Evaluating the effectiveness of shore cabled hydrophone networks as near real-time killer whale detection and tracking systems with special reference to DFO's Whale Tracking Network (WTN)

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ABSTRACT

Yurk, H., Quayle, L.,Burnham, R., MacConnachie, S., LeBlond, T. 2023. Evaluating the effectiveness of shore cabled hydrophone networks as near real-time killer whale detection and tracking systems with special reference to DFO’s Whale Tracking Network (WTN). Can. Tech. Rep. Fish. Aquat. Sci. 3543: ix + 69 p.

Shore-cabled underwater passive acoustic monitoring (PAM) systems with automated call detection and classification (DC) can be used to detect vocalizing animals in near real-time. Here, the ability of a network of five PAM stations (part of the DFO Whale Tracking Network (WTN)) to detect and track killer whales in near real-time, especially endangered Southern Resident Killer Whales (SRKW) was assessed. Probable detection ranges of calls given soundscape variations, movement of noise sources and movement of the whales on the performance of the network was investigated. While whale depth and propagation influenced spatial detection range variation, ambient and background underwater noise levels limited tracking ability of the PAM network. The tested automated DC system performed well (detection precision at or above 80%) in quieter environments when only killer whales were present and their vocal activity was high. However, the ability to track killer whales in near real-time by the five PAM stations was limited due to the movement of the whales and their location relative to noise sources such as vessels. Both whales and vessels move continuously and verifying acoustic detections requires time during which animals move away from the recorded location and vessels either move away or approach the whales. Data from systems using acoustic data in conjunction with other technologies, such as thermal imaging and observer sightings appear a better solution to track killer whales.

RÉSUMÉ

Yurk, H., Quayle, L., Burnham, MacConnachie, S., LeBlond, T. 2023. Evaluating the effectiveness of shore cabled hydrophone networks as near real-time killer whale detection and tracking systems with special reference to DFO's Whale Tracking Network (WTN). Can. Tech. Rep. Fish. Aquat. Sci. 3543: ix + 69 p.

On peut utiliser les systèmes de surveillance acoustique passive (SAP) sous-marins reliés à la terre et dotés d'un système de détection et de classification (SDC) automatisé des vocalises pour détecter les animaux qui émettent des vocalisations en temps quasi réel. On a évalué ici la capacité d'un réseau de cinq stations de SAP (faisant partie du réseau de suivi des baleines du MPO) à détecter et à suivre les épaulards en temps quasi réel, en particulier les épaulards résidents du sud. On a étudié les plages de détection, compte tenu de l'effet des variations du paysage sonore, du mouvement des sources de bruit et des déplacements des baleines sur la performance du réseau. Alors que la profondeur et la propagation des baleines ont influencé la variation des plages de détection spatiale, les niveaux de bruit ambiant et de bruit de fond sous-marin ont limité la capacité de suivi du réseau de SAP. Le SAP automatisé mis à l'essai a bien fonctionné (précision de détection égale ou supérieure à 80 %) dans les environnements plus calmes lorsque seuls des épaulards étaient présents et que leur activité vocale était élevée. Cependant, la capacité des cinq stations de SAP à suivre les épaulards en temps quasi réel était limitée en raison des déplacements des épaulards et de leur position par rapport aux sources de bruit, comme les navires. Les baleines et les navires se déplacent continuellement et la vérification des détections acoustiques nécessite du temps pendant lequel les animaux s'éloignent de l'emplacement enregistré et les navires s'éloignent ou s'approchent des baleines. Les données provenant des systèmes qui utilisent des données acoustiques en conjonction avec d'autres technologies, comme l'imagerie thermique et les observations des observateurs, semblent constituer une meilleure solution pour le suivi des épaulards.

INTRODUCTION

This technical report is a result of research undertaken by DFO Science as part of the Whale Detection and Collision Avoidance (WDCA) Initiative under the Oceans Protection Plan (OPP). The research goal of this program as a whole was to test whale detection technologies capable of providing timely information on the presence of whales with the intent to reduce the threat of vessel strikes and help protect whales on both the Atlantic and Pacific coasts. This report describes the work done by WDCA to evaluate networked shore-tethered passive acoustic monitoring (PAM) stations to detect and track Southern Resident Killer Whales (SRKW) in their designated Critical Habitat under the Species at Risk Act (SARA) along the Pacific coast. PAM was identified as one of the promising technologies to detect and track whales in Canadian waters (Theriault et al. 2020).

Passive Acoustic Monitoring (PAM) Applications for Near Real-Time Detection

PAM is a powerful tool to learn about the communication and foraging behaviour of marine mammals, especially cetaceans (e.g., Tyack 1997). The use of PAM to detect vocalizing animals has been employed as an effective tool to determine habitat presence and potential use as well as movements with different goals, including determining spatial and temporal presence in different habitat types, assessing threats, and mitigating acoustic and physical impact from human activities (Zimmer 2011, Sousa-Lima et al. 2013, Browning et al. 2017).

PAM can be implemented either separately or in addition to visual and other detection methods (Dalpaz et al. 2021). Underwater PAM can have an advantage over visual-based human observer methodologies due to its effective application in daylight and darkness, as well as its applicability and higher detection effectiveness in poor visibility conditions caused by inclement weather and poor sea state. As a result, PAM may improve the observation and monitoring efforts for a certain area or during a survey, increasing both the quantity and quality of data on animal presence and movements (Frasier et al. 2021). PAM has been demonstrated as an effective tool to increase monitoring efforts of killer whale habitat use at times when visual monitoring is difficult, especially during the winter months (Matkin et al. 2003, Yurk et al. 2010, Riera et al. 2011, Hanson et al. 2013, Burnham et al. 2016, Rice et al. 2017, Schall and Van Opzeeland 2017, Riera et al. 2019, Emmons et al. 2021, Myers et al. 2021, Leu et al. 2022, Rand et al. 2022).

The effectiveness of PAM to detect marine mammals reliably is based on the premise that most whales and dolphins produce distinctive vocalizations (that can often be assigned to the species level), and also use sound as their principal means of navigation, prey localization, and social communication and therefore vocalize regularly. The acoustic behaviour of whales, especially why whales vocalize where and when, will provide information on their anticipated presence and how long they may stay in an area. Vocal behaviour is driven primarily by biological factors, such as finding mates, finding food, defending territories, staying in contact with group members, and navigating underwater habitats (Johnstone 1997).

There is, however, large variation in vocal rates observed across cetacean species, with some baleen whales vocalizing irregularly and in bouts of less than two minutes per hour (e.g., blue whales: Boiseau et al. 2008), while many odontocetes regularly produce echolocation clicks throughout their range as they forage (e.g., Cohen et al. 2022).

These difference in vocal rates will influence the effectiveness of PAM as a near-real-time tracking tool because they vary the time periods over which the presence of a vocalization can be reported. Some odontocetes show variation in communication rates associated with differences in group or pod sizes, location, time of year and behavioural state (Jones and Sayigh 2002, Zimmer 2011, Lin et al. 2015, Visser et al. 2017). This also appears to be the case for resident killer whales, especially with regards to spatial and temporal variation in vocal rates (Ford 1989; Holt et al. 2011; Quayle et al. in prep.).

The ability to reliably detect whales, and relay that information to a monitoring station in a timely manner, becomes an important consideration when the purpose is to mitigate the negative impacts of human activities (Zimmer 2011, Todd et al. 2015, Verfuss et al. 2018), that have the potential to cause disturbance, injury, harassment, harm and even death (Wright and Moors-Murphy 2022). The need for up-to-date information on the location of whales and the path they are travelling is crucial, especially when quick interventions are necessary to reduce potential negative impacts on animals. For example: to alert an intervention team to implement meaningful mitigation strategies before whales are about to enter an area with a high risk of injury or harm (such as an oil spill area, when entering the safety/mitigation zone around a loud noise producing activity, or when entering the path of a moving vessel.

Physical injury or death may occur as a result of vessel strikes, and near real-time PAM has been applied to alert vessel operators of whales (mostly baleen whales) in the path of their vessel to mitigate strike risks (e.g., Baumgartner et al. 2019). Under these circumstances, tracking animals and predicting their movements may be necessary to mitigate the risk, however, both whales and vessels move at considerable speeds and the time of the detection may not properly reflect the time a vessel may encounter detected whales.

An understanding of how whales use an area is essential for acoustic tracking of their movements. For some species such as resident killer whales, foraging requires individuals to spread out over an area of several square kilometres to hunt for salmonids, primarily Chinook salmon that may not occur in aggregated schools. Resident killer whales have strong food sharing traditions which appears to drive the persistence of very tight knit family groups (matrilines) (Wright et al. 2016). The social, foraging and food sharing traditions require killer whales to stay connected ‘acoustically’ while foraging. As a result, there is greater likelihood for animals vocalizing when they are foraging or socializing than when matrilines are traveling alone in close proximity to each other (Ford 1989). Killer whales appear to travel in these smaller units during times when mating and social gathering are less common, and there may not be a need for them to vocalize regularly (Hanson et al. 2013).

Information on acoustic behaviour and, in particular, variation in vocal rates of species and populations need to be considered when deciding on where to place PAM stations and when to expect them to function optimally. Knowledge about the behaviour and ecological needs of SRKW (Thornton et al 2022a) needs to be considered when making decisions about where to deploy passive PAM stations to track them.

Near Real-Time PAM Systems

Underwater PAM systems capable of near-real-time (NRT) detection of whale sounds can either operate autonomously or as systems connected to a vessel or a shore station via a cable or transmitter. Autonomous operating systems such as acoustic buoys can be anchored to the ocean floor and have hydrophones suspended below the buoy via a shorter cable (10-30 m), in which case the acoustic recorder and signal detector is integrated into the buoy, or consist of two separate components—a data transmission buoy which is tethered via longer cable to a recording unit with attached hydrophones moored on the ocean floor. Vessel or shore-tethered single-hydrophone or multi-hydrophone array systems (e.g., Andre et al. 2011, Gervaise et al. 2019, 2021, Theriault et al. 2020) can record sound either at the underwater location of the hydrophone(s), onboard a vessel, or via a shore station. The hydrophones are tethered to the recorder or data is transmitted via a cable. Systems that are connected to a vessel (single hydrophones lowered into the water when the vessel is stationary, or multiple hydrophones in an array design towed behind a moving vessel) are common tools in cetacean field research. Towed hydrophone arrays have become a common tool in population assessments, where they are used as an additional tool during visual line-transect surveys (Rankin 2008, Thompson et al. 2015) or in standalone acoustic line-transect surveys (Norris et al. 2017).

A hydrophone is an analogue device, which means the strength of the sound pressure change due to the signal is translated into an electrical current that matches the strength of the change. This creates an analogue electrical signal that can either be transmitted via a cable to shore or can be converted into a digital signal underwater (digital hydrophone or recorder). The length of the cable and the depth at which either system (shore-cabled or buoy-based with bottom-mounted hydrophones) are influenced by the means of data transmission through the cable. If the acoustic data are transmitted as digital signals, the length of the cable can, on average, be longer without affecting the sound transmission than if an analog signal is transmitted. The analog transmission requires stronger amplification to travel the same distance as the digital signal, and transmission is impacted negatively by cable movements (mechanical strumming) and water flow over the cable (flow noise). This may lead to whale signals with lower signal-to-noise ratios being masked by the strum and flow noises. Digital signals need to be repeated (boosted) approximately every 100 m to maintain low levels of signal degradation, but are relatively unaffected by strumming or water flow.

Hydrophone sensitivity and dynamic ranges are important metrics that indicate how quiet a sound can be detected and how loud a sound can be before it overloads/saturates the sensor capacity and makes it impossible to record the signal appropriately. Hydrophone sensitivity is typically provided as a nominal dB value by the manufacturer while dynamic range may only be provided by some manufacturers.

Hydrophone sensitivity varies with frequency but generally hydrophones maintain a relative stable sensitivity across a certain frequency range. Across this linear range, sensitivity only fluctuates minimally.

Buoys with suspended hydrophones are sometimes affected more than bottom-mounted hydrophones by waves/swell, which move the buoy and the attached hydrophones up and down in the water column. This results in mechanical noise due to rapid flow of water across the sensor, which negatively impacts the quality of the sound recording. This effect is amplified by the noise the buoy creates when moving side to side in the surface waves. The advantage of an acoustic buoy with suspended hydrophones is, however, that they are easier to deploy and retrieve than bottom-tethered buoys, because bottom mounted hydrophones/arrays need to be anchored, which means they need to be heavier so they will not be dragged by the current and damaged in the process.

The potential advantage of the cabled systems over buoy systems is that they can be powered from a vessel or from shore, and thereby can operate continuously. Any non-cabled system relies on batteries as a power source and thereby has a limited recording time. Also, since data can be streamed via cabled systems continuously, there is no need for a large data storage capacity on the actual recording unit. Furthermore, data transmission quality and transmission rates via cable tend be higher and allow for larger data sets to be transferred than is possible via wireless transmission.

Shore-tethered monitoring systems such as those used in DFO's Whale Tracking Network (WTN; OceanSonics 2017) may consist of a single hydrophone or an array of hydrophones connected to shore via an underwater cable. Aside from detecting a call via a single shore-cabled hydrophone, arrays of hydrophones may be able to detect the direction of the incoming signal and allow localization of whales and detect their movements, especially individuals travelling or foraging on their own (Morrisey et al. 2006, Simard and Joy 2008, Gervaise et al. 2021). Tracking ability is, however, subject to the limits of the detection range of each of the PAM system and accurately tracking spread-out groups of travelling or foraging whales when individuals are in close proximity is limited. Localizing arrays require very specific designs to allow separation of the time-of-arrival of signals based on frequency specifications (volumetric arrays), which allows distance estimation of the incoming signal (Zimmer 2011). Volumetric arrays are often used in multi-hydrophone towed arrays during acoustic surveys (Barkley et al. 2016).

The capability of a hydrophone array to detect the direction of a signal such as a whale call depends on the spacing of the hydrophones on the array (Zimmer 2013). The space between the hydrophones needs to allow separation of incoming soundwaves to determine the difference in time between sound waves arriving at different sensors. This means that the distance between the sensors has to be at least as long as the wavelength of the incoming sound wave of the signal to be detected The wavelength of a sound is inversely proportional to its frequency, meaning higher sound frequencies are associated with shorter wavelengths. For example, a 1500 Hz sound wave (a common frequency used by killer whales) has a roughly 1 m wavelength while a 20 Hz sound wave (i.e., a typical fin whale call) has a wavelength of 75 m. An array that could detect the directionality of fin whale calls should therefore have a sensor spacing of 75 m or more, while the sensor spacing on an array to determine the incoming direction of a killer whale call typically does not have to be much greater than 1 m (Miller and Tyack 1998). Lower sound frequencies travel, on average, further than higher frequencies which makes fin whale calls travel further than killer whale calls. However, ambient noise is often louder in lower frequencies which makes these frequencies prone to masking (see Stojanovic and Preisig 2009 for a description of the various effects on underwater sound propagation).

Another factor that affects the functionality of an acoustic array as a detector of direction is the vertical-versus-horizontal spacing of sensors. Because the signaler moves up and down while swimming in a particular direction, dynamic changes in sound propagation result in different received levels at the different sensors. One of the commonly used geometry for acoustic arrays is a tetrahedral shape that allows for both horizontally- and vertically-spaced sensors. Tetrahedral geometry is, however, not the only way a functional acoustic array can be designed, and, especially for the detection of directionality of incoming baleen whale calls, a different design such as a circular geometry with sensors on opposite sides of a ring with a diameter large enough to separate longer wavelengths can be more effective (Gervaise et al. 2019b).

The geographical spacing of arrays in a given area can allow tracking of killer whales and other cetaceans moving through that area. However, the effectiveness of the tracking will be influenced by the topography of the underwater landscape, which affects whale movements and the soundscape, both of which ultimately affect acoustic detection ranges. Islands and rising bathymetry reliefs can create underwater acoustic shadows that limit the directions the sound can travel. It is therefore important to choose hydrophone locations that allow the tracking of sound over larger distances when sound propagation allows.

Generally, the quality of sound recordings increase with distance from shore and greater water depth. Higher background noise levels more often occur in shallower nearshore waters as a result of surf and water interaction with the shoreline in general, as well as noise from boat moorings, moored navigational aids, and human near-shore activities. Furthermore, noise from water surface agitation such as waves, wind chop and precipitation sometimes penetrate deep into the water column and may be reflected from the bottom, thereby increasing the background noise.

The maximal distance of a cabled system from shore is dependent on the length of the cable that can be used effectively, the means of transmission of signals (digital or analog), the size and structure of the intertidal zone cleared for the sensor to remain constantly underwater, the steepness of the slope on which the hydrophone/array mooring can rest safely without tipping over or sliding, and the deployment method of the mooring. If the mooring is deployed by divers, the weight of the mooring will influence the type and size that can safely be deployed. The depth at which divers can operate safely will further influence the distance. An alternative deployment method is to lower the system from a vessel to the seabed via a winch line. An acoustic release attached to a float can bring a retrieval line attached to the mooring back to the surface to lift the mooring. The size and weight of the mooring will establish whether this deployment method is suitable. Both deployment and retrieval methodologies require considerable effort involving suitable vessels and/or experienced personnel to conduct the mooring deployment retrieval safely.

Choosing appropriate locations for shore-cabled systems where potential damage to the cables and the mooring itself can be minimized will increase the functionality of the system by reducing the need for servicing. Shore-cabled systems in near-shore locations are generally easier to deploy and service while shore-cabled systems located in deeper water and further away from shore (e.g., > 100 m) on average have higher deployment and maintenance costs. Examples of shore-cabled systems that are further away from shore are the Underwater Listening Station (ULS) located in Boundary Pass BC, which is operated by JASCO Applied Sciences and funded by Transport Canada, and the acoustic nodes added to underwater observatories operated by Ocean Networks Canada (ONC) in the Strait of Georgia and off the west coast of Vancouver Island. These systems also collect oceanographic data. Each of these systems had development and installation costs of several million Canadian dollars plus operational costs in the hundreds of thousands of dollars per year.

Due to variations in sound propagation between the upper water layers and deeper water layers, there is a difference in whale detectability based on where in the water column the whale vocalizes. This is particularly pronounced during summer, when the surface water layers heat up, which causes sound to travel faster in these layers. If the hydrophones are closer to the surface, (e.g., <25 m deep) which is the case for most shore-cabled and buoy-based systems with suspended hydrophones, whale calls with low amplitude produced in lower water layers may not get picked up effectively by receivers, while calls produced in the upper layer may not get detected well by bottom-mounted hydrophones (e.g., >25 m deep), especially at greater distances between caller and receiver. On the other hand, sensors within the upper water layer may receive those sounds produced in the same layer at much greater distances due to the higher sound speed in warmer water. However, one needs to take into account that certain types of sound sources such as vessel noise are also created in these upper water layers and therefore the probability of noise interference is greater in those layers.

The optimal arrangement of PAM stations to track whales depends on the soundscape of the area to be monitored. Soundscapes vary and differences between open water versus sheltered nearshore soundscapes are substantial (Vagle et al. 2021), and even more so if nearshore waters include islands, fjords, bays, and inlets. Detection range variations should therefore be well understood before deciding on the location of PAM stations.

Effects of Detection Range Variation of Whale Calls on Effective PAM

The underwater topography, bathymetry, sediment structure, and water properties—especially temperature and salinity differences and water mixing due to tidal currents—can lead to highly stratified vertical soundscapes in which each water layer is characterized by a different sound speed and the boundaries between those layers cause sound waves to either bend upwards or downwards (Vagle et al. 2021). All of these factors influence the detection range of whale calls. Because these effects also vary on a temporal scale, detection range is not constant over a course of an hour, week, month, or year at any location but varies at much shorter time scales (Mouy et al. 2020, Vagle et al. 2021).

To detect a particular acoustic signal, such as a whale call, the signal amplitude at a receiver location needs to exceed the ambient or background noise level (Signal-to-Noise Ratio or SNR) in at least one of the frequency bands of the signal for which the receiver/detector system is sensitive. Typically, the detection threshold of an automated detector is set to exceed the ambient sound level by a considerable amount (e.g., ≥ 5 dB) to reduce the number of false detections that can occur due to tonal signals in the ambient sound (e.g., ship propeller blades turn with a specific rotation speed, which produces harmonic sounds underwater reflecting multiples of that rotation frequency, which may have the acoustic appearance of whale calls). Background noise levels at the location of the calling whale and along the path of the call from the signaler to the receiver vary due to fluctuations in natural sounds such as wind, precipitation and other biological sounds, as well as sounds from anthropogenic sources such as vessel noise. This results in variation in detectability of signals by an automated detector as a result of variation in propagation (Mouy et al. 2020).

In addition to ambient noise levels that influence the underwater propagation of a call, other environmental factors also impact the sound travelling from signaller to receiver. Bathymetry, geo-acoustic properties (e.g., hard versus soft sediment structure), and sound speed profiles all influence the amplitude of an arriving sound and the amplitude varies with the frequency of the signal. The sound speed profiles are primarily influenced by water properties such as temperature, salinity, and pressure.

Propagation of a call therefore is affected by:

- the amplitude of the sound source in each of the calls' frequency bands;
- the depths of the caller (variable) relative to the position of the hydrophone (fixed);
- environmental characteristics such bathymetry as well as water and sediment properties);
- the ambient noise levels in each of the sound's frequency bands which can lead to masking

Automated Detectors for Whale Calls

Continuous acoustic data collection via buoys or shore-cabled systems produces large amounts of data which need to be processed in a very timely fashion to achieve NRT detection and tracking of whales through an area. Manual analysis through listening to these vast amounts of data is an inadequate approach to achieve near-real-time detection. Automated analysis tools such as computer algorithms for detection and classification that can sift through large data sets and locate whale calls are therefore needed for the task.

Most of these algorithms use digital signal processing techniques based on a mathematical procedure called Fast Fourier Transformation (FFT) that converts sound energy waves of a measured length in the time domain (sound energy variation over time or soundwave form) into the frequency domain (sound energy variation over frequency or sound spectra) and displays them as sequential images showing the variation of tonal features of the sound over time (spectrograms) (Figure 1).

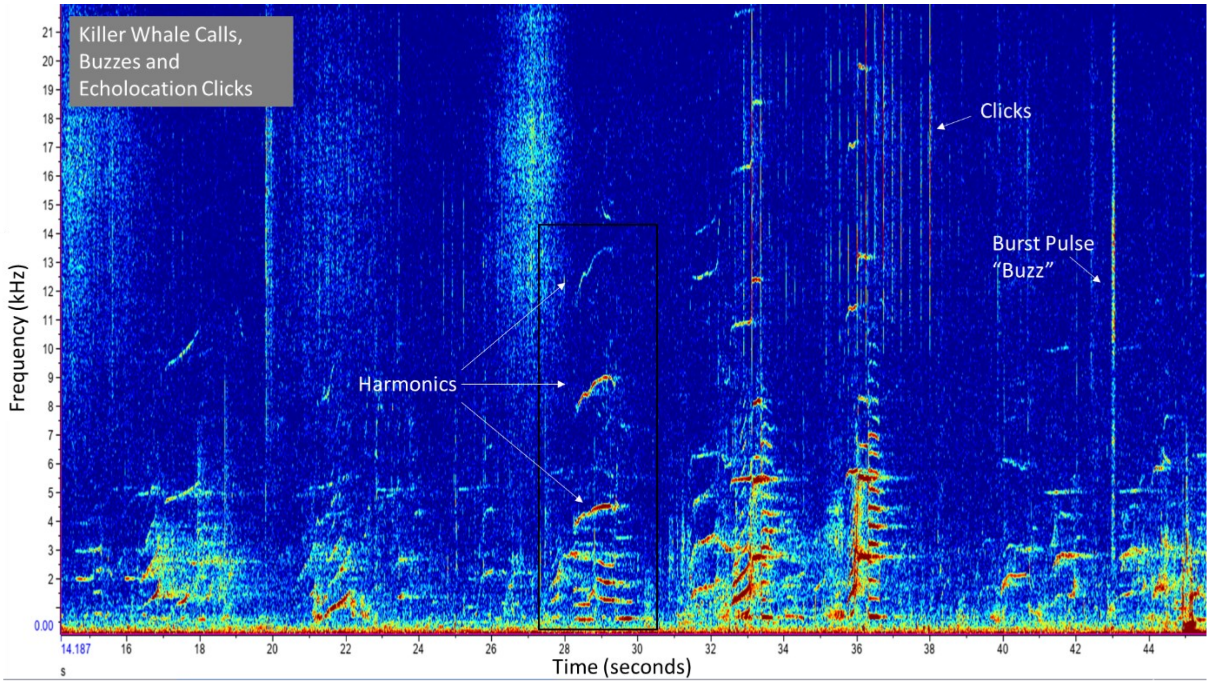

Figure 1. Spectrogram of killer whale pulsed calls, burst pulse sounds, and echolocation 'clicks' with examples of harmonic contours in red or yellow.

A spectrogram shows the harmonic features of a tonal sound and their changes over time. A spectrogram is created by computing Fast Fourier transforms (FFTs) over succussive frames of signal audio. FFTs retrieve the underlying sine waves that compose a complex sound wave. Because of the distinct harmonics of a discrete signal such as a tone, a whistle, a call, or a syllable in a spoken word, which results from the overlay of sound waves with the same frequency, the spectrogram depicts the harmonic structure of that sound. A spectrogram is sometimes called a voiceprint of a sound because recurring harmonic patterns show up as distinct and recognizable horizontal contours in a spectrogram. This allows a human to identify a specific sound visually and is also the basis for the ability of a computer algorithm to recognize specific contour patterns that could be whale calls based on spectrographic analysis (e.g. Gillespie at al. 2013). The spectrographic method works well for the recognition of tonal signals, for which it was designed, but is less accurate in distinguishing pulsating sounds that do not produce clear harmonics (e.g. burst-pulses and buzzes etc.). These sounds, however, are used by odontocetes and are a common features in dolphin vocalizations (e.g. Martin et al. 2019). The recognition method requires the contour to have a certain amplitude above the background noise (with the detection threshold usually greater than 5dB) and tends to work better when the detection threshold exceeds 10 dB (Gillespie at al. 2013).

In its simplest form an automated spectrogram-based detector detects all tonal signals in a spectrum that exceed the predefined energy detection threshold. More sophisticated detectors such as the time-frequency detector matches contour attributes of signals with contours of identified stereotyped calls or recognized signals by connecting detected contour fragments to create contours. These detectors are meant to be capable of making a distinction between contours coming from a whale or a different sound source such as a tonal noise from ship propeller. A cross-correlation based detector directly compares the contour shape of signals with a library of contours of human classified calls, often allowing for signal manipulation to account for individual differences in call production. These types of detectors can be considered detector-classifier systems. A general limitation of all detectors is the likelihood of a false detection (or false alarm), which increases as the energy detection threshold is lowered while missed detections increase when the detection threshold is set higher. The performance of a detector classifier system is typically evaluated by comparing the false alarm rate (False Positives) with the true alarm rate (True Positives) while also considering the rates of correctly missed detections (True Negatives) and incorrectly missed detection (False Negatives) (Hildebrand et al. 2022).

The goal of reducing the number of false detections has led to the development of machine learning algorithms for detection and classification, which will make statistical assumptions (probability assessments) about the source of the detected contours or contour fragments based on previous training of the algorithm to distinguish between contours or connected contour fragments that are associated with whale calls or acoustic features of whale calls (Usman et al. 2020).

In recent years artificial neural networks (ANNs) that are capable of independent learning have been successfully trained to distinguish contours of different whales either through supervised learning (where a human annotator provides feedback to the AI network on which specific contours are whale calls) or unsupervised learning where the algorithm only gets feedback on whether they have classified a call correctly or not (Roch et al. 2013, Usman et al. 2020, Rasmussen and Sirovich 2021). These AI classifiers appear to work reasonably well when the signal-to-noise ratio allows identification of harmonics in the spectrogram but do not necessarily allow the user to determine what features are responsible for the classification of a contour as a whale call contour. This makes it difficult to apply a trained algorithm that works in one area to another novel acoustic environment, even if the same species are present. Different noise conditions and different compositions of species change the signal-to-noise ratios and add distractors (contour fragments of calls from other species overlapping with the contours of the target species). This makes it necessary to retrain the algorithm for the new location. Deep learning algorithms are able to take learned decision processes and adapt them to new environments, a process called transfer learning. However, in practice it appears that none of the algorithms can produce 100% precision rates without setting the detection threshold at levels that will cause calls to be missed (Usman et al. 2020). The trade-off between detection threshold settings, missed call rate and false detection rate is different based on the goal of the automated detection usage. If correct presence of whale calls is necessary for the usage goal, the threshold should be set low enough to achieve high rates of detection (recall rate), which also will lead to high false positive rates.

Non-deep learning automated detector classifiers (DC) typically consist of a two step process. The first step is the recognition and/or extraction of sound features that are considered potential whale call candidates (Detection or D step) based on a predefined set of acoustic parameters, while the second step is the classification of features as whale calls of a particular species (Classification or C step). In this two-step process, only the second step requires the computer algorithm to learn patterns (see review of detection and classification methods in Usman et al. 2020). This process can be more easily applied to different acoustic environments because the learning is based on specific acoustic features, but may not have the same precision as a well-trained independently-learning AI-based classifier that makes internal neural network-based decisions during the detection and classification process.

The training process for either one of the machine learning computer algorithms requires annotating many calls of a species, population, or pod of whales by a human expert analyst that is familiar with the calls of a particular whale species, population, or pod/grouping. This expert will create labels for categorizing the calls, which the algorithm uses to train itself. This process often requires long periods of training to achieve high levels of precision (P), i.e., to reduce the number of false detections (False Positives or FP). In order to achieve high P and low FP rates it may still require human listeners that are verifying automatically classified calls. Despite this limitation, automated signal detection is needed if PAM data is used for NRT detection of whale calls. A reasonable detector-classifier performance is subject to interpretation and depends on the use of the detections in a specific application and the acceptable level of false and missed detections for the application of the DC results.

Due to occasional high variation in sound propagation and noise conditions, DC results vary in their degree of certainty of true whale call detections due to missing detections even when recordings from the same location are made only short time periods apart, such as hours or days. This is a limitation of the applicability of near-real-time acoustic detections as ship- or hazard-warning alert tools. Depending on which rate of false detections or missed detections is acceptable for the intended use, human verification of the automated detections may be a necessary step before an alert can be issued. The time that is required for human verification needs to be considered when using PAM as an alert tool.

DFO’s Whale Tracking Network (WTN) of Shore-Cabled PAM Systems

In 2015, sixteen potential recording sites were identified for WTN in the southern Salish Sea. In August of 2017, the network, initially deployed by OceanSonics (OceanSonics Ltd. WTN final report June 2017), consisted of a network of nine PAM stations located in the inland waters around the southern Gulf Islands and the south-west coast of Vancouver Island, which are part of the critical habitat of SRKW in the Salish Sea (Figure 2). The aim of the network was to detect SRKW presence and track their movements. Information would then be used to warn about potential threats to the whales, such as the possibility of physical disturbance from whale-vessel interactions and potential vessel strikes, as well as alerts of the approach of whales to areas with high risk of injury such as an oil spill area.

Each of the stations contains 1-4 acoustic sensors (HF-IcListen digital hydrophones, OceanSonics) configured either as single mounts or in a tetrahedral array design. This created a network of 28 sensors/hydrophones recording continuously. The sensors were connected to shore via an underwater ethernet cable to allow streaming of acoustic data as PCM wave files. Acoustic data were then transmitted via wi-fi to the nearest internet interface and from there to a central monitoring station. The number of operational stations in 2022 maybe higher and may include stations in other areas of the Salish Sea. However, the actual number of operational PAM stations was not known at the time this report was written and likely fluctuates and information of up-to-date operational stations varies.

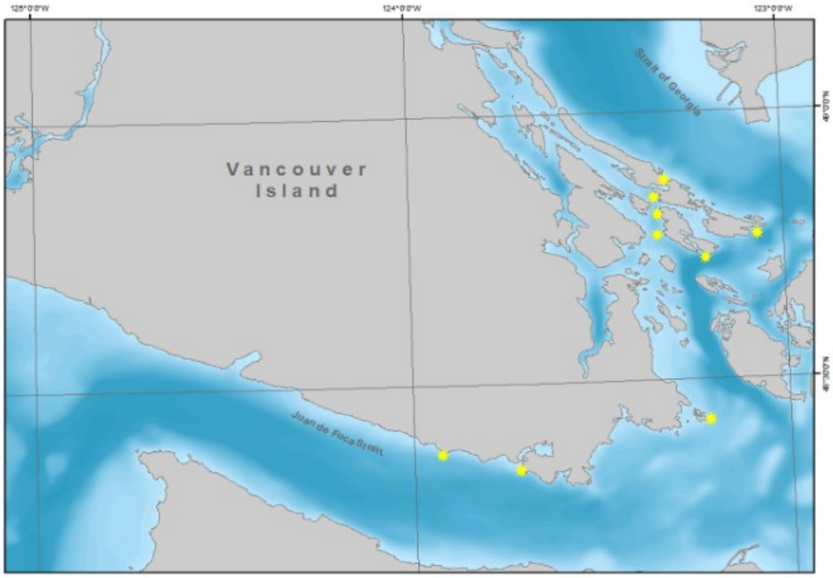

Figure 2. Nine PAM stations originally deployed by OceanSonics between 2015 and 2017 (yellow circles).

Objectives of Study

This report evaluates the effectiveness of shore-cabled PAM systems in detecting and tracking killer whales in NRT. The evaluation will focus on possible automated detectability of calls at PAM locations of DFO’s WTN network for which archival acoustic data were available and the ability to track whales via a PAM network. The study target was the ability to track animal movements between stations considering influences on detectability (range and performance of detectors) due to variations in signal propagation between signaller and receiver locations, ambient noise at receiver locations, underwater topography, vessel movements in relation to caller movements and potential differences in acoustic behaviour of the whales. The effectiveness in reducing the risk of physical disturbances, specifically vessel strikes on SRKW will be discussed and recommendations will be given as to how and where shore-cabled PAM systems can be used effectively and how they can be integrated into a multimodal SRKW tracking and forecasting systems.

METHODS

For this technical evaluation, five WTN-PAM locations (Figure 3: four of the original locations deployed by OceanSonics and one location at East Point that was added by DFO later) were selected because archival acoustic data from these locations was available, they represent different acoustic environments due to vessel presence, there is more reliable whale presence (and thus vocalizations to detect) in these areas (Thornton et al. 2022a), and because of their potential usefulness in providing information to issue alerts for commercial and recreational vessel traffic.

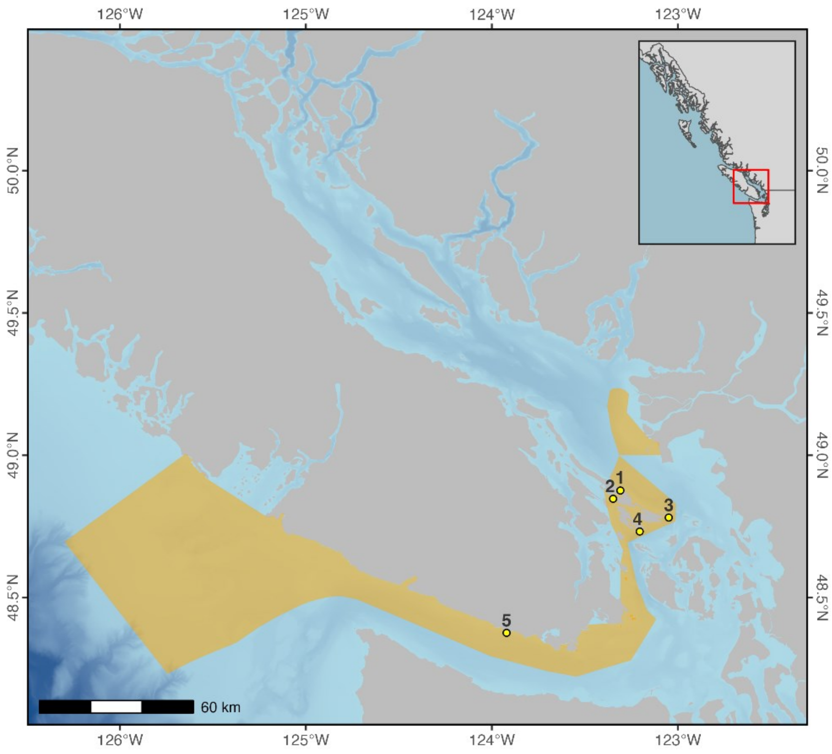

Figure 3. Five PAM stations were evaluated: 1. Sturdies Bay, 2. Enterprise Reef, 3. East Point, 4. Tilly Point, 5. Sheringham Point. The shaded area depicts the designated critical habitat of SRKW in Canadian waters.

The single mounted hydrophones and the tetrahedral array were originally deployed by OceanSonics between 2016 and 2017 at distances of less than 100 m from shore. The single mounted hydrophone at East Point was deployed by DFO a year later but the station may be currently not in operation. The Saturna Island Marine Research & Education Society (SIMRES), however, is operating a PAM station near the East Point WTN station. All hydrophones were bottom mounted at depths of less than 20 m (Table 1).

Table 1. Locations of the five evaluated (WTN) PAM stations. The number of sensors and design of the sensor constellation, the original date of deployment, depths of sensors and distance from transmitter is also given. (Information retrieved from final deployment report completed by OceanSonics in June 2017).

Recorder Position	Location (latitude, longitude)	Number of hydrophones	Original Deployment date	Water depth (m)	Distance from transmitter/ shore (m)
Sturdies Bay	48.87654N, -123.3147W	Likely 1 - single mounted	March 2-3, 2016	<20	<100
Enterprise Reef	48.84458N, -123.3482W	4-tetrahedral array	March 2-3, 2016	10	50 (navigational light platform)
Tilly Point	48.73161N, -123.2050W	3-single mounted	March 2-3, 2016	10-20	<100
East Point	Unknown	Likely 1-single mounted	n/a	18-20	< 25
Sheringham Point	48.37639N, -123.9211W	2 – single mounted	May 16-18, 2017	10-20	<100

The nominal hydrophone sensitivity was around -169 dBV re µPa at the time of deployment. Together with the self noise floor which is around 70 dB re 1µPa/Hz the IcListen HF hydrophone can detect and record sounds appropriately ranging in amplitudes from 70 to 169 dB re 1µPa. This metric is important to determine the relative dynamic range of signals that can be detected above background noise.

Based on information provided by OceanSonics, the hydrophone sensitivity of WTN sensors at frequencies of 10 Hz to 200 kHz fluctuates by +/- 3dB (details may vary for each sensor and can be provided by OceanSonics). The overall sensitivity decreases with length of usage, i.e. sensitivity decay can occur over the course of months/years depending on oceanographic and acoustic conditions at the deployment location. Information on calibration of sensors was not available. Sensitivity needs to be assessed regularly if recorded data are used to assess ambient sound levels or when signal detection ranges are estimated. Information on the tested sensitivity of the deployed IcListen hydrophones was unavailable and therefore nominal sensitivity of the sensors at the time of deployment was used for the detection range modeling. Furthermore, information on the operational sampling rate of each sensor/recorder at the five PAM stations which determine the frequency range of the recorded signals was also not available. The IcListen sensors can sample at rates of 16, 32, 64, 128, 256, and 512 kilocycles per second (kcps), which corresponds to recordable sound frequency maxima of 8, 16, 32, 64, 128, and 200 kHz. The sampling rate of the recordings used assessing the performance of the automated DC system was 32 kcps (10 Hz to 16 kHz sound frequency).

All of the IcListen hydrophones were operated in ‘tethered mode’ which means data were not stored on the instrument but were continuously streamed from each sensor to a shore/transmitter-based host station. The data received at the host station was transmitted to a central server via internet (one known internet access point is at the Coast Guard tower on Mount Parke - Mayne Island). Data were accessed through a virtual personal network (VPN) at a DFO operated central monitoring station on Annacis Island in Delta, British Columbia. Initially, data processing such as acoustic data file creation and data archiving as one-minute audio files (PCM-WAV format) may have taken place at the shore stations. This was achieved through the Lucy software provided by Ocean Sonics. Automated whale detection algorithms may have been operating at the shore stations, but more likely at the central monitoring station. Initial verification of detections may also have taken place at the central monitoring station. Details about the procedure were not available at the time this report was written. A whale acoustics expert who had remote access to the data stream intermittently undertook verifications as to whether killer whale calls were detected and which ecotype/population was present (J. Ford, Pers. Comm.).

At the time of this report, further PAM locations exist but the operational status of these WTN sites varies and the report is based on a sample network of stations for which archived acoustic data were available.

Several of the evaluated PAM stations are located in narrow waterways with significant ferry and commercial vessel traffic (Figure 4). Active Pass is a narrow waterway connecting the Strait of Georgia representing the eastern sections of the Salish Sea with Swanson Channel which is a common travel route for SRKW travelling from Haro Strait in the south to the Strait of Georgia. Active Pass had been deemed an area with potentially high ship strike risk in the initial planning phase of WDCA. No direct evidence of a ship strike has been observed in Active Pass but we have observed physical disturbance of whales including SRKW in the Pass (Quayle et al. in prep). Aside from significant ferry use the Pass is also used by tugs and barges, fishing vessels, commercial whale watch vessels and recreational boats.

Ferries are also the dominant source of commercial vessel traffic near the Enterprise Reef station, as well as fishing vessels and smaller cargo vessels. A few large commercial vessels also pass by the Reef. Larger commercial vessels such as bulk carriers, container ships, tankers and passenger vessels are predominantly travelling in the Boundary Pass shipping lane passing the two PAM stations at Tilly and East Point. The PAM station at Sheringham Point is away from direct commercial vessel traffic (~ 5 km from the outbound international shipping lane) and was chosen because SRKWs tend to travel close to shore during transit in Juan de Fuca Strait. Recreational and fishing vessel traffic is present at all PAM stations, but is the main source of vessel traffic near Sheringham Point (Figure 4).

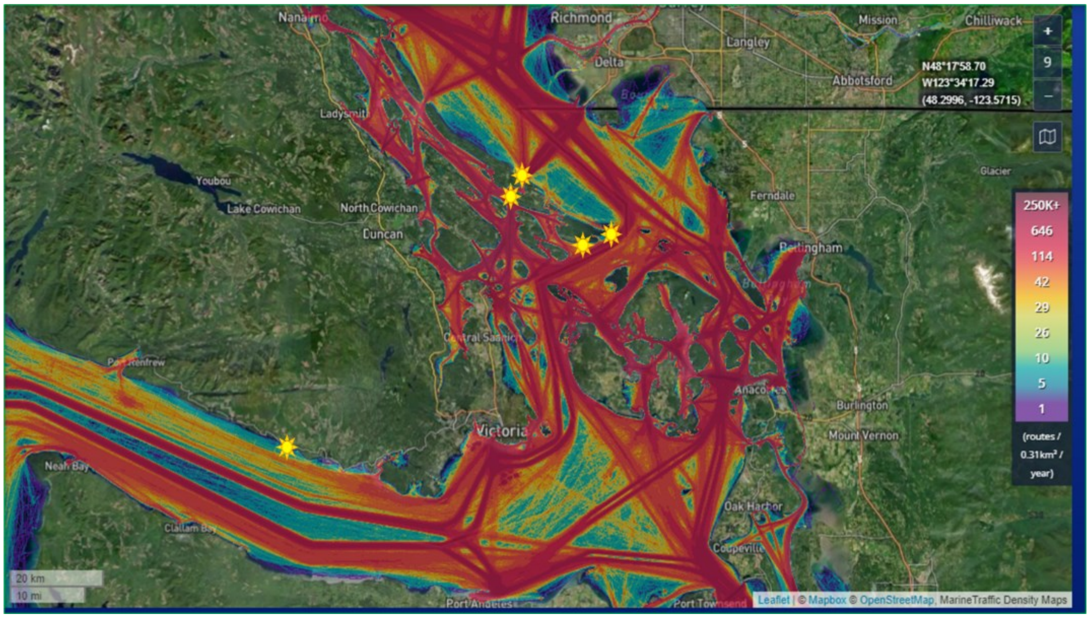

Figure 4. AIS-based density of commercial shipping traffic in parts of the Salish Sea in 2021 (downloaded from MarineTraffic.com). Evaluated PAM nodes part of the WTN are demarcated as yellow stars.

Ferries and large commercial vessels travelling within defined shipping lanes are responsible for the majority of the displayed vessel densities in Figure 4, while smaller recreational and commercial vessels, such as sport fishing vessels, are not depicted due to a lack of AIS transponders (which are only required on vessels certified to carry more than 12 passengers or vessels > 8 m and carrying passengers).

The effectiveness of the PAM stations as acoustic detection and tracking tools for killer whales including SRKW was evaluated based on:

- How far one can detect killer whale (SRKW) calls automatically from each of the PAM stations and by how much the detection range varies over time/between seasons;
- How well can SRKW be tracked via the simulated WTN network to activate an alert in a timely fashion;
- Which other factors influence automated detectability of killer whales and how the detection and tracking verification process will influence activation of a timely alert.

Modelling Call Detection Ranges at the Five (WTN) PAM Stations

In order to determine the distance over which a killer whale call can be reliably detected by an automated detection system, an understanding of call propagation is needed. Because of the multiple variables influencing signal propagation, an empiric assessment would require integrated monitoring of variables over many years at each PAM site. Instead, a modelling approach was used to estimate this detection range variation.

JASCO Applied Sciences was tasked with modelling detection ranges at the five PAM locations (Figure 4) (Mouy et al. 2020). The detection range variations at these locations were estimated using a specialized acoustic propagation model developed by JASCO Applied Sciences that used the estimated source level and depth of the caller, and associated modeled sound propagation loss (Figure 5) as stochastic input variables, while ambient noise levels were considered dependent variables based on environment conditions at that location and the time of year for fixed receiver locations.

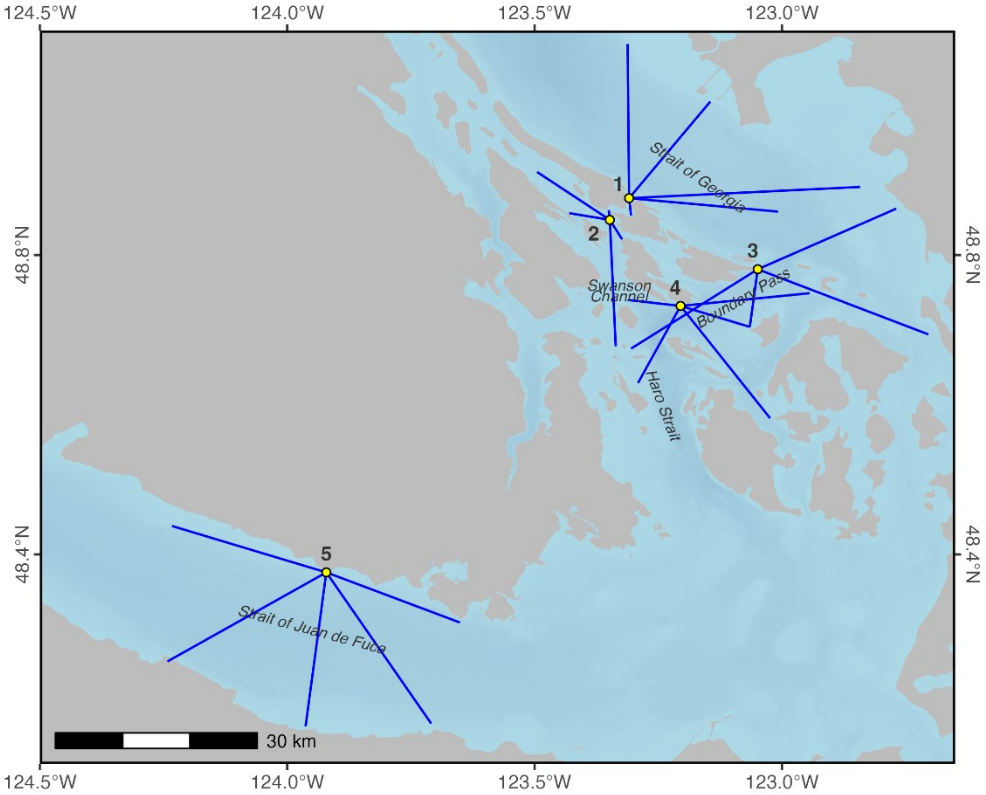

Figure 5. Modelled propagation loss transects at 5 PAM locations: 1. Sturdies Bay, 2. Enterprise Reef, 3. East Point, 4. Tilly Point and 5. Sheringham Point.

A Monte Carlo simulation was used to account for the measured variability in source levels and animal depths. Detection ranges were calculated 10,000 times for noise levels in each of the 300 Hz bands available by randomly choosing 100 normally distributed source level values, with their means and standard deviations, and 100 animal depths from a log-logistic distribution based on published animal tagging data (Wright et al. 2017). Each iteration of the Monte Carlo process provided a probability of detection at each range from the PAM station. The distribution of the 10,000 detection probabilities obtained at the end of the Monte Carlo simulation are represented for each range by the percentiles 25, 50, and 75.

The detection range variation was estimated by calculating the distance from an acoustic recorder where the received sound level of a call (RL) was higher than the detection threshold (DT) of an automated detector set to 5 dB above the ambient noise level (NL) in the same frequency band. DT was set to 5 dB for this analysis, as automated detectors typically perform well above that SNR (Mouy et al. 2012). RL is a function of call source level (SL) minus propagation or transmission loss between source and receiver (TL).

This relationship is described by this equation:

$$RL = SL - TL \quad (1),$$

where, SL is the source level in dB re 1 µPa at 1 m and TL is the transmission loss in dB re 1 m

The maximum distance at which a call can be received by an automated detector at a specific frequency using a 5 dB detection threshold[1] is given by the following formula:

$$RL(f) \geq NL(f) + DT \quad (2).$$

At a given source depth, the detection range (R) was estimated separately for each 300 Hz frequency band between 1000 and 7900 Hz (23 frequency bands total) and was calculated as:

$$R(f) = 10\hat{}((SL(f) - NL(f) - DT)/(TL(f))) \quad (3).$$

The 300 Hz frequency bandwidth was selected based on the assumption that this is the smallest bandwidth necessary for an automated detector to detect killer whale pulsed calls.

The final detection range was then defined as:

$Rmax$= arg$maxf$ $(R(f))$ (4).

---

[1] detection threshold used by JASCO strictly represented the signal processing detection threshold for an automated detector and is not related to the listening detection threshold of the animals or a human listener.

Detection ranges for each minute of the ambient noise data from recordings made with the PAM stations or autonomous acoustic recorders were calculated. The probability of detecting a killer whale call at a given range was then taken to be the number of 1-minute recordings with a detection range equal to or greater than that range divided by the total number of 1-minute recordings. This provided an estimate of the minimum probability of detecting a whale at that range.

Caller Depth Location Estimates

The depth at which an animal vocalizes greatly impacts how far from the hydrophone its call can be detected. As input in the detection range model, 100 source depths were randomly selected from a distribution representing the typical depth distribution of SRKW. The depth distribution was modelled using tag data collected by DFO's Cetacean Research Program (Brianna Wright, unpublished data).

A log-logistic model, $f(z|\mu,\sigma)$, was fitted to the tag data using Maximum Likelihood:

$f(z|\mu,\sigma)= ey\sigma z(1+ey)2$ (5),

where y= log(z)−$\mu\sigma$, z is the animal's depth (z≥0), μ= 2.0212, and σ=0.7739. Because the WTN hydrophones are located in water depths less than 200m, the log-logistic model was created using all the depths from the tag data that are less than 200m. Figure 6 shows the probability distribution of the empirical data collected by the tag (n = 2,215,700) and the probability distribution of 2,215,700 depth samples randomly drawn from the log-logistic model.

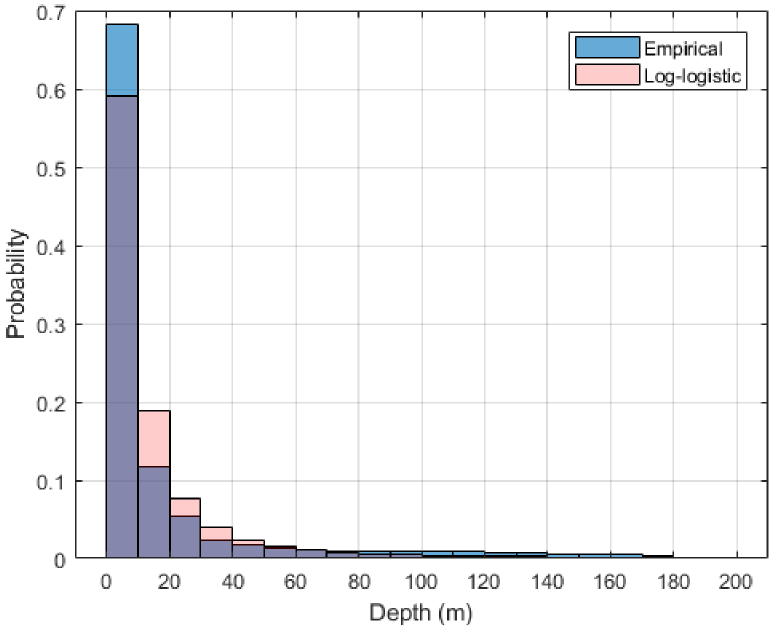

Figure 6. Dive depth probability distribution and distribution of samples drawn from the log-logistic model. (Mouy et al. 2020)

Call Source Level Estimation

Killer whales produce three primary types of sounds: echolocation ‘clicks’, narrow-band whistles, and broadband pulsed calls, which are also sometimes called ‘moans’ due to their harmonic frequency structure (Table 2). Clicks are short pulses that usually occur in a series called ‘trains’. A ‘click’ duration ranges from 0.1 to 25 ms (Ford 1989) and shows distinct energy peaks (Au et al. 2004, Leu et al. 2022). Whistles are single narrow-band tones in the 1.5–18 kHz frequency band. They have little harmonic structure. Their duration ranges from 50 ms to 12 s (Ford 1989). Pulsed calls are harmonically structured, often consisting of multiple distinct spectral components with frequency ranges between 80 Hz to > 30 kHz (Holt 2008). While most calls have energy peaks below 10 kHz, call types containing high frequency components (HFCs, Figure 16) can have secondary energy peaks above 10 kHz and some show harmonic bands up to 30 kHz or higher (Holt et al. 2011). Pulsed calls were modelled in this analysis because they appear to be the dominantly used vocalization travelling further that the other types. The broadband source levels of SRKW calls were reported by Holt et al. (2011) and cover stereotyped calls from three different pods.

Table 2. Broadband call source levels of Southern Resident Killer Whale calls.

Study area	Population	Call type	Source level in dB re 1 µPa (mean ± SD)	Reference
San Juan Islands, WA	Southern resident (J pod)	Stereotyped call S1	155.3 ± 7.4	Holt et al. (2009)
San Juan Islands, WA	Southern resident (J, K, and L pods)	Stereotyped calls	155.1 ± 6.5	Holt et al. (2011)

The energy distribution across frequencies of calls is an important parameter that can affect how far a call can be detected, because lower frequencies generally travel further than higher frequencies, but are also more likely be masked by ambient noise. Unfortunately, only broadband source levels of calls have been published (Table 2). To address this, the source level distribution of 84 SRKW pulsed calls with very high signal to noise ratios (SNR) were used. Thirty-five of those were recorded by DFO Pacific Region’s Cetacean Research Program during field sessions when the whales were in close proximity to the hydrophone and ambient noise was low (DFO unpublished data) and 49 calls were retrieved from Dtag recordings (Dtags were attached to individual whales with suction cups and recorded sound and movements of the whales) obtained by the DFO Pacific Region’s Marine Mammal Physiology Program (DFO unpublished data). Each of the calls was assessed for their source level variation across frequency range. The SRKW call data set contained at least 10 different discrete call types from a repertoire of approximately 25 call types in use by SRKW (Holt et al. 2011). Not all call types are used with the same occurrence frequency (Ford 1989, Foote et al. 2008). The data set used here was representative of the more commonly used call types of at least two of the three SRKW pods (J and L), and it was assumed that the distribution of source levels was representative of the distribution of source levels of the whole repertoire of these pods. K-pod calls may have been underrepresented in the sample.

JASCO developed a MATLAB script to calculate the sound pressure level (SPL) in each 300 Hz frequency band, and the relative source level distributions of the 84 selected pulsed calls from the provided acoustic recordings were plotted in a diagram. A linear fit to the frequency distribution was performed (least squares fit between 1,000 and 14,800 Hz) to model the median slope of the sound pressure levels (SPL) across frequencies (Figure 7). The slope of the fitted line was -0.70 per 300 Hz band. Source levels used in the Monte Carlo process that selected source levels randomly in the detection range model were all represented with this frequency distribution. The median distribution was used as a conservative measurement of call source level in 300 Hz bands to estimate the automated detectability of a call due to propagation loss.

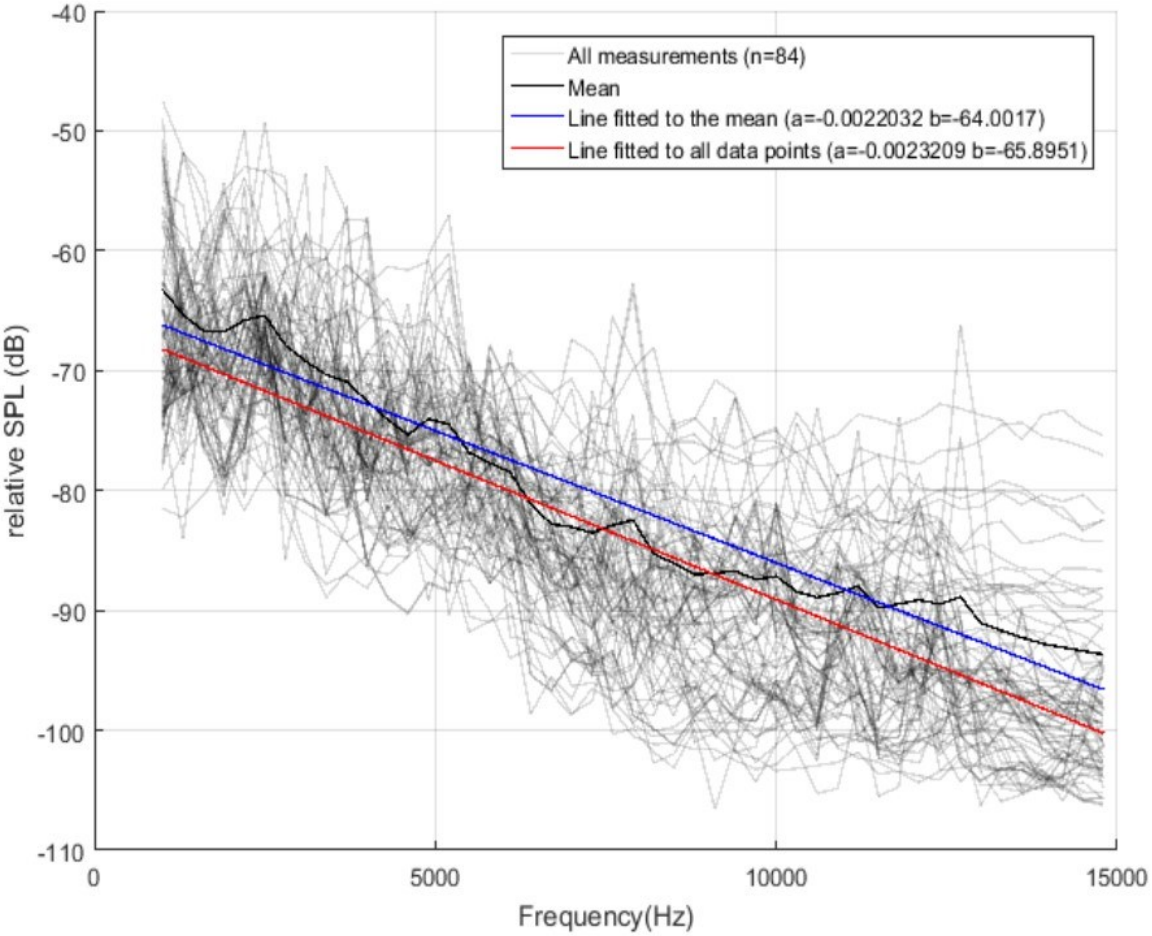

Figure 7. Call source level distribution, in 300 Hz bands, of all 84 selected Southern Resident Killer Whale (SRKW) pulsed calls. The red line indicates the linear fit of the distribution that was used in the random selection process of the detection range Monte Carlo process (from Mouy et al. 2020).

Propagation Loss Modelling

JASCO modelled propagation loss (PL) for each of the five detection range (DR) model sites along four to six transects in different directions (Figure 5 and 8), to sample the propagation loss characteristics as a function of range and azimuth from each hydrophone. The PL model inputs were the source location and depth, a geo-acoustic profile of the sediment properties, an average sound speed profile for the water column representing one summer months (July) and one winter month (January) , and a profile of the bathymetry along the modelled transects. The model also accounts for absorption, which can be important at the frequencies considered in this study. Calculations were computed at three frequencies within each 300 Hz band and averaged to provide a PL estimate for each frequency band.

All resulting propagation loss values were plotted as a function of range, and the data were fit with an equation of the form:

$$\mathrm{PL}(f,z)=A(f,z)-n(f,z)logR \text{ , (6)}$$

for frequency (f) in Hertz, depth (z) in meters, and range (R) in meters. The resulting PL values were used in the Monte Carlo simulation for the corresponding depths and frequency bands. Examples of the variation in propagation loss based on the modeling are shown in Figure 8 for three sites.

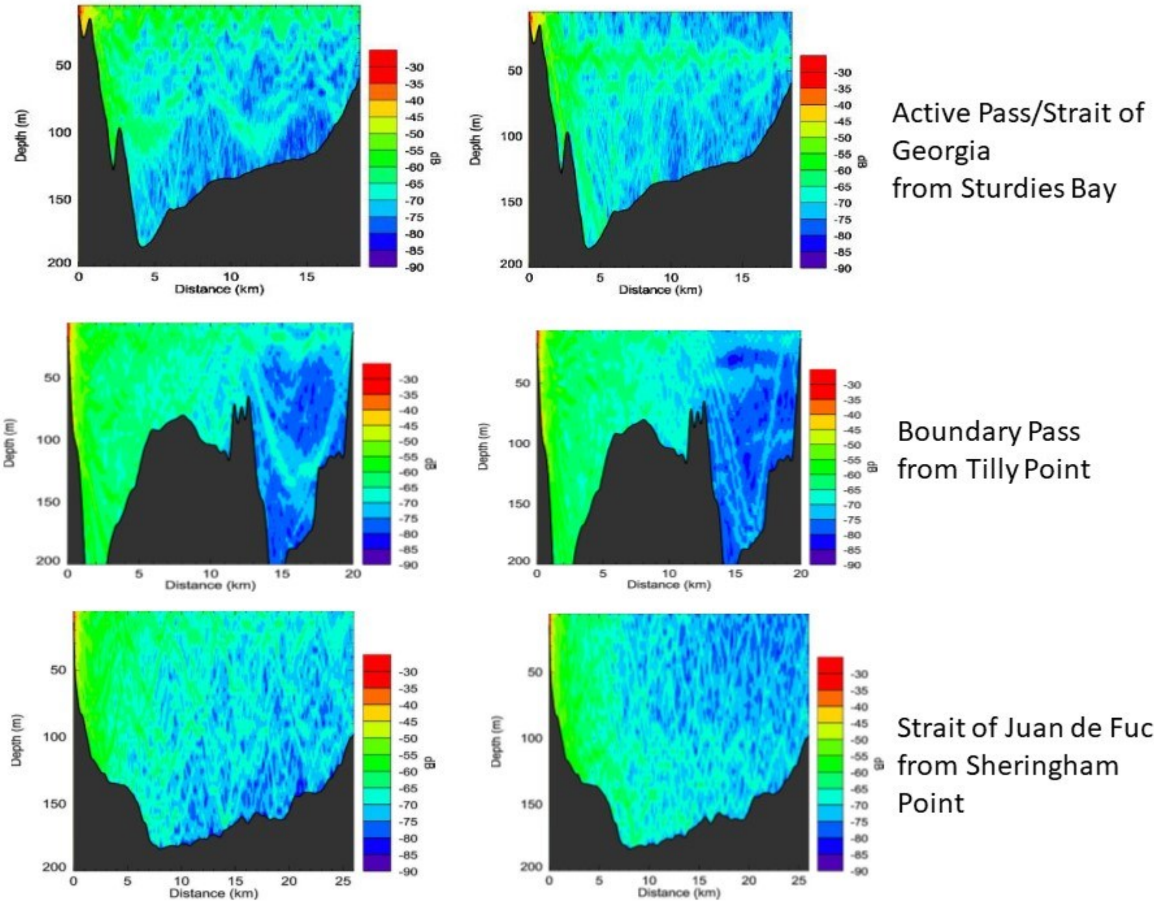

Figure 8. Example diagrams of modelled propagation loss (PL) along specific radials in **winter** (left column) and **summer** (right column) (Mouy et al. 2020). PL levels are colour-coded and the receiver locations (PAM stations) are in the upper left corner of each diagram.

PL is reciprocal, meaning the loss is the same in each direction, e.g., a sound produced at a distance of 10 km and depth of 100m east of Sturdies Bay has lost about 70 dB in source level during the winter and about 60 dB in the summer when arriving at the PAM station

Background (Ambient) Noise Level Assessment

JASCO calculated background noise levels (realistic ambient noise levels containing natural and anthropogenic sound sources) using available recordings from the PAM stations at Sturdies Bay, Enterprise Reef, Tilly Point and Sheringham Point. To assess levels at East Point, recordings made with an Autonomous Multichannel Acoustic Recorder (AMAR – JASCO Applied Sciences) in proximity to the WTN recorder location were analyzed. The East Point winter data were used with permission from the Vancouver Fraser Port Authority and Transport Canada.

JASCO used their proprietary PAMlab software to process background noise data. The raw pressure waveform data were scaled according to the mean pressure sensitivity of the recorder and adjusted for the frequency response of the hydrophone sensor. Sound pressure fluctuations over time were analyzed to determine the sound pressure level (SPL) for each minute of data. SPL was averaged over each measured time period. In order to assess if the average was influenced by the length of the measured time period, Austin and Wladichuk (2021) compared the averages of two time periods (30 seconds and 60 seconds) and found no significant difference between the averages. Average pressure levels were integrated for each 300 Hz frequency band between 1000 and 14800 Hz (46 frequency bands total). The 300 Hz frequency bandwidth was selected, as it was assumed to be the smallest bandwidth necessary for an automated detector to detect killer whale calls. The frequency boundaries between 1000 and 14800 Hz were chosen to cover the frequencies of killer whale pulsed calls containing the majority of acoustic energy (Ford 1991). Background noise was calculated for one representative winter month (January) and one representative summer month (July) (Figure 9).

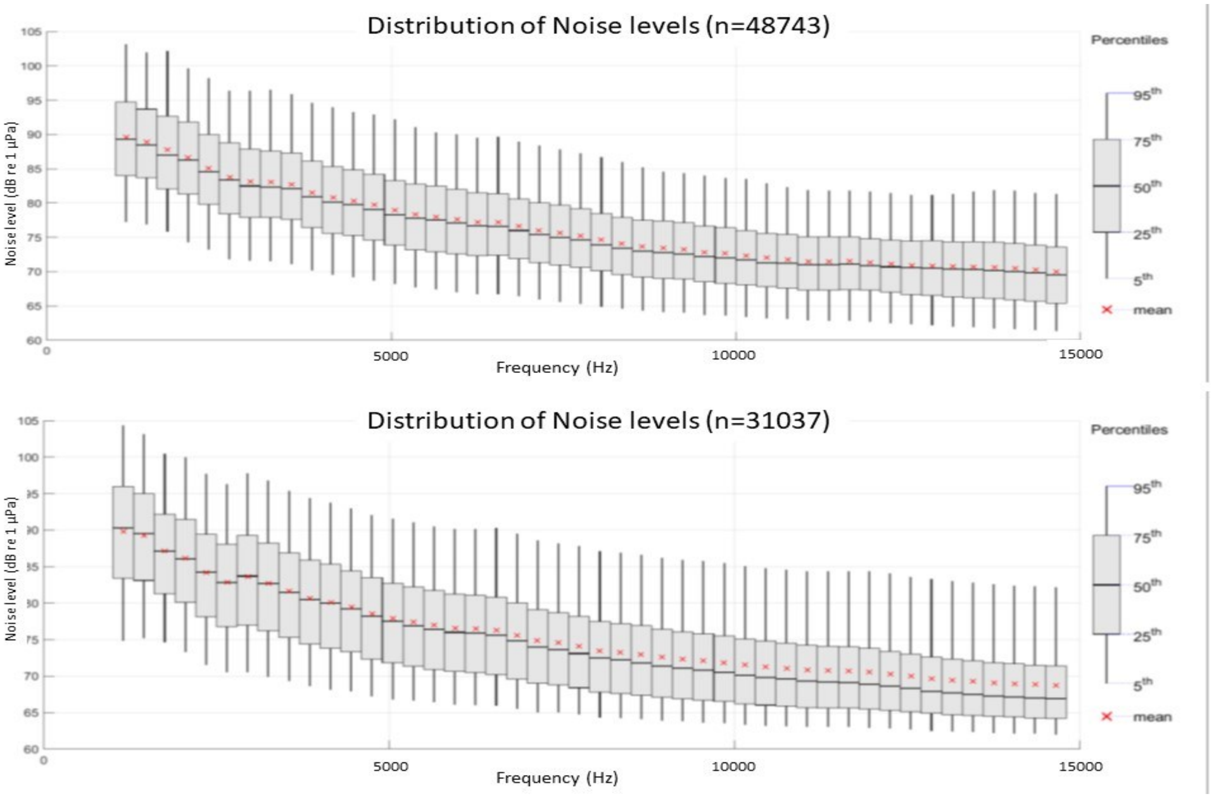

Figure 9. Percentile distribution of background sound levels (in 300 Hz bands) from the data samples recorded at Tilly Point in January (top) and July (bottom), as a function of frequency. The horizantal line in the boxplot depicts the median level.

Evaluating Automated Detectability of Killer Whale Calls via the simulated PAM network

The specific design of the automated detector-classifier (DC) currently in use with some of the PAM data was developed by Google Inc. to detect killer whale calls. The AI classifier was proprietary and was not available for review. The deep (machine) learning algorithm DC system used by Google is based on an artificial intelligence (AI) concept. A similar DC system that will be freely available is currently in development with funding from DFO and an evaluation of that deep learning algorithm-based DC system will be presented elsewhere.

PAMLab Detector-Classifier system

One detector-classifier (DC) system was evaluated specifically using available WTN acoustic data from 2017-18. The PAMLab DC system developed by JASCO Applied Sciences is currently implemented as a detection tool in a PAM system deployed in Boundary Pass, a project funded by Transport Canada and operated by JASCO Applied Sciences. PAMLab was chosen because it was the DC system underlying the results of the detection range modelling.

PAMLab is a two-step process. The first step is the signal detection process, which is similar in other detector systems such as PAMGuard's Whistle and Moan Detector. For killer whale calls, PAMLab normalizes the spectrogram of an acoustic recording from 50 Hz to 15 kHz using a split-window normalizer to attenuate long tones generated by vessels, and to increase the signal-to-noise ratio of acoustic transients. The set frequency range differs depending on the predominant frequency of the calls/species that needs to be detected. In comparison to continuous background noise, animal signals are short increases of acoustic energy that fall into the category of acoustic transients (not to be confused with the historical name of one of the killer whale populations in the North Pacific that are now called Bigg's whales).

For the detector to be able to recognize a call candidate (transient energy peak), the tonal signal needs to exceed an energy detection threshold (in dB), which can be set manually. Low numerical detection threshold settings allow the automated detector to detect more signals in the data stream while higher detection threshold settings reduce the likelihood of false detections. In turn a higher detection threshold setting increases the precision of detections, but also potentially leads to missed detections. Typically, detectors have several integrated signal processing features in their acoustic analyses software that are meant to increase the ability to detect transient tonal signals while decreasing the influence of noise. Two methods that increase precision are spectral noise suppression, which normalizes the energy in a spectrogram by subtracting the background noise and signal processing gain enhancement, which enhances the signal-to-noise ratio in the spectrogram, i.e. the call candidate becomes more visible relative to the background noise. However, unless the target signal can be enhanced by applying processing gains to the frequency bands in which the signal is located but not to all of the frequency bands in the spectrogram, which is only possible for narrow band signals, the processing gain will also enhance transient noise signals, such as vessel cavitation signals. Killer whale calls are broadband amplitude-modulated tonal sounds, which means call energy is widely distributed across the whole frequency range that the detector monitor for transients. No signal processing gain was applied here as it did not appear to increase the functionality of the PAMLab DC performance (Mouy et al. 2012). Next, the detector removed all 'click' vocalizations from the spectrogram to avoid interference of 'clicks' with the identification of segments that may hold calls. Then the spectrogram was segmented by calculating the local variance of energy values on a 2-dimensional kernel with a size of 0.1 s × 100 Hz. Transients are defined by areas of the spectrogram with a local variance greater than an empirically defined energy or sound pressure threshold. A set of 40 acoustic features are extracted from each detected transient in the spectrogram. The main extracted features are the median sound frequency of a call, the sound frequency range and time concentration, an amplitude and frequency modulation index, and the inter-quartile range of the time and frequency envelopes (Figure 10). The number of extracted features differed among detectors for different species.

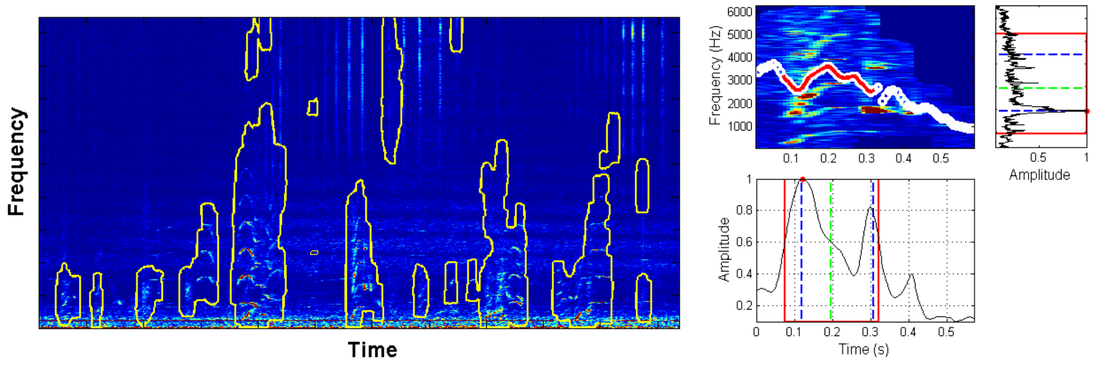

Figure 10. The PAMLab spectrogram segmentation procedure to identify acoustic transients (left) and the feature extraction process (right). (Reproduced with permission from Xavier Mouy who presented the figures at a symposium.)

During the classification process, each set of features was classified using a three-class random forest classifier to determine if the detection corresponded to a killer whale call, a humpback whale call, or to noise.

> "*A random forest classifier creates a set of decision trees from randomly selected subset of training set. It then aggregates the votes from different decision trees to decide the final class of the test object*."[2]

Random forest classifiers effectively use a "forest" of decision trees to classify input data. Accuracy can be inferred from the number of trees predicting each label. Random forest classifiers are some of the most widely used classification tools in machine learning (Liu et al. 2012). PAMLab uses a supervised machine learning algorithm involving several thousand manually annotated sounds from the three classes to build a training set. An example of the result of the workings of the classifier are depicted in Figure 11.

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[2] (*Chapter 5: Random Forest Classifier | by Savan Patel | Machine Learning 101 | Medium* downloaded on December 2, 2022

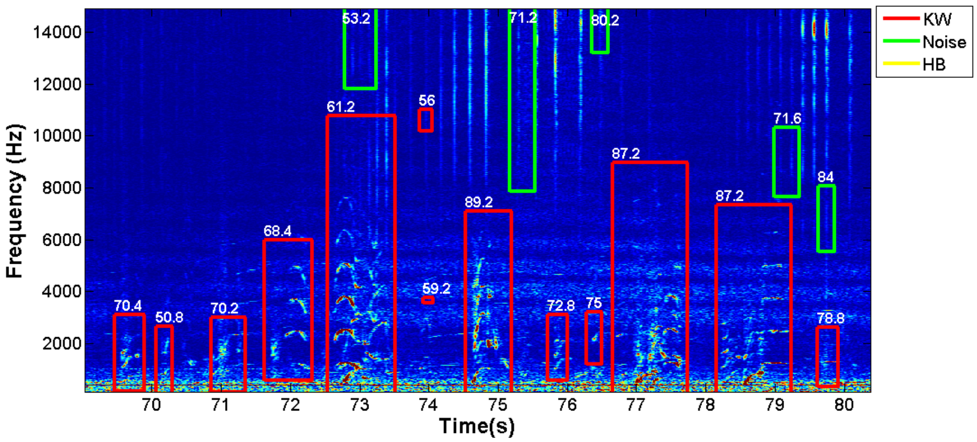


Figure 11. PAMLab Random Forest Classifier results from recordings made in the Strait of Georgia. While the spectrogram shows echolocation ‘clicks’, they are not taken into consideration by the classifier. (Reproduced with permission from Xavier Mouy who presented the figure at a symposium.)

A signal will be detected by a DC system at any detection threshold above 0dB. However, the recall and the precision of the PAMLab classifier, which determines if a detected signal is indeed a whale call, is affected by the detection threshold. A 5dB threshold showed similar recall rates for the PAMLab DC system and another detector applied to recordings with SRKW calls in noisy environments irrespective of the signal gain setting of the system (Mouy et al. 2012).

The PAMLab DC algorithms were applied to archival acoustic data recorded by WTN PAM. Spectrograms were created with a 2 Hz frequency resolution, and 0.2 second-long time windows overlapping by 0.15 s. These spectrograms were then normalized to identify segments holding acoustic transients that exceeded a 6 dB SNR. After feature extraction and random forest classifier application the positive detections were aggregated to give a value per 1-minute sound clip of the WTN recordings. The detections were also manually verified (described below). Archival WTN recordings from Sturdies Bay, Enterprise Reef, East Point and Tilly Point were analyzed using PAMLab detection algorithms.

Manual Analysis of WTN Acoustic Data

A systematic manual annotation analysis was performed on the available acoustic data for four of the WTN PAM sites (Table 3), which were also analyzed by the PAMLab DC system. The results of this analysis were compared to the results of the PAMLab classifications.

Table 3. Recording periods from four WTN Passive PAMstations

PAM Location	Recording Period	Proportion Manually Annotated (% time of recording period)
Sturdies Bay – Active Pass	28 Feb 2016 - 27 May 2016	12
Enterprise Reef – Swanson Channel	02 Mar 2016 – 19 May 2016	12
Tilly Point – Boundary Pass/West	20 Apr 2016 – 21 May 2016 & 02 Dec 2017 – 15 Dec 2017	5
East Point – Boundary Pass/East	16 Sep2016 – 25 Dec 2016	5

One-minute recordings were listened to by a human analyst, and spectrograms were visually inspected for the presence of whale calls. Spectrograms were generated with Raven Pro Interactive Sound Analysis Software (Cornell Lab of Ornithology, NY, USA) using a 256-point DFT in a Hann analysis window. Analysis windows were set to have 50% time overlap. These settings produced a 244 Hz frequency resolution. Presence of killer whale calls were noted for each 1-minute data file using a presence-absence paradigm. The number of discrete calls per file was not noted. Whistles and characteristic pulsed and tonal calls were used to denote killer whale presence. The presence of ‘clicks’ was also noted, but not used as a deciding factor for killer whale presence. The calls were not identified to eco-type or population level. The presence of vocalizations from other marine mammals were also noted, in particular those of humpback whales, as these can disrupt the accurate identification of killer whale calls. Other distractors such as mooring and vessel noise, were also noted during the manual analysis process.

Evaluation of DC Systems Performances

The evaluation of the PAMLab performance was assessed comparing the DC outputs with the manual annotations. For each of the 1-minute files annotated manually, the detector results were assigned one of the following results:

- a true positive detection (TP) was assigned when the automated detector indicated the presence of killer whale calls that were identified in the annotated set;
- a true negative detection (TN) was assigned when the automated detector did not report killer whale call presence and there were no killer whale calls in the annotated set;
- a false positive detection (FP) was assigned when the automated detector indicated presence killer whale calls and calls were not identified in the annotated set;

- a false negative detection (FN) was assigned when the automated detector did not indicate killer whale call presence but calls were identified in the annotated set.

The assigned values (#s of TP,TN, FP, and FN) for each selected annotated file were used as performance metrics indicating the detector's effectiveness in identifying killer whale calls. The metrics were used to calculate precision, recall, and accuracy of classifications in each of the analyzed 1-minute files.

The precision (P) of the DC system represents the fraction of correct positive detections/classifications (TPs) from all the combined true and false detections/classifications (TP and FP) made by the PAMLab DC system.

Precision (P) was calculated as (N is the number counted):

$$P = \frac{N(TP)}{(N(TP) + N(FP))}$$

The recall (R) of the DC system represents the fraction of correct positive detections/classifications (TPs) from the combined true detections/classifications and missed detections (TP and FN) made by the PAMLab DC system

Recall (R) was calculated as:

$$R = \frac{N\ (TP)}{(N(TP) + N(FN))}$$

The accuracy (A) of the DC system represents the fraction of correct positive (TPs) and correctly missed detections/classifications (TNs) from the total sum of detections/classifications and missed detections (TP, FP, TN, and FN) made by the PAMLab DC system

Accuracy (A) was calculated as:

$$A = \frac{(N(TP) + N(TN))}{(N(TP) + N(FP) + N(TN) + N(FN))}$$

The rate of true positives (TPs), where the DC system accurately indicated the presence of calls, and the rate of true negatives (TNs), where the system accurately indicated the absence of calls, were calculated and compared to the rate of false positives (FPs) and rate of false negatives (FN).

In order to determine biological influences on the PAMLab detector performance to detect killer whale calls, the presence of humpback whale calls and vessel sounds was also determined during the manual data analysis.

For this analysis “winter” refers to recordings made between October 1 and March 31, and “summer” refers to recordings made between April 1 and September 30. All of the data analyzed were recorded during both summer and winter periods.

Acoustic Detectability and Detection Ranges of PAM Stations of the simulated WTN Network Compared to SRKW Density and Behaviour Across Different Seasons

To assess the ability of the PAM station network to provide up-to-date information of SRKW presence in near real-time, the results of the detection range probabilities and detectability of calls by an automated DC system were compared with findings related to soundscape variation in SRKW habitat, SRKW abundance and density distribution as well as habitat use and behavioural state variation (Heimlich-Boran 1988, Hoelzel et al. 1993, Hanson et al. 2013, Olson et al. 2014, Noren and Hauser 2016, Ford et al. 2017, Rice et al. 2017, Vagle et al. 2021 and Thornton et al. 2022a, 2022b). Special attention was given to the factors that influence detection range and call detectability, such as the background noise levels and presence of acoustic distractors for DC systems.

Applicability of shore-cabled PAM systems to track SRKW throughout their critical habitat will be discussed with additional special attention being given to the risk of physical disturbance including ship strike risk.

Killer Whale Call Propagation Around Five (WTN) PAM Systems and its Effects on Call Detection Range by the PAMLab DC System.

To evaluate the ability of PAM arrays with PAMLab DC systems to track SRKWs, the travelling speed of the whales was compared with the modelled detection ranges of whales travelling between each of the five WTN locations (Figure 12, see also Figure 4 for AIS tracked marine traffic) paying special attention to the geographical location and underwater topographical features around and between stations. This information was then used to predict the arrival times of the whales at important intersections with vessel traffic. SRKWs are predominantly travelling at speeds of 0.8 to 3 m/sec (mean at 1.7: Williams and Noren 2009).

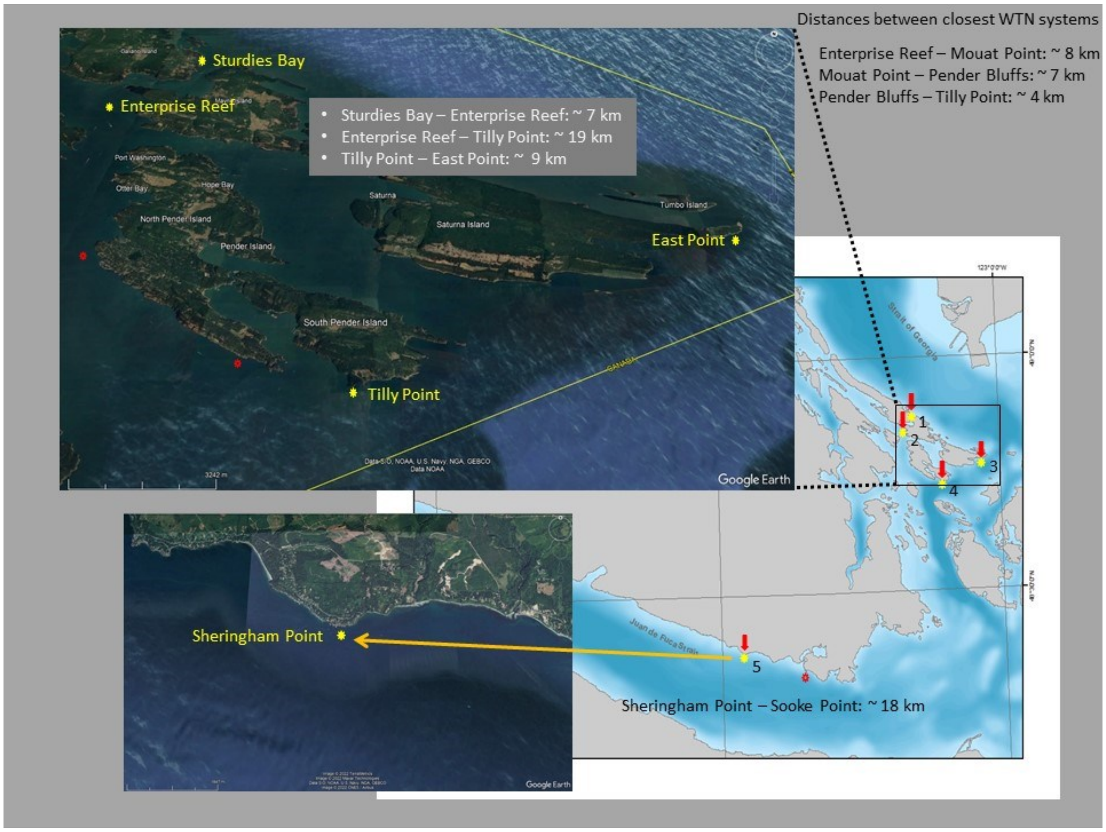


Figure 12. Detection ranges at five WTN PAM stations were modelled: 1. Sturdies Bay, 2. Enterprise Reef, 3. East Point, 4. Tilly Point, 5. Sheringham Point. Depicted are the topographical environments and bathymetry around each of the locations and the approximate distances between modelled PAM stations. Distances to the nearest possible WTN stations are also displayed. The operational status of these WTN stations is unknown.

RESULTS and DISCUSSION

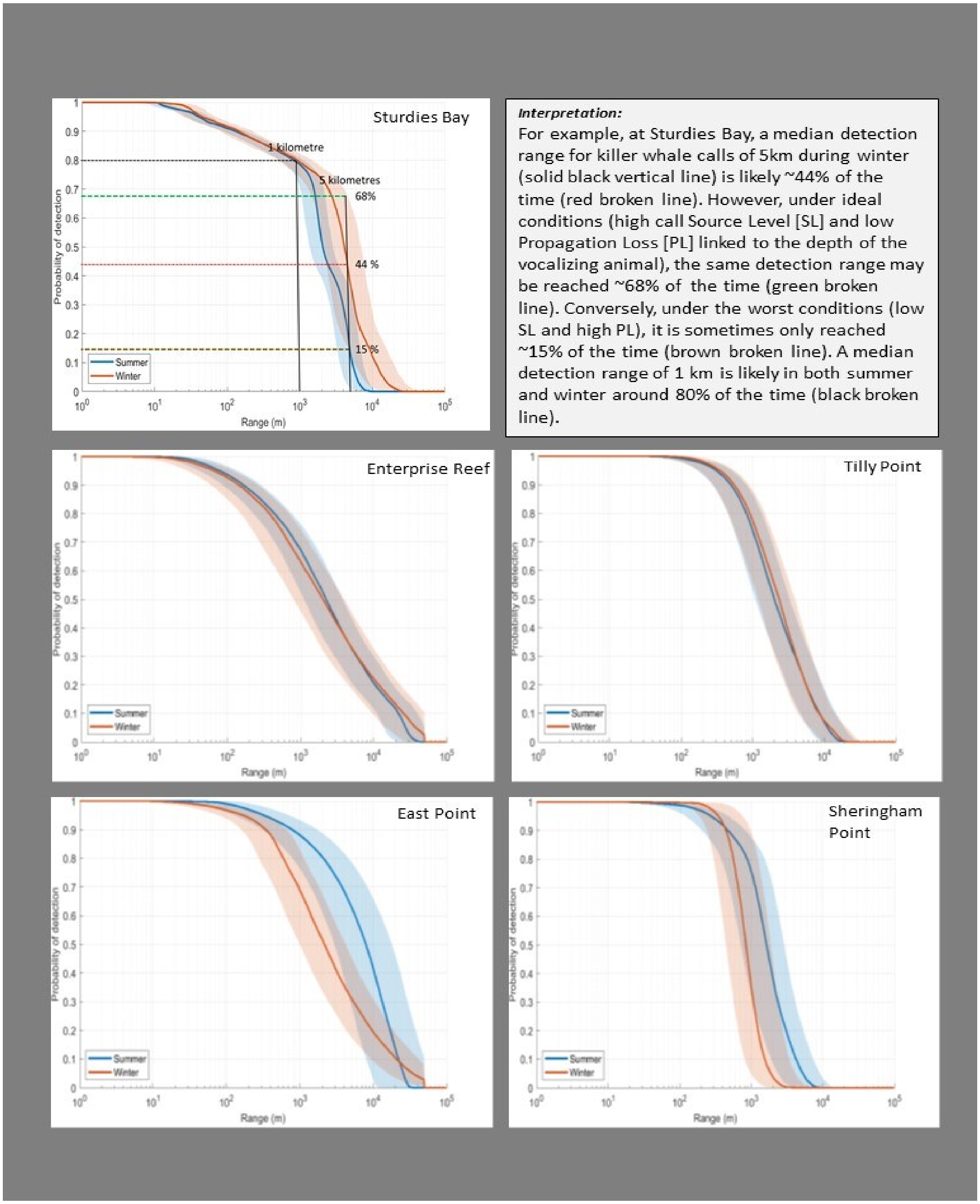
Influence of Call Detection Range Variability on Detectability of a Killer Whale Call by an Automated DC System

The effect of the input variables on the estimated detection distance for each of the evaluated PAM stations is depicted in Figure 13 as the median detection range probability over distance between seasons. The median detection range probability in metres (solid red and blue lines), plus quartiles (shaded red and blue areas), are shown. The probability was calculated from 10000 iterations of the detection range model. The variation in range probabilities for winter months (mid November to mid February) versus summer months (mid June to mid August) are plotted in the same graphs for each location.

A median probability (50% of the model iterations) of a killer whale call reaching the receiving hydrophone 50% of the time maybe less than 2 km in the summer and close to 5 km in the winter across all five stations. The choice of median range estimate (50% of the time) is conservative as it describes 50% of the possible range that a call can travel at this location while a 0.5 probability depicts 50% of the time the corresponding median range can be achieved based on the 10000 model iterations. For 25% of the time, a 50% probability of median detection is reached at a range of 3 km in the summer and close to 10 km in the winter, while 75% of the time the median range is probable is less than 1.5 km in the summer and less than 2 km in the winter. See a more detailed description of the model results in Figure 13.

The modelling work showed that there were considerable differences in overall detection ranges across locations and seasons. The primary drivers of detection range variation at a station for assessed caller depths and source levels is ambient noise while propagation loss also drives difference between locations. The maximum spatial detection ranges among different stations is demonstrated by differences in theoretically probable median detection ranges (X-axis in graphs in Figure 13), i.e. median ranges (orange curves in graphs in Figure 13) with a probability of occurring greater but close to 0 (y-axis in graphs in Figure 13) based on the 10000 model iterations. The conservatively assessed possible median detection range for the PAMLab detector was therefore 50 km at Enterprise Reef and East Point, around 35 km at Sturdies Bay, 30 km at Tilly Point, and about 10 km at Sheringham Point. The median detection ranges can vary between seasons by more than 10 km at some locations (Sturdies Bay and East Point) to less than 1 km at others (Tilly Point).

Preliminary results of an ongoing empiric assessment of call/signal propagation loss in the areas where detection range was modelled (Yurk et al. in prep.) suggest that the range probabilities produced by the JASCO model encompass ranges assessed empirically but the longest (least probable) median ranges are less conservative estimates of the overall expected ranges than minimum (most probable) median ranges.



Interpretation:

For example, at Sturdies Bay, a median detection range for killer whale calls of 5km during winter (solid black vertical line) is likely ~44% of the time (red broken line). However, under ideal conditions (high call Source Level [SL] and low Propagation Loss [PL] linked to the depth of the vocalizing animal), the same detection range may be reached ~68% of the time (green broken line). Conversely, under the worst conditions (low SL and high PL), it is sometimes only reached ~15% of the time (brown broken line). A median detection range of 1 km is likely in both summer and winter around 80% of the time (black broken line).

Figure 13. Graphic depiction of detection range probabilities for Southern Resident Killer Whale (SRKW) pulsed calls in summer (blue) and winter (orange) at the five evaluated PAM locations (A-E). The solid lines are the median values for each corresponding detection distance, and the shaded areas define the 25th and 75th percentiles around the median.

These least probable median ranges are likely theoretical in that ideal soundscape conditions would be required to reach these ranges, which tend to occur rarely or never. For comparison, Miller (2006) reported maximum detection ranges for some Northern Resident Killer Whale (NRKW) calls as high as 15 km in areas of the BC central coast. Miller (2006), however, did not report the ambient noise levels during the assessment of received levels and the applied propagation loss model used source level estimates based on back propagation via a simple spherical spreading model that did not include noise levels and did not specifically account for surface and bottom sound wave interactions nor did it include sound propagation through the substrate. Miller (2006) used a fixed correction factor of 3 dB to account for loss due to surface and bottom sound reflection and absorption. The Marine Operations Noise Model (MONM- Mouy et al. 2020) applied by JASCO to considers the frequency dependent variation in ambient noise levels and applies a more complex propagation loss calculation that takes range dependence and surface and bottom reflections as well as geo-acoustic sound propagation into account. Mouy et al. (2020) suggested that frequency dependent ambient noise level variation is an important factor if not the largest factor influencing call detection ranges. The possible detection range at a particular location is therefore not a time dependent fixed numeric value but a range of values dependent on the dynamic changes of ambient noise levels, caller depth, propagation, and call source level distribution across call frequency range. In both studies, however, only a subset of the calls used by either SRKW and NRKW were assessed. Killer whales may use different calls or call components to communicate over short versus long ranges (Pilkington, Pers. Comm.). Experimental studies to assess call propagation loss empirically that apply varying source levels are underway (Yurk et al. in prep).

Based on the JASCO detection range model, the range probability decreases more gradually over distance at locations within narrower waterways, such as Active Pass (Sturdies Bay) and Swanson Channel (Enterprise Reef) compared to locations in wider channels such as Boundary Pass (Tilly and East Points) and Juan de Fuca Strait (Sheringham Point). In the much wider Juan de Fuca Strait, detection range probability remains very high (> 80%) with a distance of one kilometre and then drops down to less than 10% probability of calls being detectable at two kilometres in the winter and less than four kilometres in the summer. The inflection point in the detection range probability curve that indicates faster decreases in detection range per measured distance and the steepness of the slope in range probability after onset appears to be correlated with differences in sound propagation loss at the different locations (Mouy et al. 2020).

The temporal detection range variation was estimated using the changes in distance over which a killer whale call can be reliably detected by an automated detection system (> than 50% median detection probability) in the winter and the summer. The distances of a median detection range for killer whale calls at 10%, 50% and 90% probability were compared at each location for winter and summer months respectively. The results are listed in Table 4.

Table 4: Median probability range of detection (P). P-10 depicts the probable median range at 10% of the time; P-50: probable median range at 50% of the time; P-90: probable median range at 90% of the time.

PAM Site	**Population**	**Season**	**P-10 (m)**	**P-50 (m)**	**P-90 (m)**
Sturdies Bay	SRKW	Winter	10,800	4,200	130
		Summer	5,300	2,000	130
Enterprise Reef	SRKW	Winter	25,000	2,000	150
		Summer	21,600	2,200	160
Tilly Point	SRKW	Winter	8,600	2,400	540
		Summer	8,600	2,000	480
East Point	SRKW	Winter	21,000	2,200	340
		Summer	21,700	7,900	800
Sheringham Point	SRKW	Winter	1,500	850	440
		Summer	4,200	1,600	470

The modelled median detection distances of SRKW calls at each PAM station varied greatly between winter and summer for calls with high source levels during good soundscape conditions (P-10), less so for median source level calls during median soundscape conditions (P-50) and very little for calls with low source levels during poor soundscape conditions (P-90). For example, the P-10 scenario assumes a detection range that could be achieved when high call source levels co-occurred with low noise levels and low propagation loss over depth. Based on the 1000 random model reiterations the median detection range displayed in Table 3 could occur around 10% of the time. The P-50 range and P-90 range in Table 3 represent conditions that involve median SL, median NL and median PL (P-50), and low SL, high NL and high PL (P-90).

Influence of killer whale movement on detection range and tracking

The P10, P50, and P90 values from Table 4 were used to calculate undetected SRKW travel distances and time periods for the three scenarios (Table 5). This was achieved by applying the minimum, mean, and maximum travel speeds of SRKWs as reported by Williams and Noren (2009): minimum speed = 0.8 m/s, mean speed = 1.7 m/s and high speed = 3.0 m/s. This demonstrated the variation in acoustic detectability that exists when SRKW movement is added as another variable for assessing the effectiveness of tracking killer whales in near-real time with shore-cabled PAM systems.

Table 5. Travel distances in metres and travel times in minutes of SRKWs between PAM stations, including distances and times that SRKWs would not be detected by the PAM stations (in red) based on different call source levels, propagation conditions, and ambient noise levels entered into probability range modelling.

Travel Route	Travel Distance (m)	Travel Time in minutes based on Mean Swim Speed (Range)	Season	High Call Source Level & Low Propagation Loss & Noise Level (P-10)		Median Call Source Level & Median Propagation Loss & Noise Level (P-50)		Low Call Source Level & High Propagation Loss & Noise Level (P-90)	
				Distance SRKW undetected (m)	Time SRKW undetected (min)	Distance SRKW undetected (m)	Time SRKW undetected (min)	Distance SRKW undetected (m)	Time SRKW undetected (min)
Sturdies Bay - Enterprise Reef	8300	81 (46-173)	Winter	0	0	2100	21 (12-44)	8020	79 (45-167)
			Summer	0	0	4100	40 (23-85)	8010	79 (45-167)
Enterprise Reef - Tilly Point	18300	179 (102-381)	Winter	0	0	13900	136 (77-290)	17610	173 (98-367)
			Summer	0	0	14100	138 (78-294)	17800	173 (98-368)
Tilly Point - East Point	12900	126 (72-269)	Winter	0	0	8300	81 (46-173)	12020	118 (67-250)
			Summer	0	0	3000	29 (17-63)	11620	114 (65-242)
Tilly Point - Sheringham Point	103110	1011 (573-2148)	Winter	93010	912 (517-1938)	99860	979 (555-2080)	102130	1001 (567-2128)
			Summer	90310	885 (502-1881)	99510	976 (553-2073)	102160	1002 (568-2128)

When call propagation conditions are optimal and ambient noise levels are low (P-10), louder calls can potentially be detected and tracked by automated systems along travel routes covered by the evaluated (WTN) PAM stations around the Southern Gulf Islands of the Salish Sea in winter and summer regardless of SRKW travel speeds (Table 5: P-10). In less-than-optimal acoustic conditions (P-50 and P-90), there were spatial and temporal limits to acoustic tracking of SRKWs along the same routes based on the detection range limits at the four evaluated stations.

The undetected distances and time periods for SRKW travelling between Sheringham Point and Tilly Point that are added in Table 5 are theoretical values. Whales may never travel directly between the two stations without visiting other places along the way where they can be detected by operational WTN stations or other means of detection. One of those places is the western shoreline of San Juan Island in Haro Strait, where there are active PAM stations operated by US-based NGOs such as Orcasound[3]. These PAM stations are streaming sound in near real-time through an automated detector, and to a network of online human listeners. The acoustic detection network is supported by a network of observers[4] that provide sightings of SRKWs and other whales. The west side of San Juan Island is considered one of the main foraging areas for SRKWs in the Salish Sea (e.g. Hauser et al 2007, Olson et al. 2018, Thornton et al.

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[3] Orcasound – Listen for whales

[4] Whale Sighting Network — Orca Network

2022a) and the likelihood of SRKWs being detected in this area by other monitoring systems or human observers is very high.

Undetected distances and times for P-50 and P-90 conditions vary with SRKW travel speed (Table 5) and different acoustic propagation conditions between stations, as well as spatio-temporal noise variation. The distances and times that SRKWs remain acoustically undetectable by automated systems also varies between seasons.

The values listed in Table 5 apply for SRKW travel in either direction between stations because sound propagation is the same in either direction. Variation in directionality of ambient noise was not considered in this analysis, but may influence the distance and time periods at some locations. Deviations from the values in Table 5 are expected in cases where vessels travel closer or further away from detected SRKWs at any given time; this variation in vessel distances is not thoroughly captured by the ambient noise assessments. Better than model estimated detectability is likely when whales are travelling between the noise sources and the receiving PAM array, whereas detectability worsened when vessels are travelling between the whales and the PAM location. The former appears most of the time at East Point and Sheringham Point where the international shipping lane is further away from shore and the whales travel closer to shore, while sometimes at Tilly Point and Enterprise Reef and often at Sturdies Bay the vessels, e.g., ferries travel closer to the PAM station than the whales (Yurk and Quayle, Pers. Comm.).

The undetected distances and time periods are a considerable limitation to the ability of a network such as the simulated WTN network to track whale positions accurately and report them in a timely fashion to vessel operators, in order to reduce the risk of ship strikes. Commercial vessels range in speeds of 4.1 to 8.33 m/sec which translates to between 4900 and 9996 m in 20 minutes.

The undetected distance and time periods increased with noisier soundscape conditions and when whales used quieter calls, which they tend to do when travelling in close proximity to each other. Under high noise and poor propagation conditions, quieter calls may not be detectable for 45 minutes to more than 2 hours and 47 minutes (mean: 79 minutes) when travelling between the two stations. Under noisy conditions, detection ranges of these calls do not differ between winter and summer.

When travelling in Swanson Channel between Tilly Point and Enterprise Reef under median conditions (P-50), SRKW calls may not be detectable by either of the two stations for at least 77 minutes when travelling fast to just under 300 minutes when travelling slow. Slow travel is expected when whales switch between travel and foraging, which is possible in Swanson Channel (Thornton et al. 2022a). There was no large difference in undetected distance and time between winter and summer. Under noisy conditions and unfavourable propagation (P-90) these times are more than one hour and a half and just over six hours for fast- and slow-travelling whales respectively.

A large difference in undetectable distances and time periods between seasons occurs in Boundary Pass. SRKWs may remain undetected for 17 to 63 minutes in the summer and 46 minutes to almost three hours in the winter. Sound propagation variation at East Point may be a driver for this difference (Figure 13 and Figure 14).

Whale movement behaviour, in addition to acoustic or soundscape conditions and calling behaviour, played an important role for whale detectability at and between the five PAM stations, especially in regards to detection range variation at each of the PAM stations and the space between stations. Undetected distances and time periods can translate into increased vessel strike risk and less severe physical disturbance as vessel operators may not be aware of the whales in their path for several hours. Ideal acoustic conditions (P-10) are especially rare in areas with high vessel traffic such as the northern sections of Swanson Channel and Active Pass due to continuous ferry traffic, and in Boundary Pass due to the international shipping lane used by large commercial vessels. Furthermore, winter periods, when fewer land-based and boat-based observers track whales due to adverse weather conditions, are also characterized by higher natural ambient noise levels affecting detection ranges.

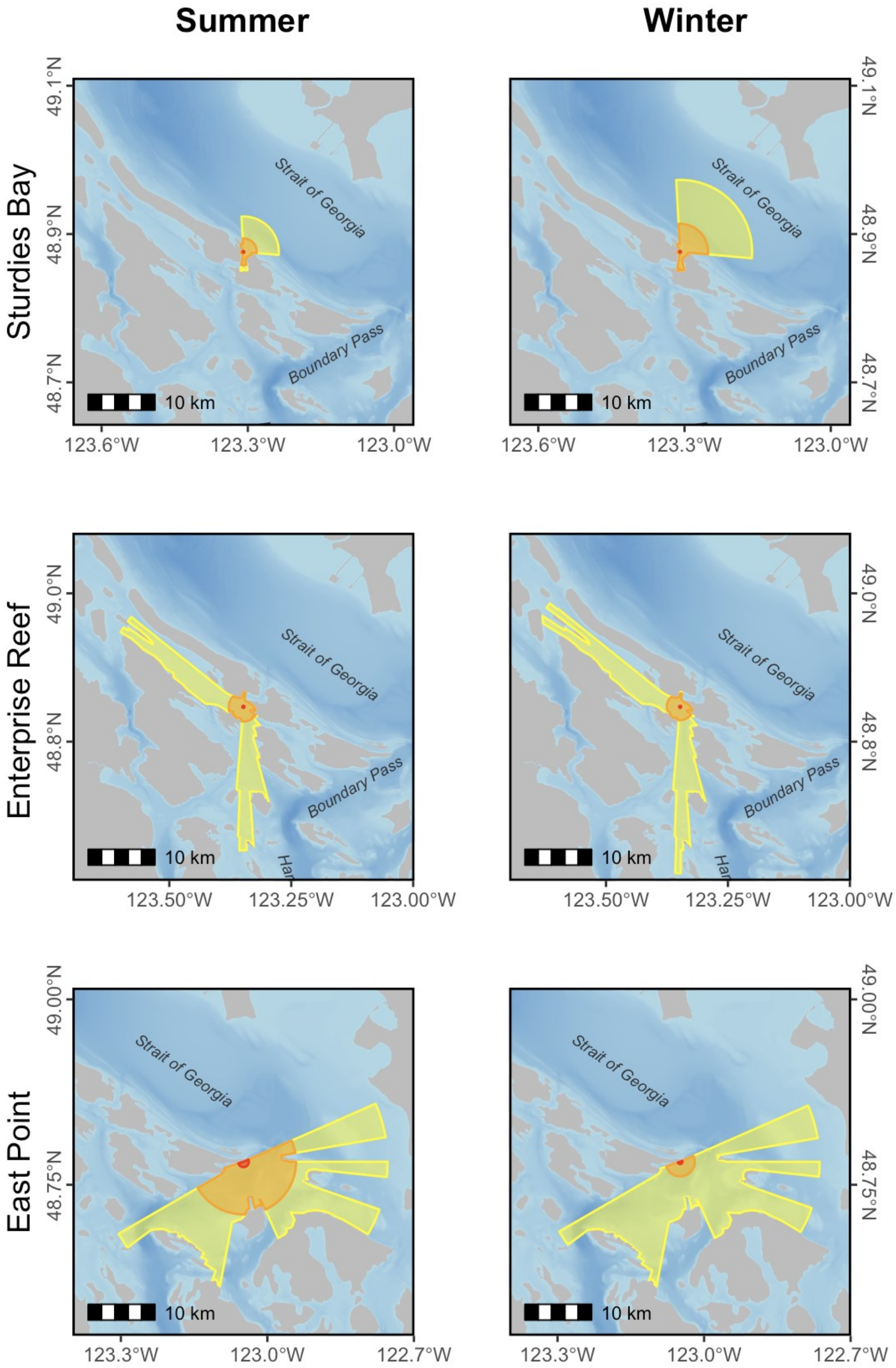
Influence of Topography on the Detection Range

Sound propagation in all directions in which there are no physical barriers is primarily attenuated by the effects of water properties, bathymetry, and the interaction of sound waves with the sea surface and bottom as well as the geo-acoustic conditions between sound source and receiver. The JASCO model estimated propagation loss (PL) along radials drawn from the receiver location outward (Mouy et al. 2020 for propagation loss model). Since the model is estimating PLs along specific radials, the reported numerical loss is the PLs along each radial but equal to PL in every direction.

The results presented in Table 5, however, do not fully account for propagation limits due to topographical underwater features such as islands and narrow or meandering channels. These features may negatively influence probable detection ranges by automated systems in specific directions and even detection capabilities of human listeners due to acoustic shadowing (i.e., sound waves failing to spread in a particular direction due to disruption by physical barriers).

When there are physical barriers between acoustic receiver stations in some directions but not others, the sound propagation will get disrupted in the direction of the PAM station, resulting in the detection range for that station being greatly reduced. While sound waves can bend and reflections allow waves to travel around corners, the sound pressure levels that continue past a physical barrier are considerably lower than before the sound waves arrive at the barrier. The resulting increased PL will reduce detectability of quiet to moderately loud calls more than loud calls because automated detectability is directly related to the excess amplitude (loudness of a call above background noise in each of the detection frequency bands). The effects of topography on detection range is illustrated in Figure 14. The effect of lower frequency waves that can bend around the corners is underestimated in the figures because directionality of calls and noise is not considered by the model.

For example, when calls are loud, propagation is good and ambient noise is low (P-10 in Table 5), the undetected distance for SRKWs travelling between Sturdies Bay and Enterprise Reef is numerically 0 based on the numerical model predictions. Due to acoustical barriers as a result of the topography of Active Pass, however, there is a 2 km long undetected stretch for whales travelling between Enterprise Reef and Sturdies Bay (Figure 14). During P-50 conditions, which are more likely to occur than P-10 due to anthropogenic and naturally occurring noise sources, the undetected median call detection ranges for whales travelling in Active Pass is confined to areas in which sound can travel unrestricted, which is only about 1.5-2 km into the Pass from the receiver stations in Sturdies Bay. Whales may not be detected at Enterprise Reef once they enter Active Pass from the south (Figure 14). Detected calls at Sturdies Bay coming from the Strait of Georgia, however, may be originating at distances of more than 4 km away in the winter, but the maximum distance is probably only possible in an easterly direction (Figure 14). The southeastern parts of Galiano Island and the northeastern parts of Mayne Island act as acoustic barriers for sounds coming from those directions (Figure 14).


Summer
Winter
Sturdies Bay
Enterprise Reef
East Point
Strait of Georgia
Boundary Pass
Har
10 km
49.1°N
48.9°N
48.7°N
49.0°N
48.8°N
49.00°N
48.75°N
123.6°W
123.3°W
123.0°W
123.50°W
123.25°W
123.00°W
122.7°W

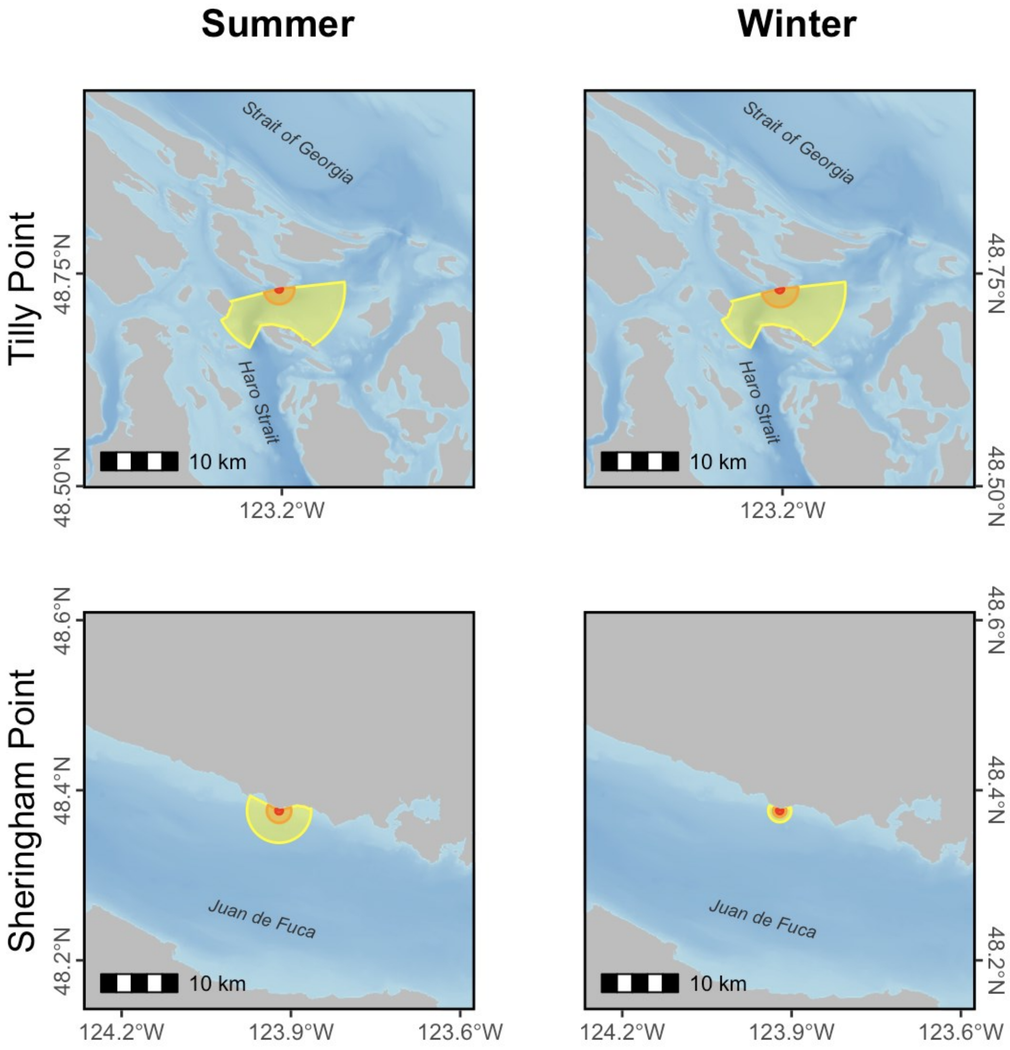


Figure 14. Geographical representation of median detection range probability as a result of variation in acoustic propagation, ambient noise levels and call loudness (P-10/yellow, P-50/beige, P-90/red) at the five evaluated PAM locations during the winter and summer.

In Boundary Pass, differences in water properties, such as temperature differences in the upper water layers between summer and winter, may play a more considerable role in influencing propagation loss and the detection range of calls. The median detection distance for SRKW calls with median source levels during P-50 conditions at East Point in Boundary Pass differs considerably between summer and winter. Calls may be detectable from distances of more than 7 km in the summer to less than 3 km in the winter (Table 4 and Figure 14). Surface temperature (i.e., water temperature to a depth of 15-25 m) is much higher in the summer than in the winter here, which results in higher sound speeds in the summer compared to winter. Calls travel further in the summer due to higher sound speeds in upper water layers. SRKWs, like other resident type killer whales, appear to spend more time in these upper water layers except when foraging (e.g., Wright et al. 2016), which increases the likelihood of whales vocalizing more often closer to the surface. Noise from vessels, however, is also generated in those upper water layers and noise propagation benefits from the higher sound speed as well. This is likely the reason for very poor detection ranges of quiet calls under P-90 conditions in Boundary Pass, but also in Swanson Channel around Enterprise Reef and in Active Pass. Overall detection range was greatly affected by ambient noise leading to larger undetected distances and time periods when vessels are travelling through these areas (P-50 and P-90).

In areas where vessels mostly travel further away from the coastline, such as in Juan de Fuca Strait near Sheringham Point, the detection range difference between P-50 and P-90 conditions are less pronounced (Figure 14). Under poor soundscape conditions (P-90), calls may be detectable by an automated system in summer and winter at comparable ranges, but under median soundscape conditions (P-50), calls may be detected twice as far in summer as is possible in winter while under good soundscape conditions (P-10) the detection range in summer is almost three times that in winter. Also, propagation loss is much more uniform in all directions in both summer and winter (Figure 14).

Influence of detection range model assumptions

The fitted linear sound energy distribution across the 1-15 kHz range of killer whale calls used to estimate call source level variation in the detection range model shows the highest relative call source levels or amplitudes at or around 1 kHz and a steady decline of source levels with increased sound frequency (Figure 15). The spectral source level distribution represents calls with omnidirectional lower frequency components well but underestimates the effect of directionality of calls containing more than one frequency component on propagation range (Figure 16). The polynomial fitted curve in Figure 15 does indicate the potential of higher variability of source levels above 7 kHz but the values did not change the predicted detection ranges in the model.

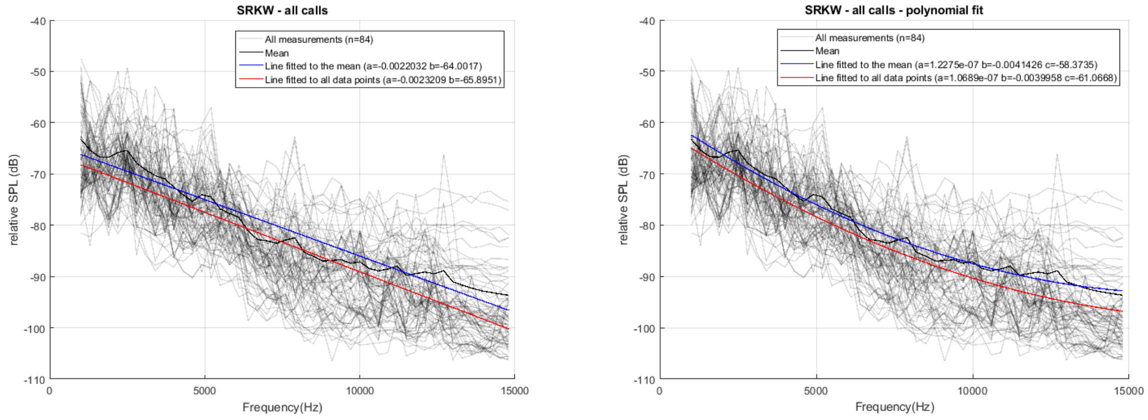


Figure 15. Linear and polynomial fitted curves to the relative spectral energy distribution of received levels of 84 SRKW calls. The data sources include calls recorded at close proximity of whales either with a hydrophone lowered from a drifting vessel or from a DTAG attached to the

whale. The peak levels around 5 kHz, 7-8 kHz and 12-13 kHz represent narrow band higher frequency components Figures provided by Melanie Austin, JASCO Applied Sciences

Killer whale calls, however, often contain multiple frequency components (Figure 16) and typically consist of either one high (typically >4 kHz) frequency component (HFC) overlapping with one or more low (<4 kHz) frequency components (LFC) or contain LFCs and HFCs in sequential order (Ford 1989, Strager 1995, Miller and Bain 2000, Yurk et al. 2002, Deecke et al. 2005, Richlen and Thomas 2008, Schall et al. 2017). The higher the frequency, the more directional HFCs are (Miller 2002). Miller and Bain (2000) suggested that two component calls propagate better than single component calls. Propagation of HFCs is also affected negatively by greater absorption of sound energy from partial physical obstructions (bends in water channels) than the omnidirectional LFCs due to higher interaction rates and directionality of sound waves.

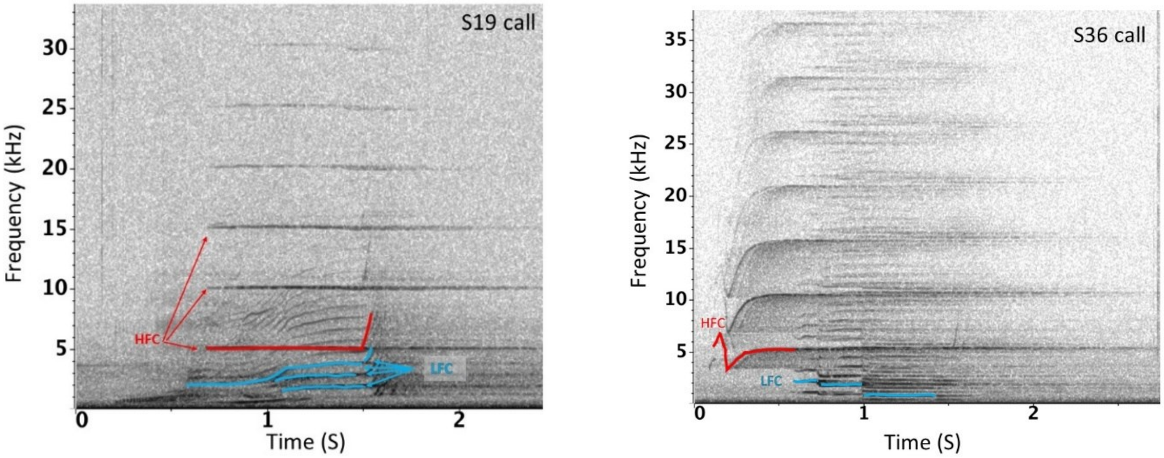


Figure 16: Spectrograms of two SRKW calls (S19-left, S36-right). S19 is an example of an overlap of HFC over LFC components, while S36 comprises a sequential order of components. Sound frequencies of approximately 4 kHz and higher are projected toward the front of the whale because the full wavelength corresponding to these frequencies is contained within the head of the whale. The contours of components may appear longer than the marked areas. The length of an uninterrupted contour indicates the length of the signal travelling in a direct path between caller and sensor while the continuation of the contour in the spectrogram represents reflections of the signal that arrive at later times. Also note that there is a low frequency humpback whale call in the S19 spectrogram.

The call sample used for the modelling may not correctly reflect the use of multi-component calls by the animals. Dtags are usually placed behind the whale’s blowhole below which the nasal passage leading to the sound generating structures (phonic lips and nasal plugs, Cranford et al. 1996) is located. This placement does not allow Dtags to accurately record the sound energy of transmitted HFCs. Further, depending on the direction that the whale was facing during the recording of a call via the hydrophone lowered over the side of the vessel, the HFC may only be partially captured by the hydrophone, limiting the ability to accurately measure source level from these recordings. This may have resulted in an under representation of the spectral energy distribution of multi-component calls in the source level input of the model.

Killer whales may be using different calls depending on the soundscape they are calling in or the distance of the intended receiver of a call. It is likely that physiological constraints in sound source level production and adaptation to noisy environments have been drivers for the development of the multi-component calls, allowing the production of louder low frequency components that propagate omnidirectionally together with directional high frequency components that have lower amplitudes, but propagate well in certain areas such as long and straight water channels, which exist at many places along the Pacific coastline from Washington to Alaska. The call structure is an important factor to consider when deciding on the location of PAM station in marine environments characterized by narrow waterways, meandering channels, and wide-open water spaces.

Multi-component calls may also propagate better in noisy environments because ambient noise levels from both natural and anthropogenic sources typically have sound energy peaks in lower frequencies (below 4 kHz) and therefore ambient noise tends to affect propagation of LFCs more than that of HFCs. By focussing on a good fit of a linear curve to the source level distributions of available recorded calls, the linear model fit may have inadvertently skewed the modelling results to better represent propagation of omnidirectional calls or call components, but may less accurately represent the propagation of calls with bi- or multi-modal source peak energies that would be expected to exist in multicomponent calls. The resulting modelled detection ranges therefore may represent environments in which calls can travel unobstructed in all directions slightly better than those that are represented by straight narrow waterways or channels which are common features of the Salish Sea. The effect should be less pronounced in waterways that are characterized by bends in their paths. However, this possible limitation needs to be considered when interpreting the model’s results.

In environments characterized by straight channels, the model may slightly underestimate detection range, while in areas where physical obstructions block the direct path of sound waves, the model may slightly overestimate detection ranges due to the differential absorption of higher frequencies. Water moving around physical obstructions tends to create eddies during tidal water movements and may result in higher turbidity and density of air bubbles. Water turbidity due to dissolved material and density of air bubbles increases sound absorption, especially for higher frequencies (shorter waves), as they interact more often with particles/bubbles in the water than lower frequencies (longer waves). Calls with higher frequency components are therefore affected more strongly than those primarily consisting of lower frequency components.

On the other hand, the 10 km long undetected stretch for whales travelling between Tilly Point and Enterprise Reef may actually be shorter because sound waves travel relatively unobstructed for long distances along the channel, and directional call components can play a greater role in call detectability as they are less affected by low frequency ambient sound levels. One of the originally deployed WTN stations was located at Mouat Point at the bending of Swanson Channel from a northwesterly trajectory to a northerly trajectory (Figure 12) when travelling north. This is a commonly observed travel path for SRKWs in Swanson Channel (Quayle et al. in prep.). A functional WTN station around Mouat Point could potentially reduce the undetected distance between Tilly Point and Enterprise Reef under median soundscape conditions and median call source levels. However, due to persistent high levels of ambient noise around Mouat Point, the 50% probable median detection range is between 1-1.5 kms in both summer and winter (Mouy et al. 2020).

Influence of the Automated Detector-Classifier Performance

Although acoustic data collected in the Salish Sea are currently analyzed using a variety of automated detections systems, the detection of a potential whale call is similar in all systems and relies on the existence of harmonics represented by contours in the spectrogram of an acoustic data stream and the detector's ability to find those contours (or fragments of them) in the data stream. Every step after the detection of a call candidate is focused on discrimination of the contour as a whale (or, less specifically, marine mammal) sound and its classification as a call produced by a particular species, population, or group of animals. The PAMLab DC algorithms were chosen for this evaluation because the system uses machine learning algorithms in addition to the detector as a discrimination and classification tool. Machine learning algorithms are commonly used tools to identify patterns in visual data, and the contours in spectrograms are in principle visual patterns (Usman et al. 2020). Specific machine learning algorithms such as the Google AI deep learning algorithm are currently tested as tools to discriminate killer whale calls in WTN acoustic data streams and other acoustic data.

The PAMLab DC algorithms have been trained to detect and classify more than 20 species, including killer whales. The algorithms were applied to available archived acoustic data recorded at PAM stations. The performance evaluation of the PAMLab detector was conducted systematically. At least 5% of the available acoustic recordings from four of the five evaluated PAM stations underwent manual annotation analysis (Table 6). Available recordings for each station varied with Tilly Point having the most recorded time (89.2 hours) and Enterprise Reef the least amount (40.7 hours). The highest proportion of manual analysis by a human analyst (17.7 %) was conducted using recordings from the Sturdies Bay WTN station, while the lowest percentage of recordings that were manually analyzed were from the East Point WTN station (5 %). The number of acoustically detected killer whale calls in 1-min clips (Table 6) did correlate with the number of recording days and the number of analyzed recording hours (Pearson Correlation Coefficient > 0.97) but not with the percentage of analyzed recordings at each location, i.e. the systematic analysis did not influence the relative number of detected calls among locations.

Table 6. Data analyzed by PAMLab in days with recordings, the total recording time analyzed manually in number of hours analyzed, also expressed as a proportion of the total available data (percentage analyzed) and the total number of detections (1-minute clips) to have killer whale calls. The last column shows the detection rate resulting from the manual analysis

Location	Days with recordings	Number of hours analyzed	Analyzed %	Number killer whale of detections	Detection Rate
Sturdies Bay	43	52.7	17.7	27	0.009
Enterprise Reef	33	40.7	6.6	1	0.0005
Tilly Point	71	89.2	5.3	225	0.042
East Point	36	41.0	5.0	9	0.004

Based on the manual analysis, the detection rate of killer whale calls at Tilly Point was 10 times higher than at East Point. Both stations are located in Boundary Pass. The detection rate of calls at Sturdies Bay was 15 times higher than at Enterprise Reef. The two PAM locations are located at either end of Active Pass. Enterprise Reef had the lowest detection rate with only one minute of verified detections in almost 41 minutes of analyzed recordings spread out over 33 days. These differences are not explained by estimated call detection range differences between locations. The vocalization rate differs among killer whale ecotypes, e.g. Bigg's killer whales mostly forage silently due to the ability of their prey to hear their calls (Deecke et al. 2005), while the typical prey of resident killer whales, Chinook salmon, are less sensitive to the sound frequencies present in resident calls (Nedwell et al. 2006). This discrimination is currently only conducted by human annotators of automated detections. Resident killer whales may also show variation in vocalization rates among different locations (B. Hanson, Pers. Comm.). The PAMLab classifier did not distinguish between calls from different ecotypes. Environmental soundscape differences and behavioural factors may influence vocalization detection rates.

Location-Specific Environmental Factors Influencing the Detector Performance

The single hydrophone WTN station in Sturdies Bay located at the northeast entrance of Active Pass is 100 metres away from a BC Ferries terminal (Figure 17). The ferry terminal is visited by 8 to 12 ferries per day between 6:00 AM and 9:00 PM. There is also a public dock beside the ferry terminal at Sturdies Bay, which is used by water taxis and private vessels. In addition to ferries servicing the terminal at Sturdies Bay, ferries servicing the Tsawwassen—Swartz Bay route pass the WTN hydrophone at distances of less than 800m about 16 times per day in the winter to 20 times in the spring and fall and 28 times during July and August. These ferries travel between 7:45 AM and 9:45 PM in winter and 6:45 AM and 11:15 PM in the middle of summer.

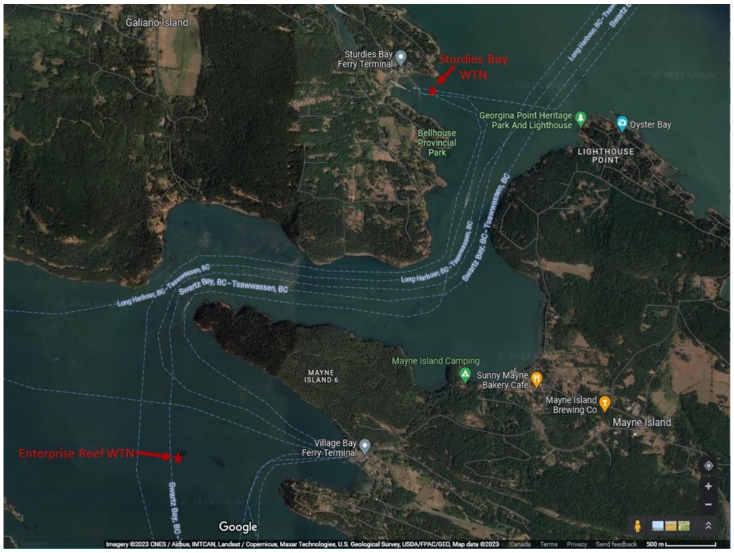


Figure 17. Active Pass and lower Tricomali/upper Swanson Channels with WTN Stations at Sturdies Bay and Enterprise Reef

These bigger ferries coming from either end of the route often meet in Active Pass. They travel at speeds of up to 5 m/s along the 4 km route through the Pass. The ferries will spend about 13.5 minutes in the Pass, but may take longer when other vessel traffic slows them down.

Newer vessels of the BC Ferries fleet produce broadband sounds with pressure source levels of around 175 dB[5]. Using a spherical spreading loss model to estimate propagation loss, the received broadband noise levels of the ferries at a distance of 1 km (the maximum distance of a ferry passing the PAM station) is approximately 115 dB and covers the full frequency range of killer whale calls and those of many other marine mammals in this area. An automated detector that is setup with a 6 dB detection threshold will start detecting whale calls that exceed received sound pressure levels of 121 dB. SRKW calls have a mean broadband source level of 155.1 ± 6.5 dB (Holt et al. 2011). Table 7 presents the typical distances at which a call can theoretically be detected by a detector with a 6 dB detection threshold given the mean plus/minus quartile source levels reported by Holt et al. (2011).

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[5] https://www.marinelink.com/news/a-bc-ferries-case-study-lessons-learned-491247

Table 7. Distances at which an automated detector using data streams from the Sturdies Bay WTN PAM station can detect a SRKW call while a ferry or other large vessel is in the Pass at various distances. Numbers (signal-to-noise exceedence in dB) have to be positive (bold) for calls to be detected.

	Vessel @ 3000 m			Vessel @ 2000 m			Vessel @ 1000 m		
SRKW distance from WTN Station (m)	SRKW Call Source Level (dB) – Received Noise Level (dB) + 6dB								
	low quartile	Mean	high quartile	low quartile	Mean	high quartile	low quartile	Mean	high quartile
1000	-22.9	-16.4	-9.9	-26.4	-19.9	-13.4	-32.4	-25.9	-19.4
500	-16.9	-10.4	-3.9	-20.4	-13.9	-7.4	-26.4	-19.9	-13.4
200	-8.9	-2.4	**4.1**	-12.4	-5.9	**0.6**	-18.4	-11.9	-5.4
100	-2.9	**3.6**	**10.1**	-6.4	**0.1**	**6.6**	-12.4	-5.9	**0.6**
50	**3.1**	**9.6**	**16.1**	-0.4	**6.1**	**12.6**	-6.4	**0.1**	**6.6**

The numbers in Table 7 represent theoretical excess dB levels for sounds travelling in a direct path between source and receiver. In a narrow waterway such as Active Pass reflection and absorption are important influences making it difficult to determine the exact propagation loss. However, both ship noise and SRKW calls are affected by reflection and absorption, which make a SRKW call detection distance of less than 200 m when vessels are less than 3 km from the receiver (which is a realistic scenario). Vessel traffic in spring, summer and fall is very high, and vessels are likely present when SRKWs are in the Pass during daylight hours. During the winter, fewer small vessels travel through the Pass, but ferries and commercial vessels still use the Pass regularly. In addition to vessel noise, a navigational buoy located near the entrance of Active Pass produces loud tonal sounds produced by movements of the mooring chain. Based on the combined presence of vessels and other background noises the detectability of a whale call during daylight hours including early morning and late evening hours is very limited. The detection range model did not consider daylight and dark hours separately and therefore did not capture this potential difference in detectability. Nevertheless, the ambient sound level assessment done by JASCO (Mouy et al. 2020) reflects the high variability of background noise in the Pass (Figure 18).

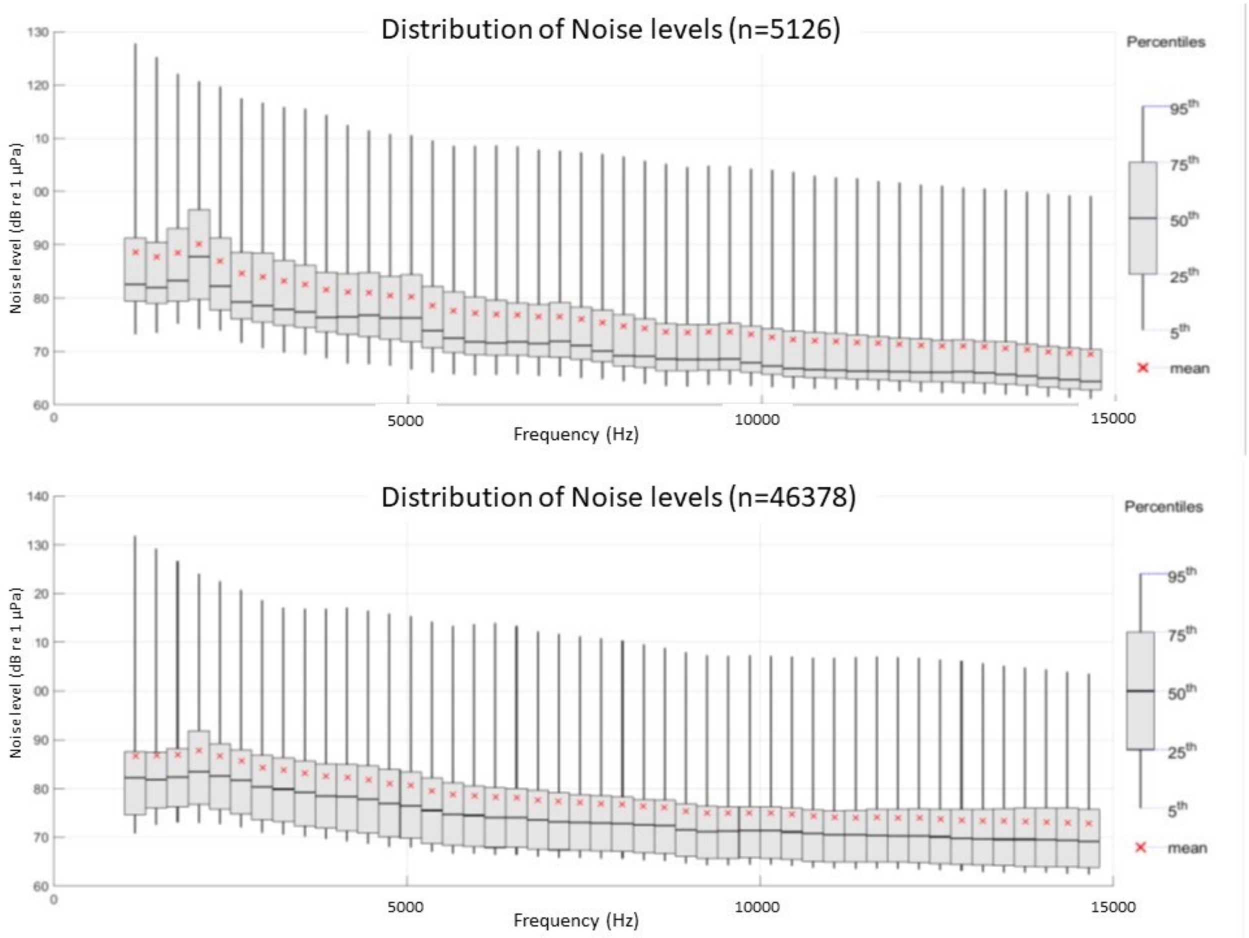

Figure 18. Ambient noise levels recorded at Sturdies Bay WTN-PAM: Percentile distribution of background sound levels (in 300 Hz bands) from the data samples recorded at the location in winter (top) and summer (bottom), as a function of frequency. (From Mouy et al. 2020)

The upper whiskers of the box plots shown in Figure 18 represent noise levels when vessels, especially ferries, are present in Active Pass. Because the assessment did not consider time of day and/or periods with and without vessels, the median which represents the level occurring 50% of the measured time series does not accurately represent the median for the time period 6 AM to 10 PM at which the level is likely higher. The estimated modelled detection range is therefore skewed towards times with fewer vessels present. The frequency with which vessels travel through Active Pass is high during daylight hours especially in the summer. This affects the ability of an automated detector to accurately detect whale call presence.

The Enterprise Reef WTN PAM station is located approximately 1 km south of the entrance to Active Pass (Figure 17) and is situated in the travel path that SRKWs take when approaching Active Pass during northbound travel. SRKWs have been rarely observed travelling southbound in this area. The station is in very close proximity to the ferry route used by vessels connecting Swartz Bay and Tsawwassen, as well as other ferries connecting terminals in the Southern Gulf Islands. The WTN station is also near a BC Ferries terminal at Village Bay on Mayne Island (<1 km) (Figure 17). The hydrophones of this station are located on the west side of the reef in shallow water, especially at low tide. SRKWs have been seen travelling through the middle of the reef at high tide or to the east of the reef when approaching Active Pass. Based on human observations and camera footage, Bigg's killer whales appear to use the whole area around the reef for foraging (Quayle, Yurk and Richter Pers. Communication).

The soundscape conditions around the Enterprise Reef PAM station are very similar to those at Sturdies Bay, but the median ambient noise levels reported in Figure A-46 of Appendix 1 (Mouy et al. 2020) is much higher than the one at Sturdies Bay. This indicates that the noise levels are generally higher at this location than at Sturdies Bay. Although the channel is wider, the background noise levels may be higher due to the placement of the hydrophones in shallow water near the reef where tidal currents can cause strong mechanical noise interference. In addition to ferry traffic, other commercial vessels also travel close to the hydrophones. The detectability of SRKW calls via an automated detection system at this location appears to be poor, which is reflected in the low number of detections per recorded time period (Table 6) versus actual observations of SRKW (Quayle, Pers. Comm.) and recorded calls at both Sturdies Bay and Tilly Point. This result is not in line with the estimated detection range resulting from the JASCO model. While the analyzed recording periods by the PAMLab detector-classifier for the Enterprise Reef and Sturdies Bay locations overlapped by more than a month, the killer whale call detection rate at Sturdies Bay was almost 15 times higher than at Enterprise Reef. Unless SRKWs that tend to continue their travel through Active Pass after passing Enterprise Reef do not vocalize as often at this location, which we are currently assessing using a bottom-mounted recorder that has been deployed south of the Reef, the PAM system at Enterprise Reef may not be situated well to detect calling whales. This might be due to the location of the hydrophones, but could also be the result of soundscape conditions such as physical underwater barriers near the hydrophones affecting sound propagation.

Median ambient noise levels at Tilly Point and East Point in Boundary Pass (Figures A45 and A52 in Mouy et al. 2020) are lower than those reported for Enterprise Reef and are very similar to each other during winter. During summer, ambient sound levels at East Point are on average 5 dB lower than at Tilly Point. The detection rate of the PAMLab detector shows, however, ten times more killer whale call detections at Tilly Point. Commercial vessel traffic in Boundary Pass occurs mostly in a designated shipping lane which is about the same distance from either WTN station in the Pass (Figure 3). Smaller vessel traffic is likely higher around Tilly Point due to a marina located inside Bedwell Harbour, which is just west of the WTN station and is used by private vessels coming from the US as an entry point into Canada. The most parsimonious explanation for the detection rate difference is a difference in vocal rate by SRKWs assuming similar rates of occurrence. Other resident killer whales are not utilizing this area and Bigg's whales have a much lower vocal rate than resident killer whales.

The median ambient noise levels reported for Sheringham Point for which no data were available for the detector evaluation, were higher than those reported for the other locations especially in winter. There is a greater likelihood of natural ambient noise; sources such wind and resulting wave action may be the cause of the higher levels Burnham et al. 2021). It was also noted that levels do not steadily decline with increasing frequency as is the case at other stations, but either level off above 10 kHz (summer) and increase again above 12.5 kHz in the winter. This may be another indicator for a strong influence by natural ambient noise sources such as wind.

Evaluation of the PAMLab's Detection Performance

The performance of the PAMLab detector-classifier (DC) system to identify killer whale calls in the acoustic data were assessed through metrics of precision, recall and accuracy (Table 8). The PAMLab DC system seems to detect and classify killer whales accurately in the acoustic data collected at Enterprise Reef and East Point and reasonably well at Tilly Point (Table 8). The data from Enterprise Reef, however, may not be representative but reflect a lack of call detections when compared to detection rates at Tilly Point and Sturdies Bay (Table 6). SRKW have been observed travelling North from the Southern entrance of Swanson Channel where they are detected by the WTN station at Tilly Point to Active Pass. Detections at Enterprise Reef presumably should reflect that travel path unless vocal rates are lower or detectability is poor. The performance of the DC system to detect killer whale calls at Sturdies Bay is limited because the system appears to have missed all of the manually detected calls at this location. This may be due to the overall low detectability of calls by an automated system at that location as described above. Although the accuracy of the PAMLab DC system applied to recordings at East Point is high, the system missed nine minutes of audio that contained killer whale calls. The performance of the system in detecting killer whale calls is best described by the results from Tilly Point. This result may, however, be tied to a higher call rate at this location seen by the recall rate and the manually determined vocal rate (Table 6).

Table 8. Performance metrics of the PAMLab detector-classifier. **BOLDED** numbers represent most reliable results due to quantity of detections

Location	TP (%)	TN (%)	FP (%)	FN (%)	Precision	Recall	Accuracy
Sturdies Bay	0.0	99.1	0.4	0.4	0	0	n/a
Enterprise Reef	0.04	99.80	0.12	0.00	0.25	1.0	1.0
Tilly Point	**1.78**	**94.17**	**1.63**	**2.47**	**0.52**	**0.42**	**0.96**
East Point	0.0	99.63	0.0	0.37	0.0	0.0	1.0

The presence of killer whales in the acoustic data was less than 1% of the data analyzed for all sites except Tilly Point (Tables 6 and 8). The presence of humpback whale calls in the data can be seen as a potential distractor in the detection of killer whale calls (e.g., source of false alarms or cause of missed calls) for the DC system's performance in detecting killer whale calls. Tilly Point recorded the greatest killer and humpback whale presence and the second lowest vessel presence based on the manually analyzed data (Table 9).

Table 9. Comparison of the proportion (%) of manually analyzed data that showed the presence of killer whales (KW), vessels, and humpbacks (HB) in archival data for each of the sites considered.

Location	KW presence (%)	Vessel presence (%)	HB presence (%)
Sturdies Bay	0.74	74.37	0.06
Enterprise Reef	0.16	75.25	0.0
Tilly Point	4.21	57.64	1.05
East Point	0.41	44.77	0.0

Seasonal differences in whale detection by species were found in the manually analyzed data. The presence of all whale calls is consistently greater at Tilly Point compared to other locations, with killer whale calls more often detected in the summer months (Table 10) and humpback whale call presence greater in the winter (Table 9). The calls most often encountered in the 'other marine mammals' category were gray whale (*Eschrichtius robustus*) knocking calls (Dahlheim 1987).

Table 10. Comparison of the proportion (%) of manually analyzed data that showed the presence of killer whales (KW), vessels, humpbacks (HB), and other marine mammals in archival data for each of the sites considered for the winter period of October to March.

Location	Hours verified	Vessel noise presence (%)	Killer Whale call presence (%)	Humpback Whale call presence (%)	Other marine mammal call presence (%)
Sturdies Bay	0.18	45.45	0.0	0.0	0.0
Enterprise Reef	13.62	87.64	0.24	0.0	0.98
Tilly Point	56.37	58.81	5.38	1.66	0.0
East Point	23.05	44.54	0.43	0.0	0.0

Table 11 Comparison of the proportion (%) of manually analyzed data that showed the presence of killer whales (KW), vessels, humpbacks (HB), and other marine mammals in archival data for each of the sites considered for the summer period of April to September.

Location	**Hours verified**	**Vessel noise presence (%)**	**Killer whale call presence (%)**	**Humpback whale call presence (%)**	**Other marine mammal call presence (%)**
Sturdies Bay	52.37	74.47	0.83	1.85	0.64
Enterprise Reef	28.75	69.56	0.0	0.06	0.29
Tilly Point	32.78	55.62	2.19	0.0	0.0
East Point	17.83	44.92	0.28	0.09	0.0

Whale call detection probability by an automated detection system at any of the evaluated WTN PAM locations appears to have a strong positive correlation with overall calling rate. The PAMLab DC system performed well in discriminating killer whale calls from other whale calls and non-whale generated sounds such as vessel noise at all locations, but did miss true killer whale and other whale calls in locations with lower call rates and high ambient noise levels. However, many of the missed detections may be better explained by local soundscape conditions and the placement of hydrophones in shallow water near vessel traffic lanes. The potential influence of physical barriers acting as acoustic barriers seem to also have affected the detection rates.

CONCLUSIONS AND RECOMMENDATIONS

PAM has long been used to detect and track whales (e.g., Clark 1990). Tracking typically requires some ability to acoustically localize whales using multiple hydrophones either as a stationary or mobile array (McDonald et al. 2001, Thode et al. 2010). Here, the effectiveness of a network of stationary single hydrophones or arrays (the WTN) to track killer whales in near real-time was evaluated.

Real-time acoustic localization has been applied for North Atlantic Right Whales (NARW) using stationary PAM systems (Gervaise et al. 2021) and for several baleen whales including NARW using acoustic gliders (Baumgartner et al. 2013) or a combination of stationary PAM and acoustic gliders (Johnson et al. 2022). Except for sperm whales (Morrisey et al. 2006, Sanguineti et al. 2021), few examples of tracking odontocetes via acoustic localization exist, with most studies focussing on localization of echolocation ‘clicks’ over short distances of a couple of hundred metres (Jang et al. 2022), or are applied to only determine the direction of calling whales relative to a hydrophone array which may be combined with visual verification of the animals location (Filatova et al. 2006).

The ability of a shore-cabled PAM station network to detect and track killer whales in near real-time, especially SRKW, is influenced by the interactions of a number of physical and biological factors. Many of these factors show considerable variation in range and magnitude of influence, thereby making it difficult to measure the combined influence empirically on both a temporally and spatially appropriate scale. Acoustic behaviour, in particular variation in vocal rates, need to be considered when deciding on where to place PAM stations and when to expect them to function optimally. Knowledge about the behaviour and ecological needs of SRKW (Thornton et al 2022a) must be considered when making decisions about where to deploy PAM stations for the purpose of tracking movements.

The influence of complex interactions on the detection range of an automated DC system was estimated using a conservative modelling approach for the range estimation, but did not consider call directionality and only estimated ranges of a single call emitted per one minute period. Killer whales may call more than once per minute and calls have directional components which likely will increase detectability but only over a short (< 1 km) range. A vessel going 8 knots travels this distance in about 5 minutes, while a travelling killer whale may cover this distance in less than 10 minutes.

The influence of an automated DC system on detection and tracking was also evaluated. While human listeners are likely superior to an automated system in detecting whale calls in most cases, the volume of acoustic data streaming from even one PAM system cannot be effectively monitored by human listeners on a 24-hour basis, let alone several PAM systems running simultaneously. Effective automated DC systems are essential for reducing the amount of data that need to be screened by a listener, and thus are a key component of a functioning whale tracking network.

To better understand the scenarios and challenging real-world conditions under which a whale tracking network should still be functional, the model results were investigated using simulated conditions at and between the WTN PAM stations. The model results were compared to the results of an automated and manual analysis of recorded data from most of those PAM stations and the results of that comparison was discussed using available information about the acoustic and physical environment and the behaviour of the whales. The automated detector was the same used as a receiver in the detection range modelling to make results comparable.

Detectability of a Killer Whale by the simulated WTN

This evaluation revealed important physical factors influencing detectability of killer whale calls via shore-cabled PAM systems such as the WTN, which included soundscape variation impacting call propagation and detection ranges around the PAM stations, the physical location of the hydrophones in the water column and their distance from shore which determines the level of captured background noise by the system, while the quality and strength of the received noise at each PAM station appeared to be an important factor influencing call detectability by an automated system. Other environmental influences included the location of the PAM stations in relation to topographical features of the environment that influence both the travel routes of the whales and the sound propagation of their calls, the mobility status (stationary or mobile) of a noise source affecting call detectability, and the movement patterns of vessels in relation to PAM stations which affects detection range and detectability both on a temporal and spatial scale. The two most important biological factors were the movement and vocal behaviour of the whales relative to the location of PAM stations.

One of the major challenges of effective acoustic tracking of killer whales across large areas and long timespans is their relative continuous movement at considerable speeds (e.g., 0.8-3.0 m/s). On the other hand, behavioural traditions such as vocal dialects (that can be used to identify groups), group/social structure, and movement patterns (often along established routes) are beneficial for acoustic tracking in that they allow identification of a group of animals and potentially predict their occurrence at specific locations. Killer whales do not vocalize everywhere at the same rate (unpublished data by the author) and vocal rate is dependent on the behavioural state of the animals (Ford 1989). Resident killer whales that travel slowly as a tight group are less likely to produce loud calls and their vocal rate is low (Ford 1989). However, when several matrilines travel together as a pod, which occurs regularly, matrilines need to vocally communicate to maintain contact. It is likely that the whales communicate at a higher rate in areas where matrilines need to make decisions on the travel route. A higher calling rate in some areas, such as at confluences of several waterways, provide a potential explanation for the higher detection rates at Tilly Point versus other areas. It is important to consider the whales' behaviour when designing an acoustic tracking network especially when the focus is to predict the whales' location into the future. Within the Salish Sea, SRKW have to make decisions about their intended direction at a number of locations where waterways part while also maintaining contact when travelling as a spread-out group.

The evaluated network in this study is a subset of the larger WTN consisting of PAM stations in Canadian waters mostly within the eastern and northern sections of the designated critical habitat of SRKW. PAM stations are mostly within the sheltered waters around the Southern Gulf Islands, nearshore areas in both the Strait of Georgia and eastern sections of Juan de Fuca Strait with Sheringham Point currently the most western PAM station. SRKW are a transboundary species whose members travel through both Canadian and US waters in the Salish Sea, limiting the effectiveness of an acoustic tracking network focused solely on Canadian waters.

The installation of shore-cabled PAM systems is limited to within a certain distance from the coastline mainly due to installation procedure and costs, including ongoing maintenance costs. The current WTN stations in most locations are within 100 m of the intertidal region. Due to demonstrated detection range limits, current WTN design cannot detect and track SRKW and other whales travelling further from shore. The use of PAM stations using the current design in the Strait of Georgia and Juan de Fuca Strait is therefore limited to areas where the whales spend time within a couple of kilometres or less than one kilometre at certain times down to a couple of hundred metres when ambient noise is high. High ambient noise levels are a typical condition in both areas.

In large parts of Juan de Fuca Strait west of Sheringham Point, SRKW travel several kilometres from shore based on the observations reported by Thornton et al (2022a) and others (Yurk, Pers. Comm.). The detection range probability estimates predict that the whales remain outside the median detection range of a shore-cabled PAM system with the current WTN design more than 50% of the time in the summer and over 90% of the time in winter based on a 2 km range estimate at Sheringham Point. Further west and on Swiftsure Bank SRKW can spend most of their foraging more than 5 km offshore and may start travelling east at that distance (Thornton et al 2022a). Detecting the initial movement east into Juan de Fuca Strait would be essential for a SRKW tracking network. Mouy et al. (2020) modelled other locations further west not described in this report that confirm the limitations in detection range in many areas of the western Juan de Fuca Strait and on Swiftsure Bank.

Shore-cabled PAM systems in those areas would require longer cable connections and potentially a change of the cable type from the currently used cable in sheltered waters to a more robust type that can withstand the high waves experienced by the intertidal in these more exposed areas. Moving the hydrophone arrays further offshore would also require the installation of signal repeater stations

Based on the high financial costs of installation and maintenance, one needs to make sure that any near real-time PAM station, shore-cabled or other technological approach, is placed at a location that has a high probability of detecting whales acoustically over a large enough area. Locations where the whales vocalize regularly, and where the system can collect reliable detection information will allow predicting movement of the whales. If the predicted movement is in a direction in which they will be at risk of experiencing high acoustic and physical disturbance including ship strikes or will enter an area of high importance for survival, mitigation can be initiated. In areas with high foraging rates where management actions may occur, such as dynamic fishing activity closures, the location and reliability of the system is essential as the whales need to be detected before entering the area to alert conservation mangers about their movement in that direction. Shore-cabled systems are not a suitable tool to achieve either of these goals in areas west of Sheringham Point.

The consistency and variation of ambient and background noise levels were identified as factors that are highly influential for the ability of an automated detection system based on shore-cabled or other PAM systems to detect killer whales. High ambient noise levels reduce detection range and overall call detectability and limit acoustic tracking capabilities of a PAM network. In places where ambient noise levels are consistently high, the detection range can become too low to allow for tracking of whales that travel a couple of hundred metres or less away from the PAM station.

Certain areas within the Salish Sea show consistently high ambient underwater noise levels year-round such as those with high commercial and non-commercial vessel traffic and other on-water or near-water human activities[6] or those with high natural ambient noise levels (Burnham et al 2021, Thornton et al. 2022b). Areas with high underwater noise levels near SRKW travel routes are: the southern sections of the Strait of Georgia especially along the eastern shorelines from the entrance of Rosario channel north to the entrance of Howe Sound, and the eastern sections of Juan de Fuca Strait to west of Sooke. The results of this evaluation showed that detection ability of automated systems applied to data streams from shore cabled systems in environments with high ambient underwater noise is greatly limited and tracking killer whales or other whales acoustically via shore-cabled systems is not effective.

The marine waters outside the estuary of the Fraser River in the Strait of Georgia are traditional foraging areas for SRKW (Heimlich-Boran 1988) and are identified as high occurrence area in Thornton et al (2022a). However, maintaining shore-cabled hydrophone systems in that area is difficult and not likely to be very successful due to the high outflow of the river transporting large amounts of silt and sand with it, which will cause the mooring to be covered and/or collapse in a short time period. Monitoring presence of SRKW in these areas would still be very important but tracking movements for the purpose of issuing alerts of their approach to this area should take place further away from the estuary.

Shore-cabled PAM systems are likely also ineffective south of the estuary due high ambient noise levels around an existing commercial vessel terminal and ferry terminal located there. A bottom-mounted acoustic array tethered to a surface buoy was tested a little further south in US waters off Point Roberts and showed reasonable detectability of killer whale calls during the winter (Yurk et al. in prep.) North of the estuary is another area with high occurrence probability off Point Grey (Thornton et al 2022a), which is close and overlapping with the international shipping lane for vessels going in out of Burrard Inlet. The area is characterized by very high small vessel traffic and high levels of other human activity due to its proximity to Vancouver. Overall, the eastern shoreline of the Strait from Tsawwassen in the south to Halfmoon Bay north of Sechelt is not very suitable for shore-cabled PAM of whales. The western shoreline of the Strait, which is used by SRKW when travelling to the northern sections of the Strait of Georgia, is more suitable for shore-cabled PAM systems for the purpose of tracking killer whales because of lower overall ambient underwater noise levels and fewer physical obstacles that negatively impact the deployment of cables.

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[6] 118037E.pdf (ceaa-acee.gc.ca)

Similarly, the western sections of Haro Strait are also not suitable for shore-cabled PAM systems because of the distance that SRKW travel away from shore and the international shipping lane that would be between the whales and the arrays most of the time. SRKW spend most of their time travelling and foraging in Haro Strait along the San Juan Islands shorelines in US waters. Several PAM stations off San Juan Island detect SRKW regularly.

At the southern end of Haro Strait around Discovery Island the tidal currents are very strong making it unsuitable for acoustic detection systems and shore-cabled systems will get damaged quickly. The eastern sections of Juan de Fuca Strait also show high ambient noise levels due to vessel traffic in and out of Victoria harbour and small vessel traffic out of Sooke harbour. Furthermore, ambient noise levels are high due to wind noise entering the water column (Burnham et al. 2021, Thornton et al. 2022b). Wind is a prominent feature in this area year-round and limits the effectiveness of acoustic detection considerably and makes it an unsuitable area for any NRT acoustic tracking.

Ambient noise can also be a factor limiting detectability of killer whale calls in the waters around the Southern Gulf Islands. Especially during daylight hours in Active Pass and Swanson Channel in the summer due to increased vessel traffic compared to winter months. The difference in expected detectability and measured detection rate at some stations such as Enterprise Reef was surprising and should be investigated further. Background noise is not only influenced by high levels of ambient sound generated by vessels or wind, rain and other natural causes but may be due to noise sources that result from the hydrophone placement in high tidal currents or near underwater rock formations that produce noise during windy conditions. Furthermore, the underwater topography around hydrophones in shallow water (< 25m) is often characterized by boulders and other obstacles that create acoustic shadows in certain directions. Especially, when the array is placed near a reef this can limit the detectability of calls considerably. Other detectability issues may result from faults in the recording system itself such a system self-noise which can be a substantial factor and make it impossible to detect calls that have their main energy in the frequency ranges affected by the system self-noise.

Based on the results of this evaluation of the PAM network and also considering other information reported in Burnham et al. (2021), Vagle et al. (2021), Thornton et al. (2022a, 2022b) one can develop a suitability range for shore-cabled PAM stations in the Salish Sea. The range needs to consider the soundscape suitability, the acoustic and movement behaviour of the whales, and identify areas where shore-cabled systems are likely too costly to install and/or maintain. Figure 19 depicts the suitability of shore-cabled PAM stations to detect killer whales and other whales in the Salish Sea.

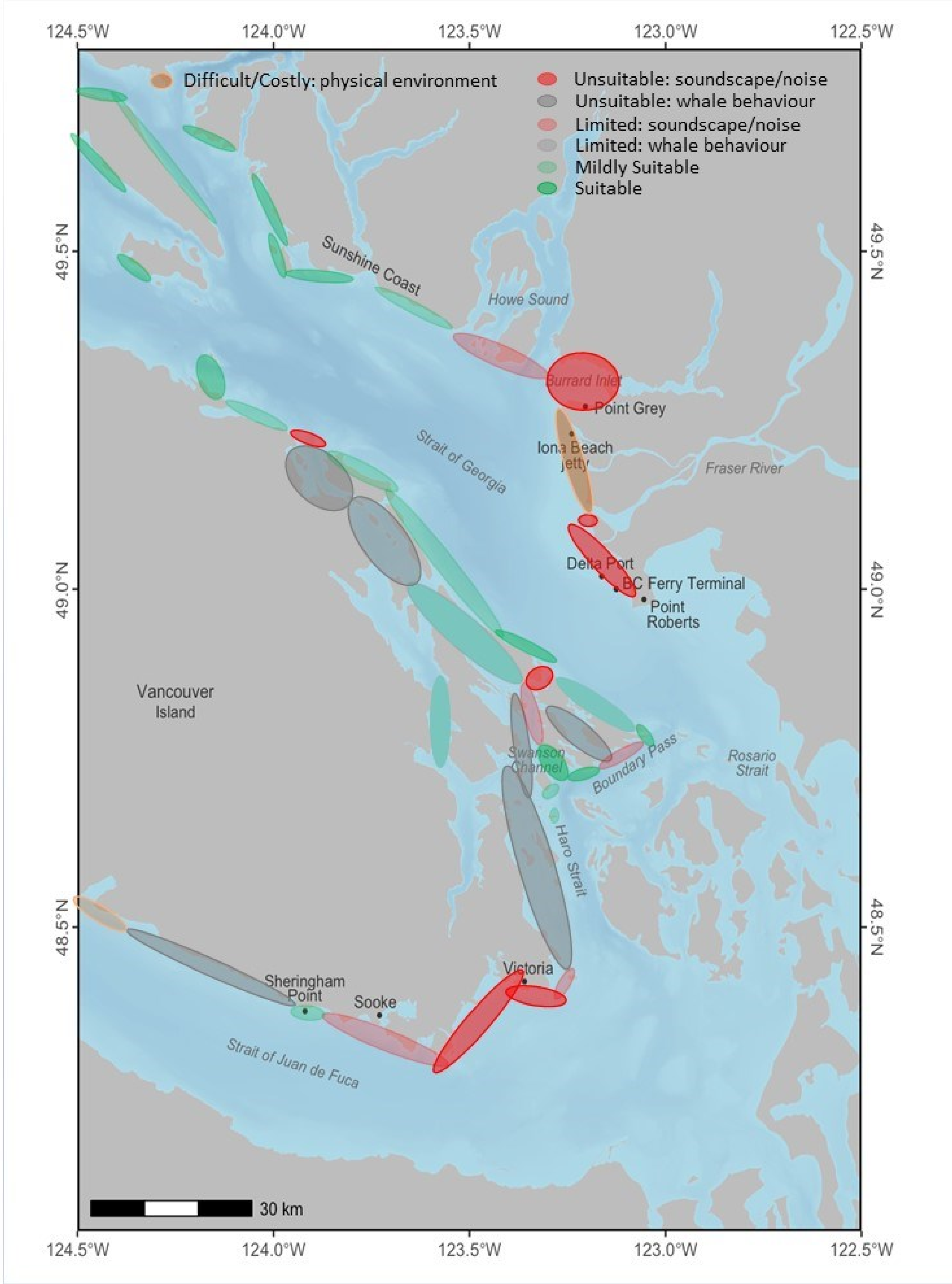

Figure 19. Suitability range of shore-cabled PAM system deployments in the Salish Sea to detect SRKW for the purpose of tracking them in near real-time.

Recommendations for the Design of a Whale Tracking Network in the Salish Sea

The evaluation of the effectiveness of a network of shore-cabled PAM systems within Canadian waters of the Salish Sea to track whales, especially killer whales in near real-time, showed that a singular technology-based monitoring system is not effective and is likely too expensive to install and maintain at certain locations. There exist, however, a number of different methods to track killer whales aside from PAM such as visual and infrared imagery that can be combined with acoustic monitoring (see Theriault et al 2020). Automated detection algorithms that use data streams from infrared cameras to detect thermal or heat signatures coming from whales and their blows have been tested in a number of places around the world including the Salish Sea (Richter et al. in prep) and appear to increase detectability especially in areas in which high underwater noise is a prominent and consistent factor limiting the use of PAM. This technology can also determine the travel direction of the whales and can be combined with PAM to create a network that is more suitable to track whales reliably in every season and at different locations. Another source of detections comes from volunteer-based observer networks that exist in a number places in both Canada and the USA, such as the volunteer observer network covering the waters around the Southern Gulf Islands[7] and another that monitors the waters around the San Juan Islands and Puget Sound in Washington State[8] as well as parts of the Southern Strait of Georgia. The detections are typically limited to daytime sightings of whales but some of the NGOs behind the observer networks operate their own PAM systems, such as the Saturna Island Marine Research and Education Society (SIMRES) who operates two PAM systems in Boundary Pass and with support from DFO one thermal imaging whale detection system. Others like the Orca Network work closely with other NGOs who operate PAM systems such as OrcaSound[9] and the Whale Museum[10] in Friday Harbor on San Juan Island who works with a private partner that specializes on acoustic impact assessment (SMRU Consulting) and operates a shore-cabled PAM systems off the west side of San Juan Island[11]. Furthermore, Transport Canada together with the ECHO program of the Vancouver Port Authority fund two shore-cabled PAM arrays operated by JASCO Applied Sciences in Boundary Pass[12]. The high-tech arrays' main purpose is to monitor and measure ship noise in the shipping lane but the deployed technology also allows whale detection and localization.

One way to improve the effectiveness of a future WTN would be to build a web-cloud-based detection and tracking framework utilizing the available whale detection data sources and verify them by providing a network of experts on whale detection access to the detections, which than can be fed into a whale movement forecasting model (Randon et al. 2022). The forecasting model can provide updated on-time information on future whale locations for various client organizations, such as the Whale Desk operated by the Marine Communication and Traffic Services (MCTS) of the Canadian

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[7] SGI WHALE SIGHTING NETWORK - SIMRES

[8] Orca Network

[9] Orcasound – Listen for whales

[10] The Whale Museum | Friday Harbor, Washington

[11] Lime Kiln Live Hydrophone — SMRU Consulting

[12] Boundary Pass Underwater Listening Station | JASCO Applied Sciences

Coast Guard which is setup to alert mariners of the presence of whales (Canadian Coast Guard opens the first Marine Mammal Desk to better protect SRKW and other cetaceans - Canada.ca. Accessed Feb 10, 2023). DFO’s conservation mangers can also benefit from these alerts that would get updated regularly via predictions from the forecasting model. These predictions could help them focus their attention to the places the whales may be in the next 2-3 hours.

The various organizations that provide the data for the framework can also receive specific alerts for their area of interest that allows them to prepare their observers for the approach of whales, which then improves the resolution of the tracking data input. The general public can have access to time-delayed detection summaries on a web site that also provides useful information for mariners on how to operate a vessel around whales. The cloud-based server can be setup to collect detection data and analyze past movements of the whales which will be useful for researchers and conservation managers alike. Finally, DFO can focus on adding monitoring capacity in areas where there are no existing observer or PAM networks using both appropriate PAM systems and thermal imaging monitoring systems at suitable locations.

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