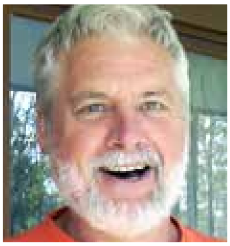
Reflections of noise



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Mike Adams

Anna Redden

Sanderson, Adams, and Redden show how two synchronized hydrophones can be used to obtain both the depth of a porpoise and its range.

Who should read this paper?

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

Why is it important?

Detection of porpoise vocalizations as a measure of animal activity has been a convenient method for environmental effects monitoring. Such monitoring is required because marine mammal interaction with tidal power installations is poorly known. This paper is one step along the transition towards convenient methods that enable source localization and measures of abundance which are required to directly examine animal interaction with tidal power installations.

It is demonstrated that vocalizations reflected from the sea surface or sea floor add valuable time of arrival information and substantially increase the effective aperture of the hydrophone array. This enables animal location and some aspects of animal behaviour to be measured with a small number of hydrophones and may improve the performance of arrays containing many hydrophones.

About the authors

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 their location. His objective is to conveniently measure porpoise abundance relative to distance from a turbine installation in order to inform responsible development of tidal power. **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 porpoises 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. **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.

USING REFLECTED CLICKS TO MONITOR RANGE AND DEPTH OF ATLANTIC HARBOUR PORPOISES

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ABSTRACT

Detection of the time of arrival of a harbour porpoise click at several synchronized broadband hydrophones, attached to a drifter, provides a method for locating porpoise and assessing any interactions with tidal turbine installations. Presently we show how two synchronized hydrophones, arranged as a vertical array, can be used to obtain both the depth of a porpoise and its range from the hydrophones. Our method applies whenever time of arrival for a porpoise click can be measured along both direct paths and paths reflected from either the sea surface or seafloor. Comparison of signal level with porpoise range from the array indicated that source levels were consistent with previous findings for wild porpoises. Signals reflected from the seafloor appeared to suffer from a high degree of scattering but their leading edge was sometimes clear and useful. Reflections from the sea surface were relatively clean and more commonly useful. The calculated porpoise depth was below/above the level of the hydrophone array whenever reflections were from the sea surface/floor, corresponding to the expected orientation of a porpoise that is rising/diving, respectively. Time of arrival is likely to be more uncertain for reflected signals than for those taking a direct path from porpoise to hydrophone. Nevertheless, using reflected signals can greatly increase the effective aperture of a hydrophone array so it may be advantageous to consider the arrival times of reflected signals even when an array has many more than two hydrophones.

KEYWORDS

Harbour porpoise; Acoustic monitoring; Range; Depth; Turbine; Avoidance

INTRODUCTION

In Canada, legislation [Fisheries Act, 1985] requires that a tidal power installation not cause serious harm to marine animals. The Atlantic harbour porpoise, *Phocoena phocoena*, is sensitive to anthropogenic sound [Wisniewska et al., 2018] and is the most commonly observed marine mammal in Minas Passage [Wood et al., 2013] where the Fundy Ocean Research Center for Energy (FORCE) has established a test site for in-stream tidal turbines. Measurements of porpoise-turbine interaction are required to assess the extent to which the advantages of low carbon production of electricity from tides might or might not be offset by other changes to the local environment, including marine life.

In order to estimate any interaction between porpoises and tidal turbines, it will be necessary to measure porpoise abundance and position relative to turbine installations. Towards this objective, detection of the time of arrival of a porpoise click at several synchronized hydrophones provides one method for locating a porpoise.

To date, there have been three deployments of OpenHydro turbines in Minas Passage, most recently in July 2018. Lossent et al. [2018] measured sound from an OpenHydro 2.2 MW turbine and suggested that source levels were sufficiently high to influence the behaviour of porpoises out to a range of 1 km. There is, therefore, reason to demonstrate methods that can assess porpoise positions relative to tidal turbines.

A 3D array of 12 hydrophones, only five of which were fully functional, was recently used to estimate the source positions of porpoises near a turbine installed in North Ramsey Sound, Wales, UK [Malinka et al., 2018]. Those measurements indicated that porpoises might avoid locations within 20 m of the turbine. The 2017 deployment of a 2 MW OpenHydro turbine at the FORCE test site had an array of four synchronized hydrophones that were separated by distances of 18 to 30 m. In principle, porpoise position could be estimated from such an array providing all hydrophones detected the same porpoise click. A porpoise click has some of its energy focused in a 16° beam [Au et al., 1999] with the rest transmitted in a more omnidirectional manner. Thus, all hydrophones might detect the focused beam when the porpoise is sufficiently far away, or they may all detect the omnidirectional part when the porpoise is sufficiently close. Unfortunately, measurements from the 2017 turbine test at the FORCE test site did not enable position to be calculated because hydrophone sample rates were initially set too low to detect porpoise clicks; subsequently, one hydrophone was physically damaged and there was a poor cable connection to two others [Ocean Sonics, 2018].

A useful objective might be to accurately estimate porpoise avoidance of a turbine by comparing the number of porpoise clicks originating from ranges and depths near the turbine to the number originating far from the turbine. As a first step, we must measure the range and depth of a clicking porpoise. Geometric considerations suggest this can be achieved using a vertical array of three or more synchronized hydrophones that all measure the time of arrival of a porpoise click. In 2017, we made preliminary measurements using a vertical array of two synchronized hydrophones to test the Coda porpoise click detector in Minas Passage and Minas Channel [Adams, 2018; Adams et al., 2019]. Examination of measurements following the arrival of detected clicks sometimes revealed associated reflections from either the sea surface or seafloor. The present work will, therefore, examine the possibility of using both reflected paths and direct paths to estimate the depth of a porpoise and its range from a vertical array of only two synchronized hydrophones.

MEASUREMENTS

A 2 m sync cable was used to synchronize two icListenHF hydrophones (Ocean Sonics Ltd.) that were each set to record pressure at a 512 kHz sample rate. Both hydrophones were calibrated by Ocean Sonics Ltd. before deployment. Bandwidth is ±6 dB over the frequency range 10 Hz to 200 kHz. Sensitivity is -169 dBV re. µPa and dynamic range is 95 dB. Synchronization accuracy is 0.25 µs.

The icListenHF includes pre-amplifier, filter, analogue to digital conversion, and data storage in one compact unit. These properties enabled us to deploy the hydrophones in a stand-alone configuration as a vertical array with hydrophones 14 m and 16 m beneath a pole float drifter (Figure 1). Such drifter configuration minimized the effects of wind drag which shifted arrays from vertical in other studies [Wahlberg et al., 2001; Macaulay et al., 2017]. Vertical alignment of the array was further ensured by attaching the hydrophones to a taut rope which ran from a subsurface buoyancy unit to an 11.5 kg lead weight. The

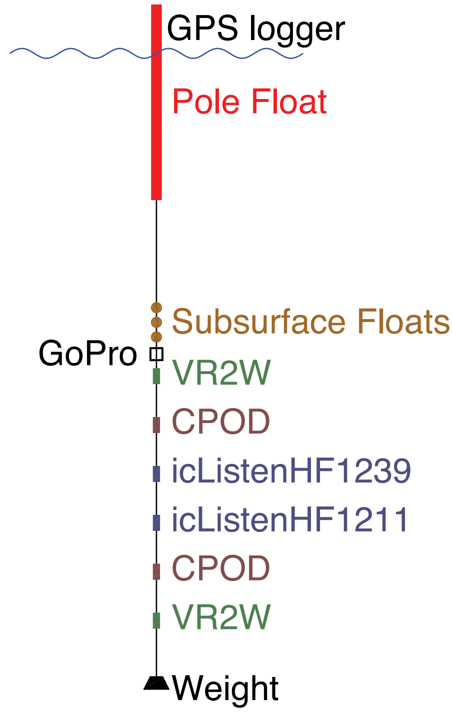

Figure 1: Pole float drifter with a vertical array of acoustic instruments: CPOD, Vemco VR2W receivers for detecting acoustic fish tags, and two Ocean Sonics icListenHF hydrophones that are synchronized with an Ocean Sonics sync cable. The icListenHF hydrophones were 14 m and 16 m below the sea surface. Position is monitored using a Garmin GPSmap 62s GPS logger. Subsurface floats each have diameter 0.2 m. The GoPro video camera (Hero3 White Edition) operated during the first two hours a drift.

cross-sectional area of the pole float was 0.0064 m^2 and the inertial mass of the entire drifter layout was 20 kg. This gives a 3.5 s buoyancy period which ensures small amplitude response to wind waves during the low-wind conditions in which measurements were made. Hydrophones had little motion relative to the water in which they were immersed so flow noise [Strasberg, 1979] was largely avoided.

The drifter-hydrophone assembly (Figure 1) was deployed in Minas Channel and Minas Passage in June 2017. In all, measurements were made along six drifter tracks in June 2017, with drift durations from five to seven hours. Only a few measurements by the synchronized

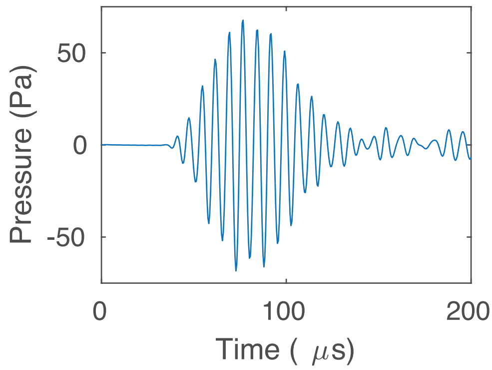

Figure 2: Hydrophone measurements of a click from nearby harbour porpoises in Minas Passage. The hydrophone measurements were high-pass filtered.

hydrophones will be presently analyzed. Adams et al. [2019] discuss results from additional instruments on the drifter assembly.

REFLECTED PORPOISE CLICKS

Harbour porpoise clicks have a 16° beam width [Au et al., 1999], source level of 178-205 dB [Villadsgaard et al., 2007], and frequency within the range 125-135 kHz. The pressure fluctuations corresponding to a click from a nearby porpoise can be clearly seen in hydrophone measurements (Figure 2). A typical click has about 100 µs duration, corresponding to a length scale of about 0.15 m. Given the generally consistent structure of harbour porpoise vocalizations, it is relatively easy to use a matched filter to search for them. The matched filter exploits the convolution theorem [Press et al., 1986] to efficiently find when a standardized porpoise click correlates best with hydrophone measurements.

Adams [2018] used the Coda algorithm (which includes a matched filter) to identify porpoise clicks within our measurements. Following such identification, it is our practice to review identified clicks using a regression method and by viewing spectrograms calculated from time series within which click trains were found. The porpoise clicks have short duration and so they appear in spectrograms as thin vertical lines spanning the frequency band 110-145 kHz, although spectrograms are not always sufficiently sensitive to clearly show all the clicks that Coda identifies. Sometimes (in about 2% of the minutes sampled) the spectrogram shows signals at porpoise frequencies – obviously associated with clicks found by Coda – where the energy is distributed over a much longer time interval than for a porpoise click (Figure 3).

The nature of these long-duration, porpoise-frequency signals was further investigated by band-pass filtering to obtain a time series view of the porpoise frequencies. The results are made more evident by using a Hilbert transform to calculate the envelope of the filtered time series. Figure 3 shows the envelopes for concurrent measurements made by the two hydrophones, one 2 metres above the other. The envelope for the upper hydrophone (14 m) is plotted in blue and the negative of the envelope for the lower hydrophone (16 m) in red. Envelopes show a sharp click followed by a longer pulse of energy that arrives with a relatively sharp leading edge but trails off over a time scale much longer than a typical click duration. Zooming in on the first click (lowest plot), we see that it arrives at the upper hydrophone fractionally before it arrives at the lower hydrophone. The broader energy pulse arrives much later, first at the lower hydrophone and then at the upper hydrophone. The most reasonable interpretation is that a porpoise emits a click near the surface as it begins its dive. The click arrives first at the upper

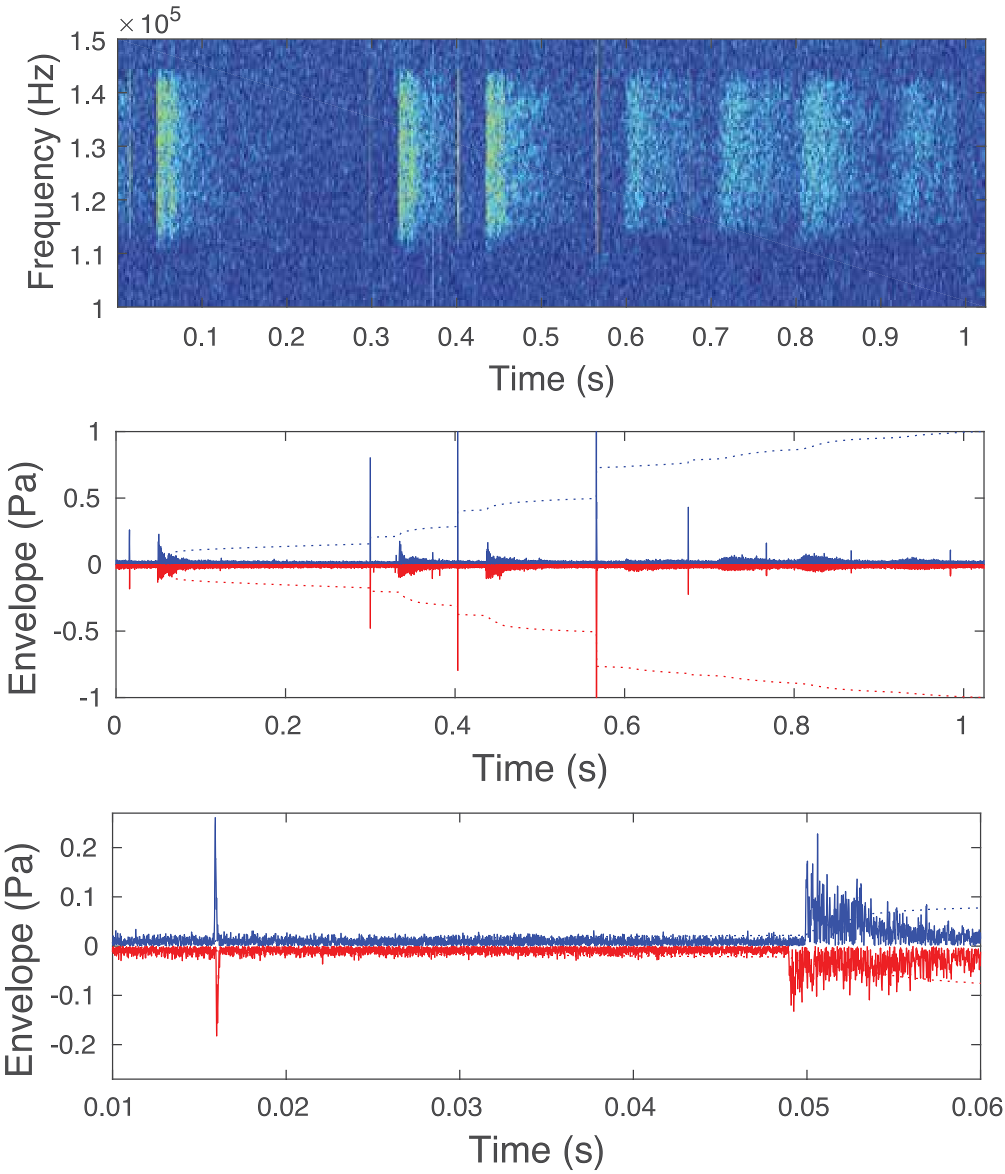

Figure 3: (Top) Spectrogram showing porpoise clicks which appear as vertical lines and signals of much longer duration. (Middle) Signal envelopes from time series that have been filtered to pass frequencies in the porpoise band. The blue line shows the upper hydrophone and the red line plots the envelope upside down for the lower hydrophone. Normalized integral of each envelope is shown with a dotted line. (Bottom) Zooming in on the envelope for first click in the time series.

hydrophone, then the lower hydrophone. Presumably the porpoise is at an appropriate range from the hydrophone for some of the click energy to reflect/scatter off the seafloor and thence up to the hydrophones, arriving first at the lower hydrophone and then at the upper hydrophone.

Adams [2018] also observed many occasions when clicks appeared as doublets, with one click closely following the next and then a much longer time delay until the next click in a train of many click doublets. No effort was made to document all such occurrences, but a few were noted and they are used for the

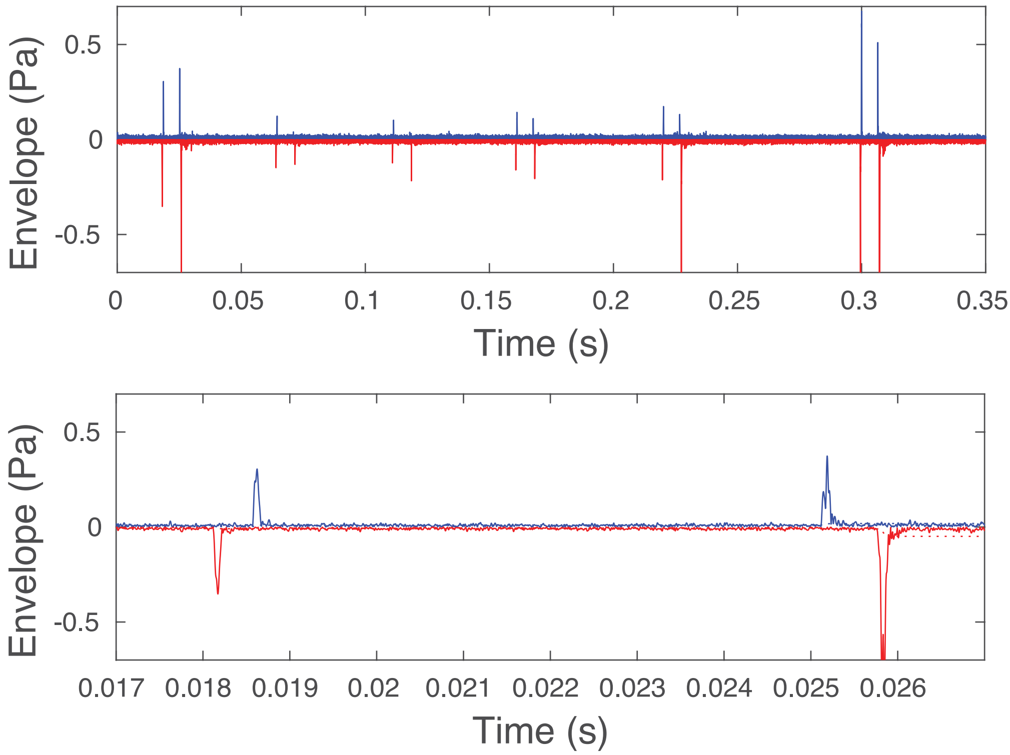

Figure 4: Envelope of porpoise-band filtered time series measured by upper (blue) and lower (red) hydrophones. For ready visualisation, the red line plots the envelope upside down. (Top) Envelopes show a train of paired peaks. (Bottom) Zooming in on the envelopes for the first pair in the click train.

present study. Again, time series were band-pass filtered for porpoise frequencies and signal envelopes calculated using a Hilbert transform. The top plot in Figure 4 shows both hydrophones collecting a train of six doublet-clicks over a 0.35 s interval. Zooming in on the first doublet, the lower plot in Figure 4 shows that what might at first appear to be a pair of clicks – one quickly following the other – will turn out to be two signals from one click. The red line shows that the first signal belonging to the doublet reaches the lower hydrophone (red) first, quickly followed by its arrival at the upper hydrophone (blue). This would correspond to click signal travelling from a position below the level of the hydrophones. After a longer interval, the second signal belonging to the doublet arrives. This second signal appears to travel from above because it arrives at the top hydrophone (blue) first and then at the lower hydrophone (red). This is what might be expected if a porpoise emitted a click from a depth lower than both hydrophones, the lower hydrophone detecting the click first as it propagated upwards and the upper hydrophone being first to detect the reflection of the click from the sea surface. Such a circumstance might be expected when the porpoise is oriented towards the sea surface as it travels upward from a deep dive.

The interpretation above, that the signal detections result from a click travelling both direct and reflected paths, is qualitative. Quantitative calculations are required to bolster our case. If these are porpoise clicks and their reflections, then they can be used to calculate the range to a porpoise and the depth

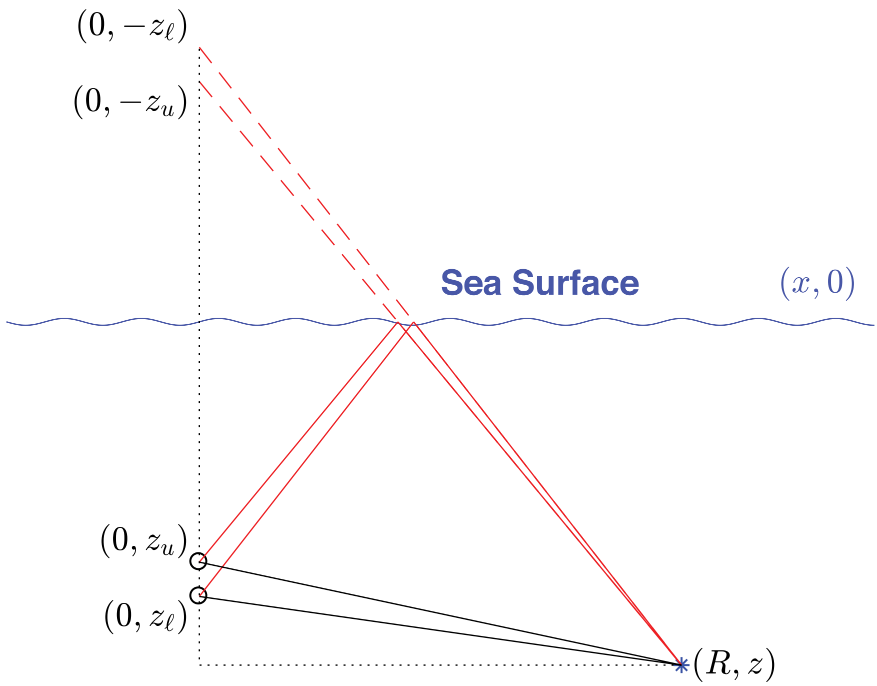

Figure 5: Reflection of a click off the sea surface.

of the porpoise when the click was emitted. Calculations were made to examine whether range and depth are parsimonious with the above qualitative interpretations for signal paths.

CALCULATIONS FOR REFLECTION FROM THE SEA SURFACE

Consider a harbour porpoise at position (R,z) which corresponds to the porpoise being at depth z beneath the sea surface and horizontal range R from a drifter that vertically suspends two hydrophones (Figure 5). The upper and lower hydrophones are at known coordinates ($0,z_u$) and ($0,z_l$), respectively. A porpoise click that follows a direct path to the hydrophones will have times of arrival t_u and t_l at the upper and lower hydrophone, respectively. A click that arrives after being reflected from the sea surface must travel a greater distance and has arrival times t_{ru} and t_{rl} at the upper and lower hydrophones. All four of these arrival times are found from the hydrophone measurements but the time t_0 at which the click was made is not known. Denote the speed of sound to be c.

Figure 5 shows the paths of direct rays from the porpoise at (R,z) to the upper ($0,z_u$) and lower ($0,z_l$) hydrophones. The paths of rays reflected from the sea surface are also shown. The path length of reflected rays can be conveniently calculated by employing the geometric construction indicated by dashed lines. Travel times for sound from the porpoise to the hydrophones are the path lengths divided by the speed of sound c.

The following Pythagorean equations apply to the direct paths from the porpoise to the hydrophones:

$$(z - z_u)^2 + R^2 = c^2(t_u - t_0)^2 \quad (1)$$

$$(z - z_l)^2 + R^2 = c^2(t_l - t_0)^2 \quad (2)$$

Similarly, the equations for signals reflected from the air-water surface are:

$$(z + z_u)^2 + R^2 = c^2(t_{ru} - t_0)^2 \tag{3}$$

$$(z + z_l)^2 + R^2 = c^2(t_{rl} - t_0)^2 \tag{4}$$

Thus we have four equations with which to solve for the three unknown variables (R,z,t_0). Expanding and rearranging, we can write the above equations in matrix form:

$$\begin{pmatrix} -2z_u & 2t_u c^2 & 1 \\ -2z_l & 2t_l c^2 & 1 \\ 2z_u & 2t_{ru} c^2 & 1 \\ 2z_l & 2t_{rl} c^2 & 1 \end{pmatrix} \begin{pmatrix} z \\ t_0 \\ C \end{pmatrix} = \begin{pmatrix} -z_u^2 + c^2 t_u^2 \\ -z_l^2 + c^2 t_l^2 \\ -z_u^2 + c^2 t_{ru}^2 \\ -z_l^2 + c^2 t_{rl}^2 \end{pmatrix} \tag{5}$$

where:

$$C = z^2 + R^2 - c^2 t_0^2 \tag{6}$$

This overdetermined system of equations is a linear regression and can be solved using singular value decomposition [Press et al., 1986] to obtain (z,t_0,C) and thus R.

Considering the narrow beam width of a porpoise click, it seems biologically improbable that the same click would reach the hydrophones by both the direct paths and the sea surface reflection unless the porpoise is beneath the level of the hydrophones and pointing in an upwards direction. For this reason, Figure 5 shows the porpoise at a lower level than the hydrophones $z < z_l$ even though the above equations will apply more generally.

It is also notable that our experimental configuration had hydrophones separated in the vertical by only 2 m. Thus, the angle subtended by the two direct rays (Figure 5) is very small, corresponding to a small aperture. The reflected rays, on the other hand, can be considered to correspond to a virtual pair of hydrophones well above the sea surface. Thus, by considering reflected rays the hydrophone array acquires larger aperture.

CALCULATIONS FOR REFLECTION FROM THE SEAFLOOR

The geometry of propagation for a click that reflects from the seafloor, at depth D, is shown by Figure 6. Again, the dashed lines show that utilizing bottom reflections will greatly increase the effective aperture of the hydrophone array, although the scattered nature of reflections from the seafloor may offset this advantage in aperture.

Figure 6 is drawn with the harbour porpoise above the hydrophones, $z < z_u$. Given the 16° beam width of a harbour porpoise click, a porpoise is expected to be above the level of the hydrophones and pointing in a downwards direction (e.g., beginning dive) in order for the direct beam and reflected beam to both reach the hydrophones. Again, this is the biological expectation, but the following mathematics will apply regardless of whether the porpoise is above or below the hydrophones.

The governing equations for the direct paths from porpoise to hydrophones will be (Equations 1, 2), as before. On the other hand, the rays reflected off the seafloor must satisfy:

$$(z - 2D + z_u)^2 + R^2 = c^2(t_{ru} - t_0)^2 \tag{7}$$

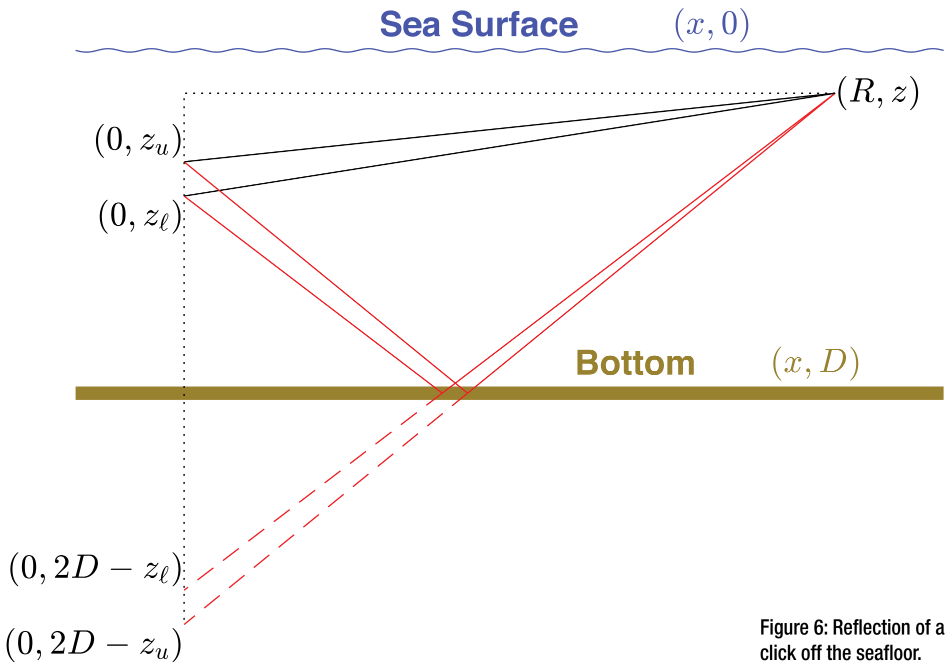

Figure 6: Reflection of a click off the seafloor.

$$(z - 2D + z_l)^2 + R^2 = c^2(t_{rl} - t_0)^2 \quad (8)$$

Equations (7,8) take the same form as Equations (3,4) if we write $\zeta_u = z_u - 2D$ and $\zeta_l = z_l - 2D$. Thus, the equations for seafloor reflections (Equations 1, 2, 7, 8) can be written in matrix form:

$$\begin{pmatrix} -2z_u & 2t_u c^2 & 1 \\ -2z_l & 2t_l c^2 & 1 \\ 2\zeta_u & 2t_{ru} c^2 & 1 \\ 2\zeta_l & 2t_{rl} c^2 & 1 \end{pmatrix} \begin{pmatrix} z \\ t_0 \\ C \end{pmatrix} = \begin{pmatrix} -z_u^2 + c^2 t_u^2 \\ -z_l^2 + c^2 t_l^2 \\ -\zeta_u^2 + c^2 t_{ru}^2 \\ -\zeta_l^2 + c^2 t_{rl}^2 \end{pmatrix} \quad (9)$$

and solved as before.

RESULTS

Time series of the envelopes of band-pass filtered hydrophone measurements were graphically examined to determine arrival times of harbour porpoise clicks and their reflections at each receiver. Presently we report results from 10 click trains. Six of these click trains had abundant reflections from the seafloor and four of them consistently showed reflections from the sea surface.

Reflections from the sea surface suffer little distortion (Figure 4) so sometimes only context makes it possible to differentiate them from clicks that arrived by a direct path. Trains with reflections from the sea surface all had at least $N = 3$ clicks for which arrival times could be confidently obtained for signals taking both direct and reflected paths (Table 1).

Clicks reflected from the seafloor have signal envelopes that are so scattered with respect to time that we might not have even associated them with porpoises were it not for their characteristics with respect to the frequency domain, as seen, for example, in

Ref. #	R (SD)	z (SD)	N	Reflected from
72	222 (12)	23 (1.3)	3	Sea surface
78	127 (24)	33 (6.4)	3	Sea surface
85	216 (27)	21 (2.6)	10	Sea surface
132	126 (13)	48 (5.1)	8	Sea surface
37	182 (21)	8 (8)	3	Seafloor
38	210 (25)	-1 (10)	3	Seafloor
40	159 (—)	14 (—)	1	Seafloor
53	145 (—)	6 (—)	1	Seafloor
93	252 (—)	3 (—)	1	Seafloor
134	217 (—)	2 (—)	1	Seafloor

Table 1: Range R and depth z of porpoises as determined from click trains. $N > 1$ sea surface or seafloor reflections were available for six of the trains but four trains only had one well-resolved reflection from the seafloor. The number of clicks with reflections is given by N. Standard deviations (SD) are indicated. Ref. # is associated to observation time and enables this table to be associated with points plotted in Figure 7 and z corresponding to the porpoise range and depth when it vocalized.

the spectrogram of Figure 3. Often the signal envelope of a reflection from the seafloor does not have an unambiguous leading edge and this makes it difficult to estimate a time of arrival. Reflections from the seafloor had only two click trains with more than $N = 1$ well determined arrival times (Table 1).

Water depth D was interpolated from bathymetry [Karsten et al., 2008] and the known position of the drifter at the times when signals were obtained. Equations (5) and (9) were then used to invert arrival times to estimate porpoise depth z and range R from the drifter. All click trains had durations less than one second and porpoise cruise speed is typically ≤ 1 m/s [Otani et al., 2000]. It is reasonable, therefore, to average estimates of R and z over the clicks within a train. Thus, each row of Table 1 presents average and standard deviations of R:

Reflections from the sea surface (Table 1) generally corresponded to detected porpoises at depths from 21 m to 48 m which are below the depth of the hydrophones (14 and 16 m). Reflections off the seafloor, on the other hand, generally corresponded to detected porpoises above the levels of the hydrophones, although there is more uncertainty when reflections are from the seafloor. Ranges R to detected porpoises are all greater than 100 m and tend to be greater for reflections from the seafloor (typically 70 m below the hydrophones) than for reflections from the sea surface (14 to 16 m above the hydrophones). These results are harmonious with our previous expectation that the relatively narrow beam width of a porpoise click would put constraints upon circumstances in which a click would be strong along both reflected and direct paths.

Signal envelopes (Figures 3 and 4) yield a level for the amplitude of each click analyzed. Crosses are used to plot level as a function of range in Figure 7. Average range for each click train is plotted against their maximum click amplitude using filled circles. The black lines in Figure 7 show mid-beam level as a function of range, based upon source levels of 178 and 205 dB (re 1 μPa at 1 m), radial beam-spreading, and absorption of 37.5 dB/km [Fisher and Simmons, 1977]. In general, we do not expect that the hydrophones will align with the middle of the 16° beam where the click signal level is highest. Porpoise clicks measured in Minas Passage have sound

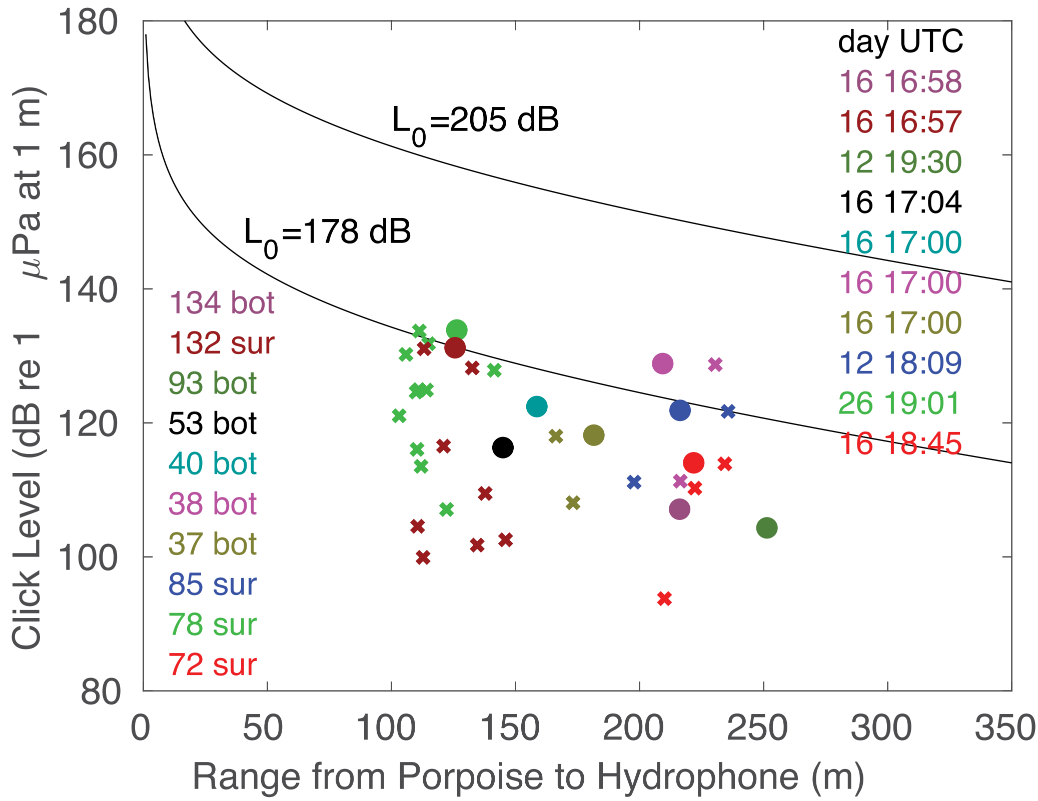

Figure 7: Pressure level of clicks at the ranges determined from arrival times of both the direct and reflected clicks. Circles show maximum signal level plotted against average radial distance. The black lines show the range of theoretical maximum signal level based upon published source levels L_0 for a porpoise click and standard formulation of absorption and radial spreading. Hydrophone separation was 2 m.

levels that seem to be broadly consistent with source levels measured for wild porpoises in Danish waters [Villadsgaard et al., 2007].

ERROR AND APERTURE

Time of arrival can usually be more accurately measured along a direct path than along a reflected path. Thus, it may seem that there would be little advantage using reflected signals if the hydrophone array had more than two hydrophones. On the other hand, the aperture can be greatly increased by including reflected signals.

Figure 8 shows two hydrophone positions that are separated by a distance a. Let the porpoise be a distance R away from both hydrophones. Thus, the position is determined by the intersection of two circles with radius R that are each centred on a hydrophone. If a is much less than the distance to the porpoise, $a \ll R$, then the angle at which the circles intersect is $\theta \approx a/R$ radians. Introducing an error Δ_t s in the time of arrival at the lower hydrophone corresponds to a radial distance error $\Delta = c\Delta_t$ m so the intersection point is now that with the magenta circle. Thus, the position of the porpoise has an azimuthal error:

$$\epsilon \approx \frac{\Delta}{\theta} \approx \frac{\Delta R}{a} \tag{10}$$

It is the ratio Δ/a that determines percentage error in the estimation of porpoise position.

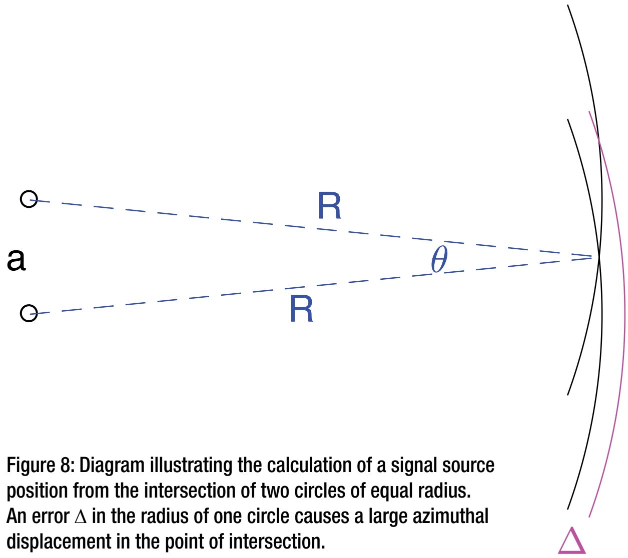

Figure 8: Diagram illustrating the calculation of a signal source position from the intersection of two circles of equal radius. An error Δ in the radius of one circle causes a large azimuthal displacement in the point of intersection.

Larger error in the arrival time of the reflected signal can be tolerated if it is associated with similarly larger aperture. Standard deviations of z (Table 1) indicate that sea surface reflections fall within that constraint.

ERROR CAUSED BY SURFACE WAVES

The above calculations of harbour porpoise depth z and range R were based upon an assumption that the sea surface was flat. According to classical theory for irrotational fluid flow, the crest of progressive surface waves can achieve a maximum slope s of 1/tan(30°) [Stokes, 1880]. On the other hand, Banner and Phillips [1974] show that a thin wind drift layer will cause wave breaking well before the above maximum steepness is achieved.

The present study did not include measurements of either waves or local winds. Measurements were made on days when relatively calm conditions were forecast. Nevertheless, local winds are highly variable during spring, and sometimes strong tide and wind caused choppy conditions. In lieu of reliable measurements, let us follow LeBlond and Mysak [1978] and consider s = ½ tan(30°) to be "a gross estimate of the maximum slope of surface gravity waves."

Given the above estimate for s, let us calculate the extent to which the path of the reflected porpoise click might vary due to surface waves. Figure 9 illustrates three paths that might be taken by a porpoise click: one path from a flat surface is bracketed by paths corresponding from reflection off surfaces with slopes $\pm s$ which correspond to opposite edges of the crest of waves with largest slope. The angle between the horizontal and the incident path is ϕ and the angle between the horizontal and the reflected path is $\phi+2\delta$ where $\delta=\pi s$. If the receiving hydrophone is at depth z_n and the porpoise at range R and depth z, then we can write:

$$\frac{z_n}{r} = \tan(\phi + 2\delta) \tag{11}$$

$$\frac{z}{R-r} = \tan(\phi) \tag{12}$$

where the click is reflected from the surface at range r (Figure 9). Consider the position of the hydrophone $(0,z_n)$ and the position of the porpoise (R,z) to be specified. Our problem is to solve the above equations for ϕ and r in order to fully determine the path for a specified angle δ of the sea surface from horizontal.

Using the trigonometric identity

$$\tan(\phi + 2\delta) = \frac{\tan\phi + \tan 2\delta}{1 - \tan\phi \tan 2\delta} \tag{13}$$

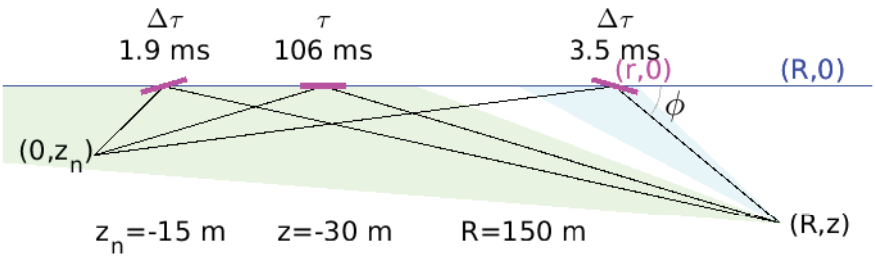

Figure 9: Diagram illustrating three paths for surface reflections: maximum wave steepness, a flat surface, and maximum wave steepness in the other sense. The magenta line shows the wave slope.

and eliminating r from Equation (11) and Equation (12), we obtain the following quadratic equation for tan ϕ:

$$a \tan^2 \phi + b \tan \phi + c' = 0 \tag{14}$$

where

$$a = (R + z_n \tan 2\delta) \tag{15}$$
$$b = (R \tan 2\delta - z - z_n) \tag{16}$$
$$c' = -z \tan 2\delta \tag{17}$$

Solving the quadratic Equation (14) gives ϕ. Having obtained ϕ,we can obtain r from either Equation (11) or (12). Thus, the path is fully defined so that path lengths and travel time can be calculated.

Figure 9 illustrates the situation for reflection from the sea surface when a porpoise has depth and range similar to results in Table 1. Travel time with reflection from a flat surface is about 106 ms whereas reflections from steep waves could cause travel time to increase by as much as 1.9-3.5 ms. The beam pattern coloured cyan indicates that it would be unlikely that a 3.5 ms error would happen because the beam does not have a direct path to the hydrophone. On the other hand, the green beam includes a path with a 1.9 ms error as well as the direct path. Our results do not seem to suffer from such large errors, perhaps because waves have broad troughs and narrow crests, but we cannot be sure.

DISCUSSION

It was not, at first, clear to us that click reflections from the sea surface and seafloor would prove useful for calculating porpoise position. Indeed, the identity of reflected clicks was most uncertain until their arrival times were put into context with the arrival times of clicks taking a direct path. In isolation, reflections from the sea surface were difficult to differentiate from clicks that had taken a direct path. It is likely that surface reflections add to the number of porpoise vocalizations detected by many monitoring methods. Reflections from the seafloor, on the other hand, had their energy smeared out over such a long interval compared to click duration that only their frequency characteristics associate them with porpoises. Strongly discriminating detection methods, such as Coda [Adams, 2018; Adams et al., 2019], would not identify reflections from the seafloor as harbour porpoise vocalizations.

Yet, it seems that a combination of clicks and their reflections can be used to obtain useful estimates of porpoise range and depth, even with only two hydrophones. A degree of confidence is obtained from the fact that estimates of range and depth were reasonably consistent for clicks belonging to a single click train. Confidence is bolstered by the observation that reflections from the sea surface corresponded to porpoise positions that were calculated to be below the hydrophones whereas seafloor reflections were all from porpoises near the sea surface, as anticipated by consideration of the 16° beam width of porpoise clicks. Finally, at the ranges measured, the level of clicks turned out to be generally consistent with source levels obtained by Villadsgaard et al. [2007].

A more definite demonstration of the utility of reflected signals might have been obtained had we used more hydrophones so that porpoise depth and range could be calculated both with and without the reflected signals. We aim to achieve such work in future. Perhaps, others might investigate the matter using existing measurements [Malinka et al., 2018].

To facilitate such future work, we observe that the present formulations for including surface reflection (Equation 5) and bottom reflections (Equation 9) use four equations to solve for range R, porpoise depth z, and the time t_0 of vocalization. That leaves one degree of freedom for assessing residuals. Given that a harbour porpoise often produces a train of many clicks within less than one second and has typical cruise speed of ≤ 1 m/s [Otani et al., 2000], there is no reason why times of arrival of all clicks within a train should not be incorporated into a single regression relationship. That being the case, one would solve for R, z, and t_{0m} where m = 1, 2, … , M pertain to a train of M clicks. In that case, there would be many more degrees of freedom and both t_{0m} and the residuals contain a great deal of information that can be profitably exploited to avoid ambiguity when signals arrive from multiple sources.

To date, it has proved difficult to install and maintain a large hydrophone array on tidal turbines [Malinka et al., 2018; Ocean Sonics, 2018]. The present results suggest that reflected signals might be used to effectively expand a small hydrophone array so that it achieves more degrees of freedom and greater aperture. For reflected signals to be of use, however, it is necessary to know from what surface they were reflected. A reflection from some unknown part of the turbine installation would only introduce ambiguity whereas a well-placed reflective surface might serve as well as additional hydrophones.

Beyond obtaining porpoise position, reflected clicks seem to provide additional information when they are placed in context with signals received along direct paths. Present results indicate vertical orientation of the porpoise. Even for pilot studies, where only one hydrophone is used, reflected clicks provide information about animal behaviour.

The examples presently analyzed occurred when the harbour porpoise was at ranges larger than 100 m. Reflected paths are expected to be useful at such ranges because path geometry and the intense part of a porpoise vocalization is contained within a narrow beam. Nevertheless, a portion of a porpoise vocalization propagates omnidirectionally, so reflections might also be useful when a porpoise is near the hydrophone array.

CONCLUSION

Estimates of harbour porpoise depth and range have been obtained using a vertical array of only two synchronized hydrophones to interpret the arrival times of clicks by both direct and reflected paths. The utility of a hydrophone array for locating harbour porpoises near a tidal turbine installation, and for understanding harbour porpoise behaviour, may be enhanced by considering reflections of their vocalizations from the sea surface, seafloor, or other well discerned surfaces.

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