the FORCE test site where in-stream tidal turbine installations include multiple sensors: imaging sonar for monitoring fish, passive acoustics for monitoring porpoise vocalizations, and ADCPs for measuring currents. The matter is doubly complicated by the fact that signals from active acoustic devices can be expected to modify porpoise behaviour [Mikkelsen et al., 2017; Wisniewska et al., 2018]. A well-designed program that uses C-PODs to monitor harbour porpoises should exclude nearby active acoustic devices.

Presently, averaging across all drifter measurements, C-DPM is 0.043 ± 0.005, and for 10-minute intervals, C-DP10M = 0.18 ± 0.03. Tollit et al. [2019] obtain C-DP10M = 0.04 by averaging 10-minute detection intervals over all C-PODs mounted to SUB-float moorings at and near the FORCE test site. Even adjusting for the seasonal cycle [Tollit et al., 2019], the value of C-DP10M from FORCE's moored instruments would be a factor of three smaller than for our drifter measurements. Tollit et al. [2019] also report a median of seven C-DPM per day, which is a factor of eight less than the C-DPM obtained from our drifter measurements. Our earlier results indicate that mooring effects might be a factor influencing DPM so let us consider another method that has been used to deploy instruments on the seafloor. Porskamp [2015] reported DPM from both icListenHFs and C-PODs that were mounted to a Lander Platform deployed at the FORCE test site during June 2014, a different year but during the same month as our drifter study. Surprisingly, our reanalysis of the icListenHF measurements reported by Porskamp [2015] gave proportion FCI-DPM that were effectively the same as those obtained by our drifter study, three years later but the same month. Accepting this equivalence at face value, it seems unlikely that detection of porpoise vocalizations could be much degraded by flow noise when the icListenHF is mounted to a stable bottom platform at the FORCE test site. On the other hand, detection of porpoise vocalizations seems to be severely degraded when a C-POD is moored using a tethered SUB-float. That leaves the instability of SUB-float moorings [Sanderson et al., 2017] as a likely cause for degraded performance of moored C-PODs at the FORCE test site.

Setting aside apparent difficulties with the SUB-float moorings used to mount C-PODs at the FORCE test site, the drifter mounted hydrophones indicate that many more porpoise vocalizations can be found from icListenHF measurements than by using a C-POD. This difference in detection of vocalizations is probably not a matter of great consequence providing the objective of environmental monitoring is restricted to documenting substantial changes in porpoise presence over months and years. Both C-POD and icListenHF essentially measure the same thing and if a C-POD determines that a porpoise is present then there is a 65% chance that an icListenHF will also (Table 4). Wood et al. [2013] deployed bottom-mounted C-PODs near an icListenHF and found that at least 50% of the C-POD DPM corresponded to icListenHF measurements that also contained evidence for porpoise vocalizations. For long-term environmental monitoring, it is reasonable to crudely characterize both instruments as obtaining incomplete measurements of harbour porpoise vocalizations, the C-POD being more incomplete and more confounded by increasing current speed. Each instrument might serve to independently measure some environmental trend, but a trend should not be deduced by comparing C-POD measurements at one time with icListenHF measurements at a different time.

Presently an icListenHF must be cabled to provide power and data storage/analysis for long-term monitoring. Until the Coda algorithm can be run on board an icListenHF, it is not a practicable tool for long-term deployments of the type reported by Tollit et al., [2019]. On the other hand, an array of synchronized icListenHF hydrophones, coupled with a matched filter, provides a method for obtaining position of a vocalizing porpoise. Position information is expected to be useful to evaluate porpoise abundance and their behaviour near in-stream tidal turbines. Long-term environmental monitoring with C-PODs and more detailed information from arrays of synchronized broadband hydrophones are complementary, as one provides context for the other. Experience to date leads us to expect that both methods will be required to provide convincing evidence of the extent that installation of in-stream turbines may or may not affect porpoise behaviour.

We would not wish to downplay the utility of visual observations relative to acoustic methods for monitoring environmental effects of in-stream tidal turbines. Comparing visual observations of harbour porpoises with vocalizations detected by C-PODs and icListenHFs suggest that the three monitoring techniques have broad compatibility. Visual methods are valuable [Mikkelsen et al., 2017]. Indeed, taken to their obvious conclusions, optical detection by a camera on a hovering drone would give porpoise position as does an array of hydrophones. Each method has limitations, but different limitations; jointly, they provide more information than separately.

CONCLUSIONS

Harbour porpoise vocalizations were effectively obtained by both icListenHF hydrophones and C-PODs mounted to a drifter in the water mass that flows through Minas Passage where there is a test site for in-stream tidal turbines. Proportion of detection positive minutes did not change significantly as the water mass made its tidal excursion along Minas Channel, through Minas Passage, and into Minas Basin.

Coda software efficiently identified individual porpoise vocalizations within hydrophone measurements, from which automated selection of click trains was achieved, and confirmed by detailed, manual inspection of each detection. Co-deployed C-PODs obtained fewer detection positive minutes but were judged reliable but incomplete when carefully compared to porpoise sightings and detection positive minutes obtained from the icListenHF hydrophone. Hydrophone records indicate that C-PODs can mistake signals from active acoustic devices for harbour porpoise vocalizations.

Lost time, caused by the C-POD memory buffer being filled with non-target noise, is the major difficulty that has been identified when operating C-PODs in these fast-flowing waters. Results from drifter-mounted devices indicated that substantial lost time might be attributed to ambient sounds associated with fast currents. Comparison of C-PODs on SUB-float moorings with drifter mounted hydrophones and hydrophones on a stable seafloor platform indicates that noise generated from instabilities of tethered SUB-float moorings may also contribute to lost detection time.

C-POD and icListenHF hydrophones (with Coda software) both give incomplete metrics of porpoise echolocation activity. Careful consideration of a great deal of contextual information is required to compare results obtained from these two passive acoustic monitoring technologies. Otherwise, monitoring measurements from one technology should not be compared with measurements from the other technology to deduce an environmental effect.

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