Minimal influence of wind and tidal height on underwater noise in Haro Strait

Scott Veirs, Beam Reach
Val Veirs, Colorado College
December 2, 2007

Introduction

Assessing the effect of wind and currents on the sound field is an important part of characterizing the acoustic environment of southern resident killer whales. Tidal currents in Haro Strait may contribute to ambient noise through breaking waves, associated bubbles, and turbulent flow. Strong currents can also induce noise at the hydrophone from turbulent flow, vibration of the support structure, and/or contact with other objects. In some situations[1], the level of ambient noise correlates with local wind and the associated rough sea surface has been implicated[2] as the dominant noise source at 1-30 kHz.

In this report, we assess the effect of wind and tidal height in a 13-month time series of underwater noise from OrcaSound, an array of hydrophones located in Haro Strait on the west side of San Juan Island, WA. The noise record was generated by monitoring the signal from calibrated hydrophones and archiving average underwater sound pressure levels as well as average spectral levels.

The data analyzed in this study are described by:

- Records from May 2005 through June 2006;
- Broadband sound pressure levels from ITC hydrophones with bandwidth 0.1-20 kHz (located ~30 m offshore at depths of ~20 m);
- Wind speeds from Kelp Reef, about 2 nm due west of the hydrophone array (courtesy Environment Canada); and,
- Tidal heights from the computer program WXTide32 (version 4.0) for Kellett Bluff, about 2 nm north of the hydrophone array.

About 14,200 underwater sound level measurements were made over the study period. Each of these observations was a 30-minute average broadband underwater sound pressure level (dB re 1 μPa) and a coinciding 30-minute power spectrum (spectrum level in dB re 1 $\mu Pa/Hz^{1/2}$) divided into 256 frequency bins between 100 and 20,000 Hz.

Environment Canada provided hourly wind data (speed in km/hr and wind direction in degrees clockwise from N) for the May 2005 through June 2006 period of this study. Tidal height was calculated for the time of each noise measurement.

---

[1] Ingenito, F. and Wolf, S. N. (1989) Site dependence of wind-dominated ambient noise in shallow water. JASA 85:141-145.

[2] Urick, R. J. (1967) Principles of underwater sound for engineers. McGraw-Hill, New York, pp. 342.

The relationship between noise and wind

A total of 14,218 broadband underwater sound level measurements were taken at OrcaSound on San Juan Island and plotted as a function of wind speed (km/hr) at Kelp Reef at the time of each of the noise measurements(Figure 1). The regression is small andline explains less than 1% of the variance[3]. However, the lower line shows that the noise floor[4] is related to the wind speed. That is, at those "quiet" times, when the sound field was not dominated by other sources such as ships and smaller vessels, the noise level was correlated with wind speed.

Figure 1 shows that the lowest sound pressure levels in Haro Strait were about 95 dB and occured when no wind was present. As wind increased, the sound pressure levels increased linearly according to the following function: dB = 90 (dB) + 0.3 WindSpeed (km/hr).

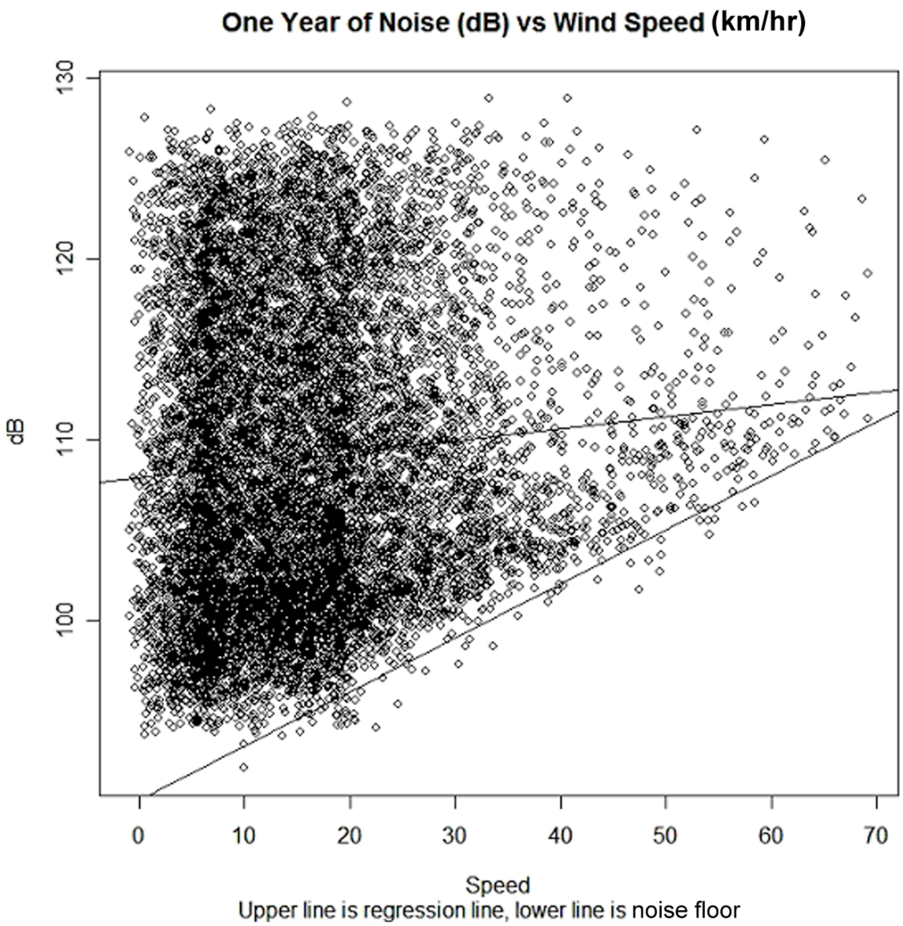

Figure 1: Scatter plot of broadband ½-hour average underwater noise (dB re 1 μ Pa) levels versus wind speed in km/hr. The lower line on the graph approximates the trend in quietest intervals (the "noise floor").

[3] See Appendix for details on regression line.
[4] The line drawn as the "noise floor" is approximate and is drawn so that >99.5% of the observed noise levels (dB) are greater than this floor.

In order to explore the noise floor, we examined the lower intensity data during each day of these observations. After calculating the mean and standard deviation for each day, we defined “quiet” noise data as observations that were more than one standard deviation below the mean for the day on which they occurred. In the following plot of these quiet data, the regression line had an R^2 of 0.12 which implies that the wind speed explained 12% of the variance[5]. The slope of this regression line (0.11 dB/km/hr) was about one-third of the slope of the noise floor.

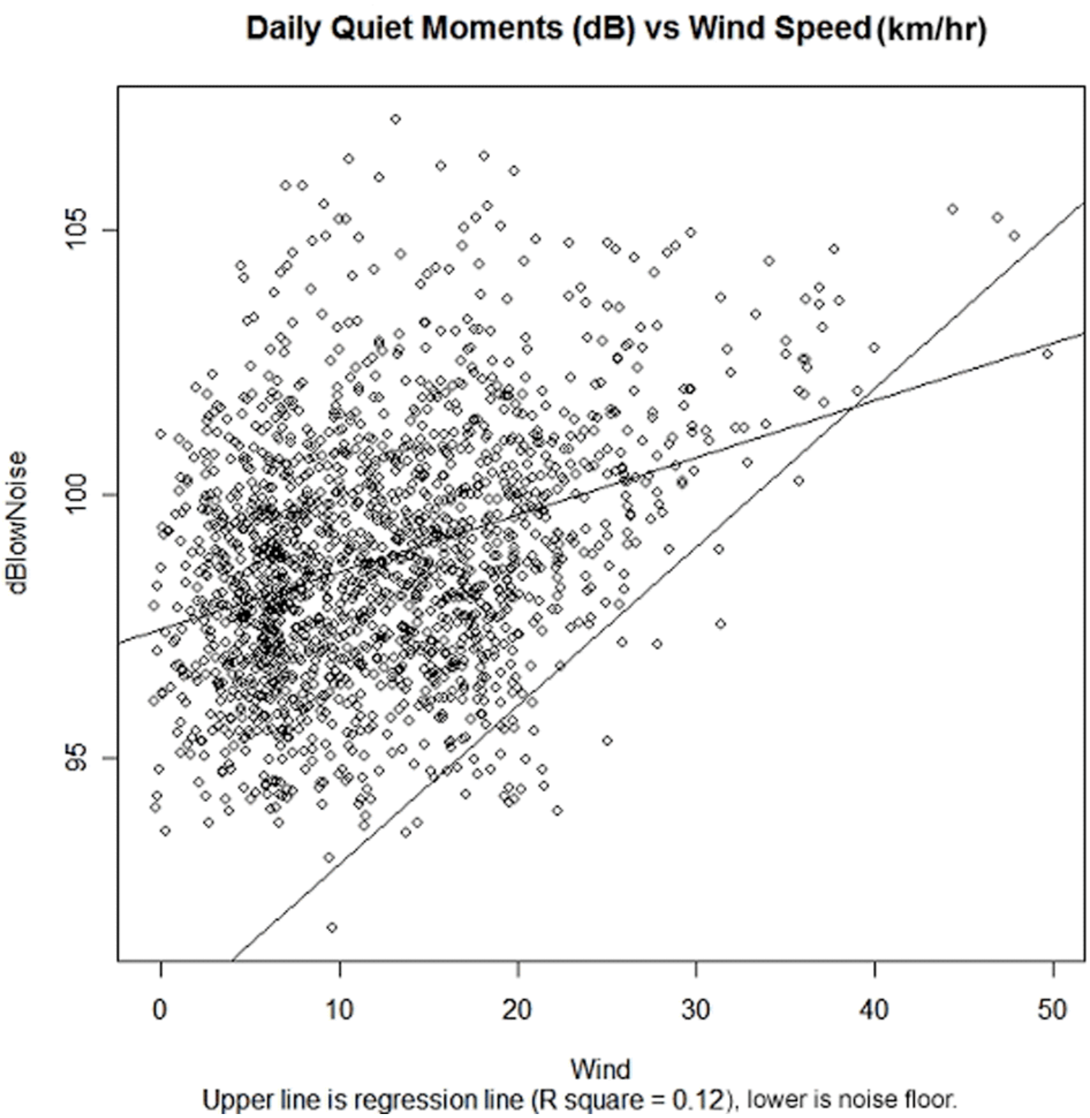

Figure 2: Scatter plot of wind speed versus quiet noise data. The upper line is a regression line (R^2=0.12) while the lower line estimates the noise floor.

Medwin and Clay observed that wind-generated noise in the open ocean has a peak intensity near ~500-? Hz and drops at about 20 dB re 1 μPa/$Hz^{1/2}$ per decade of frequency increase.[6].

[5] See Appendix for regression details.
[6] Medwin, H. and Clay, C., “Fundamentals of Acoustical Oceanography,” (1998), p. 213.

Figure 3 shows the frequency spectrum level at 500 Hz (dB re 1 µPa/Hz$^{1/2}$) for the “quiet” periods identified above. The straight line is the regression line and the curved line is the wind noise expected at 500 Hz out in the open ocean[7]. At 500 Hz, the minimum noise generated is consistent with the expected noise generated by wind[8].

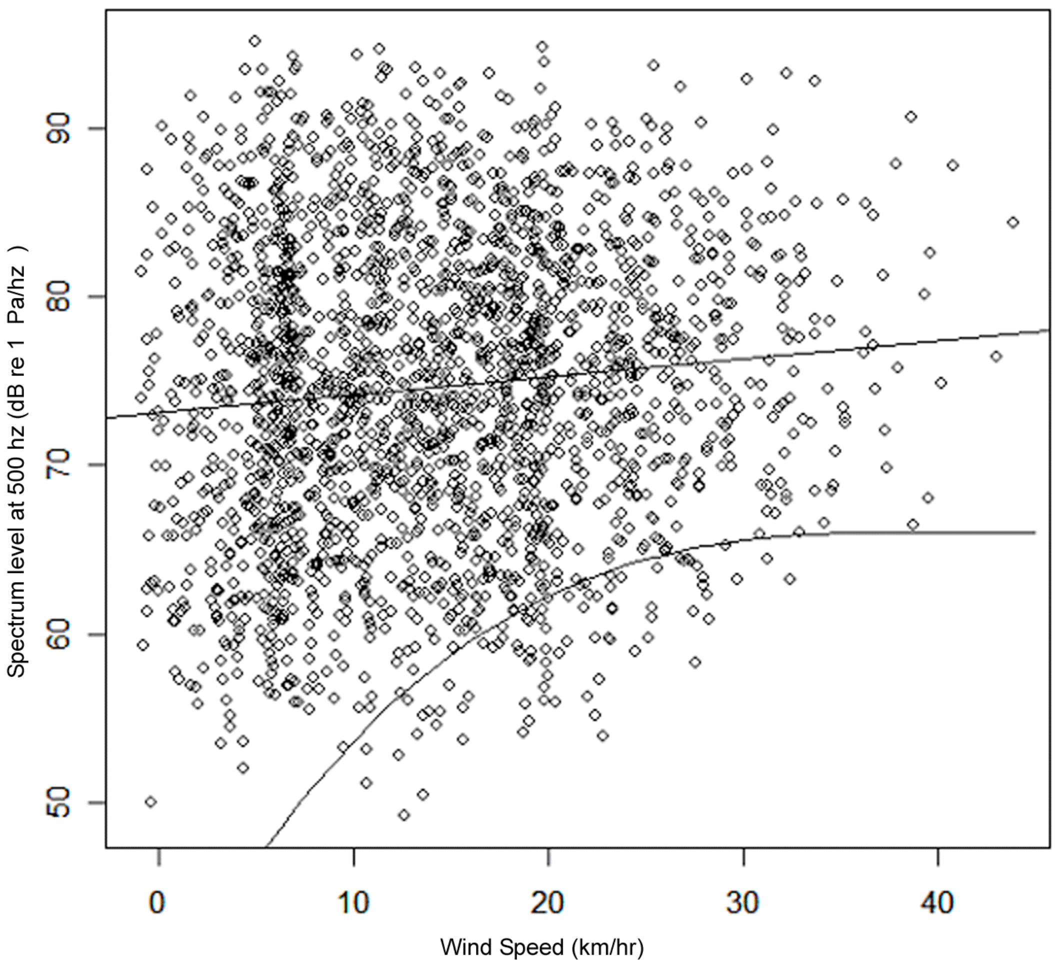

Figure 3: Spectrum levels at 500 Hz for the daily quiet periods versus wind speed. Upper line is a regression line; lower curve is the noise level at 500 Hz that is expected from wind.

Figure 4 shows the spectrum levels at 16 kHz versus wind speed for the quiet periods. Again, the expected noise from wind is comparable to the measured noise spectrum levels at that frequency[9].

---

[7] Interpolated from Medwin and Clay, op. cit.
[8] See Appendix for regression details and for details on interpolation of ocean wind noise.
[9] Details in the Appendix.

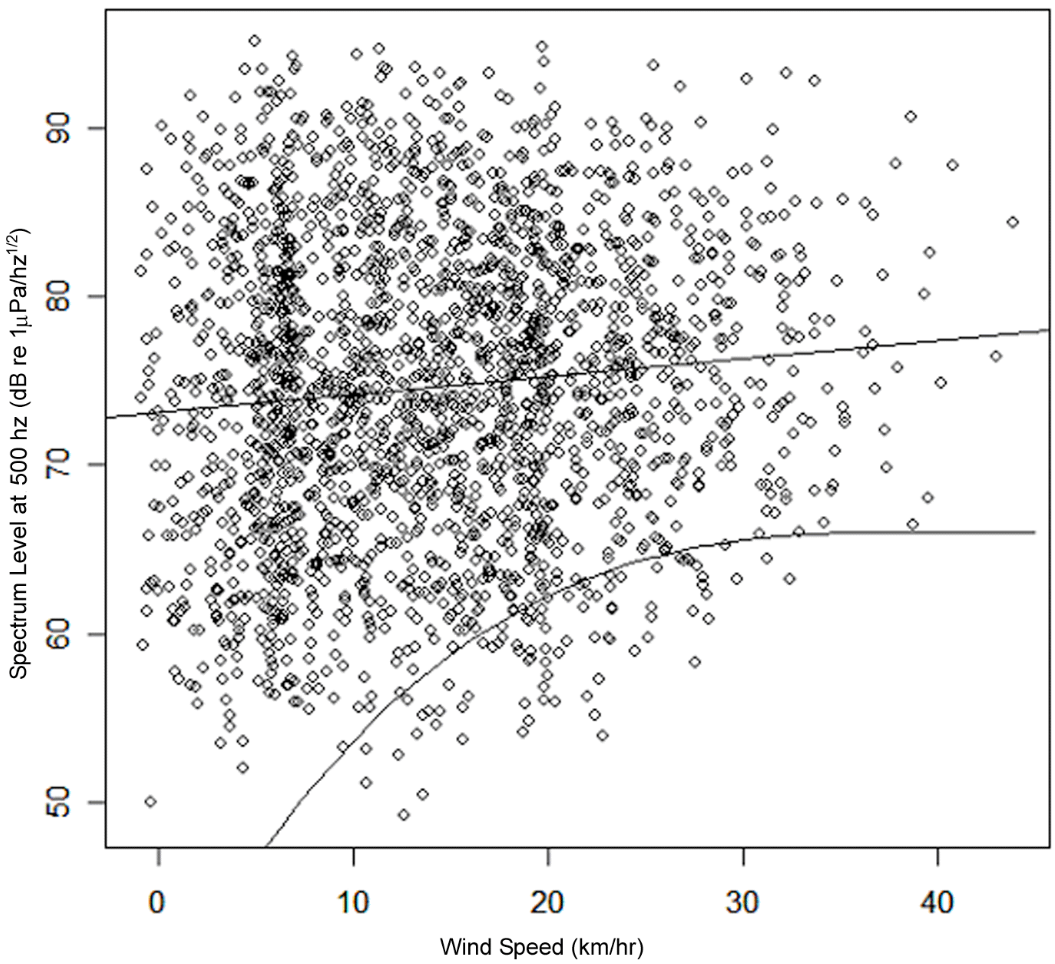

Figure 4: Spectrum level at 16 kHz versus wind speed (km/hr) again for the quiet periods. The straight line is the regression line and the curved line is the wind-generated noise expected at 16 kHz from wind in the open.

In summary, wind plays a minor role in the underwater noise budget of Haro Strait. The influence of wind is detectable only during quiet periods when ships and boats are not nearby. During a few half-hours periods each day, the background noise is dominated by wind. The majority of the time, ships and motorboats dominate the noise budget.

The relationship between noise and tidal height

We have not observed any relationship between underwater noise in Haro Strait and the state of the tide. In Figure 5, we plot all the sound data versus the height of the tide (feet) predicted at Kellett Bluff, a point about 2 nm north of OrcaSound. In Figure 6, we plot just those "quiet" data points selected as having levels less than one standard deviation below the daily mean.

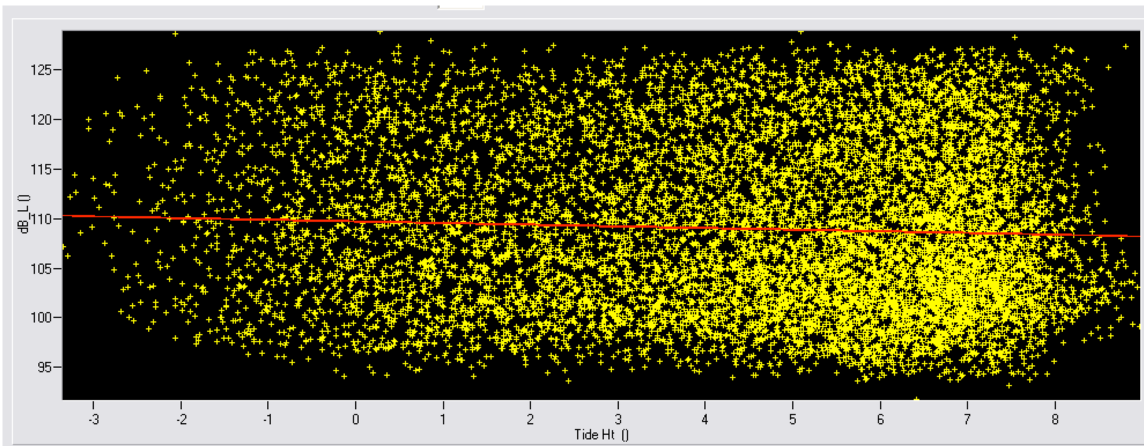

Figure 5: About 14,000 sound observations plotted versus the height of the tide . The red line is the linear regression line and shows that the tide explains none of the variation in the noise data.

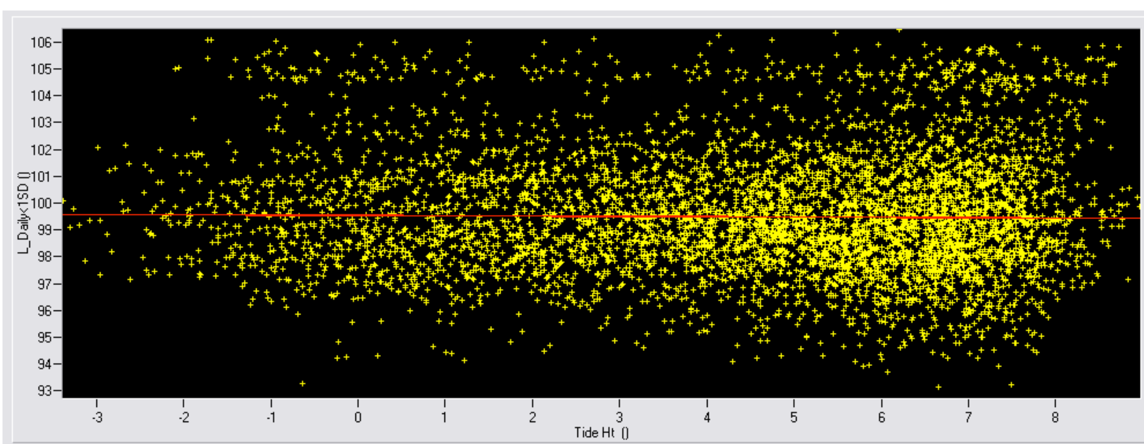

Figure 6: Plot of the quiet sounds on each day versus the height of the tide.

If tidal currents were having a significant impact on our underwater noise measurements, we would expect higher noise levels when the height of the tide is ~ 0 as this is usually when the current is strongest in Haro Strait. No such influence seems to exist in these data.

A second way to explore tidal effects on noise measurements is to examine the power spectrum of the time series of our underwater noise measurements. Figure 7 shows an analysis of the Kellett Bluff tide calculations which reveals the expected peaks at tidal frequencies.

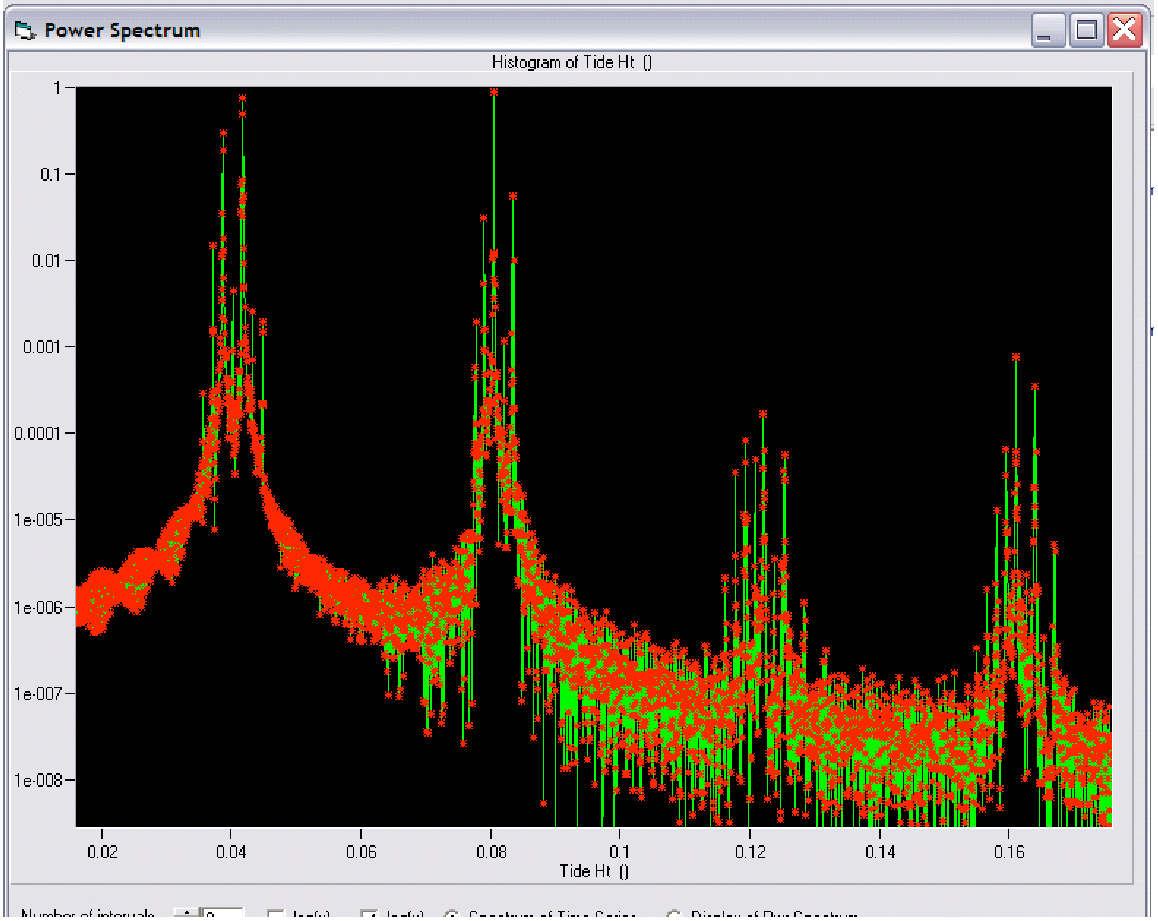

Figure 7: Power spectrum for the time series of the height of the tide in Haro Strait. The vertical scale is logarithmic and the horizontal scale is frequency in hr^{-1}. Note that 0.04 hr^{-1} is a period of 25 hr and 0.08 hr^{-1} is a period of 12.5 hr etc.

Figure 8 is a similar power spectrum, but for our underwater noise measurements. It contains no peaks at tidal periodicities, indicating that tides do not have a significant influence on the ambient noise level.

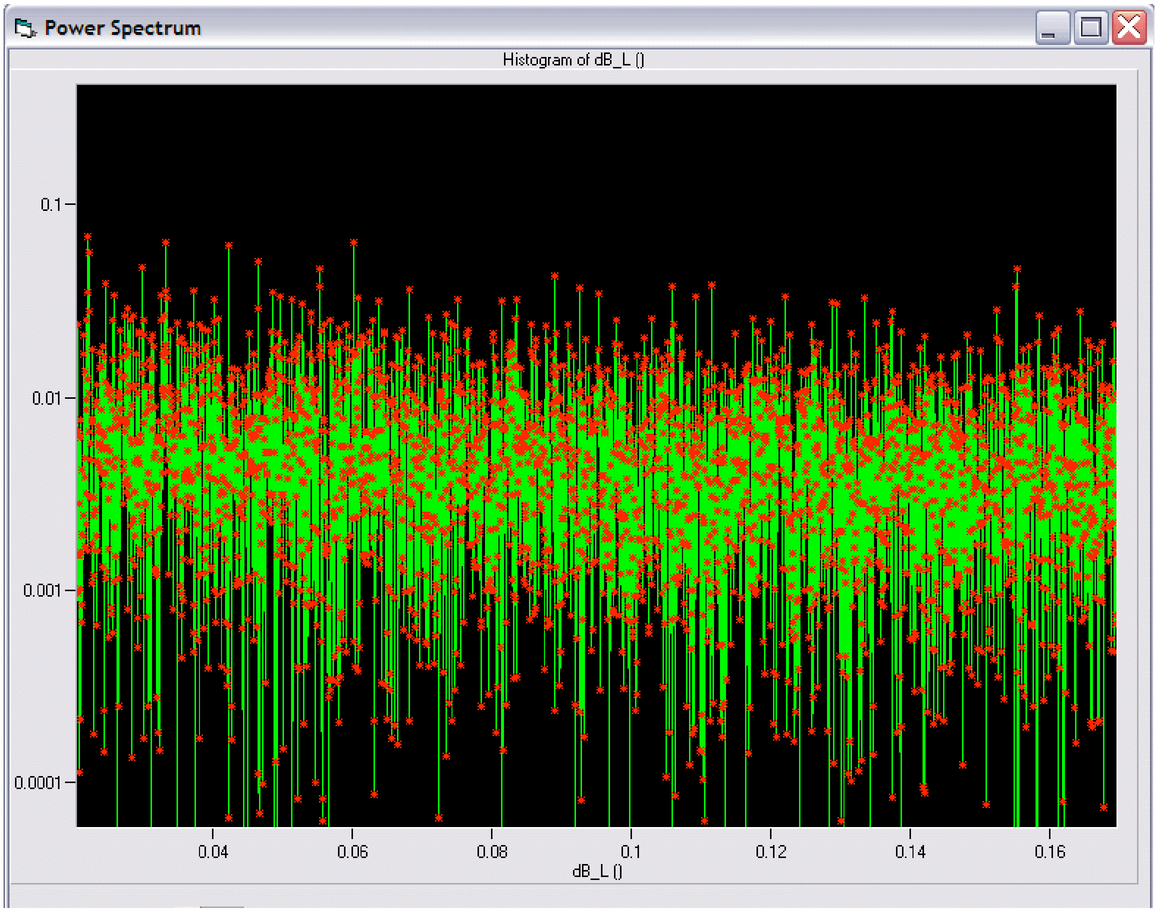

Figure 8: Power spectrum of the time series of underwater sound observations over the same frequency range for a year of noise measurements.

In summary, we do not observe a tidal influence on the time series of underwater sound level measurements acquired at OrcaSound. This result is somewhat surprising, given that the area is commonly swept by 1-2 m/s tidal currents. Nevertheless, we conclude that noise associated with tidal flow (turbulence, kelp or sand movement, and/or physical rattling) does not make a significant contribution to the Haro Strait sound budget.

Appendix: Regression statistics

Regression line calculation, using the statistical package R, for Figure 1.

```
lm(formula = dB ~ Speed)

Residuals:
    Min      1Q  Median      3Q     Max
-16.776  -6.926  -1.492   6.637  19.914

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept) 1.079e+02  1.443e-01 747.678   <2e-16 ***
Speed       6.744e-02  7.373e-03   9.147   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 8.224 on 10560 degrees of freedom
Multiple R-Squared: 0.00786,    Adjusted R-squared: 0.007766
F-statistic: 83.66 on 1 and 10560 DF,  p-value: < 2.2e-16
```

Here is the linear regression calculation for Figure 2:

```
lm(formula = Noise ~ Wind)

Residuals:
   Min     1Q Median     3Q    Max
-6.711 -1.545 -0.072  1.418  8.215

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept) 97.456171   0.102871  947.36   <2e-16 ***
Wind         0.107776   0.007117   15.14   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 2.206 on 1719 degrees of freedom
Multiple R-Squared: 0.1177,     Adjusted R-squared: 0.1172
F-statistic: 229.3 on 1 and 1719 DF,  p-value: < 2.2e-16

> summary(Wind)
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
-0.4336  6.4470 11.2800 12.3700 17.1400 49.7800
> summary(Noise)
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
  91.78   97.08   98.68   98.79  100.30  107.10
```

Linear regression calculation for Figure 3:

```
lm(formula = f.500 ~ Speed)
```

```
Residuals:
     Min       1Q   Median       3Q      Max
-25.2968  -6.5161   0.2881   6.7129  21.4459

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept) 73.16653    0.38052 192.281  < 2e-16 ***
Speed        0.10639    0.02294   4.639 3.71e-06 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 8.909 on 2186 degrees of freedom
Multiple R-Squared: 0.009747,   Adjusted R-squared: 0.009294
F-statistic: 21.52 on 1 and 2186 DF,  p-value: 3.714e-06
```

Interpolation of Medwin and Clay for Figure 3:

Calculation of wind noise model:

Get wind noise from “Fund. Of Acoustic Oceanography” p. 213

```
S
[1]  3.96  9.00 16.20 36.00 68.40
> dB_500
[1] 45 52 60 66 74

Set up a cubic “linear” model
S1=Speed
S2=Speed^2
S3=Speed^3

fCubicModel<-lm(dB_500~S1+S2+S3)

summmary(fCubicModel)

Call:
lm(formula = dB_500 ~ S + S2 + S3)

Residuals:
        1         2         3         4         5
 0.180358 -0.394713  0.252200 -0.041393  0.003548

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept)  3.723e+01  8.876e-01  41.941   0.0152 *
S            2.115e+00  1.424e-01  14.849   0.0428 *
S2          -5.147e-02  5.194e-03  -9.909   0.0640 .
S3           4.153e-04  4.882e-05   8.506   0.0745 .
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.5036 on 1 degrees of freedom
Multiple R-Squared: 0.9995,     Adjusted R-squared: 0.998
```

```
F-statistic:   682 on 3 and 1 DF,  p-value: 0.02814
```

Set up axis for graphing this model:

```
sAxis<-seq(0,45,1)
prediction<-3.723e01+2.115*sAxis-5.147e-02*sAxis^2+4.153e-04*sAxis^3
lines(sAxis,prediction)
plot(Speed,f.500)
```

Figure 4 regression calculations and interpolation:

```
lm(formula = f.16000 ~ Speed)

Residuals:
     Min       1Q   Median       3Q      Max
-26.8898  -6.6757  -0.1437   7.0172  25.8829

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept) 45.57617    0.39790 114.542   <2e-16 ***
Speed        0.21175    0.02398   8.829   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 9.316 on 2186 degrees of freedom
Multiple R-Squared: 0.03443,    Adjusted R-squared: 0.03399
F-statistic: 77.96 on 1 and 2186 DF,  p-value: < 2.2e-16
```

Wind model from "Fundamentals of Acoustical Oceanography" pg. 213

```
dB16000floor<-read.table("db_16000SpeedModel.txt",header=T)
attach(dB16000floor)
dB_16000
[1] 33 40 47 53 60
Speed
[1]  3.96  9.00 16.20 36.00 68.40
names(dB16000floor)
[1] "dB_16000" "Speed"
S1=Speed
S2=Speed^2
S3=Speed^3
floorMod<-lm(dB_16000~S1+S2+S3)
summary(floorMod)

Call:
lm(formula = dB_16000 ~ S1 + S2 + S3)

Residuals:
         1          2          3          4          5
 0.0254222 -0.0556365  0.0355487 -0.0058345  0.0005002

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
```

```
(Intercept)  2.589e+01  1.251e-01  206.98  0.00308 **
S1           1.970e+00  2.008e-02   98.11  0.00649 **
S2          -4.745e-02  7.321e-04  -64.82  0.00982 **
S3           3.793e-04  6.882e-06   55.11  0.01155 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.07099 on 1 degrees of freedom
Multiple R-Squared:     1,      Adjusted R-squared:     1
F-statistic: 2.971e+04 on 3 and 1 DF,  p-value: 0.004265

floorPredict<-25.89+1.97*sAxis-.0475*sAxis^2+3.793e-04*sAxis^3
lines(sAxis,floorPredict)
```

Here is a plot similar to that in Figure 5 using R: