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

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ABSTRACT

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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 μPa^2/Hz from 100-1000 Hz), but also at high frequencies (5-13 dB re 1 μPa^2/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 orcas for communication and echolocation. Broadband received levels (20-96,000 Hz) near the shoreline in Haro Strait (WA, USA) for the entire ship population were 111 $\pm$ 6 dB re 1 μPa on average. Mean ship speed was 14.4 $\pm$ 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 $\pm$ 7 dB re 1 μPa @ 1 m without accounting for frequency-dependent absorption, and 177 $\pm$ 13 dB re 1 μPa @ 1 m with 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 (without accounting for absorption) peak near 50 Hz for all 12 ship classes, have a maximum of 159 dB re 1 μPa^2/Hz @ 1 m for container ships, and vary between classes by over 25 dB re 1 μPa^2/Hz @ 1 m at low frequencies (50 Hz), 10 dB re 1 μPa^2/Hz @ 1 m at mid-frequencies (1,000 Hz), and about 5 dB re 1 μPa^2/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 noise is caused by shafts, gears, engines, and other machinery and generates noise mainly below 50 Hz (Richardson et al., 1995). Overall, larger vessels generate proportionally more noise at low frequencies (<1,000 Hz) because of their relatively high power, deep draft, and slower-turning (< 250 rpm) engines and propellers (Richardson et al., 1995).

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

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

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

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

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

Southern Resident Killer Whales (SRKWs) represent an endangered toothed whale species that is characterized bioacoustically and inhabits an urban estuary in which shipping traffic is high. The auditory sensitivity of killer whales peaks at 15,000-20,000 Hz (Hall and Johnson, 1972; Szymanski et al., 1999), a frequency range that overlaps with the upper range of their vocalizations and the lower range of their

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echolocation clicks. SRKW calls have fundamental frequencies at 100-6,000 Hz with harmonics extending up to 30,000 Hz (Ford, 1987). Echolocation clicks of salmon-eating Northern Resident Killer Whales have 40,000 Hz bandwidth with 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 (Williams et al., 2014). 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 Urick (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 Urick (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 (< 1000 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 (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 μPa @ 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 due to reduced populations (Ayres et al., 2012) 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). Motivated by these potential 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 96,000 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 μPa (RMS, 100-15,000 Hz) above background levels to about 115 dB re 1 μPa 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.

Study site

We deployed a calibrated hydrophone 50 m offshore of the lighthouse at Lime Kiln State Park in which The Whale Museum and Beam Reach maintain an acoustic observatory as part of the Salish Sea Hydrophone

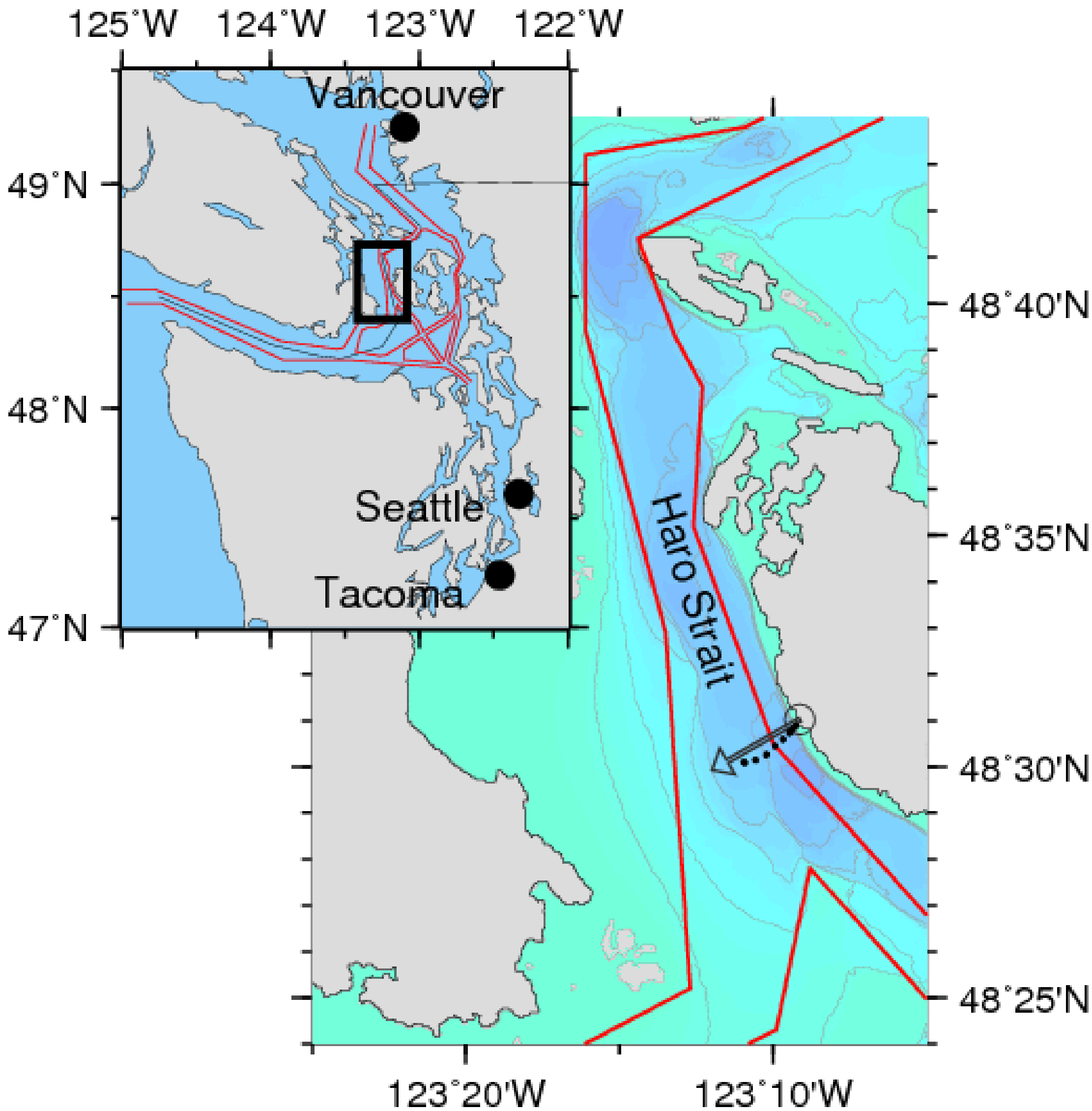

Figure 1. Inset regional map shows the study area (black rectangle) and shipping lanes (in red) leading to the major ports of the Salish Sea. The 240° bearing (gray arrow) extends from the Lime Kiln hydrophone (gray circle) through the northbound shipping lane. Bathymetric contours (50 m) show that Haro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

Network (orcasound.net). Midway along the west side of San Juan Island, Lime Kiln lighthouse sits on a point near the center of the summertime habitat of the SRKWs (Figure 1). While the killer whales sometimes swim directly over the hydrophone location, they more typically transit the site 100-300 m offshore where received levels of noise from the shipping lanes would be somewhat higher than those recorded in this study.

The hydrophone was secured to a PVC pipe projecting vertically from a cement-filled tire resulting in a position 1 m above the bottom and ~8 m deep (below MLLW). A cable protected by irrigation pipe secured in the inter- and sub-tidal zones brought the signal to recording hardware within the lighthouse

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and also housed a saltwater ground wire that helped reduce system noise.

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

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

Data acquisition

We made audio recordings of the signal from a Reson TC4032 hydrophone installed with a differential output (sensitivity of -164±3 dB re 1 V/μPa from 5-125,000 Hz) that was amplified and then digitized by a MOTU Traveller sampling at 192,000 Hz with 16 bits per sample.

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

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

All commercial ships over 65 feet are required to use the Automatic Identification System (AIS) to broadcast navigational data via VHF radio. Each ship transmits at least its identification number, location, course, and speed a few times each minute. The typical range over which these transmissions are detected is 45 km.

The Python program scanned the binary output of an AIS receiver (Comar Systems AIS-2-USB) located in the lighthouse. For each transmission received, the location of the ship was used to calculate its range (R) from the hydrophone. When R was less than 4 nautical miles (7.4 km), the program recorded the broadband received level every 0.5 nautical mile (926 m) as the ship approached and departed. When the ship crossed a line perpendicular to shore (at an azimuth angle of 240°true, see Figure 1), the Python program stored a 30-second WAV file, the date and time, and the decoded ship metadata (ship ID number,

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range, speed over the ground [*SOG*], and course over the ground). Given the orientation of the northbound shipping lane, this procedure made it likely that we recorded the starboard beam aspect noise levels of each isolated ship near the closest point of approach. Finally, the program calculated the calibrated broadband received level using the Reson calibration constant and the RMS amplitude of the 30-second file.

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

Data analysis

Isolation and identification

Archived WAV files and associated metadata were analyzed with a C++ program developed in the platform-independent Qt environment (qt-project.org). To measure the noise radiated by an individual ship, rather than multiple ships, the program used the AIS data to detect acoustically-isolated ships. A ship was deemed isolated if the previous and subsequent ships were at least 6 nautical miles (11.1 km) away from the hydrophone when the WAV file was recorded.

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

We simplified 41 ship type categories returned from online queries into 12 general ship classes: bulk carrier (includes ore carriers); container; tug (includes multi-purpose offshore, pusher tug, and tender); cargo (includes other cargo, heavy lift, wood chip carrier); vehicle carrier (includes all RoRos); tanker (includes crude oil, oil product, oil/chemical, chemical, and product tankers); military (includes Coast Guard, SAR); fishing (includes fish carrier, factory, fishing, fishing vessel, and trawler); passenger (includes cruise ships and ferries); miscellaneous (includes cable layer, reserved, unspecified, and well-stimulation); pleasure craft (includes sailing vessels, motor yacht, and yachts); and research.

Received levels

From each isolated ship's WAV file the RMS power spectral density (PSD) was calculated using a Fast Fourier Transform averaged over the 30-second duration of the file (Nyquist frequency of 96,000 Hz;

16,384 (2^{14}) sample overlapping Bartlett window). The bandwidth of each of the 8,192 frequency bins was 11.5 Hz. These RMS PSD (per Hz) values were calibrated by requiring that the integral of the PSD equal the calibrated broadband level associated with each WAV file. The resulting power spectral densities we call the total received spectrum levels.

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

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

Following the nomenclature of Erbe (2010),

$$Pwr_T(t) = k(P_S(t) + P_B(t))^2 \tag{1}$$

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

$$\langle Pwr_S \rangle = \langle Pwr_T \rangle - \langle Pwr_B \rangle \tag{2}$$

We estimate Pwr_B for each passing ship as the average of the power in two samples – the quietest 2-second sample from the hour before the ship is recorded, and quietest from the hour after the ship passage.

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

Since it is very rare to have motorboat noise overlapping with ship passage at night, we first determined the 95% quantile of each received spectrum level across all vessels recorded at night (hour >19 or hour <7) and used it as a threshold above which 'contamination' by boat noise may have occurred. Then we re-processed all ship transits, removing any data points for which the threshold was exceeded. Any recording in which at least 100 of the 8,192 spectral received levels were above threshold was omitted from further statistical analysis.

Through this robust statistics process, 539 of 3,871 transits were omitted, resulting in no difference between the ship population quantiles for ships that pass during the day and the population of ships passing at night. A sensitivity analysis shows that the process did not affect the 5% to 75% quantiles and that the 95% quantile was reduced by less than 2 dB – and only above about 20,000 Hz. The high frequency peaks seen in the 95% quantile in Figure 3 become sharper as the threshold is increased or the total number of vessels analyzed is decreased.

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

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

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

We cannot determine the signal from a ship if the associated RL_T is not greater than the estimated background level. Hence we require that the total received spectrum level at any given frequency must exceed a threshold of three times the background spectrum level at that frequency. We chose this factor (4.8 dB) by examining the statistics of typical noise recordings to assure that noise is unlikely to be taken as signal. In cases where this threshold is not met, we note that the spectrum level at these frequencies is unmeasured.

Prior to the background subtraction, our data contained persistent narrow-band noise peaks near 25, 38, and 50 kHz in background and total received level spectra, and additionally at 43, 48, 50, and 61 kHz in the 95% quantile of total received level spectra (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

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the estimated source levels (Figure 4).

Transmission loss experiment

To estimate the source spectrum level of isolated ships from RL_S we measured the transmission loss along the 240^o 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 Interoceans 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 distances from the projector to the Lime Kiln hydrophone of 290, 1035, 1446, and 2893 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 μPa (at 10,000 Hz) to 8.6 dB re 1 μPa (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 coeffiecent, TL) of -18.6 ± 0.4 dB/decade in $\log_{10}(R)$

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to represent geometric spreading out to a distance of about 3 km.

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).

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

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

We integrate the source spectrum levels over the entire frequency range (0-96,000 Hz) to compute broadband source levels of SL and SL_a (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). 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 μPa signal-noise threshold to estimate the 5% and 95% quantiles.

To facilitate comparison with past studies we generally present ship source 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 broadband levels of SL_a for each ship class and spectral power levels of SL_a for the whole ship population.

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RESULTS AND DISCUSSION

Ship statistics

Combining all ship classes over entire study, our data set describes 1582 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 sampled 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, confirming the estimate of about 20 ships/day made by Veirs and Veirs (2006).

About 1/3 of the isolated transits are bulk carriers and about 1/5 were 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 sampled 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 were 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.

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 μPa (pleasure craft) to a high of 116 dB re 1 μPa (container ships). Combining all classes, RL_S is 111±6 dB re 1 μPa which is about 20 dB re 1 μPa above the mean background level (RL_B) of 91±4 dB re 1 μPa. 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 μPa lower than the 121-133 dB re 1 μPa reported by Bassett et al. (2012), only about 2 dB re 1 μPa of this

Ship class	Isolated transits	% of total	Unique ships	RL_S dB	SL dB	SL_a dB	SOG m/s	SOG knots
All classes combined	2812		1582	111±6	173±7	178±13	7.4±2.1	14.4±4.1
Bulk carrier	966	34.3	734	111±6	173±5	176±10	7.0±0.7	13.6±1.4
Container	529	18.8	207	116±4	178±4	187±13	10.0±1.0	19.5±2.0
Tug	337	12.0	85	108±4	170±5	174±13	4.3±1.2	8.3±2.3
Cargo	307	10.9	206	113±5	175±5	180±12	7.4±1.0	14.3±1.9
Vehicle carrier	187	6.6	111	113±3	176±3	183±13	8.6±1.0	16.8±1.9
Tanker	148	5.3	101	112±4	174±4	179±12	7.1±0.7	13.8±1.4
Military	113	4.0	19	103±6	161±10	164±13	6.1±2.0	11.9±3.8
Fishing	65	2.3	28	104±5	164±9	166±12	4.5±1.1	8.8±2.1
Passenger	49	1.7	31	105±5	166±8	166±9	7.7±2.2	14.9±4.3
Miscellaneous	41	1.4	21	103±5	162±9	165±11	5.7±2.9	11.1±5.6
Pleasure craft	43	1.5	35	101±6	159±9	163±11	6.9±2.9	13.4±5.6
Research	18	0.5	5	105±4	167±5	170±14	5.7±1.1	11.1±2.1

Table 2. Ship population statistics and mean broadband sound pressure levels (0-96,000 Hz). Though abbreviated in the table as dB, the units of the received signal levels (RL_S) are dB re 1 μPa and all source levels (SL without absorption and SL_a with absorption) have units of dB re 1 μPa @ 1 m. Variability is reported as a standard deviation of the mean, and speed over ground (SOG) is provided in m/s and knots.

difference can be explained by the shorter distances to their ships (0.58-2.82 km).

Source levels

Source level without absorption (*SL*) The mean broadband source level without absorption (*SL*, Table 2) for all ship classes combined is 173±7 dB re 1 μPa @ 1 m. Comparing between ship classes, container ships have the highest *SL* at 178 dB re 1 μPa @ 1 m. Other classes with *SL* ≥174 dB re 1 μPa @ 1 m include cargo ships, vehicle carriers, tankers, and bulk carriers. Tugs and passenger vessels (primarily cruise ships, as there are no nearby ferry routes) have *SL* of 170 dB re 1 μPa @ 1 m, while the remaining vessel classes havedB re 1 μPa @ 1 m) brackets the 170-180 dB re 1 μPa @ 1 m range specified for small ships (lengths 55-85 m) by Richardson et al. (1995).

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 μPa @ 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 μPa @ 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. Possible explanations for their higher values in most classes are: a difference in engineering and/or operation between Puget Sound and Haro Strait ship populations; or the persistence of low-frequency flow noise in their data, despite their efforts to limit it by processing only samples collected when current speed was

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≤0.4 m/s. 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, absorption ignored) listed for 29 individual ships by McKenna et al. (2012) the mean values for equivalent classes in Table are 1-13 dB re 1 μPa @ 1 m lower. These differences are also evident 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. 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. 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 μPa @ 1 m, 5 dB re 1 μPa @ 1 m higher than our mean of 180 dB re 1 μPa @ 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 μPa @ 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 (45-7070 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 μPa @ 1 m lower than a tug (171 dB re 1 μPa @ 1 m at 9.7 knots), 5 dB re 1 μPa @ 1 m lower than a cargo ship (181 dB re 1 μPa @ 1 m), and 11 dB re 1 μPa @ 1 m lower than a large tanker (186 dB re 1 μPa @ 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 1μPa @ 1 yard at 10 knots and 178-195 dB re 1μPa @ 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 1μPa @ 1 m and a mean speed of 14.9±4.3 knots. Thus, our mean *SL* is 5-25 dB re 1 μPa @ 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

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Malme et al. (1989) that passenger vessels in Southeast Alaska have *SL* from 170-180 dB re 1 μPa @ 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 μPa @ 1 m. Our bulk carrier *SL* is 174±5 dB re 1 μPa @ 1 m for *SOG* of 13.6±1.4 knots, which is 10-16 dB re 1 μPa @ 1 m below the levels recorded by Arveson and Vendittis (2000) – 184 dB re 1 μPa @ 1 m and 190 dB re 1 μPa @ 1 m for comparable speeds of 12 and 14 knots, respectively.

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 interquartile 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 μPa @ 1 m) is 3.6 dB re 1 μPa @ 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 μPa @ 1 m). The loudest bulk carrier tabulated in Bassett et al. (2012) with source level of 182 dB re 1 μPa @ 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 μPa @ 1 m) is only 0.8 dB re 1 μPa @ 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 μPa @ 1 m and a maximum of 183 dB re 1 μPa @ 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 μPa @ 1 m for a container ship, 7 dB re 1 μPa @ 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 μPa @ 1 m. Our second- and third-highest maxima within a class were from a bulk carrier

(191 dB re 1 μPa @ 1 m) and a cargo ship (186 dB re 1 μPa @ 1 m). All other classes had maximum *SL* $\leq$185 dB re 1 μPa @ 1 m. The lowest maximum *SL* within a class was 176 dB re 1 μPa @ 1 m for pleasure craft.

The range of minimum broadband *SL* across all classes in our study was from 130 dB re 1 μPa @ 1 m for a cargo ship to 167 dB re 1 μPa @ 1 m for a vehicle carrier. In comparison McKenna et al. (2012) reported a minimum *SL* across all classes of 177 dB re 1 μPa @ 1 m for a chemical tanker while the minimum *SL* for a container ship in McKenna et al. (2013) was 176 dB re 1 μPa @ 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 μPa @ 1 m in *SL* minima suggests that methodological differences between the studies exert greater bias when ship signal levels are near background noise levels.

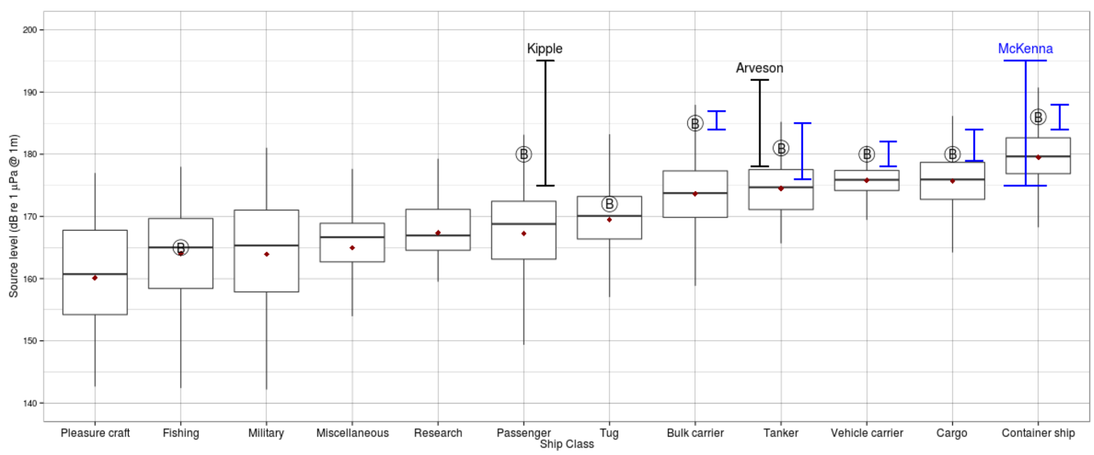

Figure 2. Broadband source level (*SL*) statistics for each ship class juxtaposed with results from recent studies of comparable classes. Bold horizontal lines are medians; box hinges are 25% and 75% quantiles; whiskers extend to the value that is most distant from the hinge but within 1.5 times the 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 bars represent means from McKenna et al. (2012) with the container ship estimate of McKenna et al. (2013) labeled McKenna; black bars represent estimates from Kipple (2002) and Arveson and Vendittis (2000).

Source level with absorption (SL_a) The mean broadband source level with absorption (SL_a) for all ship classes combined is 180$\pm$15 dB re 1 μPa @ 1 m. This value of SL_a and those for each class are typically 1-5 dB re 1 μPa @ 1 m higher than the corresponding *SL* due to the energy added to the source spectrum by accounting for frequency-dependent absorption.

The standard errors of the mean are higher for SL_a than for *SL* because some ships did not produce measurable signals (above background levels) at some high frequencies. This can occur for multiple reasons including the ship's source level frequency distribution, its range from the hydrophone, and the level of background noise. In these cases, there was not as large an absorption correction as for most other ships, yielding a population distribution for SL_a that is broader than for SL. Another manifestation of accounting for absorption across the population is that the range of minima for SL_a (132-167 dB re 1 μPa @ 1 m) is comparable to the range of minima for SL (130-167 dB re 1 μPa @ 1 m), while the range of maxima for SL_a (191-237 dB re 1 μPa @ 1 m) is mostly above the range of maxima for SL (176-195 dB re 1 μPa @ 1 m).

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, our SOG of 13.8$\pm$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. 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

Almost all 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 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

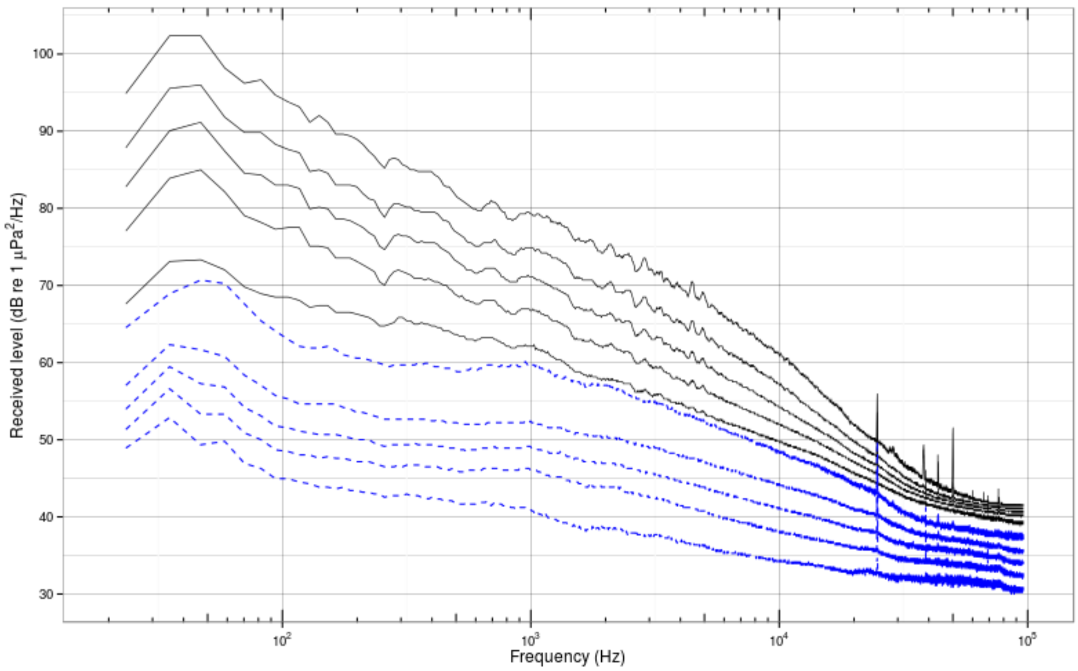

Figure 3. Quantiles (5, 25, 50, 75, & 95%) of background spectrum level (SL_B, dashed blue lines) and total received spectrum level for the entire ship population (SL_T, solid black lines).

30 dB re 1 μPa^2/Hz below 100 Hz and gradually decreases to about 11 dB re 1 μPa^2/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 8 dB re 1 μPa^2/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 (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 μPa^2/Hz across a broad band of the spectrum (600-75,000 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 μPa^2/Hz at frequencies used in killer whale echolocation (20,000-70,000 Hz) and by 17-35 dB re 1 μPa^2/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 μPa^2/Hz above the ancient ambient levels.

We gain additional confidence that our sound pressure levels are calibrated accurately 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 (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 (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 μPa^2/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 μPa^2/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 μPa^2/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 μPa^2/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 μPa^2/Hz @ 1 m and decrease at higher frequencies with a slope of about -15 dB re 1 μPa^2/Hz @ 1 m per decade (from 50-50,000 Hz). The 25% and 75% quantiles are 3-5 dB re 1 μPa^2/Hz from the median below about 10,000 Hz, but at higher frequencies the difference decreases to about 1 dB re 1 μPa^2/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. Above 40,000 Hz the slope continues decreasing to near zero and the levels reach a minimum of about 102 dB re 1 μPa^2/Hz @ 1 m.

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 μPa^2/Hz @ 1 m (20 dB re 1 μPa^2/Hz @ 1 m at 20 Hz; 5 dB re 1 μPa^2/Hz @ 1 m at 50 Hz; and 2 dB re 1 μPa^2/Hz @ 1 m at 100 Hz). Interestingly, their curve does not have a peak below 100 Hz, but instead attains a maximum at 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 μPa^2/Hz @ 1 m below 400 Hz to about 3.12 dB re 1 μPa^2/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 μPa^2/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 mean 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 μPa^2/Hz @ 1 m per decade, nearly three times less steep than the slope of -35 dB re 1 μPa^2/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 μPa^2/Hz @ 1 m per decade, (or -6 dB re 1 μPa^2/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, rising to match the 50 Hz level of SL median curve near 75,000 Hz and then attain a maximum calculated value of 166 dB re 1 μPa^2/Hz @ 1 m at 96,000 Hz. The associated 25% and 75% quantiles are within 3-5 dB re 1 μPa^2/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 μPa^2/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 μPa^2/Hz @ 1 m. Similarly, Blake et al. (1977) report noise levels from a cavitating hydrofoil of 75-110 dB re 1 μPa^2/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 μPa^2/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 Urick (1983) show levels equivalent to or bracketing our SL_a spectrum levels: 24,000 Hz spectrum levels of 118 dB re 1 μPa^2/Hz @ 1 yd for a submarine cruising at 8 knots near periscope depth; 25,000 Hz spectrum levels of 100-130 dB re 1 μPa^2/Hz @ 1 yd for torpedos moving at 20-45 knots; and 20,000 Hz spectrum levels of 115-130 dB re 1 μPa^2/Hz @ 1 yd for a suite of torpedoes.

Source 1/12- and 1/3-octave levels without absorption

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 μPa^2 per band @ 1 m for the 1/3-octave levels. Above 50 Hz, both curves without absorption have slopes of about -4 dB/decade from 100-5,000 Hz, -10 dB/decade from 5,000-40,000 Hz, and +4 dB/decade above 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 μPa^2 per 1/3-octave @ 1 m of their tug/barge levels, and no more than 10 dB re 1 μPa^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 μPa^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 that our median is derived from a sample that is much larger and includes a 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 μPa^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 μPa^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) expects slopes from 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.

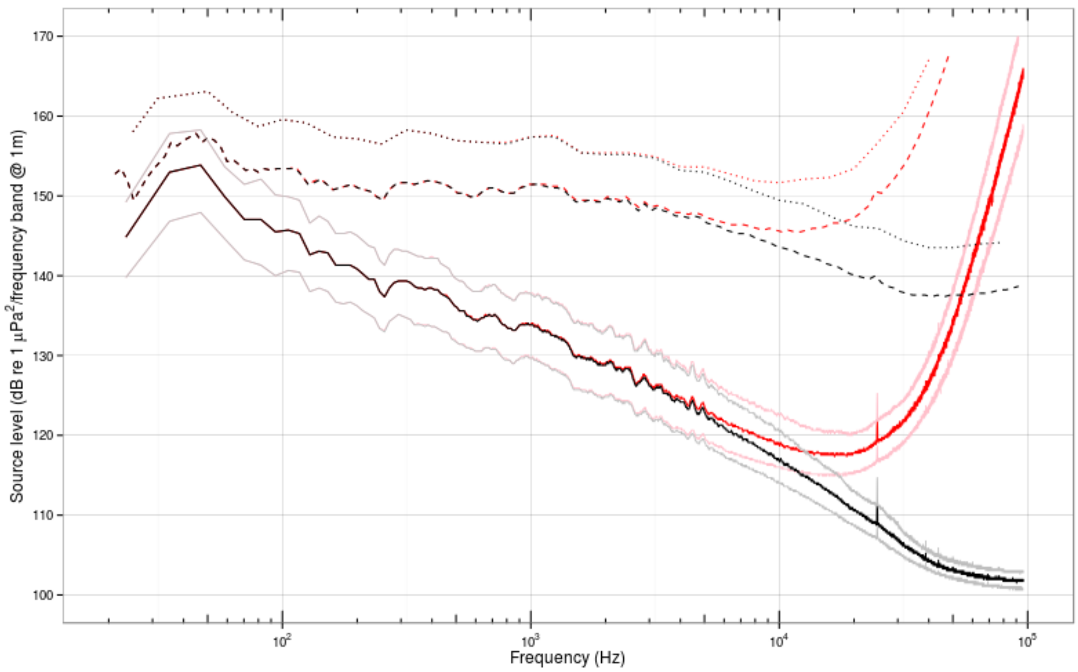

Figure 4. Source level (*SL*) spectra of the entire ship population in 1 Hz (solid), 1/12-octave (dashed), and 1/3-octave bands (dotted). Black curves are medians without absorption; red curves are medians with absorption. For the spectrum levels, we delineate 25 and 75% quantiles in lighter tones. Levels with-absorption which go off-scale for the 1/12- and 1/3-octave bands are 195 and 202 dB, respectively, at 96,000 Hz.

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

As with the spectrum levels, the 1/12- and 1/3-octave level curves with absorption are indistinguishable from those without absorption below 5,000 Hz. At higher frequencies, the SL_a median 1/12- and 1/3-octave levels rise to match the 50 Hz levels of the associated median *SL* curves near 35,000 Hz and then attain maximum measured values of 195 dB re 1 μPa^2/Hz @ 1 m and 195 dB re 1 μPa^2/Hz @ 1 m, respectively, at 96,000 Hz.

This means that when absorption is accounted for in the computation of 1/12- or 1/3-octave levels, modern ships radiate noise in bands centered near 35,000 Hz that at band levels equivalent to the low-frequency maximum band levels near 50 Hz. This fact, and the even higher power levels at frequencies

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above 35,000 Hz, is important to consider when assessing the masking potential of ship noise in habitats close to or within shipping lanes for marine species that utilize high-frequency signals. Though it is novel to state that ship noise source levels have peak power at high- rather than low-frequencies, we provide these 1/12- and 1/3-octave noise levels to facilitate accurate modeling of acoustic impacts for species that have critical bandwidths similar to these noise bandwidths Richardson et al. (1995).

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

Spectral differences between ship classes

When the ship population is broken down by class (Figure 5) the medians show a striking bifurcation. While all classes have similar median spectrum levels near 20,000 Hz, the curves diverge at lower frequencies, and below 200 Hz they bifurcate into high- and low-power groups. The high-power group 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 in Figure 4) and consists of container ships, vehicle carriers, cargo ships, bulk carriers, and tankers. The 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 – levels well below the population median or even 25% quantile – and consists of passenger vessels, tugs, military, research, fishing, miscellaneous, and pleasure vessels.

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

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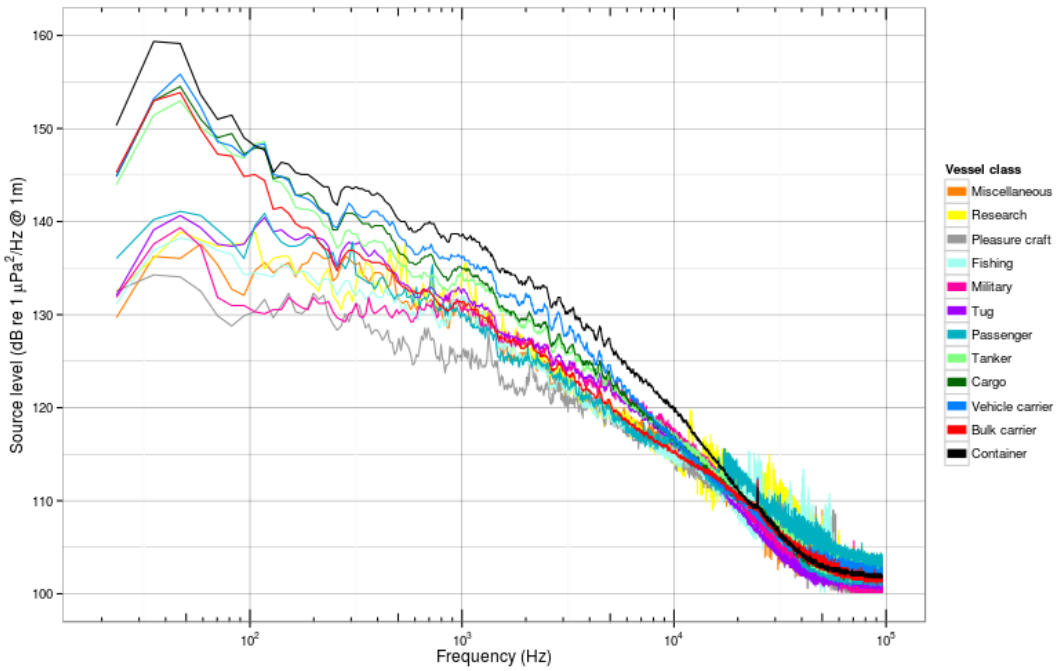

Figure 5. Comparison of median source spectrum levels (without absorption) between ship classes.

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 (10,000-96,000) 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 in this high-frequency range.

The quantiles of source level by class in Figure 6 provide further detail about inter-class differences. Comparing the 95% quantiles, container ships still have the highest peak power (165 dB re 1 μPa^2/Hz @ 1 m) near 50 Hz, but bulk and vehicle carriers, cargo ships and tankers also have peak power greater than 160 dB re 1 μPa^2/Hz @ 1 m. Other classes have peak power near 50 Hz at spectrum levels that range from 156 dB re 1 μPa^2/Hz @ 1 m (research) to 150 dB re 1 μPa^2/Hz @ 1 m (tugs). Comparing the 5% quantiles, we expected that the military class would have the lowest levels due to more advanced ship-quieting technologies. While the military class levels are much lower than container ships (10 dB re 1 μPa^2/Hz @ 1 m less at 1,000 Hz and 20 dB re 1 μPa^2/Hz @ 1 m less at 100 Hz), other

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classes have even lower levels at those frequencies, particularly fishing vessels and pleasure craft.

Spectral variability within ship classes

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

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

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

One explanation for this pattern is that the low-frequency portion of ship noise spectra is influenced by diverse design and operational details (many sources of variability), while cavitation generates high-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 (2006).

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

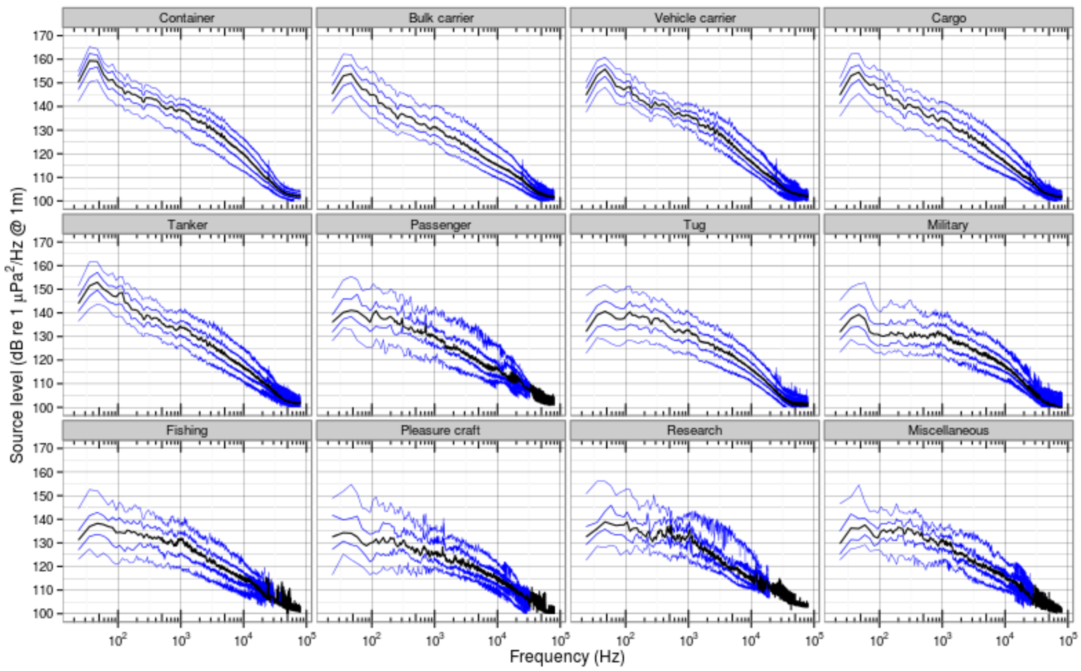

Figure 6. Quantiles of source spectrum levels for each class of ship. Median (50%) quantile (black) overlies 5, 25, 75, and 95% quantiles (blue).

container ship, a vehicle carrier, two bulk carriers, and a few tankers) all fall within a few dB re 1 μPa^2@ 1 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 μPa^2/Hz @ 1 m. This shows that 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. The alignment of the individual ship spectra from McKenna et al. (2012) with the 95% quantile from their associated class at all common frequencies – and most importantly at frequencies below our lowest transmission loss test tone – verifies our assumption of a near-spherical spreading rate at all frequencies. We take this spectral consistency across multiple classes as evidence that the ship noise received at our relatively shallow hydrophone has not undergone significant shallow water attenuation.

CONCLUSIONS

Having ensured our samples were isolated (uncontaminated by noise from other ships or boats) and subtracted estimated background levels, we are confident that median received levels of ship noise in the core of SRKW critical habitat are elevated above median background levels not only at low frequencies (20-30 dB re 1 μPa^2/Hz from 100-1000 Hz), but also at high frequencies (5-13 dB re 1 μPa^2/Hz from 10,000-96,000 Hz). Thus, underwater noise radiated by modern ships extends to high frequencies just as boat noise does (Erbe, 2002; Hildebrand, 2006; **?**). Earlier studies have also observed this aspect of ship noise, but with smaller sample size, over different frequency ranges and less diverse ship classes

(Hildebrand, 2006; **?**; Bassett et al., 2012), and/or in received rather than source levels (Hermannsen et al., 2014).

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

Average broadband received levels (20-96,000 Hz) for the entire ship population are 111 ± 6 dB re 1 μPa and ranged from 101 ± 6 dB re 1 μPa for pleasure craft to 116 ± 4 dB re 1 μPa for container ships. These results show that levels received by SRKWs at Lime Kiln from some ships, most commonly container ships, occasionally meet or exceed the 120 dB re 1 μPa threshold currently used by NOAA to define level B harassment from non-impulsive noise in the U.S.

Ships northbound in Haro Strait exhibit typical speeds with low variability (*SOG* of 14.4 ± 4.1 knots or 7.4 ± 2.1 m/s). Nevertheless, there is enough variation in speed across the whole population to reveal a linear relationship between received level and speed with a slope near $+1$ dB/knot. This suggests a potential mitigation strategy for the average ship – slowing down – that has been recommended as a operational ship quieting option (Southall and Scholik-Schlomer, 2009). This strategy has other environmental benefits, like reducing collision risks, and is consistent with recent industry efforts to increase fuel efficiency (e.g. the ”slow steaming” initiative of Maersk). For a passenger ship measured at speeds of 9-18 knots during WWII Ross (1976) shows in Figure 8.19 that reducing speed lowers source spectrum levels by at about 1.5 dB re 1 μPa @ 1 m per knot at all frequencies, but most noteably lowers them by about 3.0 dB re 1 μPa @ 1 m per knot – both at high frequencies (above 10,000 Hz) and at low frequencies (less than 100 Hz).

Average broadband source levels were 173 ± 7 dB re 1 μPa @ 1 m for the population. Comparing broadband source levels between ship classes, container ships have the highest mean *SL* of 178 ± 4 dB re 1 μPa @ 1 m. Accounting for absorption increases these estimates by 0-9 dB re 1 μPa @ 1 m, depending on the ship class. Therefore, regardless of whether source level is estimated using *SL* or SL_a, marine life within a couple kilometers of shipping lanes will commonly receive noise levels above the 120 dB re 1 μPa threshold.

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

Comparison of our broadband, spectrum, 1/12-octave, and 1/3-octave source levels for the whole population have median values that are comparable to the literature, with a few exceptions that we believe are due primarily to methodological differences. Some past analyses may not have made all recommended corrections (TC43 Acoustics, 2012); most commonly, methods sections are ambiguous about the definition and subtraction of background noise levels from total received levels prior to source level computations. It is also possible that these exceptions are due to sampling ship populations that are distinct (being composed of different individual ships/classes and/or operating differently). In any case, since our source level quantiles have slightly lower levels than some studies, particularly at low frequencies they can be taken as a conservative characterization of the current fleet when developing ship noise models or policies.

One subtle pattern we note is that compared to some previous measurements and models, our median source spectrum levels are relatively low below 200 Hz and relatively high above 20,000 Hz. One implication of this is that noise models may overestimate the low-frequency noise levels of some ship types and underestimate high-frequency noise levels. Such flattening of the spectral slope in more modern ships is described in Figure 8.20 of Ross (1976) which shows spectrum levels (below 100 Hz and from 1,000-20,000 Hz) elevated 1-3 dB re 1 $\mu Pa^2/Hz$ @ 1 m in large populations of post-War versus WWII-era vessels.

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

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

The variability we observe within ship classes indicates opportunities for reducing noise in ships, particularly those associated with the upper quantiles in each class. While the details of the spectral and temporal variability of noise from an individual ship may be important to a receiving species, metrics for 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 100,000 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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