Prince Rupert – Aurora LNG Acoustic Monitoring Study

Chatham Sound Region

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Executive Summary

The Aurora LNG Project (the Project) is a joint venture between Nexen Energy ULC, INPEX Corporation, and JGC Corporation to develop a liquefied natural gas (LNG) plant, export facility, and associated marine terminal near Prince Rupert, British Columbia. An Environmental Impact Assessment is being developed as part of this process.

This report analyzes acoustic data collected for this Project from two underwater acoustic recorders placed between Digby and Kaien Islands and across Chatham Sound near Triple Island, BC.

Stantec Consulting Ltd., under contract to Nexen Energy ULC, engaged JASCO Applied Sciences to document baseline noise conditions near the proposed Project site. JASCO made these measurements with two Autonomous Multichannel Acoustic Recorders (AMARs) that recorded acoustic data between July and October/November 2014. The first AMAR, Station 1, was located approximately 3 km southwest of Prince Rupert, near the proposed Project site. The second AMAR, Station 2, was located approximately 30 km from the Project site, near the ferry and container vessel traffic lanes. Measurements were also made at a third location, Grassy Point, because both Grassy Point and Digby Island were being considered as potential Project sites; however, Nexen has formally withdrawn the Grassy Point site so data for this location were not analyzed.

Automated analysis techniques were applied to the acoustic data to determine the presence of marine mammals in the Project area. Clicks from undistinguished species of porpoises were detected almost daily at both stations throughout the recording period, whereas calls from undistinguished ecotypes of killer whales were detected sporadically, with Station 2 having more detection days than Station 1. Pacific white-sided dolphins were detected only on one day (in July) at Station 2, but not at all at Station 1. Humpback whale calls were detected only at Station 2, with the number of detection days peaking from mid-July to late October. Fin whale calls were detected only twice (in October) and only at Station 2. Harbour seal calls were detected only at Station 1 and occurred mainly from mid-July to mid-August.

Vessels contributed to the soundscape at both stations; Station 1 had the most vessels detected per day and showed a strong diel trend with more vessels during the day than the night, while this pattern was not observed at Station 2. Wind also contributed to ambient noise at Station 2.

Sound levels at Station 1 exceeded 120 dB re 1 µPa root-mean-square sound pressure level (rms SPL), the regulatory threshold set by the United States-based organization National Oceanic and Atmospheric Administration Fisheries (NOAA) for marine mammal disturbance with non-impulsive noise sources, 8.2% of the time. At Station 2, this threshold was exceeded 2.5% of the time.

1. Introduction

The Aurora LNG project (the Project) is a joint venture between Nexen Energy ULC (Nexen), INPEX Corporation, and JGC Corporation to develop a liquefied natural gas (LNG) plant, export facility, and associated marine terminal on the southeast corner of Digby Island, approximately 3 km southwest of Prince Rupert, British Columbia (BC) (Figure 1). JASCO Applied Sciences (JASCO) was contracted by Stantec Consulting Ltd. (Stantec, under contract to Nexen) to document the baseline noise conditions near the proposed LNG site.

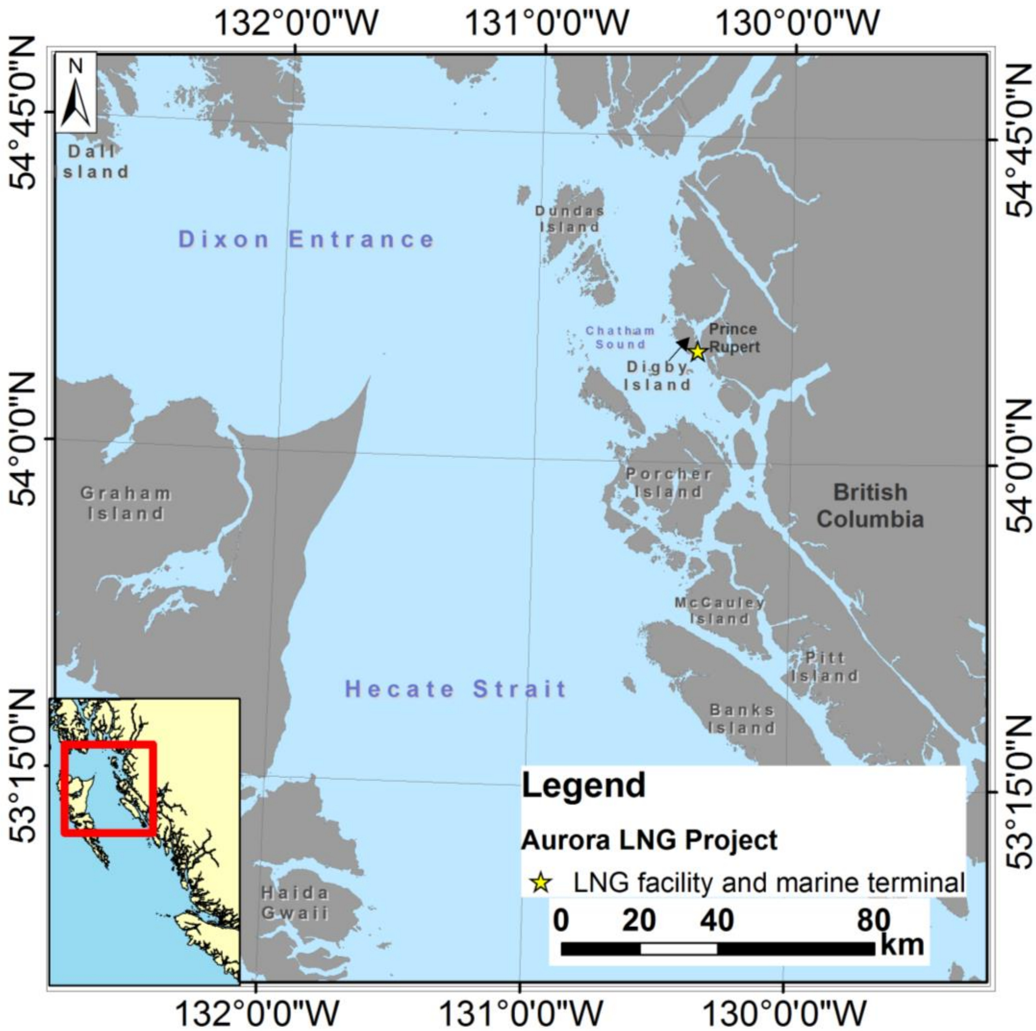

Figure 1. The Prince Rupert area, Chatham Sound, and Hecate Strait.

This report provides the results from data collected over four months (July–October/November 2014) of autonomous acoustic monitoring from Autonomous Multichannel Acoustic Recorders (AMARs) deployed near Digby Island and near Triple Island, BC (S1 and S2; Figure 2). The total sound level data provide a statistical noise distribution of the pre-project development conditions at the planned site. JASCO analyzed the underwater acoustics to characterize the existing ambient sound levels, the existing vessel traffic, and the marine mammal presence.

Measurements were also made at a third location, Grassy Point (S3; Figure 2), because both Grassy Point and Digby Island were being considered as potential Project sites; however, the Grassy Point site has been formally withdrawn by Nexen and data for this location were not analyzed as part of the scope of work for this report.

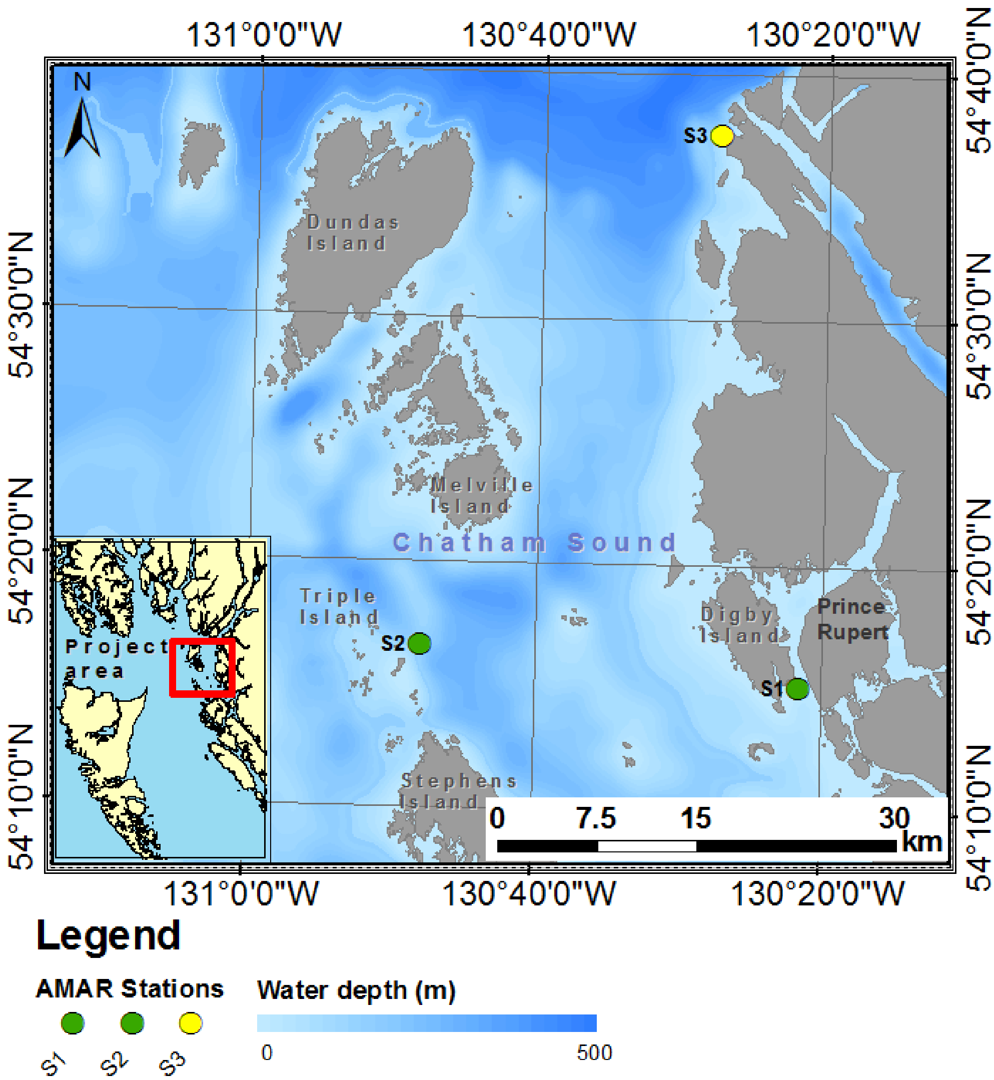

Figure 2. AMAR locations for the Aurora LNG acoustic monitoring study. Station 1 (S1) was approximately 3 km southwest of Prince Rupert, near the proposed location for the Aurora LNG Project area. Station 2 (S2) was approximately 30 km from the Project site; it is also near the ferry and container traffic lanes. Station 3 (S3) at Grassy Point, approximately 35 km north of Prince Rupert, has not been analyzed in this study.

1.1. Aurora LNG Project Background

The proposed Project will include producing, storing, transferring, and loading LNG onto carriers for marine transport to Asian markets (Aurora LNG 2015).

An onshore LNG plant is proposed for the Project site at Digby Island. The proposed infrastructure will be situated on approximately 785 ha of provincial Crown land and will include facilities needed to support the operations of storing, processing, and liquefaction of natural gas. When it is completed, the associated marine terminal will accommodate a maximum of two LNG carriers.

1.2. Acoustic Monitoring Study

The acoustic monitoring program was undertaken to determine a baseline against which to establish whether underwater noise generated by the construction and operation of the LNG facility could adversely affect the environment, including fish and marine mammals. The underwater noise sources within the terminal footprint during the construction phase might include in-water pile installation, dredging, and in-water blasting. Once the LNG facility is complete and operational, the main sources of underwater noise will be from LNG carriers standing by during loading, active berthing of LNG carriers using tugs, and sound and vibration from onshore machinery propagating into the water.

JASCO documented baseline noise conditions near the proposed Project site with AMARs that recorded acoustic data between July and October/November 2014 at three stations. Station 1 was located approximately 3 km southwest of Prince Rupert, near the proposed site. Station 2 was located approximately 30 km from the Project site, near the ferry and commercial shipping traffic lanes. Station 3 was located at Grassy Point, approximately 35 km north of Prince Rupert.

1.3. Marine Mammal Activity in Chatham Sound and Hecate Strait

Current knowledge of marine mammal presence and distribution in Hecate Strait and Chatham Sound (Table 1) is largely derived from dedicated vessel and aerial surveys (Williams and Thomas 2007, Ford 2014).

Hecate Strait is located between the BC mainland and Haida Gwaii. The Gulf of Alaska joins Hecate Strait through Dixon Entrance, between the BC mainland and Dall Island. Chatham Sound extends easterly from Dixon Entrance and includes the Prince Rupert area (Figure 1). Several cetacean (i.e., whale, dolphin, and porpoise) and pinniped (e.g., seal and sea lion) species use Hecate Strait as seasonal or year-around habitat (reviewed by Gregr 2004, Ford 2014). Four species of baleen whales, four species of odontocetes, and two species of pinnipeds (Table 1) are known to use the region regularly. A high-level summary of these species, their occurrence in the study area, and their primary calling behaviours is provided below. There have been a few rare sightings of California sea lions (*Zalophus californianus*), northern elephant seals (*Mirounga angustirostris*), and sea otters (*Enhydra lutris*) either in or near the Project area (Ford 2014).

Like most baleen whales, humpback whales (*Megaptera novaeangliae*) migrate seasonally from high-latitude feeding areas in summer to low-latitude breeding and calving areas in winter. They use BC waters primarily for feeding during the late spring through fall (Ford et al. 2010); however, some humpback whales are present year-round, particularly along the northern coast of BC (Ashe et al. 2013). Humpback whales are known to produce a wide variety of non-song vocalizations (Silber 1986, Dunlop et al. 2007, Stimpert et al. 2007, Dunlop et al. 2008) which include social and feeding calls, in addition to their complex, repetitive, patterned songs (Payne and McVay 1971, Winn and Winn 1978). Adult males produce songs that consist of a sequence of discrete sound elements, called units, separated by silence (Payne and McVay 1971). During the winter breeding season in the tropics, humpback whales regularly sing (Winn and Winn 1978, Tyack 1981), but this behaviour has also been reported along migration routes and within higher-latitude regions (Mattila et al. 1987, McSweeney et al. 1989, Charif et al. 2001).

Fin whales (*Balaenoptera physalus*) have been reported in the offshore waters of Hecate Strait and Dixon Entrance; some fin whales—mostly young—have been observed feeding in summer in both shelf-edge and on-shelf waters (COSEWIC 2005). Winter sightings of fin whales have also been reported in Hecate Strait (Gregr et al. 2005). Fin whales produce a variety of low-frequency (mostly < 100 Hz), high-intensity (up to 189 dB re: 1 µPa at 1 m), short-duration (approximately 1 s), frequency-modulated sounds (Watkins 1981, Watkins et al. 1987, Edds 1988, Širović et al. 2007). The fin whale sound most often reported is the “20 Hz pulse,” a short-frequency downsweep mostly centered around 20 Hz, which is produced by fin whales worldwide (Watkins 1981, Edds 1988, Thompson et al. 1992, Clark and Fristrup 1997, Watkins et al. 2000, Nieukirk et al. 2004, Širović et al. 2004, Castellote et al. 2012) and likely has a reproductive function since only males make these sounds (Croll et al. 2002). Another downsweep call centered at a higher frequency has been reported by Watkins (1981). This call sweeps down in frequency, generally from 75 to 40 Hz, but can range from 100 to 30 Hz; it is produced mostly during the summer during deep dives (Watkins 1981) and could be associated with a foraging function (Širović et al. 2013). Other call types have also been reported, but their social context is not well understood (Watkins 1981, Edds 1988). Because fin whales sing throughout BC waters all winter, their songs are likely associated with reproductive and feeding behaviours (Koot 2015). Koot (2015) noticed that two song types occur in BC, which suggests that two distinct populations are present.

Little is known about the seasonal movements of North Pacific minke whales (*Balaenoptera acutorostrata scammoni*) (Money and Trites 1998). Minke whales are thought to migrate south from Alaska during winter, but some also have home ranges in Washington and central California (Shelden and Rugh 2010). Within BC, it is unknown if minke whales migrate or develop home ranges. Minke whales often enter coastal areas and frequently enter bays, inlets, and estuaries to search for prey. Minke whales are known to produce a variety of vocalizations across their range of occurrence. Low-frequency downsweeps, higher frequency clicks and a variety of other sounds have been recorded in the Antarctic (Schevill and Watkins 1972, Leatherwood et al. 1981). More recently, some boing sounds have been attributed to this species (Rankin and Barlow 2005). In the Caribbean region, low-frequency pulse trains with varying interpulse interval structure have been recorded (Winn and Perkins 1976, Mellinger et al. 2000). In the Gulf of St. Lawrence, Canada, frequency-modulated downsweeps (118 to 80 Hz) have been recorded (Edds-Walton 2000). In the North Atlantic, series of clicks in the 5 to 6 kHz range have been attributed to this species (Beamish and Mitchell 1973).

Virtually the entire population of migrating grey whales (*Eschrichtius robustus*) moves through BC coastal waters in spring and winter. This population spends its winters breeding in warm temperate waters and its summers feeding in the Bering, Chukchi, and Beaufort Seas (COSEWIC 2004). Mate et al. (2015) demonstrated that some grey whales migrate across the Pacific to spend their summers in the western North Pacific (Sakhalin Island, Russia). Some grey whales do not fully migrate to Arctic feeding grounds; instead, they spend summers feeding in temperate waters off the coast of BC. These summer grey whales tend to return to the same feeding sites annually (Calambokidis et al. 2002). Because grey whales have diverse feeding habits, they likely use most of the nearshore habitat along the outer coast of BC and some sheltered bays in the inside waterways (COSEWIC 2004). Ford et al. (2013) demonstrated that Hecate Strait and Dixon Entrance, rather than the west coast of Haida Gwaii, form the primary northward migratory corridor for grey whales. Dahlheim (1987) described six grey whale call types: 1) pulses 2) clangs 3) moans 4) grunts and groans 5) bubble blasts and 6) bubble trails. When they migrate, grey whales produce four categories of signals—pulses and bonging signals, low-frequency moans, grunts, and subsurface exhalations—which are concentrated below 1500 Hz (Crane and Lashkari 1996). Most sounds produced have center frequencies below 200 Hz; low-frequency moan sounds in particular average 70–80 Hz and probably contain energy below 40 Hz. Crane and Lashkari (1996) demonstrated that grey whales did not continuously vocalize, but rather produced vocalizations between relatively long periods of silence.

Northern Resident (NR) killer whales (*Orcinus orca*) range from Juan de Fuca Strait to southeast Alaska. They occur in BC year-round and congregate during spring, summer, and fall on the northern BC coast. The NR killer whale population is divided into three clans: A, G, and R, each of which have different acoustic repertoires (Ford 1991, Ford et al. 2000). Although clans seem to have regional preferences, there is no evidence that they restrict themselves to specific regions. Of the three clans, R appears to prefer the northern extent of the population's range (Ford et al. 2000). Dialects have been described for several resident killer whale populations from the North Pacific (Ford 1991, Yurk et al. 2002, Filatova et al. 2007). Comparing killer whale acoustic repertoires is complicated by the fact that killer whale sounds are not structurally homogeneous. They comprise three distinct structural categories, common to all killer whale populations studied to date: whistles, echolocation clicks, and pulsed calls. Most pulsed calls are highly stereotyped and can be easily divided into call types (Ford 1991) which vary somewhat between types. Stereotyped whistles are structurally identical in two of the three acoustic clans (Riesch et al. 2006).

West Coast Transient (WCT) killer whales travel in small groups over a wide geographical range (California to Alaska); they are not confined to any single area (Baird 2001). Unlike NR killer whales, which feed exclusively on fish and cephalopods, WCT killer whales feed on other marine mammals, particularly harbour seals, porpoises, and sea lions (Ford et al. 1998). WCT and NR killer whales have occasionally been seen close to each other, but rarely interact (Ford and Ellis 1999). WCT killer whales vocalize (Ford 1984, Deecke et al. 2005) and produce echolocation clicks (Barrett-Lennard et al. 1996) much less frequently than NR killer whales, decreasing the odds that their prey will detect them. Foote and Nystuen (2008) found frequency parameters differed between southern resident, transient, and offshore North Pacific killer whale populations. The southern resident ecotype produced calls where the minimum and peak frequencies were significantly higher than the transient ecotype; the offshore ecotype produced calls whose minimum frequency was significantly higher than the two other ecotypes. Filatova et al. (2015) demonstrated that fundamental frequencies of North Pacific resident (Southern, Northern, Kamchatkan and Alaskan residents) and North Atlantic killer whale calls were similar, while North Pacific transients had significantly lower frequency calls.

Pacific white-sided dolphins (*Lagenorhynchus obliquidens*) are common both offshore and along continental margins in shelf and slope waters (Morton 2000). In BC, Pacific white-sided dolphins move inshore and offshore throughout the year, but more commonly occur in coastal waters during fall and winter, moving offshore in spring and summer as they follow their prey (Morton 2000). Pacific white-sided dolphins produce echolocation clicks that range in frequency from 20 to over 100 kHz (Evans 1973, Soldevilla et al. 2008). In odontocetes, echolocation clicks are primarily used to forage and navigate, and possibly to communicate. Spectral analysis has revealed two distinct echolocation click types that can readily distinguish these dolphins from one another and from other species (Soldevilla et al. 2008). The biological significance of those two click types might correspond to the two distinct populations revealed by genetic and morphological studies (Soldevilla et al. 2008). These populations differ in their diel patterns, which suggests they prefer different prey (Soldevilla et al. 2010). In addition to clicks, Pacific white-sided dolphins produce burst pulses and buzzes—series of rapid click trains with very short inter-click intervals—which they use to forage and communicate (Lammers et al. 2003, Lammers et al. 2006).

Eastern Pacific harbour porpoise (*Phocoena phocoena vomerina*) are found year-round throughout the shelf waters of BC (Olesiuk et al. 2002); they reproduce seasonally, with births occurring from May through September (Baird and Guenther 1995). Their seasonal movements appear to be from inshore to offshore, likely as a response to the abundance and distribution of food resources. Harbour porpoises echolocate and make social clicks (Busnel et al. 1963, Busnel and Dziedzic 1966, Schevill et al. 1969, Read 1999). Knowledge about free-ranging harbour porpoises' echolocation behaviour is limited. They can emit clicks singly or in groups called click trains. Harbour porpoise echolocation clicks are relatively short and tonal (Schevill et al. 1969). Clicks are emitted in a narrow beam with dominant narrow-band, high-frequency click components within 110–150 kHz (Møhl and Andersen 1973, Verboom and Kastelein 1997, Au et al. 1999, Teilmann et al. 2002, Villadsgaard et al. 2007). Harbour porpoise click durations span 61 to 300 µs (Verboom and Kastelein 1997, Teilmann et al. 2002).

Dall's porpoise (*Phocoenoides dalli*) are common in BC both offshore and in deep coastal waters, either singly or in groups of up to several hundred individuals, although there are data gaps about where Dall's porpoises calve, breed, and feed (Money and Trites 1998, Hall 2011). Far less is known about the vocal communications among Dall's porpoises than among harbour porpoises. Some newly captive Dall's porpoises make sounds almost constantly, whereas others remain silent (Ridgeway 1966). Awbrey et al. (1979) proposed that wild Dall's porpoises obtain environmental details through signal amplitude modulation and by varying the acoustic pulse characteristics (e.g., time, duration, single or double pulses, and interpulse intervals). Awbrey et al. (1979) characterized the high frequency clicks with which Dall's porpoises echolocate as having peak energy levels between 120–160 kHz. Hatakeyama et al. (1994) reported that captive Dall's porpoises emitted short high frequency pulses ranging from 135 to 140 kHz, with a pulse duration of 50 to 60 µs and a source level of 165 to 175 dB re 1 µPa. Thus, harbour and Dall's porpoises produce clicks in the frequency range between 100–170 kHz with very similar acoustic characteristics (Clausen et al. 2010) and are very hard (or even impossible) to distinguish in practice. Kyhn et al. (2013) reported some spectral differences between clicks from Dall's and harbour porpoises; however, this study used measurements that do not occur often in practice as they were taken from immediately in front of the vocalizing animal at close range.

Steller sea lions (*Eumetopias jubatus*) exhibit strong seasonal movements from rookeries during their breeding season (June–August) to more widely distributed haul-outs at other times of the year (Cummins and Haigh 2010). The underwater vocalizations of Steller sea lions are relatively unknown, but Schusterman et al. (1970) reported a sound called "belching", similar to the aerial vocalization that the male of this species frequently produces. The recording showed some underwater clicks as a series of rather discrete, low frequency pulses at the rate of approximately 20 to 30 per second. Barking and clicks have also been reported (Orr and Poulter 1967, Poulter and del Carlo 1971).

Pacific harbour seals (*Phoca vitulina richardii*) exhibit some site fidelity; they use the lower Skeena River and surrounding area (near Prince Rupert) year-round (Olesiuk et al. 1990, DFO 2010). Hanggi and Schusterman (1994) first described underwater vocalizations for adult harbor seals in situ in Moss Cove, central California, and hypothesized that these calls were related to breeding activity. The most common vocalization this species makes is a broadband, nonharmonic roar with energy between 50 and 4000 Hz. This roar is the only harbour seal vocalization that is reported from all areas studied, i.e., for populations in Norway and Sweden (Bjørgesæter et al. 2004), UK (Van Parijs et al. 1997, Van Parijs et al. 2000, Bjørgesæter et al. 2004), USA (Hanggi and Schusterman 1994, Hayes et al. 2004), and eastern Canada (Coltman et al. 1997, Van Parijs and Kovacs 2002, Van Parijs et al. 2003, Boness et al. 2006).

Passive acoustic monitoring using multiple recorders is a reliable method for measuring temporal and spatial distributions of sound-producing marine mammals for long periods over large areas, including in remote locations and during adverse weather conditions or seasons that would otherwise prohibit direct observation (e.g., Hannay et al. 2013). Acoustic detection and subsequent classification of marine mammal calls require that animals produce acoustic signals of sufficient amplitude that they will be detected in the presence of other sounds, and that these signals are distinctive of each species. Thus, the results that can be obtained from acoustic studies apply only to acoustically active animals producing relatively unique calls within a given distance from the recorders. Species with high vocalization rates and long calling bouts (e.g., humpback whale songs) are more likely to be recorded incidentally compared to species with lower vocalization rates, short calling bouts, or whose calls do not propagate as far (e.g., Pacific white-sided dolphins). Sounds below 1 kHz (typical of mysticete calls) experience significantly less absorption loss in seawater than sounds above 10 kHz (typical of odontocete calls), and thus can be detected at greater distances (Mellinger et al. 2004). Mysticete calls are commonly detected on a single hydrophone at ranges of several tens of kilometres (Stafford et al. 2007), whereas odontocete clicks and whistles can be detected at ranges of 1–6 km (Quintana-Rizzo et al. 2006, Wang et al. 2006, Jensen et al. 2012, Ainslie 2013).

Table 1. Occurrence of known marine mammal species in Hecate Strait and Chatham Sound and the characteristics of the underwater sounds they produce. Status assessments by the Committee on the Status of Endangered Wildlife in Canada (2003b, 2003a, 2004, 2006, 2009, 2011), the Species at Risk Act (2002) and BC's Wildlife Act (B.C. Conservation Data Centre 2015).

Species	Main period of residency	Vocalization frequency range and references	COSEWIC status	SARA status	BC Wildlife Act status
Baleen whales					
Humpback whale	Year-round	10–8000 Hz Winn and Winn (1978), Thompson et al. (1979), Payne and Payne (1985), Thompson et al. (1986), Dunlop et al. (2007)	Special concern	Threatened	Formerly vulnerable
Fin whale	Summer	15–150 Hz Watkins (1981), Clark et al. (2002)	Threatened	Threatened	Threatened
Minke whale	Unknown	60–5000 Hz Schevill and Watkins (1972), Edds-Walton (2000), Mellinger et al. (2000), Rankin and Barlow (2005)	Not at risk	Not at risk	Not at risk
Grey whale	Migration: Spring and Winter	10–1500 Hz Crane and Lashkari (1996)	Special concern	Special concern	Formerly vulnerable
Toothed whales					
Killer whale (Northern Resident and West Coast Transient)	Year-round	500–50000 Hz Awbrey et al. (1982), Ford and Fisher (1983), Moore et al. (1988), Barrett-Lennard et al. (1996), Deecke et al. (2005), Riesch et al. (2006), Simonis et al. (2012)	Threatened	Threatened	Threatened
Pacific white-sided dolphin	Year-round	20–100 kHz Evans (1973), Soldevilla et al. (2008)	Not at risk	Not at risk	Not at risk
Harbour porpoise	Year-round	Peak frequency 128-141 kHz Au et al. (1999), Kyhn et al. (2013)	Special concern	Special concern	Formerly vulnerable
Dall's porpoise	Year-round	Peak frequency ~ 137 kHz Kyhn et al. (2013)	Not at risk	Not at risk	Not at risk
Pinnipeds					
Steller sea lion	Summer	< 3 kHz, Belching, barking and clicks Orr and Poulter (1967), Schusterman et al. (1970), Poulter and del Carlo (1971)	Special concern	Special concern	Formerly vulnerable
Harbour seal	Year-round	< 2 kHz, HF clicks possible Van Parijs and Kovacs (2002)	Not at risk	Not at risk	Not at risk

2. Methods

The acoustic monitoring study was performed with autonomous acoustic recorders deployed on the seabed for four months at three stations in Chatham Sound. Data collected at the Grassy Point station were not analyzed for this report.

Automated analysis techniques quantified total sound levels and vessel passages, as well as counts of various kinds of marine mammal moans, whistles, and clicks.

Unless otherwise noted, all times in this report are local time (PDT: Pacific Daylight Time; UTC-7).

2.1. Acquiring Acoustic Data

2.1.1. Recorder configuration and duration

Underwater sound was recorded with three Autonomous Multichannel Acoustic Recorders (AMARs, JASCO Applied Sciences, Figure 3). Each AMAR was fitted with an M8E-35dB omnidirectional hydrophone (GeoSpectrum Technologies Inc., −165 ± 3 dB re 1 V/µPa sensitivity). Hydrophones were protected by a metal cage, which was covered with a fabric shroud to minimize noise artifacts from water flow. The hydrophone data were recorded continuously on two AMAR channels: a 24-bit channel sampling at 16 ksps (for a recording bandwidth of 10 Hz to 8 kHz), and a 16-bit channel sampling at 375 ksps (for a recording bandwidth of 10 Hz to 187.5 kHz). Each AMAR was set up to record repeating cycles consisting of 475 s of sampling at 16 ksps (24-bit resolution with 6 dB gain) followed by 87 s of sampling at 375 ksps (16-bit resolution with 0 dB gain), then a sleep mode of 38 s. The acoustic data were stored in 1.8TB of internal solid-state flash memory. Each hydrophone was calibrated in the field before deployment and after retrieval.

Figure 3. Autonomous Multichannel Acoustic Recorder (AMAR; JASCO Applied Sciences).

2.1.2. Monitoring period

The AMARs were deployed in Chatham Sound (Figure 2) on 11 Jul 2014, and retrieved from 19–21 Nov from the M/V *Inlet Provider* (Figure 4). The AMARs at Stations 1 and 3 operated from deployment to retrieval, while the AMAR at Station 2 recorded up to 31 Oct 2014 (Table 2).

Table 2. Station coordinates (see Figure 2) and recording durations for the 4-month deployment.

Station	Latitude (°N)	Longitude (°W)	Water Depth (m)	Deployment	Retrieval	Recording days
1	54° 15.084'	130° 21.640'	18.9	11 Jul	19 Nov	132
2	54° 16.558"	130° 48.067'	122	11 Jul	21 Nov	113
3	54° 37.540"	130° 27.724'	28.3	11 Jul	20 Nov	133

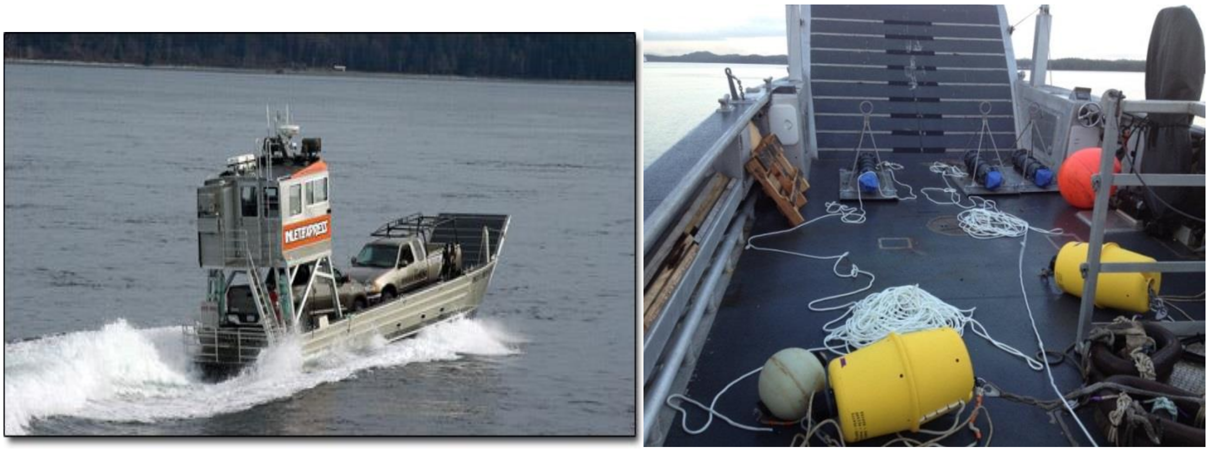

Figure 4. Photos of the M/V *Inlet Provider* used to retrieve and deploy the AMARs. Photo on the left from http://www.inletexpress.com/.

2.1.3. Mooring configurations

For the two shallower stations (Station 1 and Station 3), the AMAR was fastened to a 28 kg anchor weight and attached to a SPORT LF (EdgeTech) pop-up acoustic release for retrieval. The mooring configuration allowed for a grapple backup in case the acoustic release failed (Figure 5). For the deeper station (Station 2), the AMAR was fastened to a 48 kg anchor weight and attached to two releases (SPORT LF and PORT LF, EdgeTech), which provided a backup acoustic release in case one failed. The mooring configuration also allowed for a grapple backup in case both acoustic releases failed (Figure 6).

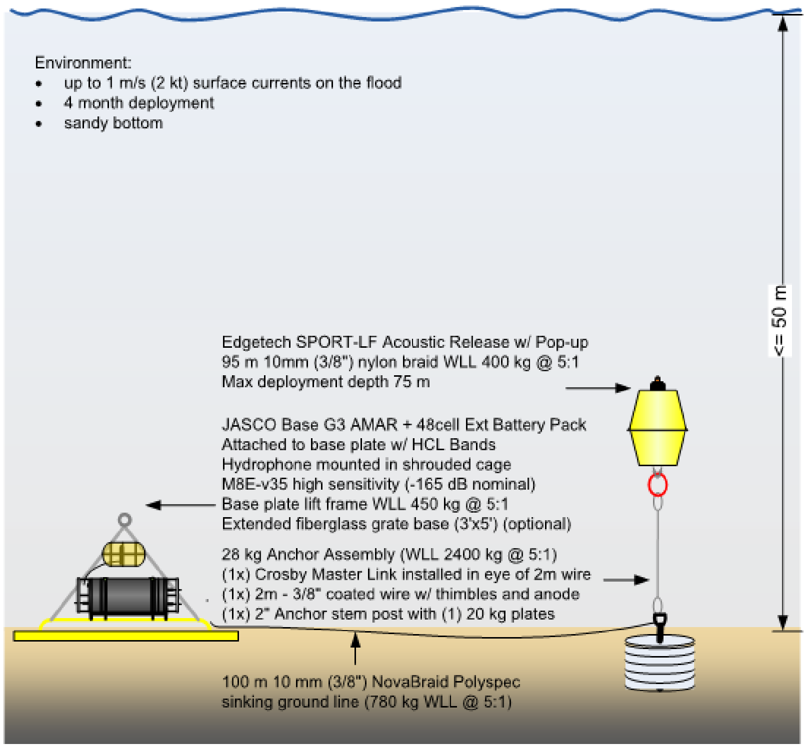

Figure 5. Autonomous Multichannel Acoustic Recorder (AMAR) with an acoustic release and grapple backup for retrieval. This mooring design was used at the shallow water locations Station 1 and Station 3.

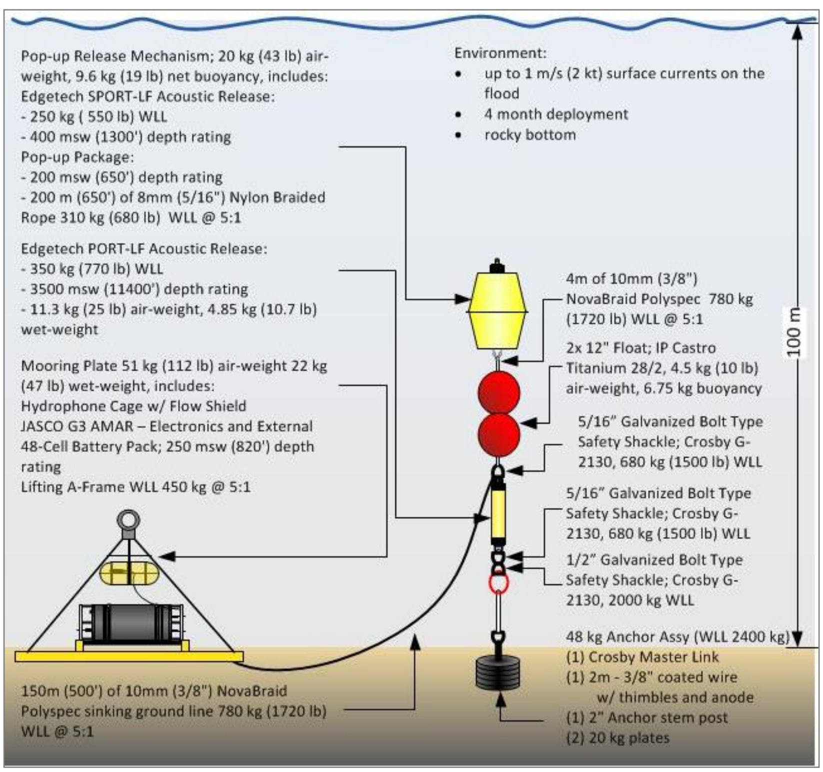

Figure 6. Autonomous Multichannel Acoustic Recorder (AMAR) with two acoustic releases in tandem and grapple backup for retrieval. This mooring design was used for Station 2, the deep water location.

2.2. Analyzing Data

The data sampled at 16 ksps were analyzed for ambient sound, vessel noise, and marine mammal calls except porpoise clicks. Porpoise click detection was performed on the data sampled at 375 ksps. This section describes the automatic algorithms (Figure 7) and the manual analysis procedure used.

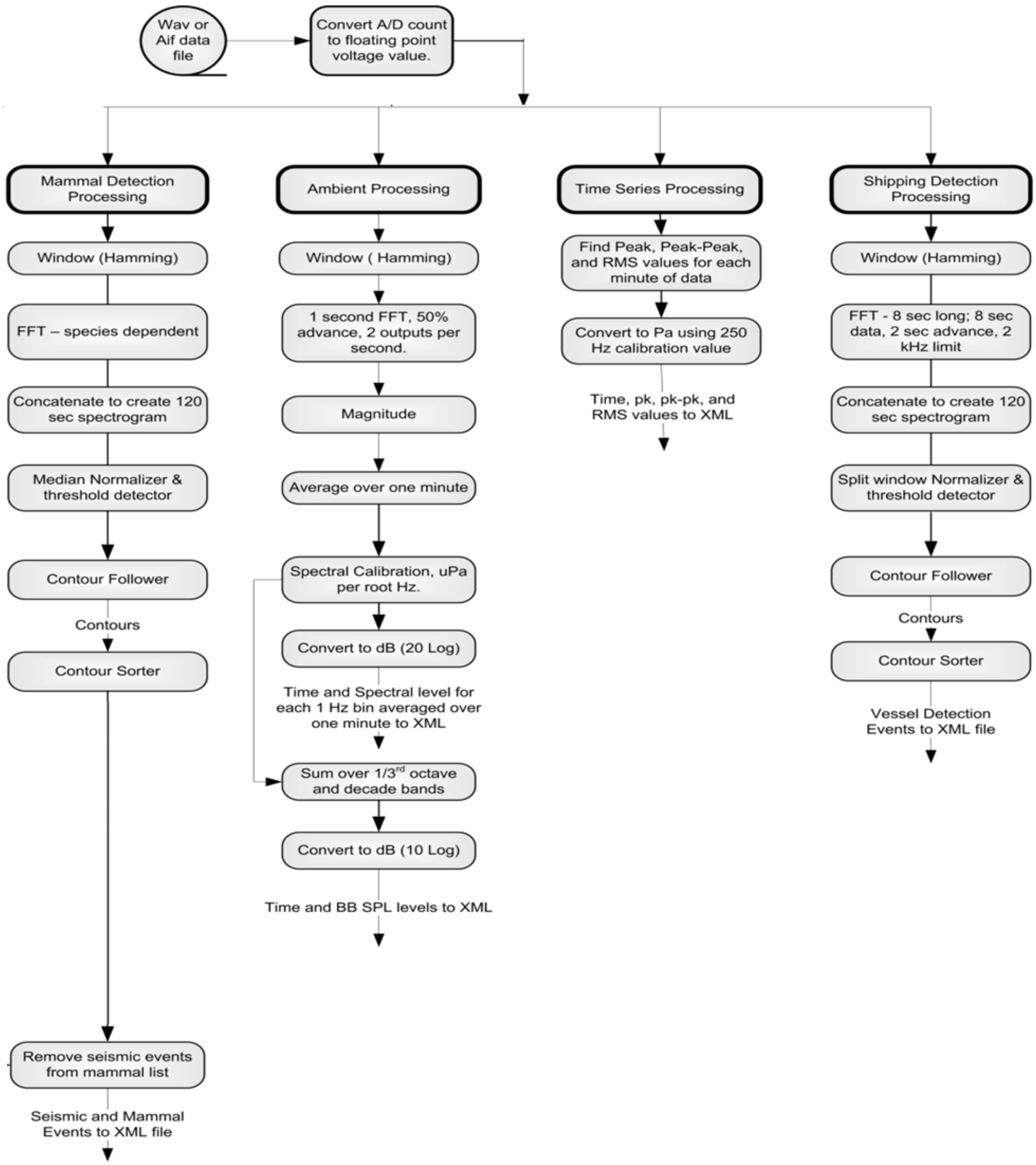

Figure 7. Component blocks of JASCO's automated acoustic analysis software. Not all of these processing stages are used in the present study.

2.2.1. Total ambient sound levels

To describe the existing underwater soundscape in the area before the Aurora LNG facility is constructed, JASCO staff analyzed data recorded at 16 ksps. The analysis is based on the 1-minute average power spectral density of the data computed from fast Fourier transforms (FFTs) of 1 s of data overlapped by 0.5 s (120 averages).

The following acoustic metrics are used to quantify ambient sound:

- **root-mean-square sound pressure level (rms SPL)**: the SPL averaged over a stated time window (here each minute) within a given frequency band. It is expressed in decibels (dB) re 1 µPa.
- **Power spectral density (PSD) level**: a description of how the acoustic power is distributed over different frequencies within a spectrum. It is expressed in dB re 1 $\mu Pa^2/Hz$.
- **Daily sound exposure levels (daily SELs)**: the linear sum of the 1-min SELs over 24 h, where the SEL describes the total sound energy flux density over a given period and is commonly used as a surrogate for the received energy.
- **Daily equivalent continuous sound level (daily L_{eq})**: the SPL of a continuous sound that has the same total energy as the measured, time-varying sound over 24 h. The L_{eq} represents the time-varying sound levels as a single decibel value by averaging the total sound energy over 24 h. It is equivalent to the rms SPL computed over an averaging period of 24 h.

Sound level statistics, namely exceedance percentiles, were used to quantify the distribution of recorded sound levels. Following standard acoustical practice, the *n*th percentile level (L_n) is the level (i.e., PSD level, rms SPL, or daily SEL) exceeded by *n*% of the data. L_{max} is the maximum recorded sound level. L_{mean} is the linear arithmetic mean of the sound power, which can significantly differ from the median sound level L_{50}. The median level, rather than the mean, was used to compare the most typical sound level between stations since the median is less affected by high outliers than the mean sound level. L_5, the level exceeded by only 5% of the data, represents the highest typical sound levels measured; sound levels between L_5 and L_{max} are generally from very close passes of vessels, very intense weather events, or other infrequent conditions. L_{95} represents the quietest typical conditions.

The PSD exceedance percentiles are directly comparable to the Wenz curves (Wenz 1962), which describe the PSD levels of marine ambient sound from weather, wind, geological activity, and commercial shipping. Figure 8 shows the Wenz curves along with the source levels of various types of anthropogenic sound sources. The 'limits of prevailing noise' of the Wenz curves (black lines in Figure 8) represent the typical range of ambient sound PSD levels in the ocean and are plotted as orange dashed lines on the ambient sound PSD results in Section 3.1 for comparison.

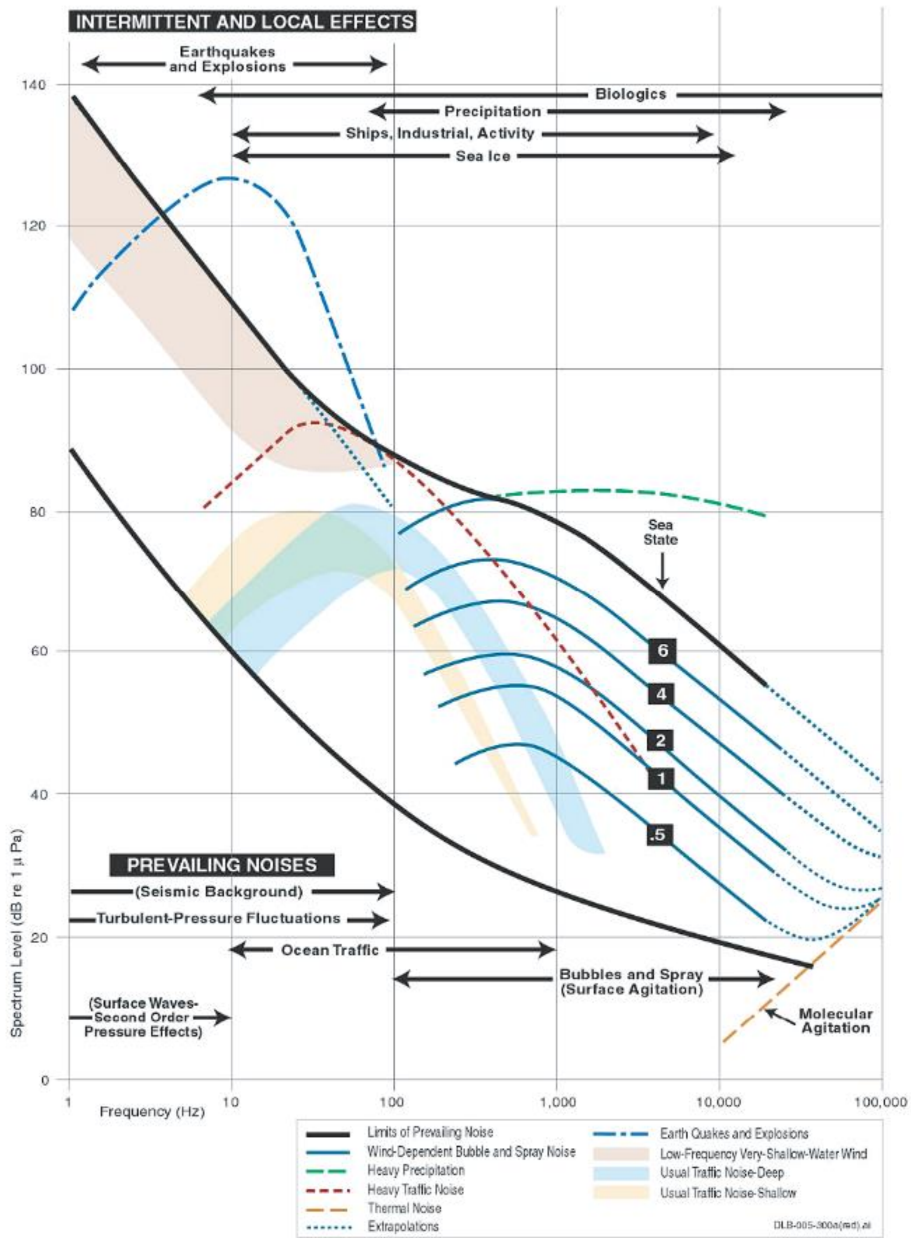

Figure 8. Wenz curves describing pressure spectral density levels of marine ambient noise from weather, wind, geological activity, and commercial shipping. Thick lines indicate limits of prevailing noise. Figure reproduced from National Research Council (2003) and Wenz (1962).

2.2.2. Vessel sound detections

The contribution of vessel sound energy to the total measured sound field was estimated. Ship propulsion systems, other rotating machinery, and broadband energy from propeller cavitation produce narrowband sinusoidal tones (tonals) (Arveson and Vendittis 2000). Vessel detection was performed on all the data sampled at 16 ksps in three steps, which detected both tonals and broadband sound.

During the first step, the tonals in each 2-second time bin were detected in each WAV file using an 8-second long FFT that advanced 2 s per FFT. The number of frequency bins (tonals) that were present and detected for at least 20 s each minute were counted and saved for further analysis.

The second step was performed on the combined results from each WAV file. In the 'shipping band', which is defined as 40–315 Hz (the frequency band typical for large shipping vessel sounds), the rms SPL was calculated for each minute. Background estimates of the shipping band rms SPL and the total rms SPL were compared to their median values over the 12-hour window centered on the current time. Based on the one-minute average rms SPL, the noise is attributed to shipping when all the following conditions are true:

- the rms SPL in the shipping band is at least 3 dB above the median
- at least five shipping tonals are present
- the rms SPL in the shipping band is within 8 dB of the total rms SPL (example in Figure 9).

In the third step, the detector searched for broadband shipping vessel sounds. Broadband shipping is deemed to be detected if:

- the rms SPL in the shipping band is greater than 105 dB
- the 1/3-octave-band SPL at 630 Hz exceeds the SPL at 6300 Hz by at least 10 dB. This constraint is equivalent to the 20 dB/decade slope discussed by Wenz (1962).
- tonals are detected within 30 min of the current time

Details about the detector and its performance have been discussed in Martin (2013).

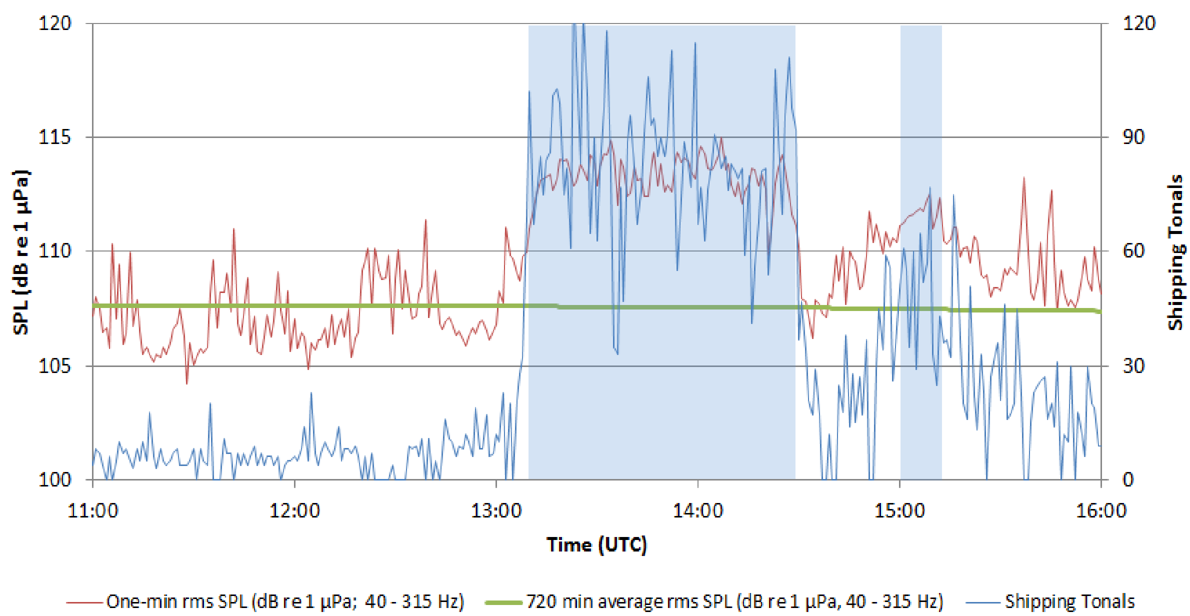

Figure 9. Root-mean-square (rms) sound pressure levels (SPL) in the 40-315 Hz band and the number of 0.125 Hz wide tonals detected per minute from a passing ship. The shaded areas are periods of shipping detections. All tonals are from the same vessel.

2.2.3. Marine mammal call detections

Three of JASCO's automated vocalization detectors were used to detect marine mammal calls. One detector allowed to detect and classify non-stereotyped tonal vocalizations and was used for Pacific white-sided dolphins, and killer, humpback, and grey whales. Another detector was use to detect the stereotyped fin whale calls. Finally, a detector was used to detect and classify odontocete clicks. For each day and each species, files were manually verified (spot-checked) by examining recordings that yielded automated detections until we were able to confirm the presence of the species on that day.

2.2.3.1. *Detecting Pacific white-sided dolphins, and killer, humpback, and grey whales*

Killer whale, Pacific white-sided dolphin, humpback whale, and grey whale vocalizations were detected from acoustic recordings by a detection algorithm (Moloney et al. 2014, Dewey et al. 2015) whose steps are illustrated in Figure 10.

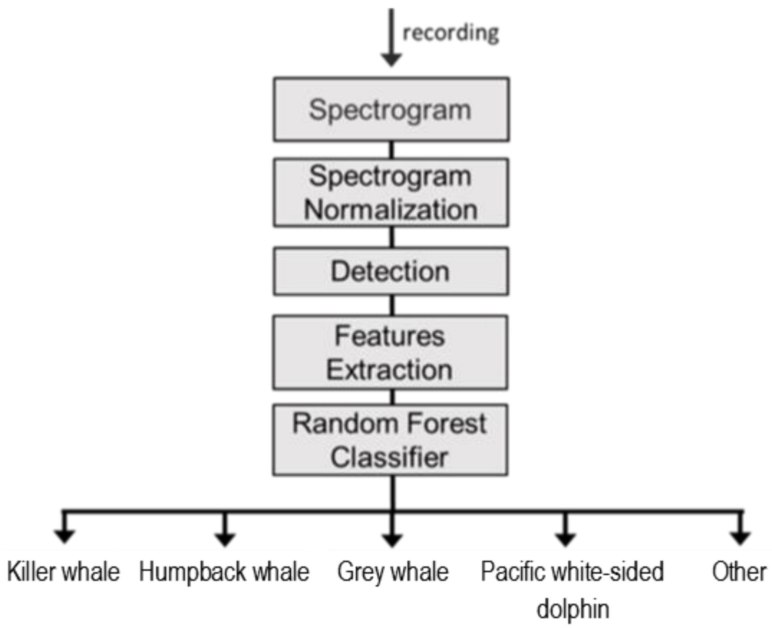

Figure 10. Diagram of the automated processing for marine mammal call detection.

First, a spectrogram was created and normalized for each frequency band. It was then segmented to detect acoustic events between 10 Hz and 8 kHz. For each event, a set of features representing salient characteristics of the spectrogram were extracted. Extracted features were presented to a five-class random forest classifier to determine the class of the sound detected: ‘killer whale’, ‘humpback whale’, ‘grey whale’, ‘Pacific white-sided dolphin’, or ‘other’. The random forest classifier needs to be trained with known sounds (i.e., manual annotations). Figure 11 illustrates the key processing steps of the detector on a recording that contained killer whale vocalizations.

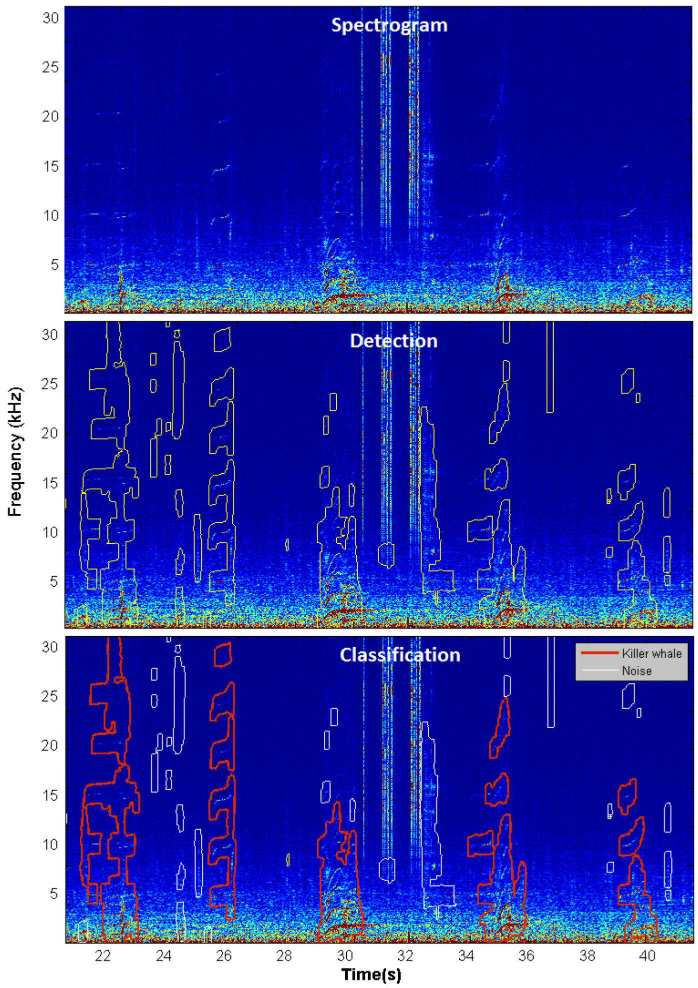

Figure 11. Key processing steps of the detector. Top panel: Spectrogram with killer whale calls. Middle panel: Acoustic events detected in the spectrogram. Bottom panel: Classification of killer whale calls using a random forest classifier.

2.2.3.2. Detecting fin whale vocalizations

Fin whale calls were automatically detected using a spectrogram template matching method based on Mellinger and Clark (1997, 2000) and Mouy et al. (2009). Figure 12 illustrates the call detection process for fin whales.

The spectrogram was first normalized with a split window normalizer, then the normalized spectrogram was binarized by setting the frequency bins with energy less than the threshold (T_{norm} = 2) to 0, and the frequency bins with energy higher than T_{norm} to 1.

A synthetic binary time-frequency template representing a typical fin whale downsweep was created with the following parameters, which were empirically determined from analysis of fin whale calls in a set of recordings collected by JASCO as well as frequency characteristics of fin whale calls provided by Barbara Koot (University of British Columbia):

- Starting frequency (F_1 = 32 Hz)
- Ending frequency (F_2 = 15 Hz)
- Duration (D = 1.5 s)
- Frequency width (df = 5 Hz)

- Frequency span (*FB* = 5 to 40 Hz)
- A duration of silence before and after the call (*dt*= 0.2 s)

To create a detection function, a correlation index that measured how well the synthetic template matched the binary spectrogram was defined for each time step of the spectrogram. A correlation index of 1 indicates a perfect match between the synthetic template and the binary spectrogram. The occurrences of fin whale call detections were defined by parts of the detection function that exceeded the empirically chosen threshold T_{detec}.

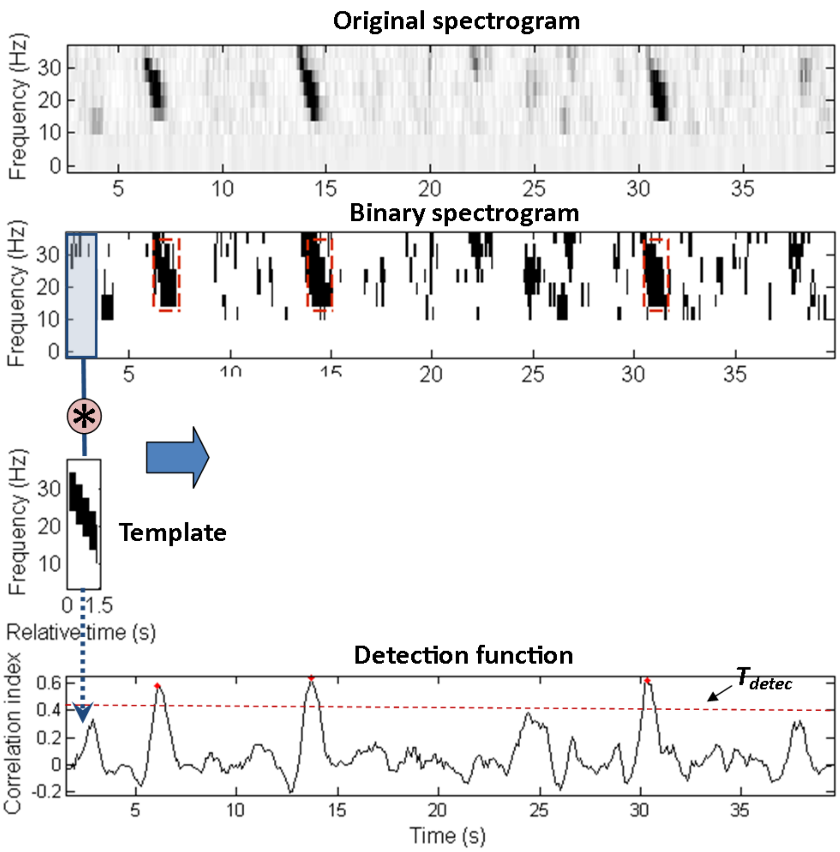

Figure 12. Fin whale call detection process.

2.2.3.3. Detecting porpoise clicks

Clicks from both porpoise species—Dall's and harbour—were detected automatically in the 375 ksps data based on the energy ratios between several frequency bands.

The steps below describe the detection process:

1. The spectrogram of the acoustic signal was calculated using 256-sample Hamming-weighted windows overlapped by 50 percent.
2. The spectrogram was normalized with a split-window normalizer using a 2 ms frame and a 0.5 ms notch (Struzinski and Lowe 1984). Frequency bins in the normalized spectrogram that had normalized energy less than the threshold T_{norm} = 2 were set to zero.
3. To create a detection function, the ratio of the number of positive bins over the number of null bins in the frequency band 100–170 kHz was defined for each time step of the spectrogram. Parts of the

detection function that exceeded the empirically chosen threshold T_{detec}= 0.3 defined the times of potential porpoise click detections.

4. The normalized spectrogram for each of the potential porpoise click detections was used to calculate ratio R of the energy in the frequency bands 105–170 kHz and 30–100 kHz. We attributed a detection to a porpoise click only if the energy ratio R exceeded the decision threshold T_{ER} = 4.9.

Figure 13 illustrates the porpoise click detection process.

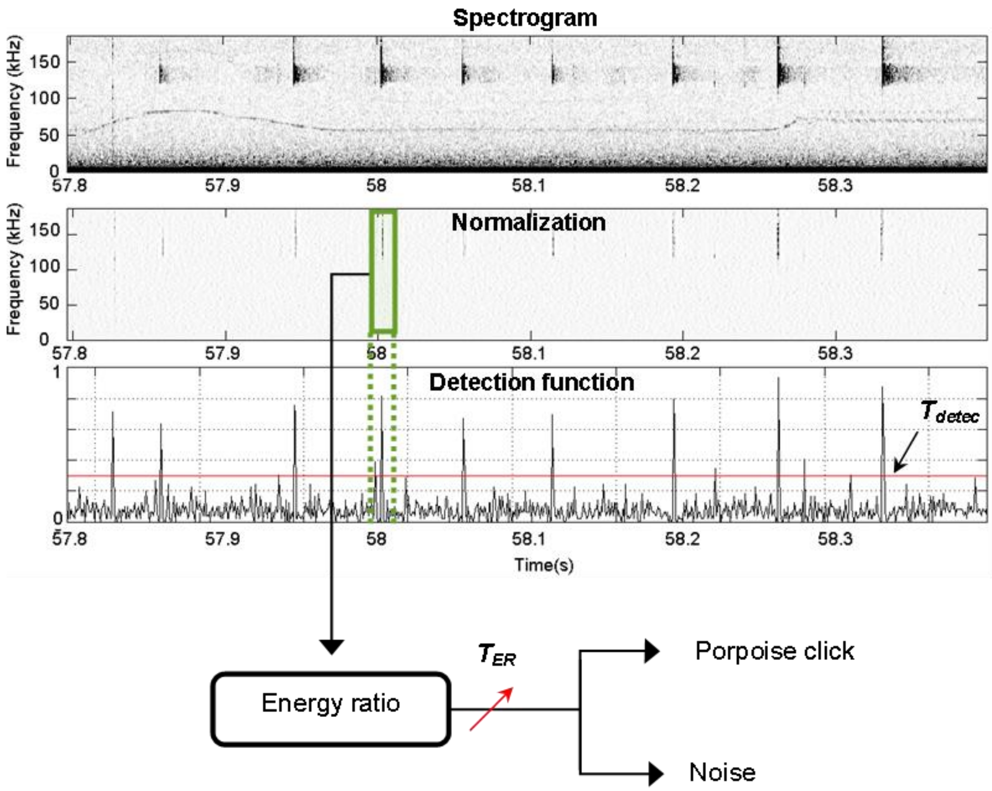

Figure 13. The automated porpoise click detection process.

2.2.3.4. Detecting harbour seal calls

Harbour seal calls were identified manually during the verification of automatic processing for other species.

3. Results

3.1. Ambient Sound Levels

The results of the ambient sound analysis are shown below for all data recorded at 16 ksps at each AMAR location throughout the recording period (11 Jul to 19 Nov 2014 at Station 1 and 11 Jul to 31 Oct 2014 at Station 2). These results document the range of sound levels in the study area and their relative rate of occurrence.

During the study period, vessels (Section 3.2) were the primary source of noise at all stations, dominating sound from weather events. Unlike large ships, small vessels like fishing boats, zodiacs, and pleasure crafts were detected for brief periods (3-5 min) as they passed within close range of the recorders (example in Figure 14). The recorder at Station 2 also detected bell sounds (Figure 15), which have been identified as originating from a bell-buoy.

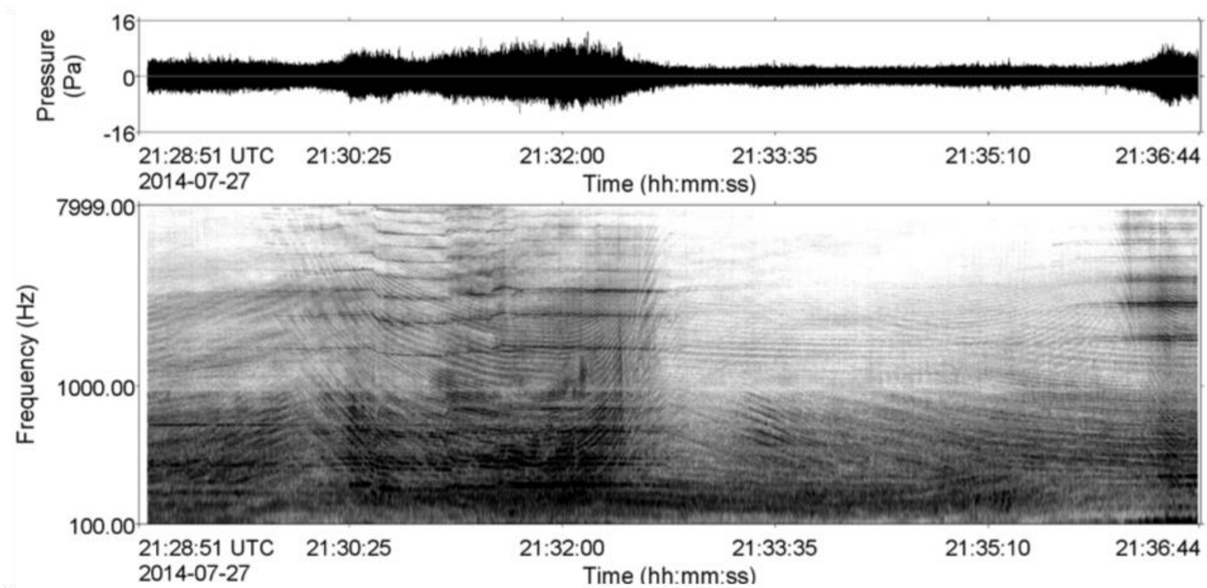

Figure 14. Spectrogram sample of vessel noise recorded at Station 1 on 27 Jul 2014 (UTC) in Chatham Sound. The horizontal lines are tonal signals from a small engine. The U-shaped (Lloyd’s mirror) interference pattern identifies the time of the closest point of approach of a vessel (2 Hz frequency resolution, 128 ms time window, 32 ms time step, Hamming window).

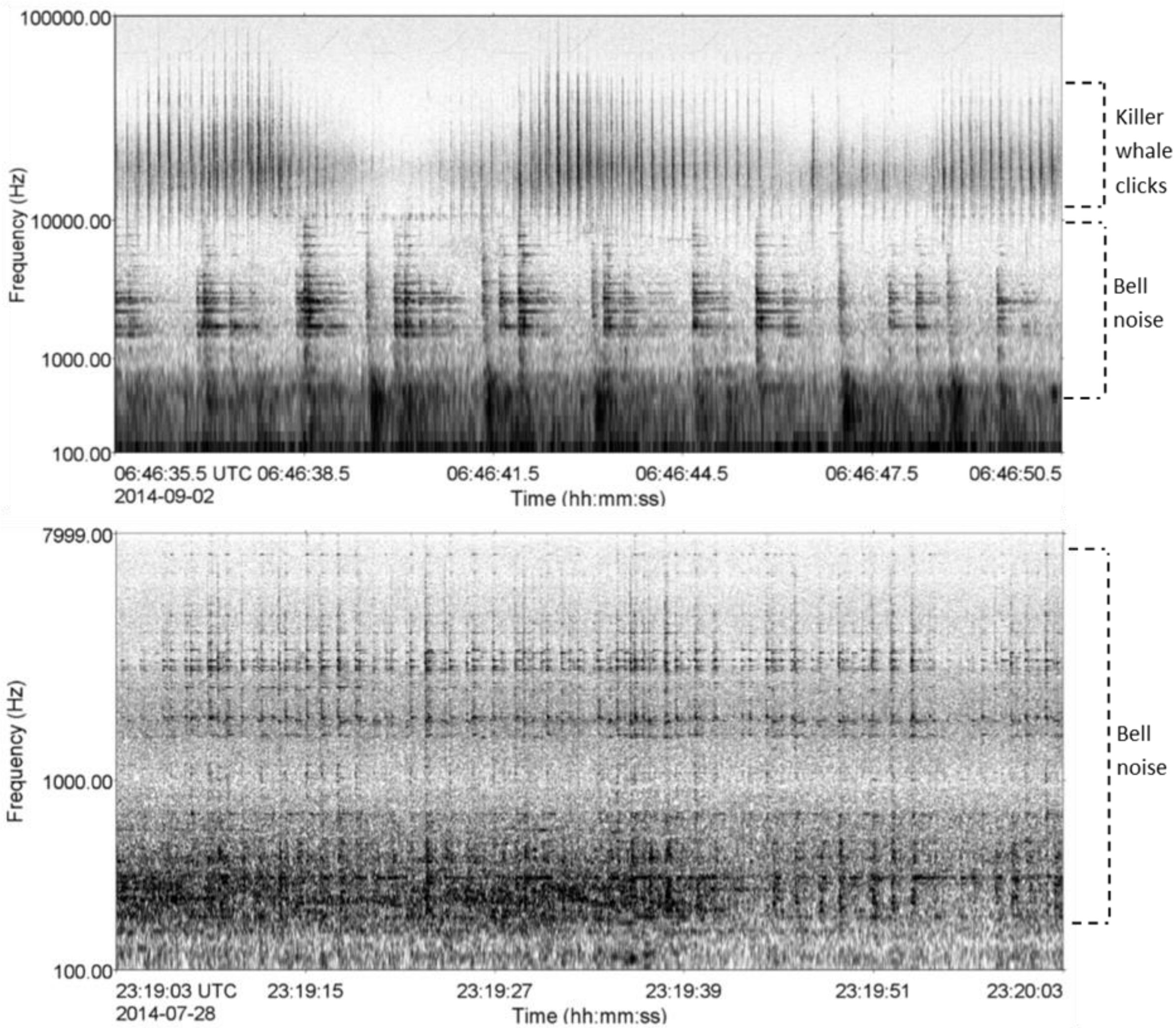

Figure 15. Spectrograms of bell noise recorded at Station 2. Top figure: 20 s of data from the 375-ksps recordings (64 Hz frequency resolution, 12.8 ms time window, 3.3 ms time step, Hamming window). Bottom figure: 60 s of data from the 16-ksps recordings (2 Hz frequency resolution, 128 ms time window, 32 ms time step, Hamming window). Killer whale clicks are also identified.

The spectrograms in Figures 16 and 17 show the long-term frequency distribution of the sound recorded at each station. Tonals that emanate from vessels' propulsion and onboard power generating systems show as pronounced peaks in the exceedance percentiles of the PSD levels in Figures 18 and 19. In addition to the peaks, vessel noise contributions are apparent in each PSD level percentile curve as a broad hump from about 30 Hz to 1 kHz. Moreover, at Station 2, bell noise peaks are apparent in PSD levels (Figure 19). At Station 1, only the L_5 percentile is above the upper limit of prevailing noise of the Wenz curves, and only above 100 Hz.

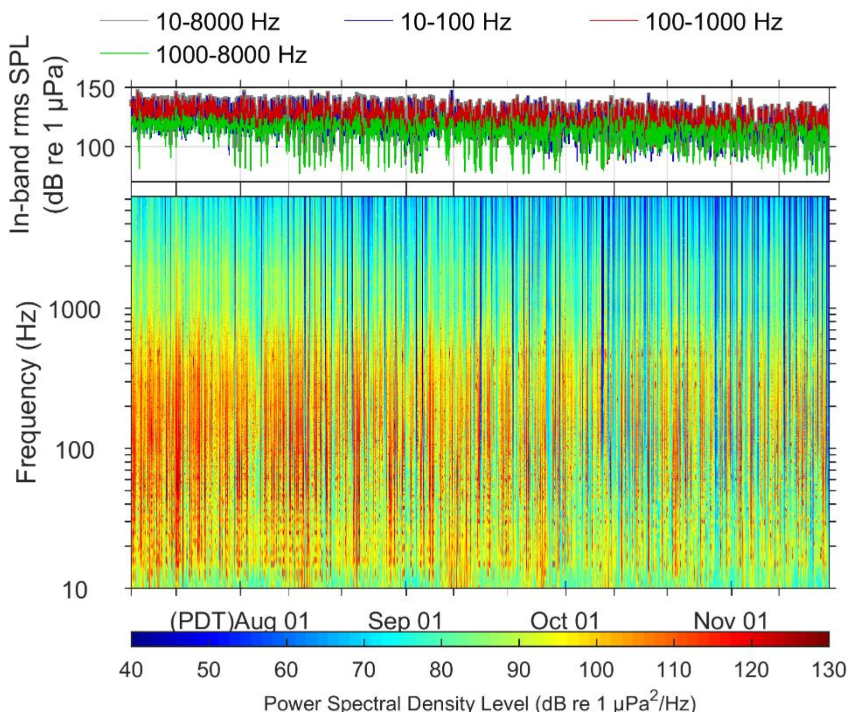

Figure 16. Ambient sound at Station 1, near the proposed location for the Aurora LNG Project area: (Top) The rms SPLs in various frequency bands (Hz) and (bottom) spectrogram over time of the underwater sound at Station 1, 11 Jul to 19 Nov 2014.

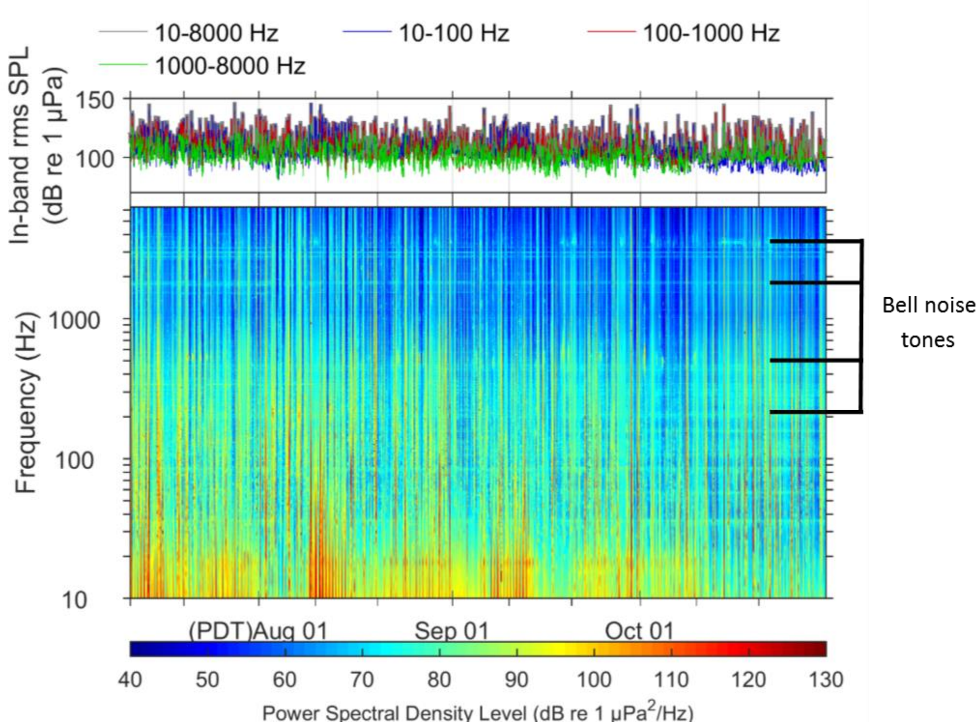

Figure 17. Ambient sound at Station 2, in Chatham Sound: (Top) The rms SPLs in various frequency bands (Hz) and (bottom) spectrogram over time of the underwater sound at Station 2, 11 Jul to 31 Oct 2014.

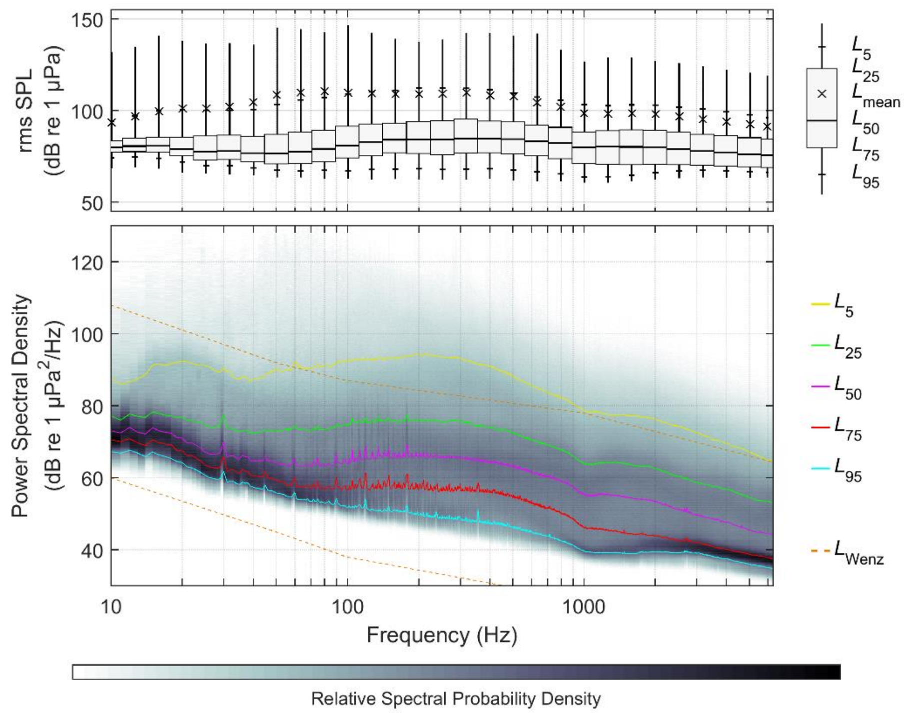

Figure 18. Distribution of ambient sound levels at Station 1, 11 Jul to 19 Nov 2014: (Top) Exceedance percentiles and mean of 1/3-octave-band rms SPLs. (Bottom) Exceedance percentiles and probability density (greyscale) of 1-min PSD levels compared to the Wenz curve limits of prevailing noise (Wenz 1962, see Figure 8).

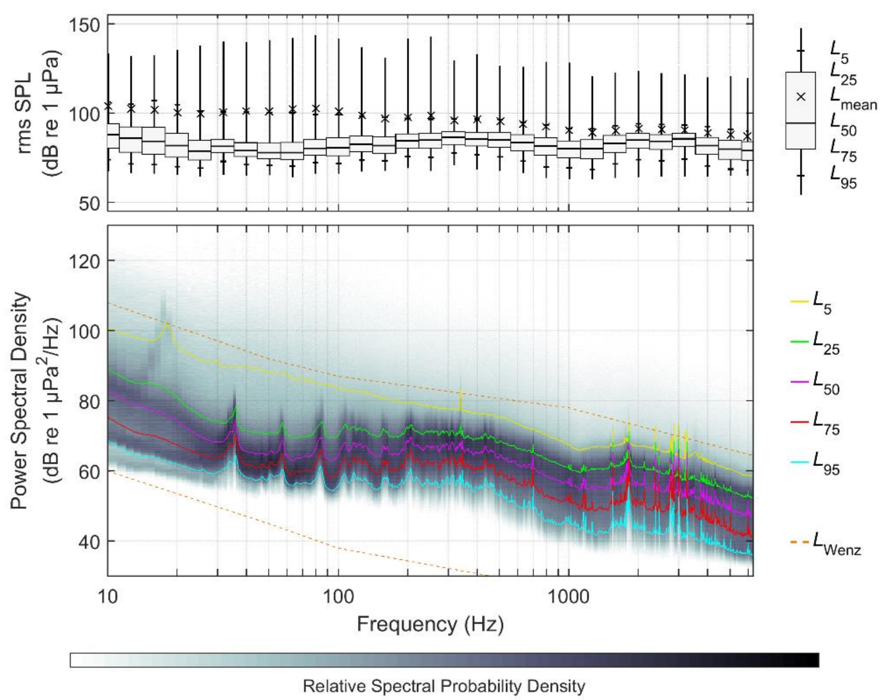

Figure 19. Distribution of ambient sound levels at Station 2, 11 Jul to 31 Oct 2014*:* (Top) Exceedance percentiles and mean of 1/3-octave-band rms SPLs. (Bottom) Exceedance percentiles and probability density (greyscale) of 1-min PSD levels compared to the Wenz curve limits of prevailing noise (Wenz 1962, see Figure 8).

Station 1 recorded a maximum 1-minute broadband rms SPL of 149.5 dB re 1 µPa on 12 Jul 2014 at 21:04 (PDT). Station 2 recorded a maximum 1-minute broadband rms SPL of 147.7 dB re 1 µPa on 14 Oct 2014 at 10:22 (PDT). The median (L_{50}) of the 1-minute broadband rms SPLs at Stations 1 and 2 was 98.6 and 100 dB re 1 µPa, respectively (Figure 20, Table 3).

Table 3. Median broadband and decade-band sound levels: Median of the 1-minute rms SPLs recorded at each station during the Aurora LNG acoustic monitoring study over the entire recorded frequency band and within each decade band.

Station	Median 1 min rms SPL (dB re 1 µPa) in stated bands			
	10–8000 Hz	10–100 Hz	100–1000 Hz	1000–8000 Hz
1	98.6	91.2	95.1	88.8
2	100	94.1	94.8	92.5

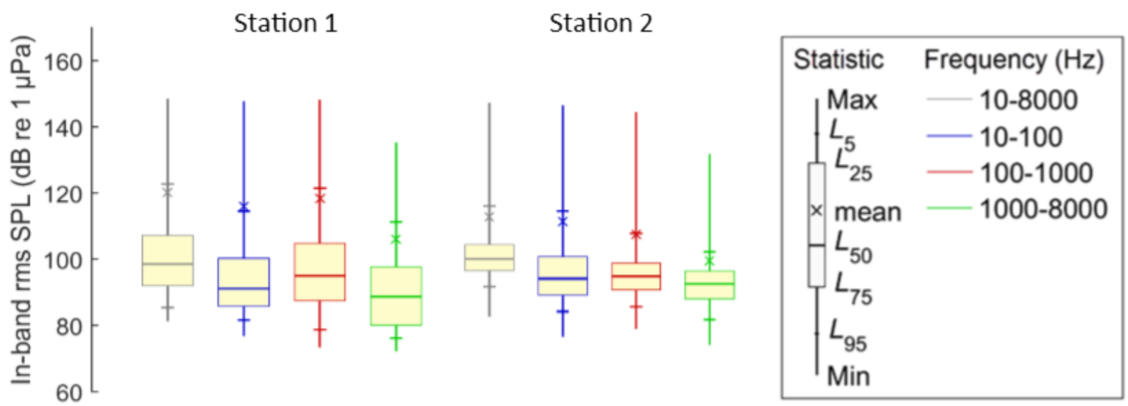

Figure 20. Distribution of broadband and decade-band sound levels at each station. Statistical distribution of 1 minute rms SPLs for the entire recorded bandwidth and for each decade band within the recorded bandwidth during the Aurora LNG acoustic monitoring study.

3.2. Vessel Detections

Vessel noise detection analysis was performed on the data sampled at 16 ksps. Figure 21 shows the daily SELs and equivalent sound levels (L_{eq}) at each station for the total received sound energy and for the sound energy the automated detector attributed to vessel noise. The daily SEL is the sum of the 1-minute SELs over 24 hours. For the vessel noise, the 1-minute SELs are the linear 1-minute squared rms SPLs for each minute with detected vessel noise multiplied by the duration, 60 s.

Figure 22 shows the statistical distribution of these daily SELs and statistical distribution of daily vessel detections. In both figures and for both stations, the levels from vessels are almost identical to the total levels, indicating that the daily SELs are almost entirely due to vessel noise. The maximum daily total SELs at Stations 1 and 2 were 174.3 dB re 1 µPa on 13 Jul and 171 dB re 1 µPa on 10 Aug, respectively (Table 4).

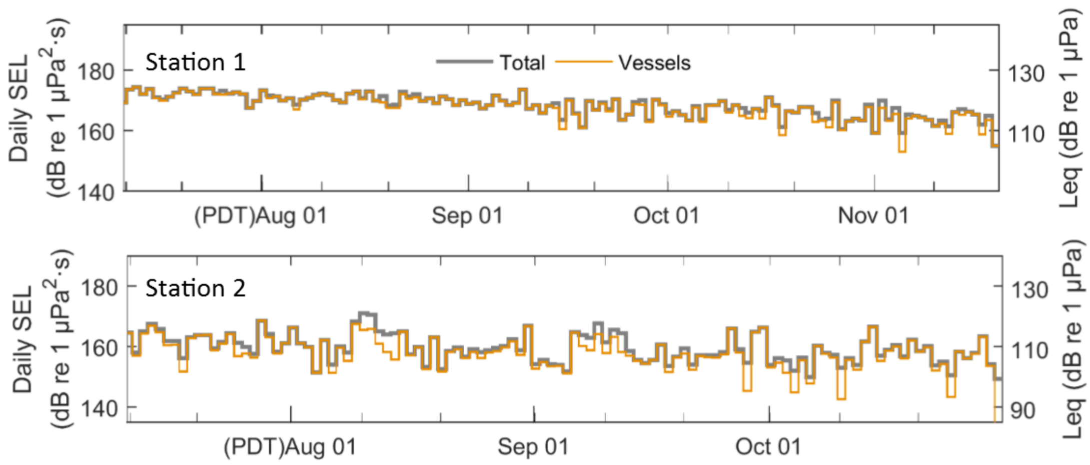

Figure 21. Daily SELs and equivalent continuous sound levels (L_{eq}) for the total received sound energy and for the sound energy attributed to vessels at each station during the study.

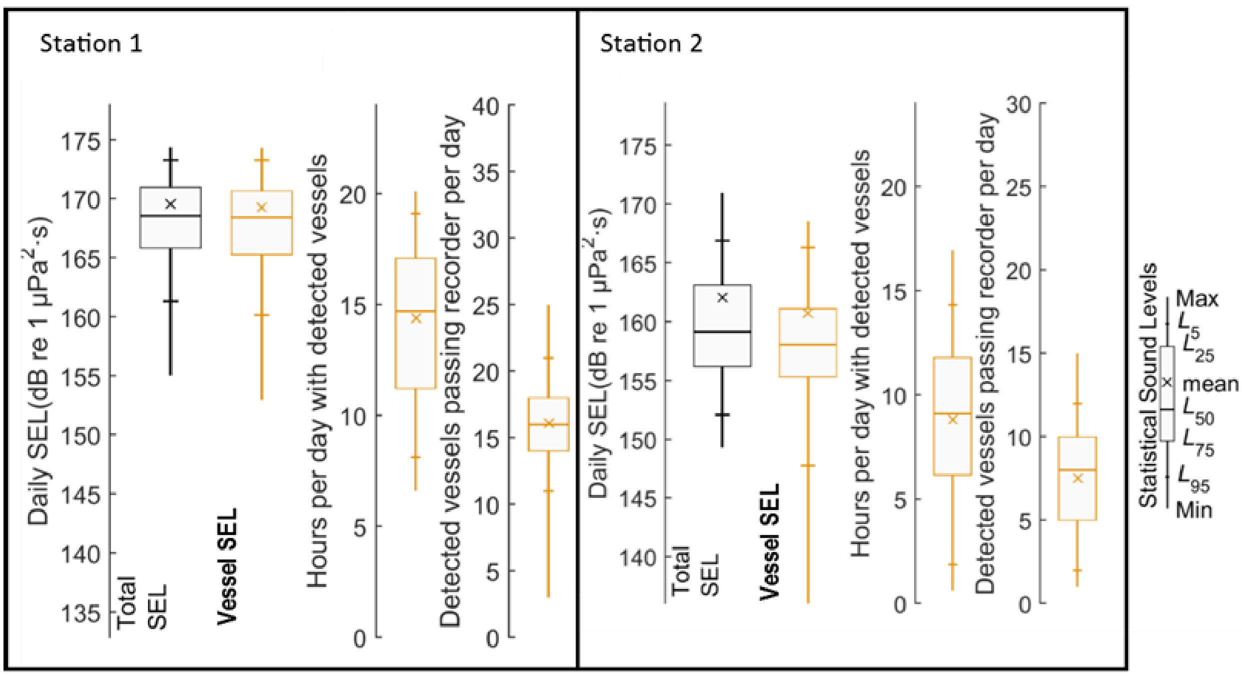

Figure 22: Statistical distribution of daily SELs and statistical distribution of daily vessel detections at each station: Minimum, mean, maximum, and exceedance percentiles of the daily SEL for the total received sound energy and for the sound energy attributed to vessels at each AMAR station during the Aurora LNG acoustic monitoring study.

Table 4. Daily SELs for both stations. Station 1 from 11 Jul to 19 Nov 2014. Station 2 from 11 Jul to 31 Oct 2014.

Sound level statistic	Daily SEL (dB re 1 µPa²·s, normalized for effort)		Daily SEL from shipping (dB re 1 µPa·s, normalized for effort)		% of the Daily SEL from periods with detected vessels	
	Station 1	Station 2	Station 1	Station 2	Station 1	Station 2
Min	155	149.3	153	134.8	23.8	3.6
L_{95}	161.3	152.1	160.1	147.8	54.3	19.6
L_{75}	165.9	156.2	165.3	155.3	85.5	69
L_{50}	168.6	159.1	168.4	158.1	98.7	84.8
L_{25}	171	163.1	170.7	161.1	99.7	94.1
L_{5}	173.3	166.9	173.3	166.3	99.9	98.6
Max	174.3	171	174.3	168.6	100	99.5
Mean	169.6	162.1	169.3	160.7	90.5	76.4

The vessel detector produces estimates of the hours per day when vessels are present and the number of vessels recorded per day (Table 5). Station 1 had an average of 16 vessels recorded per day, while Station 2 had an average of 7.5 vessels recorded per day. Vessels were detected at Station 1 for an average of 14.4 hours per day, and at Station 2 for 8.8 hours per day (Figure 22 and Table 5).

Table 5. Shipping detection statistics for both stations. Station 1 from 11 Jul to 19 Nov 2014. Station 2 from 11 Jul to 31 Oct 2014.

Sound level statistic	Hours per day when vessels are present		Vessels recorded per day	
	Station 1	Station 2	Station 1	Station 2
Min	6.6	0.6	3	1
L_{95}	8.1	1.9	11	2
L_{75}	11.2	6.2	14	5
L_{50}	14.7	9.1	16	8
L_{25}	17.1	11.8	18	10
L_{5}	19.1	14.3	21	12
Max	20.1	17	25	15
Mean	14.4	8.8	16.1	7.5

3.3. Marine Mammal Detections

Sample waveforms and/or spectrograms and daily presence timelines for the detected species (humpback whales, fin whales, killer whales, Pacific white sided-dolphins, and porpoises) are presented in the following sections. Calls from these species were detected using automated detectors and manual verification. Harbour seal calls were detected manually only. Grey whale vocalizations were not detected. While blue whales (*Balaenoptera musculus*) were not expected in the study area, our auto-detection processing, included scans for vocalizations of this species (call detection process similar to the one used for fin whales in section 2.2.3.2) and none were detected. Data collected was not analyzed for minke whale and Steller sea lion vocalizations so no conclusions can be drawn regarding their presence in the study area.

3.3.1. Humpback whales

Humpback whale calls (examples in Figure 23) were detected 67 days at Station 2, between 18 Jul and 29 Oct 2014 (Figure 24). Humpback whale calls were not detected at Station 1.

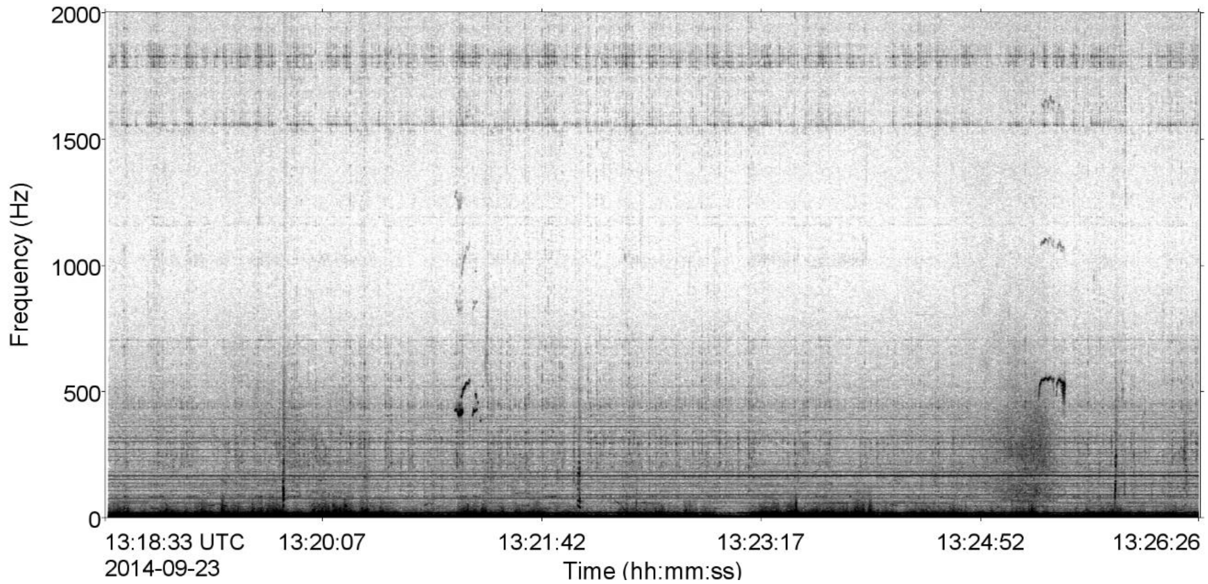

Figure 23. Spectrogram of humpback whale calls recorded at Station 2 on 23 Sep 2014 (UTC) in Chatham Sound (1 Hz frequency resolution, 1 s time window, 0.1 s time step, Hamming window).

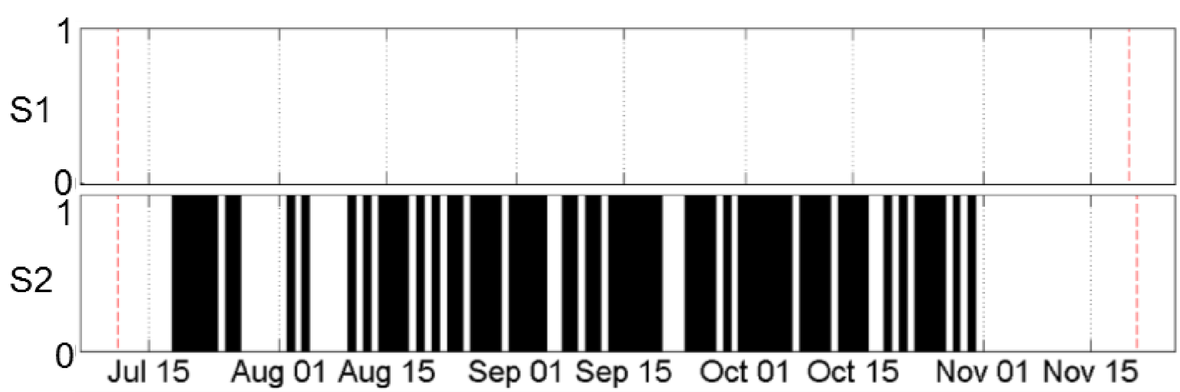

Figure 24. Daily presence of humpback whales (black line) at each station (S1 and S2) based on the automated detection of their calls. Red dashed lines indicate AMAR deployments and retrievals. The AMAR at Station 2 recorded until 31 Oct 2014.

3.3.2. Fin whales

Fin whale calls (Figure 25) were detected only at Station 2 on two days: 4 and 17 Oct 2014.

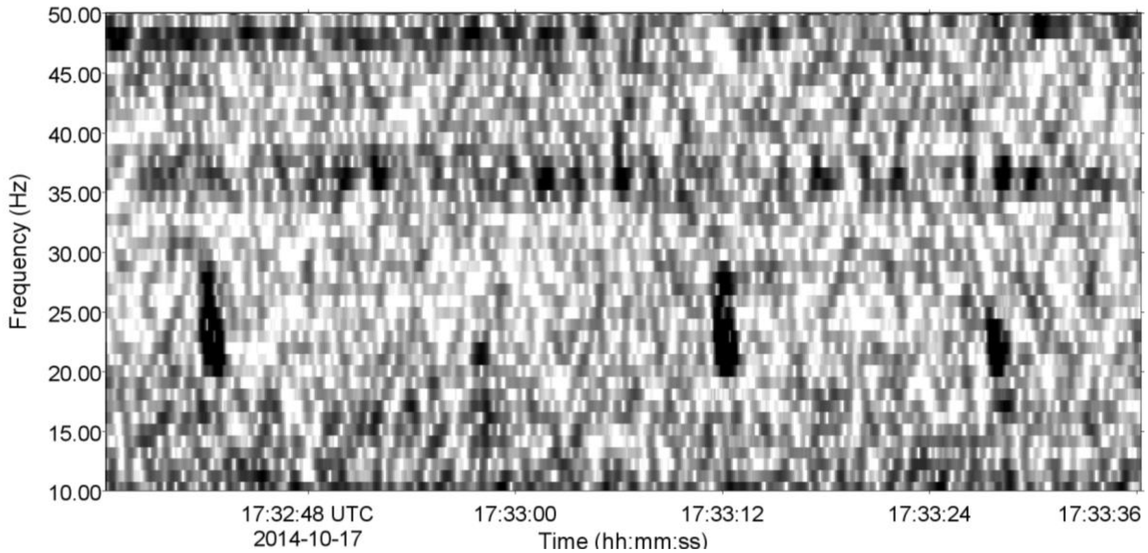

Figure 25. Spectrogram of fin whale 20 Hz downsweeps recorded at Station 2 on 17 Oct 2014 (UTC) in Chatham Sound (1 Hz frequency resolution, 1 s time window, 0.1 s time step, Hamming window).

3.3.3. Killer whales

Killer whale call detections consisted of pulse calls and whistles (Figure 26). This species was detected three days at Station 1 (13 Jul, and 6 and 19 Nov) and 32 days at Station 2 (between 14 Jul and 25 Oct) (Figure 27).

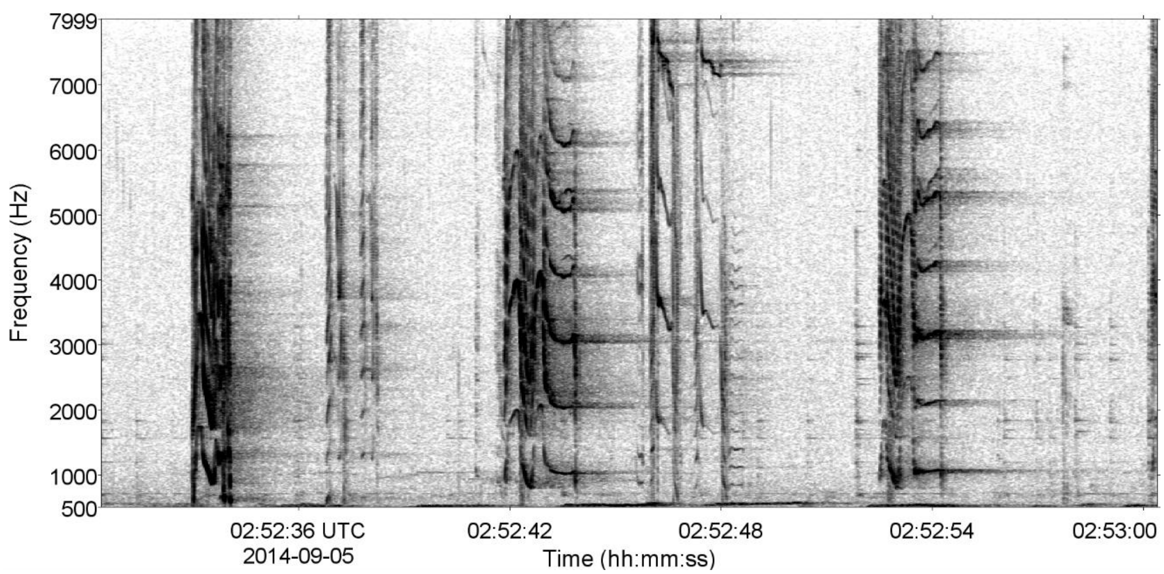

Figure 26. Spectrogram of a killer whale sound segment recorded at Station 2 on 5 Sep 2014 in Chatham Sound (1.95 Hz frequency resolution, 128 ms time window, 32 ms step size, Reisz window).

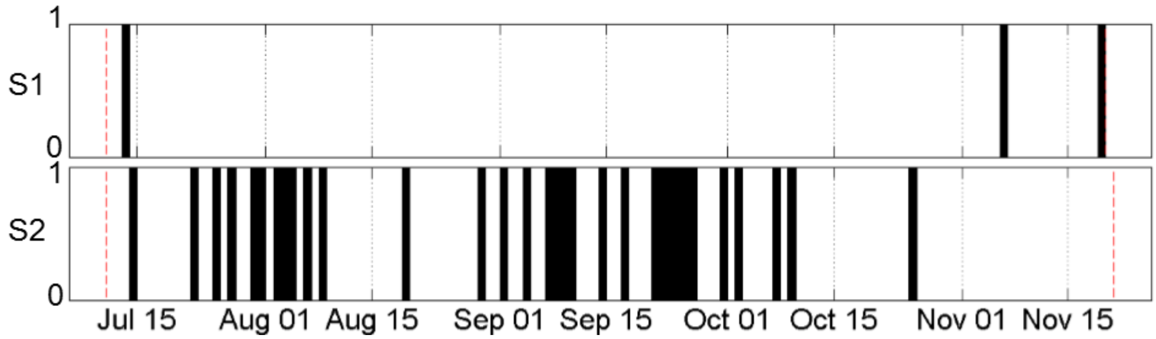

Figure 27. Daily presence of killer whales (black line) at each station (S1 and S2) based on the automated detection of their calls. Red dashed lines indicate AMAR deployments and retrievals. The AMAR at Station 2 recorded until 31 Oct 2014.

3.3.4. Pacific white-sided dolphins

Pacific white-sided dolphin clicks were detected once at Station 2 on 22 Jul 2014 (Figure 28). None were detected at Station 1.

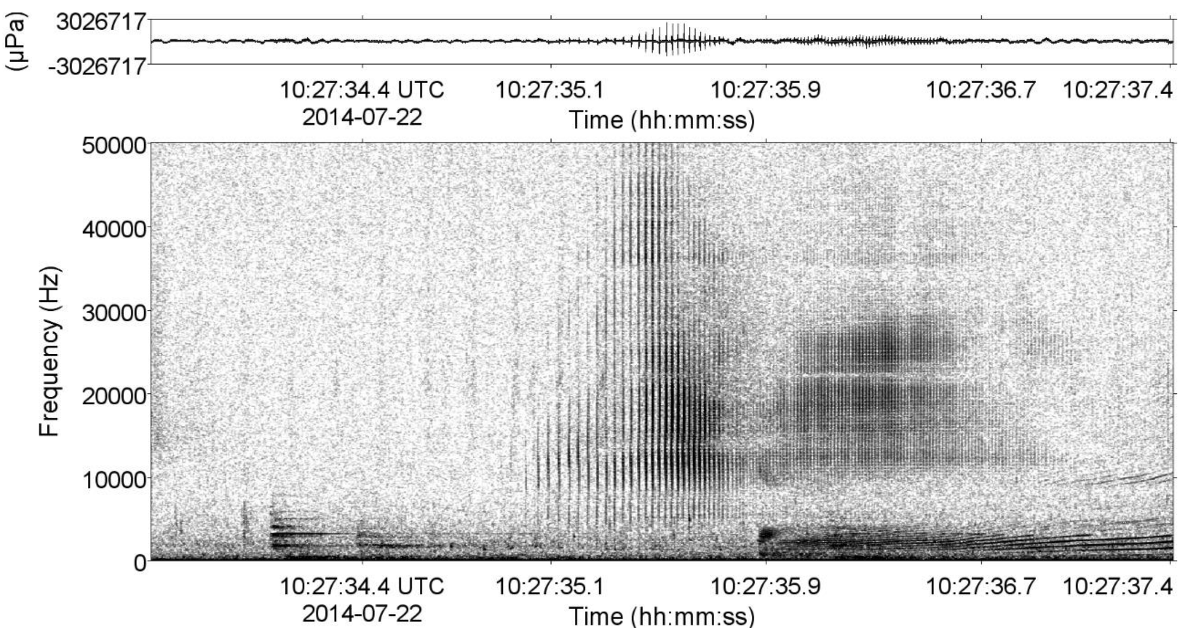

Figure 28. (Top panel) waveform and (bottom panel) spectrogram of Pacific white-sided dolphin clicks recorded at Station 2 on 22 Jul 2014 (UTC) in Chatham Sound (64 Hz frequency resolution, 12.8 ms time window, 3.3 ms time step, Hamming window).

3.3.5. Porpoises

Porpoise clicks (Figure 29) were detected every day at Station 1 during the 132-day recording period (11 Jul to 19 Nov 2014) and on 100 days at Station 2 during the 113-day recording period (from 11 Jul to 31 Oct 2014) (Figure 30).

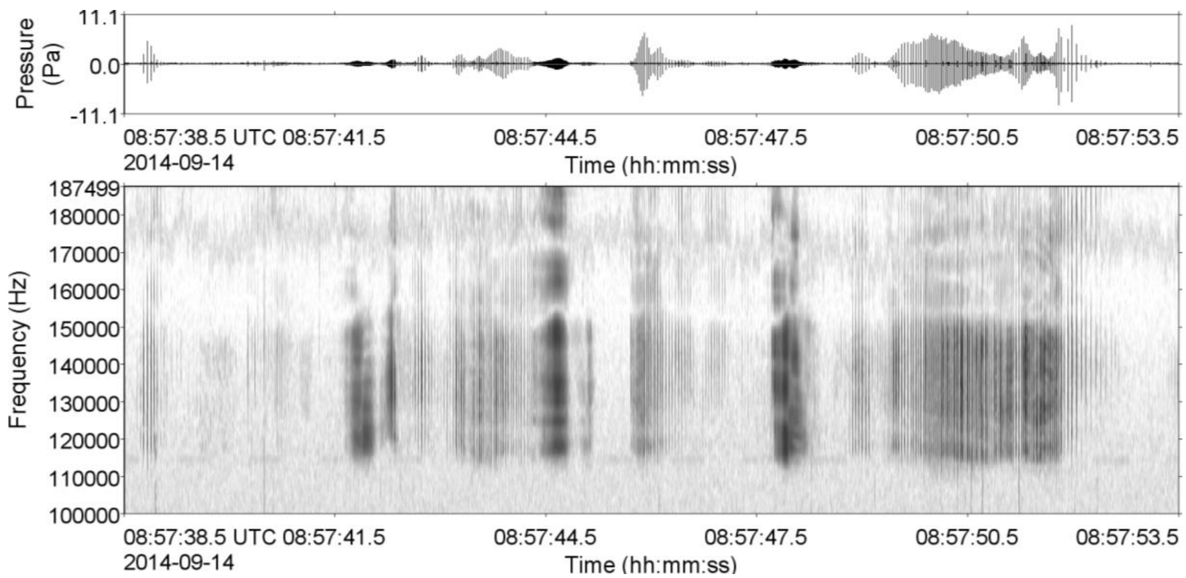

Figure 29. (Top panel) waveform and (bottom panel) spectrogram of a porpoise click train recorded at Station 1 on 14 Sep 2014 (UTC) (732 Hz frequency resolution, 0.7 ms time window, 0.34 ms time step, Hamming window).

Figure 30. Daily presence of porpoises (black line) at each station (S1 and S2) based on the automated detection of their calls. Red dashed lines indicate AMAR deployments and retrievals. The AMAR at Station 2 recorded until 31 Oct 2014.

3.3.6. Harbour seals

Harbour seal calls, consisting almost exclusively of roars (Figure 31), were detected for 36 days at Station 1; Station 2 had no detections (Figure 32). Most of the detections occurred between 11 Jul and 18 Aug; late August through early September showed only sporadic detections, the last one occurring on 17 Nov 2014.

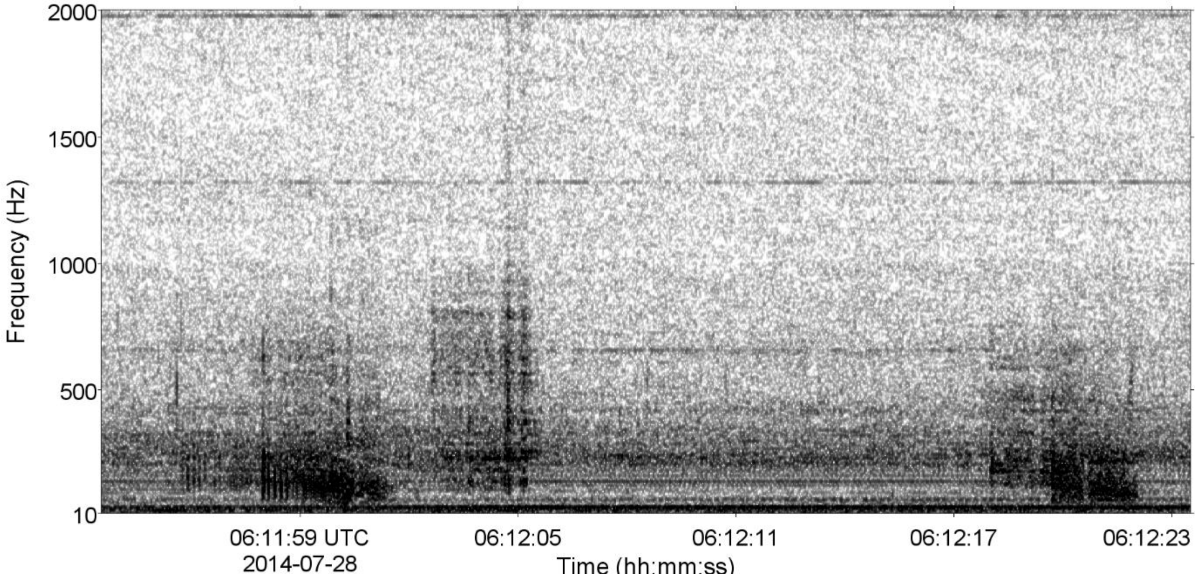

Figure 31. Spectrogram of harbour seal roars recorded at Station 1 on 28 Jul 2014 (UTC) in Chatham Sound (2 Hz frequency resolution, 128 ms time window, 32 ms time step, Hamming window).

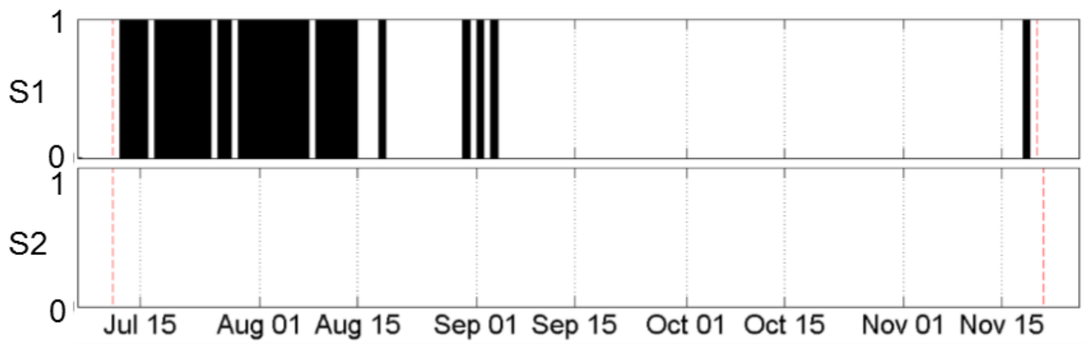

Figure 32. Daily presence of harbour seals (black line) at each station (S1 and S2). Red dashed lines indicate AMAR deployments and retrievals. The AMAR at Station 2 recorded until 31 Oct 2014.

4. Discussion

4.1. Ambient Sounds and Vessel Noise

This report has documented the natural and anthropogenic acoustic environment at two recording locations near the proposed Aurora LNG site. The daily SEL values reported indicate levels at fixed sites and therefore do not reflect the exposure accumulated by moving biological receptors such as migrating marine mammals.

Stations, notably Station 1, recorded most sound energy in the decade band of 100–1000 Hz (Figure 20, Table 3); this is associated with noise from smaller vessels as well as wind and wave noise. As illustrated in Figure 33, some periods of elevated ambient noise appear to coincide with increases in wind speed especially at Station 2 (Figure 34). The area around Station 2 had much greater fetch, which allowed the seas to build giving rise to wind-driven waves (Vagle et al. 1990).

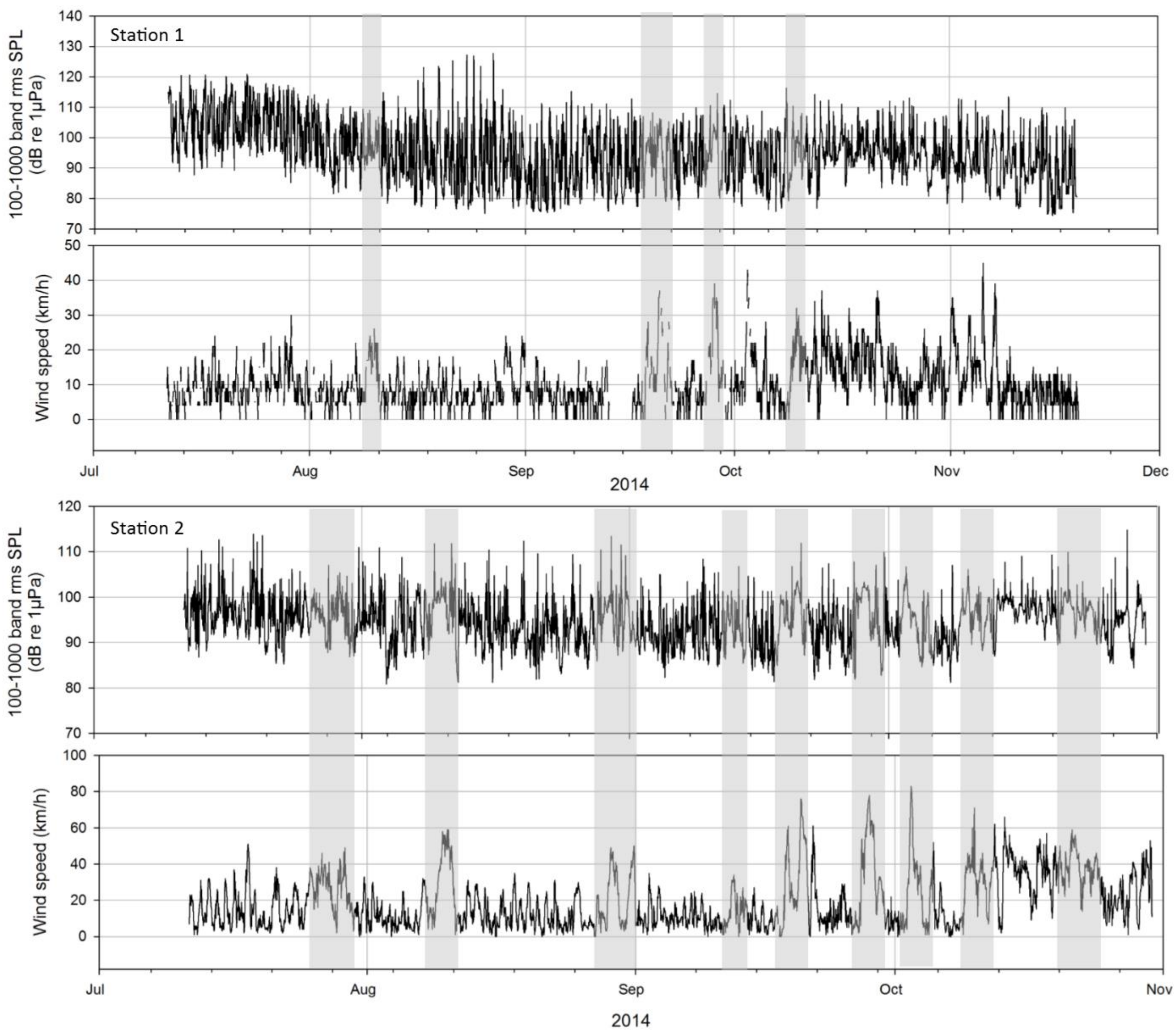

Figure 33. Time series of 100–1000 Hz band sound pressure levels and wind speed (km/h) at both stations. Wind speed values from the weather stations in Prince Rupert (4.1 km from Station 1) and Lucy Island (17.6 km from Station 2) (http://climate.weather.gc.ca). Shaded periods show correlations between ambient noise and weather (wind) events.

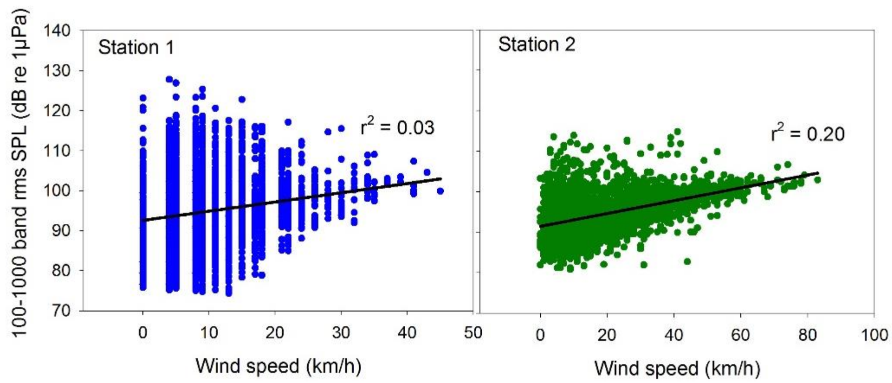

Figure 34. Correlation plots between ambient noise (100–1000 band rms SPL) and wind speed at both stations during the Aurora LNG acoustic monitoring study. Coefficient of determination is shown in the labels.

The effects of vessels on the total sound levels are better understood by comparing the mean and median rms SPLs. As Figure 20 shows Station 1 had a higher mean rms SPL than Station 2, but a lower median rms SPL, denoting that the received noise was more transient at the first station. This can be associated with a greater prominence of transient sound levels that can be ascribed to passing vessels, which is corroborated by the number of vessels acoustically detected per day (mean of 16 at Station 1 versus 8 at Station 2). Independent data from publically available Automated Identification System (AIS) receivers also shows that more intense vessel traffic typically exists near Station 1 than Station 2 (Figure 35).

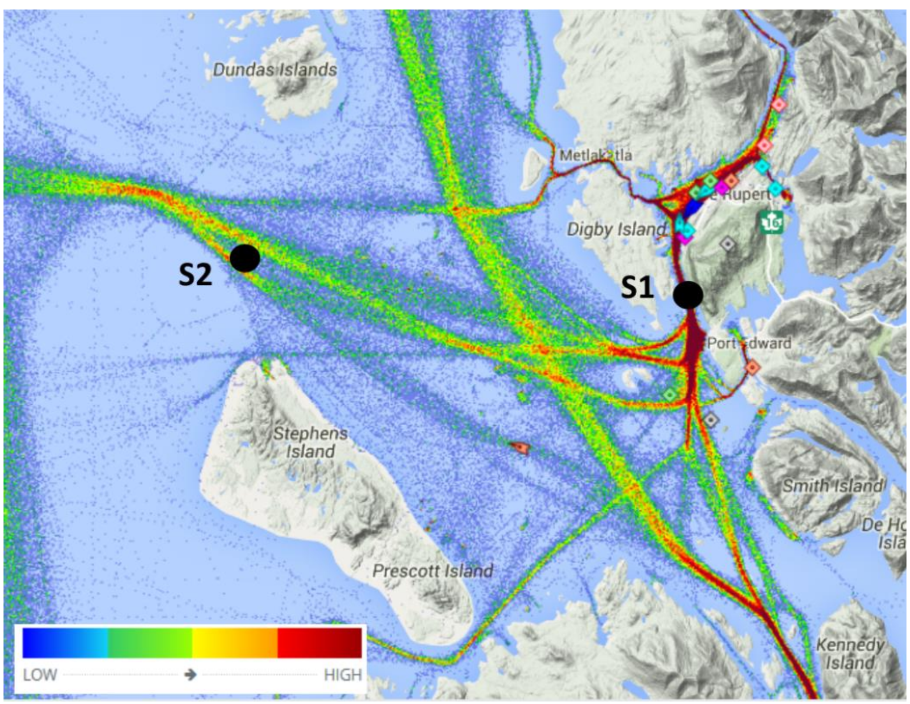

Figure 35. Marine vessel traffic density for 2014 in the Aurora LNG acoustic monitoring study area based on Automatic Identification System data. Figure adapted from Marine Traffic (2015); used with permission.

Ship passage detections at Station 2 were lower in the fall compared to summer (Figure 36). This could be due to less fishing and recreational traffic in the fall season or an increase in ambient noise levels from increased wind speeds which would mask vessel detection (Figure 33).

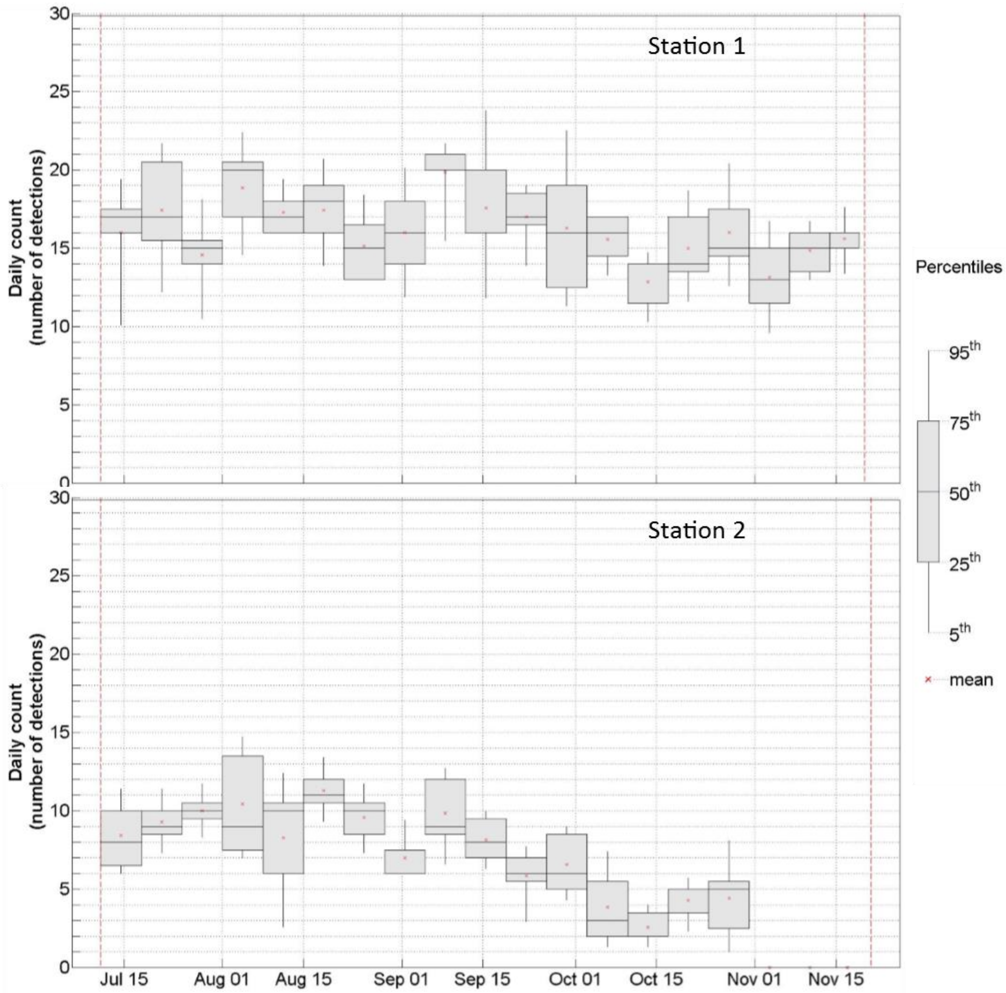

Figure 36. Vessel detections at both stations during the study. Distribution of the daily count of vessel passages for every consecutive 7-day period. Vertical dashed lines indicate AMAR deployments and retrievals.

At Station 1, the median rms SPLs were higher during the day than at night and peaked between 06:00 and 19:00 PDT; this trend is absent at Station 2 (Figure 37). The trend at Station 1 is similar on all days (Figure 38).

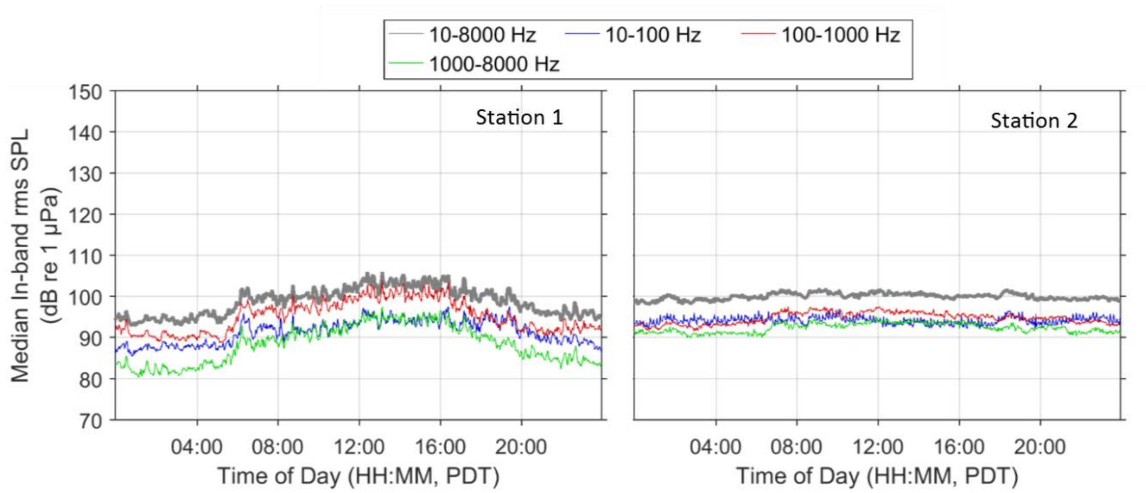

Figure 37. Diel trend in sound levels: Median rms SPL in various frequency bands (Hz) as functions of the time of day at each station during the Aurora LNG acoustic monitoring study.

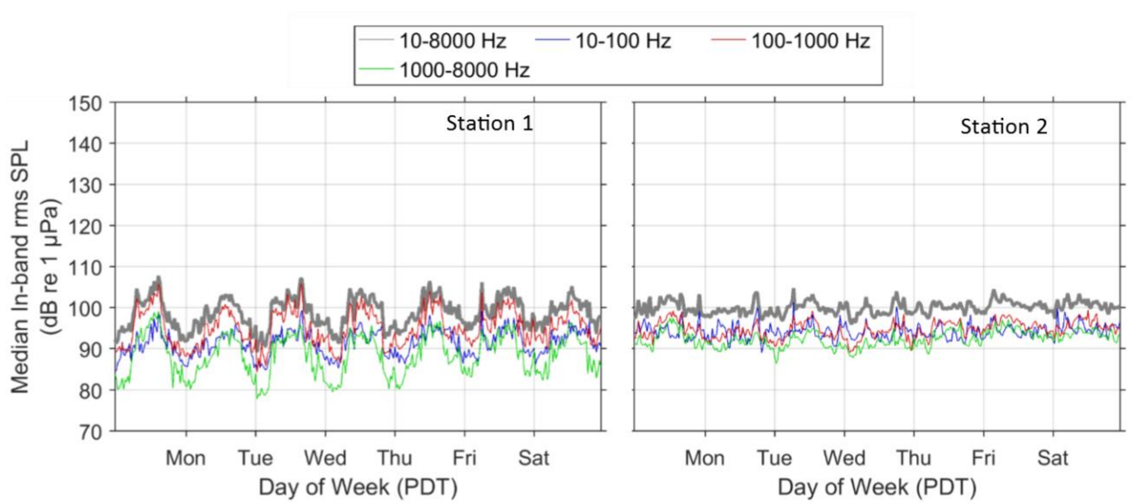

Figure 38. Weekly trend in sound levels: Median rms SPL in various frequency bands (Hz) as functions of the time of the week at each station during the Aurora LNG acoustic monitoring study.

4.2. Marine Mammal Vocalization Detections

4.2.1. Humpback whales

Humpback whale calls were only detected at Station 2. The higher number of detections at this station could be due to higher local productivity.

Like most baleen whales, humpback whales exhibit seasonal migrations from high-latitude feeding areas in summer to low-latitude breeding and calving areas in winter. In our study the presence of summer and fall detections of vocalizations suggest these whales are feeding near the coast of BC (Calambokidis and Barlow 2004).

Humpback songs consist of long complicated repetitive sequences produced by males primarily during the winter breeding season (Winn and Winn 1978), although singing also occurs during migration (Clapham and Mattila 1990) and extensively at feeding grounds (Vu et al. 2012). Humpback whale songs were detected in our dataset in October (for example Figure 39), which suggests that males practice their songs, or start to sing, well before they have reached their breeding sites. It also suggests that some males either travel to their breeding grounds late in the season or forgo travelling at all.

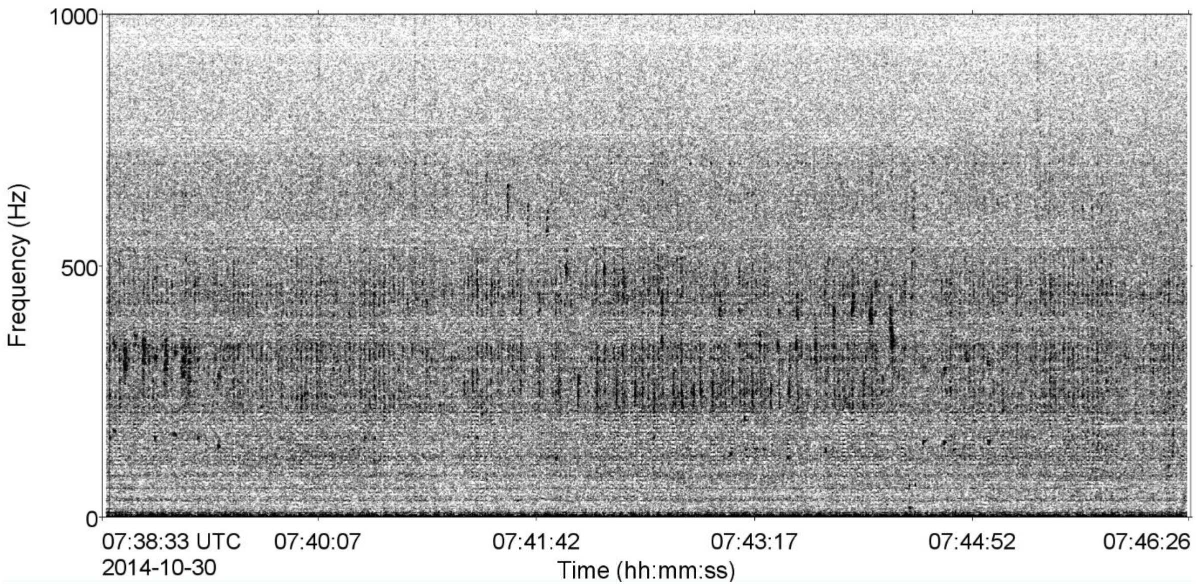

Figure 39. Spectrogram of humpback whale songs recorded at Station 2 on 30 Oct 2014 (UTC) in Chatham Sound (1 Hz frequency resolution, 1 s time window, 0.1 s time step, Hamming window).

4.2.2. Fin whales

Fin whale 20 Hz calls were detected only twice (in October) and only at Station 2. Širović et al. (2012) have demonstrated that peaks in 20-Hz calling occur mainly in the fall (between late September and November) in the eastern North Pacific. Ford (2014) mentioned that fin whale sightings are common in western Dixon Entrance and in certain areas of Hecate Strait.

4.2.3. Killer whales

Killer whale calls were occasionally detected at both stations during the study. Peak numbers of detections occurred at Station 2 between late July to early August and from early September to early October. It should be noted that while killer whale calls can be distinguished to ecotype, this manual analysis was not requested for this report.

Killer whales are found throughout BC’s marine waters, including in long inlets, narrow channels, and deep embayments (Baird 2001). In our study, the number of detections were higher at Station 2 than Station 1. This is consistent with density surfaces estimated by Williams and O'Hara (2010), which indicated that there were more whales close to Dixon Entrance than in the northeastern confined regions.

4.2.4. Pacific white-sided dolphins

The Pacific white-sided dolphin is distributed throughout the temperate waters of the North Pacific Ocean. Seasonal movements have been reported, notably an inshore/offshore movement off California and BC (Stacey and Baird 1991). Over the four months of data collected during the present study, Pacific white-sided dolphin clicks were detected only once: on 22 Jul 2014 at Station 2. Williams and Thomas (2007) noted in their BC survey, conducted in the 2004–2005 season, that dolphins were frequently seen in the southern part of Queen Charlotte Basin. This observation suggests that during the summer Pacific white-sided dolphins are rare or absent from Chatham Sound, which is in keeping with Ford (2014)'s note that these dolphins seem to shift offshore somewhat during the summer months.

4.2.5. Porpoises

Porpoise clicks were detected through the entire monitoring study. Because harbour and Dall's porpoise clicks have very similar frequency characteristics, they could not be discriminated from one another. Kyhn et al. (2013) measured a 4 kHz difference between the median frequency of Dall's and harbour porpoise clicks recorded on-axis (i.e., animal facing the recorder) and at close range (< 65 m). Because clicks detected with passive acoustic recorders are often off-axis and at greater distances, we need to further investigate how we can apply this knowledge to our data (Mouy et al. 2013).

4.2.6. Harbour seals

Harbour seal calls occurred only at Station 1. Peak numbers of calls were detected between mid-July and mid-August. This period corresponds to the mating season, which typically occurs in summer after females have weaned their pups (Bigg 1969, Temte and Wiig 1991).

This species has one of the most extensive global ranges of any pinniped, inhabiting coastal waters throughout the northern hemisphere (Olesiuk et al. 1990, DFO 2010). Throughout the year, harbour seals might travel long distances to forage; most individuals, however, are believed to be philopatric (Stanley et al. 1996) and are often found in their home ranges in breeding season (Bigg 1969, Temte and Wiig 1991).

The fact that only adult males are known to produce underwater vocalizations (Ralls et al. 1985) and that calls are produced most frequently during or just before the breeding season (Coltman et al. 1997, Van Parijs et al. 1997, Hayes et al. 2004) supports the hypothesis that male vocal signals are a breeding display. One call in particular, the roar, has been documented in every harbour seal population that has been studied, and is assumed to indicate fitness (Hanggi and Schusterman 1994).

4.3. Marine Biota and Noise

Sound impact criteria must consider an animal's frequency-dependent hearing ability relative to the frequency distribution of the noise to which it is exposed, and relative to that of the background or ambient noise. Masking will start to occur when the anthropogenic sound level exceeds both the animal's hearing threshold and the ambient noise level. If the sound is below the animal's hearing threshold, then it will not be audible in any circumstance. If it is below ambient noise level then it will be masked and not detected by the animal. The analysis of sound audibility must also consider the ability of hearing organs (primarily the cochlea in mammals) to filter sounds of different frequency; the ear can still detect lower amplitude sounds in the presence of higher-amplitude interfering sounds when these sounds occur sufficiently-separated in frequency. The "critical band" refers to the frequency bandwidth of auditory filters. Few measurements of critical bands are available for species other than humans. A common approximation is to assume 1/3-octave critical bandwidths – which is an overestimate by a factor of about 2 times that for humans over frequencies of 500 Hz to 10 kHz.

Figure 40 shows nominal species-dependent audiograms that indicate the frequency-dependent hearing thresholds of several species present in the study area. Audiograms indicate the lowest amplitude tone sound levels that are audible in the absence of ambient noise. The ear is likely less sensitive to broadband sounds than tones, so audiograms represent a conservative (more sensitive) estimate of hearing threshold over critical bandwidths. Figure 40 also shows measured mean 1/3-octave band ambient noise sound levels at Stations 1 and 2 for comparison with the audiogram levels.

All of the mammalian species audiograms shown in Figure 40 extend below ambient noise levels over substantial frequency ranges. Therefore, zones of audibility and masking by anthropogenic sounds will be limited by the ambient levels rather than the animal's hearing ability within those frequency ranges. The audiograms of the two fish species (salmon and herring) occur largely above ambient noise levels, so their audiogram levels will define respective zones of audibility and masking[1].

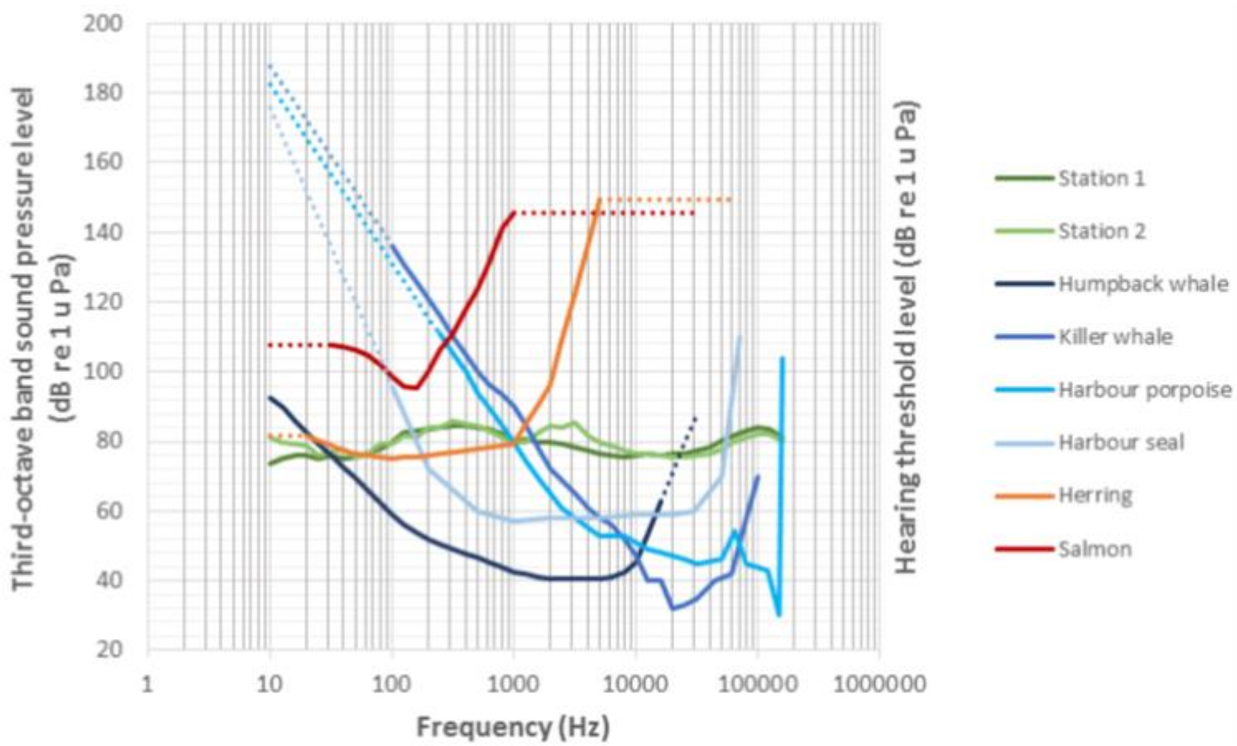

Figure 40. Comparison of marine mammal (humpback whale, killer whale, harbour porpoise, and harbour seal) and fish (salmon and herring) audiograms to mean 1/3-octave-band SPLs measured over the study period. Killer whale audiogram data are issued from the model from Erbe (2002), which is based on data from Hall and Johnson (1971). Humpback whale audiogram data are from Clark and Ellison (2004) and Houser et al. (2001). Harbour porpoise audiogram data are issued from composite behaviour values extracted from Kastelein et al. (2002), Kastelein et al. (2012), and Andersen (1970). Harbour seal audiogram data are from Møhl (1968), Terhune (1988), Kastelein et al. (2009), and Reichmuth et al. (2013). Chinook salmon (*Oncorhynchus tshawytscha*) and Atlantic salmon (*Salmo salar*) audiograms were combined from Oxman et al. (2007) and Hawkins and Johnstone (1978). Herring (*Clupea harengus*) audiogram is from Enger (1967). Dotted lines show extrapolated values.

As discussed above, any assessment of masking or chronic disturbance should take into account the audiogram values and ambient noise levels presented in Figure 40. These effects are typically associated with much lower sound levels than those that would lead to auditory injury or acute disturbance.

There was fairly high variability observed in the noise level measurements over the study periods at both sites. The mean levels of 1-minute SPL's over the entire measurement period are approximately 10 dB greater than the corresponding median levels. The 5th and 95th percentile levels were approximately 25 dB different (Figure 41). Effects studies should consider this variability, and should recognize that median and mean levels can be quite different.

[1] Fish audiograms are included for comparison with ambient noise as zones of audibility for salmon and herring are calculated in the modelling report.

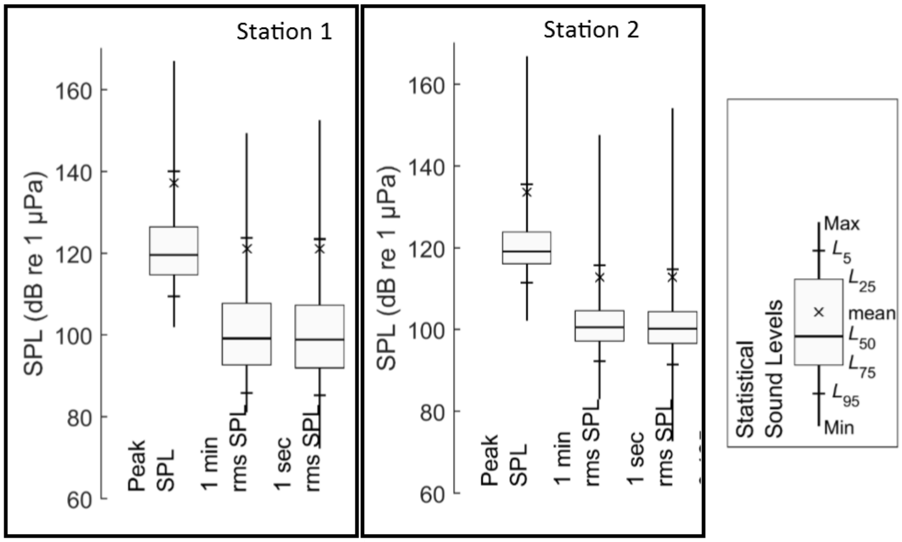

Figure 41. Statistical sound levels (received peak SPL, 1 min rms SPL and 1 s rms SPL) from Station 1, 11 Jul to 19 Nov, and Station 2, 11 Jul to 31 Oct 2014.

Sound levels at Station 1 exceeded 120 dB re 1 µPa root-mean-square sound pressure level (rms SPL), the regulatory threshold set by the United States-based organization National Oceanic and Atmospheric Administration Fisheries (NOAA) for marine mammal disturbance with non-impulsive noise sources, 8.2% of the time (Table 6). At Station 2, this threshold was exceeded 2.5% of the time (Table 6).

Table 6. Percentage of the data (received SPL) exceeding behavioural disturbance threshold.

Behavioural disturbance threshold	Averaging duration	Station 1	Station 2
Marine mammals (120 dB re 1 µPa)	1 min rms SPL	8.16	2.54
	1 s rms SPL	7.77	2.24

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Glossary

1/3-octave-band
Non-overlapping passbands that are one-third of an octave wide (where the ratio of upper to lower frequency is a factor of $2^{1/3}$). Three adjacent 1/3-octave-bands make up one octave. One-third-octave-bands have larger bandwidths (measured in Hz) with increasing band frequency. See also octave.

ambient sound
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.

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

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.

continuous sound
A sound whose sound pressure level remains above ambient sound during the observation period (ANSI/ASA S1.13-2005 R2010). A sound that gradually varies in intensity with time, for example, sound from a marine vessel.

critical band
The auditory bandwidth within which background noise strongly contributes to masking of a single tone. Unit: hertz (Hz).

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).

fast Fourier transform (FFT)
A computationally efficiently algorithm for computing the discrete Fourier transform.

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.

hearing threshold
The sound pressure level that is barely audible for a given individual in the absence of significant background noise during a specific percentage of experimental trials.

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

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

masking
Obscuring of sounds of interest by other (typically unwanted) sounds.

median
The 50th percentile of a statistical distribution.

mysticete
Mysticeti, a suborder of cetaceans, use their baleen plates, rather than teeth, to filter food from water. They are not known to echolocate, but use sound for communication. Members of this group include rorquals (*Balaenopteridae*), right whales (*Balaenidae*), and the grey whale (*Eschrichtius robustus*).

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

peak sound pressure level (peak SPL)
The maximum instantaneous sound pressure level, in a stated frequency band, within a stated period. Also called zero-to-peak sound pressure level. Unit: decibel (dB).

percentile level, exceedance
The sound level exceeded *n*% of the time during a measurement.

pinniped
A common term used to describe all three groups that form the superfamily Pinnipedia: phocids (true seals or earless seals), otariids (eared seals or fur seals and sea lions), and walrus.

power spectral 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*.

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

received level
The sound level measured at a receiver.

rms
root-mean-square.

rms sound pressure level (rms SPL)
The root-mean-square average of the instantaneous sound pressure as measured over some specified time interval. For continuous sound, the time interval is one second. See also sound pressure level (SPL) and 90% rms SPL.

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

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

sound exposure level (SEL)
A measure related to the sound energy in one or more pulses. Unit: dB re 1 $\mu Pa^2 \cdot s$.

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 (rms SPL).

spectrogram
A visual representation of acoustic amplitude versus time and frequency.

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

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Appendix A. 1/3-octave-bands

A 1/3-octave-band represents a range of frequencies defined by lower (f_{lo}) and upper (f_{hi}) frequency limits with the ratio of these frequencies being $2^{1/3}$. The center frequency of the ith 1/3-octave-band, $f_c(i)$, is defined as:

$$f_c(i) = 10^{i/10} \tag{1}$$

and the low and high frequency limits of the ith 1/3-octave-band are defined as:

$$f_{lo} = 10^{-1/20} f_c(i) \text{ and } f_{hi} = 10^{1/20} f_c(i) \tag{2}$$

The 1/3-octave-bands become wider with increasing frequency, and on a logarithmic scale, the bands appear equally spaced (Figure A-1).

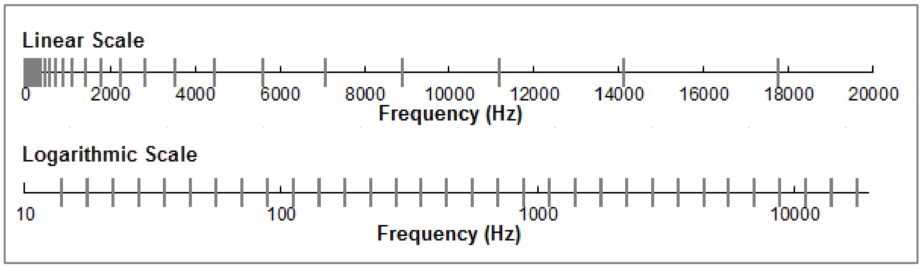

Figure A-1. One-third-octave-bands shown on a linear frequency scale and on a logarithmic scale. The 1/3-octave-bands appear equally spaced on the logarithmic scale.

The sound pressure level in the ith 1/3-octave-band $(L_b^{(i)})$ is computed from the power spectrum $S(f)$ between f_{lo} and f_{hi}:

$$L_b^{(i)} = 10 \log_{10} \left(\int_{f_{lo}}^{f_{hi}} S(f) df \right) \tag{3}$$

Summing the sound pressure level of all the 1/3-octave-bands yields the broadband sound pressure level:

$$\text{Broadband SPL} = 10 \log_{10} \sum_i 10^{L_b^{(i)}/10} \tag{4}$$

Figure A-2 below illustrates how the 1/3-octave-band sound pressure levels compare to the power spectrum of an ambient sound signal. Because the 1/3-octave-bands are wider with increasing frequency, the 1/3-octave-band SPL is higher than the power spectrum, especially at higher frequencies.

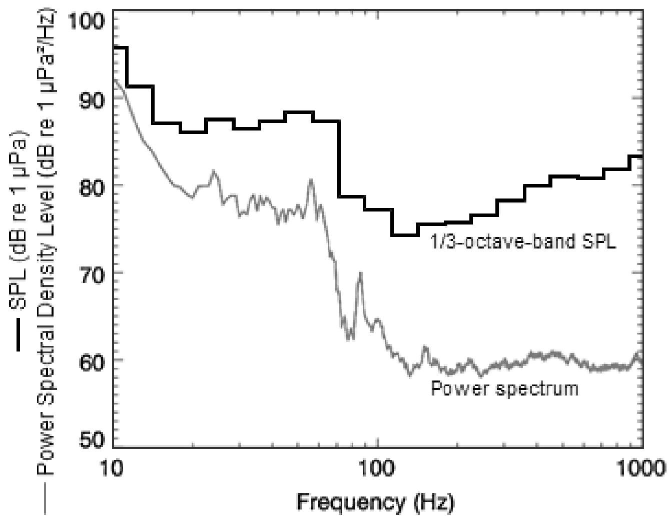

Figure A-2. A power spectrum and the corresponding 1/3-octave-band sound pressure levels of ambient sound shown on a logarithmic frequency scale. Because the 1/3-octave-bands widen with increasing frequency, the 1/3-octave-band SPL is higher than the power spectrum.