

**Analysis of the ability of boat noise to mask killer whale
(*Orcinus orca*) communication through modeling**

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Literature Review:

Killer whales (*Orcinus orca*) rely underwater sounds for communication. These acoustics are broken down into three categories, clicks, whistles, and pulsed calls. Clicks are brief pulses of sound, typically used in succession as a method of echolocation (Au et al. 2004). They have no particular pattern and vary in structure, duration, and intervals (Ford 1989). In comparison, whistles and calls are used for communication. Thomsen et al. (2002) found that in northern resident killer whales, whistles are primarily used during social interactions and close-range communication whereas calls are for the most part used in long-range activities and when individual whales are widely dispersed. Whistles are identified as a continuous waveform; a tonal sound with little to no harmonics associated with it. Ford (1989) also determined that whistles occurred most frequently between frequencies 1.5 and 18 kHz. Calls are the most commonly produced vocalizations by killer whales. They are burst-pulsed tones that often contain varying pulse rates and patterns. This variance results in a large number of individually distinctive calls (Thomsen et al. 2002).

There are three essential parts to mammalian hearing, the outer ear that captures sound, the middle ear that filters and amplifies sounds, and the inner ear or cochlea that is a band-pass filter (Ketten 1994). Killer whales receive sound through their lower jaw, soft tissue and bone surrounding the ear. They have the broadest acoustic range of any known mammal group (Ketten 1994). While whale's inner ears are similar physically to humans, their external ears are nonexistent, and their middle ears are drastically different (National Research Council 2003). This is due to the evolutionary adaptations to an

aquatic environment. Killer whales do have small exterior ear holes, which are located a few centimeters behind the eye.

The direction of boat noise in relation to the perception organs of a killer whale can have an effect on the masking ability of the sound. Masking is defined as the obscuring of sounds of interest by interfering sounds, generally at similar frequencies (Richardson et al. 1995). It has been found that a noise made in the front of a whale has a greater masking potential than noises to the side of or behind a whale (Williams et al. 2002).

Audiograms are used to determine how well an individual can perceive varying sound frequencies. Szymanski et al. (1999) measured audiograms for two trained adult female killer whales using behavioral responses and auditory evoked potentials (AEPs). Before this study, there were no published experiments comparing the behavioral and AEP audiogram of the same individual. This comparison can help to determine the threshold, or the minimum amount of stimulus power needed to evoke a response greater than background noise, of killer whales (Elberling and Don 1987).

In this study, each killer whale responded to stimuli at frequencies between 1 and 100 kHz, with the most sensitive frequency being 20 kHz. From this, Szymanski et al. (1999) defined a sensitivity range at 10 dB from the most sensitive tone, making the range 18 to 42 kHz. The results from the behavioral audiogram and the audio brainstem response (ABR) audiogram were relatively consistent. The behavioral audiogram had a mean of 12 dB more sensitive at each frequency than the ABR audiogram, however, in the sensitivity range, it was only 5dB more sensitive (Szymanski et al. 1999). This

information holds great significance in determining the masking effects of vessel created noise on the communication between killer whales. However, this data was collected from only two individuals and thus little is known about intraspecific sensitivity threshold variability (Richardson et al. 1995).

In 2004 there were an average of 22 boats following the whales on any given day during daylight hours. This number has increased over time while the population of whales has been decreasing over time (Foote et al. 2004). The southern resident population decreased by 17% between 1995 and 2001, making the current population about 86 individuals (NRS 2005). Soundwatch, a boater education program operating out of The Whale Museum in Friday Harbor Washington, spent 66% of their time on the water doing whale watch surveys. The distribution of vessels when whales were present from May to September 2005 was as follows: Canadian commercial whale watching boats 28%, private whale watching boats 24%, US commercial whale watching boats 13%, Kayaks 18%, Private fishing vessels 7%, research vessels 7%, aircraft 5%, and shipping vessels 2% (Koski 2005). These figures are significant for this experiment as it is a numerical representation of the types of boats that are present with the whales, and thus important in determining the different underwater sounds produced.

Both large and small boats create noises at frequencies that overlap with killer whale hearing and vocalization ranges (Galli et al. 2002). It has been determined that specific types of boats and engines make these noises within the hearing threshold of killer whales. However, what is not known is the effect it has on the ability of whales to communicate with one another, and at what distance it has the greatest effect.

Background noise can have a large impact on the ability of a species to sense and differentiate acoustical signals from another individual. In essence, background noise, specifically anthropogenic sound has the potential to interrupt communication within a species. Masking of meaningful sounds or damaged hearing could occur. Hearing loss could be a temporary threshold shift (TTS) or permanent threshold shift (PTS) (Griffin and Bain 2006). In a study by Foote et al. (2004) it was found that all three southern resident killer whale pods increased the duration of their calls when there was significant boat traffic in the vicinity. It also states that initially there was no change in call length but as the number of boats increased, notably fivefold between 1990 and 2000, the call duration did increase. It was concluded from this that the whales adjusted to the increase in anthropogenic noise only after it had reached a threshold level. Other strategies to prevent acoustic communication from being masked by vessel noise once it has surpassed a critical level could be to change the frequency, amplitude, or number of repetitions of calls. Another study looking at potential effects of boats on killer whales using an acoustic impact model found that if whales were exposed to noise close to the critical level over a prolonged period of time it could experience permanent hearing loss (Erbe. 2002).

Boat traffic can also have an effect on the behavior of the killer whales. Northern resident killer whales were found to alter their behavior when there was a strong presence of boats. In females, swimming speed increased by 25% and the mean angle of deviation between surfacing increased by 29%. In males, they traveled in paths that were less direct than when not surrounded by boats (Williams et al. 2002). These changes in behavior

could impact the stress level, energy level, and thus nutritional health and foraging tactics of the animal.

Studies on this subject will be helpful in planning the most appropriate course of action for recovery and conservation of killer whales. This study may shed light on management approaches as well as the appropriateness of the 100m rule as it was not based on any scientific data. It also may highlight the need for more legally binding guidelines, and for development of new boat technologies that would mitigate what is determined to be the most harmful underwater sounds. Since this population is endangered and down to around 86 individuals, protection is important for many reasons, including the intrinsic values of the species, genetic variation, as well as keeping the larger functioning ecosystem in balance.

The objective of this experiment is to see if underwater sounds created by different vessels have the ability to mask vocalizations made by killer whales. This is very important in determining if anthropogenic noise has an effect on the ability of biologically significant killer whale calls to be heard and at what distances it has the greatest effect. The motivation for this research is to determine what steps can be taken to lessen the impact that people, whether engaged in research, whale watching, private boating, fishing, or commercial shipping, have on the Southern Resident killer whales.

Materials and Methods:

Study Area-

This experiment was conducted between August 21 and October 29, 2006. The research was completed on the southern resident fish eating killer whales in the northern

inland waters of Washington and British Columbia. The platform was a 42-foot bio diesel electric catamaran, the Gato Verde.

Attenuation-

To determine the correct spreading equation to use for this project, the dinghy, a NOAA marine rescue pipe and hammer were deployed. A series of 10 pipe pings were recorded at ten, 25, 50, and 75 meters away. Each time the dinghy and pipe was positioned on the same axis. The pings were then individually isolated and saved as one-second wave files. Each ping file was imported into MatLab, a cross correlation was then done and each file was moved the appropriate amount so that the max cross correlations lined up. These 10 aligned files were then stacked (summed). Since the stacking increased the amplitude above 1 each stacked file was divided by 1.7 to avoid clipping, and then saved as a wave file. The RMS amplitude of the stacked ping at each distance was then determined using Raven. The selection taken to find the RMA amplitude was 0.175 seconds long, starting just before the beginning of each ping (J. Wood, Pers. Comm.).

Boat Data-

A single towed omni directional long-life receiver hydrophone (ITC-4066) was used to continuously record acoustic activity when with the whales. The hydrophone was connected to a custom pre-amp power source. Ten-minute files were recorded onto a Marantz, a digital solid-state recorder with a constant gain setting. The hydrophone was calibrated using a F-42b hydrophone Navy calibrated blue box as a tanker passed by. From this a calibration factor to determine the received pressure level in dB re 1 microPascal was found: $dB = 20 * \log_{10}(RMS) + 66.42$

Boat counts were used from a fellow Beam Reach student project (Escebedo BeamReach 2006). The total number of boats and the number of boats motoring were taken. Using the recorded acoustic data from the single towed hydrophone, the received pressure level of the background noise was determined. The RMS amplitude was calculated for a minute sample using the sound analysis program Raven. This minute is determined as 30 seconds before and 30 seconds after the time of each boat count. From the RMS amplitude, the received pressure level calculated using the calibration correction factor. Five boat clips were used as representative levels of boat noise for modeling the zone of masking. The clips picked were equidistant apart and spanned the range of received pressure levels. Each was then classified as “low”, “low-medium”, “medium”, “high-medium”, and “high” levels.

Calls-

Fifteen southern resident call audio files and their corresponding three-dimensional locations were obtained from Dr. Val Veirs. These calls were recorded on a four element stationary array along the shore of the west side of San Juan Island. The array consists of one ITC-6050C hydrophone and three ITC- 4066 hydrophones (Veirs, Draft).

The peak frequency was found for every call. The critical bandwidth used for this experiment was $1/6$ of an octave around standard center frequencies. This was chosen in reference to what is known for other dolphin species, as there is limited research on the critical bandwidths of killer whales (Finneran 2002). Each of the calls was then filtered between the upper and lower frequency range of the bandwidth that its peak frequency fell in. The RMS amplitudes and then received pressure levels were found. The source level of each filtered call was then found taking into account their individual locations and spherical spreading loss.

Modeling-

The distance at which the call would be masked or the distance at which the signal to noise ratio (SNR) would equal zero was determined for each of the levels of boat noise. To do this, each of the boat noise clips was filtered with the same 15 bandwidths as the calls. The RMS amplitude and the received pressure levels were found for each of the filtered clips. Using the source level of each call and the received pressure levels at each level of boat noise the distance at which the SNR would equal zero was found. Assuming that:

$$\text{SNR (0)} = \text{Received Level}_{\text{Call}} - \text{Received Level}_{\text{Boat}}$$

and,

$$\text{Received Level}_{\text{Call}} = \text{Source Level}_{\text{Call}} - (20 \times \log_{10} (R)),$$

The equation $R = 10^{((- \text{Received Level}_{\text{Boat Noise}} + \text{source level}_{\text{Call}}) / 20)}$ was used to find the distance.

To account for the fact that all of the data collected is taken from a position on the boat and not at the exact location of the whales, it is assumed that our location is a whale trying to receive a call and the distance where the SNR equals zero is the distance from which another whale is calling where it will be masked by boat noise.

The same analysis was done for five of the 15 calls and the five boat levels but instead of using 1/6 octave bandwidth filters around standard center frequencies, the calls and boat clips were filtered according to the width of each call. The width of each call was defined as the frequencies between the highest and lowest harmonics.

Results:

To determine the spreading loss equation to use, the log of the distance was plotted against the amplitude in dB of the stacked pings. The slope of the trend line was found to be -21.5 (Figure 1). Spherical spreading uses 20 so that equation was used for this experiment: $dB_{Source} = dB_{Received} + 20\log_{10}R$.

A total of 73 boat counts were taken. The unfiltered received pressure levels of the corresponding 73 minute long boat clips ranged from 120.5 dB to 140.4 dB with an average of 131.2 dB. The “low” level of boat noise was 120.5 dB, “low-medium” was 127.5 dB, “medium” was 131.2 dB, “high-medium” was 133.9 dB, and the “high” level of boat noise was 140.4 dB.

The “medium” level of boat noise was filtered at all the consecutive 1/6 octave bandwidths ranging from the lowest band a calls peak frequency fell in to the highest band in which a calls peak frequency fell. Even if no calls peak frequency fell within one of the consecutive bands, the boat clip was filtered with that band. The center frequency of each band was then plotted against the received pressure level of the call filtered at different bandwidths. (Figure 2) This shows at what bands, most of the energy from the boat noise is concentrated.

The average distance at which the SNR equals zero for each level of boat noise was plotted against the received level of boat noise at each center frequency (Figure 3). Judging from the distribution of energy in figure 2 the higher the center frequency, the greater the distance the signal will travel until the SNR reaches zero. Figure 3 is not consistent with that due to the varying source levels of each call. The same plot was constructed but the source level of each call was set at 165.0 dB re 1 microPascal @ 1

meter, or the average of all 15 source levels (Figure 4). This is consistent with figure 2 in that the lower the center frequency the shorter distance the call will travel before it is masked.

The average distance where the SNR equals zero of all 15 calls filtered using 1/6 octave bandwidths for “low” boat noise is 7794.1 m, “low-medium” is 1916.3 m, “medium” is 1660.0 m, “high-medium” is 1813.7, and for the “high” level of boat noise it is 541.2. Figure 5 shows these means with 95% confidence level. The average distance where the SNR reached zero for the five of the 15 calls filtered the width of each call for “low” boat noise is 5664.1 m, “low-medium” is 1708.0 m, “medium” is 1323.7 m, “high-medium” is 1734.6, and for the “high” level of boat noise it is 399.8. Figure 6 shows these means with 95% confidence level (to see all the distances along with the corresponding source levels and received pressure levels of boat noise for both the 1/6 octave filter and the width of the call filter see tables 1 and 2)

The average distance where the SNR equals zero for the same five of 15 calls were found for both the 1/6 octave bandwidth and for the width of the call. These means with 95% confidence level were compared (Figure 7).

Discussion:

There has been a significant increase in the number of boats around the whales in the past years. In this study, strong relationship between the number of boats and the amount of noise was not found (Figure 8). However that count did not take into consideration boats further than five hundred meters from the boat, the type, motoring state, or style of engine. In fact, in this figure, it shows that in general, as the number of boats increased, the received pressure level decreased. A more accurate way to look at it

is the correlation between the number of boats motoring and the amount of noise (Figure 9). This does not have a strong relationship either, but as the number of boats motoring increases, so does the received pressure level. To determine more precisely this relationship, more variables such as boat type, motor type, speed, direction, and distance from the boat should be taken into consideration for all boats within acoustic range. The boat data for this experiment was taken in the off-season so the amount of boat noise may not be the best representation of the boat traffic in the summer months when it is at its peak.

Throughout this study, the calculated received pressure level of boat noise took into consideration all the noise in the clip. The ambient noise was not subtracted out, which may account for the higher levels of boat noise found in this study as compared to others. In addition, the background noise during each recording could have been different due to varying locations, weather conditions, and travel speeds. For example, the faster the hydrophone was being towed, the greater potential there was for flow noise. Because of these factors, ambient noise may have contributed different degrees to each recording thus having varying slight impacts on the received pressure levels of boat noise calculated.

The average level of boat noise recorded was filtered and graphed against the center frequency of the bandwidth (Figure 2). From this, the distribution of the energy in the boat noise was found to be greatest at the lower frequencies generally decreasing as the frequency increases. Using five levels of recorded boat noise, and fifteen different calls, the distance at which the call would be masked was found (Figure 5). The lower the boat noise is, the more dependant the masking distance is on source level of the call. This is

determined by the much larger range of masking distances at the lower level of boat noise. With that being said, the 1/6-octave bandwidth source levels filtered around their peak frequencies used in this project ranged from 151.6 dB to 184.9 dB with a mean of 165.2 dB. This is higher than source levels used in other research. Erbe 2002 used between 105-124 dB and Miller 2006 found the source level for whistles to be 140.2 ± 4.1 dB, variable calls to be 146.6 ± 6.6 dB, and stereotyped to be 152.6 ± 5.9 dB (all source levels re 1 micro Pascal @ 1 meter). This may be due to the fact that in this project the source level was found for the part of the call with the greatest amplitude and that the recording conditions may have been different, so the amount of background noise behind calls could affect the source level.

The critical ratio, or the difference between source level and the level of background noise within the critical bandwidth (Richardson et al. 1995), is not known for Southern Resident killer whales as tests to determine this need to be done in captivity. This project assumed that a call will be masked when the SNR equals zero, however, it is possible that a whale may be able to interpret biologically significant calls when the critical ratio is somewhere above or below zero.

Another factor that is unknown is the critical bandwidth of Southern Resident killer whales. Erbe 2002 used 1/12-octave critical bandwidths and Miller 2006 used 1/3-octave critical bandwidths. 1/6-octave critical bandwidths were used for this analysis, as it is known to be the critical bandwidth of a related dolphin species. This was the best estimate of how similar in frequencies the call and boat noise must be in order for auditory masking to occur. Regardless of the critical bandwidth, how much of a call a whale need to hear in order to understand the meaning of the call Because of this it may

not be appropriate to filter around the peak frequency as the masking distance found would be the greatest possible distance the call could be heard without the accompanying harmonics. That is why the distance where the SNR equals zero was also found using a filter the width of the call, thus including all harmonics. The combined histogram shown at the 95% confidence level does not look to be statistically significant (Figure 7). However, the masking distance is greater when filtered 1/6 octave around the peak frequency compared to when filtered the width of the call at all five levels of boat noise. Also, even if the difference is not statistically different, it could still be biologically significant for the whales.

Other variables included in modeling that were tested in this project were attenuation and the depth profile of the speed of sound. The spreading equation used in this experiment was spherical as determined by the Figure 1. The speed of sound at different depths was taken at two different locations (Figures 10 & 11). This remained fairly constant at the different depths and locations.

Factors that were not taken into consideration in this model are surface absorption, bottom absorption, the bathymetry, and frequency dependent spreading. The decibels lost per kilometer from frequency dependant absorption is $\alpha = 0.036 f^{1.5}$. This would have a significant effect at 50 kilometers, which is the maximum masking distance found in this experiment.

From an evolutionary standpoint, if the number of boats around the whales remains constant or continues to follow the current trend and increase, the boat noise that the whales must communicate over may cause them to alter their communication habits.

Since the majority of the energy in boat noise is concentrated in the lower frequencies, in order to avoid those frequencies, the whales may move their peak frequencies higher. They may increase the source levels, change the harmonic structure, increase the duration, or repeat their calls more to combat boat noise. Also, increased levels and exposure to boat noise may cause temporary threshold shifts or even permanent threshold shifts. All of these changes could potentially increase the energy usage of each whale, adding more stress to an already endangered species.

On the other side, there are steps that can be taken to reduce the amount of underwater noise created by boats. The boat from which all recordings for this project were made ran using an electric motor. The propulsion system of the Gato Verde creates minimal underwater noise and creates fewer harmful emissions than the standard diesel motors. Another way to manage the level of boat noise as well as the time the whales are exposed to this noise is to enforce legally binding guidelines for motoring around the whales, or to reexamine the “Be Whale Wise Guideline”, specifically the 100 meter rule.

In conclusion, there are many variables that have an effect on auditory masking. Some but not all of those variables were examined in this project to determine the distance where communication between Southern Resident killer whales would be masked by varying levels of boat noise. Further research to include all variables will give us a better idea of masking in killer whales. However, we still do not know which of these variables is the most biologically significant.

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Appendix:

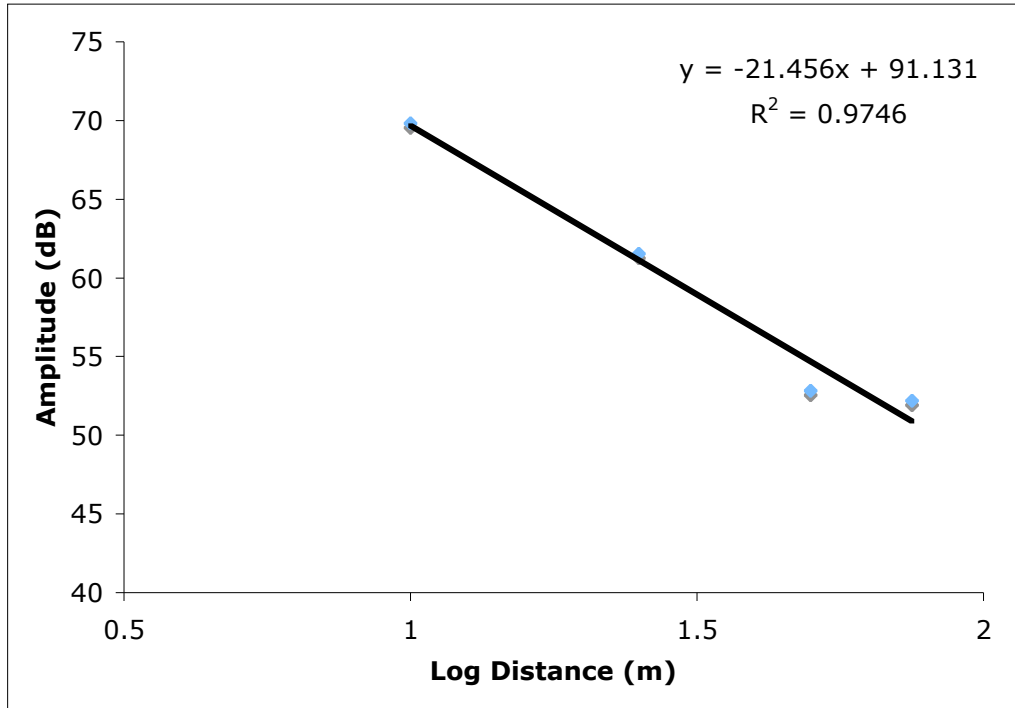


Figure 1: RMS amplitude of four pipe pings at 10, 25, 50, and 75 meters taken over 0.15 seconds starting at the beginning of the ping. Ten pings recorded at each distance were stacked to improve SNR.

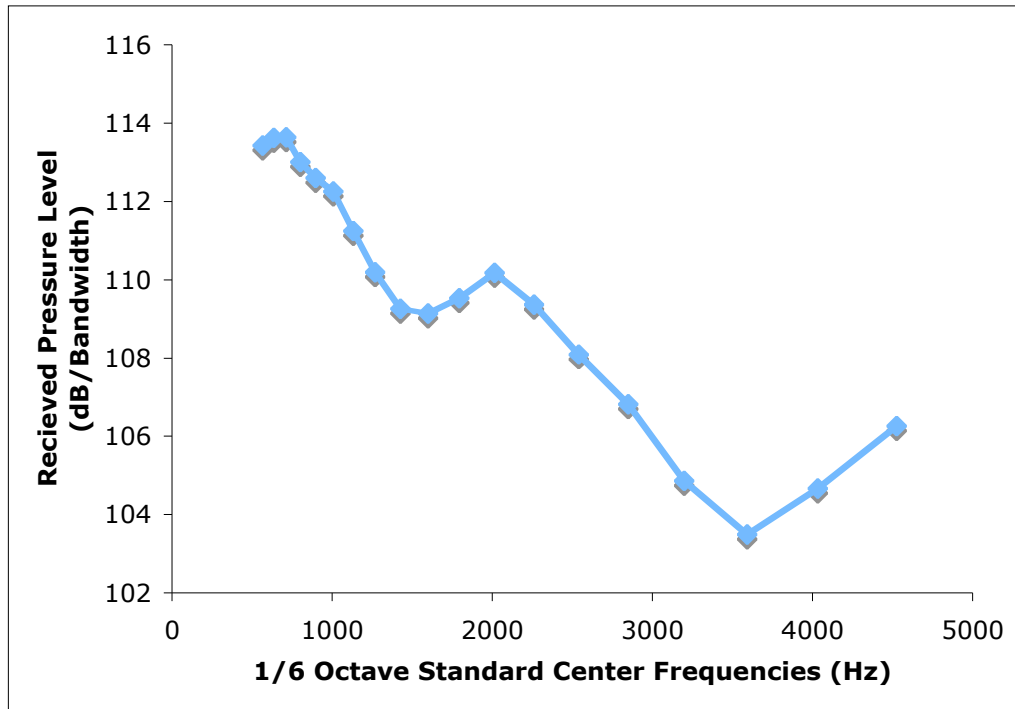


Figure 2: Received pressure level of the “medium” (average) sample of boat noise filtered at each critical bandwidth within the range of peak frequencies for each call. This shows the impact of boat noise across frequencies of interest.

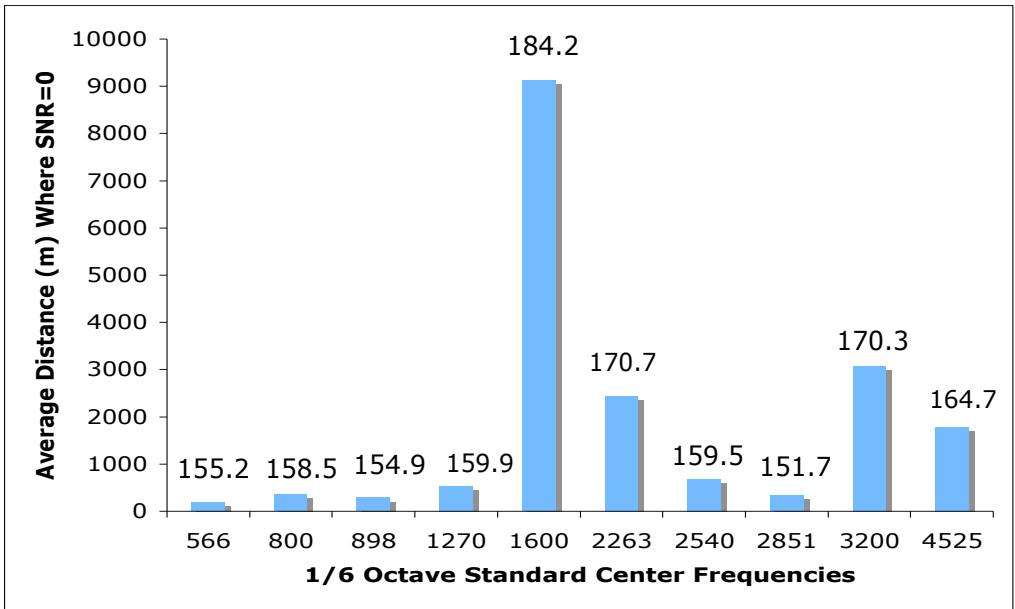


Figure 3: The received pressure level and average distance where the SNR reaches zero for each level of boat noise at each center frequency. The numbers above each bar represent the source level re one microPascal at one meter for a call at that center frequency.

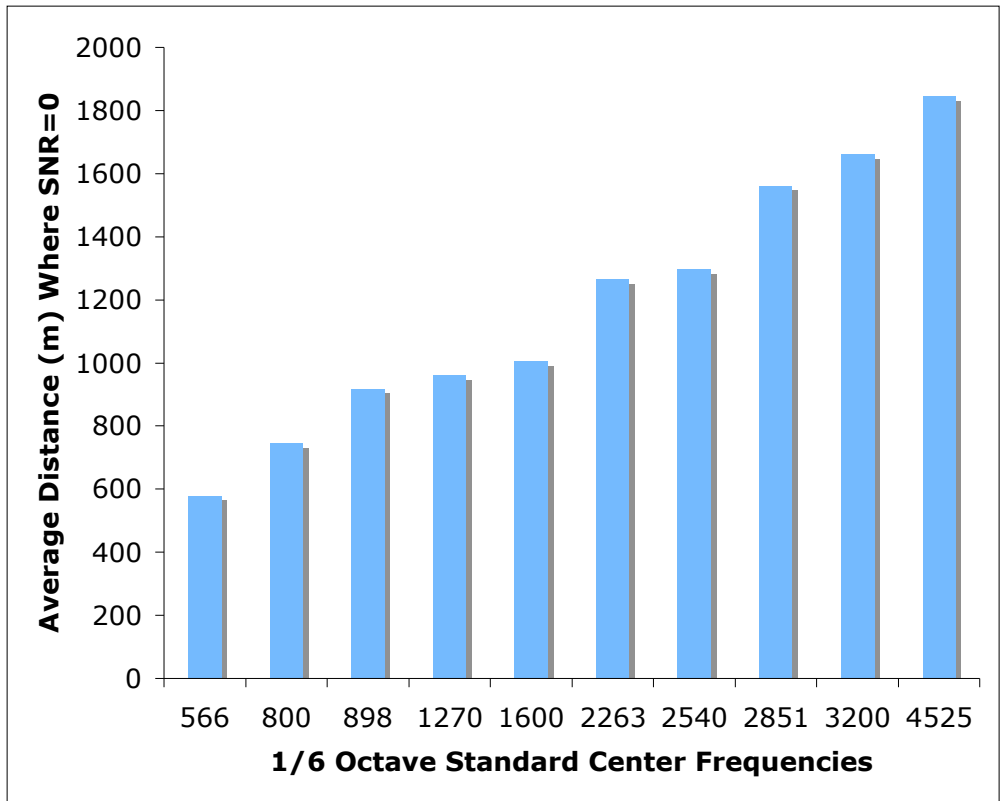


Figure 4: The received pressure level and average distance where the SNR reaches zero for each level of boat noise at each center frequency. The source level was kept constant at 165.0 dB (average) to show the relationship between the masking distance and the center frequency.

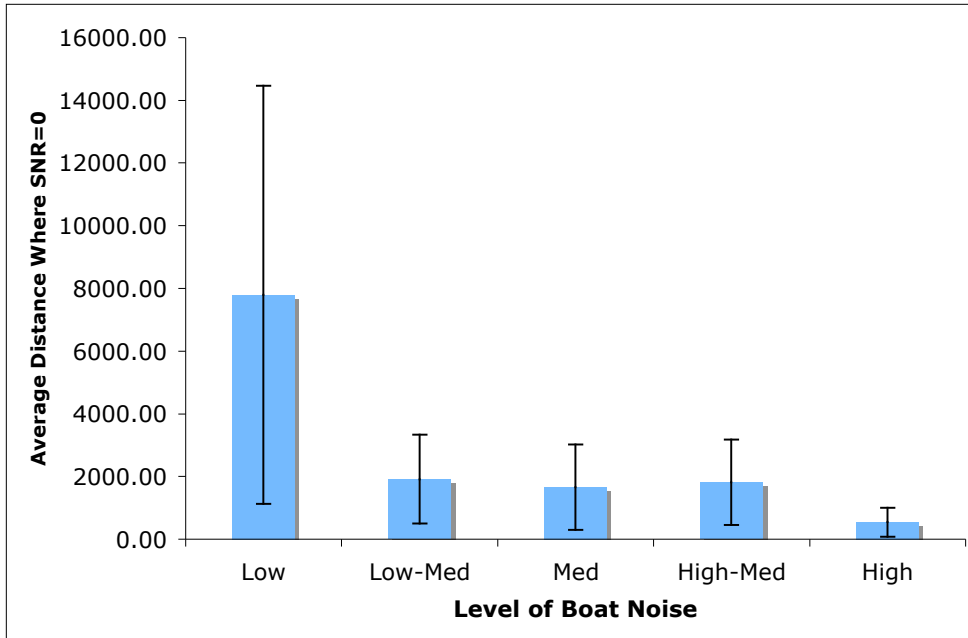


Figure 5: Average distance where the SNR reaches zero at the different levels of recorded boat noise. The 15 calls and each of the five boat clips were filtered at 1/6 octave bandwidths around standard center frequencies. The bars represent the 95% confidence level.

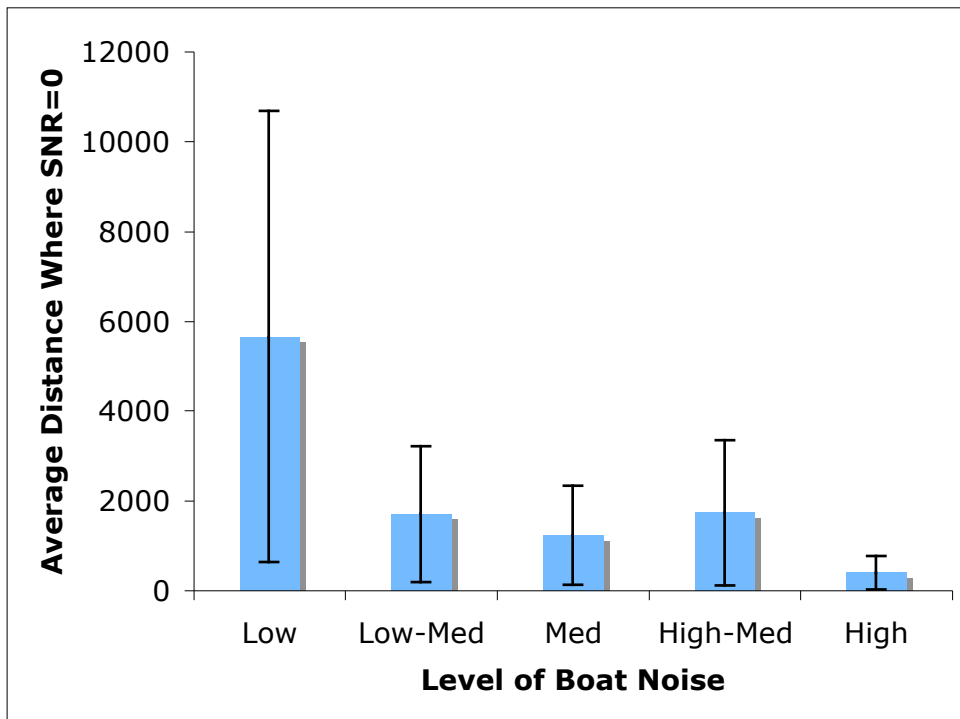


Figure 6: Average distance where the SNR reaches zero at the different levels of recorded boat noise. Five calls and each of the five boat noise clips were filtered the width of the harmonics in the call (i.e. much wider bandwidth than 1/6 octave bandwidths). The bars represent the 95% confidence level.

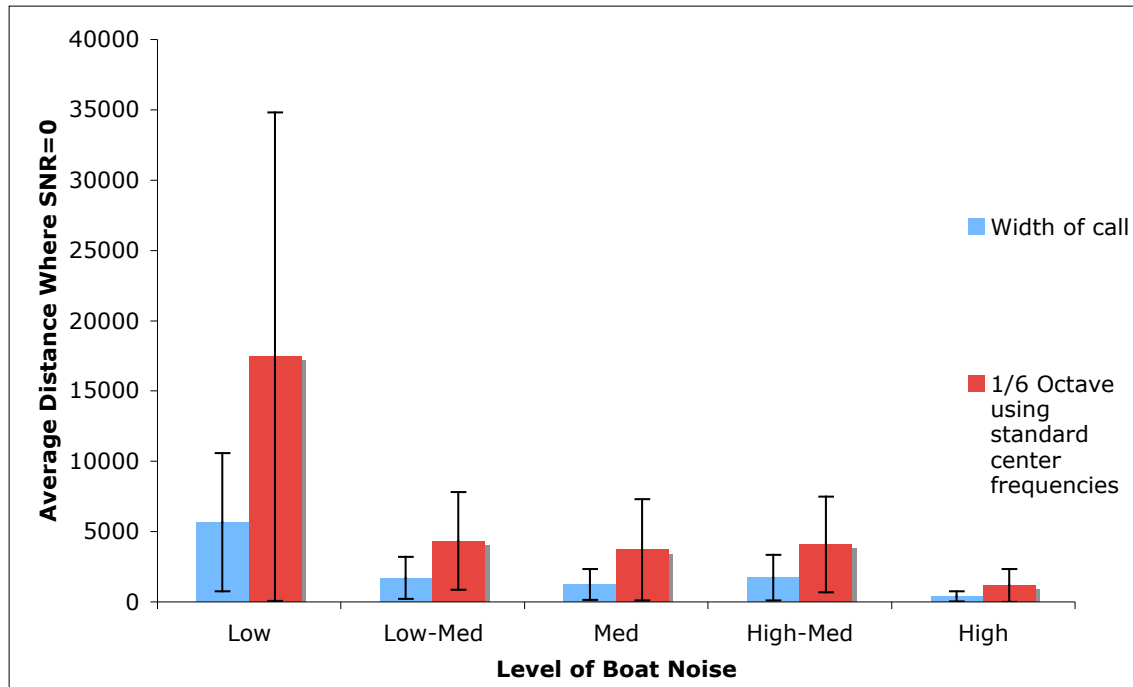


Figure 7: Combined average distance where the SNR reaches zero at the different levels of recorded boat noise. The average distance was taken from the same five calls filtered both the width of each call and 1/6 octave using standard center frequencies. Bars represent the 95% confidence level.

Table 1: Filtered source level of calls re 1 microPascal @ 1 meter and filtered received level of low, low-medium, medium, high-medium, and high levels of boat noise for each call using 1/6 octave bandwidth around standard center frequencies. Distance was determined using the equation for spherical spreading:

$$\text{Distance} = 10^{((- \text{Received Level}_{\text{Boat Noise}} + \text{source level}_{\text{Call}}) / 20)}$$

Level of Boat Noise	Call	Lower Frequency of Bandwidth (Hz)	Upper Frequency of Bandwidth (Hz)	Source Level of Call (dB)	Recived Level of Clip (dB)	Distance Where SNR=0
Low	1	1200.65	1347.68	172.69	98.57	5083.00
	2	3025.44	3395.94	184.91	90.82	50655.43
	3	2139.31	2401.29	163.40	93.88	2994.47
	4	4278.62	4802.58	164.71	90.06	5400.57
	5	1512.72	1697.97	184.17	96.89	23102.01
	6	2139.31	2401.29	167.18	93.88	4626.81
	7	2139.31	2401.29	170.73	93.88	6957.31

	8	756.36	848.98	158.53	100.97	754.64
	9	2695.36	3025.44	160.30	91.33	2808.72
	10	3025.44	3395.94	170.33	90.82	9449.09
	11	1200.65	1347.68	159.92	98.57	1167.69
	12	848.98	952.95	154.89	99.35	598.77
	13	534.83	600.32	155.18	104.81	330.02
	14	2401.29	2695.36	159.47	93.69	1944.94
	15	2695.36	3025.44	151.66	91.33	1038.34
Low-Medium	1	1200.65	1347.68	172.69	105.82	2206.45
	2	3025.44	3395.94	184.91	105.68	9159.91
	3	2139.31	2401.29	163.40	105.64	773.19
	4	4278.62	4802.58	164.71	101.38	1465.87
	5	1512.72	1697.97	184.17	106.04	8062.77
	6	2139.31	2401.29	167.18	105.64	1194.67
	7	2139.31	2401.29	170.73	105.64	1796.42
	8	756.36	848.98	158.53	111.66	220.33
	9	2695.36	3025.44	160.30	105.61	542.63
	10	3025.44	3395.94	170.33	105.68	1708.66
	11	1200.65	1347.68	159.92	105.82	506.88
	12	848.98	952.95	154.89	108.27	214.43
	13	534.83	600.32	155.18	108.76	209.51
	14	2401.29	2695.36	159.47	105.80	482.58
	15	2695.36	3025.44	151.66	105.61	200.60
Medium	1	1200.65	1347.68	172.69	110.20	1331.57
	2	3025.44	3395.94	184.91	104.86	10058.38
	3	2139.31	2401.29	163.40	106.78	678.21
	4	4278.62	4802.58	164.71	106.29	833.39
	5	1512.72	1697.97	184.17	109.15	5636.28
	6	2139.31	2401.29	167.18	106.78	1047.91
	7	2139.31	2401.29	170.73	106.78	1575.74
	8	756.36	848.98	158.53	113.01	188.75
	9	2695.36	3025.44	160.30	106.82	472.14
	10	3025.44	3395.94	170.33	104.86	1876.25
	11	1200.65	1347.68	159.92	110.20	305.90
	12	848.98	952.95	154.89	107.69	229.26
	13	534.83	600.32	155.18	113.42	122.49
	14	2401.29	2695.36	159.47	108.10	370.08

	15	2695.36	3025.44	151.66	106.82	174.54
High-Medium	1	1200.65	1347.68	172.69	104.77	2489.26
	2	3025.44	3395.94	184.91	106.08	8740.96
	3	2139.31	2401.29	163.40	108.42	561.31
	4	4278.62	4802.58	164.71	106.02	859.57
	5	1512.72	1697.97	184.17	106.37	7762.65
	6	2139.31	2401.29	167.18	108.42	867.30
	7	2139.31	2401.29	170.73	108.42	1304.15
	8	756.36	848.98	158.53	104.12	525.39
	9	2695.36	3025.44	160.30	104.94	586.40
	10	3025.44	3395.94	170.33	106.08	1630.51
	11	1200.65	1347.68	159.92	104.77	571.84
	12	848.98	952.95	154.89	104.87	316.91
	13	534.83	600.32	155.18	107.35	246.41
	14	2401.29	2695.36	159.47	105.04	526.71
	15	2695.36	3025.44	151.66	104.94	216.78
High	1	1200.65	1347.68	172.69	117.99	543.60
	2	3025.44	3395.94	184.91	113.71	3630.74
	3	2139.31	2401.29	163.40	115.39	251.58
	4	4278.62	4802.58	164.71	113.49	363.55
	5	1512.72	1697.97	184.17	123.47	1084.17
	6	2139.31	2401.29	167.18	115.39	388.72
	7	2139.31	2401.29	170.73	115.39	584.52
	8	756.36	848.98	158.53	120.54	79.28
	9	2695.36	3025.44	160.30	117.79	133.53
	10	3025.44	3395.94	170.33	113.71	677.27
	11	1200.65	1347.68	159.92	117.99	124.88
	12	848.98	952.95	154.89	117.51	73.99
	13	534.83	600.32	155.18	126.48	27.22
	14	2401.29	2695.36	159.47	118.94	106.24
	15	2695.36	3025.44	151.66	117.79	49.36

Table 2: Filtered source level of calls re 1 microPascal @ 1 meter and filtered received level of low, low-medium, medium, high-medium, and high levels of boat noise for each call using the width of the call as the bandwidth. Distance was determined using the equation for spherical spreading:

$$\text{Distance} = 10^{((- \text{Received Level}_{\text{Boat Noise}} + \text{source level}_{\text{Call}}) / 20)}$$

Level of Boat Noise	Call	Lower Frequency of Bandwidth (Hz)	Upper Frequency of Bandwidth (Hz)	Source Level of Call (dB)	Received Level of Boat Noise (dB)	Distance Where SNR=0
Low	1	1005	10448	177.40	108.90	2660.81
	2	968	11013	187.57	109.11	8373.45
	3	875	11006	172.54	109.62	1399.27
	4	857	10988	172.49	109.72	1375.57
	5	745	10634	193.73	110.50	14511.1
Low-Medium	1	1005	10448	177.40	119.36	798.54
	2	968	11013	187.57	119.53	2523.89
	3	875	11006	172.54	119.91	427.92
	4	857	10988	172.49	119.98	422.14
	5	745	10634	193.73	120.93	4367.28
Medium	1	1005	10448	177.40	122.14	580.01
	2	968	11013	187.57	122.39	1815.34
	3	875	11006	172.54	122.97	300.79
	4	857	10988	172.49	123.08	295.53
	5	745	10634	193.73	123.71	3171.59
High-Medium	1	1005	10448	177.40	119.84	755.45
	2	968	11013	187.57	119.92	2411.37
	3	875	11006	172.54	120.11	417.93
	4	857	10988	172.49	120.15	413.97
	5	745	10634	193.73	120.34	4674.33
High	1	1005	10448	177.40	132.54	175.15
	2	968	11013	187.57	132.65	557.06
	3	875	11006	172.54	132.65	98.72
	4	857	10988	172.49	132.82	96.21
	5	745	10634	193.73	133.13	1072.05

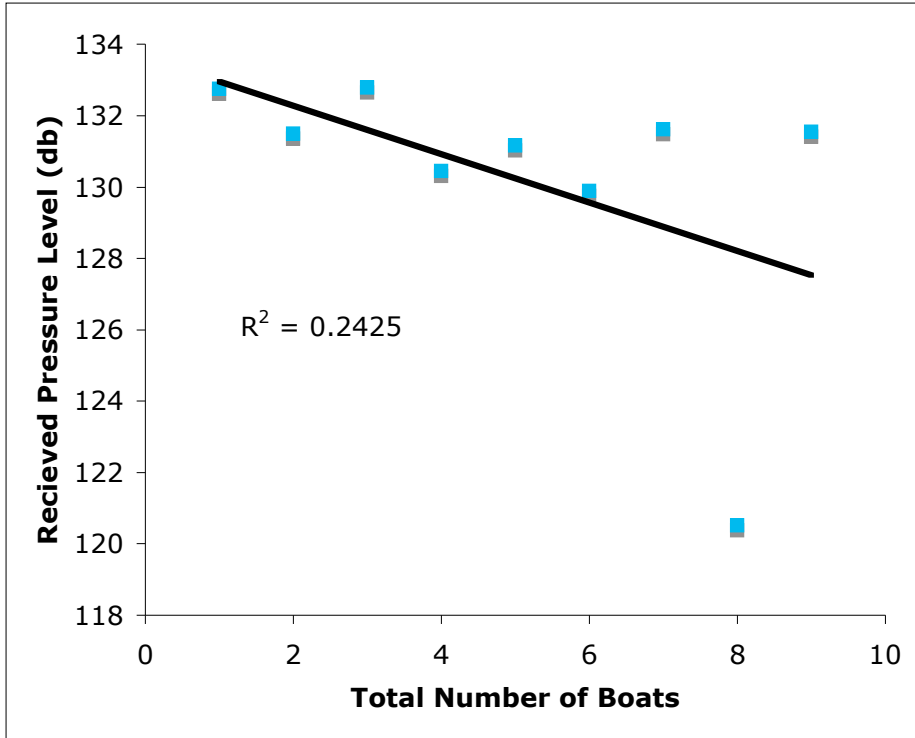


Figure 8: Average received pressure level for all data points with the same boat count total.

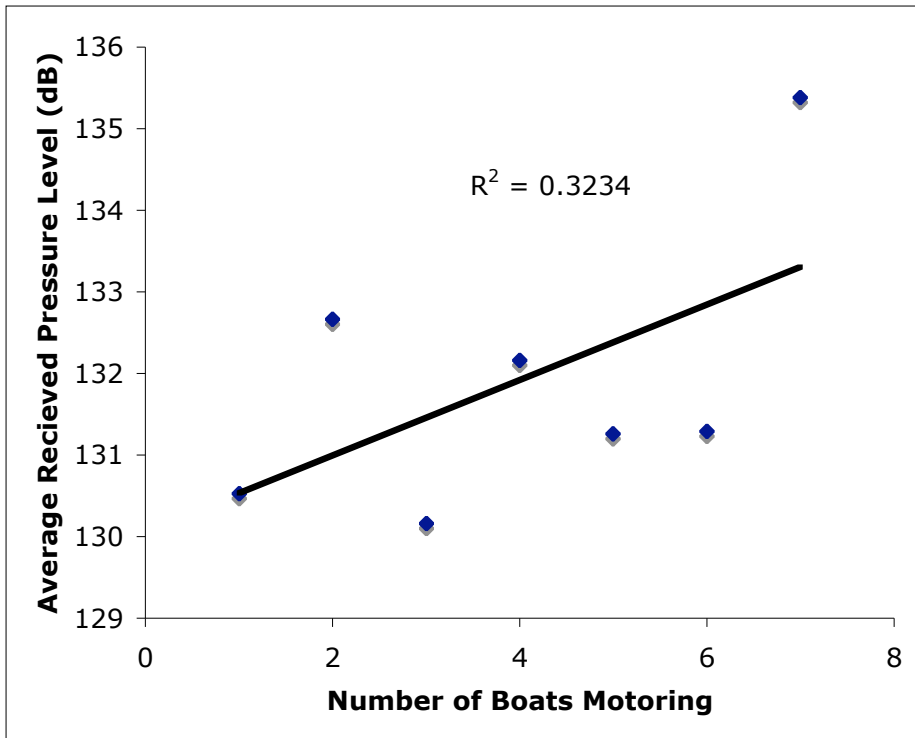


Figure 9: Average received pressure level for all data points with the same number of boats recorded as motoring.

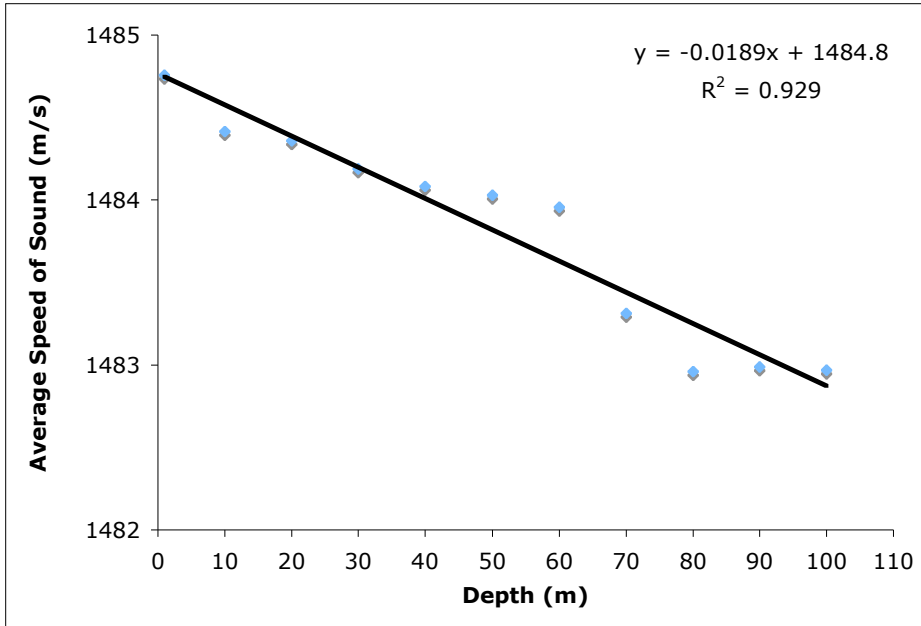


Figure 10: Sound speed depth profile for South Haro Strait.

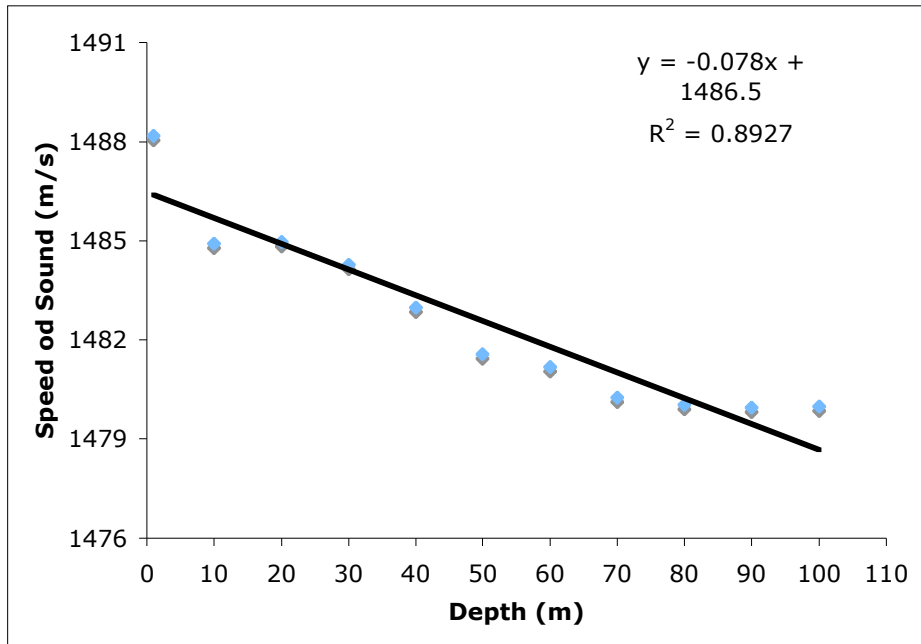


Figure 11: Sound speed depth profile for Turn Point.

A Conductivity Temperature recorder was deployed at Turn Point and South Haro Strait. Ten samples were taken at one meter below the surface and every ten meters up to 100 meters. From these readings, the speed of sound underwater was determined for each location. There was not much variation so the average of both locations was used for this project (1984.12 meters per second).