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Ship noise in an urban estuary extends to frequencies used for echolocation by endangered killer whales

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ABSTRACT

Combining calibrated hydrophone measurements with vessel location data from the Automatic Identification System, we estimate underwater sound pressure levels for 1,582 unique ships that transited the core critical habitat of the endangered Southern Resident killer whales during 28 months between March, 2011, and October, 2013. Median received spectrum levels of noise from 2,812 isolated transits are elevated relative to median background levels not only at low frequencies (20-30 dB re 1 $\mu\text{Pa}^2/\text{Hz}$ from 100-1000 Hz), but also at high frequencies (5-13 dB re 1 $\mu\text{Pa}^2/\text{Hz}$ from 10,000-96,000 Hz). Thus, noise received from ships at ranges less than 3 km extends to frequencies used by odontocetes like the southern resident killer whales for communication and echolocation. Broadband received levels (11.5-40,000 Hz) near the shoreline in Haro Strait (WA, USA) for the entire ship population were 111 ± 6 dB re 1 μPa on average. Mean ship speed was 14.4 ± 4.1 knots. Most ship classes show a linear relationship between received level and speed with a slope near +1 dB/knot. Assuming near-spherical spreading based on a transmission loss experiment we compute mean broadband source levels for the ship population of 173 ± 7 dB re 1 μPa @ 1 m without accounting for frequency-dependent absorption. Spectrum, 1/12-octave, and 1/3-octave source levels for the whole population have median values that are comparable to previous measurements and models at most frequencies, but for select studies may be relatively low below 200 Hz and high above 20,000 Hz. Median source spectrum levels peak near 50 Hz for all 12 ship classes, have a maximum of 159 dB re 1 $\mu\text{Pa}^2/\text{Hz}$ @ 1 m for container ships, and vary between classes by about 25 dB re 1 $\mu\text{Pa}^2/\text{Hz}$ @ 1 m at low frequencies (50 Hz), 13 dB re 1 $\mu\text{Pa}^2/\text{Hz}$ @ 1 m at mid-frequencies (1,000 Hz), and 5 dB re 1 $\mu\text{Pa}^2/\text{Hz}$ @ 1 m at high frequencies (10,000 Hz). Below 200 Hz, the class-specific median spectrum levels bifurcate with large commercial ships grouping as higher power noise sources. Within all ship classes spectrum levels vary more at low frequencies than at high frequencies, and the degree of variability is almost halved for classes that have smaller speed standard deviations.

Keywords: noise, ship, hydrophone, killer whale, orca, odontocete, marine mammal

1 INTRODUCTION

Commercial ships radiate noise underwater with peak spectral power at 20-200 Hz (Ross, 1976). Ship noise is generated primarily from propeller cavitation, propeller singing, and propulsion or other reciprocating machinery (Richardson et al., 1995; Wales and Heitmeyer, 2002; Hildebrand, 2009). The dominant noise source is usually propeller cavitation which has peak power near 50-150 Hz (at blade rates and their harmonics), but also radiates broadband power at higher frequencies, at least up to 100,000 Hz (Ross, 1976; Gray and Greeley, 1980; Arveson and Vendittis, 2000). While propeller singing is caused by blades resonating at vortex shedding frequencies and emits strong tones between 100 and 1000 Hz, propulsion

9 noise is caused by shafts, gears, engines, and other machinery and generates noise mainly below 50 Hz
10 (Richardson et al., 1995). Overall, larger vessels generate more noise at low frequencies (<1,000 Hz)
11 because of their relatively high power, deep draft, and slower-turning (< 250 rpm) engines and propellers
12 (Richardson et al., 1995).

13 This low-frequency energy from ships is the principal source of ambient noise within the deep ocean
14 from approximately 5-1000 Hz (Wenz, 1962; Urlick, 1983; National Research Council et al., 2003).
15 Growth of the global shipping fleet and possibly the average size of ships has raised deep-ocean ambient
16 noise levels in low-frequency bands near 40 Hz by up to 20 dB relative to pre-industrial conditions
17 (Hildebrand, 2009) and 8-10 dB since the 1960s (Andrew et al., 2002; McDonald et al., 2006).

18 As these ships enter shallow waters and traverse the estuarine habitat typically occupied by major
19 ports, the noise they radiate may impact marine life. Since many marine mammals rely on sound to find
20 prey, moderate social interactions, and facilitate mating (Tyack, 2008), noise from anthropogenic sound
21 sources like ships can interfere with these functions, but only if the noise spectrum overlaps with the
22 hearing sensitivity of the marine mammal (Southall et al., 2007; Clark et al., 2009; Hatch et al., 2012).

23 Mysticetes (baleen whales) constitute a low-frequency functional hearing group that is likely most
24 sensitive at frequencies 10-10,000 Hz (Southall et al., 2007). They typically emit signals with fundamental
25 frequencies well below 1,000 Hz (Cerchio et al., 2001; Au et al., 2006; Munger et al., 2008) although
26 non-song humpback signals have peak power near 800 and 1700 Hz (Stimpert, 2010) and humpback song
27 harmonics extend up to 24,000 Hz (Au et al., 2006).

28 The frequency overlap of peak power in ship noise and baleen whale signals (and inferred maximum
29 hearing sensitivity) is verified by observed behavioral and physiological responses of mysticetes to ship
30 noise. As examples, the probability of detecting a blue whale D call increases in ship noise, suggesting a
31 Lombard effect (Melcon et al., 2012) and Rolland et al. (2012) found decreased stress levels in North
32 Atlantic right whales when ship noise was absent.

33 Odontocetes (toothed whales) constitute mid-frequency or high-frequency functional hearing groups
34 (Southall et al., 2007). Generally they emit social sounds at about 1,000-20,000 Hz and echolocate at
35 10,000-100,000 Hz or higher. In contrast to baleen whales, auditory response curves have been obtained
36 for many toothed whale species. These curves show maximum auditory sensitivity near the frequencies
37 where toothed whale signals have peak power (Mooney et al., 2012; Tougaard et al., 2014).

38 Southern resident killer whales (SRKW) represent an endangered toothed whale species that is
39 characterized bioacoustically and inhabits an urban estuary in which shipping traffic is common. Their
40 auditory sensitivity, extrapolated from captive killer whales (Hall and Johnson, 1972; Szymanski et al.,
41 1999), peaks at 15,000-20,000 Hz – a frequency range that overlaps with the upper range of their

vocalizations and the lower range of their echolocation clicks. SRKW calls have fundamental frequencies at 100-6,000 Hz with harmonics extending up to 30,000 Hz (Ford, 1987). Their echolocation clicks are likely similar to those of salmon-eating northern resident killer whales which have a 40,000 Hz bandwidth and a mean center frequency of 50,000 Hz (Au et al., 2004). SRKWs whistle between 2,000 and 16,000 Hz (Riesch et al., 2006) with a mean dominant frequency of 8,300 Hz (Thomsen et al., 2000).

Behavioral responses to boat (as opposed to ship) noise have been documented in toothed whales, including SRKWs. For example, bottlenose dolphins whistle (at 4,000-20,000 Hz) less when exposed to boat noise at 500-12,000 Hz (Buckstaff, 2004) and Indo-Pacific bottlenose dolphins lower their 5,000-10,000 Hz whistle frequencies when noise is increased by boats in a band from 5,000-18,000 Hz (Morisaka et al., 2005). For every 1 dB increase in broadband underwater noise (1,000-40,000 Hz) associated with nearby boats, SRKWs compensate by increasing the amplitude of their most common call by 1 dB (Holt et al., 2009).

Experiments confirm that cavitation generates high frequency noise up to at least 100,000 Hz (Wenz, 1962). Cavitation noise from spinning rods and water jets has spectral power that rises through low frequencies at a rate of 40 dB/decade to a peak near 1,000 Hz and thereafter descends at -20 dB/decade (Mellen, 1954; Jorgensen, 1961). Noise from foil cavitation also has peak spectral power at 1,000 Hz, as well as a secondary peak at 31,000 Hz (Blake et al., 1977). In the vicinity of the higher peak, 1/3-octave levels increase about 10 dB upon cavitation inception (Blake et al., 1977).

World War II studies of ship noise, particularly measurements of thousands of transits of hundreds of ships of all types, identified propeller cavitation as the dominant source of noise radiated by ships, including at high frequencies (Dow et al., 1945). In reviewing these studies Ross (1976) and Urlick (1983) noted that increases of >40 dB in the 10,000-30,000 Hz band were diagnostic of cavitation inception on accelerating twin-screw submarines and Urlick (1983) attributed a 1 dB/knot rise in torpedo spectrum levels from 10,000-75,000 Hz to propeller cavitation.

More recently, cavitation has been implicated in ship noise measurements made at close range (< 1,000 m) which show levels between 1,000-160,000 Hz that not only are significantly above background levels, but also rise with increased ship speed faster than at lower frequencies (Arveson and Vendittis, 2000; Kipple, 2002; Hermannsen et al., 2014). Even when portions of the high-frequency energy are excluded, broadband source levels of cavitating propellers are high. Erbe and Farmer (2000) reported median broadband (100-20,000 Hz) source levels for an icebreaker with a cavitating propeller of 197 dB re 1 μ Pa @ 1 m.

In the open ocean or on the outer continental shelf far from shipping lanes high-frequency noise radiated by a ship will be absorbed within about 10 km (Erbe and Farmer, 2000), typically before reaching

a species of concern. In urban estuaries, however, marine mammals are exposed to noise from ships at ranges of 1-10 km routinely, and less than 100 m occasionally. For example, SRKWs frequently transit Haro Strait within 10 to 300 m of the shoreline at Lime Kiln Point where they are about 2 km from the center of the northbound (nearest) shipping lane (Figure 1). Since the absorption rate is only about 3 dB/km at 20,000 Hz, compared to 30 dB/km at 100,000 Hz (Francois and Garrison, 1982), ship noise near 20,000 Hz (where SRKWs are most sensitive) in such close quarters may retain the potential to mask echolocation clicks, as well as other high-frequency signals.

In an environment where SRKWs may already be food-stressed (Ayres et al., 2012) due to reduced populations of their primary prey – Chinook salmon (Hanson et al., 2010) – echolocation masking could have grave population-level consequences. The potential impacts of ship noise on foraging efficiency may be compounded by simultaneous masking of communication calls, some of which may help coordinate foraging or prey sharing (Ford and Ellis, 2006). One case study has suggested that ship noise may reduce foraging efficiency by 50% in Curvier Beaked whales (Aguilar Soto et al., 2006). Motivated by the possible impacts of ship noise on odontocetes and the scarcity of ship noise measurements made at close range over the full range of frequencies used by SRKWs, we endeavored to estimate source spectrum levels up to 40,000 Hz for a wide variety of ships from measurements made at a range of less than a few kilometers.

METHODS

Our study site is an area of the inland waters of Washington State and British Columbia known as the Salish Sea. This urban estuary hosts the commercial shipping ports of Vancouver, Seattle, and Tacoma (see Figure 1).

Shipping traffic primarily associated with Vancouver – about 20 large (> 65 feet or 19.8 m) vessels per day (Veirs and Veirs, 2006) – transits Haro Strait, the core of the summertime habitat of the SRKWs (Hauser et al., 2007). Each ship typically raises sound pressure levels near the shoreline about 20 dB re 1 μ Pa (RMS, 100-15,000 Hz) above background levels to about 115 dB re 1 μ Pa for approximately 20 minutes/transit (Veirs and Veirs, 2006). We define ships as all vessels with overall length (LOA) greater than 65 feet (19.8 m); the remaining, shorter vessels (boats) are not characterized in this study.

We measured underwater noise radiated by these ships, collecting data continuously during 28 months between March 7, 2011, and October 10, 2013, except for occasional 1-2 day interruptions caused by power outages. About 3.5 months of data were excised due to systematic noise caused during equipment repairs made between July 22, 2011, and November 9, 2011. Consequently, we sampled every month of the year at least twice.

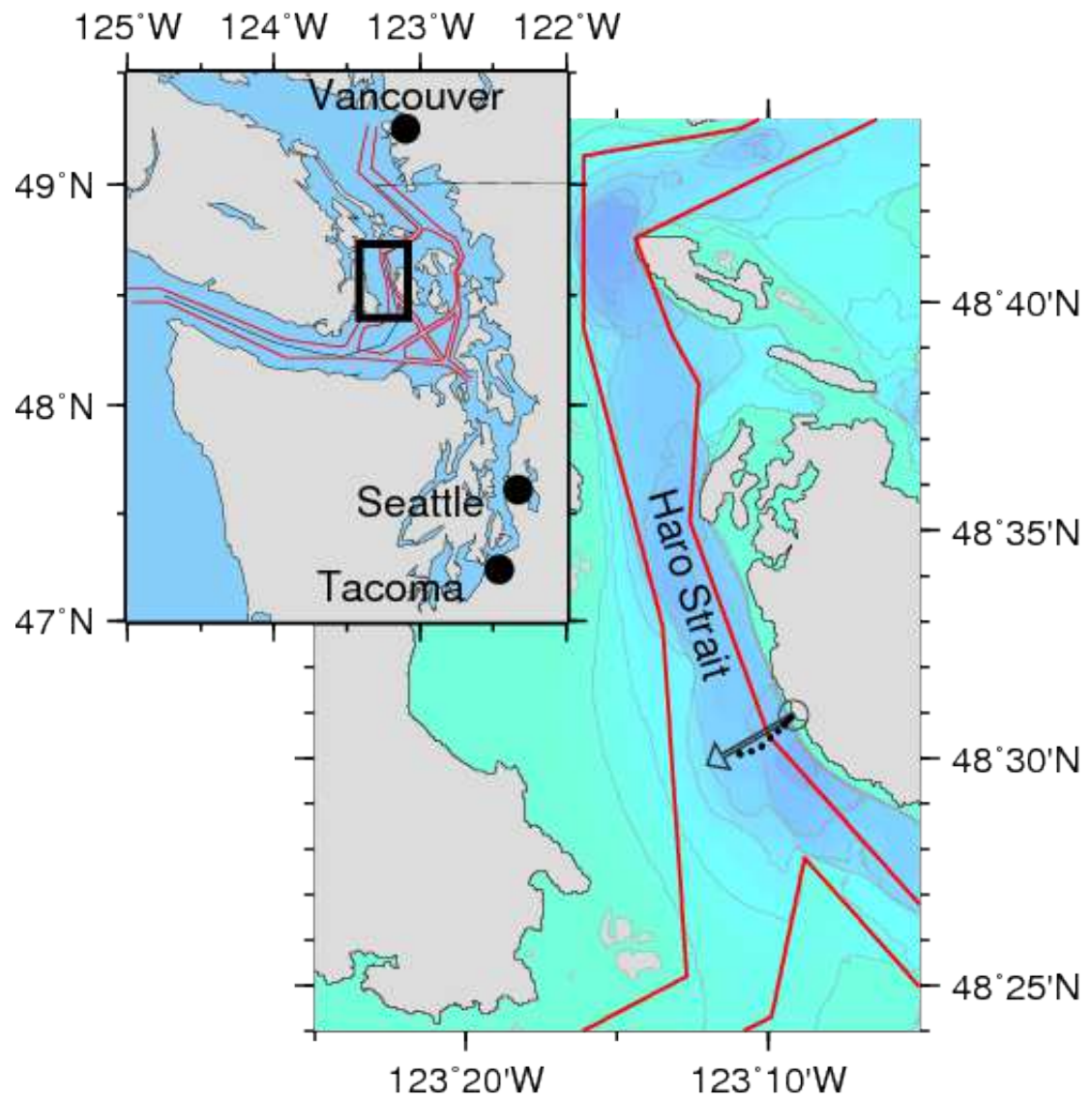


Figure 1. Inset regional map shows the study area (black rectangle) and shipping lanes (in red) leading to the major ports of the Salish Sea. The 240° bearing (gray arrow) extends from the Lime Kiln hydrophone (gray circle) through the northbound shipping lane. Bathymetric contours (50 m) show that Haro Strait is a steep-sided 200-300 m-deep channel. Sound projection locations (black dots) are sites used for the transmission loss experiment.

107 Study site

108 We deployed a calibrated hydrophone 50 m offshore of the lighthouse at Lime Kiln State Park in which The
 109 Whale Museum and Beam Reach maintain an acoustic observatory as part of the Salish Sea Hydrophone
 110 Network (orcasound.net). Midway along the west side of San Juan Island, Lime Kiln lighthouse sits on
 111 a point near the center of the summertime habitat of the SRKWs (Figure 1). While the killer whales
 112 sometimes swim directly over the hydrophone location, they more typically transit the site 100-300 m
 113 offshore where received levels of noise from the shipping lanes would be somewhat higher than those
 114 recorded in this study.

115 The hydrophone was secured to a PVC pipe projecting vertically from a cement-filled tire resulting in
116 a position 1 m above the bottom at a depth of 8 m (below mean lower low water). A cable protected by
117 irrigation pipe secured in the inter- and sub-tidal zones brought the signal to recording hardware within
118 the lighthouse and also housed a saltwater ground wire that helped reduce system noise.

119 The local bathymetry on a transect perpendicular to the shoreline (240° bearing) and running from
120 the hydrophone to the northbound shipping lane descends to deep (>200 m) water within 300 m of the
121 shoreline. The nearshore region (<150 m from shore) has a substrate of boulders and gravel covered with
122 marine vegetation and descends at a slope of about 20°. Further from shore the bottom descends at a
123 slope of about 45°.

124 Relative to the northbound shipping lane the hydrophone position is 1.3 km from the eastern edge,
125 2.25 km from the center of the lane, and about 3.7 km from the center of the traffic separation zone. A
126 histogram of the range to all ships in our database shows peaks at 2.3 and 5.0 km, corresponding with the
127 middle of the north- and south-bound lanes, respectively.

128 Data acquisition

129 We made audio recordings of the signal from a Reson TC4032 hydrophone installed with a differential
130 output (sensitivity of -164 ± 3 dB re 1 V/ μ Pa from 5-125,000 Hz) that was amplified and then digitized by
131 a MOTU Traveller sampling at 192,000 Hz with 16 bits per sample. The maximum signal that could be
132 recorded without clipping was 140 dB.

133 A Windows XP computer analyzed and archived the recorded signal. We calibrated the recording
134 system with the analog output of an Interocceans 902 (acoustic listening calibration system) while a ship
135 was passing the lighthouse, thereby converting the samples to decibels (dB) referenced to 1 μ Pa (hereafter
136 dB re 1 μ Pa). This procedure was carried out occasionally to check and make minor changes in the Reson
137 calibration constant during the 28 month study period.

138 A Python program analyzed the digitized hydrophone signal. The program continuously computed
139 running 2-second mean square voltage levels. Each hour the program archived the 2-second recordings
140 that yielded the minimum and maximum averages. We used the minimum files to determine background
141 noise levels.

142 Generally, all commercial ships over 300 tons are required to use the Automatic Identification System
143 (AIS) to broadcast navigational data via VHF radio. The AIS carriage requirements of the U.S. Coast
144 Guard (33 CFR 164.46) and Canada within a vessel traffic service area like Haro Strait mean that some
145 fishing and passenger vessels may be underrepresented in our data set. Each AIS-equipped ship transmits
146 at least its identification number, location, course, and speed a few times each minute. The typical range
147 over which these transmissions are detected is 45 km.

148 The Python program scanned the binary output of an AIS receiver (Comar Systems AIS-2-USB)
149 located in the lighthouse. For each transmission received, the location of the ship was used to calculate its
150 range (R) from the hydrophone. When R was less than 4 nautical miles (7.4 km), the program recorded
151 the broadband received level every 0.5 nautical mile (926 m) as the ship approached and departed. When
152 the ship crossed a line perpendicular to shore (at an azimuth angle of 240° true, see Figure 1), the Python
153 program stored a 30-second WAV file, the date and time, and the decoded ship metadata (ship ID number,
154 range, speed over the ground [SOG], and course over the ground). Given the orientation of the northbound
155 shipping lane, this procedure made it likely that we recorded the starboard beam aspect noise levels
156 of each isolated ship near the closest point of approach. Finally, the program calculated the calibrated
157 broadband received level using the Reson calibration constant and the RMS amplitude of the 30-second
158 file.

159 To maximize the detection of any high-frequency signal generated by passing ships, and to reduce
160 the spatial extent of our transmission loss experiment, we elected to compute source levels for only the
161 closer, northbound portion of the traffic in Haro Strait. Southbound traffic was recorded, counted, and
162 archived, but is not included in this analysis. For the northbound traffic presented herein, the mean and
163 standard deviation of R is 2.30 ± 0.39 km, and the minimum and maximum R are 0.95 km and 3.65 km,
164 respectively.

165 Data analysis

166 Isolation and identification

167 Archived WAV files and associated metadata were analyzed with a C++ program developed in the
168 platform-independent Qt environment (qt-project.org). To measure the noise radiated by an individual
169 ship, rather than multiple ships, the program used the AIS data to detect acoustically-isolated ships. A
170 ship was deemed isolated if the previous and subsequent ships were at least 6 nautical miles (11.1 km)
171 away from the hydrophone when the WAV file was recorded. It is only at closer range that human listeners
172 can detect ship noise above ambient levels.

173 For each isolated ship, the program used the ship's identification (Maritime Mobile Service Identity, or
174 MMSI) number to look up details about the ship from online web sites such as the Marine Traffic network
175 (www.marinetraffic.com). These metadata, saved in a MySQL database, include (when available): MMSI,
176 ship name, ship type, year built, length, breadth, dead weight, maximum and mean speed, flag, call sign,
177 IMO, draft, maximum draft, and photographs.

178 We simplified 41 ship type categories returned from online queries into 12 general ship classes: bulk
179 carrier (includes ore carriers); container; tug (includes multi-purpose offshore, pusher tug, and tender);
180 cargo (includes other cargo, heavy lift, wood chip carrier); vehicle carrier (includes all roll-on roll-offs);

181 tanker (includes crude oil, oil product, oil/chemical, chemical, and product tankers); military (includes
182 Coast Guard, search and rescue); fishing (includes fish carrier, factory, fishing, fishing vessel, and trawler);
183 passenger (includes cruise ships and ferries); miscellaneous (includes cable layer, reserved, unspecified,
184 and well-stimulation); pleasure craft (includes sailing vessels, motor yacht, and yachts); and research.

185 **Received levels**

186 From each isolated ship's WAV file the RMS power spectral density (PSD) was calculated using a Fast
187 Fourier Transform averaged over the 30-second duration of the file (Nyquist frequency of 96,000 Hz;
188 16,384 (2^{14}) sample overlapping Bartlett window). The bandwidth of each of the 8,192 frequency bins
189 was 11.5 Hz. These RMS PSD (per Hz) values were calibrated by requiring that the integral of the PSD
190 equal the calibrated broadband level associated with each WAV file. The resulting power spectral densities
191 we call the total received spectrum levels.

192 The total received spectrum level is a composite of the power that originated from the ship and the
193 power associated with the background noise at the time of the ship passage. To enable estimation of the
194 background level at the time of ship passage we continuously observed 2-second sound samples, saving
195 the lowest power 2-second sample every hour.

196 The subtraction of the estimated background received level (RL_B) from the total received level (RL_T)
197 to determine the received level associated with the ship (RL_S) is based on the fact that when two or more
198 waves pass at once, the pressure on the hydrophone (P) is the sum of the instantaneous pressure from each
199 wave. The power that we calculate is proportional to the square of the pressure on the hydrophone and is
200 represented in decibels. These relationships apply both for the power at individual frequencies (PSD) and
201 the total power (Pwr_T) integrated over all frequencies.

Following the nomenclature of Erbe (2010),

$$Pwr_T(t) = k(P_S(t) + P_B(t))^2 \quad (1)$$

202 where k is a constant dependent on the construction of the hydrophone and t is time. Averaging over the
203 30 seconds of each WAV file, we assume that the pressure due to the ship at each moment in time is not
204 correlated with the pressure due to other (background) noise sources. Thus, the power received from the
205 ship is the average total power minus the average background power:

$$\langle Pwr_S \rangle = \langle Pwr_T \rangle - \langle Pwr_B \rangle \quad (2)$$

206 We estimate Pwr_B for each passing ship as the average of the power in two samples – the quietest

207 2-second sample from the hour before the ship is recorded, and quietest from the hour after the ship
208 passage.

209 On occasion during daylight hours, ship recordings contain noise from vessels unequipped with
210 AIS (usually recreational motorboats and occasionally larger vessels operating without AIS). This
211 contamination is limited to the 50, 75, and 95% quantiles above 20,000 Hz, has peak spectrum levels
212 near 50,000 Hz – a frequency commonly used for depth sounders – and is rare, but we have nevertheless
213 reduced it via a 2-step statistical process.

214 Since it is very rare to have motorboat noise overlapping with ship passage at night, we first determined
215 the 95% quantile of each received spectrum level across all vessels recorded at night (hour of day greater
216 than 19:00 or less than 07:00) and used it as a threshold above which contamination by boat noise may
217 have occurred. Then we re-processed all ship transits, removing any data points for which the threshold
218 was exceeded. Any recording in which at least 100 of the 8,192 spectral received levels were above
219 threshold was omitted from further statistical analysis.

220 Through this robust statistics process, about 15% of transits were omitted, resulting in no difference
221 between the ship population quantiles for ships that pass during the day versus the night. A sensitivity
222 analysis shows that the process did not affect the 5% to 75% quantiles and that the 95% quantile was
223 reduced by less than 2 dB – and only above about 20,000 Hz. The high frequency peaks seen in the 95%
224 quantile in Figure 3 become sharper as the threshold is increased or the total number of vessels analyzed
225 is decreased.

226 Finally, we report received levels (RL) in decibels relative to a reference pressure of 1 μ Pascal and
227 estimate ship received levels as:

$$RL_S = 10 \log_{10} \left(10^{RL_T/10} - 10^{RL_B/10} \right) \quad (3)$$

228 Often RL_T is much higher than RL_B at all frequencies. In such cases, subtraction of the background
229 has little effect on RL_S . But for many ships RL_T is close to RL_B , at least at some frequencies. Therefore,
230 we subtract the estimated background from the RL_T at all frequencies for every isolated ship, yielding the
231 received spectrum level of ship noise, RL_S .

232 We cannot determine RL_S if the associated RL_T is not greater than RL_B . Hence we require that RL_T
233 at any given frequency must exceed a threshold of three times the background spectrum level at that
234 frequency. We choose this factor (4.8 dB) by examining the statistics of typical ship and background
235 recordings to assure that noise is unlikely to be taken as signal. We refrain from reporting ship source
236 spectra above 40,000 Hz because the sample size in bands above this frequency falls below about 10% of

the mean sample size at lower frequencies. Furthermore, to calculate broadband source levels with or without absorption we integrate the spectrum levels only up to this 40,000 Hz upper limit.

Prior to the background subtraction, our data commonly contained narrow-band noise peaks near 25, 38, 43, 50 and 69 kHz in many of the background and total received level quantiles (Figure 3). Unknown sources of transient systematic noise (most commonly near 77 kHz), typically lasted only a few days. Because these noise sources are narrow or brief, they contain little power. Also, since they occur in both the received level and background data, they tend to be removed through background subtraction, and therefore do not significantly contaminate the estimated source levels (Figure 4). One exception is the peak near 25 kHz – likely associated with the Jim Creek Naval Radio Station (transmitting at 24.8 kHz) – which persists in many source level spectra, probably indicating that the submarine communications are intermittent, at times occurring during a ship passage but not during the corresponding background measurements.

Transmission loss experiment

To estimate the source spectrum level of isolated ships from RL_S we measured the transmission loss along the 240° true bearing line from the near-shore hydrophone at Lime Kiln into the northbound shipping lane (Figure 1). The transmission loss is a combination of geometric spreading and frequency-dependent absorption.

We determined the geometric spreading via a field experiment conducted in March 2014 from a 10 m catamaran. We projected a sequence of 2-second tones (Table 1) using a Lubell 9816 underwater speaker lowered in a bifilar harness from the bows and attached to a power amplifier and a digital sound player. During each tone sequence, we noted the location of the projector on the sailboat's GPS and measured the projected sound level with the Interocceans 402 hydrophone, having positioned its calibrated hydrophone near the stern, about 10 m from the projector. We oriented the projection system toward the lighthouse as we played each sequence at the following distances from the projector to the Lime Kiln hydrophone: 290; 1,035; 1,446; and 2,893 m.

This study focuses on determining the source levels of ships that are northbound at Lime Kiln lighthouse. By limiting our analysis to northbound vessels we reduce the difficulty of determining accurate transmission loss by limiting the variation in range of the targets. Furthermore, our underwater speaker used to measure transmission loss did not have sufficient power especially at high frequencies (near 20,000 Hz) to provide detectable signals at ranges much larger than the 2893 m range that brackets the more distant edge of the north bound traffic lane.

We analyzed the spreading of the test tones by measuring the calibrated RMS level received at the Lime Kiln hydrophone for each tone at each distance. The received signal was determined by subtracting

the calibrated background level from the received level of the corresponding tone (Equation 3). To determine the geometric spreading contribution to transmission loss, we added to the received signal levels the amount of absorption expected for each frequency and range (straight line path, R). Following Francois and Garrison (1982) we used R to calculate the absorption loss at each frequency. For our highest test tone frequencies and range, accounting for absorption added from 2 dB re 1 μ Pa (at 10,000 Hz) to 8.6 dB re 1 μ Pa (at 20,000 Hz) back into the received signal levels.

We used linear regression to model the absorption-corrected received signal levels as a function of the base 10 logarithm of the range from receiver to source in meters separately for each of our test tones. The slopes and goodness of fit are shown in Table 1. Since these slopes are not correlated with the frequency (correlation coefficient of 0.003), we average them and use the resulting near-spherical geometric spreading coefficient (transmission loss coefficient, TL) of -18.6 ± 0.4 dB/decade in $\log_{10}(R)$ to represent geometric spreading out to a distance of about 3 km. Also, as these slopes vary little over a factor of 30 in frequency we assume that we can use this mean slope to extrapolate down from 630 Hz to our 20 Hz lower frequency cutoff and up from 20,000 Hz to our 96,000 Hz upper frequency Nyquist cutoff.

Frequency (kHz)	TL (dB/decade)	coefficient of determination
00.63	-18.85	0.926
01.26	-18.08	0.991
02.51	-18.99	0.986
05.00	-18.24	0.964
10.00	-18.37	0.974
15.00	-19.09	0.987
20.10	-18.67	0.971

Table 1. Results of the transmission loss experiment. For each projected frequency, the geometric spreading rate (TL) is near-spherical, with an average slope of -18.6 ± 0.4 dB/decade.

Source levels

We calculate source spectrum levels of ship noise first by ignoring absorption in equation (4) and then by accounting for it in equation (5), determining α from Francois and Garrison (1982).

$$SL = RL_S + 18.6 \log_{10}(R) \quad (4)$$

$$SL_a = RL_S + 18.6 \log_{10}(R) + \alpha(f)R \quad (5)$$

We integrate the source spectrum levels from 11.5 Hz up to 40,000 Hz to compute broadband source

levels (SL) (Table 2). We also integrate the source spectrum levels over both 1/3-octave and 1/12-octave bands where the centers of octave bands are determined by $f(i) = f_o 2^{\frac{i}{N}}$ where i is an integer and N is the number of partitions of each octave. This is both consistent with ISO center frequencies and allows comparison with the proposed annual mean noise thresholds at 63 and 125 Hz Tasker et al. (2010); Merchant et al. (2014). Finally, when plotting quantiles of levels we exclude the lowest frequency bin (11.5 Hz) because for some classes an insufficient number of ships passed the 4.8 dB re 1 μ Pa signal-noise threshold to estimate the 5% and 95% quantiles.

To facilitate comparison with past studies we generally present ship source spectrum levels as SL . However, due to the presence of high-frequency ship noise in our recordings and its potential impact on marine life exposed at close range, we also present absorption-corrected spectral power levels (SL_a) for the whole ship population.

RESULTS AND DISCUSSION

Ship statistics

Combining all ship classes over the entire study, our data set describes 1,582 unique vessels that made a total of 2,812 isolated, northbound transits of the shipping lanes in Haro Strait (Table 2). The 2,812 isolated transits sample 17.1% of the total transits through Haro Strait (16,357, northbound and southbound) logged by our AIS system during the study period. Of 7,671 total northbound transits, 36% were sampled, suggesting that about 2/3 of the traffic in Haro Strait is not isolated. Dividing the total transits by the 850 day study period shows that the average daily ship traffic is 19.5 ships/day. This amount of traffic is comparable to previous estimates for Haro Strait: about 20 ships/day (Veirs and Veirs, 2006) and about 1 ship/hour (Erbe et al., 2012).

About 1/3 of the isolated transits are bulk carriers and about 1/5 are container ships. The next 4 most prevalent ship classes – tugs, cargo ships, vehicle carriers, and tankers – constitute another 1/3 of the isolated transits. Of the remaining less-prevalent ship classes, we sample military ships 113 times (19 unique vessels), and other ship classes 18 to 65 times.

Together, bulk carriers and container ships comprise more than half (53%) of the isolated shipping traffic in Haro Strait. About 3/4 of isolated bulk carrier transits are unique vessels, in contrast to container ships which are unique only about 40% of the time. This may indicate that the global bulk carrier fleet is larger than the container fleet, or that shipping economics or logistics limit the diversity of container ships transiting Haro Strait. For example, container ships may ply routes that are more fixed, and therefore repeat transits through Haro Strait more frequently than bulk carriers.

Those ship classes that have many isolated transits by a small number of unique ships offer us

opportunities to study variability of noise from individual ships. Military vessels, a category with 19 unique ships sampled on 113 isolated transits, have about 7 isolated transits per unique ship, while tugs and research vessels have about 4 and container ships have about 3.

Ship class	Isolated transits	% of total	Unique ships	RL_S dB	SL dB	SOG m/s	SOG knots
All classes combined	2,812		1,582	111±6	173±7	7.4±2.1	14.4±4.1
Bulk carrier	966	34.3	734	111±6	173±5	7.0±0.7	13.6±1.4
Container	529	18.8	207	116±4	178±4	10.0±1.0	19.5±2.0
Tug	337	12.0	85	108±4	170±5	4.3±1.2	8.3±2.3
Cargo	307	10.9	206	113±5	175±5	7.4±1.0	14.3±1.9
Vehicle carrier	187	6.6	111	113±3	176±3	8.6±1.0	16.8±1.9
Tanker	148	5.3	101	112±4	174±4	7.1±0.7	13.8±1.4
Military	113	4.0	19	103±6	161±10	6.1±2.0	11.9±3.8
Fishing	65	2.3	28	104±5	164±9	4.5±1.1	8.8±2.1
Passenger	49	1.7	31	105±5	166±8	7.7±2.2	14.9±4.3
Miscellaneous	41	1.4	21	103±5	162±9	5.7±2.9	11.1±5.6
Pleasure craft	43	1.5	35	101±6	159±9	6.9±2.9	13.4±5.6
Research	18	0.5	5	105±4	167±5	5.7±1.1	11.1±2.1

Table 2. Ship population statistics and mean broadband sound pressure levels (20-40,000 Hz). Though abbreviated in the table as dB, the units of the received signal levels (RL_S) are dB re 1 μ Pa and source levels have units of dB re 1 μ Pa @ 1 m. Variability is reported as a standard deviation of the mean, and speed over ground (SOG) is provided in m/s and knots.

Broadband levels

Received levels

Broadband population mean received levels (RL_S , Table 2) vary between ship classes from a low of 101 dB re 1 μ Pa (pleasure craft) to a high of 116 dB re 1 μ Pa (container ships). Combining all classes, RL_S is 111±6 dB re 1 μ Pa which is about 20 dB re 1 μ Pa above the mean background level (RL_B) of 91±4 dB re 1 μ Pa. These levels are comparable to anthropogenic and background received levels noted in previous studies at similar distances to shipping lanes and over similar frequency ranges (Veirs and Veirs, 2006; McKenna et al., 2012). While our RL_S from ships 0.95-3.65 km away is 10-20 dB re 1 μ Pa lower than the 121-133 dB re 1 μ Pa reported by Bassett et al. (2012), only about 2 dB re 1 μ Pa of this difference can be explained by the shorter distances to their ships (0.58-2.82 km).

Source levels (SL)

The mean broadband source level (SL , Table 2) for all ship classes combined is 173±7 dB re 1 μ Pa @ 1 m. Comparing between ship classes, container ships have the highest SL at 178 dB re 1 μ Pa @ 1 m. Other classes with $SL \geq 174$ dB re 1 μ Pa @ 1 m include vehicle carriers, cargo ships, tankers, and bulk carriers. Tugs, research, and passenger vessels (primarily cruise ships, as there are no nearby ferry routes) have SL of 166-170 dB re 1 μ Pa @ 1 m, while the remaining vessel classes have SL from

159-164 dB re 1 μ Pa @ 1 m. This range of *SL* across classes (159-178 dB re 1 μ Pa @ 1 m) overlaps the 170-180 dB re 1 μ Pa @ 1 m range specified for small ships (lengths 55-85 m) by Richardson et al. (1995). When frequency dependent absorption is included, mean broadband source levels increase by 0.5-1 dB (we have limited the upper frequency to 40,000 Hz).

Our range of mean values is similar to recent estimates of broadband source levels for similar-sized modern vessels, but for some classes other estimates are 1-11 dB re 1 μ Pa @ 1 m higher than our estimates. Figure 2 depicts broadband *SL* statistics for each class we studied and juxtaposes the results from other studies of modern ships for comparable classes.

Compared with mean broadband source levels (20–30,000 Hz, *TL* of -15, absorption assumed negligible) computed by Bassett et al. (2012) our means are 0-6 dB re 1 μ Pa @ 1 m lower, depending on the class. The comparatively low values of our means cannot be explained by distinct methodology; their study used a narrower broadband bandwidth and a lower (modeled) transmission loss. The most likely explanation for the differences in most classes is a difference in distinct ship design and/or operating characteristics between Puget Sound and Haro Strait populations. There is some evidence that ships measured by Bassett et al. (2012) may have higher speeds than in our study. Of the 24 select ships for which Bassett et al. (2012) provide speed data, 38% have *SOG* greater than 1 standard deviation above our mean values for the corresponding class. The average elevation of *SOG* for those ships is +3.8 knots.

Compared with broadband source levels (20-1000 Hz, *TL* of -20) listed for 29 individual ships by McKenna et al. (2012) the mean values for equivalent classes in Table are 1-13 dB re 1 μ Pa @ 1 m lower. These differences are also depicted in Figure 2. Accounting for the difference in *TL* (1.4 dB/decade of range) between the studies would raise our *SL* values an average of 4.7 dB, thereby causing our inter-quartile range to overlap with or encompass the ranges of McKenna et al. (2012) for all comparable classes except bulk carriers. As with the Bassett et al. (2012) study, adjusting for differences in broadband bandwidth would raise their individual ship source levels even higher above our means, so cannot help explain the differences. Examining the *SOG* differences by class offers less of an explanation in this case; of the 29 ships, only 3 (about 10%) have speeds that exceed our mean *SOG* in the associated class, and only by an average of 1 m/s (about 2 knots).

A study of 593 container ships by McKenna et al. (2013) yielded a mean source level (20-1000 Hz, *TL* of -20) for the population of 185 dB re 1 μ Pa @ 1 m, 5 dB re 1 μ Pa @ 1 m higher than our mean of 180 dB re 1 μ Pa @ 1 m for 716 container ships. While McKenna et al. (2013) do not directly provide speed or range statistics, one figure indicates that speed varied from 4.9-13.6 m/s with a mean of approximately 10.5 m/s – roughly 0.5 m/s above our container ship mean speed of 10.0 m/s. This speed difference could only account for about 0.5 dB re 1 μ Pa @ 1 m of the source level discrepancy between the studies, based

on the 1.1 dB/knot relationship between broadband source level and speed portrayed for a single ship in McKenna et al. (2013).

Compared with broadband source levels (45-7,070 Hz) of individual vessels measured by Malme et al. (1982, 1989) and tabulated by Richardson et al. (1995) our means for respective classes are 1 dB re 1 μ Pa @ 1 m lower than a tug (171 dB re 1 μ Pa @ 1 m at 9.7 knots), 5 dB re 1 μ Pa @ 1 m lower than a cargo ship (181 dB re 1 μ Pa @ 1 m), and 11 dB re 1 μ Pa @ 1 m lower than a large tanker (186 dB re 1 μ Pa @ 1 m). This difference might be due to more modern ships decreasing their speed (at least while in coastal waters) or increasing their propulsion efficiency.

Kipple (2002) measured 6 cruise ships at a range of 500 yards and reported broadband source levels (10-40,000 Hz, *TL* of -20, absorption ignored) of 175-185 dB re 1 μ Pa @ 1 yard at 10 knots and 178-195 dB re 1 μ Pa @ 1 yard at 14-19 knots. In comparison, our population of passenger ships (including cruise ships) has a mean *SL* of 170 ± 8 dB re 1 μ Pa @ 1 m and a mean speed of 14.9 ± 4.3 knots. Thus, our mean *SL* is 5-25 dB re 1 μ Pa @ 1 m lower than the full range reported by Kipple (2002). One possible explanation for the difference is an unspecified upward correction of received levels below 300 Hz that Kipple (2002) made to account for multipath propagation effects. This is substantiated by a statement by Malme et al. (1989) that passenger vessels in Southeast Alaska have *SL* from 170-180 dB re 1 μ Pa @ 1 m, a range that falls between our mean and maximum *SL* for passenger vessels and mostly below the ranges given by Kipple (2002).

Finally, Arveson and Vendittis (2000) measured a bulk carrier at 8-16 knots and found broadband source levels (3-40,000 Hz, *TL* of -20) of 178-192 dB re 1 μ Pa @ 1 m. The levels they recorded for speeds of 12 and 14 knots, 184 dB re 1 μ Pa @ 1 m and 190 dB re 1 μ Pa @ 1 m, respectively, are most comparable to our bulk carrier population with *SOG* of 13.6 ± 1.4 knots. Without correction for the different transmission loss assumptions, our bulk carrier *SL* of 174 ± 5 dB re 1 μ Pa @ 1 m is 10-16 dB re 1 μ Pa @ 1 m below their levels.

While this pattern could be interpreted as an underestimation of *SL* by our methods, we believe our population statistics represent an accurate estimate of source levels for modern ships operating in coastal waterways. In almost all of the cases that we have discussed, the maximum discrepancy is less than 1.5 times the inter-quartile distance (25% vs 75% quantiles) for the comparable ship class (see Figure 2). Exceptions are some of the louder container ships in McKenna et al. (2013) and vehicle carriers in McKenna et al. (2012), the large tanker mentioned in Richardson et al. (1995), the higher-speed cruise ships of Kipple (2002), and the bulk carrier of Arveson and Vendittis (2000) when its speed was greater than 8 knots.

Even these exceptional upper values from the literature are almost completely contained within the

distribution of our broadband *SL* population. Our maximum *SL* for a bulk carrier (191 dB re 1 μ Pa @ 1 m) is 3.6 dB re 1 μ Pa @ 1 m higher than the loudest bulk carrier tabulated in McKenna et al. (2012) and above the bulk carrier source levels obtained by Arveson and Vendittis (2000) at all speeds except 16 knots (192 dB re 1 μ Pa @ 1 m). The loudest bulk carrier tabulated in Bassett et al. (2012) with source level of 182 dB re 1 μ Pa @ 1 m is equal to the 95% quantile of *SL* within our bulk carrier class. The loudest ship tabulated by Richardson et al. (1995), a tanker with *SL* of 186 dB re 1 μ Pa @ 1 m) is only 0.8 dB re 1 μ Pa @ 1 m above our loudest tanker. One explanation for this outlier is that the ship was a supertanker driven by a steam-turbine – and therefore may represent the “upper range of large merchant vessels” (Malme et al., 1989). Finally, our passenger vessel population has a 95% quantile of 177 dB re 1 μ Pa @ 1 m and a maximum of 183 dB re 1 μ Pa @ 1 m, a range that encompasses most of the slow ships and the lower portion of the faster ships assessed by Kipple (2002).

Across all classes, the maximum broadband *SL* for an individual ship was 195 dB re 1 μ Pa @ 1 m for a container ship, 7 dB re 1 μ Pa @ 1 m above the highest overall values reported by McKenna et al. (2012) and Bassett et al. (2012) – both for container ships, as well. Our maximum is consistent with the study of 593 container ships by McKenna et al. (2013) in which the maximum source level was also 195 dB re 1 μ Pa @ 1 m. Our second- and third-highest maxima within a class were from a bulk carrier (191 dB re 1 μ Pa @ 1 m) and a cargo ship (186 dB re 1 μ Pa @ 1 m). All other classes had maximum *SL* $\leq$ 185 dB re 1 μ Pa @ 1 m. The lowest maximum *SL* within a class was 176 dB re 1 μ Pa @ 1 m for pleasure craft.

The range of minimum broadband *SL* across all classes in our study was from 130 dB re 1 μ Pa @ 1 m for a cargo ship to 167 dB re 1 μ Pa @ 1 m for a vehicle carrier. In comparison McKenna et al. (2012) reported a minimum *SL* across all classes of 177 dB re 1 μ Pa @ 1 m for a chemical tanker while the minimum *SL* for a container ship in McKenna et al. (2013) was 176 dB re 1 μ Pa @ 1 m. In contrast with the exact agreement of the maxima between our container ship population and the data set of McKenna et al. (2013), this discrepancy of at least 9-10 dB re 1 μ Pa @ 1 m in *SL* minima suggests that methodological differences between the studies may exert greater bias when ship signal levels are near background noise levels.

Ship speed

Averaged across all vessels, the *SOG* of isolated ships northbound in Haro Strait is $\sim 14.4 \pm 4.1$ knots. This is higher than the mean of 10-12 knots observed during WWII, but possibly lower than the post-war (mid-1970s) mean of about 15 knots (Ross, 1976).

In our study, the fastest classes are container ships (mean *SOG* of 19.5 knots) and vehicle carriers (16.8 knots), while the slowest vessels are fishing boats (8.8 knots) and tugs (8.3 knots). For tankers,

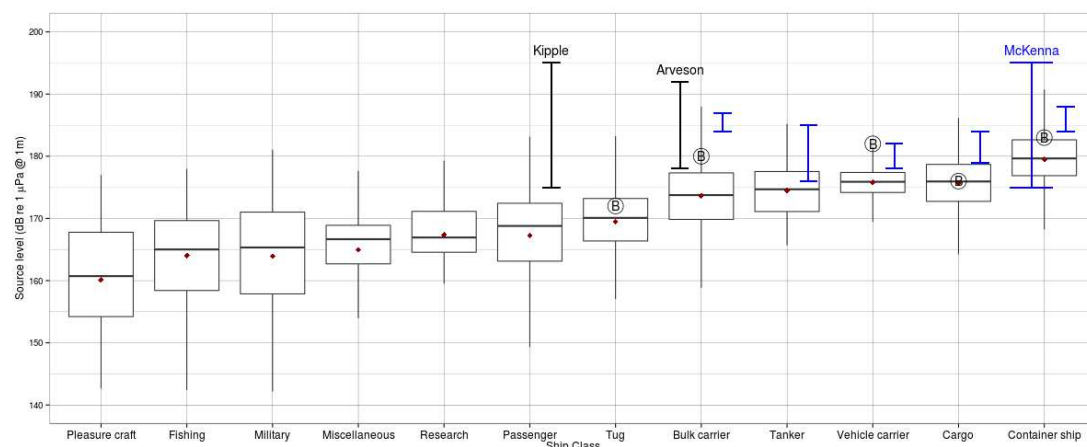


Figure 2. Broadband source level (*SL*) statistics for each ship class juxtaposed with results from recent studies of comparable classes. Bold horizontal lines are medians; gray box hinges are 25% and 75% quantiles; gray whiskers extend to the value that is most distant from the hinge but within 1.5 times the inter-quartile range (distance between the 25% and 75% quantiles); red dots are mean values from Table 2. Each encircled letter B represents a mean from Bassett et al. (2012); blue vertical bars represent means from McKenna et al. (2012) with the container ship estimate of McKenna et al. (2013) labeled McKenna; black vertical bars represent estimates from Kipple (2002) and Arveson and Vendittis (2000).

our *SOG* of 13.8 ± 1.4 knots is slightly below the 14-16 knot range for “T2 tankers” in WWII and the 14-16 knot range for supertankers built after about 1960 reported by (Ross, 1976).

Overall, our data set samples a small range of ship speeds within any given class. Because Haro Strait is relatively long and straight, most vessels transit it without changing speed. Whether north- or south-bound, they have consistent *SOG* means and standard deviations. This low variability in speed limits our ability to search for relationships between noise and speed, but may help us discern in future work the influence of other variables – like propeller type, draft (loading), or maintenance levels – building on insights from McKenna et al. (2013).

Relationship between speed and broadband source level

Upon linear regression of *SL* versus *SOG* for all data, we find a slope of +0.97 dB/knot. Slopes vary from +0.10 to +1.73 dB/knot between vessel classes. Examination of repeated transits of individual ships shows that the variation in slope is high between individual ships within a class. While slopes are positive for most individual ships, some are zero or negative. These variations indicate that the overall population slope should not necessarily be applied to all ship classes or individual ships, echoing the recommendations of McKenna et al. (2012).

Received spectra

Most ships transiting Haro Strait raise background noise levels in the core summertime habitat of SRKWs at all measured frequencies (Figure 3). Specifically, 95% of the ships generate received spectrum levels

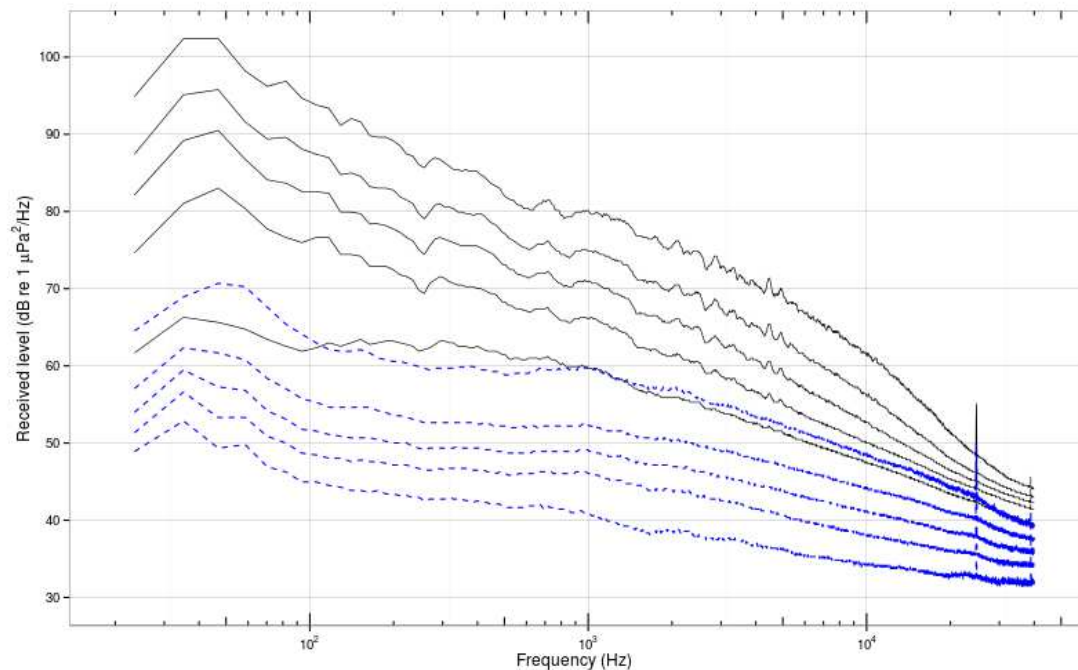


Figure 3. Quantiles (5, 25, 50, 75, & 95%) of background spectrum level (SL_B , dashed blue lines) and total received spectrum level for the entire ship population (SL_T , solid black lines).

at or above the 95% quantile of background levels from 20-96,000 Hz. Thus, at ranges of a couple kilometers, commercial ships cause significant underwater noise pollution not only at low frequencies, but also at high-frequencies.

The difference in median spectrum levels between ship and background noise levels is more than 30 dB re $1 \mu\text{Pa}^2/\text{Hz}$ below 100 Hz and gradually decreases to about 10 dB re $1 \mu\text{Pa}^2/\text{Hz}$ at 20,000 Hz. In the high frequency range of 20,000-96,000 Hz the median ship noise is elevated above median background levels by at least 5 dB re $1 \mu\text{Pa}^2/\text{Hz}$. This significant elevation of background levels at high frequencies is what motivated us to account for absorption when computing ship source levels and is consistent with an observation by Hildebrand et al. (2006) of a single commercial ship in Haro Strait at a range of 442 m that elevated the ambient noise spectrum levels by as much as 30-40 dB re $1 \mu\text{Pa}^2/\text{Hz}$ across a broad band of the spectrum (60-75,000 Hz).

If we define the 5% quantile of background noise as an “ancient” ambient condition (Clark et al., 2009) then the typical (median) modern ship raises noise levels above ancient levels by 12-17 dB re $1 \mu\text{Pa}^2/\text{Hz}$ at frequencies used in killer whale echolocation (20,000-70,000 Hz) and by 17-35 dB re $1 \mu\text{Pa}^2/\text{Hz}$ at frequencies used in killer whale social vocalization (200-20,000 Hz). In the frequency range used by vocalizing baleen whales (20-200 Hz), the median ship noise levels are about 32-35 dB re $1 \mu\text{Pa}^2/\text{Hz}$ above the ancient ambient levels.

We gain additional confidence in the accuracy of our sound pressure levels (and implicitly our system

calibration) by comparing the received spectrum levels in Figure 3 with ambient noise spectra from other studies. Our background quantiles are bracketed by the average deep-water ambient noise levels associated with sea state 1 to 3, though the slope of our median curve from 1,000-10,000 Hz is -8 dB/decade, about half as steep as the open-ocean slope of -17 dB/decade Urick (1983). The “usual lowest ocean noise” curve of Cato depicted in Plate 5 of National Research Council et al. (2003) is bounded by our 5% and 25% quantiles from about 30 to 10,000 Hz. Two ambient noise spectra obtained in Haro Strait by Hildebrand et al. (2006) have levels that are bounded by our 5% and 95% quantiles of background noise from 300 Hz to 30,000 Hz. The single ship spectrum (60 Hz to 75,000 Hz) obtained opportunistically by Hildebrand et al. (2006) at a range of 442 m has levels that are greater than our 75% quantile of RL_B at all frequencies.

Similarly, our quantiles of total received level are consistent with previous studies. For example, the noise spectrum levels recorded in U.S. bays and harbors during World War II by Urick (1983) are entirely bounded by our quantiles of RL_T from 100 Hz to 10,000 Hz. The peak levels (at about 50 Hz) of the shipping contribution to deep water ambient noise estimated by Ross (1976) for “remote, light, moderate, and heavy” traffic are approximately 71, 77, 85, and 95 dB re $1 \mu\text{Pa}^2/\text{Hz}$, respectively; the upper three traffic levels are encompassed by our 5% and 95% quantiles, while the “remote” levels are no more than 2 dB re $1 \mu\text{Pa}^2/\text{Hz}$ below our 5% quantile. Finally, the quantiles of unweighted received spectrum levels in Bassett et al. (2012) peak near 50 Hz and have levels that are within about 5 dB re $1 \mu\text{Pa}^2/\text{Hz}$ of our levels for corresponding quantiles at all frequencies common to the two studies. Even at high-frequencies our data are consistent; Knudsen et al. (1948) reported total received levels of 40-50 dB re $1 \mu\text{Pa}^2/\text{Hz}$ at 30,000 Hz in coastal waters, a range which brackets our quantiles at that frequency.

Source spectra

Median source spectra for the whole ship population are shown in Figure 4 as spectrum, 1/12-octave, and 1/3-octave levels, with and without accounting for absorption. For the spectrum levels, we also present 25% and 75% quantiles.

Source spectrum levels without absorption

The median spectrum levels peak near 50 Hz at about 154 dB re $1 \mu\text{Pa}^2/\text{Hz}$ @ 1 m and decrease at higher frequencies with a slope of about -15 dB re $1 \mu\text{Pa}^2/\text{Hz}$ @ 1 m per decade (from 50-40,000 Hz). The 25% and 75% quantiles are 3-5 dB re $1 \mu\text{Pa}^2/\text{Hz}$ from the median below about 10,000 Hz, but at higher frequencies the difference decreases to about 1 dB re $1 \mu\text{Pa}^2/\text{Hz}$ @ 1 m. In the region between 700 and 40,000 Hz the median spectrum has a subtle slope break near 5,000 Hz, with a slope of about -10 below and about -20 above.

Previous observations, models, and experimental results all help contextualize these whole-population

spectrum levels. Unfortunately, many previous studies of ship noise are not comparable due to presenting species-specific band levels (e.g. Hatch et al. 2012) or band levels rather than spectrum levels, or other limitations: small sample size, non-overlapping frequency ranges, and ship classes with low diversity, distinct definitions, or incomparable ships (e.g. ice breakers in Erbe and Farmer 2000).

One exception that allows comparison up to 1,200 Hz is the analysis of 54 ships at ranges of 360-1,800 m by Wales and Heitmeyer (2002). Their measured average source spectral levels are bounded by our 25% and 75% quantiles from 400-1200 Hz. At lower frequencies (below 400 Hz) their mean levels exceed our 75% quantile by 2-20 dB re $1 \mu\text{Pa}^2/\text{Hz}$ @ 1 m (20 dB re $1 \mu\text{Pa}^2/\text{Hz}$ @ 1 m at 20 Hz; 5 dB re $1 \mu\text{Pa}^2/\text{Hz}$ @ 1 m at 50 Hz; and 2 dB re $1 \mu\text{Pa}^2/\text{Hz}$ @ 1 m at 100 Hz). Interestingly, their curve does peak near 50 Hz, but instead continues rising as the frequency decreases to 30 Hz, the lowest frequency they measured. The slope of their mean curve is about -30 dB/decade below 100 Hz, and -20 dB/decade above. They note that the variance around their mean levels decreases with rising frequency from a standard deviation as high as 5.32 dB re $1 \mu\text{Pa}^2/\text{Hz}$ @ 1 m below 400 Hz to about 3.12 dB re $1 \mu\text{Pa}^2/\text{Hz}$ @ 1 m above it. This suggests that a partial explanation for the elevation of their mean values relative to our 75% quantile may be variability in low-frequency power between ships.

Models of ship noise that output spectrum levels provide another point of comparison. Our 50% and 75% quantiles are encompassed in the spectrum levels presented by National Research Council et al. (2003) for 3 classes of tankers, as well as merchant and fishing classes, based on the RANDI model (Wagstaff, 1973; Breeding et al., 1994) parameterized with data from Emery et al. (2001) and Mazzuca (2001). The 25% quantile is also encompassed, except below 30 Hz. Below 300 Hz, our median values lie between the fishing and merchant class levels of National Research Council et al. (2003); at higher frequencies – up to 1,000 Hz, the upper limit of their estimates – our median values are above their merchant class but below their intermediate tanker class (length 153-214 m, speed 7.7-9.3 m/s). Overall, this comparison suggests that our median spectra validate the RANDI model as parameterized in National Research Council et al. (2003) at intermediate frequencies (100-1,000 Hz), but below 100 Hz our median levels are lower (by about 5-30 dB re $1 \mu\text{Pa}^2/\text{Hz}$ @ 1 m) than the RANDI model predicts for all classes except fishing vessels (length and speed bins of 15-46 m, 3.6-5.1 m/s).

Other noticeable differences between our population median spectrum levels and those modeled in National Research Council et al. (2003) are the frequency of the peak power, the general slope of the spectra above the peak, and secondary peaks resolved in our data. While our spectra peak near 50 Hz, the peak power in the spectra of National Research Council et al. (2003) occurs slightly lower, at 30 Hz. Between 100 and 1,000 Hz, the slope of our median spectrum is -12 dB re $1 \mu\text{Pa}^2/\text{Hz}$ @ 1 m per decade, nearly three times less steep than the slope of -35 dB re $1 \mu\text{Pa}^2/\text{Hz}$ @ 1 m per decade in National

Research Council et al. (2003). Our spectrum levels have detailed structure where the RANDI model curves of National Research Council et al. (2003) are smooth. Our quantiles show secondary power peaks between 80 and 1,100 Hz and many narrowband peaks in 1,100-10,000 Hz range, similar to the frequency dependence of spectral line complexity observed by Wales and Heitmeyer (2002).

Experiments with cavitation provide a final comparison with our whole-population spectrum levels. Above 5,000 Hz the slope of our median spectrum matches the slope observed during cavitation of a spinning rod (Mellen, 1954) and a water jet Jorgensen (1961) – -20 dB re 1 $\mu\text{Pa}^2/\text{Hz}$ @ 1 m per decade, (or -6 dB re 1 $\mu\text{Pa}^2/\text{Hz}$ @ 1 m per octave).

Source spectrum levels with absorption

The spectrum levels with absorption are indistinguishable from those without absorption below about 5,000 Hz. At higher frequencies, the SL_a median spectrum level curve diverges from the SL curve, and starts to rise rapidly at the 40 kHz cut-off of this study. The associated 25% and 75% quantiles are within 3-5 dB re 1 $\mu\text{Pa}^2/\text{Hz}$ @ 1 m of the median values throughout the region of divergence.

While these alternative source spectra look unfamiliar at high frequencies, we believe they are rooted in accurate physics and we note that the spectrum levels of SL_a are in agreement with some measurements and theory of underwater noise radiated during fully developed cavitation. For example, Lesunovskii and Khokha (1968) specify rotating bar noise spectrum levels of 95-115 dB re 1 $\mu\text{Pa}^2/\text{Hz}$ @ 1 m at 10,000 Hz while our 25% to 75% quantiles of SL_a spectrum level at that frequency are 114-120 dB re 1 $\mu\text{Pa}^2/\text{Hz}$ @ 1 m. Similarly, Blake et al. (1977) report noise levels from a cavitating hydrofoil of 75-110 dB re 1 $\mu\text{Pa}^2/\text{Hz}$ @ 1 yd at 31,500 Hz which is approaching our 25% to 75% quantiles of SL_a at that frequency (120-125 dB re 1 $\mu\text{Pa}^2/\text{Hz}$ @ 1 m).

We expect that propeller cavitation noise intensity will be greater than laboratory measurements due to increased length scale and number of the blades on ships. Evidence from World War II studies of torpedo and submarine noise attributed to cavitation supports this expectation. Figures 10.21-10.23 of Urlick (1983) show levels equivalent to or bracketing our SL_a spectrum levels: 24,000 Hz spectrum levels of 118 dB re 1 $\mu\text{Pa}^2/\text{Hz}$ @ 1 yd for a submarine cruising at 8 knots near periscope depth; 25,000 Hz spectrum levels of 100-130 dB re 1 $\mu\text{Pa}^2/\text{Hz}$ @ 1 yd for torpedos moving at 20-45 knots; and 20,000 Hz spectrum levels of 115-130 dB re 1 $\mu\text{Pa}^2/\text{Hz}$ @ 1 yd for a suite of torpedoes.

Source 1/12- and 1/3-octave levels

The median 1/12- and 1/3-octave level curves in Figure 4 are elevated relative to the median spectrum levels and diverge from them above 50 Hz due to the integration of spectrum levels over bands that get progressively wider with increasing center frequency. Like the spectrum levels, these curves have a peak near 50 Hz. Peak values are 158 dB re 1 μPa^2 per band @ 1 m for the 1/12-octave levels and

163 dB re $1 \mu\text{Pa}^2$ per band @ 1 m for the 1/3-octave levels. Above 50 Hz, both curves have slopes of about -4 dB/decade from 100-5,000 Hz, -10 dB/decade from 5,000-40,000 Hz.

While we are unaware of a comparable aggregation of source spectra from multiple ship classes presented as 1/3-octave levels, there are many studies of individual ships or classes that present 1/3-octave source levels. We compare them here with the median 1/3-octave curve for our ship population because we present only spectrum levels when assessing inter- and intra-class differences in subsequent sections.

Our median 1/3-octave levels are entirely bounded by the estimated levels for 6 diverse ship types presented in Figure 3.14 of [Malme et al. \(1989\)](#) at all comparable frequencies (20-16,000 Hz). Similarly, our levels are within the estimated 1/3-octave source levels (10-10,000 Hz) summarized in Figure 6.5 of [Richardson et al. \(1995\)](#) for an ice breaker, a composite of supertankers, and a tug/barge at almost all frequencies. Only above about 2,000 Hz is our median curve slightly below comparable vessels described by [Richardson et al. \(1995\)](#): ours is within 2 dB re $1 \mu\text{Pa}^2$ per 1/3-octave @ 1 m of their tug/barge levels, and no more than 10 dB re $1 \mu\text{Pa}^2$ per 1/3-octave @ 1 m below their supertanker levels. Overall, we find the consistency of our results with these two studies to be remarkable.

Comparing our median curve with the 7 ships (representing five of our classes) for which [McKenna et al. \(2012\)](#) presented 1/3-octave levels, our levels are 5-10 dB re $1 \mu\text{Pa}^2$ per 1/3-octave @ 1 m lower at all common frequencies (20-1,000 Hz). As discussed when presenting spectrum levels, we are not sure how to account for this difference, other than to recognize key differences between the studies: distinct transmission loss, our much larger sample size, and our higher diversity of classes.

Studies of ship noise in which speed was varied present a range of levels that is also consistent with our results. Compared with the maximum-minimum envelopes of 1/3-octave source levels (referenced to 1 yard) from 6 cruise ships presented by [Kipple \(2002\)](#) our 1/3-octave levels are within the envelope for both 10 knot and 14-19 knot samples, except below 25 Hz where our levels are lower by 1-7 dB re $1 \mu\text{Pa}^2$ per 1/3-octave @ 1 m. Our levels also fall within (but near the lower edge) of the range of 1/3-octave spectra reported by [Arveson and Vendittis \(2000\)](#) for a bulk carrier tested from 68-148 rpm.

Our 1/3-octave levels help validate the RANDI model used by [Erbe et al. \(2012\)](#) to compute 1/3-octave spectra for five ship length classes over a range of speeds observed in traffic off the coasts of British Columbia and Washington State. Overall, our median levels are entirely within the range of their estimated levels at all modeled frequencies (10-2,000Hz). More specifically, though, our median crosses their size-specific curves, because it has a less steep slope. Below 400 Hz our levels are bounded by their L1 and L3 classes (representing lengths less than 50 m); above 400 Hz our median levels are between their L4 and L5 classes (greater than 50 m).

An even more dramatic crossing of model curves by our median curve is evident upon comparison

with Figure 1 of Williams et al. (2014). While our median source levels are equivalent to or bounded by the 1/3-octave levels for each of their modeled ship types (tug, cruise ship, container ship) near or below 250 Hz, at higher frequencies our levels exceed the modeled ones by 7-10 dB re $1 \mu\text{Pa}^2$ per 1/3-octave @ 1 m.

The crossing of such modeled spectra by our 1/3-octave median curve is one manifestation of a subtle slope difference between our results and previous studies (Arveson and Vendittis, 2000; Kipple, 2002; Erbe et al., 2012; Williams et al., 2014). While Arveson and Vendittis (2000) observe slopes from above a 55 Hz cavitation “hump” up to about 30,000 Hz to be -10 dB/decade on a 1/3-octave plot, our slope over the same frequency range is shallower (-6.5 dB/decade) and we observe a slope break near 3,000 Hz. Below the break the slope is about -4.5 dB/decade, while above it is -10 dB/decade.

The similarity of our 1/3-octave levels with those from available studies at frequencies below 630 Hz (the lowest tone used in our transmission loss experiment) is the first evidence that our measurements of low-frequency radiated noise are accurate. The lower slope relative to other studies suggests that the ship population in this study is generating proportionally more high-frequency noise than ships in previous studies.

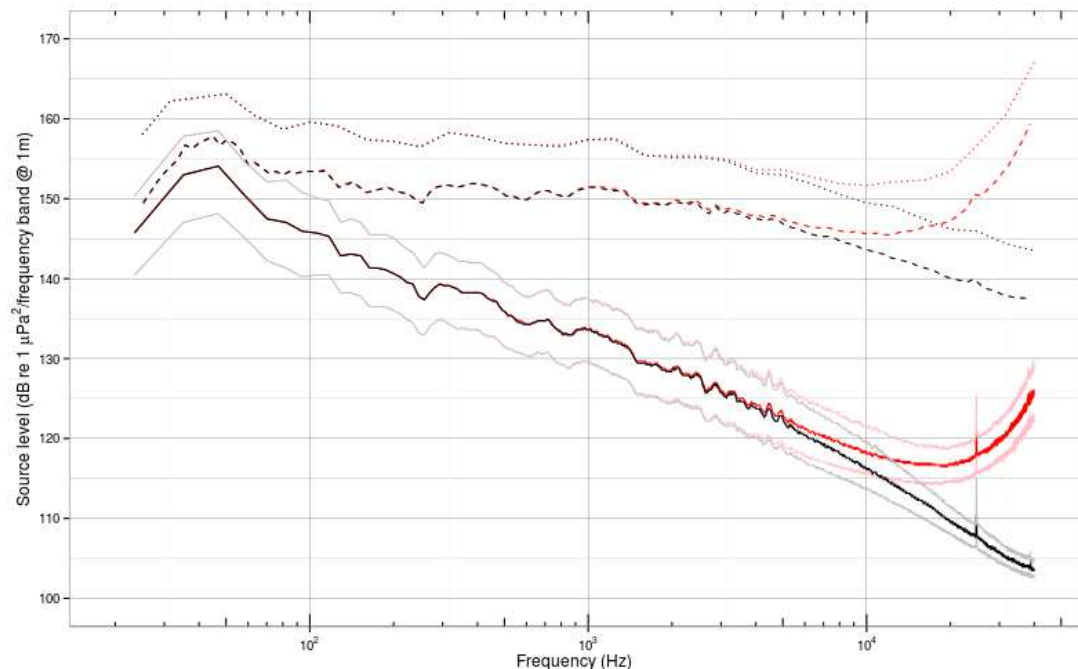


Figure 4. Source level (SL) spectra of the entire ship population in 1 Hz (solid), 1/12-octave (dashed), and 1/3-octave bands (dotted). Black curves are medians without absorption; red curves are medians with absorption. For the spectrum levels, we delineate 25 and 75% quantiles in lighter tones. Levels with absorption start to increase rapidly above 15-20 kHz for both the 1/12- and 1/3-octave bands.

620 **Source 1/12- and 1/3-octave levels with absorption**

621 As with the spectrum levels, the 1/12- and 1/3-octave level curves with absorption are indistinguishable
622 from those without absorption below 5,000 Hz. At higher frequencies, the SL_a median 1/12- and 1/3-
623 octave levels rise to match the 50 Hz levels of the associated median SL curves near 35,000 Hz and then
624 continue to increase at higher frequencies.

625 This means that when we account for absorption when computing 1/12- or 1/3-octave levels, modern
626 ships radiate noise in high-frequency bands (centered near 35,000 Hz) at levels equivalent to the low-
627 frequency maxima near 50 Hz. This surprising equivalency, and the theoretically even higher power levels
628 in bands above 35,000 Hz, are important to consider when assessing the masking potential of ship noise
629 in habitats close to or within shipping lanes for marine species that utilize high-frequency signals. Though
630 it is novel to state that ship noise source levels have peak power at high- as well as low-frequencies, we
631 provide these 1/12- and 1/3-octave noise levels to facilitate accurate modeling of acoustic impacts for
632 species that have critical bands overlapping these octave bands Richardson et al. (1995).

633 While the median 1/12-octave source levels reported by Erbe and Farmer (2000) for the cavitating
634 propeller of an ice breaker are not comparable to any of our ship classes, we note that the slope of their
635 median curve is -13 dB/decade from 1,000-10,000 Hz. Importantly, Erbe and Farmer (2000) is rare in
636 stipulating that absorption was accounted for in computing source levels. Their slope is about twice as
637 steep as our 1/12-octave median slope of -7 dB/decade in the same frequency range.

638 **Spectral differences between ship classes**

639 When the ship population is broken down by class (Figure 5) the medians show a striking bifurcation.
640 While all classes have similar median spectrum levels near 20,000 Hz, the curves diverge at lower
641 frequencies, and below 200 Hz they bifurcate into high- and low-power groups. The high-power group
642 has peak power of 153-159 dB re $1 \mu\text{Pa}^2/\text{Hz}$ @ 1 m near 50 Hz (just above the population median shown
643 in Figure 4) and consists of container ships, vehicle carriers, cargo ships, bulk carriers, and tankers. The
644 low-power group has peak power of 134-141 dB re $1 \mu\text{Pa}^2/\text{Hz}$ @ 1 m near 50 Hz or just above 100 Hz –
645 levels well below the population median or even 25% quantile – and consists of passenger vessels, tugs,
646 military, research, fishing, miscellaneous, and pleasure vessels.

647 The 25%, median, and 75% spectrum levels at the power peak near 50 Hz in Figure 4 bracket the
648 50 Hz levels of the high-power group of ships in Figure 5. The median of the whole population is most
649 similar to the spectra in the high-power group (e.g. the bulk carrier curve) because the aggregated sample
650 size is much higher in the high-power group than in the low-power one (see Table 2). Modelers interested
651 in assessing impacts of specific ship classes, particularly those in the lower-power group, should not use
652 the median or 25% quantile levels for the whole population, but instead select class-specific levels from

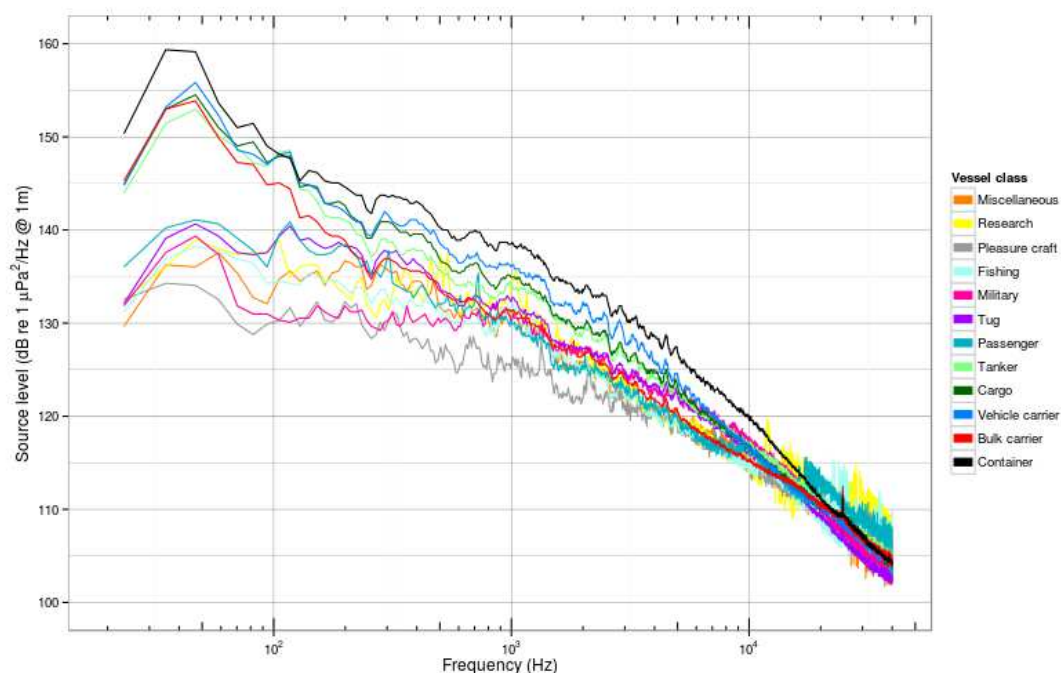


Figure 5. Comparison of median source spectrum levels (without absorption) between ship classes.

the curves in Figure 5.

Container ships have the highest median power of all classes at almost all frequencies below 10,000 Hz with peak power of 159 dB re 1 $\mu\text{Pa}^2/\text{Hz}$ @ 1 m near 40 Hz. This is likely because of their relatively large size and high mean speed (10 m/s) compared to pleasure craft or military ships – the classes with the lowest median power at all frequencies below 400 Hz.

Many of the ship classes show secondary peaks in the median spectrum levels from 100-5,000 Hz. For example, most classes show a 2 dB re 1 $\mu\text{Pa}^2/\text{Hz}$ @ 1 m dip near 250 Hz and at least container ships, vehicle carriers, cargo ships, and tankers have peaks near 300, 700, and 1,000 Hz. There are also narrower peaks for these same classes between 1,000-10,000 Hz, most prominently at 2,000 Hz and near 3,000 Hz.

The variability of the median source level in each class decreases above 5,000 Hz and remains low until about 10,000 Hz. At higher frequencies (10,000-40,000 Hz) the variability increases again for most ship classes, but the degree of increase is a strong function of sample size within a class. While we know from examining spectrograms from individual ships that some of the narrow peaks are associated with active acoustic sources (depth sounders, scientific echosounders, and fish finders), in Figure 5 the high variance above 10,000 Hz is due primarily to some ships having spectrum levels that do not meet the robust threshold at higher frequencies. Particularly in classes where the sample size is already small this leads to some high frequency bins having many fewer data points than adjacent bins which in turn results in more-variable median values across this high-frequency range.

671 The quantiles of source level by class in Figure 6 provide further detail about inter-class differences.
672 Comparing the 95% quantiles, container ships still have the highest peak power (165 dB re $1 \mu\text{Pa}^2/\text{Hz}$ @ 1 m)
673 near 50 Hz, but bulk and vehicle carriers, cargo ships and tankers also have peak power greater than
674 160 dB re $1 \mu\text{Pa}^2/\text{Hz}$ @ 1 m. Other classes have peak power in the 95% quantiles near 50 Hz at spectrum
675 levels that range from 156 dB re $1 \mu\text{Pa}^2/\text{Hz}$ @ 1 m (research) to 150 dB re $1 \mu\text{Pa}^2/\text{Hz}$ @ 1 m (tugs).
676 Comparing the 5% quantiles, we expected that the military class would have the lowest levels due to more
677 advanced ship-quieting technologies. While the military class levels are much lower than container ships
678 (10 dB re $1 \mu\text{Pa}^2/\text{Hz}$ @ 1 m less at 1,000 Hz and 20 dB re $1 \mu\text{Pa}^2/\text{Hz}$ @ 1 m less at 100 Hz), other
679 classes have even lower levels at those frequencies, particularly fishing vessels and pleasure craft.

680 ***Spectral variability within ship classes***

681 All classes of ships have spectrum levels that vary more at low frequencies than at high frequencies
682 (Figure 6). Near 50 Hz there is a 15-35 dB re $1 \mu\text{Pa}^2/\text{Hz}$ @ 1 m difference between the 5% and 95%
683 quantile levels. That difference decreases with rising frequency until above 20,000 Hz it is typically less
684 than 10 dB re $1 \mu\text{Pa}^2/\text{Hz}$ @ 1 m.

685 Below 20,000 Hz, source level variability in Figure 6 tends to be lower for the classes that have
686 smaller speed over ground standard deviations and that have larger sample size as shown in Table 2.
687 While container and cargo ships, bulk and vehicle carriers, and tankers have 95-5% spectrum level
688 differences of about 15 dB re $1 \mu\text{Pa}^2/\text{Hz}$ @ 1 m, the other classes exhibit larger differences up to
689 25-30 dB re $1 \mu\text{Pa}^2/\text{Hz}$ @ 1 m. The classes with the largest number of vessels are most uniform in
690 their speed over ground and most consistent in their vessel design and operation. Tugs are a special
691 case because there are many transits and their speed is not unusually variable, but their loading is. Our
692 passenger vessels are all cruise ships and hence similar in design, but their speeds are quite variable as
693 they adjust their arrival times in the Port of Vancouver. Finally, the small numbers of pleasure craft and
694 vessels classed as miscellaneous are highly variable in both their designs and their operations.

695 Other studies have observed a similar pattern of source level variability with frequency. In mean
696 source spectrum levels from 54 ships Wales and Heitmeyer (2002) noted higher, more-variable standard
697 deviations from 30-400 Hz and lower, more-constant ones from 400-1200 Hz. Figure 8 of McKenna et al.
698 (2013) displays histograms of octave-band power for 593 container ships which have widths that decrease
699 from about 35 dB re $1 \mu\text{Pa}^2$ per octave @ 1 m in the 16 Hz band to 26 dB re $1 \mu\text{Pa}^2$ per octave @ 1 m in
700 the 500 Hz band.

701 One explanation for this pattern is that the low-frequency portion of ship noise spectra is influenced
702 by diverse design and operational details (many sources of variability), while cavitation generates high-
703 frequency broadband noise (including up to 100,000 Hz) no matter its source. As mentioned in the

introduction, there are many sources of ship noise below 1,000 Hz that should be expected to vary between individual ships in a particular class. Conversely, a wide range of vessels have been documented to radiate elevated high-frequency noise upon increased engine RPM or SOG – conditions reasonably associated with increased cavitation (Erbe and Farmer, 2000; Kipple, 2002; Hildebrand et al., 2006).

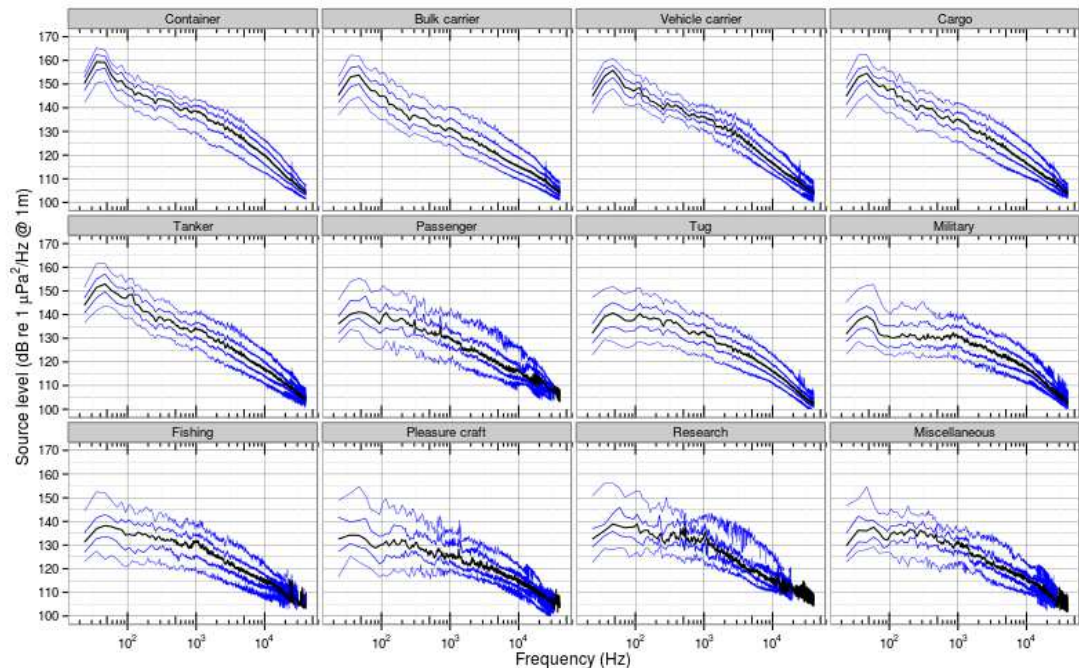


Figure 6. Quantiles of source spectrum levels for each class of ship. Median (50%) quantile (black) overlies 5, 25, 75, and 95% quantiles (blue).

The literature offers a handful of spectra for particular classes that can be compared with the quantiles of Figure 6. These spectra typically come from individual ships, though, so can only serve to verify the range of our quantiles, rather than assessing the accuracy of the quantiles themselves.

The spectrum levels provided by McKenna et al. (2012) for individual ships in comparable classes (a container ship, a vehicle carrier, two bulk carriers, and a few tankers) all fall within a few dB re $1 \mu\text{Pa}^2 @ 1 \text{ m}$ of our 95% quantile. Only their bulk carrier deviates from this pattern with levels near 100 Hz higher by about 10 dB re $1 \mu\text{Pa}^2/\text{Hz} @ 1 \text{ m}$. Overall, the broadband and spectrum levels of ships associated with the port of Los Angeles (McKenna et al., 2012) are most comparable to the noisiest 5% of ships transiting Haro Strait.

Similarly, the source spectrum levels for a single container ship measured in the middle of Haro Strait by Hildebrand et al. (2006) also fall within the 5% and 95% quantiles of our cargo class (from 90 Hz to 40,000 Hz). The alignment of such individual ship spectra within the quantiles of their associated class at all common frequencies – and most importantly at frequencies below that of our lowest transmission loss test tone – helps verify our extrapolation of the near-spherical spreading we observed from 630-20,100 Hz

722 to all frequencies reported in our study.

723 We take this spectral consistency across multiple classes as evidence that the ship noise received at our
724 nearshore hydrophone has not undergone shallow water attenuation. While normal mode theory (Urlick,
725 1983) would predict a cutoff frequency of about 50 Hz if our hydrophone were in a shallow channel 8 m
726 deep, that is not the bathymetric situation at our study site. Instead, Haro Strait is a 250-300 m deep
727 channel with a steep western wall of sparsely sedimented solid rock (Jones and Wolfson, 2006) and our
728 hydrophone is positioned near the top of the wall where the offshore bottom slope is 20-30 degrees. In this
729 situation, Jones and Wolfson (2006) expect not only destructive interference at ranges much greater than
730 the source depth, but also upslope enhancement. In our transmission loss experiment, we did not observe
731 any frequency dependent attenuation consistent with these phenomena. Furthermore, the theoretical
732 cutoff frequency for a 250 m deep channel is 1.5 Hz (Urlick, 1983), well below our lowest measured
733 frequency band. We therefore argue that any effects of interference and backscatter are averaged out in
734 our study, primarily because each isolated ship ensonifies the full width of this reverberating channel and
735 moves 150-300 m during a 30-second recording (1-2 times the 130 m wavelength or our lowest measured
736 frequency, 11.5 Hz).

737 CONCLUSIONS

738 Having ensured our samples were isolated (uncontaminated by noise from other ships or boats) and
739 subtracted estimated background levels, we are confident that median received levels of ship noise in the
740 core of SRKW critical habitat are elevated above median background levels not only at low frequencies
741 (20-30 dB re 1 $\mu\text{Pa}^2/\text{Hz}$ from 100-1000 Hz), but also at high frequencies (5-13 dB re 1 $\mu\text{Pa}^2/\text{Hz}$ from
742 10,000-40,000 Hz). Thus, underwater noise radiated by modern ships extends to high frequencies just as
743 boat noise does (Erbe, 2002; Kipple and Gabriele, 2004; Hildebrand et al., 2006). Earlier studies have
744 also observed this aspect of ship noise, but with smaller sample size, over different frequency ranges and
745 less diverse ship classes (Kipple and Gabriele, 2004; Hildebrand et al., 2006; Bassett et al., 2012), and/or
746 in received rather than source levels (Hermannsen et al., 2014).

747 Such ship noise has the potential to mask odontocete signals, especially in coastal environments
748 where shipping lanes are close enough to the shoreline (< 10 km) that high frequency sound is not fully
749 absorbed. In the summertime habitat of the endangered SRKWs ship noise may interfere not only with
750 SRKW communication (vocalizations) but also foraging and navigation (echolocation clicks).

751 Average broadband received levels (11.5-40,000 Hz) for the entire ship population are 111 ± 6 dB re 1 μPa
752 and ranged from 101 ± 6 dB re 1 μPa for pleasure craft to 116 ± 4 dB re 1 μPa for container ships. The
753 range of *RL* for container ships (112-120 dB re 1 μPa) show that levels received by SRKWs along the

754 coastline at Lime Kiln from some container ships occasionally meet or exceed the 120 dB re 1 μ Pa
755 threshold currently used by NOAA to define level B harassment from non-impulsive noise in the U.S.

756 Ships northbound in Haro Strait exhibit typical speeds with low variability (*SOG* of 14.4 ± 4.1 knots
757 or 7.4 ± 2.1 m/s). Nevertheless, there is enough variation in speed across the whole population to reveal
758 a linear relationship between received level and speed with a slope near +1 dB/knot. This suggests
759 a potential mitigation strategy for the average ship – slowing down – that has been recommended
760 previously as an operational ship quieting option (?). This strategy has other environmental benefits,
761 like reducing collision risks, and is consistent with recent industry efforts to increase fuel efficiency
762 (e.g. the “slow steaming” initiative of Maersk). For a passenger ship measured at speeds of 9-18 knots
763 during WWII Ross (1976) shows in Figure 8.19 that reducing speed lowers source spectrum levels by
764 at about 1.5 dB re 1 μ Pa @ 1 m per knot at all frequencies, but most notably lowers them by about
765 3.0 dB re 1 μ Pa @ 1 m per knot – both at high frequencies (above 10,000 Hz) and at low frequencies
766 (less than 100 Hz).

767 Average broadband source levels were 173 ± 7 dB re 1 μ Pa @ 1 m for the population. Comparing
768 broadband source levels between ship classes, container ships have the highest mean *SL* of
769 178 ± 4 dB re 1 μ Pa @ 1 m. Therefore, assuming near-spherical transmission loss, marine life within a
770 couple kilometers of shipping lanes will commonly receive noise levels above NOAA’s 120 dB re 1 μ Pa
771 threshold. At ranges less than about a kilometer, receive levels from many ships in Haro Strait will exceed
772 the 130-150 dB modeled ship noise (10-50,000 Hz) dose associated with minor changes in northern
773 resident killer whale behavior (Williams et al., 2014).

774 At distances of less than about a kilometer, it is likely that received 1/12- or 1/3-octave band levels at
775 high frequencies are equal or greater than they are at low frequencies. Further research should be carried
776 out to measure ship spectrum levels at ranges of a few hundred meters in order to more fully quantify the
777 high frequency (40-100 kHz) components of ship sound signatures.

778 Models of noise impacts in habitat containing shipping lanes will be more accurate if parameterized
779 with spectral data, as opposed to broadband levels. Since we observe spectral variability between and
780 within the 12 classes of vessels in this study, most prominently the bifurcation at low frequencies between
781 classes, such models should use the class-specific spectrum level quantiles if possible, rather than the
782 whole-population spectrum and band level medians we have presented.

783 Our broadband, spectrum, 1/12-octave, and 1/3-octave source levels for the whole population have
784 median values that are comparable to the literature, with a few exceptions that we believe are due primarily
785 to methodological differences. Some past analyses may not have made all recommended corrections
786 (TC43 Acoustics, 2012); most commonly, methods sections are ambiguous about the definition and

787 subtraction of background noise levels from total received levels prior to source level computations. It is
788 also possible that these exceptions are due to sampling ship populations that are distinct (being composed
789 of different individual ships/classes and/or operating differently). In any case, since our source level
790 quantiles have slightly lower levels than some studies, particularly at low frequencies, they can be taken
791 as a conservative characterization of the current fleet when developing ship noise models or policies.

792 One subtle pattern we note is that compared to some previous measurements and models, our median
793 source spectrum levels are relatively low below 200 Hz and relatively high above 20,000 Hz. One
794 implication of this is that noise models using previous measurements may overestimate the low-frequency
795 noise levels of some ship types and underestimate high-frequency noise levels. Such flattening of the
796 spectral slope in more modern ships is described in Figure 8.20 of Ross (1976) which shows spectrum
797 levels (below 100 Hz and from 1,000-20,000 Hz) elevated 1-3 dB re $1 \mu\text{Pa}^2/\text{Hz}$ @ 1 m in large populations
798 of post-War versus WWII-era vessels. Some studies show a flattening of spectra above 100-1,000 Hz as
799 ship and engine speed increases (Ross, 1976; Arveson and Vendittis, 2000; Kipple, 2002). We speculate
800 that this historical trend may be continuing and recommend further investigation of the evolution of both
801 ship speed (Leaper et al., 2014) and the mitigation of low-frequency internal noise on ships for human
802 health reasons.

803 We recommend that future ship noise studies statistically characterize populations of ships – both
804 their broadband and spectrum source levels. Having struggled to discern which studies in the literature are
805 comparable to our results, we also suggest that future method sections be explicit about ship classification,
806 calibration procedures, background subtraction and/or criteria for isolation from other sources, models
807 and/or measurements of transmission loss, band width(s) and centers, absorption, and any other corrections.
808 Metadata should include statistical representations of ship speeds and measurement ranges.

809 Future work should also assess covariates other than speed, such as size, as well as azimuthal and
810 temporal variability in source spectrum levels. We know from years of listening to live audio streams
811 of Salish Sea ship noise (free via orcasound.net) that there is great temporal variability in the noise
812 radiated by many ships. A small percentage of ships emit periodic strong mid-frequency tones that are
813 likely caused by singing propellers (Ross, 1976). Our next step is to explore such temporal variations
814 in amplitude and frequency, identify statistical outliers that may represent extreme masking cases, and
815 further investigate possible governing variables, including speed, class, azimuth, and loading.

816 The variability we observe within ship classes indicates opportunities for reducing noise in ships,
817 particularly those associated with the upper quantiles in each class. While the details of the spectral and
818 temporal variability of noise from an individual ship may be important to a receiving species, metrics for
819 measuring and regulating underwater noise will practically involve some temporal averaging, and possibly

integration over bands wider than 1 Hz. We suggest a reasonable time scale for averaging ship noise is seconds or minutes, rather than a year as stipulated in the European Union's Marine Strategy Framework Directive 2008/56/EC (Tasker et al., 2010). Additionally, based on the received signal above background noise that we observe at high frequencies, we recommend that future guidelines for monitoring ship noise raise the upper frequency limit of recording systems from 20,000 Hz (Dekeling et al., 2014) to at least 50,000 Hz. As Registered Ship Classification Societies continue to issue underwater radiated noise notations, we hope that these data can be used to assess their validity.

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REFERENCES

- Aguilar Soto, N., Johnson, M., Madsen, P. T., Tyack, P. L., Bocconcelli, A., and Fabrizio Borsani, J. (2006). Does intense ship noise disrupt foraging in deep-diving Cuvier's beaked whales (*Ziphius cavirostris*)? *Marine Mammal Science*, 22(3):690–699.
- Andrew, R. K., Howe, B. M., Mercer, J. A., and Dzieciuch, M. A. (2002). Ocean ambient sound: comparing the 1960s with the 1990s for a receiver off the California coast. *Acoustics Research Letters Online*, 3(2):65–70.
- Arveson, P. T. and Vendittis, D. J. (2000). Radiated noise characteristics of a modern cargo ship. *The Journal of the Acoustical Society of America*, 107(1):118–129.
- Au, W. W., Pack, A. A., Lammers, M. O., Herman, L. M., Deakos, M. H., and Andrews, K. (2006). Acoustic properties of humpback whale songs. *The Journal of the Acoustical Society of America*, 120(2):1103–1110.

- 851 Au, W. W. L., Ford, J. K. B., Horne, J. K., and Allman, K. A. N. (2004). Echolocation signals of
852 free-ranging killer whales (*Orcinus orca*) and modeling of foraging for chinook salmon (*Oncorhynchus*
853 *tshawytscha*). *The Journal of the Acoustical Society of America*, 115(2):901.
- 854 Ayres, K. L., Booth, R. K., Hempelmann, J. a., Koski, K. L., Emmons, C. K., Baird, R. W., Balcomb-
855 Bartok, K., Hanson, M. B., Ford, M. J., and Wasser, S. K. (2012). Distinguishing the Impacts of
856 Inadequate Prey and Vessel Traffic on an Endangered Killer Whale (*Orcinus orca*) Population. *PLoS*
857 *ONE*, 7(6):e36842.
- 858 Bassett, C., Polagye, B., Holt, M., and Thomson, J. (2012). A vessel noise budget for Admiralty Inlet,
859 Puget Sound, Washington (USA). *The Journal of the Acoustical Society of America*, 132(6):3706–3719.
- 860 Blake, W. K., Wolpert, M. J., and Geib, F. E. (1977). Cavitation noise and inception as influenced by
861 boundary-layer development on a hydrofoil. *Journal of Fluid Mechanics*, 80(04):617–640.
- 862 Breeding, J. E., Pflug, L. A., Bradley, M., Hebert, M., and Wooten, M. (1994). RANDI 3.1 User's Guide.
863 Technical report, DTIC Document. 00009.
- 864 Buckstaff, K. C. (2004). Effects of watercraft noise on the acoustic behavior of bottlenose dolphins,
865 *Tursiops truncatus*, in Sarasota Bay, Florida. *Marine Mammal Science*, 20(October):709–725.
- 866 Cerchio, S., Jacobsen, J. K., and Norris, T. F. (2001). Temporal and geographical variation in songs of
867 humpback whales, *Megaptera novaeangliae*: synchronous change in Hawaiian and Mexican breeding
868 assemblages. *Animal behaviour*, 62(2):313–329.
- 869 Clark, C. W., Ellison, W., Southall, B., Hatch, L., Van Parijs, S., Frankel, A., and Ponirakis, D. (2009).
870 Acoustic masking in marine ecosystems: intuitions, analysis, and implication. *Marine Ecology Progress*
871 *Series*, 395:201–222.
- 872 Dekeling, R., Tasker, M., Graaf, S. V. D., Ainslie, M., Andersson, M., André, M., Borsani, J. F., Brensing,
873 K., Castellote, M., Cronin, D., Dalen, J., Folegot, J., Leaper, R., Pajala, J., Redman, P., Robinson, S. P.,
874 Sigray, P., Sutton, G., Thomsen, F., Werner, S., Wittekind, D., and Young, J. V. (2014). Monitoring
875 Guidance for Underwater Noise in European Seas-Part II: Monitoring Guidance Specifications. JRC
876 Scientific and Policy Report UR 26555 EN, Publications Office of the European Union, Luxembourg.
- 877 Dow, M. T., Emling, J. W., and Knudsen, V. O. (1945). Survey of Underwater Sound No. 4: Sounds from
878 Surface Ships. *National Defense Research Committee, Div, 6*.
- 879 Emery, L., Bradley, M., and Hall, T. (2001). Data base description (DBD) for the historical temporal
880 shipping data base (HITS), Version 4.0. *Planning Systems Incorporated*, pages 1–40. 00010.
- 881 Erbe, C. (2002). Underwater noise of whale-watching boats and potential effects on killer whales (*Orcinus*
882 *orca*), based on an acoustic impact model. *Marine Mammal Science*, 18(2):394–418.
- 883 Erbe, C. (2010). *Underwater acoustics: Noise and the effects on marine mammals*. Pocketbook, printed

- 884 by JASCO Applied Sciences, Brisbane, QLD, Australia.
- 885 Erbe, C. and Farmer, D. M. (2000). Zones of impact around icebreakers affecting beluga whales in the
- 886 Beaufort Sea. *The Journal of the Acoustical Society of America*, 108:1332.
- 887 Erbe, C., MacGillivray, A., and Williams, R. (2012). Mapping cumulative noise from shipping to inform
- 888 marine spatial planning. *The Journal of the Acoustical Society of America*, 132(5):EL423–EL428.
- 889 Ford, J. K. B. (1987). A catalogue of underwater calls produced by killer whales (*Orcinus orca*) in British
- 890 Columbia. Technical report, Department of Fisheries and Oceans.
- 891 Ford, J. K. B. and Ellis, G. M. (2006). Selective foraging by fish-eating killer whales. *Marine Ecology*
- 892 *Progress Series*, 316:185–199.
- 893 Francois, R. E. and Garrison, G. R. (1982). Sound absorption based on ocean measurements. Part II:
- 894 Boric acid contribution and equation for total absorption. *The Journal of the Acoustical Society of*
- 895 *America*, 72(6):1879–1890.
- 896 Gray, L. M. and Greeley, D. S. (1980). Source level model for propeller blade rate radiation for the
- 897 world's merchant fleet. *The Journal of the Acoustical Society of America*, 67(2):516–522.
- 898 Hall, J. D. and Johnson, C. S. (1972). Auditory thresholds of a killer whale *Orcinus orca* Linnaeus. *The*
- 899 *Journal of the Acoustical Society of America*, 51(2B):515–517.
- 900 Hanson, M. B., Baird, R. W., Ford, J. K. B., Hempelmann-Halos, J., Van Doornik, D., Candy, J., Emmons,
- 901 C. K., Gregory Schorr, Brian Gisborne, Katherine Ayres, Samuel Wasser, Kelley Balcomb-Bartok, John
- 902 Sneva, and Michael Ford (2010). Species and stock identification of prey consumed by endangered
- 903 southern resident killer whales in their summer range. *Endangered Species Research*, 11:69–82.
- 904 Hatch, L. T., Clark, C. W., Van Parijs, S. M., Frankel, A. S., and Ponirakis, D. W. (2012). Quantifying
- 905 loss of acoustic communication space for right whales in and around a U.S. National Marine Sanctuary.
- 906 *Conservation Biology*.
- 907 Hauser, D. D. W., Logsdon, M. G., Holmes, E. E., VanBlaricom, G. R., and Osborne, R. W. (2007).
- 908 Summer distribution patterns of southern resident killer whales *Orcinus orca*: core areas and spatial
- 909 segregation of social groups. *Marine Ecology Progress Series*, 351:301–310.
- 910 Hermannsen, L., Beedholm, K., Tougaard, J., and Madsen, P. T. (2014). High frequency components of
- 911 ship noise in shallow water with a discussion of implications for harbor porpoises (*Phocoena phocoena*).
- 912 *The Journal of the Acoustical Society of America*, 136(4):1640–1653.
- 913 Hildebrand, J., McDonald, M. A., Calambokidis, J., and Balcomb, K. (2006). Whale watch vessel ambient
- 914 noise in the Haro Strait. Technical Report MPL TM-490.
- 915 Hildebrand, J. A. (2009). Anthropogenic and natural sources of ambient noise in the ocean. *Marine*
- 916 *Ecology Progress Series*, 395:5–20.

- 917 Holt, M. M., Noren, D. P., Veirs, V., Emmons, C. K., and Veirs, S. (2009). Speaking up: Killer whales
918 (Orcinus orca) increase their call amplitude in response to vessel noise. *The Journal of the Acoustical*
919 *Society of America*, 125(1):EL27.
- 920 Jones, C. D. and Wolfson, M. A. (2006). Acoustic environment of Haro Strait: Preliminary propagation
921 modeling and data analysis. Technical report, DTIC Document.
- 922 Jorgensen, D. W. (1961). Noise from Cavitating Submerged Water Jets. *The Journal of the Acoustical*
923 *Society of America*, 33(10):1334–1338.
- 924 Kipple, B. (2002). Southeast Alaska Cruise Ship Underwater Acoustic Noise. Technical Report NSWCCD-
925 71-TR-2002/574, Naval Surface Warfare Center – Detachment Bremerton.
- 926 Kipple, B. and Gabriele, C. (2004). Underwater noise from skiffs to ships. In *Proc. of Glacier Bay*
927 *Science Symposium*.
- 928 Knudsen, V. O., Alford, R. S., and Emling, J. W. (1948). Underwater ambient noise. *J. Mar. Res.*, 7.
- 929 Leaper, R., Renilson, M., and Ryan, C. (2014). Shhh... do you hear that? *Journal of Ocean Technology*,
930 9(1):20.
- 931 Lesunovskii, V. P. and Khokha, Y. V. (1968). Characteristics of the noise spectrum of hydrodynamic
932 cavitation on rotating bars in water. *Akust. Zh*, 14:566–571.
- 933 Malme, C. I., Miles, P. R., and McElroy, P. T. (1982). The acoustic environment of humpback whales in
934 Glacier Bay and Frederick Sound/Stephens Passage, Alaska. Bolt, Baranek, and Newman, Inc. 4848,
935 NMFS/MML.
- 936 Malme, C. I., Miles, P. R., Miller, G. W., Richardson, W. J., Roseneau, D. J., Thomson, D. H., and
937 Greene Jr, C. R. (1989). Analysis and ranking of the acoustic disturbance potential of petroleum
938 industry activities and other sources of noise in the environment of marine mammals. Technical Report
939 6945, BBN Systems and Technologies Corporation.
- 940 Mazzuca, L. L. (2001). *Potential effects of low frequency sound (LFS) from commercial vessels on large*
941 *whales*. PhD thesis, University of Washington. 00009.
- 942 McDonald, M. A., Hildebrand, J. A., and Wiggins, S. M. (2006). Increases in deep ocean ambient noise
943 in the Northeast Pacific west of San Nicolas Island, California. *The Journal of the Acoustical Society of*
944 *America*, 120(2):711–718.
- 945 McKenna, M. F., Ross, D., Wiggins, S. M., and Hildebrand, J. a. (2012). Underwater radiated noise from
946 modern commercial ships. *The Journal of the Acoustical Society of America*, 131(1):92–103.
- 947 McKenna, M. F., Wiggins, S. M., and Hildebrand, J. A. (2013). Relationship between container ship
948 underwater noise levels and ship design, operational and oceanographic conditions. *Scientific Reports*,
949 3.

- 950 Melcon, M. L., Cummins, A. J., Kerosky, S. M., Roche, L. K., Wiggins, S. M., and Hildebrand, J. A.
951 (2012). Blue whales respond to anthropogenic noise. *PloS one*, 7(2):e32681.
- 952 Mellen, R. H. (1954). Ultrasonic Spectrum of Cavitation Noise in Water. *The Journal of the Acoustical*
953 *Society of America*, 26(3):356–360.
- 954 Merchant, N. D., Pirotta, E., Barton, T. R., and Thompson, P. M. (2014). Monitoring ship noise to assess
955 the impact of coastal developments on marine mammals. *Marine Pollution Bulletin*, 78(1-2):85–95.
956 00006.
- 957 Mooney, T. A., Yamato, M., and Branstetter, B. K. (2012). Hearing in cetaceans: from natural history to
958 experimental biology. In *Advances in Marine Biology*, volume 63, pages 197–246. Academic Press.
- 959 Morisaka, T., Shinohara, M., Nakahara, F., and Akamatsu, T. (2005). Effects of ambient noise on the
960 whistles of Indo-Pacific bottlenose dolphin populations. *Journal of Mammalogy*, 86(3):541–546.
- 961 Munger, L. M., Wiggins, S. M., Moore, S. E., and Hildebrand, J. A. (2008). North Pacific right whale
962 (*Eubalaena japonica*) seasonal and diel calling patterns from long-term acoustic recordings in the
963 southeastern Bering Sea, 2000–2006. *Marine Mammal Science*, 24(4):795–814.
- 964 National Research Council, Committee on Potential Impacts of Ambient Noise in the Ocean on Marine
965 Mammals, Ocean Studies Board, and Division on Earth and Life Studies (2003). *Ocean Noise and*
966 *Marine Mammals*. National Academies Press.
- 967 Richardson, W. J., Greene Jr, C. R., Malme, C. I., and Thomson, D. H. (1995). *Marine Mammals and*
968 *Noise*. Academic Press, New York.
- 969 Riesch, R., Ford, J., and Thomsen, F. (2006). Stability and group specificity of stereotyped whistles in
970 resident killer whales, *Orcinus orca*, off British Columbia. *Animal Behaviour*, 71(1):79–91.
- 971 Rolland, R. M., Parks, S. E., Hunt, K. E., Castellote, M., Corkeron, P. J., Nowacek, D. P., Wasser, S. K.,
972 and Kraus, S. D. (2012). Evidence that ship noise increases stress in right whales. *Proceedings of the*
973 *Royal Society B: Biological Sciences*, (February).
- 974 Ross, D. (1976). *Mechanics of underwater noise*. Pergamon Press.
- 975 Southall, B. L., Bowles, A. E., Ellison, W. T., Finneran, J. J., Gentry, R. L., Greene Jr, C. R., Kastak,
976 D., Ketten, D. R., Miller, J. H., and Nachtigall, P. E. (2007). Marine mammal noise exposure criteria:
977 Initial scientific recommendations. *Aquatic Mammals*, 33(4):411–509.
- 978 Stimpert, A. K. (2010). Non-song sound production and its behavioral context in humpback whales
979 (*Megaptera novaeangliae*). *Ann Arbor*, 1001:48106–1346.
- 980 Szymanski, M. D., Bain, D. E., Kiehl, K., Pennington, S., Wong, S., and Henry, K. R. (1999). Killer
981 whale (*Orcinus orca*) hearing: Auditory brainstem response and behavioral audiograms. *Journal of the*
982 *Acoustical Society of America*, 106(2):1134–1141.

- 983 Tasker, M. L., Amundin, M., Andre, M., Hawkins, A., Lang, W., Merck, T., Scholik-Schlomer, A.,
984 Teilmann, J., Thomsen, F., Werner, S., and others (2010). Marine Strategy Framework Directive (Task
985 Group 11 Report) Underwater noise and other forms of energy. *Report No. EUR*, 24341. 00026.
986 TC43 Acoustics (2012). Acoustics. Quantities and procedures for description and measurement of
987 underwater sound from ships. Part 1: General requirements for measurements in deep water. Publicly
988 Available Specification 17208-1, International Organization for Standardization.
- 989 Thomsen, F., Franck, D., and Ford, J. K. B. (2000). Characteristics of whistles from the acoustic
990 repertoire of resident killer whales (*Orcinus orca*) off Vancouver Island, British Columbia. *Journal of*
991 *the Acoustical Society of America*, 109(3):1240–1246.
- 992 Tougaard, J., Wright, A. J., and Madsen, P. T. (2014). Cetacean noise criteria revisited in the light of
993 proposed exposure limits for harbour porpoises. *Marine Pollution Bulletin*.
- 994 Tyack, P. L. (2008). Implications for marine mammals of large-scale changes in the marine acoustic
995 environment. *Journal of Mammalogy*, 89(3):549–558.
- 996 Urick, R. J. (1983). *Principles of underwater sound*, volume 3. McGraw-Hill New York.
- 997 Veirs, V. and Veirs, S. (2006). Average levels and power spectra of ambient sound in the habitat of
998 Southern Resident orcas. *NOAA/NMFS/NWFSC*.
- 999 Wagstaff, R. A. (1973). RANDI: Research ambient noise directionality model. Technical report, DTIC
1000 Document. 00015.
- 1001 Wales, S. C. and Heitmeyer, R. M. (2002). An ensemble source spectra model for merchant ship-radiated
1002 noise. *The Journal of the Acoustical Society of America*, 111(3):1211–1231.
- 1003 Wenz, G. M. (1962). Acoustic ambient noise in the ocean: spectra and sources. *Journal of the Acoustical*
1004 *Society of America*, 34(12):1936–1956.
- 1005 Williams, R., Erbe, C., Ashe, E., Beerman, A., and Smith, J. (2014). Severity of killer whale behavioral
1006 responses to ship noise: A dose–response study. *Marine Pollution Bulletin*, 79(1-2):254–260.