TP 15508E

Assessing Sonar Sound Levels from Commercial Ships

Version 2.0

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Assessing Sonar Sound Levels from Commercial Ships

Final Report
Version 2.0

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JASCO Applied Sciences (Canada) Ltd

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NOTICES

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D.E. Hannay. Recreation vessel with southern resident killer whales.

J. Koblitz. Southern resident killer whale.

Un sommaire français se trouve avant la table des matières

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16. Abstract

Transport Canada tasked JASCO Applied Sciences to study the occurrence of sonar sounds in the acoustic data recorded at sample rates of 128 kHz (usable data up to 60 kHz) on the Georgia Strait underwater listening station (ULS) and on the autonomous recorders deployed at Boundary Pass up to October 2019. Sonars were detected in 1.3% of the vessel passages. Three types of sonars were identified: single frequency echosounders, multi-frequency echosounders, and a continuous ultrasonic source. Both types of echosounders had highly directional beampatterns, which means the sounds were directed down towards the seabed and were generally only audible for 2–5 minutes during a vessel passage. High-frequency cetaceans (porpoise) that are directly underneath these sonars are expected to experience a temporary change in their hearing thresholds (TTS). The continuous ultrasonic source occupied the frequency band of 18–26 kHz. It was not directional and was audible 4–6 km from the vessel. High-frequency cetaceans within 1 km of a vessel track are likely to experience TTS, and southern resident killer whales have greatly reduced echolocation ranges for periods of 15–20 minutes during the vessel passage. A key recommendation from this study is to identify this continuous ultrasonic source and prohibit its use in Canadian waters. This analysis should be revisited with the Boundary Pass ULS data, which has usable acoustic data up to 250 kHz.

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16. Résumé

Transports Canada a chargé JASCO Applied Sciences d'étudier la présence des sons de sonar dans les données acoustiques enregistrées à des taux d'échantillonnage de 128 kHz (données utilisables jusqu'à 60 kHz) à la station d'écoute sous-marine du détroit de Georgia et sur les enregistreurs autonomes déployés au passage Boundary jusqu'en octobre 2019. Les sonars ont été détectés dans 1,3 % des passages de navires. Trois types de sonars ont été recensés : des échosondeurs à fréquence unique, des échosondeurs multifréquences et une source ultrasonique continue. Les deux types d'échosondeurs avaient des diagrammes de faisceau hautement directionnels, ce qui signifie que les sons étaient dirigés vers le plancher océanique et n'étaient généralement audibles que pendant 2 à 5 minutes lors du passage d'un navire. Les cétacés dotés d'une ouïe à hautes fréquences (marsouins) qui se trouvent directement sous ces sonars subissent probablement une modification temporaire de leur seuil auditif. La source continue d'ultrasons occupait la bande de fréquence de 18-26 kHz. Elle n'était pas directionnelle et était audible à 4-6 km du navire. Les cétacés dotés d'une ouïe à hautes fréquences se trouvant à moins de 1 km de la trajectoire d'un navire sont susceptibles de subir une modification temporaire de leur seuil auditif, et les épaulards résidents du Sud ont des portées d'écholocation fortement réduites pendant des périodes de 15 à 20 minutes lors du passage du navire. Une recommandation clé de cette étude est de déterminer cette source continue d'ultrasons et d'en interdire l'utilisation dans les eaux canadiennes. Cette analyse devrait être réexaminée avec les données de la station d'écoute sous-marine du passage Boundary, qui possède des données acoustiques utilisables jusqu'à 250 kHz.

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EXECUTIVE SUMMARY

The Vancouver Fraser Port Authority’s Enhanced Cetacean Habitat and Observation (ECHO) Program operated an underwater listening station (ULS) in the Strait of Georgia from September 2015 to April 2018. In December 2018, autonomous acoustic recorders were deployed in Boundary Pass to continue the vessel source level measurements that were begun with the ULS. These stations measured the sound levels generated by several thousand vessels transiting to terminal in Vancouver. The last year of the ULS data and all the Boundary Pass data had a 128 kHz sampling rate, which provided measurements up to 64 kHz of the sounds generated by the vessels. The new measurements included anomalously high sound levels at higher frequencies (above 20 kHz) that have been attributed to depth sounders, navigation sonars, fisheries sonars, and a variety of other sources.

While the measured energy from these high-frequency sources was generally lower than the sounds from the vessel’s propulsion, at close ranges the levels could disturb and injure odontocetes. This group includes dolphins, porpoises, and southern resident killer whales (SRKW). It is therefore important to understand the sound levels of these sonars and the distances from the vessel at which they may have effects on marine mammals. Possible effects include hearing threshold shifts and masking that could affect the echolocation space for the animals. JASCO Applied Sciences was tasked by Transport Canada to study the sonar emissions from the full range of commercial vessels in the data sets.

This study analyzed the 2-to-5-minute-long segments of acoustic data associated with the 16000 vessel source level measurements that had been performed using the ECHO ULS and Boundary Pass observatories up to October 2019. Sonar emissions were identified in 221 cases, representing 1.3% of the vessel measurements. The sonar emissions were categorized into three groups—single frequency echosounders (~50% of the sonars), multi-frequency echosounders (~20% of the sonars), and a continuous ultrasonic source in the 18–26 kHz range (30% of the measurements).

The analysis focused on the 20–63 kHz decidecade frequency bands, which are associated with the echolocation frequencies of SRKW. The sound levels radiating vertically and horizontally from the sonars were estimated, as well as the reduction in the echolocation listening range for SRKW—i.e., how much the presence of vessels and sonars affect the ability of the SRKW to hear echoes from their foraging clicks.

Received sound levels from the single and multi-frequency echosounders had median levels 3 dB higher than for vessels that did not have sonar emissions. The direct overpass of a multi-frequency echosounder at the ECHO ULS allowed the beampattern of the sonar to be measured, which confirmed that energy directed to the seabed is much higher than energy radiating horizontally from the sonar. The computed echolocation listening range for SRKW exposed to the horizontally propagating energy was reduced by at least 75% during the 1–2 minutes that either type of vessel was within 500 m of the recording location, indicating that foraging and navigating is substantially impacted by vessel passages. Odontocetes, especially porpoises, that are exposed to an echosounder directly above them are likely to experience temporary threshold shifts (TTS) in hearing sensitivity.

Received levels from the continuous ultrasonic source had median sound exposure levels 20 dB higher than from the echosounders. These systems did not have the highly directional beampattern directed at the seabed that was characteristic of the echosounders. These sources were detectable at ranges of 4–6 km from the recording location. Their SEL were high enough to suggest that porpoises and other high-frequency cetaceans within 1 km of a vessel passage could experience TTS. The frequency at which the TTS occurs overlaps with killer whale echolocation clicks and would impact the porpoises’ ability to detect them. The continuous ultrasonic source completely inhibits killer whale echolocation in the 20–30 kHz frequency range for 15–20 minutes during the passage of the vessel.

Recommendations arising from this study include:

- Implementing real-time sonar detection on the Boundary Pass observatory and educating vessel master’s with active sonars about the impacts associated with their unnecessary use.
- Conducting a study to find which systems generate the continuous ultrasound and banning their use in Canadian waters.
- Authoring a peer-reviewed publication on the continuous ultrasound source.
- Lobbying the International Maritime Organization (IMO) to ban the continuous ultrasonic source; and
- Revisiting this study in 2022 to examine how implementing real-time notifications has changed sonar use at Boundary Pass and if there are sonar emissions above 60 kHz that are present in the Boundary Pass ULS data that were not recorded by the ECHO ULS and autonomous recorders.

SOMMAIRE

Le programme d’observation et de soutien aux cétacés (Enhancing Cetacean Habitat and Observation [ECHO] Program) de l’Administration portuaire Vancouver Fraser a exploité une station d’écoute sous-marine (SES) dans le détroit de Georgia de septembre 2015 à avril 2018. En décembre 2018, des enregistreurs acoustiques autonomes ont été déployés dans le passage Boundary afin de poursuivre les mesures du niveau de la source des navires qui ont débuté avec la SES. Ces stations ont mesuré les niveaux sonores générés par plusieurs milliers de navires transitant vers le terminal de Vancouver. La dernière année des données de la SES et toutes les données du passage Boundary présentaient un taux d’échantillonnage de 128 kHz, ce qui a fourni des mesures des sons générés par les navires jusqu’à 64 kHz. Les nouvelles mesures comprenaient des niveaux sonores anormalement élevés à des fréquences plus élevées (au-dessus de 20 kHz) qui ont été attribués aux échosondeurs, aux sonars de navigation, aux sonars de pêche et à diverses autres sources.

Bien que l’énergie mesurée de ces sources à haute fréquence était généralement inférieure aux sons de la propulsion du navire, à courte distance, les niveaux pouvaient perturber et blesser les odontocètes. Ce groupe comprend les dauphins, les marsouins et les épaulards résidents du sud (ERS). Il est donc important de comprendre les niveaux sonores de ces sonars et les distances du navire auxquelles ils peuvent avoir des effets sur les mammifères marins. Les effets possibles comprennent des déplacements du seuil auditif et un masquage qui pourraient affecter l’espace d’écholocalisation pour les animaux. Transports Canada a chargé JASCO Applied Sciences d’étudier les émissions de sonar de la gamme complète de navires commerciaux dans les ensembles de données.

Cette étude a analysé les segments de données acoustiques de 2 à 5 minutes associés aux 16 000 mesures du niveau de la source des navires qui avaient été effectuées à l’aide de la SES du programme ECHO et des observatoires du passage Boundary jusqu’en octobre 2019. Des émissions de sonar ont été identifiées dans 221 cas, représentant 1,3 % des mesures des navires. Les émissions de sonar ont été classées en trois groupes : les échosondeurs monofréquences (environ 50 % des sonars), les échosondeurs multifréquences (environ 20 % des sonars) et une source ultrasonore continue dans la plage de 18 à 26 kHz (30 % des mesures).

L’analyse était axée sur les bandes de fréquences de 20 à 63 kHz, qui sont associées aux fréquences d’écholocalisation de l’ERS. Les niveaux sonores rayonnant verticalement et horizontalement à partir des sonars ont été estimés, ainsi que la réduction de la portée d’écoute de l’écholocalisation pour l’ERS – c’est-à-dire la mesure dans laquelle la présence de navires et de sonars affecte la capacité de l’ERS à entendre les échos de ses clics de recherche de nourriture.

Les niveaux sonores détectés par les échosondeurs monofréquences et multifréquences indiquaient des niveaux médians supérieurs de 3 dB à ceux des navires qui n’avaient pas d’émissions de sonar. Le passage direct d’un échosondeur multifréquence à la SES du programme ECHO a permis de mesurer le diagramme de faisceau du sonar, ce qui a confirmé que l’énergie dirigée vers le fond marin est nettement supérieure à l’énergie rayonnant du sonar horizontalement. La portée d’écoute calculée de l’écholocalisation pour l’ERS exposé à l’énergie se propageant horizontalement a été réduite d’au moins 75 % pendant les 1 à 2 minutes où l’un ou l’autre type de navire se trouvait à moins de 500 m du lieu d’enregistrement, ce qui indique que la recherche de nourriture et la navigation sont considérablement affectées par les passages de navires. Les odontocètes, en particulier les marsouins, qui sont exposés à un échosondeur se trouvant directement au-dessus d’eux sont susceptibles de subir des déplacements temporaires de seuil (TTS) de la sensibilité auditive.

Les niveaux détectés de la source ultrasonore continue indiquaient des niveaux d’exposition sonore médians supérieurs de 20 dB à ceux des échosondeurs. Ces systèmes n’étaient pas munis du diagramme de faisceau hautement directionnel dirigé vers le fond marin propre aux échosondeurs. Ces sources étaient détectables à des distances de 4 à 6 km du lieu

d’enregistrement. Leur niveau d’exposition au bruit (SEL) était suffisamment élevé pour suggérer que les marsouins et autres cétacés vocalisant à haute fréquence qui se trouvent à moins de 1 km du passage d’un navire pourraient subir des TTS. La fréquence à laquelle le TTS se produit chevauche les clics d’écholocalisation des épaulards et aurait une incidence sur la capacité des marsouins à les détecter. La source ultrasonore continue inhibe complètement l’écholocalisation des épaulards dans la gamme de fréquences de 20 à 30 kHz pendant 15 à 20 minutes lors du passage du navire.

Voici les recommandations découlant de cette étude :

- Mettre en œuvre la détection par sonar en temps réel à l’observatoire du passage Boundary et éduquer les capitaines de navires équipés de sonars actifs sur les répercussions associées à leur utilisation inutile.
- Mener une étude pour trouver quels systèmes génèrent des ultrasons continus et interdire leur utilisation dans les eaux canadiennes.
- Rédiger une publication à comité de lecture sur la source ultrasonore continue.
- Faire du lobbying auprès de l’Organisation maritime internationale (OMI) pour interdire la source ultrasonore continue.
- Réviser cette étude en 2022 afin de déterminer dans quelle mesure la mise en œuvre des notifications en temps réel a modifié l’utilisation du sonar au passage Boundary et si des émissions de sonar supérieures à 60 kHz sont présentes dans les données de la SES du passage Boundary qui n’ont pas été enregistrées par la SES du programme ECHO et les enregistreurs autonomes.

]

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GLOSSARY

1/3-octave-band
Non-overlapping passbands that are one-third of an octave wide (where an octave is a doubling of frequency). Three adjacent 1/3-octave-bands comprise one octave. One-third-octave-bands become wider with increasing frequency. Also see octave.

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

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

automated identification system (AIS)
A radio-based tracking system whereby vessels regularly broadcast their identity, location, speed, heading, dimensions, class, and other information to nearby receivers.

broadband sound level
The total sound pressure level measured over a specified frequency range. If the frequency range is unspecified, it refers to the entire measured frequency range.

cavitation
A rapid formation and collapse of vapor cavities (i.e., bubbles or voids) in water, most often caused by a rapid change in pressure. Fast-spinning vessel propellers typically cause cavitation, which creates a lot of noise.

cetacean
Any animal in the order Cetacea. These are aquatic, mostly marine mammals and include whales, dolphins, and porpoises.

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

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

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

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

ECHO
Enhancing Cetacean Habitat and Observation Program.

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

hertz (Hz)
A unit of frequency defined as one cycle per second.

IMO
International Maritime Organization

octave
The interval between a sound and another sound with double or half the frequency. For example, one octave above 200 Hz is 400 Hz, and one octave below 200 Hz is 100 Hz.

power spectrum density
The acoustic signal power per unit frequency as measured at a single frequency. Unit: $\mu Pa^2/Hz$, or $\mu Pa^2 \cdot s$.

power spectral density level
The decibel level ($10\log_{10}$) of the power spectrum density, usually presented in 1 Hz bins. Unit: dB re 1 $\mu Pa^2/Hz$.

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

received level
The sound level measured at a receiver.

rms
root-mean-square.

SRKW
southern resident killer whale

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

sound exposure level (SEL)
A cumulative measure related to the sound energy in one or more pulses. Unit: dB re 1 $\mu Pa^2 \cdot s$. SEL is expressed over the summation period (e.g., per-pulse SEL [for airguns], single-strike SEL [for pile drivers], 24-hour SEL).

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

For sound in water, the reference sound pressure is one micropascal (p_0 = 1 μPa) and the unit for SPL is dB re 1 μPa:

$$\mathrm{SPL} = 10\log_{10}\left(p^2/p_0^2\right) = 20\log_{10}\left(p/p_0\right)$$

Unless otherwise stated, SPL refers to the root-mean-square sound pressure level. See also 90% sound pressure level and fast-average sound pressure level.

source level (SL)
The sound level measured in the far-field and scaled back to a standard reference distance of 1 metre from the acoustic centre of the source. Unit: dB re 1 µPa @ 1 m (sound pressure level) or dB re 1 µPa^2·s (sound exposure level).

spectrum
An acoustic signal represented in terms of its power (or energy) distribution compared with frequency.

sound speed profile
The speed of sound in the water column as a function of depth below the water surface.

temporary threshold shift (TTS)
Reversible loss of hearing sensitivity. TTS can be caused by noise exposure.

ULS
Underwater Listening Station.

wavelength
Distance over which a wave completes one oscillation cycle. Unit: metre (m). Symbol: λ.

1. INTRODUCTION

The Vancouver Fraser Port Authority's Enhanced Cetacean Habitat and Observation (ECHO) Program operated an underwater listening station (ULS) in the Strait of Georgia from September 2015 to April 2018. In December 2018, autonomous acoustic recorders were deployed in Boundary Pass to continue the vessel source level measurements that were begun with the ULS. These stations measured the sound levels generated by several thousand vessels transiting to terminal in Vancouver. The last year of the ULS data and all the Boundary Pass data had a 128 kHz sampling rate, which provided measurements up to 64 kHz of the sounds generated by the vessels. The new measurements include anomalously high sound levels at higher frequencies (above 20 kHz) that have been attributed to depth sounders, navigation sonars, fisheries sonars, and a variety of other sources.

In a previous study focused only on passenger vessels, MacGillivray and Li (2018) found that 44 of 156 cruise ship measurements collected over a period of approximately 6 months included high-frequency emissions. There were two types of sound in the data—a nearly continuous band of energy in the 18–26 kHz range and a short pulse of sound above 45 kHz that was repeated every 0.1–3 seconds. The source of the continuous sound was unidentified but may be a relatively new device, an ultrasonic hull cleaner. The second source was most likely a 50 kHz depth sounder that is used to ensure a ship is not in danger of running aground.

In general, the sonar sound levels at a long distance from the vessels are lower than the low-frequency propulsion sounds; however, at close ranges the levels can become high enough to be considered a possible disturbance to odontocetes. This group includes dolphins, porpoises, and the southern resident killer whales (SRKW). It is therefore important to understand the sound levels of these sonars and the distances from the vessel at which they may have effects on marine mammals. Possible effects include hearing threshold shifts and masking that could affect echolocation space for the animals.

To help address this knowledge gap, JASCO Applied Sciences was tasked by Transport Canada to study the sonar emissions from the full range of commercial vessels in the ECHO data set. The tasks were:

1. Review ECHO's measurements to identify the instances where sonar sound levels are significant.
2. Analyze the data in one-second windows during each pass to quantify the received sound levels in the sonar bands, including identifying the sonar bands by type of sonar.
3. Evaluate the sonar source levels as a function of range and bearing to the vessels.
4. Evaluate the potential for the sonars to impact marine mammals, including reductions in SRKW echolocation space.
5. Report on the results of the analysis.

This study provides the results requested by Transport Canada. The remainder of Section 1 provides an overview of typical sonar sound sources employed on commercial vessels and a review of the available literature on the characteristics and effects on marine mammals of those sonars. Section 2 describes the methods used in the analysis of the ECHO data. Section 3 presents the results of the sonar analysis as well as the echolocation space reduction. Section 4 discusses the results in the context of the possible effects on the marine mammals. Section 5 presents the study conclusions and recommendations for further investigations.

1.1. Commercial Vessel Sonars

Commercial vessels employ sonars for a wide variety of applications. Most vessels have a depth sounder that allows them to measure the distance to the seabed to help them safely navigate nearshore. Fishing vessels and research vessels often have fisheries echosounders that emit multiple frequencies locate different sized fish in the water column. Specialized survey vessels have multibeam echosounders that provide fine-scale images of the seabed for a variety of applications. Underwater acoustic modems and acoustic positioning systems are becoming common place in areas with in-water commercial construction and infrastructure, including fish farms. Finally, ultrasonic transducers are employed to reduce biofouling on vessel hulls; these transducers appear to generate ultrasound that propagates in water.

Commercial sonars generally emit a short sound and then switch to a listening mode to receive reflections for their target of interest—the seabed, fish, or other transducers. Sonars are characterized by the following key parameters (also see Figure 1):

1. Centre frequency: For the sonars considered here the sonar frequency may be 12 kHz up to hundreds of kHz. High frequencies provide finer spatial resolutions and reflect from smaller targets; they to not travel as far as low frequencies (see Section 1.1.3). In Figure 1, single vessel is showing three sonar frequencies at 28, 38 and 50 kHz. Often sonars transducers are not ‘clean’, and stray energy at multiples of the intended frequency are emitted. In Figure 1, we see the first harmonic of the 28 kHz sonar at 56 kHz.
2. Pulse type: Pulses can be simple sounds at a single frequency, more complex swept frequencies, or communications signals that “hop” between frequencies; the signal shape affects the type of information that can be obtained about the target or communicated between source and receiver. The sonars in Figure 1 have a simple pulse shape at a single frequency as shown in the inset.
3. Pulse duration: This is the length of time that a transmitter is on. This parameter affects the range resolution of the sonar, the minimum sensing distance, and how much energy is emitted (which affects detection range). Pulse durations range from tens of microseconds to several milliseconds for most pulse-based sonars. Some types of sonars and sound sources can also generate continuous sounds.
4. Inter-pulse interval (IPI): This is the time between pulses (i.e. the reciprocal of the pulse repetition rate). The IPI is directly related to the maximum distance from the sonar that can be sensed because the sound must travel from the sonar to the target and back again before the next pulse is emitted. In Figure 1, there are three IPIs: IPI 1 at 28 kHz is 0.56 s, IPI 2 is 0.39 s, and IPI 3 is 0.28 s.
5. Source level: This is a measure of the output sound power. Because sonars measure sound reflected from their target, they need to have high source levels, especially for long range detection. In Figure 1, the recording includes visible reflections and reverberation from the seabed.
6. Transducer beampattern which describes the directionality of the sound emitted by the sonar (see Section 1.1.1).

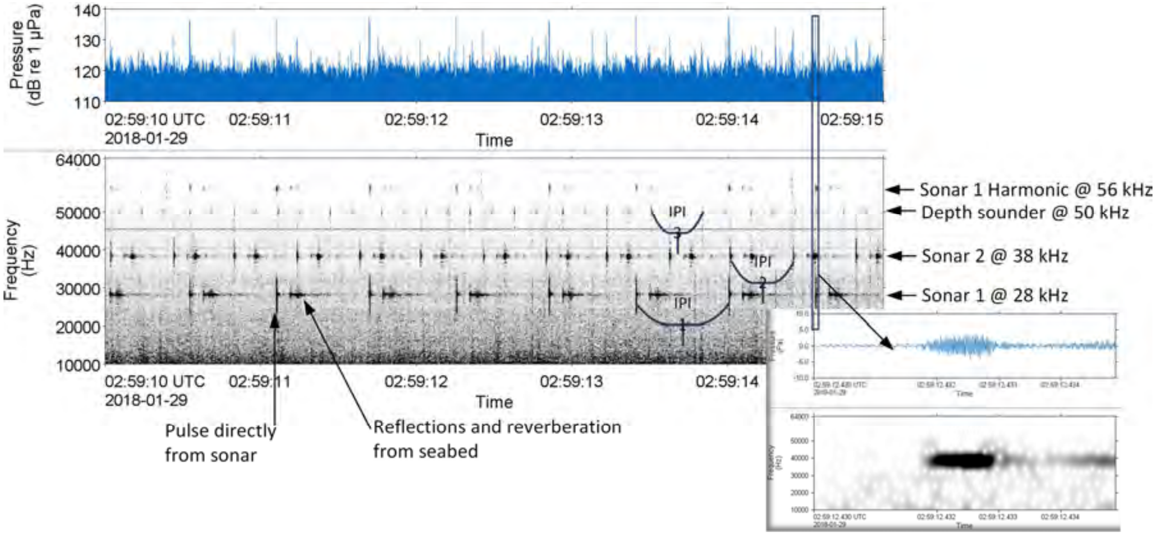


Figure 1. A five-second high-frequency acoustic scene as a 58 m fishing vessel approached the Enhanced Cetacean Habitat and Observation (ECHO) Program underwater listening station (ULS) on 29 Jan 2018. Three echosounders were active at 28, 38, and 50 kHz. The inset at the bottom right shows the (top) time series and (bottom) spectrogram of a single 1 ms long sonar pulse at 38 kHz.

1.1.1. Sonar Beampatterns

High-frequency underwater acoustic sources used in sonars create an oscillatory overpressure through rapid vibration of a surface, using either electromagnetic forces or the piezoelectric effect of some materials. A vibratory source based on the piezoelectric effect is commonly referred to as a transducer and might be capable of receiving as well as emitting signals. Transducers are usually designed to produce an acoustic wave of a specific frequency, often in a highly directive beam. The directional capability increases with increasing operating frequency. The main parameter characterizing the directivity is the beamwidth, defined as the angle subtended by diametrically opposite “half power” (−3 dB) points of the main lobe. For different transducers, the beamwidth can vary from only a few degrees to almost omnidirectional (180°).

Transducers are usually built with either circular or rectangular active surfaces. For circular transducers, the beamwidth in the horizontal plane (assuming a downward pointing main beam) is equal in all directions. Rectangular transducers produce more complex beam patterns with variable beamwidth in the horizontal plane; two beamwidth values are usually specified for orthogonal axes.

The acoustic radiation pattern, or beam pattern, of a transducer is the relative measure of the acoustic power as a function of spatial angle. Directionality is generally measured in decibels relative to the maximum radiation level along the central axis, perpendicular to the transducer surface. The pattern is defined largely by the operating frequency, size, and shape of the transducer.

Beam patterns generally consist of a main lobe, extending along the central axis of the transducer, and multiple secondary lobes separated by nulls. The width of the main lobe depends on the size of the active surface relative to the sound wavelength in the medium, with larger transducers producing narrower beams. Figure 2 presents a 3-D visualization of a generic beam pattern of a circular transducer.

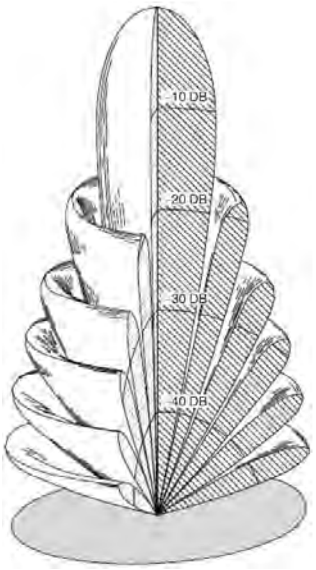


Figure 2. Typical 3-D beam pattern of a circular transducer (Massa 2003).

The beamwidth, a key characteristic of transducers, is generally defined as the total angular range where the sound pressure level of the main beam is within 3 dB of the on-axis peak power (Massa 2003). The true beam pattern of a transducer, especially the secondary lobes, can be irregularly shaped (Figure 3) and thus might differ from the beam pattern calculated through transducer theory. The true beam pattern of a transducer can be obtained only by measuring the emitted energy around the device when it is in place. Such data, however, are not always available.

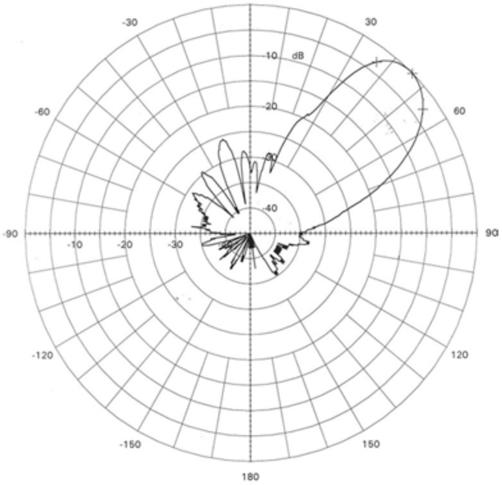


Figure 3. Polar representation (vertical slice) of a beam pattern obtained by in situ measurement of a transducer used by Kongsberg (obtained through personal communications with the manufacturer).

In the current analysis, the beampattern affected the received levels and our ability to estimate source levels for the sonars. The sonars measured were generally pointed toward the seabed. The desired path of commercial vessels past the ULS was along a track 150–500 m horizontal range from the ULS location (in water 170 m deep) so that the angle of the sound arriving was between 15 and 45 degrees from horizontal. Therefore, the sound received at the ULS from highly directional sonars from sidelobes of the transducer, which are often 25–40 dB below the main lobe (Figure 3).

1.1.2. Types of Commercial Sonars

There are five common types of commercial sonars that are introduced in this section. A survey of commercial sonar specifications is shown in Table 1.

- *Depth Sounders*: Depth sounders are used to determine the water depth under a vessel for navigation purposes; virtually all vessels have this type of instrument, including most pleasure craft that travel along the British Columbian coast. Common frequencies for depth sounders are 27 and 50 kHz.
- *Fisheries Echosounders*: These devices may range from recreational fish finders to powerful multi-frequency systems that provide information on the size of fish as well as their depth. Common frequencies for these systems are 12, 18, 38, 70, 125, and 200 kHz.
- *Multibeam Sonars*: Multibeam sonars are sophisticated versions of depth sounders that are used to provide fine resolution images of the seabed. The images may be used for developing bathymetry maps or for visualizing sea-floor objects such as wrecks or subsea infrastructure (pipelines, moorings etc.). Modern multibeam systems emit sound over a wide frequency range using complex waveforms that improve the resolution of the images, the depths that can be mapped and how fast the data can be collected.
- *Acoustic Modems*: Many research and commercial ocean operations (aquaculture, oil and gas, wind farms) have remote data collection systems that relay data over networks spanning several kilometres. These underwater networks are based on acoustic modems that emit sound in the range of 9–50 kHz. A variety of modulation techniques are used to improve the data rate and reliability of the networks so that spectrograms of sound from these systems shows a continuous stream of energy that jumps between different frequencies with times on the order of 0.1–1 second.
- *Acoustic Positioning Systems*: In many applications it is important to know the relative location of a surface object compared to a sub-surface structure, or a subsurface vehicle (ROV) relative to a surface vessel. Acoustic Positioning Systems use high-frequency pulses to provide range and bearing between the objects with accuracies on the order of 10 cm. Typical frequencies for these systems are 10–30 kHz.
- *Ultrasonic Hull Cleaners*: These are relatively new devices that place ultrasonic transducers along the hull; the vibrations make it difficult for marine life to bond to the hull and biofoul the vessel. These systems are available for full size commercial vessels as well as pleasure craft.

Table 1. Specifications of commercial sonars. Note that source level data are very difficult to obtain for most commercial sonars. All systems have variable pulse durations and IPIs that are generally determined by the maximum depth setting on the system control units.

Type	Manufacturer	Model	Centre frequency (kHz)	Source level re 1 uPa^2 m^2 (dB)
Depth sounder	Kongsberg	EA440	38–500	
	Benthowave	BII-8050	38–420	
	Wärtsilä	ELAC LAZ 5100	24–200	
Fisheries echosounder	Kongsberg	Simrad EK-80	10 to 500	
	Kongsberg	SIMRAD CS90	70–90 in 1 Hz increments	
	BioSonics	DT-X AMS	38, 70,120, 200, 420, or 1000	
Multibeam sonar	Teledyne	SeaBat T50-R	200 or 400	
	Benthowave	BII-7660	120, 240, or 450	
	Kongsberg	EM 122	12	
	Kongsberg	EM 710	40–100	
Acoustic modem	Sonardyne	MODEM 6 STANDARD	21–32.5	190–202 (4 Levels)
	EvoLogics	18/34 Devices	18–34	
	Teledyne	Benthos	9–14 (LF), 16–21 (MF), and 22–27 (Band C)	
Acoustic positioning system	Kongsberg	HIPAP	21–31	190–206
	Teledyne	Trackit USBL System	22–27	
Ultrasonic hull cleaner	PYI Inc.	Sonihull Duo	19.5–55	
	ShipSonic	IP63, IP67	17–40	

1.1.3. Absorption of High-Frequency Sound by Sea-Water

Acoustic absorption affects sound at the frequencies generated by sonars much more so than the low frequencies generated by vessel propulsion and cavitation. Propagating sound interacts with the constituents of seawater at the molecular level through a range of mechanisms, resulting in absorption of some of the sound energy (François and Garrison 1982b, 1982a). This occurs even in completely particulate-free waters and is in addition to energy losses from scattering by objects such as zooplankton or suspended sediments. The absorption coefficient of the water depends on such factors as temperature, salinity, and pressure, and varies with the frequency of the acoustic wave. The UK National Physical Laboratory provides an online tool that may be used to explore the effects of these parameters, as well as different equations for their contributions (National Physical Laboratory 2018).

The magnitude of the loss of sound energy by absorption is expressed as an attenuation coefficient in units of decibels per kilometre (dB/km). This coefficient is computed from empirical equations and generally increases with the square of the frequency. The absorption of the acoustic wave energy is virtually nil at low frequencies (below 500 Hz). It starts to have a noticeable effect (of at least 1 dB over ranges of 10–20 km) at frequencies above 1 kHz. The absorption loss increases markedly for higher frequencies: for a 100 kHz sound wave, the absorption loss can exceed 30 dB over 1 km propagation distance.

When calculating the sonar source levels in the current analysis, we calculated the absorption coefficient using the method of François and Garrison (1982b, 1982a) with 8 °C water temperature, pH of 8, 90 m depth, and practical salinity of 32 . The absorption losses were computed for the centre frequencies of the 20, 25, 31.5, 40, 50, and 63 kHz decidecade bands; the values are 3.5, 5.2, 7.7, 11.2, 15.3, and 20.3 dB/km.

1.2. Possible Impacts of Sonars on Marine Life

The effects of noise on humans and animals can be simplistically visualized as a series of four zones around the noise source (Figure 4). In Zone 1, the sound exposure leads to barotrauma injury (for examples see Halvorsen et al. 2012) or permanent threshold shift (PTS), meaning that hearing is damaged and does not recover. In Zone 2, the sound exposure causes a temporary threshold shift (TTS) where hearing recovers after some duration (e.g., the morning after a rock concert). In Zone 3, the noise source masks an animal’s ability to hear another sound of importance (e.g., conspecifics, predators, prey, environmental queues). In Zone 4, the sound is still audible and may evoke a behavioural response (e.g., orientation, movement) or physiological response (e.g., stress hormones).

The zone-view of the effects of noise does not accurately reflect the complexity of auditory injury or impairment and the choices animals make to accept sound exposure for other advantages such as feeding or mating (Ellison et al. 2012). When animals make the choice not to respond to noise, they can stay in an area where very long sound exposures result in auditory injury and impairment, and thus Zone 2 may be larger than Zone 4 (Hawkins and Popper 2017). Similarly, behavioural reactions to sound can cause animals to rapidly leave an area, which could result in dangerously rapid depth changes (Jepson et al. 2003, Blix et al. 2013) or entering an area that results in stranding (Cox et al. 2006); in this manner Zone 4 can become Zone 1.

The first noise mitigation regulations based on noise thresholds were based on keeping the sound pressure level below the level associated with measured injuries to the hearing of marine life (NMFS and NOAA 1995, NOAA 1998, FHWG 2008). Evidence has since demonstrated that the total sound exposure level (SEL) and the peak sound pressure level (PK) are better indicators of injury than the rms sound pressure level (SPL) (Southall et al. 2007, Popper et al. 2014). As a general rule, North American noise regulations are imposed on human activities to minimize injury to marine mammals and other endangered marine life rather than to reduce disturbance (Erbe 2013).

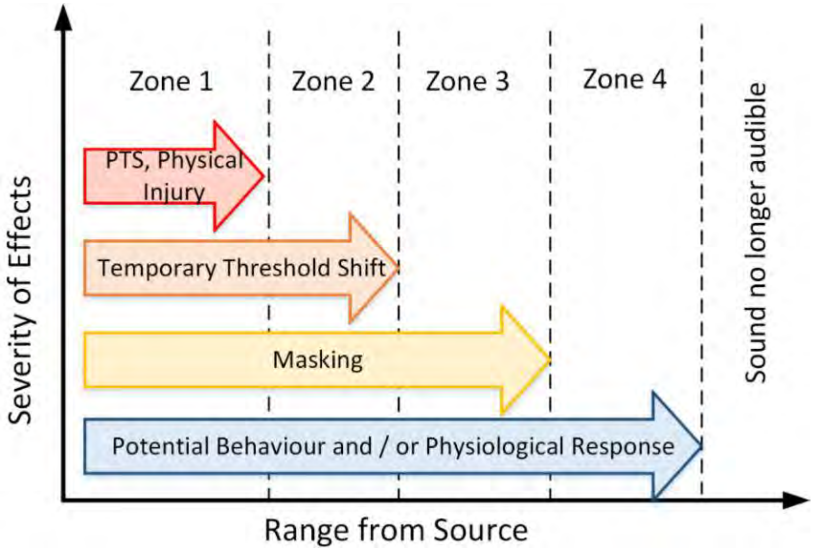


Figure 4. General principles of noise exposure (after Dooling et al. (2015)).

The most recent underwater noise exposure criteria for marine mammals have been published in the US NMFS *Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing* (NMFS 2018). This Guidance provides new criteria for the onset of noise induced hearing impairment (Level A harassment) but no update of behavioural disturbance (Level B harassment) criteria. It is worth noting that the Level B harassment criteria are the same for all marine mammals whereas the Level A criteria are tailored for different hearing groups by applying specific auditory frequency weighting functions. The species of concern in the project area are killer whales (*Orcinus orca*), which are part of the mid-frequency cetacean hearing group, and harbour porpoises (*Phocoena phocoena*), which are part of the high-frequency cetacean hearing group.

For each hearing group, the Guidance provides thresholds on the maximum daily sound exposure level. Two thresholds are provided per group—one for impulsive sound and one for non-impulsive. Impulsive sources are known to have greater effects on hearing than non-impulsive (Ward 1962, Roberto et al. 1985, Finneran 2015, Kastelein et al. 2015). The Guidance defines impulsive sources as those that produce sounds that are transient, less than 1 second long, broadband, and have high peak sound pressure with rapid rise time and rapid decay. The Guidance does not address the question of the effects of repeated impulses, even though the time between pulses may increase or decrease their effects (Buck et al. 1984, Danielson et al. 1991, Finneran et al. 2002, Kastelein et al. 2014). The auditory frequency weighted (see Appendix A.3) kurtosis has been shown to be an effective metric for combining pulse amplitude, duration, rise and decay times, and repetition rates into a single quantity for assessing impulsiveness (Hamernik et al. 2007, Qiu et al. 2013, Martin et al. 2020).

Classifying sonar pulses as impulsive or non-impulsive presents a challenge for international regulators. The Guidance (NMFS, 2018) groups them with the non-impulsive sources due to their narrowband nature and because they often have relative long rise and fall times (at least for naval sonars). Sonar pulses are considered impulsive by the European Union Expert Group on Noise (Dekeling et al. 2014). The kurtosis analysis by Martin et al. (2020) found that echosounders typically had a auditory frequency weighted kurtosis between 30 and 60, which is indicative of an impulsive sound. If a sonar does result in a hearing threshold shift, it is known that it affects hearing at the frequency of the sonar and half an octave above the sonar's band (see for example Popov et al. 2011, Finneran and Schlundt 2013, Popov et al. 2013). However, it is possible to compensate for a narrowband threshold shift by listening at frequencies that contain the same information as but are outside the narrowband that is affected (Branstetter et al. 2016). Thus communication after TTS from sonars is more likely to be maintained than after exposure to a broadband impulse such as impact pile driving and seismic surveys. It is also known that odontocetes like killer whales and porpoises are able to reduce their hearing sensitivity if they can predict the arrival of impulses (Nachtigall et al. 2018).

The behavioural reactions of odontocetes to sonars and echosounders likely occur over longer distances than hearing threshold shifts. Miller et al. (2014) found that the reaction of killer whales to approaching sonars depended on the individual animal and context of what it was doing during the exposure; one of the most serious effects they observed was the temporary separation of a mother-calf pair. Southall et al. (2013) found that the most likely cause of a mass stranding of melon-headed whales in Madagascar was a high-power 12 kHz multi-beam echosounder system operated intermittently by a survey vessel that moved in a directed manner down the shelf-break the day before the mass stranding event. Curé et al. (2016) found that sonar sounds elicited behavioural reactions in sperm whales that included avoiding the area and cessing feeding; however, the reactions were not as profound as their reaction to killer whale sounds, which included grouping behaviours. Cholewiak et al. (2017) found that beaked whales avoided research vessels when echosounders were active.

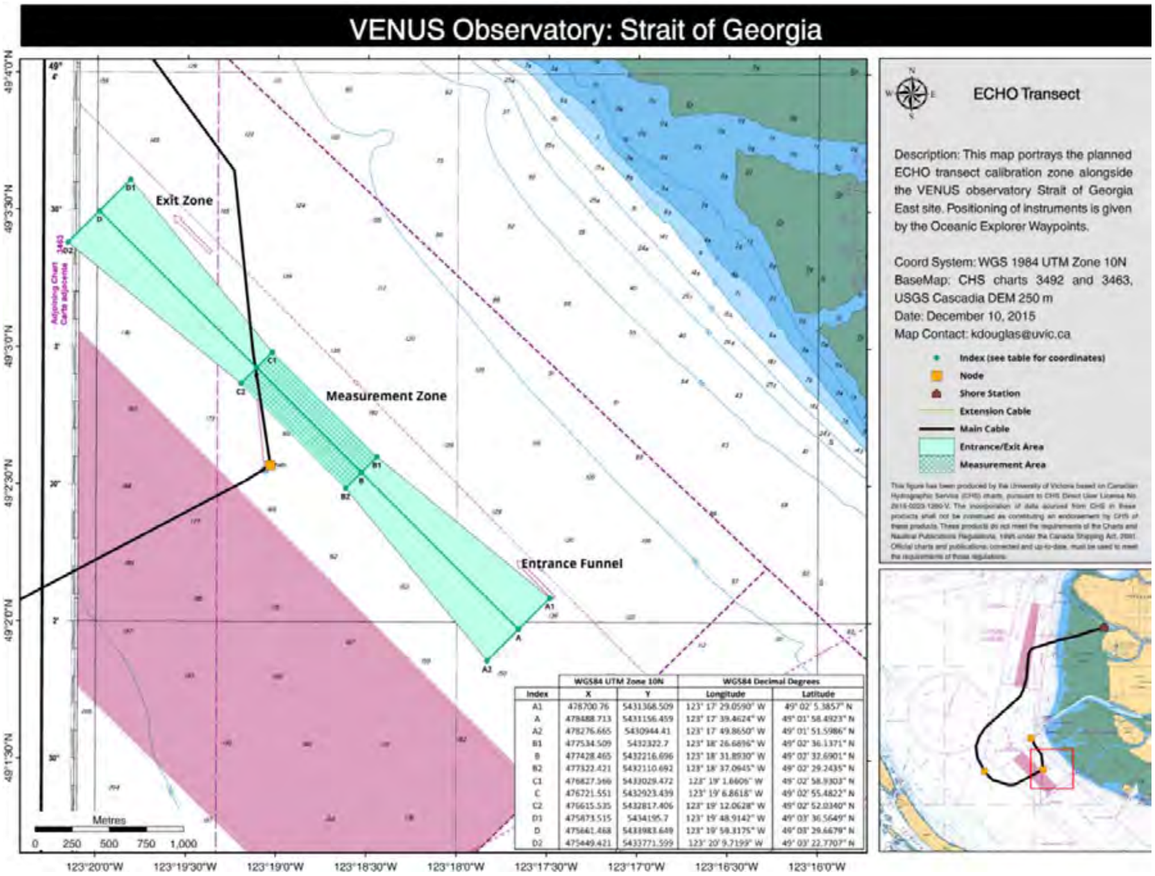
Masking of communications is likely the most pervasive effect of human sounds on marine life (Erbe et al. 2016). The effects of masking are often expressed by a change in the communication space available to the animals (Hatch et al. 2012). Williams et al. (2013) found that in British Columbia killer whale communication space for social calls was reduced by 62% in median noise conditions and 97% in noisy conditions. Sonars have the potential to mask the echolocation pulses of foraging killer whales which has implications for the killer whale’s ability to feed, but also the ability of other marine mammals to hear the echolocation pulses of the the killer whales. Southern resident killer whale echolocation clicks have centre frequencies in the range of 40–60 kHz, with bandwidths of 35–50 kHz (Au et al. 2003). Killer whales are able to increase their call amplitudes in response to noise, however, there are limits to their ability to compensate for human noise sources (Holt et al. 2011). Other strategies that animals can use to limit the effects of noise on communications are spatial release of masking and gap listening (Erbe et al. 2016). Gap listening, which is attempting to communicate between noise events, may be relevant for echolocation by killer whales if they can click between sonar pulses.

2. METHODS

2.1. ECHO ULS Data Collection

The data presented in this report were recorded at the ECHO Program Underwater Listening Stations (ULS), situated next to the shipping lanes in the Strait of Georgia (Figure 5), and at the Boundary Pass autonomous recording site (Figure 6). This work was performed by JASCO as part of collaborative projects with Vancouver Fraser Port Authority and Ocean Networks Canada (ONC). Hydrophone data were analyzed using ShipSound, a component of JASCO's PortListen® noise measurement system. PortListen tracks passing vessels on Automated Identification System (AIS) and automatically calculates their underwater acoustic source levels using calibrated hydrophone data.

The vessel information and raw acoustic data stored in the PortListen database were accessed to obtain the data for analysis. The closest point of approach (CPA) time and distance were used as a guide in this analysis. The raw acoustic data durations varied between 120–300 seconds.



	WGS84 UTM Zone 10N		WGS84 Decimal Degrees	
Index	X	Y	Longitude	Latitude
A1	478700.76	5431368.509	123° 17' 29.0590" W	49° 02' 5.3857" N
A	478488.713	5431156.459	123° 17' 39.4624" W	49° 01' 58.4923" N
A2	478276.665	5430944.41	123° 17' 49.8650" W	49° 01' 51.5986" N
B1	477534.509	5432322.7	123° 18' 26.6896" W	49° 02' 36.1371" N
B	477428.465	5432216.696	123° 18' 31.8930" W	49° 02' 32.6901" N
B2	477322.421	5432110.692	123° 18' 37.0945" W	49° 02' 29.2435" N
C1	476827.566	5433029.472	123° 19' 1.6606" W	49° 02' 58.9303" N
C	476721.551	5432923.439	123° 19' 6.8618" W	49° 02' 55.4822" N
C2	476615.535	5432817.406	123° 19' 12.0628" W	49° 02' 52.0340" N
D1	475873.515	5434195.7	123° 19' 48.9142" W	49° 03' 36.5649" N
D	475661.468	5433983.649	123° 19' 58.3175" W	49° 03' 29.6679" N
D2	475449.421	5433771.599	123° 20' 9.7199" W	49° 03' 22.7707" N

Figure 5. Cabled underwater listening station (ULS) hydrophone location (yellow square) and measurement funnel (cyan area) in the Strait of Georgia. This ULS operated from September 2015 to April 2018.

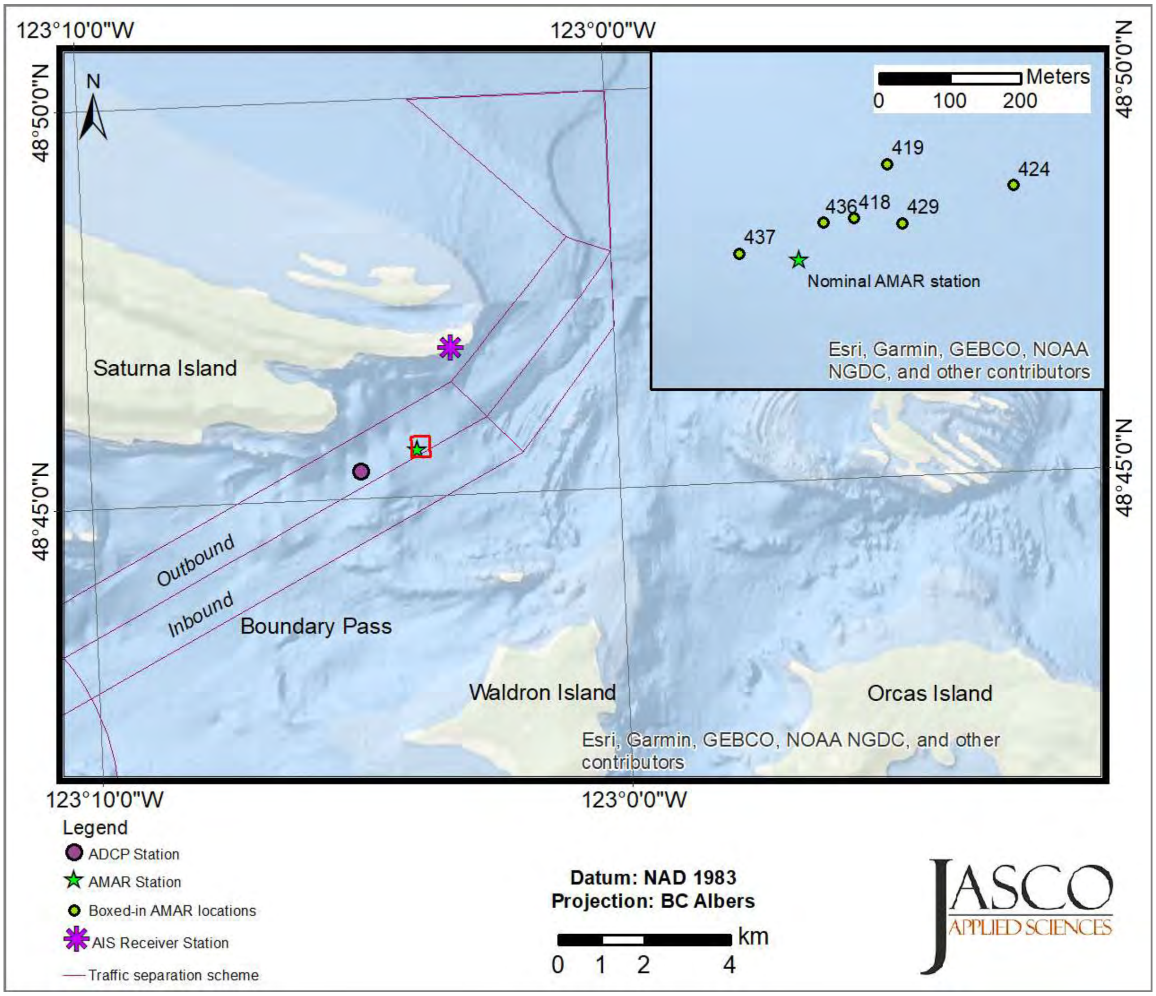


Figure 6. Vessel source level measurement location using autonomous recorders at Boundary Pass. Data recorded at this location from December 2018 to October 2019 were used in this analysis.

2.2. Sonar Detection

2.2.1. Identification of Candidate Vessel Passages

The objective of this analysis was to study the sonar sound levels from commercial vessels. To achieve the objective, we needed to identify the vessel passages that contained substantial sound levels in the sonar bands, which we identified as the decidecades centred at 20, 35, 31.5, 40, 50, and 63 kHz. For each vessel passage analyzed by ShipSound, the PortListen database contains the decidecade received sound levels as well as the associated metadata that describes the vessel. In general, the received decidecade band sound pressure levels peaked at ~50 Hz and then decreased monotonically with frequency (Figure 7). The sound from sonars greatly increased the received levels in the sonar bands. These passages were easily identified as having decidecade SPL in the sonar bands of at least 100 dB *and* having an SPL in one of the decidecades that was at least 3 dB higher than the level in the 10 kHz decidecade band.

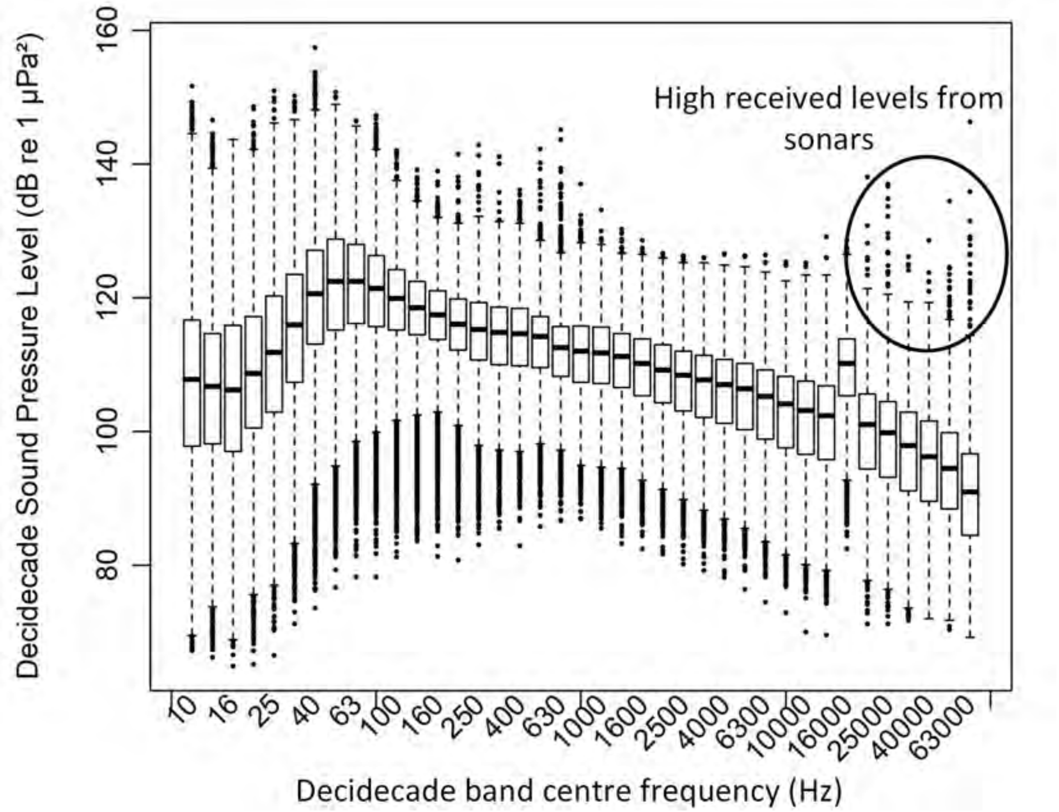


Figure 7. Box-and-whisker plot of decidecade band sound pressure levels (1-minute averaging time) from all ECHO Program ULS vessel passages (September 2015 to March 2018). The boxes shown the interquartile range (i.e., the middle half of the distribution). The dark horizontal line in the box is the median value. The vertical lines show the range of values for the 25% of the data above or below the middle half. The dots above or below the line indicate outlier values. The high-frequency high-amplitude measurements in the circle are from sonars.

2.2.2. Manual Analysis

For each vessel passage that was identified as having a sonar present (Section 2.2.1), a former naval sonar analyst assessed the associated acoustic data file to identify the type of sonar. The analyst measured the following parameters:

- Sonar type.
- Highest pulse received sound pressure level.
- Pulse duration.
- Pulse bandwidth; and
- Centre frequency.

For each sonar, a spectrogram was generated, examples of which are presented in Section 3.

2.3. Sound Level Metrics

The signals of interest range in duration from less than 1 ms to continuous sounds. The sound intensity metrics employed must provide levels that are comparable across these durations, as well as metrics that are relevant to effects of sound on marine life, including echolocation space reduction. The peak sound pressure level, unweighted sound exposure level and the auditory frequency weighted sound exposure level are recommended for assessing the possible effects of sound on animal hearing (Popper et al. 2014, Southall et al. 2019). The one-minute auditory frequency weighted sound pressure level may also be used to assess whether the sound exceeds effective quiet—that is, whether a sound is loud enough to possibly cause hearing threshold shifts (Martin et al. 2020).

To assess effects on communication, the listening space or communication space are recommended (Hatch et al. 2012, Pine et al (2020, in prep), Pine et al. 2018). To assess the variable effects of impulsive sound, a fixed window duration is required when computing the sound pressure level (Madsen 2005, Martin et al. 2017, Pine et al (2020, in prep)). A duration of 0.1 seconds is recommended as it approximates the integration time of marine mammal hearing (Madsen 2005, Tougaard et al. 2015).

The sonar sounds are restricted to relatively narrow frequency bands (e.g., Figure 1). Therefore, to evaluate the effects of the sonar on communication sounds and hearing, we require metrics that are divided into appropriate frequency bands. Effects of sound on hearing have been shown to occur at the frequency of the sound and 1/2 octave above the sound (Popov et al. 2011, Finneran and Schlundt 2013, Popov et al. 2013). Therefore, decidecade bands (approximately equal to 1/3 of an octave) were employed in this analysis.

Based on these considerations, the following metrics were employed:

1. 0.1 second SPL in decidecade bands for echolocation listening range reduction analysis and beampatterns of continuous sound sources.
2. 0.1 second SEL in decidecade bands assessing sonar source levels.
3. The per-ping peak sound pressure level for assessing the sonar source levels and beampatterns.
4. Auditory frequency weighted SEL across each CPA to assess whether the vessel passage had enough sound intensity to elicit a hearing threshold shift at the measurement location.

This report follows the terminology and reference units contained in ISO standard 18405 (2017).

2.4. Estimating the Sonar Source Levels

The analysis required to estimate the sonar source level is different than those for analyzing vessel source levels. The analysis was simplified in that the sound is directed down, so that we do not need to consider surface reflection effects. However analysis is complicated by: 1) the frequencies, which are high enough that seawater absorption must be accounted for; and 2) the sonar beampatterns which means that we are only measuring the full source level if the vessel passed directly over the recording location.

The source level along a beampattern line between the vessel and recorder is given by:

$$SL = RL + 20\log_{10}(R/(1\text{ m}))\text{ dB} + \alpha(f)\,R \qquad (1)$$

where SL is the source level, RL is the received level at the closest point of approach, R is the distance at the closest point of approach, and α is the sea water absorption that is a function of frequency (f). RL was the 0.1 second decidecade SPL. The absorption values are given in Section 1.1.3.

2.5. Sonar Beampatterns

As shown in Figure 3, sonar beampatterns depend on elevation and azimuthal angles. To measure the beampattern the acoustic metrics of interest must be determined as a function of the vessel location relative to the recorder was required. The positional information was available in the PortListen database. The acoustic metric depended on the type of sonar. For continuous sound sources the 0.1 second decidecade SPLs were employed. For impulsive sonars, the per-ping measurements were required. JASCO's odontocete click detector was configured to identify three types of sonar pings for this analysis: pings centred at 28, 38, and 50 kHz. For each ping, the peak sound pressure level was measured and employed for beampattern analysis. The pulse detection algorithm is described in Appendix A.4.

The sonars on most commercial vessels are echosounders used for finding the seabed or fish stocks directly below the vessel. As a result, the sonar beampattern has its maximum directly below the vessel and it decreases with elevation and azimuthal angle (see Figure 3). In most cases, the beampattern is assumed to be symmetric; that is, the levels are same for angles in front and behind the vessel as well as for angles to the port and starboard. To verify this concept, we analyzed data from two types of vessel passes—those where the vessel transited directly over the recorder and those where the vessel passed several hundred metres to the side of the recorder. It was anticipated that these geometries would allow us to measure the vertical and horizontal beampatterns of the sonars.

2.6. Echolocation Listening Range Reduction

Human sounds have the ability to mask sounds that marine life use for navigating, detecting predators, foraging, and communicating with conspecifics (Clark et al. 2009, Slabbekoorn et al. 2010, Erbe et al. 2016). Echolocation pulses (generally above 20 kHz) employed by odontocetes for foraging may be masked by the commercial sonars.

Listening range reduction (LRR) is a method for assessing masking from the perspective of the listener instead of the sender, which simplifies the analysis because details of the vocalization source structures are not required (Pine et al. 2018). Listening range is defined as the distance surrounding a listener within which a biologically-important signal can be detected. It is the percentage difference in the distance a sound can be perceived when a human sound source is present compared to baseline quiet conditions. LRR is applicable to a broad range of contexts, which has distinct advantages for management.

LRR is defined in Equation 2 where NL_2 is the sound pressure level with the masking noise present, NL_1 is the sound pressure level without the masking present, and N is the geometric spreading coefficient for the acoustic propagation environment. The sound pressure levels are computed for 1/3-octave-bands that are representative of the important listening frequencies for animals of interest.

$$LRR = 100 * (1 - 10^{\frac{NL_2 - NL_1}{N\ \mathrm{dB}}}) \tag{2}$$

In cases where NL_1 is below the hearing threshold of an animal, the value is replaced by the hearing threshold. The value of N should be representative of the geometric spreading losses in the environment at the frequencies of interest. For passive listening, a value of ~17 or 18 is appropriate for the project area. For echolocation listening the value employed was 40 because two-way acoustic propagation was studied.

For the current analysis, we studied the LRR for killer whales in their echolocation bands (20 kHz decidecade and above). NL_1 was the median one-minute sound pressure level measured on the ECHO ULS in each decidecade band (Figure 8), which was always above the killer whale audiogram (see Appendix A.3.1). The median noise values in Figure 7 for the 20–63 kHz decidecade bands are very close to the minimum values, which indicates that the measurements were near the system noise floor. Because the sonar pulses vary rapidly in time and frequency (see Figure 1), analysis was performed using a 0.1 second time window for each decidecade band in the echolocation frequency range. The percent LRR was expressed using shading where blue is 100% LRR and black was zero LRR. The analysis was performed using the received levels at the recorder for typical passes of each type of sonar.

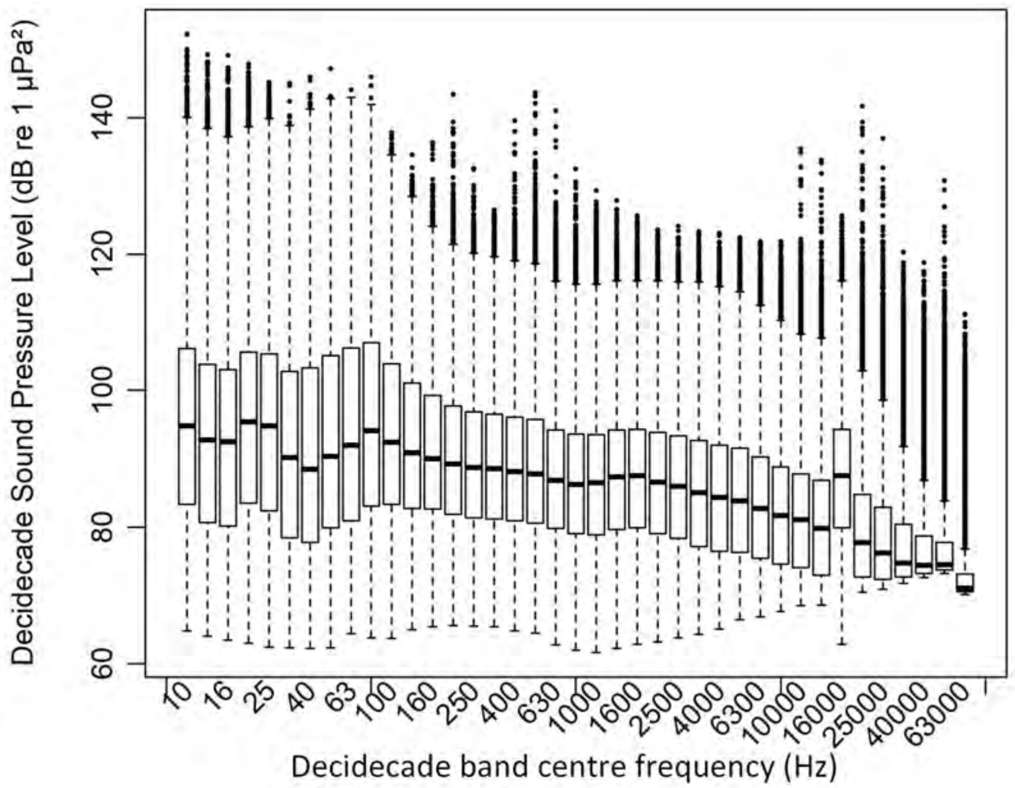


Figure 8. Distribution of one-minute decidecade sound pressure levels (SPL) at the ECHO Program ULS site. The killer whale audiograms are in the range of 50–60 dB re 1 µPa² from 10–60 kHz (Szymanski et al. 1999, Branstetter et al. 2017). The boxes shown the interquartile range (i.e., the middle half of the distribution). The dark horizontal line in the box is the median value. The vertical lines show the range of values for the 25% of the data above or below the middle half. The dots above or below the line indicate outlier values

3. RESULTS

A total of 15972 vessel passages were extracted from the PortListen database, of which 210 vessel passage were identified has having sonar sound levels high enough to be detected as described in Section 2.2.1. This represents ~1.3% of the total overpasses.

3.1. Types of Sonars in the ECHO ULS Data

The sonars found in the ECHO ULS data were grouped according to their acoustic properties. Three basic groups were found: single frequency echosounders (Section 3.1.1), multi-frequency echosounders Section (3.1.2), continuous ultrasound systems (Section 3.1.3), and occasionally other sonar signals (Section 3.1.4).

3.1.1. Single Frequency Systems

Table 2 shows single frequency echosounders accounted for 110 of the detected sonars. The division of the sonars by centre frequency. Examples of a 50 kHz and a 38 kHz single frequency echosounder are shown in Figures 9 and 10, respectively.

Table 2. Number of passages associated with each single frequency echosounder detected.

Centre frequency (kHz)	Number of vessel passages detected	Number of unique vessels
18	1	1
22	1	1
28	11	8
30	9	4
38	29	4*
50	59	41

* 23/29 were from a single fishing vessel.

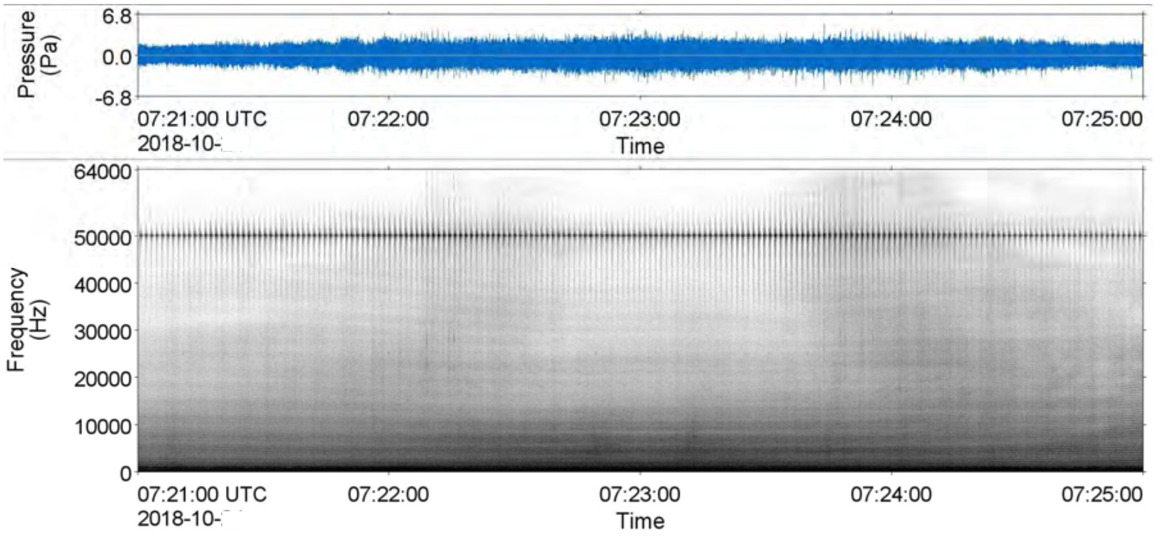


Figure 9. 50 kHz echosounder recorded in Oct 2018 while passing the ECHO Program ULS at a radial distance of 455 m.

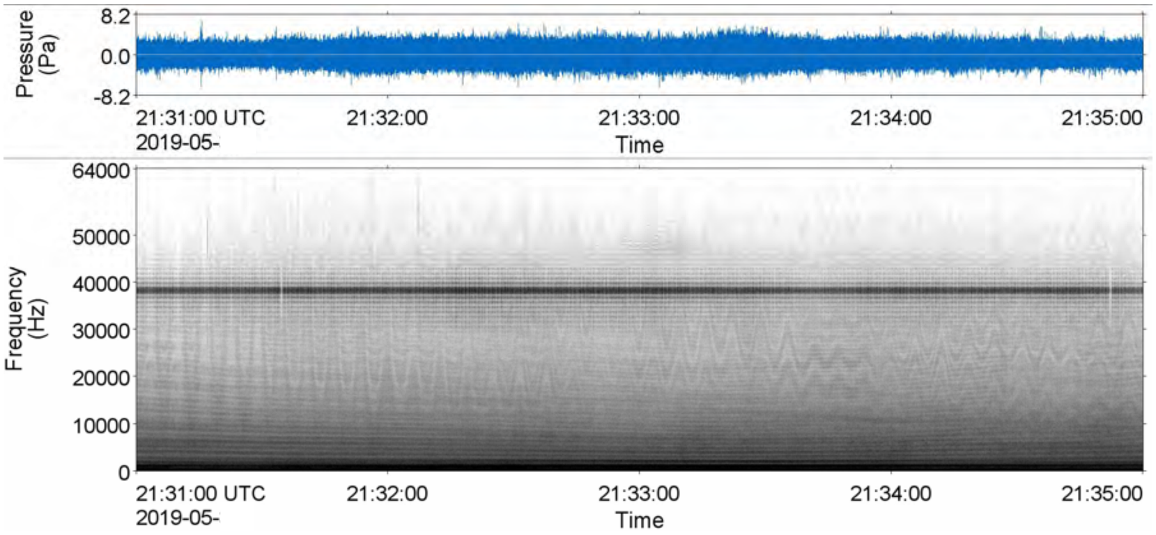


Figure 10. 38 kHz sonar from the passing the Boundary Pass Autonomous Multichannel Acoustic Recorder (AMAR) in May 2019 at a radial distance of 625 m.

3.1.2. Multi-Frequency Systems

Multi-frequency echosounder systems (e.g., Figure 11) were detected 39 times from 20 different vessels. In general, these were associated with research vessels and government vessels, as well as larger fishing vessels. Most of these systems are likely also capable of detecting fish in the water column. The complex signal shown in Figure 12 was recorded three times during the overpass of a passenger vessel.

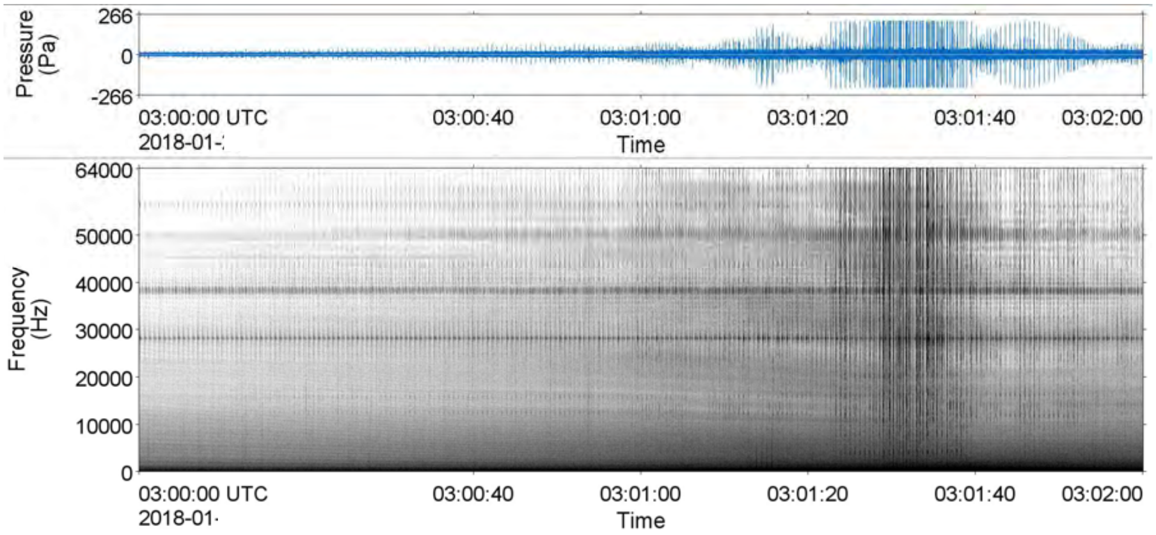


Figure 11. Example of a 28, 38, and 50 kHz echosounder recorded on the ECHO Program ULS on in Jan 2018 from a fishing vessel with a closest radial range of 5 m.

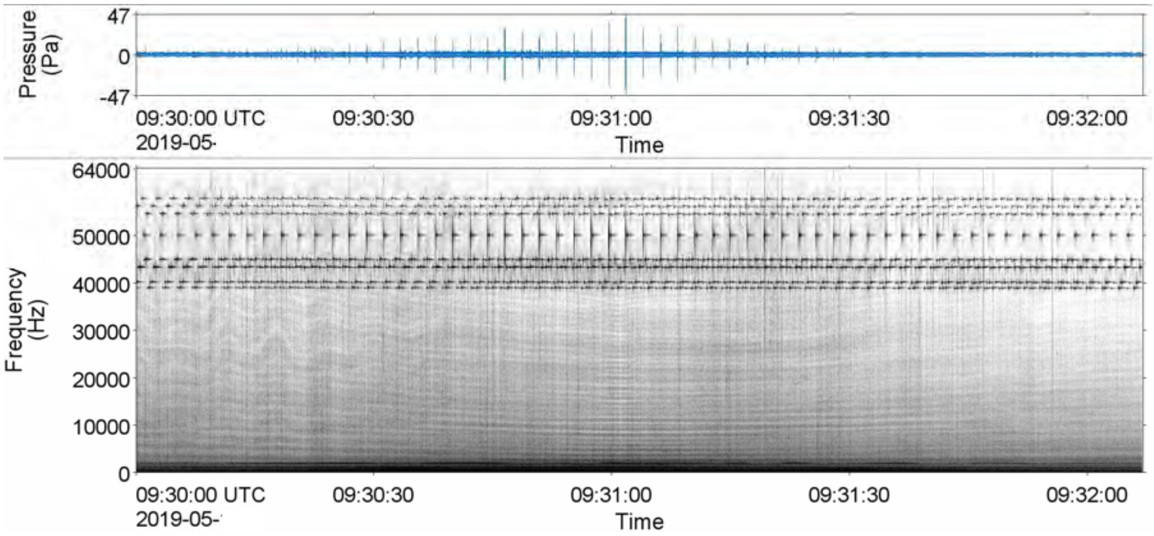


Figure 12. Example of a complex multifrequency echosounder recorded as a passenger vessel went over the Boundary Pass recording location on three occasions. This example was recorded at a radial distance of 25 m.

3.1.3. Continuous Ultrasound Systems

Continuous ultrasound systems (Figure 13) were detected 59 times. Two passages were associated with tugs, two with bulkers, and the remainder with ten different passenger vessels. The source of this sound needs to be confirmed; it is believed to be ultrasonic hull cleaners.

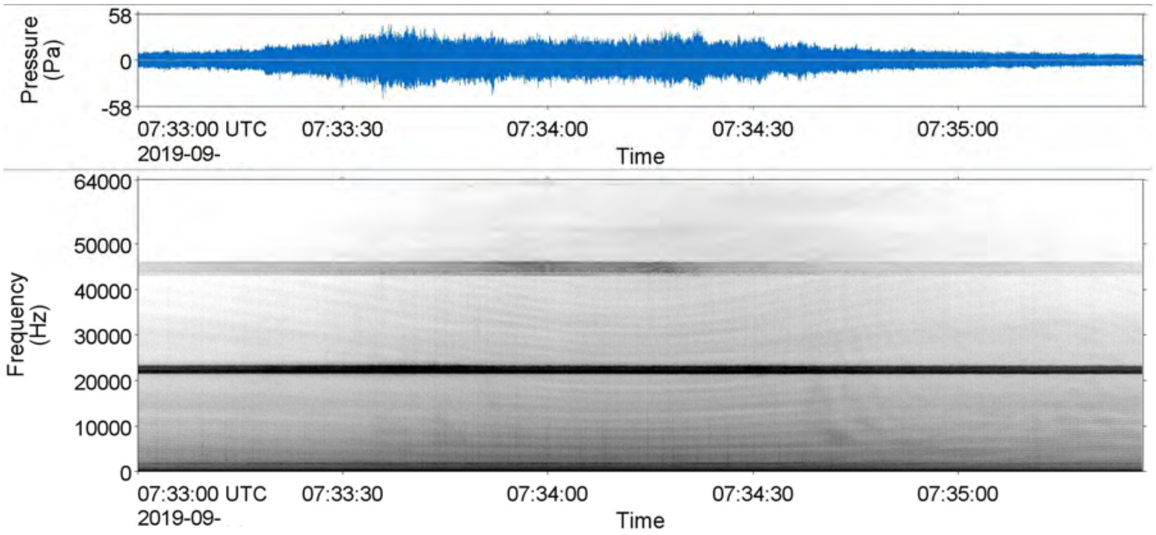


Figure 13. Example of a continuous ultrasound system recorded during the overpass of a passenger cruise ship in Sep 2019 at a radial distance of 180 m.

3.1.4. Other Sonar Signals

Six examples of a frequency-hopping sonar were found in the data (Figure 14) and were always associated with the same container vessel. This vessel was analyzed as a 50 kHz single frequency sonar for remainder of this review.

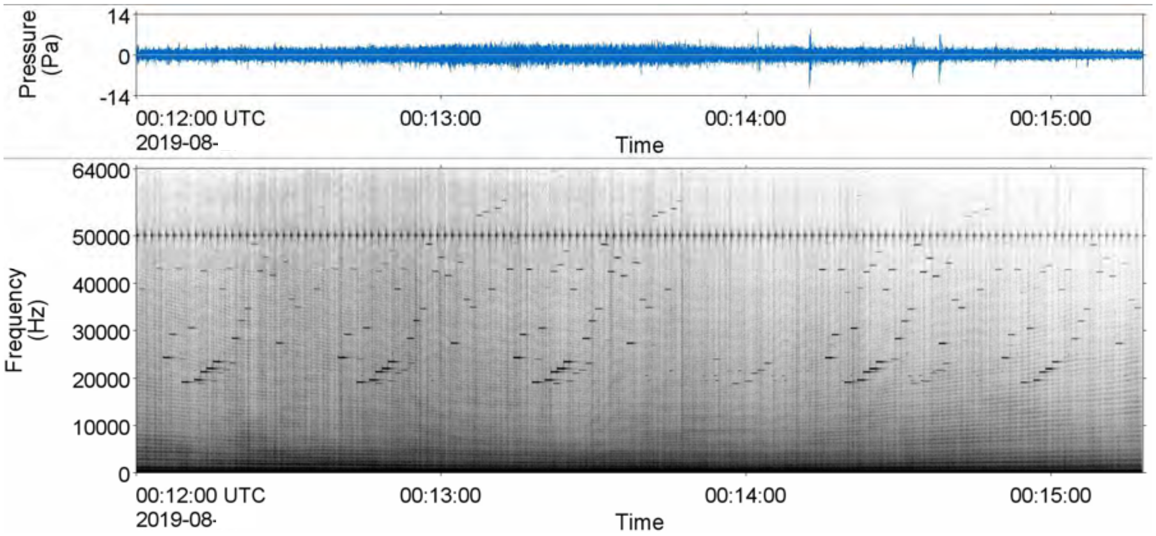


Figure 14. Example of a 50 kHz echosounder as well as a frequency hopping sound source recorder from a container vessel passing over AMAR1 in Boundary Pass in August 2019. This sound type was not detected in the Enhanced Cetacean Habitat and Observation (ECHO) Program underwater listening station (ULS) data.

3.2. Sonar Sound Levels

3.2.1. Sonar Sound Levels at Source

The pulses from the echosounders were all short, on the order of 1–10 ms, with several hundred milliseconds between pulses. Therefore a 100 ms (.1 s) window is appropriate for capturing the full sound exposure level (or energy) from one pulse. The maximum 0.1 s received SEL were converted to the energy source level at the sonar by adding the propagation loss shown in Equation 1. The distribution of energy source levels are shown in Figure 15. To provide a baseline for comparison against the data with sonars, 122 passages of ships without detected sonars were randomly selected and included in the analysis.

The energy source level varies with the percentage of the spectrum that has sound (multi-frequency greater than single frequency) and percent of the 0.1 second time window with signal (the continuous source has much more energy than the pulsed sources). Having a single frequency echosounder does not appear to affect the received energy compared to vessels that did not have echosounders. Note that these are the energy source levels (ESL) received for the maximum beampattern lobes measured by the recorder and that the full ESL is likely 20–30 dB higher.

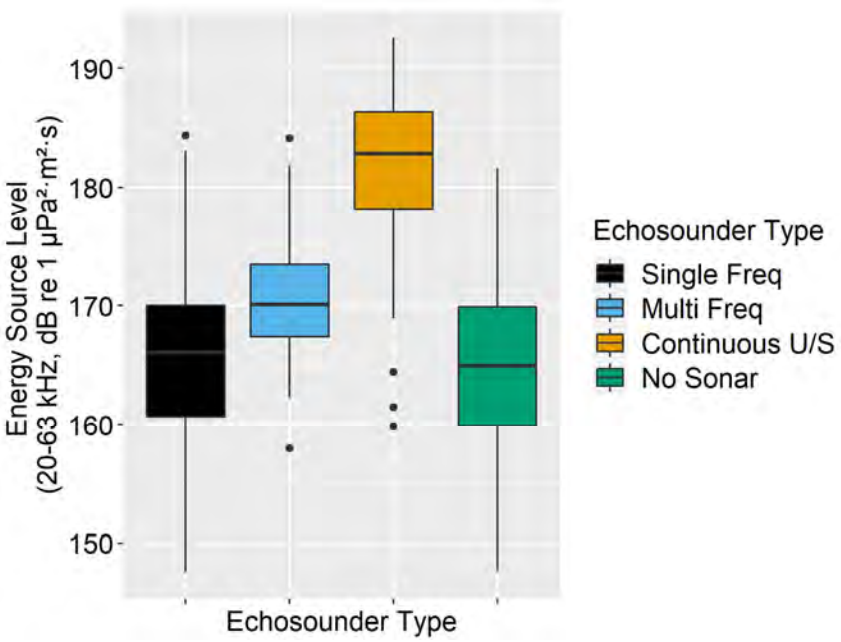


Figure 15. Estimates of the distribution of sonar energy source levels computed from the maximum 0.1 s SEL in the band of 20–63 kHz from all vessel passages with detected sonar as well as 122 vessel passages without sonar. Beampattern effects are included in these results; the main lobe ESL are likely 20–30 dB higher. For each echosounder type the boxes shown the interquartile range (i.e., the middle half of the distribution). The horizontal line in the box is the median value. The vertical lines show the range of values for the 25% of the data above or below the middle half. The dots above or below the line indicate outlier values

3.2.2. Received Sound Exposure Levels

The total sound exposure in the 20–63 kHz bands was calculated over the duration of the available raw acoustic data and the distributions presented as box-and-whisker plots (Figure 16). The SEL were in the range of 114–163 dB re 1 µPa²·s. For comparison, the median SEL for 180 seconds at the ECHO ULS for the 20–63 kHz decidecade bands was 105 dB re 1 µPa²·s (see Figure 8). The results shown are the received SEL measured at slant ranges of 170–995 m from the vessels (median 435 m) and replicate what a marine mammal located at the recorder would have experienced as the vessels passed. The passage of a vessel with single frequency echosounders were comparable to those without echosounders, with SEL 25 dB higher than the median SEL for the ECHO site in the echolocation band. The SEL from multi-frequency echosounders were ~3 dB higher than for single frequency vessels, and the continuous ultrasound systems increased the passage SEL by another ~18 dB, for median values that were ~45 dB above the normal for the recorder location.

The SEL shown in Figure 16 are for the 20–63 kHz decidecade bands. In this frequency range, the NMFS (2018) auditory frequency range for mid-frequency cetaceans (including killer whales) and high-frequency cetaceans (including harbour porpoises) are virtually flat, i.e., all energy at these frequencies contributes to the auditory frequency weighted daily SEL limits. The temporary threshold shift limit (TTS) for high-frequency cetaceans exposed to continuous sound sources are included in Figure 16.

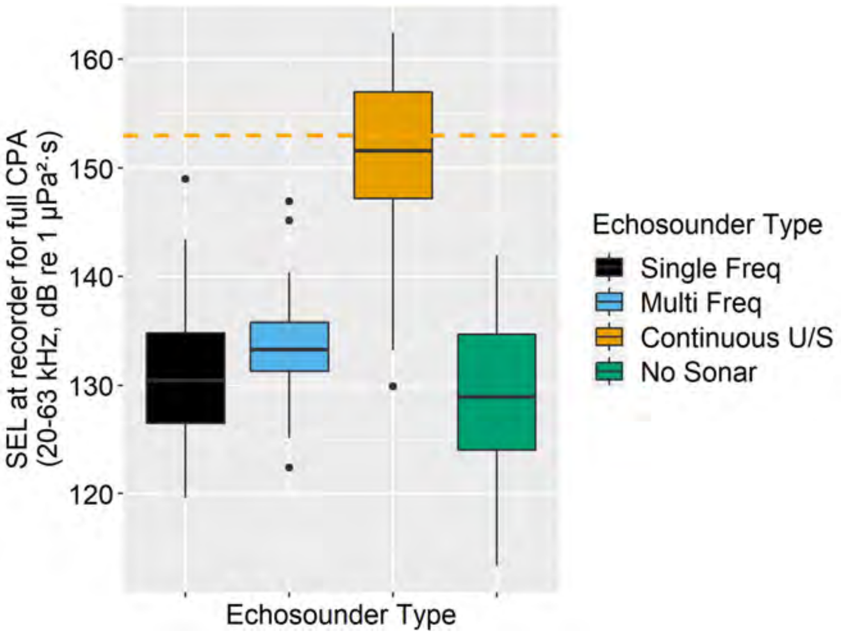


Figure 16. Sound exposure level (SEL) in the 20–63 kHz decidecade bands for the vessel passages with sonar. A similar number of vessel passages without sonars were also analyzed for comparison. The slant range to the vessels was 170–995 m. The median SEL for 180 seconds at the ECHO ULS for the 20–63 kHz decidecade bands was 105 dB re 1 µPa²·s (see Figure 8). For each echosounder type the boxes show the interquartile range (i.e., the middle half of the distribution). The horizontal line in the box is the median value. The vertical lines show the range of values for the 25% of the data above or below the middle half. The dots above or below the line indicate outlier values.

3.3. Beampatterns

3.3.1. Impulsive Sonars

In Jan 2018, a fishing vessel passed directly over the ECHO ULS with a multi-frequency echosounder active while travelling at 18.7 knots (see Figure 11). This passage was analyzed to extract the ping peak sound pressure levels to examine the vertical echosounder beampatterns as a function of frequency (Figure 17; the maximum levels exceed the hydrophone measurement level which resulted in a flat top at 161 dB re 1 µPa). The beampattern is shown against two horizontal measurements—the distance (left) and the elevation angle (right). In both figures you can see the lobed structure of the received sound levels. The distance from the ship that the lobes extend, and the lobe widths decrease as the sonar frequency increases. For the 38 kHz sonar the lobes extended to ~65 degrees, and for the 50 kHz to ~50 degrees. By comparing the vertical and horizontal beampatterns it is easy to see that the main lobe sound levels are likely 20–30 dB higher than what we typically measured using the ECHO ULS.

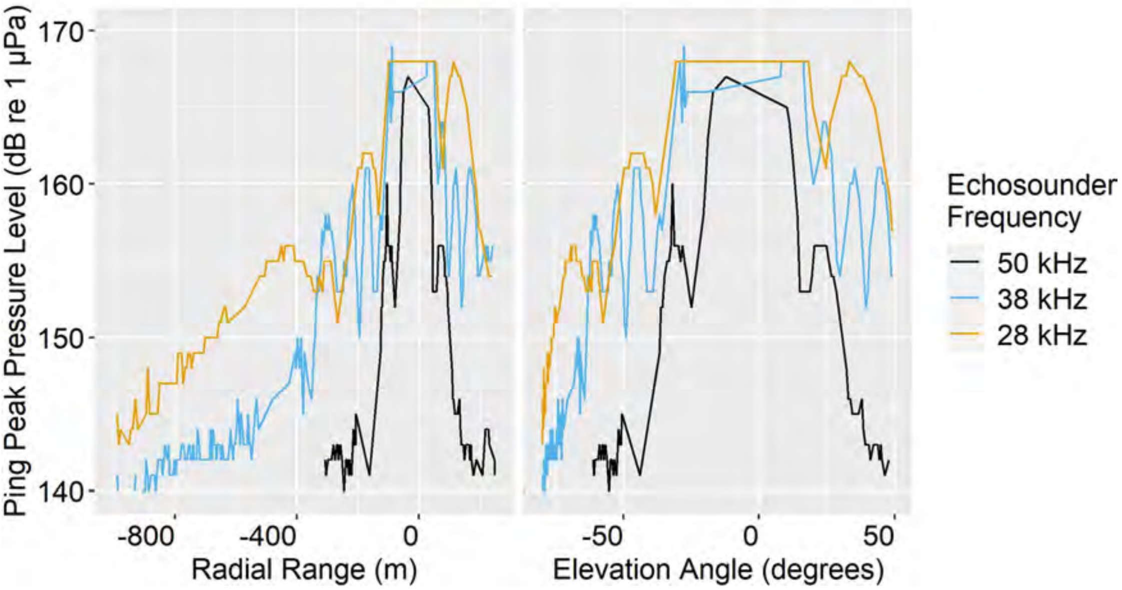


Figure 17. Vertical beampattern for the three echosounder frequencies recorded from a fishing vessel on in Jan 2018 (see Figure 11). (Left) the peak sound pressure level from each detected ping as a function of range to the vessel. (Right) The peak sound pressure level of each detected ping plotted against the elevation angle. The peak sound pressure levels exceeded the maximum measurement level during the closest point of approach.

The clear beampattern measured in the vertical orientation was not replicated in the horizontal direction, likely due to limited energy arriving at the higher elevation angles that were associated with the horizontal measurements. Figure 18 presents the inter-relationship between elevation angle, azimuthal angle, and the received levels for the passage of a 38 kHz and a 50 kHz sonar at a minimum radial distance of 450 m.

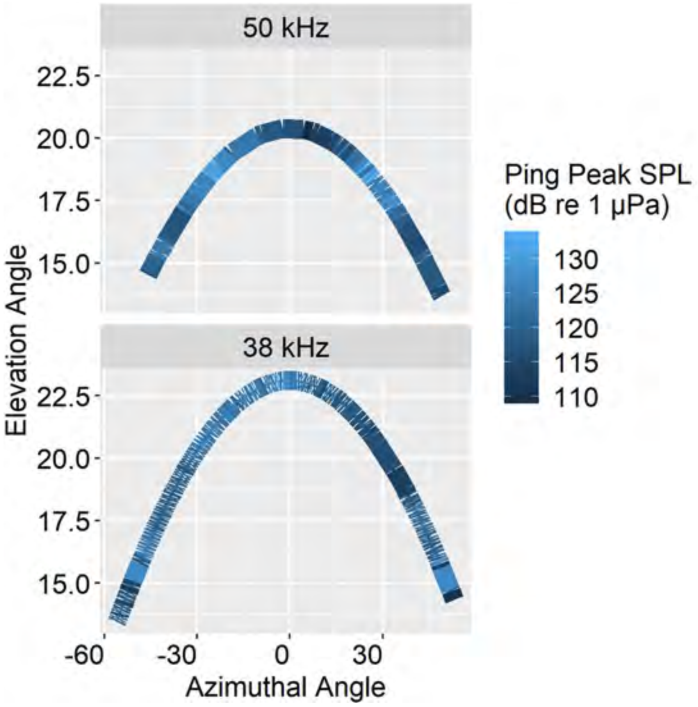


Figure 18. Variation in per-ping peak sound pressure level for the passage of a 50 kHz sonar (passage shown in Figure 9) and a 38 kHz sonar (data shown in Figure 10). The closest point of approach to the recorder occurred at the azimuthal angle of zero.

3.3.2. Continuous Ultrasonic Source

The beampatterns for the continuous ultrasonic source was evaluated using transits of passenger vessels at radial distances of 33, 135, 182, and 271 m (Figure 19). No clear beampattern in the vertical (black) or at increasing azimuthal angles can be detected. Contrary to expectations, the received sound levels did not reach their maximum at the vessel's closest points of approach, rather they were highest when the vessel was ~300 m from the recorder, regardless of the elevation or azimuthal angles (Figure 20). It is proposed that this indicates the source is an extended sound source rather than a point source.

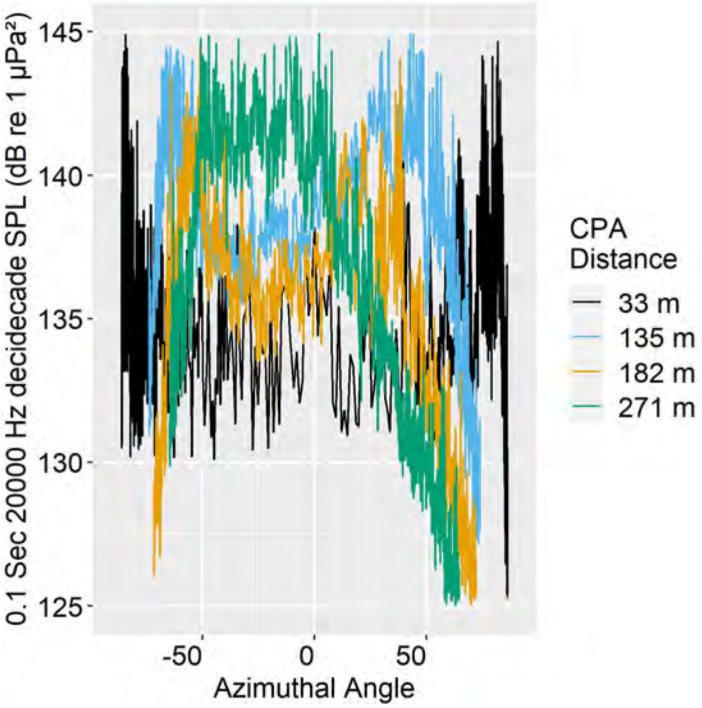


Figure 19. 0.1 second received sound pressure level in the 20 kHz decidecade band plotted as a function of azimuthal angle for four passes of the passenger vessels with the ultrasonic sonar at different radial distances from the recorder.

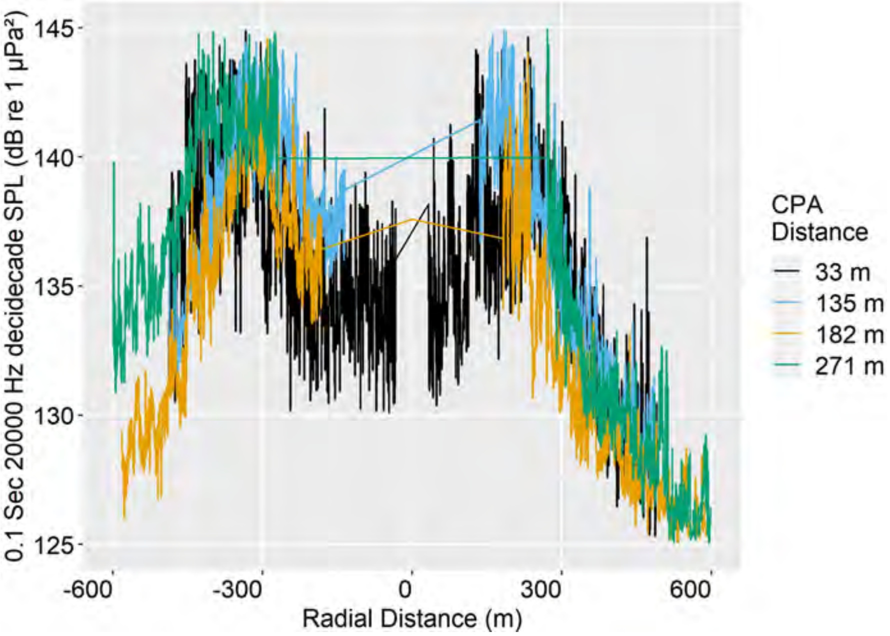


Figure 20. Received sound pressure level in the 20 kHz decidecade band plotted as a function of radial distance for four passes of passenger vessels with the continuous ultrasonic source at different radial distances from the recorder.

3.4. Listening Range Reduction

The listening range reduction method provides an indication of how an animal’s ability to hear sounds changes in the presence of a novel sound source (NL_2 in Equation 2) compared to a reference state (NL_1 in Equation 2). In this case, the median sound levels from three months of data at the ECHO ULS were used as the reference level, meaning that the listening range is ‘normal’ 50% of the time; this does not represent the maximum hearing capability of the SRKW. Figure 21 shows the LRR for 1 hour of data in Feb 2018 that was selected because it was relatively quiet. Toward the end of the hour, a vessel approached the recording location increasing the LRR.

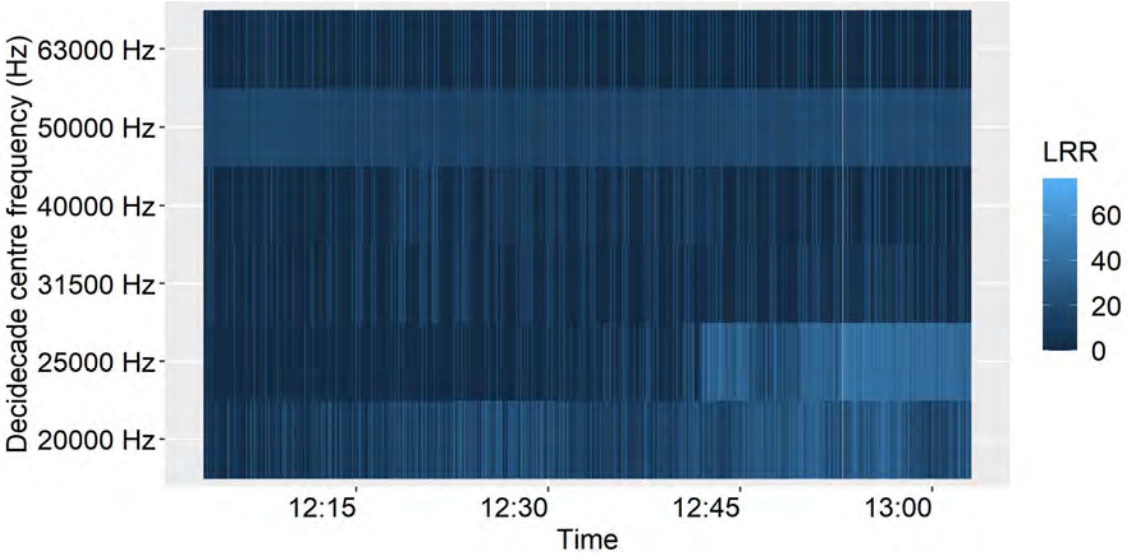


Figure 21. Example of Listening Range Reduction (LRR) showing minimal LRR for an hour of data on in Feb 2018 that was selected because it was relatively quiet.

LRR at the recorder during the passage of the vessel with a 50 kHz echosounder at a radial distance of 450 m (see Figure 9) is shown in Figure 22. The pulses from the 50 kHz echosounder resulted in many short events at 50 kHz where the SRKW listening range was reduced to near zero. It is also interesting to note that the broadband energy from the vessel passage intermittently reduced the listening range across most of the echolocation band by 50–75% for several minutes.

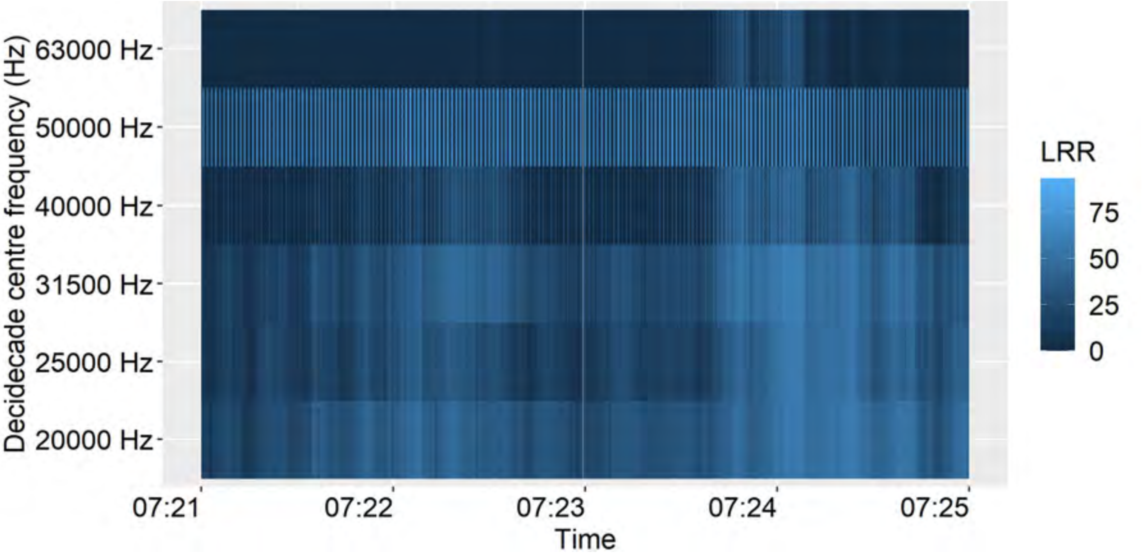


Figure 22. Listening Range Reduction (LRR) for the passage of the vessel shown in Figure 9 with a single 50 kHz echosounder operating.

LRR at the recorder during the passage of a fishing vessel with multi-frequency echosounders active (see Figure 11) is shown in Figure 23. In this example, the listening range is reduced by more than 90% throughout the echolocation band both by the individual pulses of the sonars but also by the broadband noise from the vessel. There was no opportunity for listening between pulses.

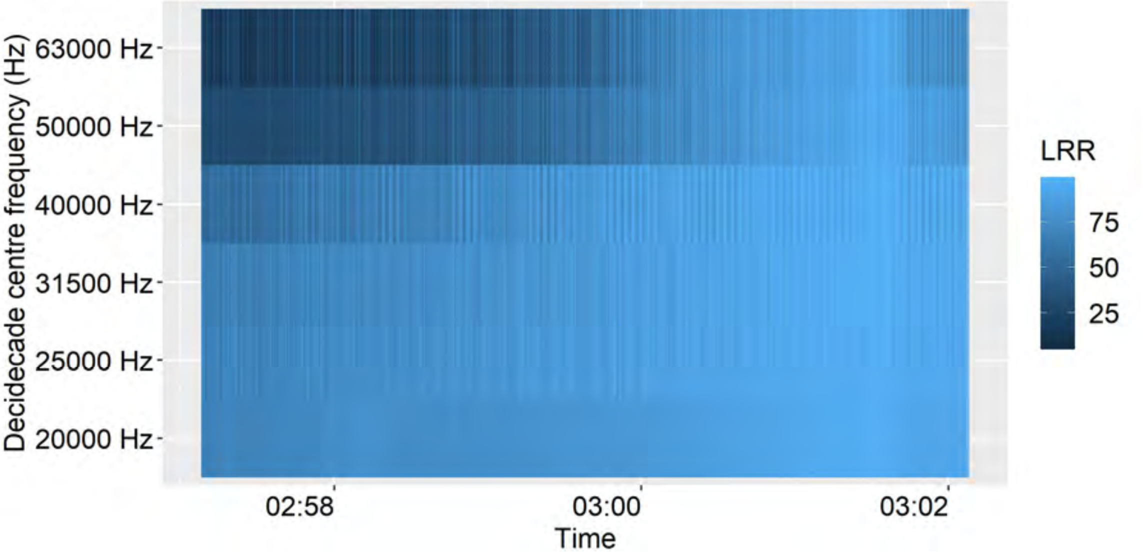


Figure 23. Listening Range Reduction (LRR) for the passage of the fishing vessel (Figure 11) with multiple echosounders operating

LRR from the passage of a vessel with the continuous ultrasonic source (see Figure 13) is shown in Figure 24. In this situation the source caused in 100% LRR in the 20 and 25 kHz bands for the duration of the passage. The vessel's broadband noise generated substantial LRR during the closest point of approach.

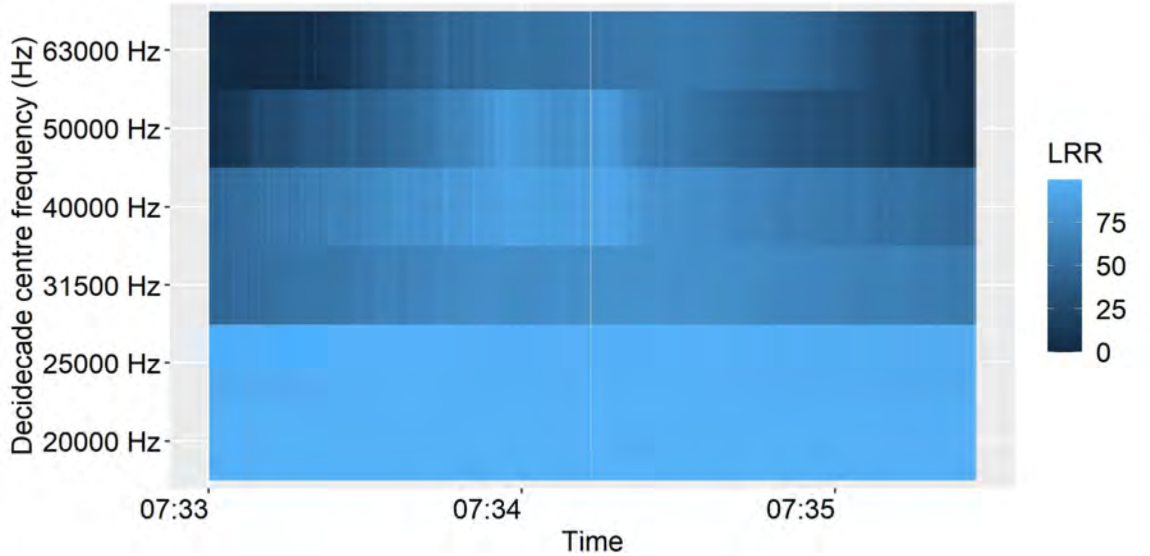


Figure 24. Listening range reduction (LRR) for the passage of a continuous ultrasonic source (shown in Figure 13).

4. DISCUSSION

Commercial sonars were detected in 221 (1.3%) of the 16,000 vessel passages analyzed from the ECHO ULS and the autonomous recorders in Boundary Pass. The 221 passages involved 88 unique vessels, out of a total of 3588 unique vessels, or 2.5% of all vessels measured. This indicates that the vessels that were detected with sonars active did not always do so. This includes the continuous ultrasonic source where 92 passages of similar vessels were measured, and the source was detected in 53 of them.

The detected sonars were assigned to three groups—single frequency, multi-frequency, and the continuous ultrasonic source. Most of the single frequency and multi-frequency sonars generated sound exposures in the 20–63 kHz band that were like those from vessels without sonars. The outliers are believed to have been caused by the sonars that passed directly over the recorders (e.g., Figure 11). The beampattern of a sonar that passed over the ECHO ULS (Figure 17) showed that the energy from the sonars was much greater directly below the vessel than what was radiated horizontally.

The continuous ultrasound source did not have as narrow a beampattern as the single and multi-frequency echosounders. It was detectable at ranges of 4–6 km from vessel. For a vessel moving at 14 knots, this equates to 10–15 minutes on either side of the vessel CPA (Figure 25); the LRR was greater than 75% throughout that time (Figure 26). The sound exposure levels from the continuous source was 20 dB higher than for the echosounders. High-frequency cetaceans, such as porpoises, that are within a kilometre of a passing vessel with a continuous ultrasonic system for 2–3 minutes may experience TTS. The sounds are likely to illicit an avoidance reaction that will cause the animals to cease their activities and relocate. If TTS does occur, it will affect a bandwidth of one octave centred at the source frequency (see Section 2.3). This is likely to affect the porpoises' ability to hear killer whale echolocation clicks but is unlikely to affect their ability to hear their own echolocation employed for navigation and foraging.

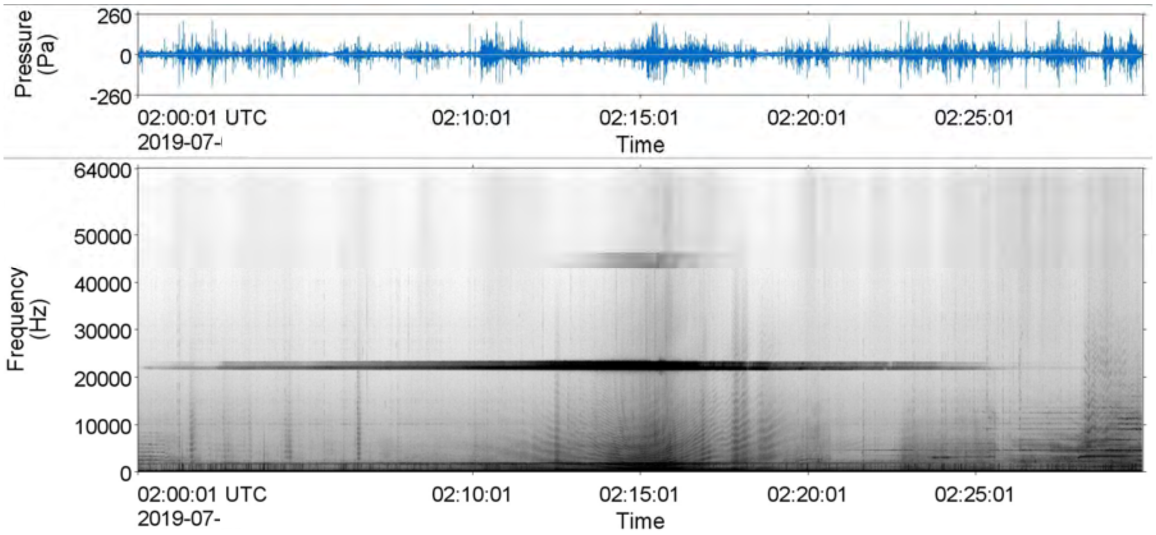


Figure 25. 30-minute time-series and spectrogram during the passage of passenger vessel with the ultrasonic source at the Boundary Pass recorder in Jul 2019 at a speed of 14 knots at a minimum radial distance of 331 m. The source was detectable for 25 minutes, 15 minutes before the vessel closest point of approach (CPA) and 10 minutes after.

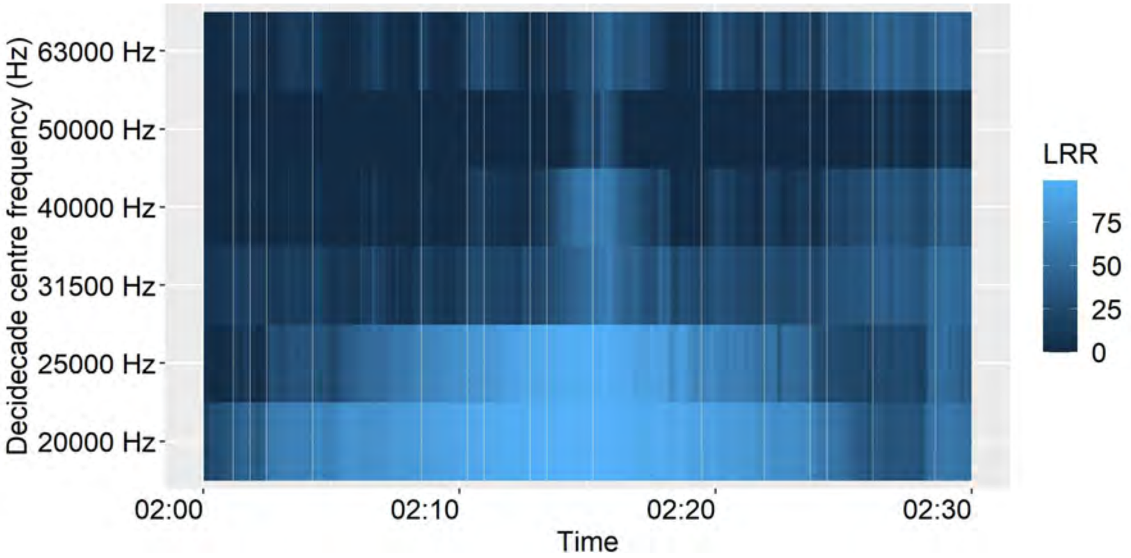


Figure 26. 30-minute Listening Range Reduction for the transit of a vessel with the ultrasound source by the Boundary Pass observatory in Jul 2019 at a speed of 14 knots at a minimum radial distance of 331 m.

Killer whales exposed to sonars in the project area will experience greatly reduced listening ranges when vessels pass nearby. This is true for normal vessels as well as those with sonars. The pulse rates for the sonars measured were generally less than 1 second (see Figure 1), which would make it difficult for killer whales to employ gap listening as a mechanism to reduce the effects of masking (e.g., Figures 22 and 23). Gap listening is not a possibility for the continuous ultrasonic source.

5. CONCLUSIONS AND RECOMMENDATIONS

This study found that sonar emitted by commercial vessels in the project area is an infrequent occurrence. The occurrences do not expose marine life to sound levels much higher than those from vessels without sonar unless the vessel passes directly overhead.

Vessels transiting in the recording area did not need echosounders enabled in most cases, and it appears that most vessels turn them off. The simple sonar detection algorithm employed in this study can be easily implemented on the Boundary Pass observatory system; it is recommended that sonar detection be included in the vessel noise reporting from the observatory. When it is detected during inbound transits, the vessel master should be educated about the possible negative effects and asked to disable their echosounders when not required for safe navigation.

The continuous ultrasonic source has a greater noise footprint than the echosounders. It appears that porpoises and other high-frequency cetaceans exposed to this source could experience TTS in the 20–25 kHz band from several minutes' exposure to this source if they are within 1 km of the vessel. It is recommended that further investigation of what this source is associated with be conducted. For example, monitor the Boundary Pass observatory during the inbound transit of passenger vessels to determine if the source is present. While in port, discuss the possible sound sources with the Master and arrange to have them turn each source on and off during their out-bound transit—the correlation of the acoustic record with the vessel's on/off record will identify which source is responsible for the identified sounds. This source should be prohibited in Canadian waters. A publication on the characteristics of the source in the peer-reviewed literature is recommended. Discussions with the IMO to ban the source are encouraged.

This study examined the sonar emissions up to 64 kHz since the sampling rate of the data was 128 kHz. The new ULS being installed at Boundary Pass will sample at 512 kHz, allowing for an analysis of sonars up to 256 kHz. It is recommended that this study be revisited in 2022 to see if notifications to vessels has reduced the incidence of sonar emissions in the Boundary Pass data, and if there are other sonars active above 60 kHz.

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APPENDIX A. METHODS IN DETAIL

A.1. Acoustic Metrics

Underwater sound pressure amplitude is measured in decibels (dB) relative to a fixed reference pressure of p_0 = 1 μPa. Because the perceived loudness of sound, especially pulsed noise such as from seismic airguns, pile driving, and sonar, is not generally proportional to the instantaneous acoustic pressure, several sound level metrics are commonly used to evaluate noise and its effects on marine life. We provide specific definitions of relevant metrics used in the accompanying report. Where possible we follow ISO standard definitions and symbols for sound metrics.

The sound pressure level (SPL; dB re 1 μPa) is the rms pressure level in a stated frequency band over a specified time window (*T*, s) containing the acoustic event of interest. It is important to note that SPL always refers to a rms pressure level and therefore not instantaneous pressure:

$$L_p = 10\log_{10}\left(\frac{1}{T}\int_T p^2(t)dt \Big/ p_0^2\right) \text{ dB.}$$

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. The SPL represents a nominal effective continuous sound over the duration of an acoustic event, such as the emission of one acoustic pulse, a marine mammal vocalization, the passage of a vessel, or over a fixed duration. Because the window length, *T*, is the divisor, events with similar sound exposure level (SEL) but more spread out in time have a lower SPL.

The sound exposure level (SEL, dB re 1 μPa^2·s) is a measure related to the acoustic energy contained in one or more acoustic events (*N*). The SEL for a single event is computed from the time-integral of the squared pressure over the full event duration (*T*):

$$L_E = 10\log_{10}\left(\int_T p^2(t)dt \Big/ T_0 p_0^2\right) \text{ dB,}$$

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where T_0 is a reference time interval of 1 s. The SEL continues to increase with time when non-zero pressure signals are present. It therefore can be construed as a dose-type measurement, so the integration time used must be carefully considered in terms of relevance for impact to the exposed recipients.

SEL can be calculated over periods with multiple acoustic events or over a fixed duration. For a fixed duration, the square pressure is integrated over the duration of interest. For multiple events, the SEL can be computed by summing (in linear units) the SEL of the *N* individual events:

$$L_{E,N} = 10\log_{10}\left(\sum_{i=1}^{N} 10^{\frac{L_{E,i}}{10}}\right) \text{ dB .}$$

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A.2. Decidecade-Band Analysis

The distribution of a sound's power with frequency is described by the sound's spectrum. The sound spectrum can be split into a series of adjacent frequency bands. Splitting a spectrum into 1 Hz wide bands, called passbands, yields the power spectral density of the sound. This splitting of the spectrum into passbands of a constant width of 1 Hz, however, does not represent how animals perceive sound.

Because animals perceive exponential increases in frequency rather than linear increases, analyzing a sound spectrum with passbands that increase exponentially in size better approximates real-world scenarios. In underwater acoustics, a spectrum is commonly split into decidecade-bands, which are one-tenth of a decade wide; each decade represents a multiplication by 10 in sound frequency. The centre frequency of the *i*th decidecade-band, $f_c(i)$, is defined as:

$$f_c(i) = 10^{i/10} \text{ kHz}$$

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and the low (f_{lo}) and high (f_{hi}) frequency limits of the *i*th decidecade band are defined as:

$$f_{lo} = 10^{-1/20} f_c(i) \text{ and } f_{hi} = 10^{1/20} f_c(i)$$

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The decidecade bands become wider with increasing frequency, and on a logarithmic scale the bands appear equally spaced (Figure Error**! No text of specified style in document.**-1).

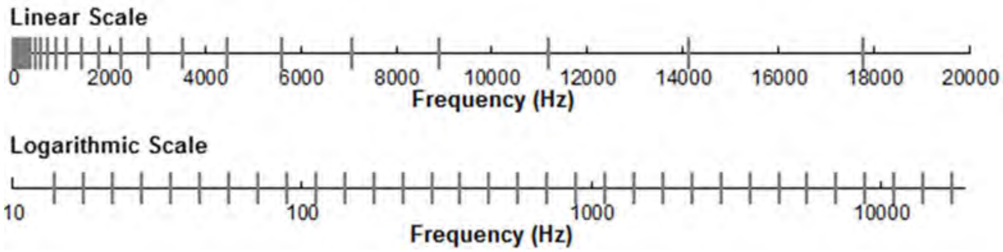

Figure **Error! No text of specified style in document.**-1. Decidecade bands shown on a linear frequency scale and on a logarithmic scale.

The sound pressure level in the *i*th decidecade band $(L_b^{(i)})$ is computed from the power spectrum $S(f)$ between f_{lo} and f_{hi}:

$$L_b^{(i)} = 10\log_{10}\left(\int_{f_{lo}}^{f_{hi}} S(f)df\right) \text{ dB}$$

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Figure Error**! No text of specified style in document.**-2 shows an example of how the decidecade band sound pressure levels compare to the power spectrum of an ambient noise signal. Because the decidecade bands are wider with increasing frequency, the decidecade band SPL is higher than the power spectrum at high frequency. Acoustic modelling of decidecade bands require less computation time than 1 Hz bands and still resolves the frequency-dependence of the sound source and the propagation environment.

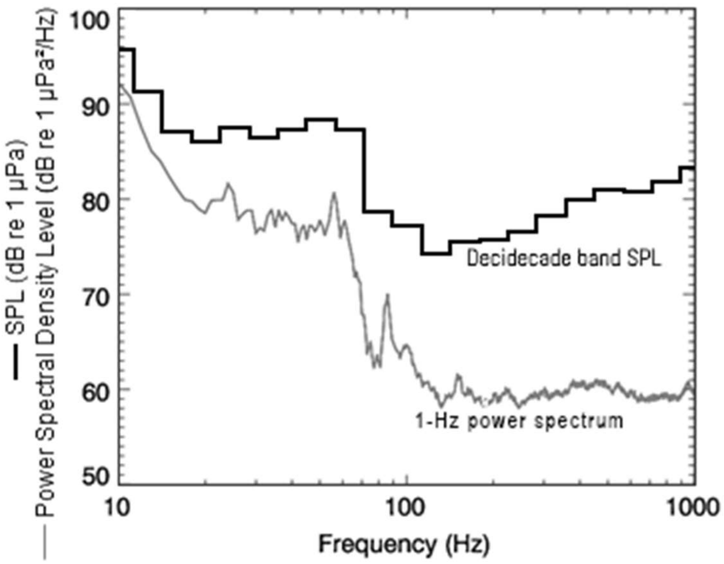

Figure **Error! No text of specified style in document.**-2. Sound pressure spectral density levels and the corresponding decidecade band sound pressure levels of example ambient sound shown on a logarithmic frequency scale. Because the decidecade bands are wider with increasing frequency, the 1/3-octave-band SPL is higher than the power spectrum.

A.3. Marine Mammal Frequency Weighting

The potential for noise to affect animals depends on how well the animals can hear it. Noises are less likely to disturb or injure an animal if they are at frequencies that the animal cannot hear well. An exception occurs when the sound pressure is so high that it can physically injure an animal by non-auditory means (i.e., barotrauma). For sound levels below such extremes, the importance of sound components at particular frequencies can be scaled by frequency weighting that is relevant to an animal's sensitivity to those frequencies (Nedwell and Turnpenny 1998, Nedwell et al. 2007).

A.3.1. SRKW Audiogram-Weighting

Audiograms represent the hearing threshold for tonal sounds (i.e., single-frequency sinusoidal signals) as a function of the tone frequency. These species-unique sensitivity curves are generally U-shaped, with higher hearing thresholds at low and high frequencies. Noise levels above hearing threshold are calculated by subtracting species-unique audiograms from the received 1/3-octave-band noise levels. The audiogram-weighted 1/3-octave-band levels are summed to yield broadband noise levels relative to each species' hearing threshold.

SRKW use sound actively when foraging to echolocate their prey. The echolocation signals range in frequency from 15 and 100 kHz (Au et al. 2004). SRKW also produce communication calls when foraging. Groups can spread out over several kilometres while foraging, but the area they cover is limited by the distance where they can detect calls. Calls typically range in frequency from 500 Hz to 40 kHz (Miller 2006). Although substantially louder below 1 kHz, ship noise reaches above 60 kHz. Thus, shipping noise may determine the distance between SRKW while foraging.

The SRKW audiogram used in this study is presented in Figure Error**! No text of specified style in document.**-3. Based on values from Szymanski et al. (1999) and Branstetter et al. (2017), it was extrapolated from the lowest measured frequency down to 10 Hz using a 12 dB/octave slope, which represents the hearing roll-off toward the infrasound range for mammals (Marquardt et al. 2007). Although the validity of the extrapolation for marine mammals is not physiologically confirmed, it is likely that these animals have a higher hearing threshold at frequencies outside their hearing range than the terminal trend of their audiogram predicts.

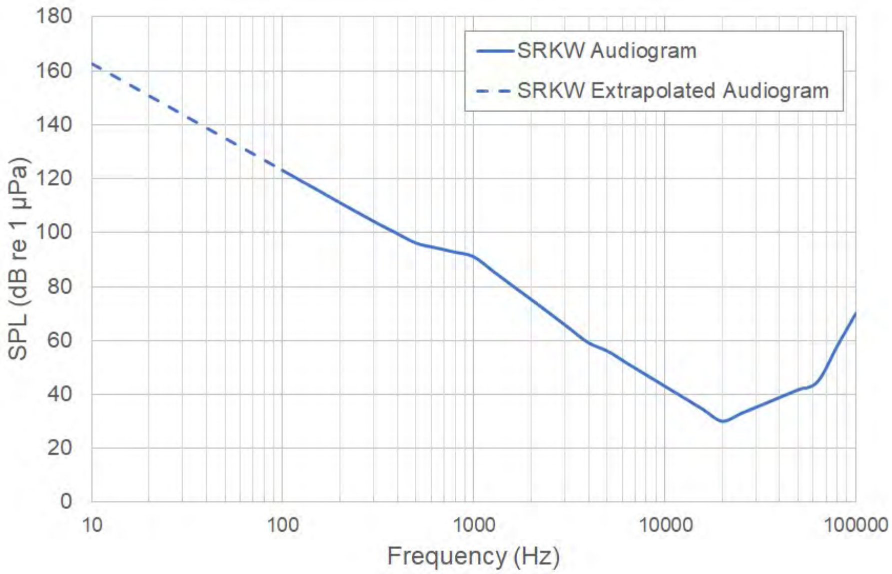

Figure **Error! No text of specified style in document.**-3. Southern Resident Killer Whale (SRKW) audiogram used for this study, based on Szymanski et al. (1999) and Branstetter et al. (2017). The dashed curve is extrapolated low-frequency threshold.

A.4. Automated Click Detector for Odontocetes Applied to Sonar Pulses

We applied an automated click detector/classifier to the data to detect sonar pulses. This detector/classifier is based on the zero-crossings in the acoustic time series. Zero-crossings are the rapid oscillations of a click's pressure waveform above and below the signal's normal level (e.g., Figure Error**! No text of specified style in document.**-4.). Pulses are detected by the following steps (Figure Error**! No text of specified style in document.**-4.):

1. The raw data is high-pass filtered to remove all energy below 8 kHz. This removes most energy from other sources such as shrimp, vessels, wind, and cetacean tonal calls, yet allows the energy from the sonar types of interest to pass.
5. The filtered samples are summed to create a 0.5 ms rms time series. Most commercial echosounders pings have a 1–4 ms duration.
6. Possible click events are amplified from the background with a split-window normalizer that divides the 'test' bin of the time series by the mean of the 6 'window' bins on either side of the test bin, leaving a 1-bin wide 'notch'.
7. A Teager-Kaiser energy detector identifies possible click events.
8. The high-pass filtered data is searched to find the maximum peak signal within 1 ms of the detected peak.
9. The high-pass filtered data is searched backwards and forwards to find the time span where the local data maxima are within 9 dB of the maximum peak. The sonar implementation of the algorithm allows for four zero-crossings to occur where the local peak is not within 9 dB of the maximum before stopping the search. This defines the time window of the detected click.

10. The classification parameters are extracted. The number of zero crossings within the click, the median time separation between zero crossings, and the slope of the change in time separation between zero crossings are computed. The slope parameter helps to identify beaked whale clicks, as beaked whales can be identified by the increase in frequency (upsweep) of their clicks.
11. The Mahalanobis distance between the extracted classification parameters and the templates of known click types is computed. The covariance matrices for the known click types, computed from thousands of manually identified clicks for each species, are stored in an external file. Each click is classified as a type with the minimum Mahalanobis distance unless none of them are less than the specified distance threshold.

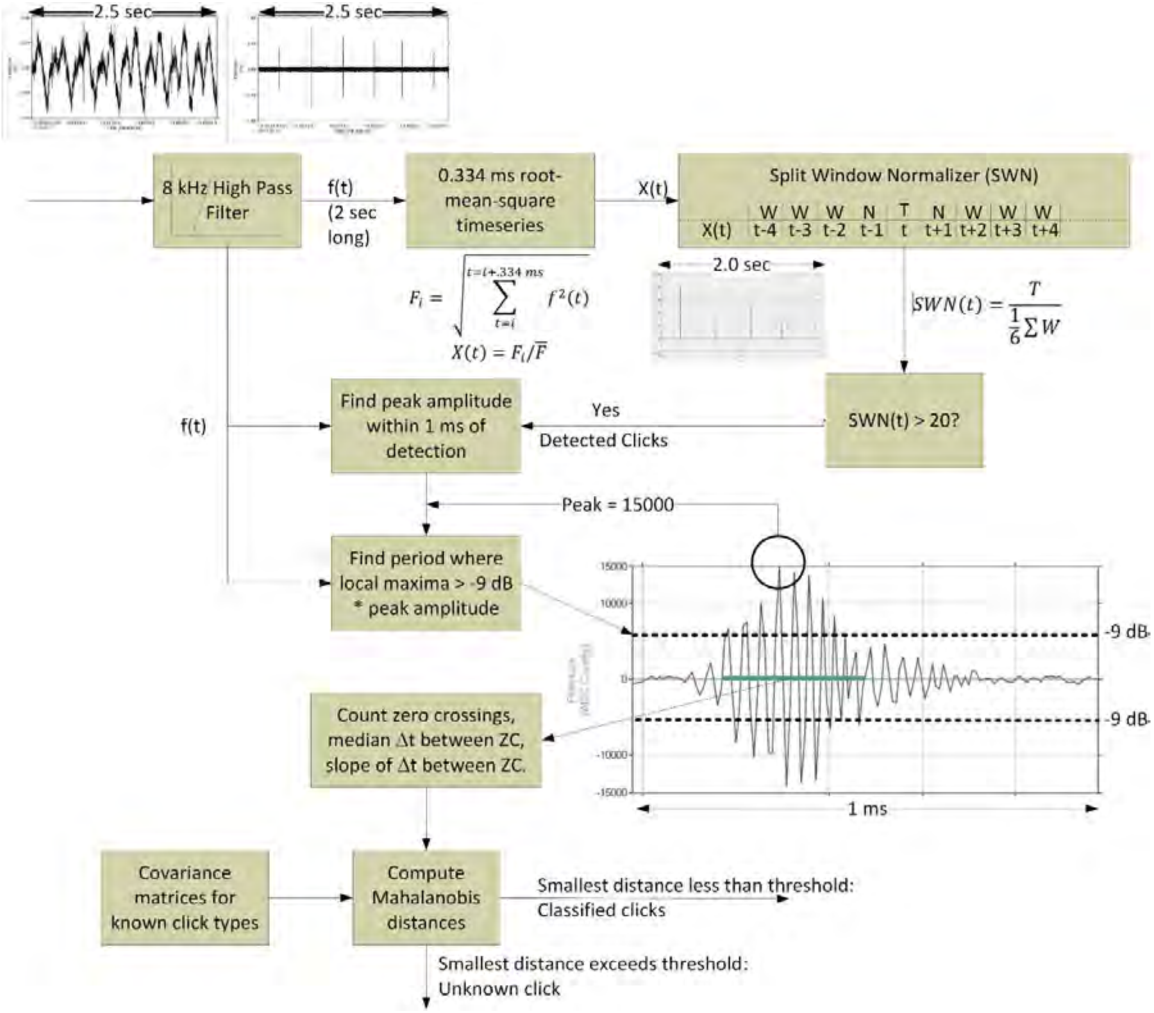

Figure **Error! No text of specified style in document.**-4. The odontocete click detector/classifier block diagram. For sonar pulses the root-mean-square duration was 0.5 ms and the split window normalizer threshold was changed to 12.