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# Feasibility study: vessel-based Hector's dolphin acoustic monitoring systems

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## EXECUTIVE SUMMARY

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There are concerns for the potential of negative interactions between Hector's dolphins (*Cephalorhynchus hectori*) and commercial fishery operations such as set gillnet and inshore trawl which could lead to dolphin mortality. Understanding the presence and movements of Hector's dolphins around fishing equipment can provide critical information about the potential entanglement risks to the dolphins.

Fishermen in the South Island east coast trawl fishery operating out of Timaru are unable to determine if the dolphins dive and interact with the trawl nets which target demersal fish. To understand the potential risks to the dolphins from bottom trawl fishing operations, it is necessary to understand the presence, acoustic behaviour, and locations of dolphins under the water, and if they are often close to the bottom near trawl fishing operations. The aim of this project was to assess the feasibility of increasing the understanding of the aforementioned items, and to recommend if progression to field trials is warranted.

This feasibility assessment considers passive acoustic monitoring systems, using the echolocation and communication clicks of the Hector's dolphins to estimate their location within the water column, and therefore the proximity to demersal trawl fishing equipment. The study examines different array and localisation tracking concepts, possible detection ranges, and installation locations for hydrophones using theoretical simulations.

The results demonstrate that although detection ranges are limited, when the dolphins are within approximately 150 m of a hydrophone array in water depths of approximately 40 m, if the array has an inter-element spacing of 80 cm, then it is feasible to estimate their location within the water column, and thus understand if they are interacting with the net at the seafloor. The study also determined that the optimal location for the hydrophones is on the trawl boards (or doors). The closer the dolphins are to the hydrophone, the higher the chance of success, however performance will also be increased by compensating for uncertainty by including more sophisticated range/depth propagation models in the analysis, or by averaging over many detections to study the ensemble of location estimates knowing that some percentage of them will have incorrect values. Field trials will determine the possible performance increase of multiple hydrophone pairs.

The study recommends that good design processes, including that systems go through detailed design and trials before being implemented in their final form, be adhered to. Trial systems should be closely matched in capability to any permanent systems, and both they, and any permanent systems which do not require telemetry, should be autonomous to reduce complexity and costs. Autonomous systems will be able to gather the same data and allow different design concepts to be tested in the real world. This includes examining different hydrophone array concepts, benefits of multiple arrays, detection ranges, noise and vibration influences from the trawl door and mounting concepts.

The project is feasible because the technology required can be clearly defined and is commercially available, rather than requiring further research and development; the identified challenges associated with the at times violent fishing operation are able to be surmounted; and the data processing capability exists.

## 1. INTRODUCTION

JASCO Applied Sciences (JASCO) was engaged to conduct a feasibility assessment and desktop design of an effective Hector's dolphin passive acoustic monitoring system for the South Island east coast trawl fishery for Fisheries New Zealand.

There are concerns for the potential of negative interactions between Hector's dolphins (*Cephalorhynchus hectori*) and commercial fishery operations such as set gillnet and inshore trawl which could lead to dolphin mortality. Understanding the presence and movements of Hector's dolphins around fishing equipment can provide critical information about the potential entanglement risks to the dolphins.

Dolphins, including Hector's dolphins, are obligate echolocators, using their clicks for both echolocation and communication (Dawson 1991). They are often found in turbid water (Dawson et al. 2013), and therefore require the use of acoustics to find their prey which is distributed throughout the water column. Hector's dolphins have been characterised as opportunistic feeders taking a wide range of prey, mainly fish and squid, throughout the water column (Slooten & Dawson 1988). Although studies indicated that there could be significant differences between the diets of east and west coast Hector's dolphins around the South Island (Miller et al. 2013), other studies found that between Kaikōura and Timaru, bony fish contribute the most to their diet (Miller 2015).

Fishermen in the South Island east coast trawl fishery operating out of Timaru often see Hector's dolphins on the surface when fishing; however, they have been unable to determine if the dolphins dive and interact with the trawl nets which target demersal fish (R. Mitchell, 2020, pers. comm.). To understand the potential risks to the dolphins from bottom trawl fishing operations, it is necessary to understand the presence, acoustic behaviour, and locations of dolphins under the water, and if they are often close to the bottom near trawl fishing operations.

Visual survey methods conducted by trained observers in perfect weather conditions could allow the dive times of individuals to be observed; however, this provides no information about the dive depth, swimming trajectories, or acoustic behaviour of the dolphins under observation. Therefore, technology which allows the observation of dolphins underneath the water is required. In the turbid coastal waters of the South Island, cameras only have limited usefulness, leaving either active or passive acoustics as possible methods of observation.

This feasibility assessment considers passive acoustic monitoring systems, using the echolocation and communication clicks of the Hector's dolphins to estimate their location within the water column, and therefore the proximity to demersal trawl fishing equipment. This study provides guidance for the feasibility of pursuing this approach, along with considerations for installation and implementation of the system as either a trial or a commercial system; with the ability to record, analyse, manage, and store fit-for-purpose data over a fishing season. The study also considers methods of localisation, possible dolphin detection ranges, and position estimate accuracy, and how vessel masters might interact with the system and the outputs.

There are often significant differences between monitoring systems used for research purposes and those able to be implemented on commercial fishing vessels for monitoring during typical operations. This study has considered the possibilities for systems which could be used for either purpose.

## 2. SUMMARY OF HECTOR'S DOLPHINS

### 2.1 Size

Hector's/Māui dolphins are the smallest species of dolphin in the world, with a range in length of 1.2–1.6 m and weight of 40–60 kg (Slooten & Dawson 1994). Harbour porpoises are comparable in length and weight with females typically 1.5–1.6 m and 55 kg and males 1.4–1.5 m and 50 kg (Lockyer 1995, Lockyer 2003).

### 2.2 Vocalisations

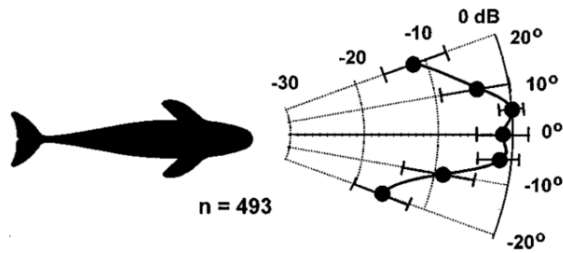
The first studies focused on recording and describing the vocal repertoire Hector's dolphins began in the late 1970s to early 1990s (e.g., Watkins et al. 1977, Dawson 1988, Dawson & Thorpe 1990). At that time, studies on this species' vocalisations were considered difficult given the lack of sophisticated high-frequency recording equipment suitable for the marine environment and the fact that this species is thought to be unusually quiet relative to other species (Dawson 1990).

The sounds of all of the *Cephalorhynchus* species (i.e., the taxonomic unit or 'genus' Hector's/Māui dolphins belong to) seem very similar (Dawson 2017, Jensen et al. 2018). Dawson (1990) found most of the sounds emitted by Hector's/Māui dolphins were within a narrow range of high frequencies, mainly clicks, centred around 120–125 kilohertz (kHz). Less than 2% of their vocalisation sounds occurred below 100 kHz, and the highest frequency was 141 kHz. Their clicks are considered simple in structure consisting of mainly single and double pulses. Their clicks can be described as narrow band high-frequency (NBHF) echolocation clicks.

Kyhn et al. (2009) used a four element hydrophone array and documented clicks with a mean peak frequency of 129 kHz, 3 dB bandwidth of 20 kHz, 57  $\mu$ s 10 dB duration, and mean apparent source level (ASL) of 177 dB re 1  $\mu$ Pa (peak-to-peak). In addition to having vocalisations of a relatively low ASL, Hector's dolphins also likely have quite a focused beampattern similar to those for harbour porpoise. The beampattern of harbour porpoise echolocation clicks was measured by Au et al. (1999) who demonstrated that the clicks have their peak source levels only over a narrow angular window in elevation and azimuth (Figure 1). Hector's dolphin clicks are expected to have similarly low source levels off-axis. Thus, in this study, considering the information presented by Kyhn et al. (2009), to allow for a conservative estimate of detection, the source level for most clicks is assumed to be of the order of 150 re 1  $\mu$ Pa (peak-to-peak) unless the dolphins are echolocating directly at the receiver. This is a relatively simplistic approach because dolphins, like porpoises, can alter their clicks depending up their purpose (Wisniewska et al. 2015). They can adjust their emitted sound intensity and click rate to target range, and terminate prey pursuits with high repetition-rate, low-intensity buzzes. However, their narrow acoustic field of view is considered stable throughout their approach to the target. Wisniewska et al. (2015) showed that harbour porpoises can broaden their biosonar beam during the terminal phase of attack and maintain the ability to change beamwidth within this phase.

All odontocetes emit click trains – that is a sequence of closely spaced clicks. Typically there are two types of click trains, those with a relatively long pause of 50–300 ms between clicks, and those associated with detection and imaging of close objects and / or prey capture where the click rate can increase to once every 2–5 ms (DeRuiter et al. 2009) (Figure 2). An example of clicks from a Hector's dolphin within Queen Charlotte Sound is shown in Figure 3.

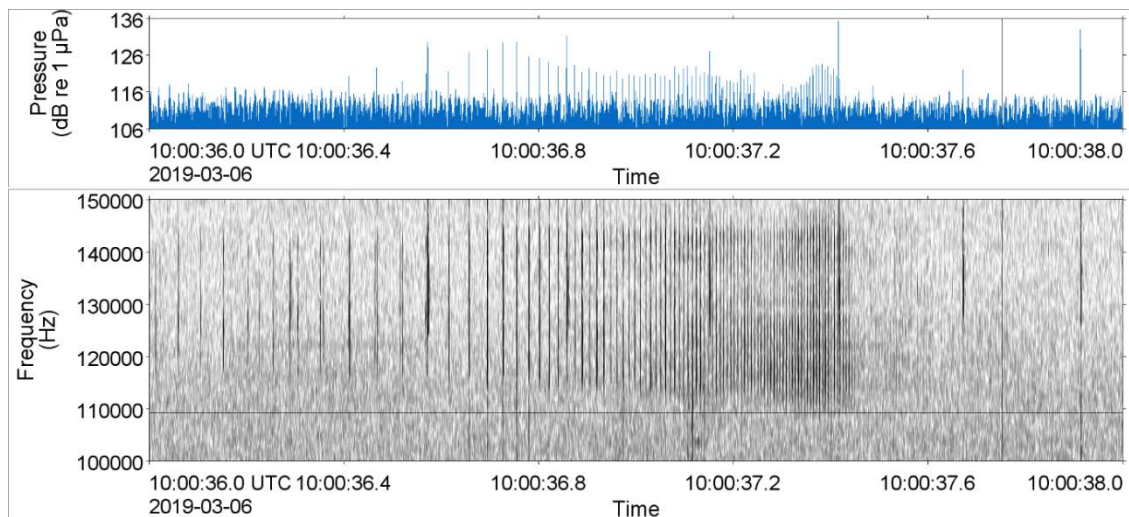
Considering the likely beampattern of a Hector's dolphin (Figure 1), the horizontal beamwidth can be estimated at different distances from the dolphin (Table 1).



**Figure 1:** Horizontal beampattern (how the sound level changes with angle) of a harbour porpoise echolocation click (figure 3 from Au et al. (1999)); the vertical beampattern was similar.

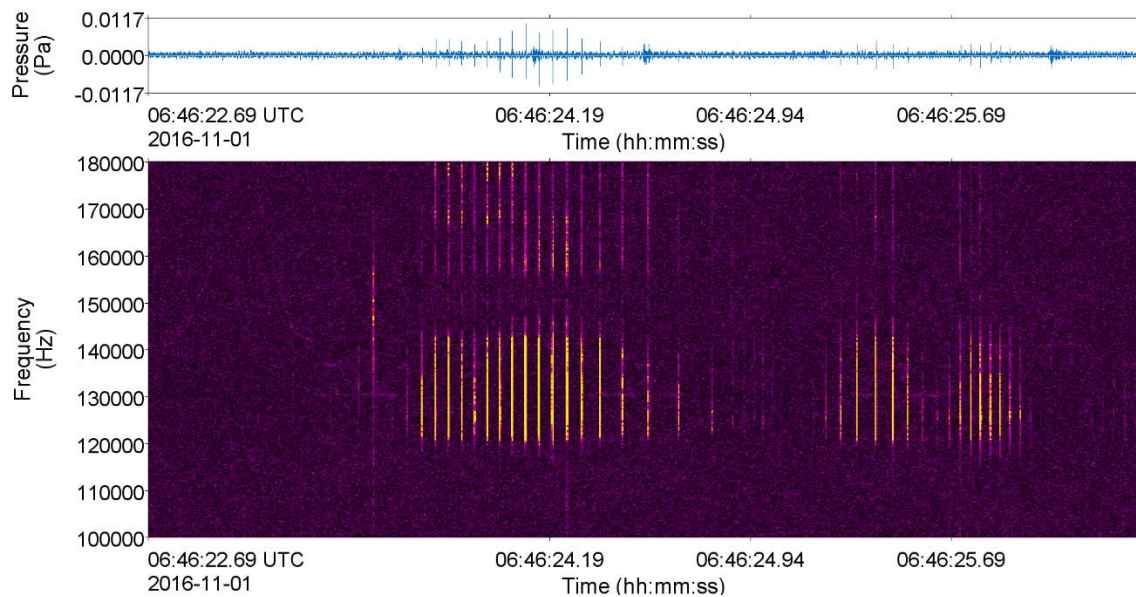
**Table 1:** Estimate of horizontal beamwidth (in metres) at distances from the dolphin for a Hector's dolphin, based on a beamwidth of 20° (Figure 1).

Distance from dolphin (m)	Approximate beamwidth (m)
50	36
60	44
70	51
80	58
90	66
100	73
110	80
120	87
130	95
140	102
150	109



**Figure 2:** Example of a harbour porpoise click train that evolved from about 60 ms between clicks at the start of the clicking to 5 ms at the end. All odontocetes exhibit this type of click behaviour.





**Figure 3: Spectrogram of Hector's dolphin click train recorded in Queen Charlotte Sound on a JASCO AMAR, 1 Nov 2016 (46 Hz frequency resolution, 0.01 s time window, 0.005 s time step, Hamming window) (reproduced from Delarue et al. 2017).**

### 2.3 Behaviour near trawl equipment

Discussions with Raymond Mitchell, owner and master of the vessel *F.V. Achernar*, which operates out of Timaru, provided insight into the typical behaviour of dolphins around the trawl operations (R. Mitchell, 2020, pers. comm.). The dolphins are often seen on the surface during trawling operations, including during the retrieval of the net, but none have appeared to be at risk of entanglement. It is unknown, but assumed, that the dolphins have similar behaviours at night, when their use of acoustics is their only way to interpret the environment around them.

Although the *F.V. Achernar* has not caught any dolphins, it is thought that the highest periods of risk for potential bycatch are the trawl and retrieval stages of the fishing operation, not deployment (R. Mitchell, 2020, pers. comm.). It was concluded that the project should concentrate on these sections of the trawl operation.

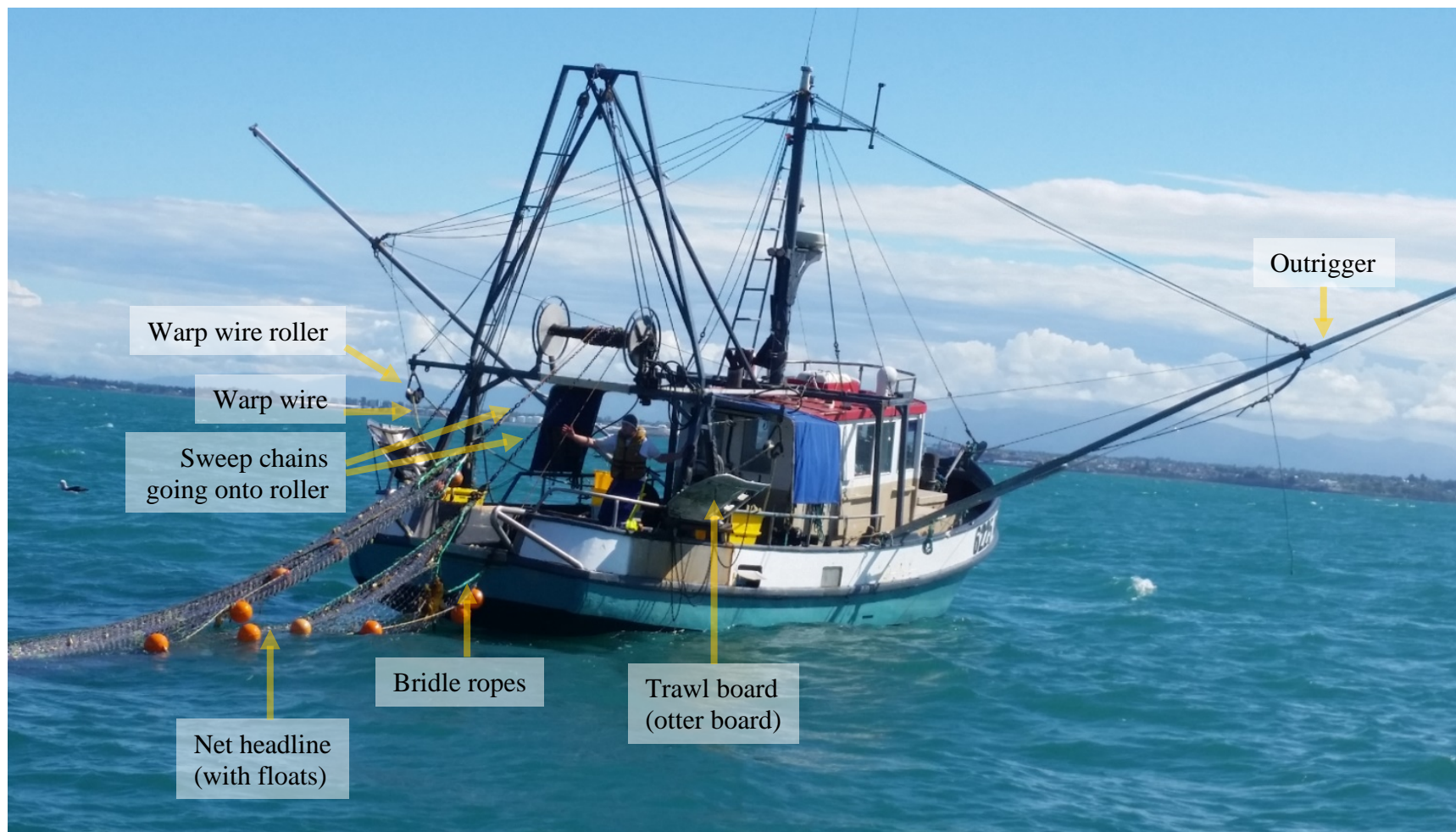
## 3. TRAWLING OPERATIONS

Raymond Mitchell provided three photos of the *F.V. Achernar* during the retrieval of the trawl equipment. This vessel is typical of those within the fleet and can be used to inform discussions and this feasibility study. The vessel is shown in a stern-on view in Figure 4, and with a side-on aspect in Figure 5. Figure 5 includes labels for key components of the vessel and trawl equipment, such as the warp wire, trawl boards, sweep chain, bridle ropes, and net headline.

The outrigger booms are not involved in the trawl fishing operations, but rather used for trolling for pelagic fish such as tuna.

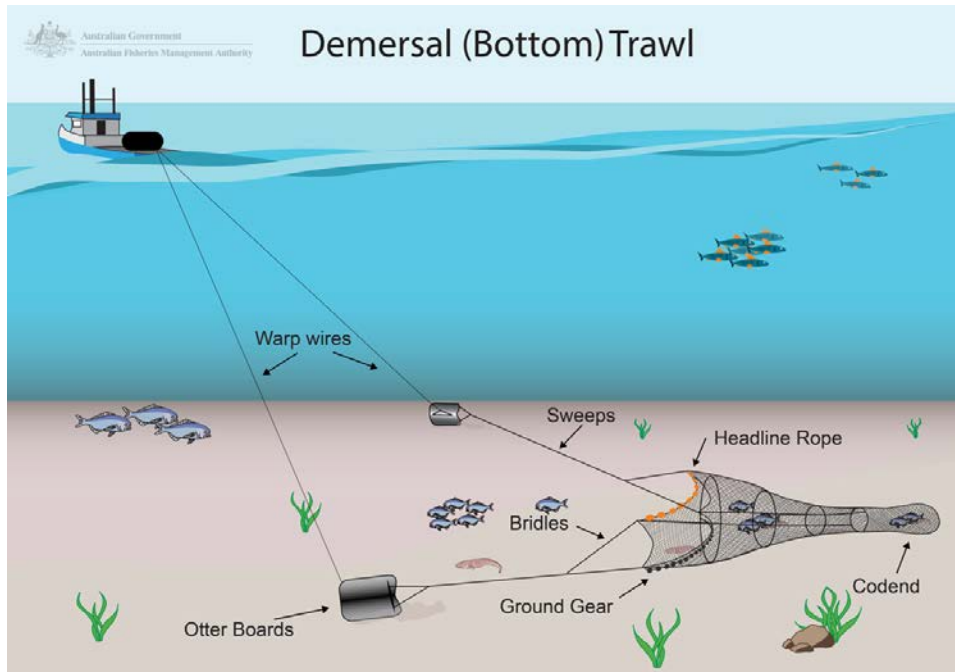


**Figure 4:** F.V. *Achernar* during final stages of net retrieval.

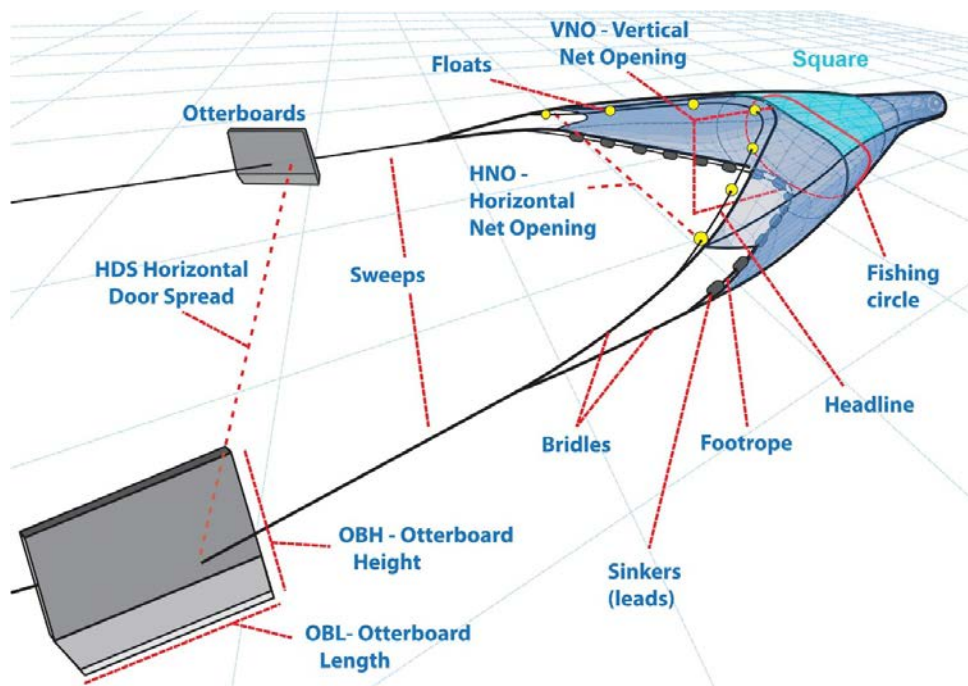


**Figure 5: F.V. *Achernar* during net retrieval, with trawl boards and sweep chains stowed but the net still in the water.**

The demersal trawl fishing equipment (Figure 6) uses a trawl net shaped like a cone or funnel with a wide opening to catch fish or crustaceans and a narrow, closed 'cod-end'. Demersal (bottom) and midwater trawls use trawl boards (also referred to as trawl doors and otter boards) to keep the mouth of the net open. A schematic of the equipment from the trawl boards to the cod-end labelling all the parts is shown in Figure 7. The typical ratio of warp wire to water depth is 5:1.



**Figure 6: Diagram of demersal trawl fishing equipment in the configuration for operational trawling (reproduced from Australian Fisheries Management Authority 2020).**



**Figure 7: Schematic representation of the main gear metrics for demersal trawl (reproduced from Sala et al. 2019).**

The typical water depth of the fishery is 15–40 m (R. Mitchell, 2020, pers. comm.). The F.V. *Achernar* operates with a single chain sweep on each side (each 80 m in length) which drags along the seafloor, a Vertical Net Opening (VNO) of 1–1.5 m, a Horizontal Net Opening (HNO) of approximately 15 m. The Horizontal Door Spread (HDS) was specified at 40–50 m. For context, given an 80 m sweep, the start point of the net HNO is offset from the trawl boards by approximately 15–18 degrees. The trawl boards sit on the bottom, in a vertical orientation with a ‘wear shoe’ skimming along the seabed.

Vessels of different power, with different sized nets, will operate with different HDS and HNO, with the relationship between the variables being complex (Sala et al. 2019). Therefore, different vessels in the fleet are likely to have different parameters for equipment.

Fishing is a dynamic operation, with the net position changed frequently due to operational considerations such as course changes, obstacle avoidance, and variable substrate topography. However, indicative locations and distances based upon the layout concepts outlined above can be estimated (Table 2) and used to assist the feasibility study.

During retrieval, the distances will all shorten because the boards and net slowly ‘collapse’ together and the net is brought to the surface and onto the vessel.

**Table 2: Relationship between water depth, warp wire length, and the distance of the trawl boards and net opening behind the vessel.**

Water depth (m)	Length of warp wire (m)	Trawl door distance behind vessel (m)	Approximate net opening distance behind vessel (m) <sup>1</sup>
15	75	74	154
20	100	98	178
25	125	123	203
30	150	147	227
35	175	172	252
40	200	196	276

<sup>1</sup> Assuming trawl door to net perpendicular distance is 80 m.

## 4. SYSTEM CONCEPT OVERVIEW AND CONSIDERATIONS

### 4.1 Concept overview

The concept for the passive acoustic system being considered within this study is as follows:

- It will operate during the highest periods of risk for potential bycatch: the trawl and retrieval stages of the fishing operation.
- It will use the NBHF echolocation and communication clicks of the Hector’s dolphins to estimate their location within the water column.
  - There is no need to distinguish individuals, or track movement, with the goal to determine if the dolphins are in locations in which they might interact with the net.
- The outputs of the system will allow the proximity of the dolphins to demersal trawl fishing equipment to be estimated in real time, and the results provided to the vessel master.
- It will be rugged and able to handle the harsh conditions associated with demersal trawling, during which the trawl boards and net are in constant contact with the seafloor.
- It must be able to be used by a fisherman acting alone or with a single deck hand.

## 4.2 Considerations for equipment placement

The authors' understanding is that the typical vessel size in the fishery is relatively small. Due to this, current operators have developed streamlined single or two-person gear handling systems for all aspects of the trawling operation. There is likely to be little space available in the fishing deck area for assistance with safe deployment of acoustic monitoring equipment, except perhaps another fishery operator with a good working understanding of that vessel and working in company with the vessel master.

The most likely scenario for an achievable acoustic monitoring system would be for deployment conducted by the vessel and operator to be limited to acoustic gear activation prior to setting gear, and after hauling of gear (allowing some time for all gear to be stowed for operational safety). Any suggestion of simultaneous deployment of any kind of passive acoustic recording equipment to a scale of hundreds of metres from the stern of the already crammed rear deck area would most likely be impossible or dangerous to vessel stability if the gear was stowed above the heavily utilised rear deck area.

The most appropriate passive recording system would therefore be integrated into the existing fishing equipment, such as placed on the trawl boards themselves or around parts of the net.

Very few examples of passive acoustic monitoring systems being implemented on fishing equipment exist. One of these examples is the work by Connelly et al. (1997), in which passive acoustic localisation of northern hemisphere dolphins in and around pelagic fish trawls was accomplished because there was sufficient personnel and space on board the work deck for acoustic recorders to be fitted, and retrieved from, around the margins of the net opening to provide the 3D localisation data required. That will not occur on vessels the size of the F.V. *Achernar*.

With an understanding of the fishing operation, and the strain likely to be exerted on the acoustic equipment, it is thought that the most suitable position for deployment of acoustic sensors and associated acoustic recording hardware is on the upper part of the trawl boards themselves. Figure 5 demonstrates the stowed position of the trawl boards on F.V. *Achernar*. The area of least likely impact with the vessel or seafloor obstacles, and therefore the safest, would be at the top of the trawl board and above the chains that attach to the tow points distributed around the board to the central tow point. To reduce the water flow effect around the trawl board, sensors could be mounted slightly above and outward of the board.

A risk in some poor sea conditions could be that a trawl board might flip or spin between leaving the water to its stowed position as held in Figure 5. The potential for equipment damage exists in such a scenario, and the equipment would need to be sufficiently protected to reduce risk.

## 5. PASSIVE ACOUSTIC POSITION ESTIMATION

Tracking, localisation, and position estimation of odontocetes such as Hector's dolphins, harbour porpoise, or beaked whales and other marine mammals (such as beluga) using clicks, is a well-studied problem. Approaches for studying these different animals have involved vertical arrays, horizontal (towed) arrays, and compact arrays (e.g., Dawson 1991, Villadsgaard et al. 2007, Kyhn et al. 2009, Gassmann et al. 2015, Macaulay et al. 2017, Urazghildiiev et al. 2020, Urazghildiiev et al. 2021), with each approach having benefits and compromises.

This section examines different array and localisation tracking concepts, possible detection ranges, and installation locations for hydrophones.

## 5.1 Hydrophone array concepts

### 5.1.1 Estimating angle of arrival from arrays of hydrophones

In this report the term “array” refers to a set of hydrophones arranged in space according to a known geometric configuration. Even if the individual hydrophones are omnidirectional (e.g., they record acoustic signals simultaneously from all directions in space, with no ability to discriminate the direction from which a signal is coming), by ‘combining’ the individual data streams from an array of hydrophones it is possible to use the array as an acoustic directional antenna. This process is called ‘steering’ and is accomplished—without physically changing the orientation of the array in space—by appropriately summing the signals from the individual sensors. This provides directivity that allows the array to detect a signal from a particular direction, even when the signal is affected by noise reaching the hydrophones from other directions at the same time.

To accurately *steer* the array in azimuth and elevation, it is important that its physical configuration be as rigid as possible. This can be easily understood considering the simplest array configuration: a pair of hydrophones separated by a distance  $d$ . The separation is used to estimate the angle from which a signal emitted by a source at a distance from the array reaches the array. For example, in Figure 8, two hydrophones (sensors) are represented by the two circles in positions 1 and 2. An acoustic wave front generated by a faraway source is travelling at an angle  $\theta$  from the horizontal direction, from the top right corner towards the bottom left corner, at a speed of  $c$  m/s. The wavefront is first intercepted by hydrophone 1 at time  $t_1$  and by hydrophone 2 at time  $t_2 > t_1$ . In this simple example, the delay  $\Delta t = (t_2 - t_1)$ , i.e., the time the wave front takes to travel from A to B, is linked to the signal direction of arrival  $\theta$  and the hydrophone separation  $d$  by the simple relation  $\Delta t = d \sin \theta / c$ . As a result, any uncertainty in the relative positioning of the hydrophones (e.g., in the orientation of the hydrophone pair with respect to the horizontal, or in the value of  $d$ ) will produce an error in the estimate of the direction from which an intercepted signal originates. This uncertainty can be minimised by mounting the hydrophones on a rigid support.

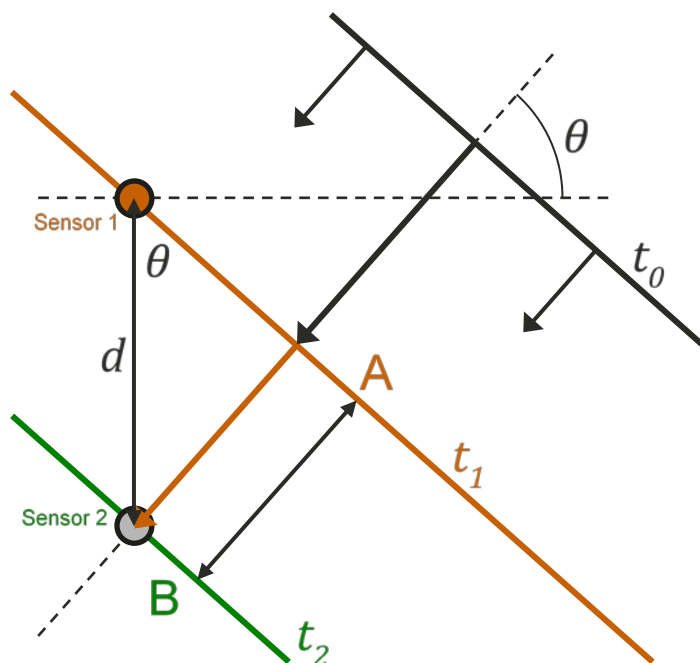


Figure 8: Schematic of the time delay of arrival of a wavefront travelling between sensors.

There are two ways to analyse the data provided by multiple hydrophones to find the direction to a sound's source. The first is to assume the sound is coming from a particular angle  $\theta$  and determine the resulting time delay  $\Delta t$ . The data from channel 2 at time  $t$ , and channel 1 at time  $t - \Delta t$  may then be

added, which amplifies the signal if it came from angle  $\theta$ . This works for frequencies with wavelengths at most  $d/2$  (where  $d$  is the separation between sensors). The second approach is suited for high signal-to-noise conditions and transient signals. In this method, the data from the two channels is cross-correlated to determine the delay  $\Delta t$  which is then converted to the angle of arrival using  $\theta = \sin^{-1} c\Delta t/d$ .

The cross-correlation approach is the one considered for localisation of the Hector's dolphins.

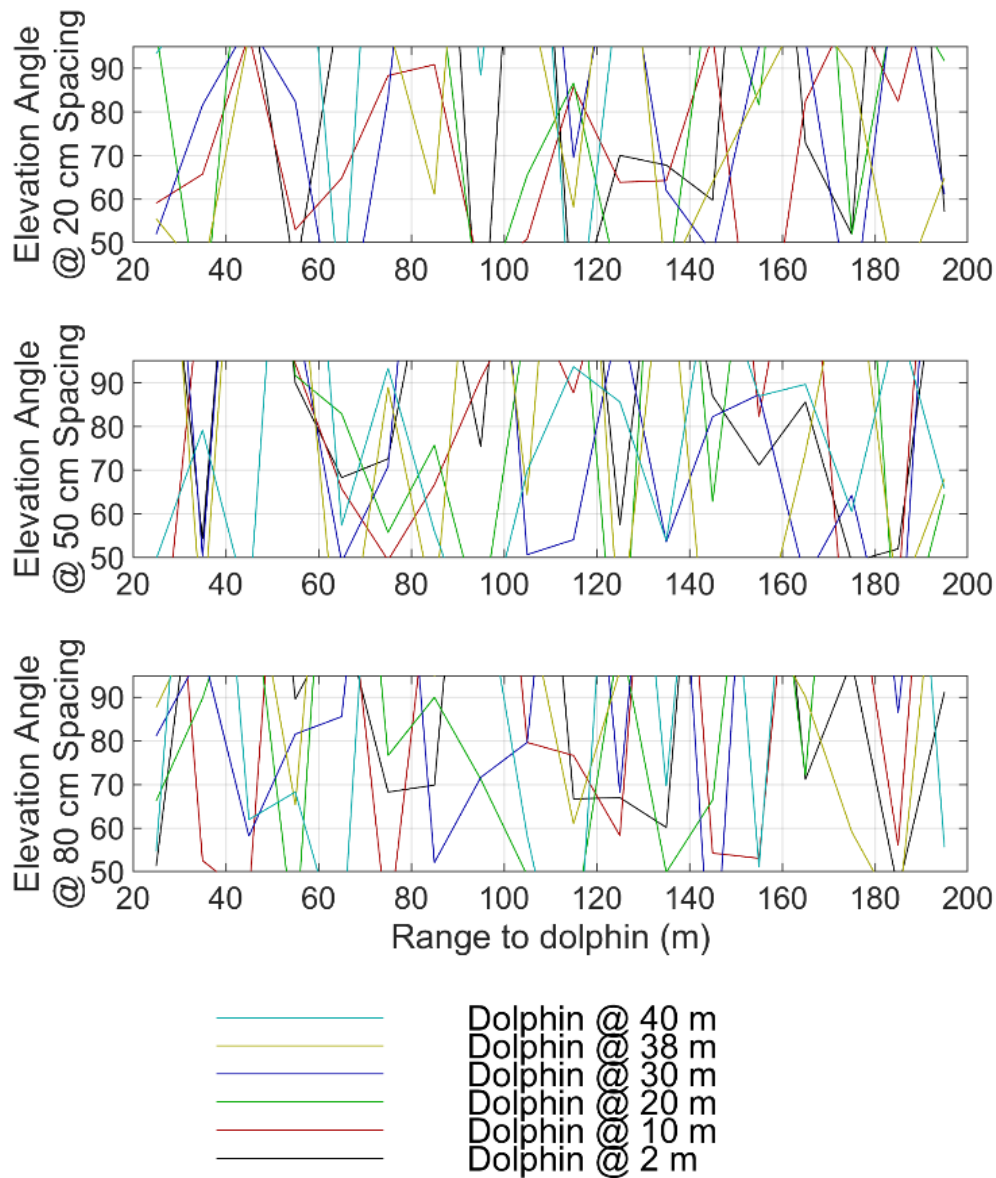
### 5.1.2 Localisation capability of pairs of closely spaced hydrophones using cross-correlation

In this sub-section the ability of a pair of hydrophones to localise a sound source is examined. From the relationship  $\theta = \sin^{-1} c\Delta t/d$  the hydrophone configuration must be far enough apart for  $c\Delta t/d$  to have a range of values suitable for resolving the direction of arrival and change in the direction of arrival. Any uncertainty in the hydrophone locations or the estimate of  $\Delta t$  will reduce the system's ability to resolve where a source is located.

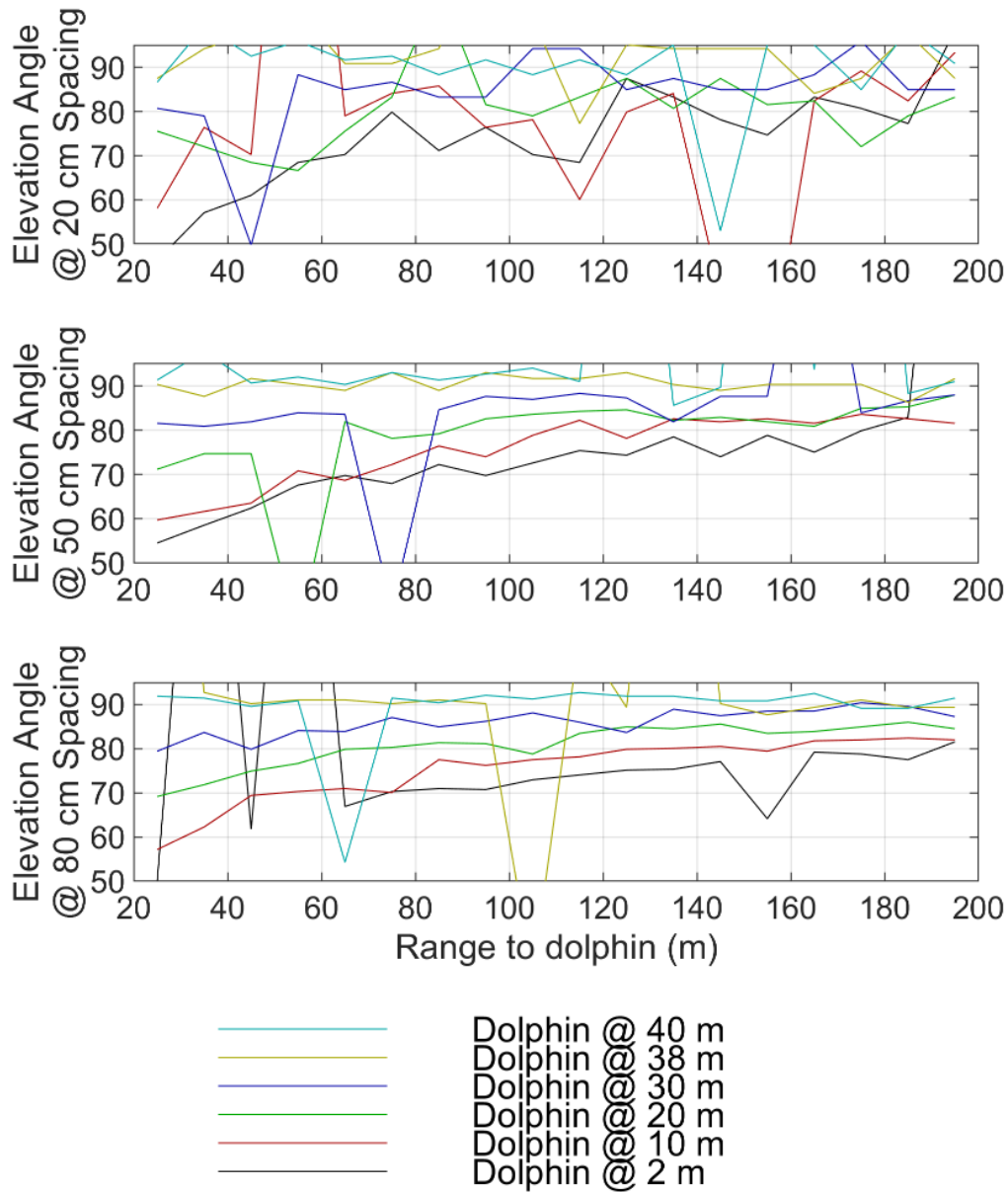
To study this effect, the sound produced by the Hector's dolphin was simulated, using MATLAB (MATLAB 2019), as a short pulse with a centre frequency of 129 kHz, a duration of 40  $\mu$ s, and an amplitude that increased and decreased as a half-sine wave (Hann window). The key outcome of this study is determining where in the water column the dolphins are, and for how long. Therefore, the simulated pair of hydrophones was oriented vertically and spacings of 20, 50, and 80 cm were evaluated. The hydrophones of sensors were simulated as being 2 m from the seabed in 40 m of water. The simulated dolphin was then 'positioned' every 10 m in range and at depths of 2, 10, 20, 30, 38, and 40 m deep. The arrival time of the signal at each of the two hydrophones was computed, and a time delayed version of the signal was added to uncorrelated Gaussian white noise with an adjustable signal-to-noise ratio (SNR). The signals on the two channels were cross-correlated and the resulting estimated angles plotted.

Figures 9–11 show the performance prediction from the simulation. The figures plot the estimated elevation angle of the dolphin as a function of distance from the hydrophones (horizontal axis) and depth of the dolphin (shown by the colour of the line). The results indicate that the hydrophone separation of at least 50 cm is required and signal-to-noise ratios of at least 20 dB are necessary for good localisation performance. Good localisation performance is defined as being able to resolve if a dolphin is near the seabed or surface at a range of 200 m. As the dolphin gets closer to the hydrophones the difference in angle between the seabed and the surface increases, which makes it easier to confidently determine their depths. At 100 m the difference in elevation angle between the surface and the seabed is approximately 20 degrees, decreasing to 10 degrees at 200 m.

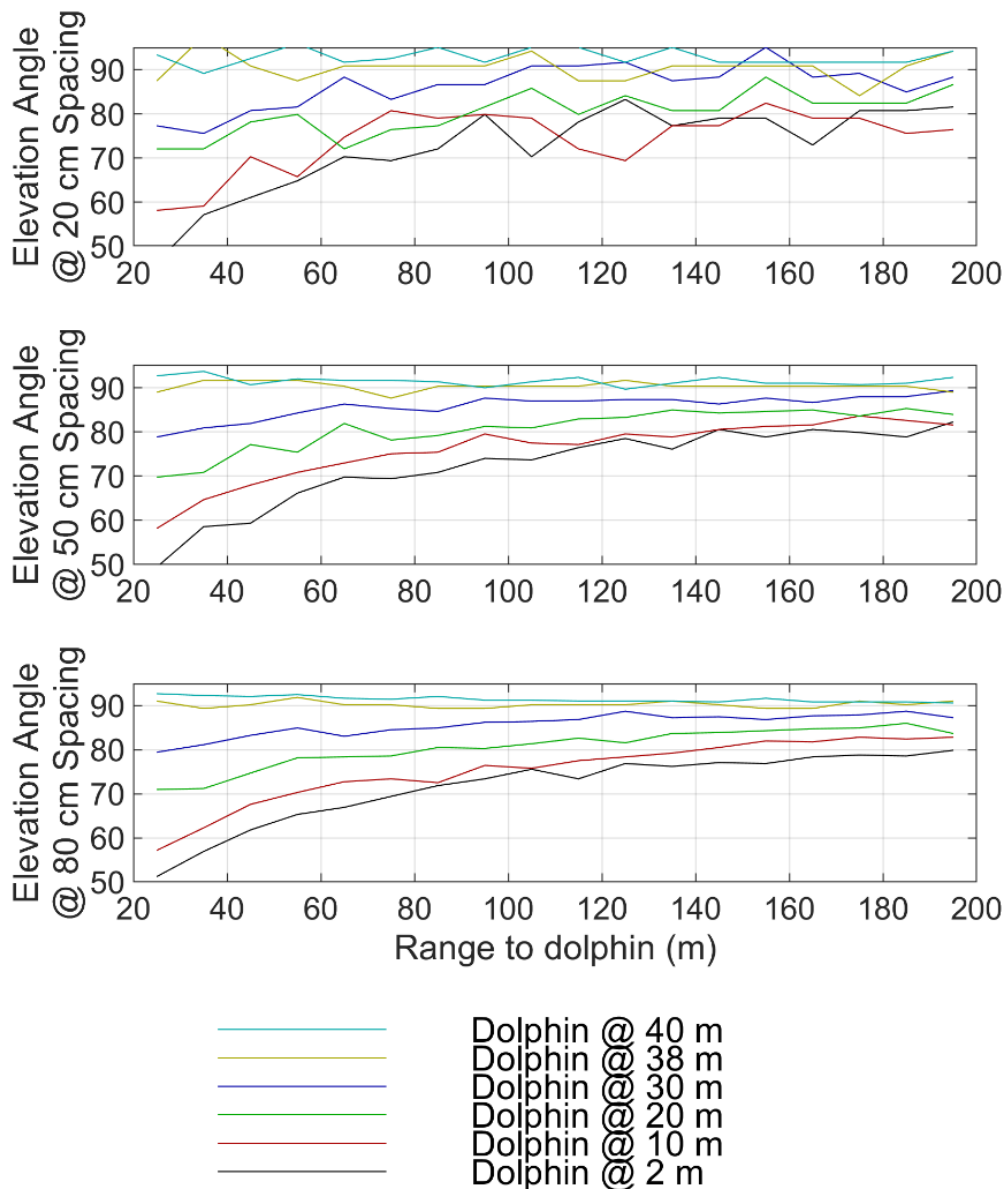




**Figure 9:** Estimated elevation angle of arrival for a signal-to-noise ratio of 10 dB for three hydrophone spacings – 20 cm (top), 50 cm (middle), and 80 cm (bottom). Accurate elevation angles were rarely obtained at this SNR.



**Figure 10: Estimated elevation angle of arrival for a signal-to-noise ratio of 15 dB for three hydrophone spacings – 20 cm (top), 50 cm (middle), and 80 cm (bottom). Accurate elevation angles were occasionally obtained at this SNR.**

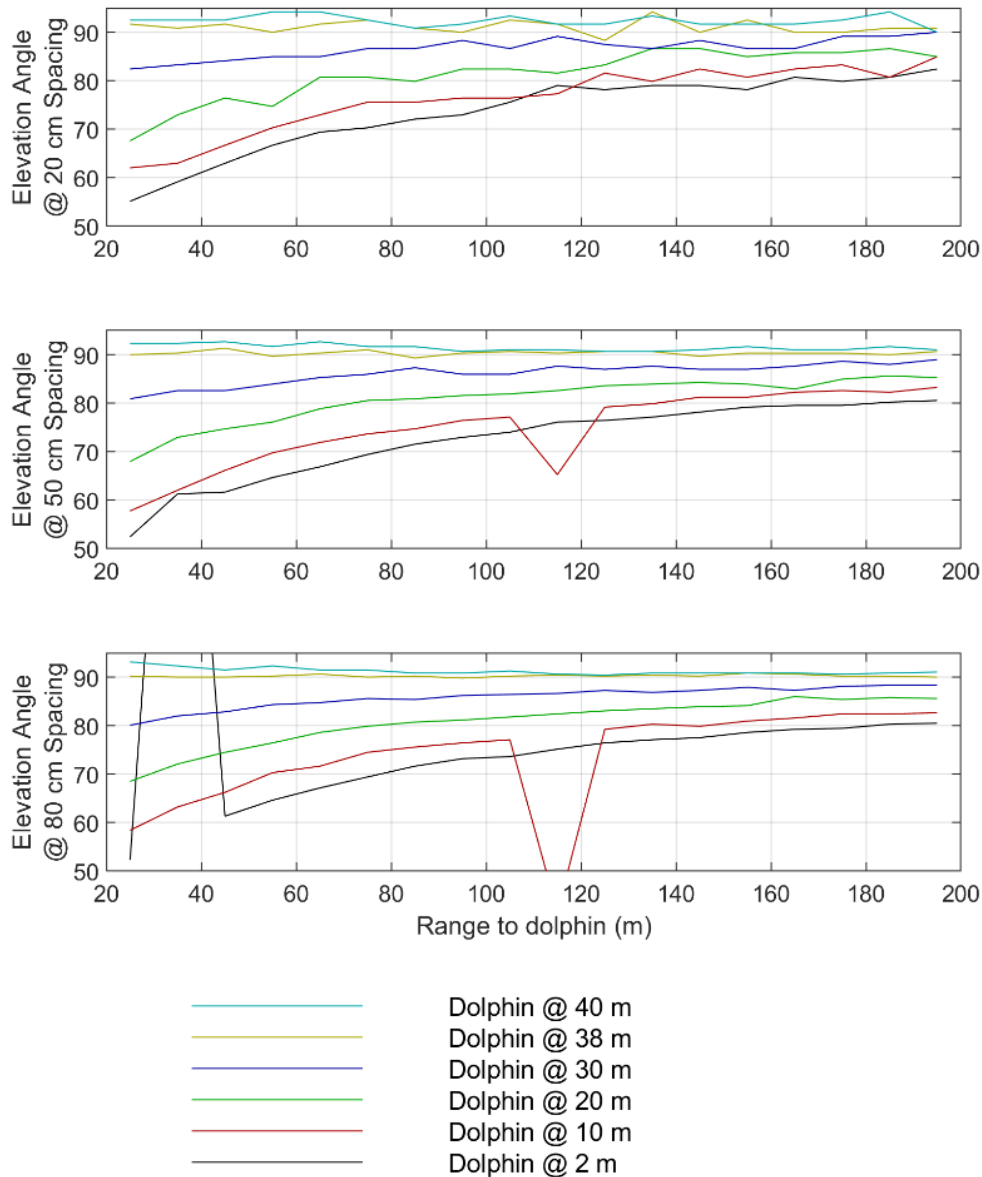


**Figure 11: Estimated elevation angle of arrival for a signal-to-noise ratio of 20 dB for three hydrophone spacings – 20 cm (top), 50 cm (middle), and 80 cm (bottom). Usable elevation angles were obtained at this SNR for spacings of 50 and 80 cm. The wider spacing of 80 cm produced less variability in the estimates and it was easier to distinguish the depth of the dolphin for this spacing.**

Given the success of the idealised simulation described above, a more advanced simulation was performed. In this version, the dolphin clicks were allowed to reflect from the seabed or surface as a possible interfering sound that would disrupt the cross-correlation operation. The results (e.g., Figure 12) were similar to those from the idealised case. However, the reflections did result in significantly erroneous elevation angles for some dolphin depths and ranges. This will likely occur in the real data as well. It is possible to compensate for this by including more sophisticated range/depth propagation models in the analysis, or by averaging over many detections to study the ensemble of location estimates knowing that some percentage of them will have incorrect values.

The approach described here would work equally well at determining the azimuthal angle of arrival for a pair of hydrophones oriented horizontally.

The approach can be extended by adding more hydrophones to the system. Each pair of hydrophones would provide a bearing estimate that can be averaged to reduce the variance in the estimate. Adding hydrophones is especially useful if the noise source is uncorrelated, which occurs with electronic noise and high-frequency flow noise over the hydrophones. It may not be true for noise induced by physical vibrations or sediment interaction of the trawl boards.

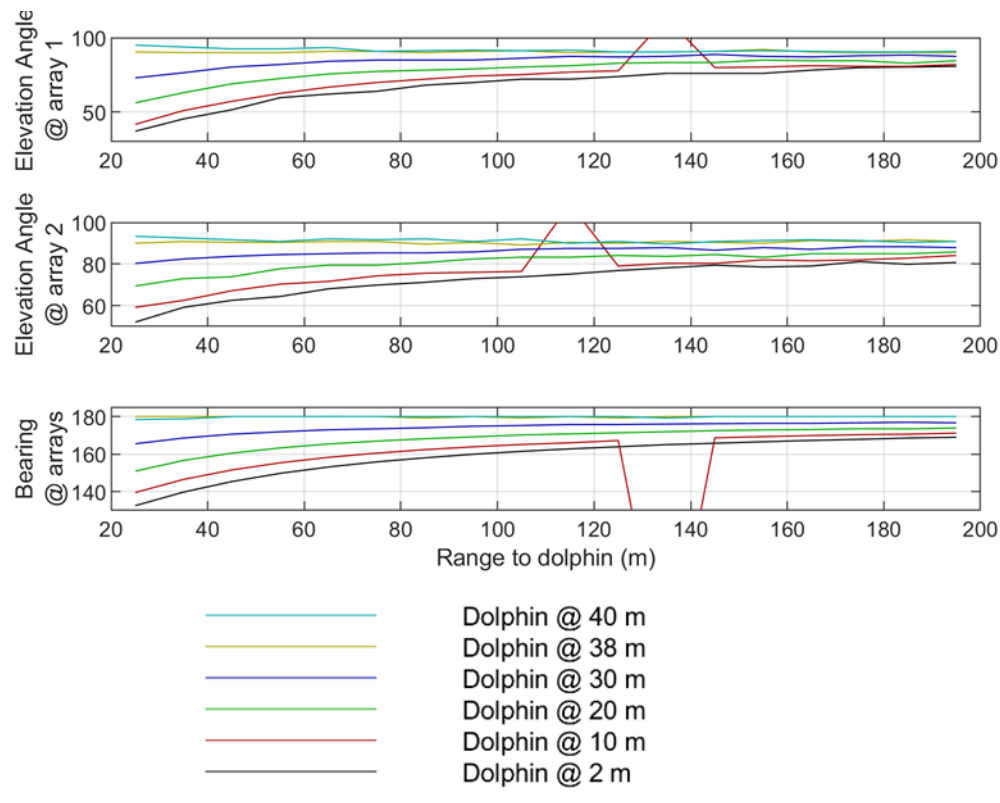


**Figure 12: Estimated elevation angle of arrival for a signal-to-noise ratio of 20 dB for three hydrophone spacings – 20 cm (top), 50 cm (middle), and 80 cm (bottom) using the enhanced simulation that included multipath propagation. Similar to the ideal example, the results were best for a spacing of 80 cm and 20 dB SNR or better. In this example, the multipath reflections caused errors at some dolphin positions and distances.**

### 5.1.3 Correlations between widely spaced pairs of hydrophones

The analysis in Section 5.1.2 provided information on how pairs of closely spaced hydrophones could be used to locate a Hector’s dolphin in elevation, or in bearing if the hydrophones were spaced horizontally. There are several locations that could also be used to widely separate hydrophones with distances of the order of 5–8 m at the stern of the vessel, or 40–50 m on the two trawl boards. The

analysis performed for the closely spaced hydrophones is theoretically valid for these separations as well (Figure 13).



**Figure 13: Example of the localisation of a single simulated Hector’s dolphin click detected at two pairs of hydrophones that are 40 m apart. Each pair was vertically oriented at a spacing of 80 cm and the click had an SNR of 20 dB.**

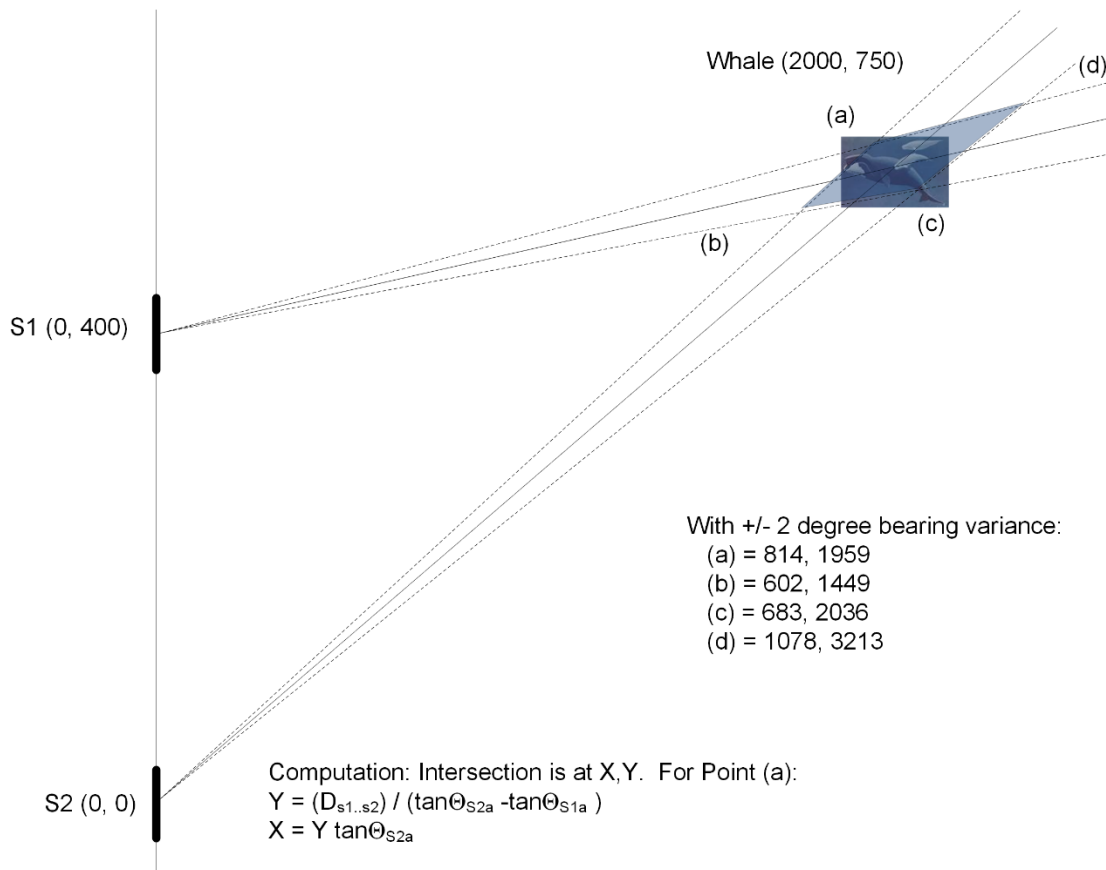
The wide spacing introduces an additional difficulty for analysis – determining which clicks on sensor 1 to associate with those on sensor 2. During the cross-correlation, the time series of the click on one channel is compared with the total duration of the possible time series on the other channel where a related click could occur. The maximum time delay of arrival between the sensors is  $t = 2*d/c$  which is only 1 ms for an 80 cm separation, but it is 10 ms at 8 m and 50 ms at 40 m. Over a period of 50 ms the dolphins could produce 10 or more clicks and clicks from multiple dolphins could easily overlap, all of which could associated with the click on the first channel.

The association problem is further complicated by the beampattern (Figure 1) which means that sensors 40 m apart could measure clicks with amplitudes that are 15–25 dB different and are likely to also have different frequency content (Finneran et al. 2014). However, at least the beampattern should be wide enough to allow detection at two arrays 40 m apart if the dolphin is greater than 60 m away and located midway between the two arrays (Table 1). The association issue can be partially mitigated by comparing a full click train (1–2 seconds long) on each channel, however, this may not be effective at low SNR (probably need 30 dB or more) or if there are multiple dolphins present.

#### 5.1.4 Combining bearings from widely spaced groups of closely spaced hydrophones

An alternate means of obtaining the bearing to a sound source from widely spaced groups of closely spaced hydrophones is the method of cross-fixing that is often employed during towed passive-acoustic monitoring projects (Figure 14). In this method, the bearing to a source is determined independently at each of two sensor groups, and then the intersection of the lines of bearing provide the most likely location of the source, plus or minus an area of uncertainty determined by the variance of the original bearing estimates. The area of uncertainty grows rapidly as the distance to the source increases. As a rule of thumb, the maximum distance to the source should be ten times the distance between the sensors,

and a distance of no more than five times the sensor group spacing is preferred. This method simplifies, but does not eliminate, the click association problem discussed in Section 5.1.3.



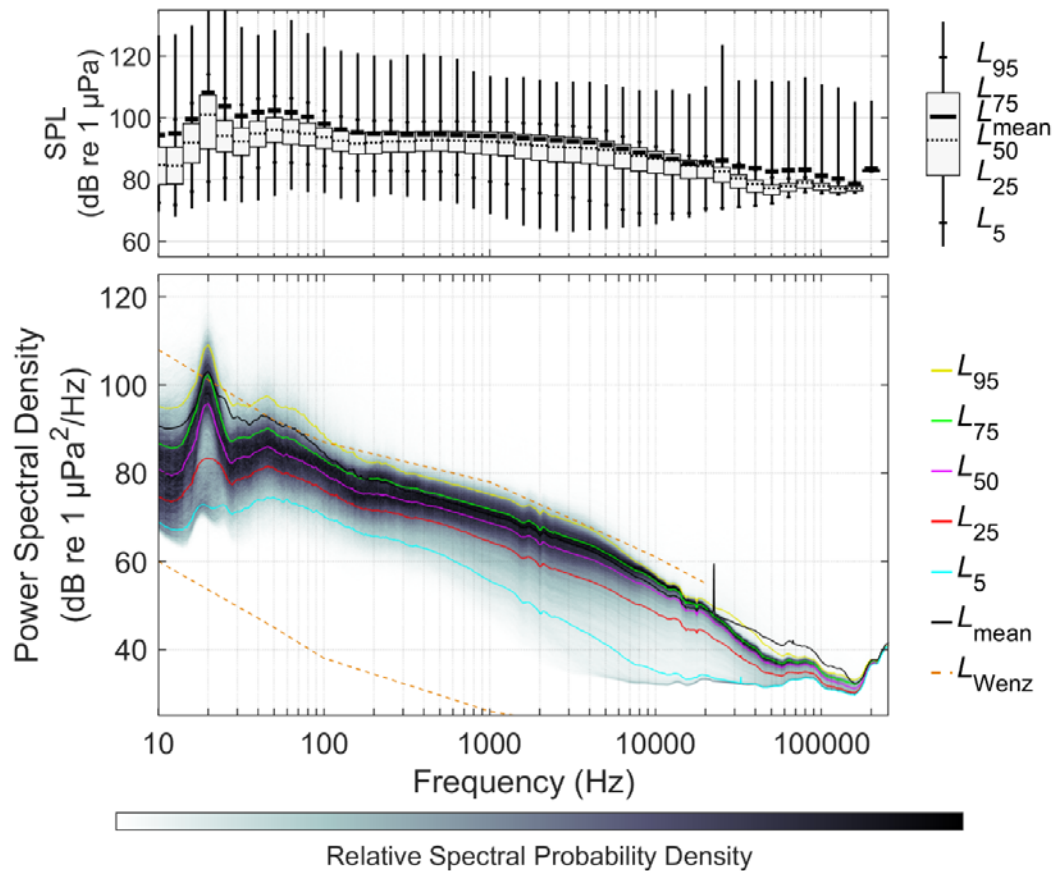
**Figure 14: Explanation of the accuracy of a cross-fix localisation from two clusters of hydrophones. In this example there are two sensor groups separated by 400 m. The groups are able to determine the bearing to a sound source with a variance of 2 degrees. Even with this accuracy the resulting area of uncertainty about the most likely location is large.**

## 5.2 Detection range

The goal of this system is detection and localisation of the Hector’s dolphins. To detect the dolphins the amplitude of the echolocation clicks must exceed the noise received in the same frequency band by the detection threshold of the system: i.e.,  $RL > NL + DT$  where  $RL$  is the received level,  $NL$  is the noise level, and  $DT$  is the detection threshold. For purposes of estimating the minimum detectable received level, we will consider the noise level from a high-performance data collection system (AMAR G4, <https://www.jasco.com/amar-g4>) in the 125 kHz decade band. Conservatively, the noise floor is 80 dB re 1  $\mu$ Pa (Figure 15); we make the reasonable assumption that flow and vessel noise in the environment does not affect the 125 kHz frequency band. This assumption is expected to be true for pelagic trawl boards, but maybe false for trawl boards that ride along the seafloor. We assume a detection threshold ( $DT$ ) of 20 dB to support the localisation requirement discussed in Section 5.1.2. Based on these parameters, the amplitude of the Hector’s clicks at the hydrophones must exceed 100 dB re 1  $\mu$ Pa.

The received level of a dolphin click at some distance ‘ $r$ ’ from the dolphin is given by  $RL = SL - PL$  where  $SL$  is the source level (150 dB re 1  $\mu$ Pa, Section 2.2) and  $PL$  is the propagation loss, which is approximately  $20 \cdot \log_{10}(r) + \alpha \cdot r$ . ‘ $\alpha$ ’ is the absorption of sound by seawater, approximately 0.04 dB/m at 125 kHz for the conditions in the project area (using the parameters from Kyhn et al. (2009)). Given

the requirement to have a received level of 100 dB, the maximum propagation loss is 50 dB, which occurs at a distance of about 150 m. Therefore, it is approximated that, to detect a dolphin, it must be within 150 m of the hydrophone.



**Figure 15:** Noise performance of an AMAR G4 recorder generated from 1-minute data samples over an 8-month recording programme. (Top) the decade band sound pressure levels as box and whisker plots. In these plots the boxes represent the middle 50% of all data measured; the vertical lines show the extent of the lowest and highest 25% of the measured data. The 125 kHz decade is the third from the right. (Bottom) the same data shown as power spectral densities (vertical) using a logarithmically spaced frequency axis (horizontal). Above about 50 kHz, most of the measured data is system noise limited.

### 5.3 Installation locations

The approximate minimum distance of the net opening behind the vessel is 150 m (Table 2). Given that approximately 150 m is the maximum distance of detectability (Section 5.2), this precludes placing hydrophones on or near the vessel and requires them to be closer to the net.

The trawl boards were identified in Section 4.2 as being the most suitable location close to the net to mount hydrophones and recording equipment. The F.V. *Achernar* uses trawl boards which are in contact with the seafloor, as opposed to a trawl operation which uses boards suspended just above the bottom. This could be a potential source of noise or high frequency vibration which could negatively influence acoustic recordings, although this is only a possibility, and needs to be confirmed through field trials.

Despite this potential issue, the trawl boards are the recommended installation location for hydrophone arrays. They are close enough to the net to allow dolphin signals to be received at SNRs which allow for detection and localisation, and they can provide a relatively stable platform (in the context of a mobile fishing operation). Additionally if an array is placed on both boards (applying the concepts from

Section 5.1.4), their separation could allow a dolphin approaching either from the bow or directly astern mid-way between the boards within 60 m (Table 1) to be detected. This is approximately 20 m in front of the net opening. If a dolphin approaches from side-on, there is a higher likelihood of detection at both boards, however, correlating the detections can have challenges (Section 5.1.3). However, all of this is dependent upon the acoustic field of view the dolphin is selecting to use at a point in time (Wisniewska et al. 2015).

## 6. DISCUSSION

Adherence to good design processes requires that systems go through detailed design and trials before being implemented in their final form. It is recommended that this occurs with any Hector's dolphin acoustic monitoring system.

Trial systems will allow testing to occur in a cost-effective manner, information to be obtained which can be used to inform decisions about the benefit of progressing to permanent systems, and identification of any system configuration changes which may be needed.

The equipment used for recording the acoustic data, from hydrophones through to data acquisition systems, will need to be able to deliver high quality data reliably while operating in a harsh environment. Although a number of the potential requirements could be considered bespoke, all of the equipment which could be required currently exists either directly as a commercial-off-the-shelf (COTS) product or could be achieved through minor modifications to COTS products. Therefore, no new equipment needs to be built or designed from scratch to meet any of the potential requirements. There is significant risk in the process of product development, because the development of recording equipment, hydrophone arrays, and data processing algorithms is complex. Therefore, from the point of view of 'Acoustic Data Recording, Processing and Telemetry', the system is considered to be feasible, with the assumption that the project team involved in the system compilation and integration includes personnel with the required experience.

To work backwards from the computer system installed on the vessel, a key consideration is telemetry, and the transfer of data from the trawl boards to the vessel. The distance is a significant hurdle, because it limits the types of equipment which can be used. Cable runs for ethernet (IEEE 802.3) and current-loop hydrophones are limited to a maximum distance of 100 m, and because the trawl boards could be up to 200 m behind the vessel in 40 m of water, they are excluded from consideration. Cables such as fibre-optic, twisted pair, or coaxial are all options; however, there are positives and negatives for each. Fibre-optic cable is expensive, and the handling requirements are likely beyond the scope of what can be managed by vessels within the fleet, therefore it is also excluded from consideration. There are a number of different vessel cabled video telemetry system products, such as LH Camera (<https://lh-camera.dk/en/products/underwater-video-cables-and-rubber-molding-on-cables/>) which provide a feasible solution.

However, cables are complex to manage and require reels with slip rings. To successfully implement on small vessels, they either need to be load bearing to replace existing warp wires, or on a dedicated winch, but somehow connected in tandem with the warp wires. These problems are widely known within the fishing industry when it comes to monitoring at the net and displaying information on the vessel, as demonstrated by this 2019 request for proposal: <https://em4.fish/wp-content/uploads/2019/04/EDF-SBI-RFP-Smart-Underwater-Trawl-Cameras-2019-1.pdf>.

If all the collected data are to be streamed from an acoustic monitoring system at the trawl board to the vessel, the amount of data required to be transmitted is significant. Considering the transmission of a single channel of 512 kbps (kilo-samples per second) acoustic data with 24-bit resolution, which is likely the quality of data required for this project, this is 12 288 kbps (kilobits per second) or 1536 kBps (kilobytes per second) or 1.536 MBps (megabytes per second), and that is without accounting for any communication protocol overhead. For two or three hydrophones, again without protocol overhead, the



data transfer rate required is 3072 MBps or 4608 MBps. It is impossible to move this amount of data from the trawl board to the vessel without a cable.

For small fishing vessels, where additional cables can be dangerous or require space which doesn't exist, and be too costly to implement, alternatives are required. There are many trawl monitoring systems which rely on acoustic communication to transfer data from sensors on the net to the vessel, similarly to underwater short baseline (USBL) positioning systems. Examples of trawl monitoring systems include those by Marpol ([www.marport.com](http://www.marport.com)), Kongsberg (<https://www.kongsberg.com/maritime/products/commercial-fisheries/>), whereas USBL systems which operate at close range and could be useful for monitoring the location of trawl boards include the Micro Ranger 2 (<https://www.sonardyne.com/product/micro-ranger-2-shallow-water-usbl-system/>) and the Micropap (<https://www.kongsberg.com/maritime/products/Acoustics-Positioning-and-Communication/acoustic-positioning-systems/pap-micropap-compact-acoustic-positioning-system/>).

The communication frequencies are typically around 30 kHz and thus will not interfere with Hector's dolphin echolocation clicks or any attempt to track them acoustically. Positioning systems are critical if a vessel uses off-bottom trawl boards.

Acoustic systems which can record and process data from multiple hydrophones at the trawl board, and then use an acoustic modem to transmit the data to the vessel where it can be received and then displayed to the vessel master, are likely to be the easiest and most reliable and cost-effective solutions to implement. This could involve acquisition and processing systems such as the JASCO OceanObserver™ (<https://www.jasco.com/oceanobserver/>), and communication systems such as the Kongsberg Cnode-minis (<https://www.kongsberg.com/maritime/products/Acoustics-Positioning-and-Communication/modems/cnode-minis/>) or the Sonardyne Modem 6 (<https://www.sonardyne.com/product/underwater-acoustic-modems/>).

Acquisition and processing systems will need the following capabilities to be suitable:

- High sample rate and minimum of 24-bit for high resolution
- Low noise floor at high frequencies
- Ability to integrate high pass filters (to remove data below the frequencies of interest)
- Multiple hydrophone capability
- Large capacity data storage
- Onboard processing of multiple channel data
- Ability to operate on battery power for required periods
- Small form factor and able to be mounted in rugged, shock proof housings

The acquisition and processing system housing will need to be mounted to the trawl door on vibration reducing mounts.

Hydrophones will need to have a noise floor, sensitivity, frequency response, and power draw suitable for the application, but also be rugged enough to survive the potential vibrations from the trawl door. Possible hydrophones include the GeoSpectrum Technologies M36 (<https://geospectrum.ca/wp-content/uploads/2018/11/M36-900-v4.pdf>). The hydrophones will need to be mounted with vibration reducing mounts and be shielded from potential impacts.

Modifications to the top of the trawl door may need to be investigated to allow for the mounting of additional hydrophones. One possible modification could be welding a flat bar across the top to allow two extra hydrophones to be mounted to the top of the door, so two arrays perpendicular to each other can be used.

Hydrophone arrays with an element spacing of at least 50 cm should be trialled (Sections 5.1.2), and the possibilities for using an array on each trawl door (Sections 5.1.3 and 5.1.4) should also be investigated in the field.

Trial systems should be closely matched in capability to any permanent systems. Initial trial systems, or indeed permanent systems which do not require telemetry, should be autonomous to reduce complexity and costs. Autonomous systems will be able to gather the same data and allow different design concepts to be tested in the real world. This includes examining:

- Different hydrophone array concepts (Section 5.1)
- Benefits of multiple arrays
- Detection ranges (Section 5.2)
- Noise and vibration influences from the trawl door
- Mounting concepts

The data collected can be post processed to aid in making a decision about the validity of progressing the use of passive acoustic monitoring systems, and to improve system designs and functionality.

## **6.1 Vessel interface concept**

Fishermen are typically focused on the fishing operation and navigation, and interfaces which require too much attention, or cause a distraction, are impractical. Therefore, the system interface needs to be as automated as possible, and though significant data records may be stored behind the scenes, the fisherman will require a clear notification coupled with a simple informative output.

It is envisaged that a console operated audio or visual alert indication on a dedicated unobtrusive system separate to the rest of the vessel equipment would be ideal. The output would need to indicate the presence of dolphins relative to the trawl mouth and permit vessel masters to implement pre-determined procedures to mitigate potential bycatch.

It is therefore suggested that a vessel interface could consist of the following components:

- Small, dedicated Uninterruptible Power Supply (UPS).
- A powerful mini-PC with a small form factor, such as an Intel NUC.
- Purpose built user interface, with alerts for different items of interest, such as dolphin presence, dolphin depth and proximity to net.
- External hard drive for data storage.
- A small (10–12-inch) touchscreen monitor.
- A speaker and USB controllable LED – emitting different sounds and colours for different alerts.

## **6.2 Operational benefits**

Different phases of the inshore trawl fishing operation may well provide differential access for dolphins to the open mouth of the net or potential prey directly in front of the net. The process of setting and retrieval of nets sometimes involves speed changes, or course changes, associated with a trawl direction change or surface operation associated with net handling that could temporarily change the nature of the net opening. A temporarily altered net opening might encourage entry by adjacent dolphins.

If the vessel master is notified by an automated detection system of the presence of dolphins, and their approximated locations, it would assist them to manage fishing operations in a way as to minimise risk to the dolphins, such as avoiding altering the net opening by turning or changing speed.

## 7. SYSTEM APPLICATIONS

This section summaries two application concepts for monitoring systems.

### 7.1 Hector's dolphin behaviour assessment

The underwater and acoustic behaviour of Hector's dolphins in the presence of fishing equipment has not been quantified in conjunction with the fishing industry. The system concepts proposed in this study would allow information to be provided which could be of significant benefit to fisheries management related to Hector's and Māui dolphins.

### 7.2 Assessment of mitigation approach effectiveness

A key application for a system which can monitor Hector's dolphins around fishing equipment is in the context of trials of methods to mitigate interactions between the dolphins and fishing equipment. These methods could involve altering the physical properties or configuration of the net, or the use of acoustic 'pingers'. To determine the effectiveness of mitigation measures, (Hamilton & Baker 2019) describe the requirement for understanding: *“the biological and behavioural characteristics of target and bycatch species, temporal and spatial overlap of bycatch species with fishing activities and operational factors is needed (Baker et al. 2014). Determining mitigation efficacy should include species- and fisheries-specific testing with adequate scientific rigour, and a quantitative target to enable efficacy assessment.”*

The system focused on within this feasibility study can be used to provide a significant proportion of the background understanding requirements, but also used during technology trials. Results obtained through installation of an acoustic monitoring system can provide baseline data prior to trials of any mitigation approaches.

Background information on acoustic mitigation devices to understand the types of devices and monitoring considerations for Hector's dolphins is provided in Section 7.2.1. The only way to examine if Hector's dolphins change their acoustic behaviour in relation to mitigation approaches, including net material and acoustic mitigation devices, will be to examine their vocalisations. This can be done in tandem with estimation of their location underwater in relation to fishing equipment, which can be used to assess the risk of potential interactions.

Building an unbiased method of testing the functionality of acoustic deterrent devices is important to build trust and buy-in to the mitigation within a fishing industry. If a fishery is going to rely on a particular mitigation device, information such as knowing that the device is reliable and that it will have a net positive benefit will be key. This is in contrast to the approach often taken, where devices are pushed onto fishermen which may or may not be species or operationally appropriate, may not be reliable, may not be safe and easy for the fishermen to use, and may not have any positive influence on dolphin-fishery interactions.

#### 7.2.1 Acoustic mitigation devices

Within the New Zealand lexicon there has been a focus on the use of the term 'Dolphin Deterrent Device' to describe high-amplitude pingers. There are a number of different pinger device types or descriptions which have been historically used for different species, fisheries, and purposes. This ranges from low-frequency bycatch mitigation devices for humpback whales which emit a tonal type of signal (e.g., McPherson et al. 2001, McPherson et al. 2004, Erbe et al. 2011, Erbe & McPherson 2012), higher frequency bycatch mitigation devices for odontocetes which emit a tonal type of signal (e.g., Kastelein et al. 2007, Palka et al. 2008) and broadband dissuader type devices, which can be referred to also as deterrents (e.g., Northridge et al. 2010). When discussing these different devices, it is important to clearly define their acoustic outputs (amplitude, frequency, duty cycle, signal type) and the designed applicability of the devices.

In the context of acoustic mitigation and trawl fisheries, which have a dynamic operation, it is likely that the most suitable devices will be those often described using terms such as ‘depredation mitigation, dissuader, or deterrent’. These devices are louder and have a much more complex signal than a typical bycatch mitigation pinger; they include devices such as the STM Products ‘Dolphin Deterrent Device’ (DDD), which has been shown to be effective in trawl and other more ‘active’ fisheries for high-frequency odontocetes (e.g., Northridge et al. 2010).

This type of device is quite different from the typically low amplitude bycatch mitigation devices designed to act as a warning device, not a deterrent. These devices are not loud enough, and do not emit a signal which can interfere with echolocation, and it is apparent that they are designed to act as a device which alerts the animal to the presence of a net. As described by (Erbe & McPherson 2012), they are typically placed on gillnets to ‘highlight’ the nets, notifying marine mammals of their presence and location and hence reducing entanglements (Kastelein et al. 2007).

Although higher-amplitude devices (Hamilton & Baker 2019) can be used to dissuade or more simplistically ‘deter’ dolphins from an area close to fishing equipment and thus mitigate negative interactions, none of the devices aimed at dolphins state that their aims are to cause dolphins to avoid an area. However, the marketing material from manufacturers needs to be considered carefully, with many devices having specific applications (McPherson et al. 2012), and some devices proving to be not robust enough to withstand field trials on commercial fishing vessels (R. Mitchell, 2020, pers. comm.).

The behaviour of marine mammals is extremely context dependent (Ellison et al. 2012), and it would be inappropriate to assume that fishing mitigation devices have to elicit a physical response from the animal and trigger spatial avoidance to be effective. Acoustic devices are potentially more likely to trigger changes in acoustic behaviour, something which can occur in response to many anthropogenic sound sources (Blackwell et al. 2015, Blackwell et al. 2017, Cholewiak et al. 2017, Kastelein et al. 2018, Southall et al. 2019, Wensveen et al. 2019).

Acoustic modelling can be conducted to estimate the range at which an acoustic mitigation device may be audible to a marine mammal (e.g., McPherson et al. 2001, McPherson et al. 2004, Erbe et al. 2011, Erbe & McPherson 2012); however, understanding the response elicited by the device is more complex. In addition, understanding the behaviour of marine mammals around fishing equipment and thus prey is very different to static trials of equipment which bear little to no resemblance to real world applications.

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<https://doi.org/10.7554/eLife.05651>.



## 10. GLOSSARY

### **absorption**

The reduction of acoustic pressure amplitude due to acoustic particle motion energy converting to heat in the propagation medium.

### **ambient noise**

All-encompassing sound at a given place, usually a composite of sound from many sources near and far (ANSI S1.1-1994 R2004), e.g., shipping vessels, seismic activity, precipitation, sea ice movement, wave action, and biological activity.

### **automated detector**

An algorithm that includes both the automated detection of a sound of interest based on how it stands out from the background and its automated classification based on similarities to templates in a library of reference signals.

### **azimuth**

A horizontal angle relative to a reference direction, which is often magnetic north or the direction of travel. In navigation it is also called bearing.

### **bandwidth**

The range of frequencies over which a sound occurs. Broadband refers to a source that produces sound over a broad range of frequencies (e.g., seismic airguns, vessels) whereas narrowband sources produce sounds over a narrow frequency range (e.g., sonar) (ANSI/ASA S1.13-2005 R2010).

### **decade**

Logarithmic frequency interval whose upper bound is ten times larger than its lower bound (ISO 2006).

### **decidecade**

One tenth of a decade (ISO 2017). Note: An alternative name for decidecade (symbol ddec) is “one-tenth decade”. A decidecade is approximately equal to one third of an octave ( $1 \text{ ddec} \approx 0.3322 \text{ oct}$ ) and for this reason is sometimes referred to as a “one-third octave”.

### **decidecade band**

Frequency band whose bandwidth is one decidecade. Note: The bandwidth of a decidecade band increases with increasing centre frequency.

### **decibel (dB)**

One-tenth of a bel. Unit of level when the base of the logarithm is the tenth root of ten, and the quantities concerned are proportional to power (ANSI S1.1-1994 R2004).

### **delphinid**

Family of oceanic dolphins, or Delphinidae, composed of approximately thirty extant species, including dolphins, porpoises, and killer whales.

### **frequency**

The rate of oscillation of a periodic function measured in cycles-per-unit-time. The reciprocal of the period. Unit: hertz (Hz). Symbol:  $f$ . 1 Hz is equal to 1 cycle per second.

### **hertz (Hz)**

A unit of frequency defined as one cycle per second.

**hydrophone**

An underwater sound pressure transducer. A passive electronic device for recording or listening to underwater sound.

**odontocete**

The presence of teeth, rather than baleen, characterizes these whales. Members of the Odontoceti are a suborder of cetaceans, a group comprised of whales, dolphins, and porpoises. The skulls of toothed whales are mostly asymmetric, an adaptation for their echolocation. This group includes sperm whales, killer whales, belugas, narwhals, dolphins, and porpoises.

**pressure, acoustic**

The deviation from the ambient hydrostatic pressure caused by a sound wave. Also called overpressure. Unit: pascal (Pa). Symbol:  $p$ .

**pressure, hydrostatic**

The pressure at any given depth in a static liquid that is the result of the weight of the liquid acting on a unit area at that depth, plus any pressure acting on the surface of the liquid. Unit: pascal (Pa).

**received level (RL)**

The sound level measured (or that would be measured) at a defined location.

**rms**

root-mean-square.

**sound**

A time-varying pressure disturbance generated by mechanical vibration waves travelling through a fluid medium such as air or water.

**sound exposure**

Time integral of squared, instantaneous frequency-weighted sound pressure over a stated time interval or event. Unit: pascal-squared second ( $\text{Pa}^2 \cdot \text{s}$ ) (ANSI S1.1-1994 R2004).

**sound field**

Region containing sound waves (ANSI S1.1-1994 R2004).

**sound intensity**

Sound energy flowing through a unit area perpendicular to the direction of propagation per unit time.

**sound pressure level (SPL)**

The decibel ratio of the time-mean-square sound pressure, in a stated frequency band, to the square of the reference sound pressure (ANSI S1.1-1994 R2004).

For sound in water, the reference sound pressure is one micropascal ( $p_0 = 1 \mu\text{Pa}$ ) and the unit for SPL is dB re  $1 \mu\text{Pa}^2$ :

$$L_p = 10 \log_{10}(p^2/p_0^2) = 20 \log_{10}(p/p_0)$$

Unless otherwise stated, SPL refers to the root-mean-square (rms) pressure level. Non-rectangular time window functions may be applied during calculation of the rms value, in which case the SPL unit should identify the window type.

**source level (SL)**

The sound level measured in the far-field and scaled back to a standard reference distance of 1 metre from the acoustic centre of the source. Unit: dB re  $1 \mu\text{Pa} \cdot \text{m}$  (pressure level) or dB re  $1 \mu\text{Pa}^2 \cdot \text{s} \cdot \text{m}$  (exposure level).

**spectral density level**

The decibel level ( $10 \cdot \log_{10}$ ) of the spectral density of a given parameter such as SPL or SEL, for which the units are dB re  $1 \mu\text{Pa}^2/\text{Hz}$  and dB re  $1 \mu\text{Pa}^2 \cdot \text{s}/\text{Hz}$ , respectively.

**transmission loss (TL)**

The decibel reduction in sound level between two stated points that results from sound spreading away from an acoustic source subject to the influence of the surrounding environment. Also referred to as propagation loss.

**wavelength**

Distance over which a wave completes one cycle of oscillation. Unit: metre (m). Symbol:  $\lambda$ .