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

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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 ~95-130 dB. The overall average SPL is ~115 dB; the SPL is ~2 dB during summer days. The broadband ambient sound field in Haro Strait is dominated by noise from large vessels (commercial ships) that increase SPL ~20-25 dB for 10-30 minute periods and cause the long-term 20 dB difference between minimum and average SPL. Smaller vessels (motor boats) increase SPL about as much as ships (~15-20 dB) but do so for short periods of time. Nevertheless, boats add ~2 dB during mid-afternoon hours in the summer and increase spectral 10-20 kHz, where a summer day is more than 10 dB re 1 mPa/Hz1/2 higher than a summer night or a day or night in the winter.

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). If anthropogenic sounds are intense enough, occur often enough, and are in the right frequency range, human activities that are common in the Salish Sea – like commercial shipping, boat-based whale watching, and recreational boating – may affect the hearing of the southern residents. Measuring sound pressure levels of ambient sound (natural or anthropogenic) is a critical step in determining how often anthropogenic noise negatively impacts the orcas. Given an estimate of the threshold level of a biological effect, our measurements quantify what percentage of the time noise in Haro Strait interferes with the sounds that orcas use to communicate, forage, and navigate.

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. The array is 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 (Figure 1). 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, 2005).

[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).

Data presented in this report were collected with two ITC-4066 hydrophones (International Transducer Corporation, www.itc-transducers.com) spaced ~250 m apart, at the southern and northern extremes of the array. A custom-built preamp (AD524 integrated circuit, voltage gain of 100) attached directly to each hydrophone increased the signal-to-noise ratio before transmission. On shore, isolation amplifiers removed 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 hydrophones used in this study were pre-calibrated in situ during April 2004, using a J9 projector deployed from a recreational vessel[3]. The relationship between digitized voltage in the laboratory and sound pressure level received at the hydrophone was established by combining the source level of the projected sound (known) and the projector-to-hydrophone distance (computed from GPS coordinates) in an appropriate spreading model (determined through separate experiments) (Veirs and Veirs, in preparation, 2005).

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

The Orcasound computers analyze underwater sound from the four hydrophones in the array in real time. 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) and generate average SPL and power spectra with data from just the two most-separated hydrophones (presented here). Widely separated hydrophones help 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.

In this report 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 averages. We sort the averages temporally (in Pacific Standard Time) by hour (with hourly bin edges on the half hour, e.g. 12:30-13:30), by night versus day (bounded at 8:00 and 20:00), by day of month, day of week, and month (with daily bin edges at midnight), and by season (with summer months defined as July and August).

During this interval, the system operated 70% of the time (18,062 records of the two data products were saved over 17 months). 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.

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

Since May 28, 2005, a third product was also logged every half hour: 512 average power spectrum levels (from 0.1-20 kHz) for each hydrophone. We used a continuous fast Fourier transform (1024-point Hamming window, no overlap) to generate these half-hour average spectrum levels. Finally, we computed the monthly average power spectra, again using midnight bin boundaries. During this nearly six-month interval, the system operated 98% of the time, recording 8280 data records.

Results

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 Figures 2 (winter) and 3 (summer). These time series exemplify that the ambient sound field in Haro Strait is dominated by vessel noise. 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 adding ~20 dB to the 12-hour average SPL. Small vessels like recreational power boats, whale watch boats, and sail boats under power (hereafter "boats") also add ~20 dB to the long-term average SPL, but they pass faster and closer to the hydrophones, typically creating a spike in amplitude that lasts only 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).

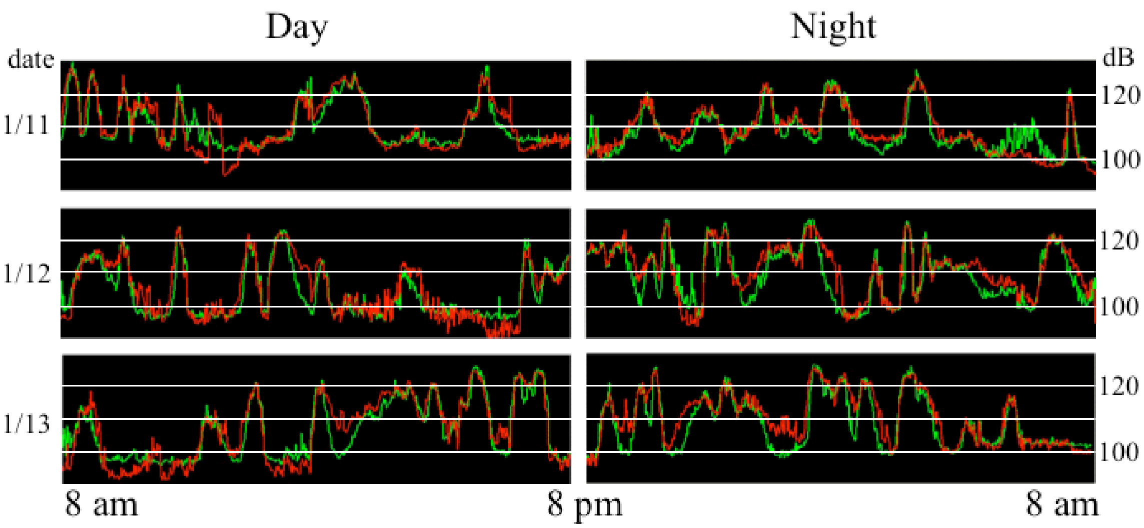

Figure 2: Three consecutive winter days (Jan 11-14) of ambient sound amplitude received at two widely spaced hydrophones in the Orcasound array. One hydrophone signal is in red; the other is in green. The two plots in each row include data from 8:00-24:00 of the date that labels the row (at left), as 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.

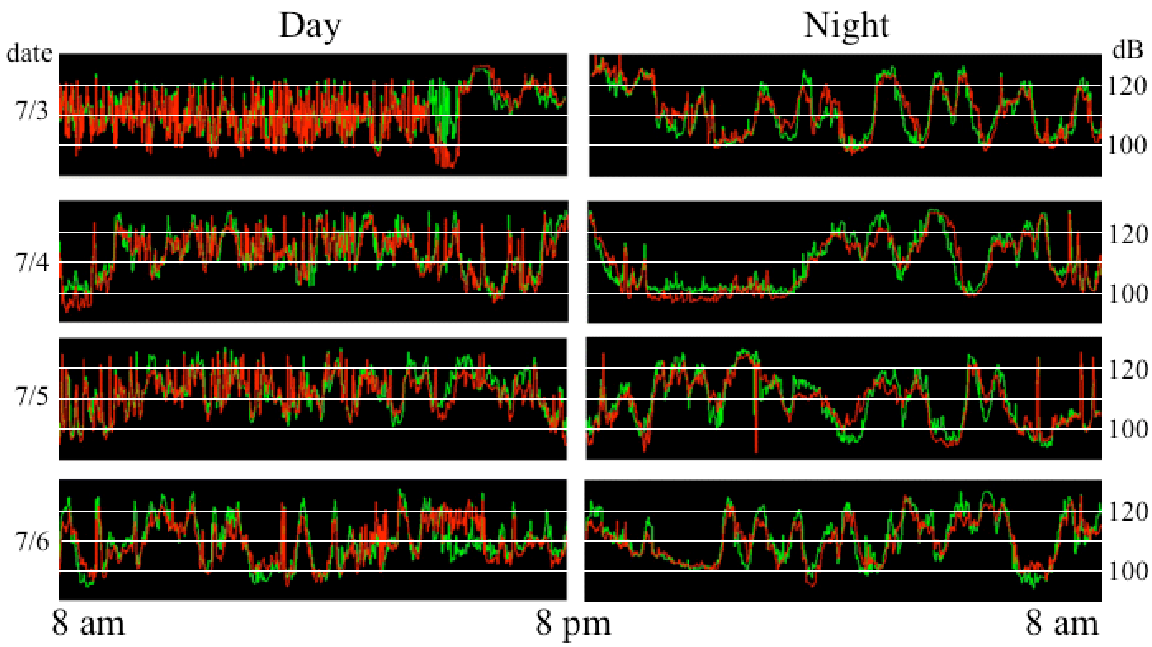

Figure 3: Four consecutive summer days of ambient sound amplitude (dB) received at the Orcasound array. This period includes the Fourth of July weekend, 2004). Colors and time axis are the same as in Figure 2.

The only extended hiatus in vessel noise shown in Figure 3 occurred on the Fourth of July at night (21:15-24:30). Apparently even foreign-flagged ships bound in/out of Canada were not transiting Haro Strait around the time of the U.S. fireworks displays. Boat traffic was exceptionally continuous on July 3, probably because many boats pass the array en route to Roche Harbor (a popular fireworks site). As Figure 3 illustrates, boat traffic is common in Haro Strait on summer days from 06:00 until about 22:00.

Temporal averages

SPL versus hour of day

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. At all other hours, the average SPL data for summer and non-summer months have remarkably similar magnitude and trends.

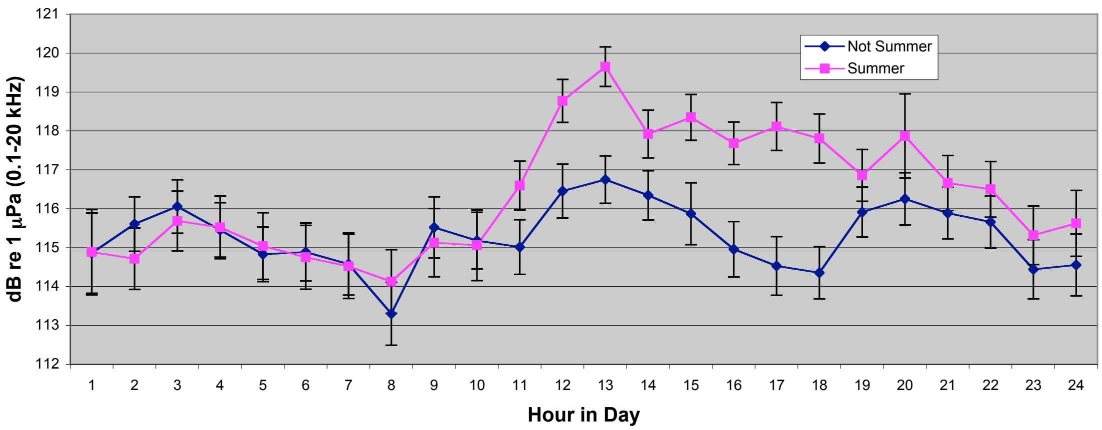

Figure 4: Comparison of hourly average SPL from summer (July-August) and non-summer (October-April) months. Error bars represent standard error of the mean for each hour.

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.

SPL versus month

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 144.5 dB is in April, 2005.

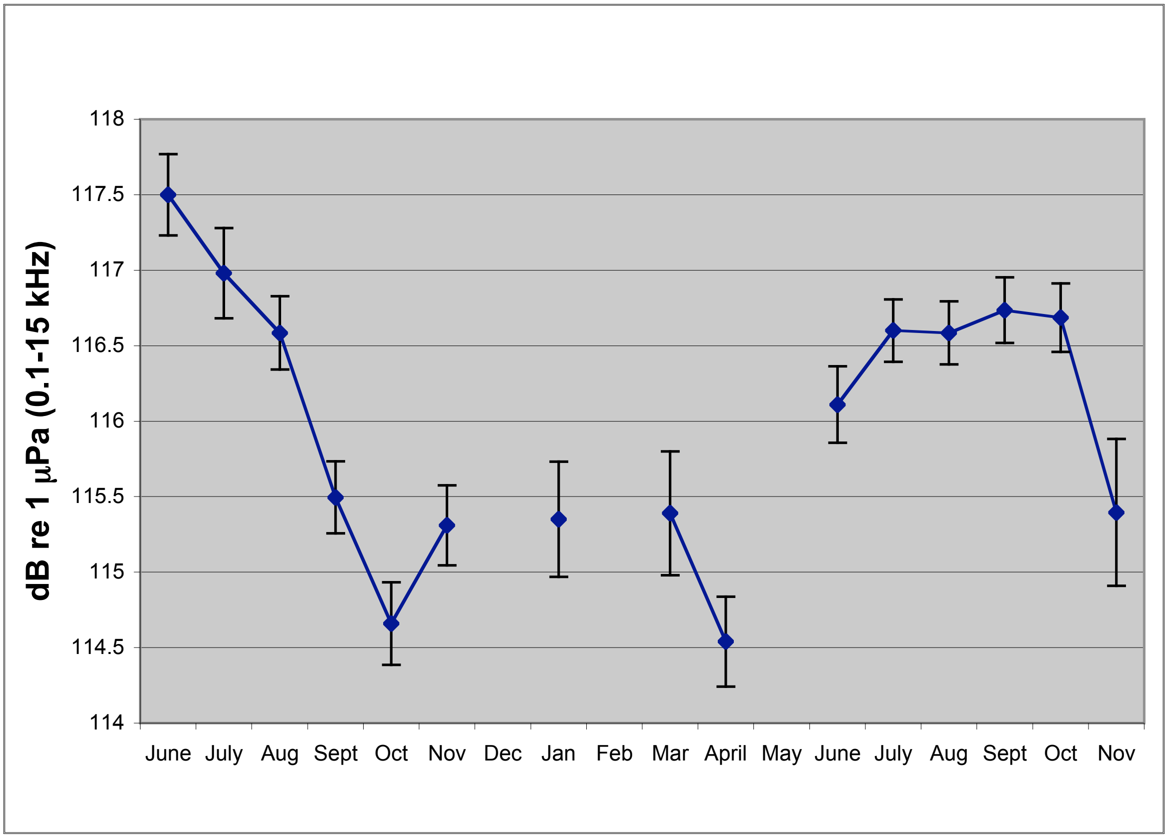

Figure 5: Monthly average SPL from June 2004 - November 2005. Error bars are standard error of the mean. Larger error bars (e.g., November, 2005) are due to relatively few samples in that month.

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 ~111 dB during the winter, ~113 dB during summer nights, and ~121 dB during summer days.

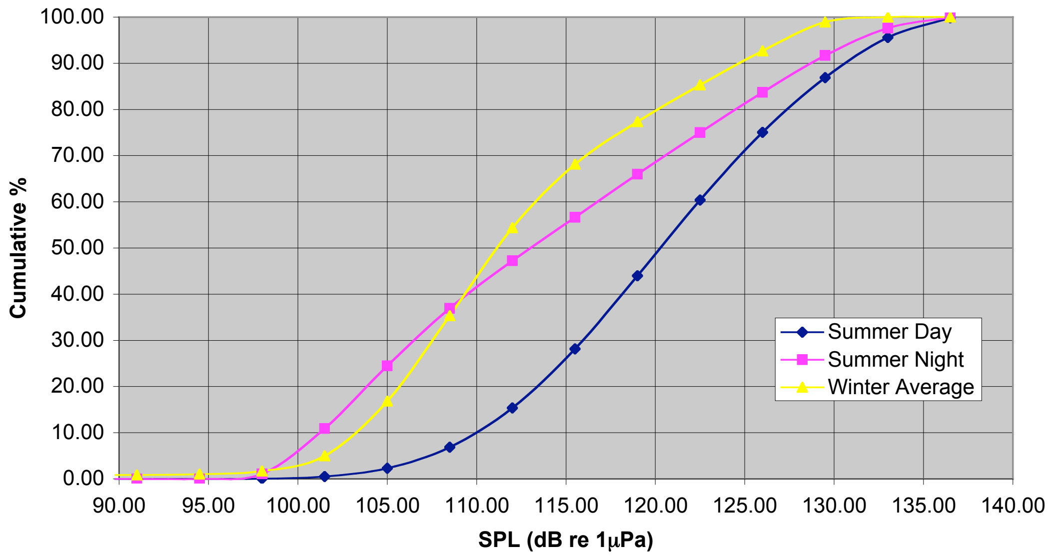

Figure 6: Cumulative distribution of two-second average SPL. "Summer Day" refers to the 12-hour average from 8:00-20:00. "Summer Night" refers to the other 12 hours.

Figure 6 also quantifies how frequently SPL is less than a threshold value. For example, the average SPL is less than 110 dB about 40% of the time during the winter and during summer nights. In sharp contrast, during summer days, the average SPL is less than 110 dB about 10% of the time. If 110 dB were a threshold above which some forms of orca communication were inhibited, then Figure 6 indicates that such inhibition would occur 90% of the time during summer days and about 60% of the time during summer nights or in the winter.

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.

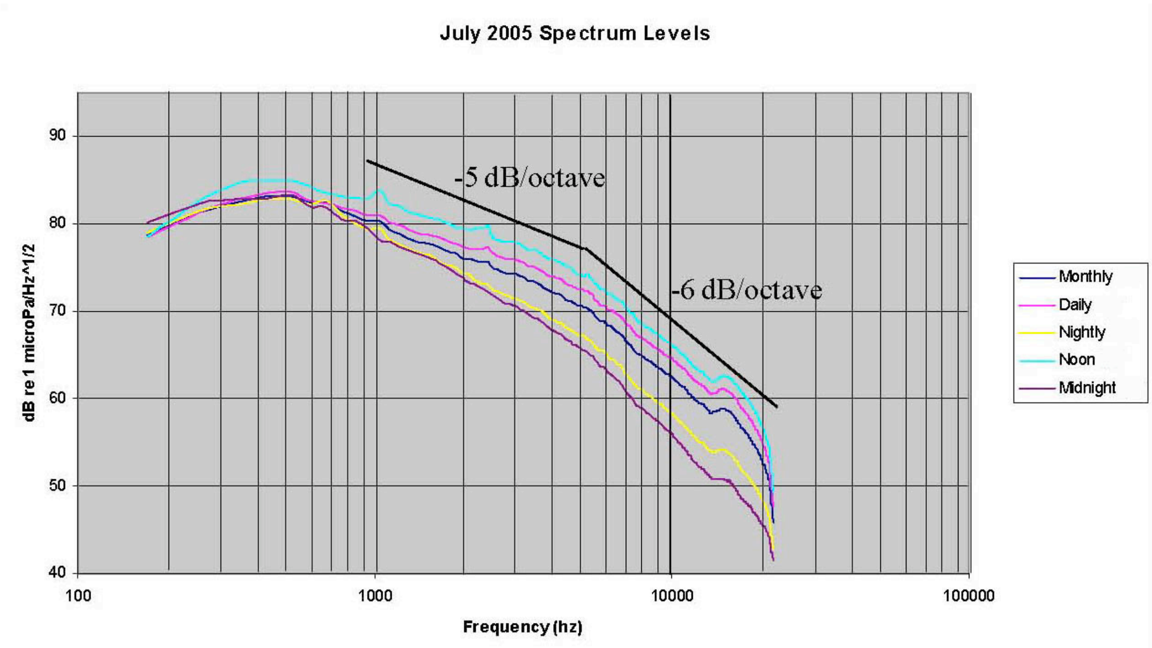

Figure 7: Spectrum levels for July 2005.

In Figure 7, the power peaks near 500 kHz 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[4]. 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. These sub-peaks are most evident in the noon average spectrum because the averaging time is relatively short and boats are common around noon. 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.

[4] Snapping shrimp may generate the 15 kHz peak; species 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, both 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 (when echolocating orcas aren't).

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.

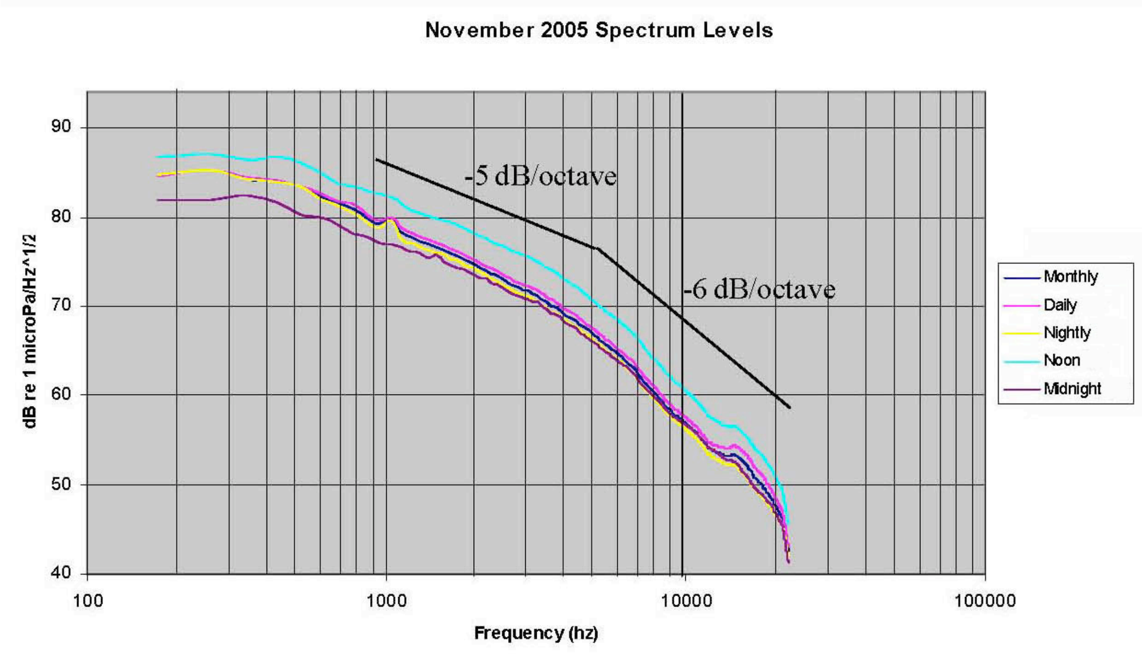

Figure 8: Spectrum levels for November 2005.

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 present in the 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.

Boats are active during summer days from 8:00-18:00 and make a significant contribution[5] 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). Over the last five years, we sense (but have not quantified) a trend of whale watching boats starting earlier in the morning and continuing later in the evening.

Boats cause short-term increases in SPL of ~15-20 dB on summer days (Figures 2 and 3, two-second data). Because boat noise is relatively brief it affects long-term averages less, increasing the 12-hour average SPL by ~2.0 dB (Table 1, day-night SPL). The seasonal difference in daytime 12-hour average SPL has a similar value (1.9 dB, Table 1) because the average SPL during summer nights and winter days are statistically equivalent (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)	117.5	0.7	115.5	0.8	2.0
Non-summer (Oct-Apr)	115.6	0.8	115.0	0.8	0.6
Seasonal difference	1.9		0.5		

Ships cause short-term increases in SPL of ~20-25 dB year-round (Figures 2 and 3, two-second data). The pervasiveness of their noise, however, makes ships responsible for the ~20 dB difference between the average non-summer SPL (~115 dB, Table 1) and the

[5] 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.

typical minimum of the two-second averages (~95 dB; e.g., 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).

Implication of power spectra

The most powerful sounds in Haro Strait are emitted on average at 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) implies that other types of traffic (emitting energy at ~0.5-1 kHz) also contribute to the ~0.5 kHz peak. Smaller 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) make noise with maximum spectral power below ~1 kHz (Erbe, 2002); our observations of real-time sonograms indicate that this is true for most boats (whale watching and recreational vessels, alike).

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.

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.

Biases and limitations

Our study is limited geographically. We have assumed that measurements from one location on the west side of San Juan Island are representative of the habitat of the southern residents. 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 we expect 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 obviously should not be applied to the portions of the range in the open or coastal Northeast Pacific that the southern residents use 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* 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, and thereby assessing whether anthropogenic noise has a negative impact on the southern residents. Once we have published average ambient SPL and orca source levels, we will be prepared to supplement historic assessments (e.g., Erbe, 2002; Foote et al, 2004) with our own. A critical next step will be characterizing the source levels of a representative sample of vessels that frequent the habitat of the southern residents.

We are motivated to pursue this research direction because we have preliminary indications that the southern residents vocalize preferentially between peaks in ship noise. The majority of ~500 calls localized near the Orcasound hydrophone array to compute orca call's average source level (Veirs and Veirs, in preparation, 2005) were observed during low SPL periods: 13 calls were observed between ships when the average SPL was 111 +/- 3 dB; 66 calls were observed between ship and boat peaks when SPL was 107 +/- 5 dB; 39 calls were observed between two ships when SPL was 105 +/- 5 dB; and 14 calls were observed during afternoon small vessel traffic when SPL was 112 +- 3 dB. Thus far, orca vocalizations have not been localized nearby the array when boat or vessel noise has raised the background SPL above ~112 dB.

Acknowledgements

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