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Average levels and power spectra of ambient sound in the habitat of southern resident orcas

Val Veirs, Colorado College, Colorado Springs, Colorado
vveirs@coloradocollege.edu | (360) 378-7302

Scott Veirs, Beam Reach Marine Science and Sustainability School, Seattle, Washington
scott@beamreach.org | (206) 251-5554

Abstract

We used a pair of hydrophones to monitor sound pressure levels (SPL, dB re 1 μPa) and frequency spectra of ambient sounds in Haro Strait during 18 months (April 2004 - November 2005). Half-hour average SPL in the broad frequency band 0.1-15 kHz ranges from minimum (background) levels of 95 dB to maximum levels of 130 dB. The average SPL over 17 months is 115 dB. The broadband sound field is dominated by noise from large vessels (commercial ships). They increase two-second average SPL ~20-25 dB for 10-30 minute periods about 20 times per day, thereby elevating the 17-month average SPL ~20 dB above background levels. Smaller vessels (motor boats) raise two-second SPL about as much as ships (15-20 dB) but do so for shorter periods and at higher frequencies (10-20 kHz). Their prevalence during summer afternoons explains why the average SPL during summer days (118 dB) is 3 dB higher than during summer nights, winter days, or winter nights.

Introduction

Southern resident orcas (*Orcinus orca*) are acoustically active. When observed in the Northwest Straits region of Washington State by students in the 2005 Beam Reach program[1], the orcas called an average of 25% of the time when traveling (Laura Christoferson, Beam Reach student paper, fall, 2005) and emitted an average of ~400 clicks/minute during foraging periods (Wilfredo Santiago, Beam Reach student paper, fall, 2005). Compared with transient orcas, the southern residents are noisy (Ford and Fisher, 1982); only when resting are they silent for extended periods (Osborne, 1986; Laura Christoferson, Beam Reach student paper, fall, 2005). Southern resident orcas

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[1] http://beamreach.org/051/

typically produce complex series of calls, whistles, and clicks (Ford and Fisher, 1982; Ford, 1989).

Anthropogenic underwater sounds constitute a potential threat to the orcas (National Marine Fisheries Service. 2005). The ability of orcas to communicate, navigate, and hunt may be affected if anthropogenic sounds are intense enough, occur often enough, and are in the right frequency range (Erbe, 2002). Our measurements of pressure and spectrum levels of ambient sound (natural or anthropogenic) represent a key step in determining whether anthropogenic noise impacts orcas.

This report describes the average acoustic environment based on calibrated, near-continuous data collected over an 18-month period from June 9, 2004, through November 18, 2005. Our goal is to quantify the average sound pressure levels and power spectra of ambient noise in Haro Strait.

Methods

Study site and fixed array

Since March 2000, the Orca Vocalization And Localization (OVAL) project[2] has maintained a fixed array of four hydrophones on the west side of San Juan Island, Washington (Figure 1). The hydrophones are deployed permanently along ~250 m of the coast at OrcaSound, an acoustic laboratory ~5 km north of Lime Kiln State Park in the heart of the orcas' summer range. Hydrophones are supported ~0.5 m above the bottom on tripods located at 10-25 m depth and 25-65 m offshore. The OVAL project was initiated in spring, 2000, as a collaborative effort of the physics department at Colorado College and The Whale Museum. Since then, the array has been developed, maintained, and operated by Val and his students with generous financial support from Colorado College. The details of the OrcaSound array are fully described in Veirs and Veirs (in progress, 2006). During much of the year the signal from two hydrophones is monitored in real-time by observers in the laboratory (with a clear view of Haro Strait) or by neighbors along the coast via a stereo low-power FM transmission.

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[2] http://www.coloradocollege.edu/dept/ev/Research/Faculty/OVALItems/newOVAL_Project.html

Figure 1: The location of the OrcaSound fixed hydrophone array and acoustic laboratory (red circle) on the west side of San Juan Island. Southern residents are most common throughout the summer within ~1 km of the west side (Heimlich-Boran, 1989) where the average sighting rate is ~20 sightings/day/km^2 (Donna Hauser, personal communication, 2005).

The system used to collect data for this report consists of ITC-4066 hydrophones with custom-built preamps (AD524 integrated circuit; voltage gain of 100). On shore, isolation amplifiers remove the common-mode electrical noise that arises in the long (~200 m) cables between hydrophone and laboratory computer. The frequency response of this system is flat from 0.1-15 kHz (band pass 3 dB points at 70 Hz and 22 kHz), a range that covers most anthropogenic noise and orca vocalizations. The sensitivity of each of these hydrophone and amplifier systems is approximately –105 dB re 1V/µPa. Upon reaching the laboratory computer the signals are digitized with 16-bit precision and a sampling frequency of 44.1 kHz. The relationship between digitized voltage in the laboratory and SPL at the hydrophones is based on an *in situ* pre-calibration performed in April, 2004, with a J9 projector deployed from a recreational vessel[3].

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[3] The J-9 projector and a calibrated F-42b hydrophone were rented from the Naval Undersea Warfare Center in Newport, RI.

In this report, we specify received sound pressure level (hereafter "SPL") in decibels referenced to 1 μPa, symbolized simply by the unit "dB." We compute all averages of amplitude in units of μPa and then convert to dB. Similarly, we calculate all averages of power spectrum levels in units of $W/m^2/\mu Pa$ and then convert to dB re 1 $\mu Pa/Hz^{1/2}$

Data collection and analysis

While four hydrophones monitor underwater sound in real time at the OrcaSound array[4], we compute average SPL and power spectra with data from only two hydrophones – those at the north and south ends of the array. By using widely separated hydrophones we can determine whether we are measuring ambient (large-scale) underwater sound levels or a sound generated locally (e.g. through contact of kelp or crab with the hydrophone or by a motorboat hovering overhead).

From June 9, 2004 to November 18, 2005, we derived two products every half hour: a histogram of 900 two-second averages of SPL and the half-hour average SPL (the integral of the histogram). Intermittently, we also saved representative 12-hour time series of two-second average SPL on each hydrophone as images. During this 2004-2005 interval, the system operated 70% of the time[5]. Data was lost during parts of winter, 2004-5, when the system – attended only intermittently for months at a time – either did not restart after a utility power failure or filled a hard drive to capacity.

Our preliminary examination of the data from the summer of 2004 showed a dramatic difference between day and night SPL. To understand this difference we began logging a third product, spectrum levels, on May 28, 2005. We computed 512 average power spectrum levels (from 0.1-20 kHz) every half hour for each hydrophone through a continuous fast Fourier transform (1024-point Hamming window, no overlap). We summarize these half-hour spectral data by sorting and averaging them over longer periods: monthly; day vs night during that month; and noon vs midnight during that month. During this six-month interval, the system operated 98% of the time, yielding 8280 data records.

Results

We present a few examples of the 12-hour time series and a cumulative distribution based on the histograms, but focus primarily on the half-hour average SPL and spectra. We sort and average the data over a variety of temporal scales: hour of day; night versus day

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[4] Because the data rate is ~720 Mb/hr, we do not save all raw data. Instead we automatically detect, localize, and archive sounds of interest in the four-hydrophone data stream (e.g., Veirs and Veirs, in preparation, 2005).

[5] Data were not collected during the following interval: (VAL). 18,062 records of the two data products were saved over 17 months.

(bounded at 8:00 and 20:00); day of month; day of week; month (with daily bin edges at midnight); and season (with summer months defined as July and August).

Typical time series

We illustrate the ambient sound received on typical winter and summer days by juxtaposing archived images of consecutive 12-hour amplitude series in Figure 2 (winter) and Figure 3 (summer). These time series demonstrate that the broadband ambient sound field in Haro Strait is dominated by noise from vessels rather than natural sources. Based on abundant visual and photographic observations, there is an unambiguous correlation between SPL and the presence of vessels.

Large vessels like tankers, container carriers, ocean liners, fishing vessels, and tugs (hereafter "ships") pass in the shipping channels on the order of a kilometer from the hydrophones and create broad peaks in amplitude, typically lasting 15-60 minutes and having maximum amplitude ~20 dB above ambient SPL. These broad features begin as a ship enters the acoustic field (typically at a distance of 10-15 km), peak during the closest approach, and diminish to inaudibility again at a distance of up to 10-15 km. Small vessels like recreational power boats, whale watch boats, and sail boats under power (hereafter "boats") also add ~20 dB to the 12-hour average SPL; boats pass faster and closer to the hydrophones, typically creating a spike in amplitude that lasts a few minutes.

Winter

We characterize winter conditions with data from 8 a.m. on January 11 to 8 a.m. on January 14, 2005 (Figure 2). This three-day period has very few recreational boats because it lies in the depth of the winter months, is separated from major holidays, and is in the middle of the week (January 11 was a Tuesday). Whale watching traffic was also at a minimum because most southern residents were in Puget Sound; only a small group was sighted in Haro Strait at 13:45 on January 12 (www.orcanetwork.org/sightings/jan05.html).

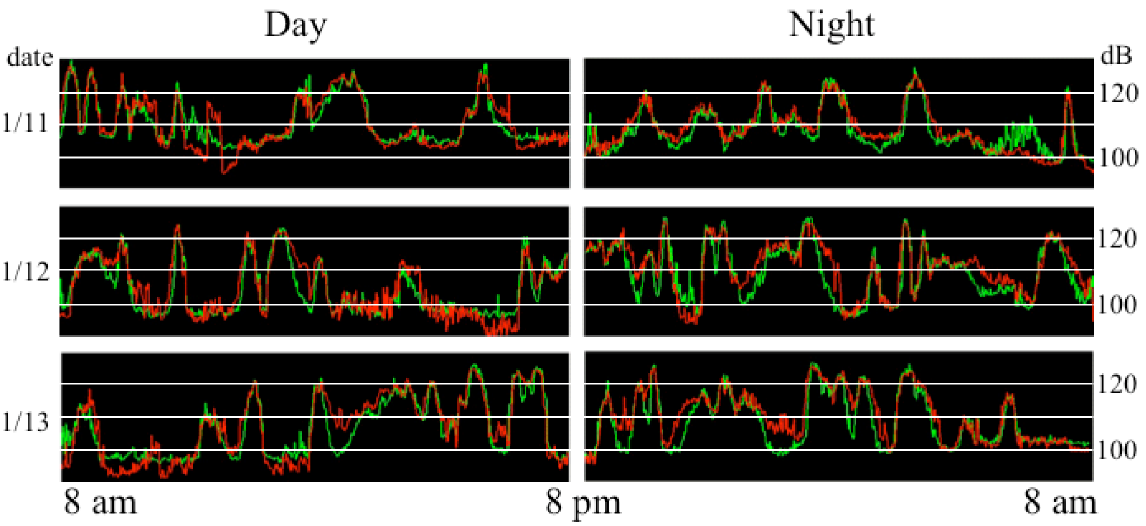

Figure 2: Three consecutive winter days (Jan 11-14) of ambient sound amplitude received by two hydrophones at the ends of the OrcaSound array. One hydrophone signal is in red; the other is in green. The two plots in each row include data from 8:00-24:00 (Pacific Standard Time) of the date that labels the row (at left), as well as the first eight hours (0:00-8:00) of the subsequent day.

During winter days like those in Figure 2, a ship passes the array approximately every hour on average; ~20 ships transit the Strait every 24 hours. Each ship usually adds 20-25 dB to the received SPL; some add nearly 30 dB and a few add only 10 dB. The maximum 2-second average SPL in Figure 2 is ~130 dB while the minimum is ~95 dB.

The relatively quiet periods between ships are usually less than 30 minutes, but sometimes last a few hours, particularly during the early morning hours. If we assume that vessels move at constant velocity through Haro Strait and are audible (in a line of sight) along a ~12 nm distance, then the 30-90 minute acoustic durations correspond to vessel speeds of 24-8 knots. That range is consistent with the speeds of ships (empty cargo container ships to heavily laden tug-boats) that we commonly observe in Haro Strait.

On rare occasions, the signals from the two widely spaced hydrophones differ from each other (e.g. in Figure 2, at 11 a.m. on January 11, 6 a.m. on January 12). We believe these differences are due primarily to local sounds that are detected only by one hydrophone. Often the local sound seems to be made by an object – possibly kelp, crabs, or jetsam – contacting the hydrophone or adjacent cable/tripod system. Sometimes a power boat idling near one end of the array is responsible. It is also possible that in some configurations of hydrophones, sound sources, bathymetry, and hydrography one hydrophone may be shielded relative to the other. In any case, these anomalies usually last less than one hour and rarely have a magnitude greater than 10 dB. Because of the logarithmic nature of the decibel scale, these differences are more apparent in Figures 2 and 3 when the SPL is lower.

Summer

During a characteristic summer period (Figure 3) sounds of boats are prevalent during the day, but ships still predominate at night. The ships again typically add ~20-25 dB to the ambient SPL, while boats usually add 15-20 dB. The maximum SPL during this summer period is nearly 130 dB (9 p.m. on July 3) and appears to be due to a ship and a boat passing the array simultaneously. The maximum amplitude associated with a single, isolated vessel (boat or ship) is ~125 dB. The minimum SPL is again ~95 dB.

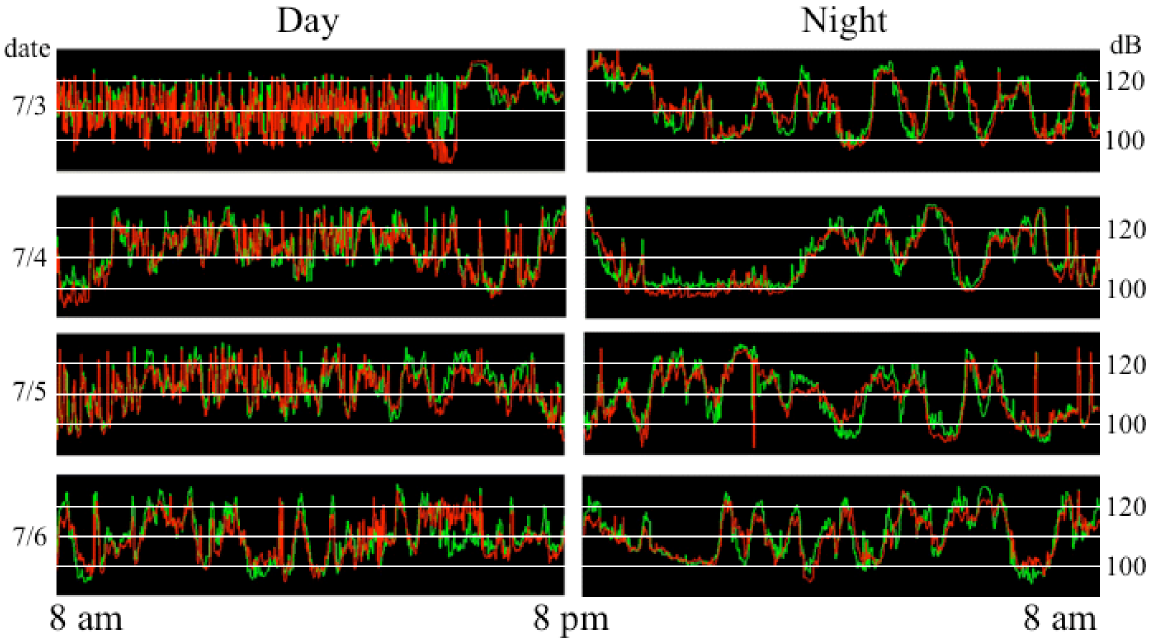

Figure 3: Four consecutive summer days of ambient sound amplitude (dB) received at the OrcaSound array. This period includes the Fourth of July weekend, 2004). Colors and time axis are the same as in Figure 2.

The only extended period with SPL near background levels in Figure 3 occurred on the Fourth of July at night (21:15-24:30, ~100 dB). Shorter periods of relative quiet are common between ship passages, but boat traffic often raises SPL during such periods on summer days (between about 07:00 and 21:00).

Temporal averages

Diurnal variation

The average SPL for each hour of the day (Figure 4) shows that the ambient sound levels are generally higher during the day than at night. Between 10:30 and 18:30 significantly higher levels are measured during the summer than in non-summer months[6]. At all other hours, the average SPL data for summer and non-summer months have remarkably similar magnitude and trends.

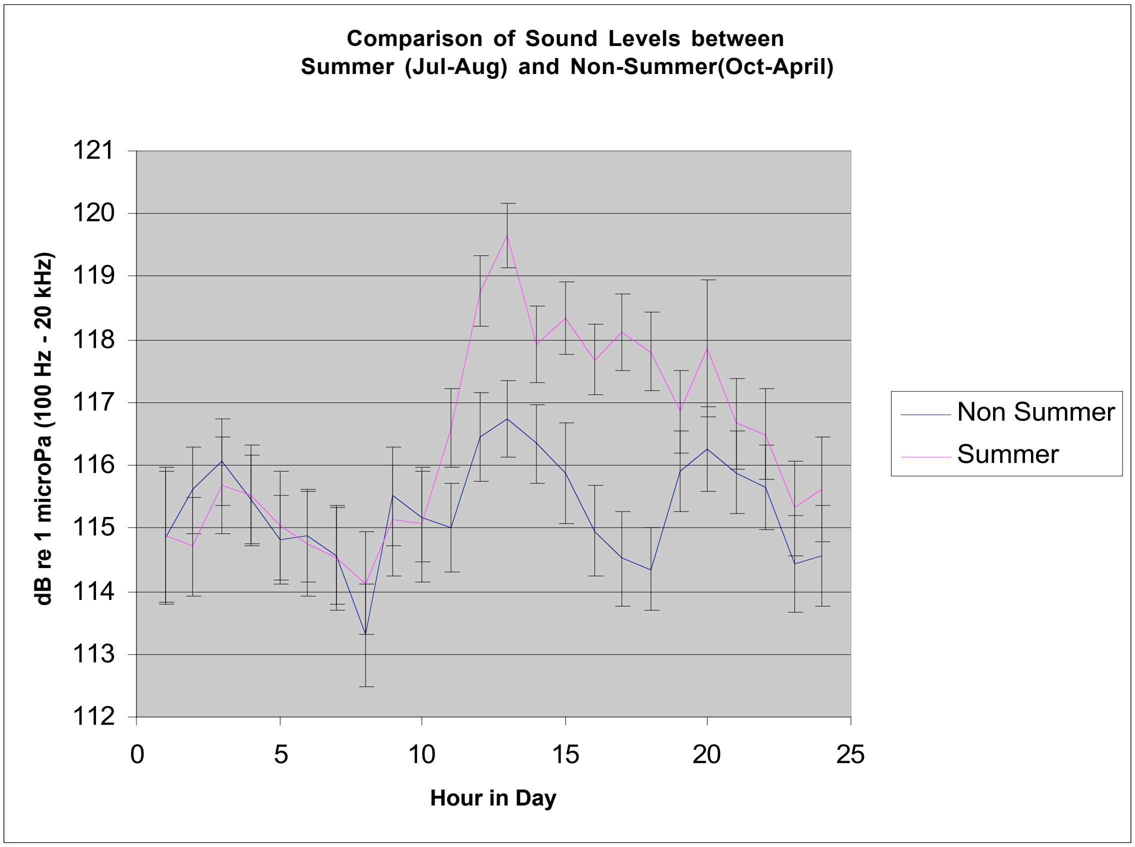

Figure 4: Comparison of hourly average SPL from summer (July-August) and non-summer (October-April) months. Hourly bin edges lie on the half hour, e.g. 12:30-13:30 (local time). Error bars represent standard error of the mean for each hour.

During both summer and non-summer months, the minimum SPL is observed from 7:30-8:30 and the maximum SPL is centered at 13:00. The daily range (maximum-minimum) is ~5.4 dB in the summer and ~3.3 dB in the non-summer months.

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[6] We define non-summer months as October-April to avoid the shoulders of the recreational boating season and clearly separate the summer and winter regimes.

Seasonal variation

The monthly average SPL (Figure 5) also demonstrates that ambient noise levels are higher during summer months than winter months. Levels are generally high from June through July, with a maximum of 117.5 dB in June, 2004. September and October levels are more variable, with 2004 levels well below 2005 levels. The monthly SPL during winter (November-March) is consistently less than 115.5 dB, and the minimum of 114.5 dB is in April, 2005.

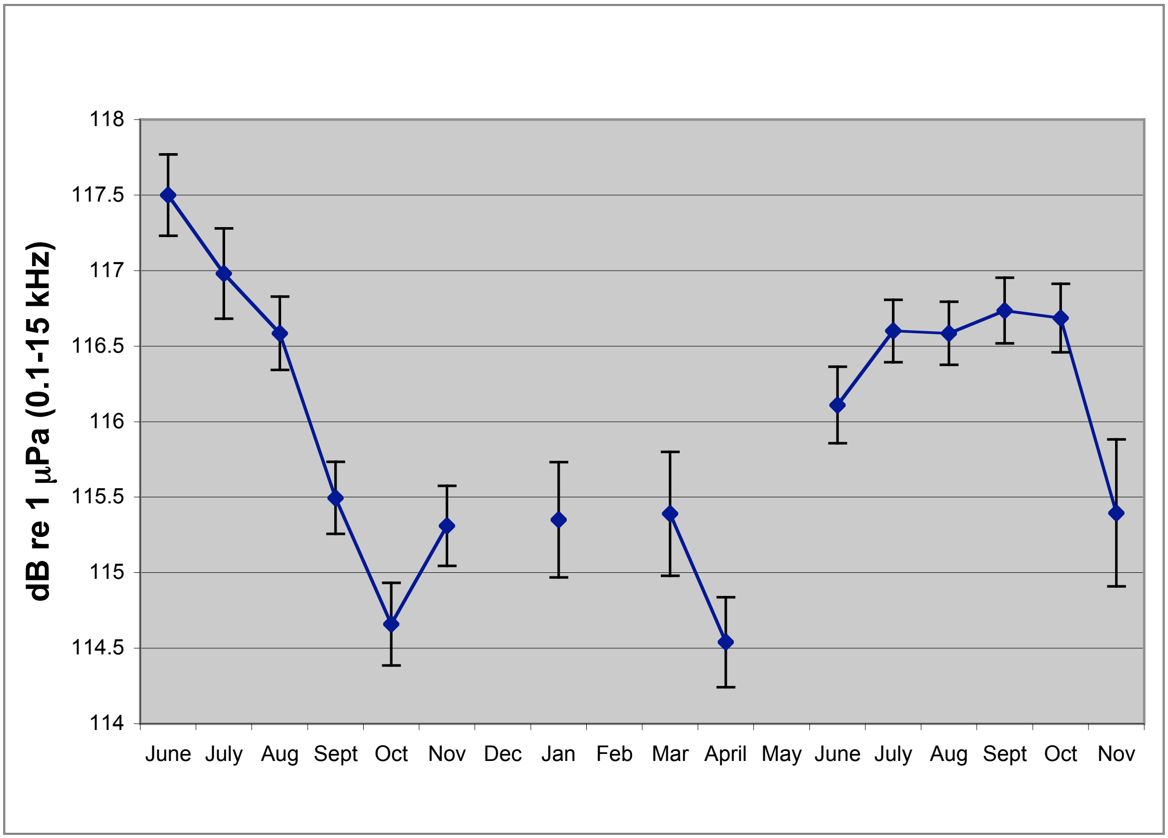

Figure 5: Monthly average SPL from June 2004 - November 2005. Error bars are standard error of the mean. Larger error bars (e.g., November, 2005) are due to relatively few samples in that month.

In calculating monthly average SPL, we have excluded some data. We do not compute averages for February and May, 2005, because the system ran just 12% and 11% of the time, respectively. In calculating averages for June, 2005, we exclude data from the right hydrophone (the one furthest north) because a systematic drop in half-hourly average amplitude is evident in the right channel from late May through June. The right and left channels are previously and subsequently consistent, suggesting that the north hydrophone was temporarily less sensitive (possibly from spring fouling that was naturally removed). While the right hydrophone also showed some desensitization during part of April, 2005, the effect was minor and we include both channels in that monthly average. If we exclude the right channel from the April average, the value increases 0.5 dB to ~115 dB.

Cumulative distribution of SPL

The cumulative distribution of SPL (Figure 6) is derived from the archived histograms of all two-second averages. It shows that ambient two-second SPL in Haro Strait rarely is less than 100 dB or greater than 135 dB. It also implies that the median two-second average SPL over the 0.1-15 kHz bandwidth is ~115 dB during the winter, ~116 dB during summer nights, and ~118 dB during summer days.

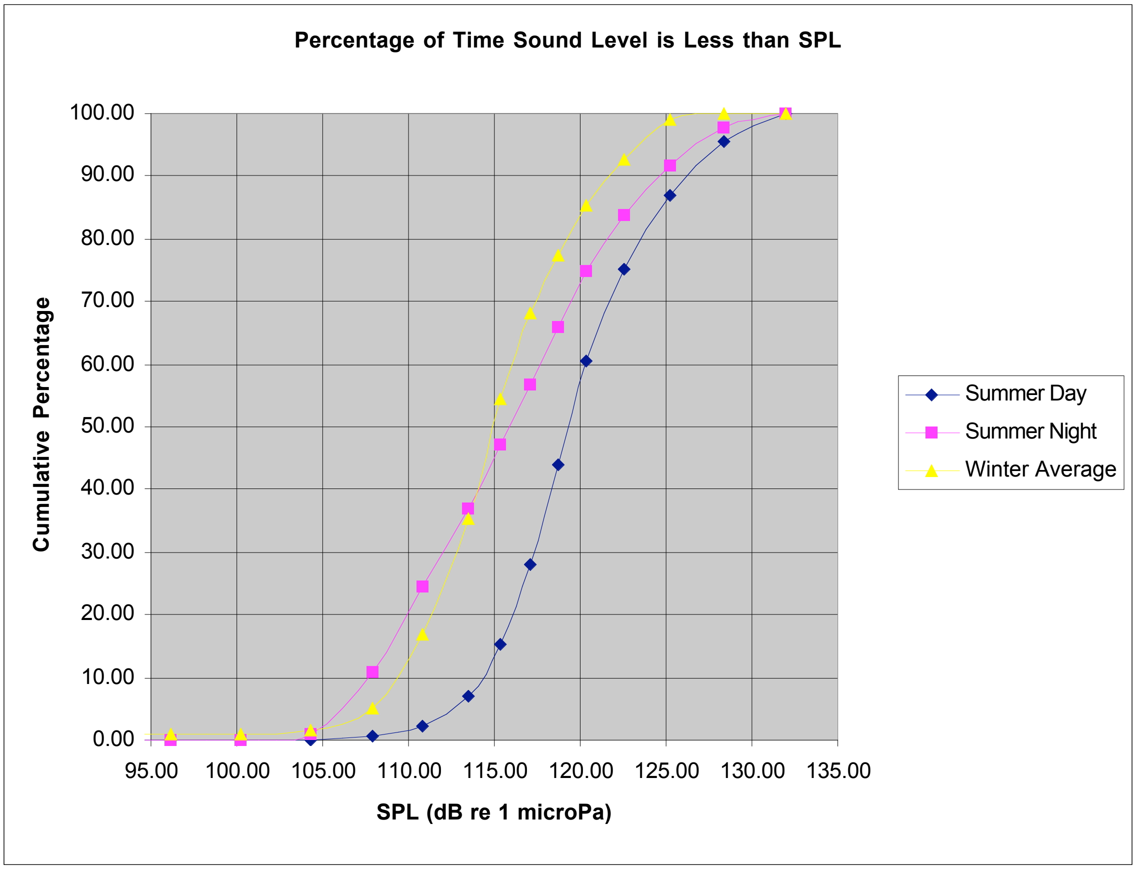

Figure 6: Cumulative distribution of two-second average SPL. "Summer Day" refers to the 12-hour average from 8:00-20:00. "Summer Night" refers to the other 12 hours.

Frequency distributions

Like the average SPL, the average power spectrum of ambient noise in Haro Strait varies diurnally and seasonally. The seasonal differences are characterized by comparing data from two months in 2005: July (Figure 7) and November (Figure 8). In each figure, the monthly average spectrum levels are generally between the daytime average (higher power) and nighttime average (lower power). The highest powers are usually associated with the noon average, while the lowest powers generally occur at midnight. At frequencies above ~1 kHz, the daily average spectrum levels are always higher than the monthly average, while the nightly average spectrum levels are always lower, no matter the month (May-November, 2005).

Summer spectrum levels

During July, 2005 (Figure 7), the maximum diurnal power difference (daily-nightly averages) is ~5 dB re 1 μPa/Hz$^{1/2}$ at 10-20 kHz. In other months the maximum difference also occurs in the 10-20 kHz range, but the difference in July is the largest that is observed annually. Below ~0.8 kHz the diurnal difference in Figure 7 is negligible.

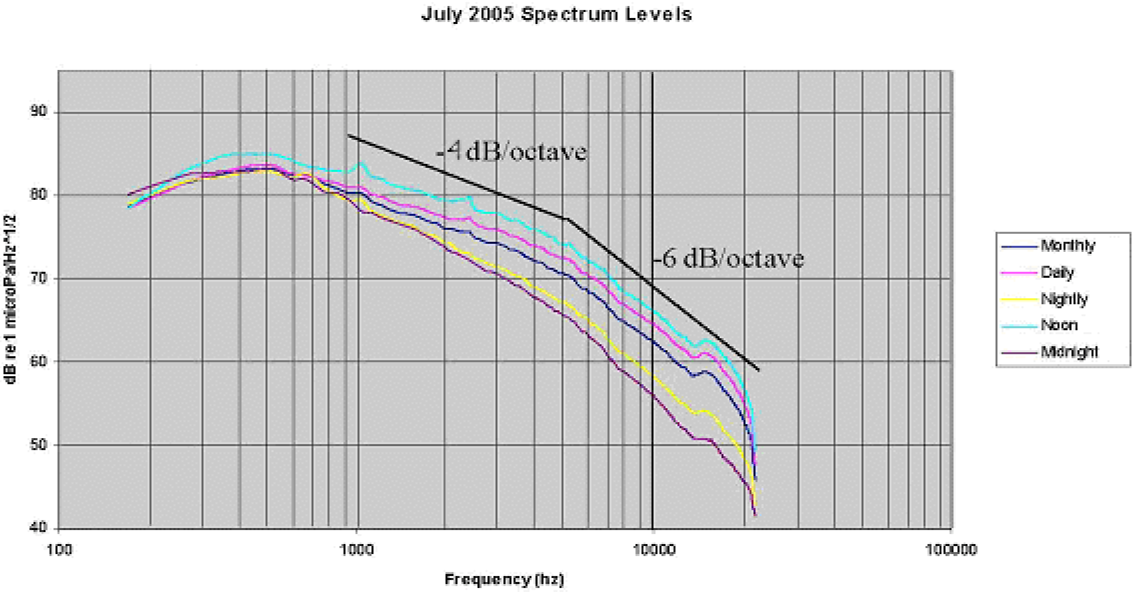

Figure 7: Spectrum levels for July 2005.

In Figure 7, the power peaks near 500 Hz and falls off at higher frequencies (by ~4 dB/octave below 5 kHz and 6 dB/octave thereafter). The most prominent sub-peak is at ~15 kHz; its origin is uncertain[7]. Smaller, narrower sub-peaks at 1-8 kHz are common in July (and other summer months) and can be explained as frequencies that are commonly emitted by boat propulsion systems (e.g. Erbe, 2002). These sub-peaks are most evident

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[7] Local crustaceans may generate the 15 kHz peak; species of snapping shrimp off San Diego, Oahu, Midway, and in the Bahamas generate maximum power at 10-20 kHz (Knudsen et al, 1948). Although wind/rain and orca echolocations generate energy at 15 kHz, all are ruled out: the power of the 15 kHz peak decreases in the winter (when wind and rain intensify), yet the peak is still present then (when echolocating orcas are rare).

in the noon average spectrum because boats are common around noon no matter the day of the month. The sub-peaks are reduced or absent in the midnight average because high frequency sources rarely pass the hydrophones at that hour. The monthly averages smooth out the majority of the sub-peaks.

Winter spectrum levels

In November, 2005 (Figure 8), the maximum diurnal power difference (daily-nightly averages) is near zero at many frequencies and reduced to less than ~2 dB re 1 μPa/Hz$^{1/2}$ at 10-20 kHz. Overall, the power still peaks near 500 kHz, but falls off more quickly (by ~5 dB/octave) up to 5 kHz; thereafter it declines at the same rate as in July (~6 dB/octave). The sub-peak at 10.5 kHz is less prominent and sub-peaks at 1-8 kHz are reduced or not evident.

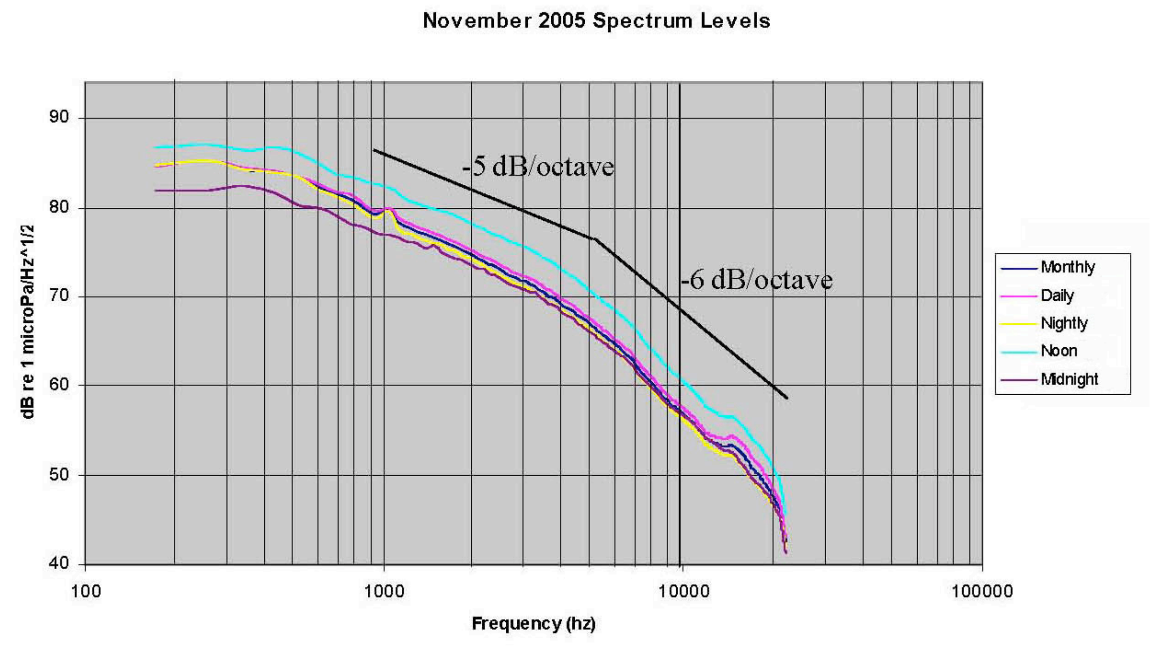

Figure 8: Spectrum levels for November 2005.

The difference in average power between noon and midnight is minimal in Figure 7 below ~0.7 kHz. In contrast, the difference in Figure 8 is greatest in that frequency range.

Discussion

Dominant sources of sound in Haro Strait

The time series, temporal patterns in average SPL, and spectral summaries indicate that vessel noise is the main anthropogenic contribution to the ambient sound field in Haro Strait. When no vessels are visible in Haro Strait, the background average SPL in the frequency range 0.1-15 kHz is ~90-95 dB (Figures 2 and 3). Ships are the dominant source during the winter (day and night) and during summer nights. During summer days, a significant contribution is made by boats (primarily recreational power boats, but also whale watching vessels) that emit energy above ~1 kHz (e.g. Erbe, 2002).

Ships cause short-term increases in SPL of ~20-25 dB year-round (Figures 2 and 3, two-second data). The pervasiveness of ship noise results in ~20 dB difference between the average non-summer SPL (~115 dB, Table 1) and the typical minimum of the two-second averages (~95 dB; Figure 2 or 3). While it possible that other phenomena are also contributing to the magnitude of this difference, the mostly likely candidate – weather – is ruled out by the near equality of the summertime night and wintertime average SPL (Table 1).

Boats are active during summer days from 8:00-18:00 and make a significant contribution[8] to the noise budget from 10:30-18:30 (Figure 4). While recreational boats not engaged in whale watching constitute some of the activity, a correlation with whale watching is indicated by the similarity of these intervals to periods of commercial viewing activity during the summer: generally 9:00-21:00; highest viewing intensities 10:00-17:00; earliest viewing 6:00 (National Marine Fisheries Service, 2005).

Boats increase two-second SPL ~15-20 dB above the typical minimum levels (~95 dB) on summer days (Figures 2 and 3). Because boat noise is relatively brief and concentrated during summer afternoons, it changes average SPL less than ship noise; 12-hour average SPL increases 2.9-3.0 dB both diurnally in the summer and seasonally during the day (Table 1).

Table 1: Comparison of seasonal and diurnal difference in SPL (12-hour average) and standard error (σ). All values have units of dB re 1 μPa. Note: when no boats are present, the background average SPL is ~95 dB.

	Day (7:30-15:30)		**Night (15:30-7:30)**		**Diurnal Difference**
	SPL	**σ**	**SPL**	**σ**	
Summer (Jul & Aug)	118.5	0.7	115.5	0.8	3.0
Non-summer (Oct-Apr)	115.6	0.8	115.0	0.8	0.6
Seasonal difference	2.9		0.5		

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[8] Commercial and private whale watching occurs near the OrcaSound hydrophones only occasionally (~1-3 times per day in the summer). Such local, audible whale watching makes only a small contribution to the sound budget, but many of the boats that transit the array are engaged in whale watching elsewhere.

Implications of power spectra

In general, the average power spectra (Figures 7 and 8) have slopes of –5 to -6 dB/decade above ~0.5 kHz, indicative of sea surface noise, and flatter slopes in the frequency range (~0.1-0.5 kHz) typical of vessel noise (Urick, 1967). Despite the dramatic winter weather and high current speeds in Haro Strait, we find ambient noise amplitude uncorrelated with either wind speed (based on OrcaSound anemometer records) or tidal height.

The most powerful sounds in Haro Strait have frequencies of ~0.5 kHz and are primarily due to ships. This frequency is at the upper edge of the range usually associated with commercial shipping traffic (5-500 Hz; National Research Council, 2003) or with distant ship traffic (50-500 Hz, Urick, 1967; 20-300 Hz, Richardson, 1995).

However, the breadth of the maxima in our monthly average spectra (e.g., Figures 7 and 8) indicates that other types of traffic (emitting energy at ~0.5-1 kHz) also contribute to the ~0.5 kHz peak. Small ships (like fishing vessels or tugs) are probably the main source, but smaller vessels may also make a significant contribution. Even the smallest whale watching vessels (inflatables with outboards) make noise with maximum spectral power below ~1 kHz (Erbe, 2002). Our observations of real-time sonograms confirm that most boats (whale watching and recreational vessels, alike) generate spectra that peak at 0.5-1 kHz and diminish above ~5 kHz.

The consistent elevation of daily average spectrum levels over nightly levels at frequencies greater than ~1 kHz (Figures 7 and 8) indicates that the increase in broadband SPL observed during daytime versus nighttime hours (Figure 4) is due to high frequency (>1 kHz) sound sources. Similarly, the greater diurnal power difference observed during summer (e.g., Figure 7) versus winter months (e.g., Figure 8) is observed only above ~1 kHz, confirming that the summertime increase in monthly average SPL (Figure 5) can also be attributed primarily to boats.

Biases and limitations

Our study is limited geographically. Yet our title implies that we have assumed that measurements from the center of the core summer habitat of the southern residents (Donna Hauser, pers. comm.) are representative of their entire habitat. We believe this assumption is justified for the Haro Strait region, but the sound field may be significantly different in Puget Sound and the Strait of Juan de Fuca, where ship traffic and other anthropogenic sound sources may be more intense. This may also be the case in the Strait of Georgia where sound associated with Haro Strait traffic is supplemented by ships that transit Rosario Strait and human activities concentrated near Vancouver. Our results probably should not be applied to the portions of the open or coastal Northeast Pacific that the southern residents may frequent during the winter.

Our pre-calibration gives us confidence that the SPL values reported here are accurate. However, we would be even more confident if we could ensure that instrumental drift has not occurred. We did detect intermittent drift in the left channel (relative to the right channel) and suspect that it was due to temporary fouling. While we have excluded the drifting data in this analysis and emphasize that the major results of this study involve *relative* differences in SPL and frequency spectra, it would be ideal to post-calibrate both hydrophones in order to quantify average SPL *absolute magnitude* with greater certainty.

Future work and curiosities

Quantifying ambient SPL is one step towards modeling masking and active space (Erbe, 2002), and thereby assessing whether anthropogenic noise affects the southern residents (e.g., Foote et al, 2004). Critical next steps are to measure the source levels of both the southern residents (Veirs and Veirs, 2006, in prep.) and the vessels that frequent their habitat.

Acknowledgements

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