Masking of High Frequency Echolocation Signals– Does Boat Traffic Interfere With the Ability of Southern Resident Killer Whales to Find Food? A Study of Echolocation Signals and Their Sound Propagation

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The ability to hear and produce sound is vital to the survival of fish eating "Resident" killer whales. Killer whales rely on sound in order to communicate with other whales, to navigate, and find food. Like other delphinids**,** killer whales produce high frequency signals in order to listen for the echoes that bounce off objects in their path. The type of echo a killer whale hears helps the whale distinguish the size, location, and composition of the surface or object it encounters (Bain and Dahlheim 1994).

Clicks are usually either single brief pulses 0.1 to 25 milliseconds long, or in click trains of multiple clicks that usually last 2-8 seconds (sometimes exceeding 10 seconds), with repetition rates on average of 2-50 clicks per second, and with maximum counts of 300 clicks per second. These high frequency calls, generally used to find prey and for navigation, are very directional so as to get the most energy in echoes bouncing off the objects the killer whales are trying to locate. Slower click trains are used for navigation, while rapid click trains are used for objects within 10m (National Marine Fisheries Service 2008).

Both Northern and Southern Resident killer whales feed on schools of fish. The Southern Resident population primarily tends to feed on Pacific Salmon (McCluskey 2006). Acoustic research has shown that non-fish-feeding populations such as the Transients rarely use echolocation signals, but that Residents frequently produce echolocation signals while foraging for salmon (Au et al. 2004). The Transients' main source of prey tends to be other marine mammals, which also have excellent hearing capabilities and are harder to sneak up on, while Residents must narrow-in on a very small and quicker moving target. Echolocation is vital to the survival of Residents, and without it they would not be very successful in catching prey.

In the last few decades a growth in the number of vessels on the water surrounding the summer habitat of the Southern Resident killer whale has likely caused an increase in the amount of anthropogenic noise underwater where the population forages for salmon. Commercial shipping, whale watching, ferry, and recreational vessels have all become a daily presence to the Southern Residents. Since 1977, the whale watching industry has grown dramatically, with currently 41 companies using 76 different boats in the Washington/British Columbia area (National Marine Fisheries Service 2008). Whale watch boats are also increasing the amount of time during the day they are out and also extending their season length, with some even going out in the winter months. On average in 1990 there were about 5 boats following the Southern Residents at any given day in the summer, and by 2006 that average increased to 18-26 boats. Maximum numbers of boats following a group of whales have reached 72 – 120 vessels. With this increase in amount of vessel noise, along with other factors such as drilling, dredging, and

SONAR, a growing concern about the potential of killer whale sounds and hearing to be masked has been raised (National Marine Fisheries Service 2008).

Masking is the inability of an animal to detect a sound even when that sound signal is within their hearing threshold (Richardson et al.). In other words, in order for a background noise to mask a signal, the noise must have the same or greater critical bandwidth of the signal and have a loud enough source level. In order to accurately assess whether a back ground noise has the potential to mask a signal, there is certain information that must be obtained about the signal, background noise, and hearing ability of the subject. The critical bandwidth, or the limit of the frequency spread of the noise in its ability to mask a signal at a particular frequency (Holt 2008), of the signal and background noise must be obtained. The amplitude and spectrum of the signal and the background noise must also be known. The audiogram of a killer whale must also be know in order to know what the sensitivity range of their hearing is. Also, it is important to point out that the masking of a noise is the strongest when the background noise is coming from the front of or slightly below the whale (Bain and Dahlheim 1994).

Au et al. (2004) found that killer whale echolocation clicks were very broadband with bandwidths of 35-50 kHz. They also found that clicks have center frequencies in the range of about 20-80 kHz, and that 75% of source levels measured in the study to be between 195 to 210 dB re 1 μpa Peak to Peak. Erbe (2002) found that motor-powered whale watching boat source levels from various vessels ranged from 140-170 dB re 1 μpa. For this study, I am assuming a 1/6th octave for the Critical Bandwidth a killer whale echolocation click.

The hearing ability of a killer whale is also an important facet in understanding potential masking affects. Szymanski et al. (1999)'s audiogram of two captive killer whales shows that both whales responded to tones between 1-100 kHz (with a few responses at 120 kHz). The audiogram was a U-shaped curve with its most sensitive frequency at 20 kHz. Szymanski et al. (1999) defined sensitivity range as 10 dB from the most sensitive frequency, which results in a sensitivity range of 18-42 kHz (Szymanski et al. 1999). According to this audiogram, killer whales could only be expected to hear sounds above the U-shaped curve, where the sensitivity range is the range in which they can hear the quietest sounds. See *Figure 1*.

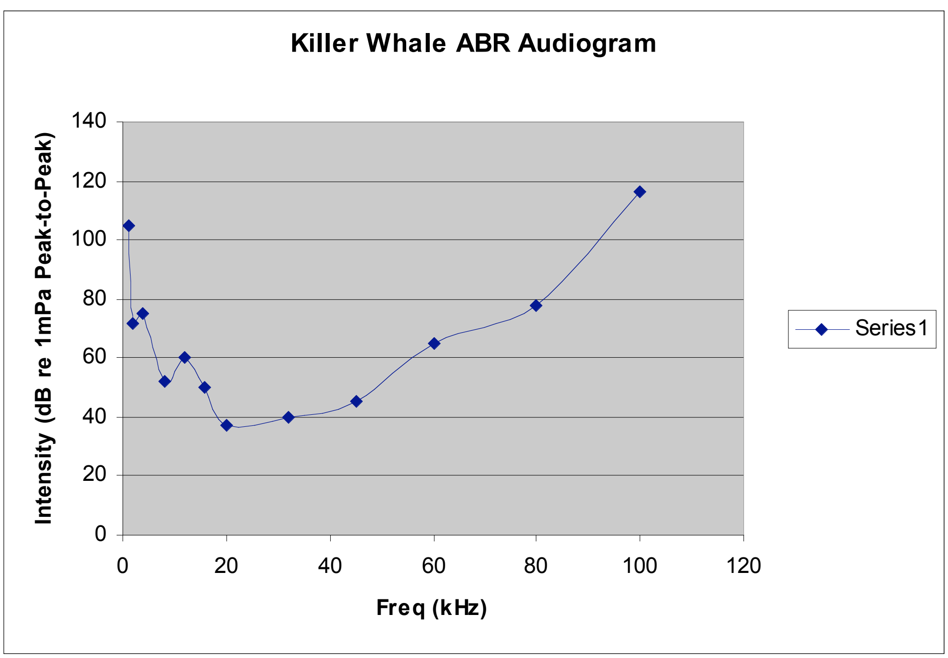

Fig 1 *adapted from* Szymanski et al. (1999)
Auditory Brainstem Response (ABR) Audiogram for Killer Whale hearing of two captive whales. The U-shaped curve shows at what frequencies the whales were able to hear the quietest of sounds. This sensitivity range is from 18-42 kHz.

Problem Statement:

There has been much study on the potential masking of lower-frequency killer whale calls and whistles because the majority of vessel traffic is strongest at frequencies below 10 kHz (Bain and Dahlheim 1994). As Holt 2008 states, "A common assumption is that masking of echolocation signals is not much of a concern compared to communication signals because echolocation signals are strongest about 20 kHz." But as she goes on to say, killer whale hearing is tuned to higher frequencies and whales probably need to hear faint echoes bouncing off objects from their echolocation signals (Holt 2008). Sound pressure decreases as it travels due to spreading loss. Sound strength is also lost because sound does not travel through water directly. Energy is scattered and absorbed, so by the time the echo is received after the initially sent signal, losses are usually 10-20 times the log of the propagation distance (Bain and Dahlheim 1994). So even if initial high frequency clicks are not masked by lower frequency vessel noise, there is a high possibility of the faint returning echoes not being heard.

The potential of higher frequency killer whale signals to be masked has yet to really be studied. Most acoustical analyses have been limited to lower frequency calls**.** Past masking studies such as the Erbe (2002) study only used hydrophones that recorded frequencies up to 40 kHz, much lower than the range of echolocation click frequencies. (Bain and Dahlheim 1994) The model created by Erbe's study found that fast moving boats with source levels ranging from 145 to 169 dB can mask killer whale calls of source levels 105- 124 dB within 14km (Erbe 2002).

A study by past Beam Reach student Tim Hunt found that small vessels with outboard motors at certain speeds produce high frequency underwater noise (Hunt 2007). If vessels can make noise at the same frequency as echolocation signals, then it is possible for echolocation signals to be masked, causing the range of area they are able to find food to be reduced. As Bain and Dahlheim (1994) state, "The impact of reduced detection distances is likely to be felt most strongly in increased difficulty to find food," meaning if back ground noise is able to reduce the distance echolocation clicks can travel, the range in which Southern Residents are able to forage will decrease, making it harder to find fish. In additional to the growing decline of the Chinook salmon population, high frequency vessel noise may be another factor in making it increasingly difficult for Southern Resident killer whales to forage.

The purpose of this study is to find out whether boat traffic interferes with the ability of Southern Residents to find food by masking echolocation clicks. If indeed underwater vessel noise decreases the range over which the whales can forage, then perhaps the guidelines pertaining to how far vessels must be and how fast they are going need to be further assessed. Boat with specific types of motors may even need to be farther away from the population when they are foraging, or specific foraging habitat no-go-zones could be established.

METHODS

Synopsis:

Instead of creating a model to estimate potential masking, I pursued to document masking by making "pseudo" echolocation clicks of similar frequency and source levels of wild killer whale clicks. To do this, I had to follow several steps of mini experiments and comparisons in order to accurately perform a masking experiment. To simplify, I will organize this paper by my four mini-experiments in four parts with their own corresponding methods and results sections. These were the following steps:

Step 1: Determine what frequency and source level to make pseudo clicks by studying real killer whale echolocation clicks, preferably at the same frequency and amplitude of a foraging click.

Step 2: Create a device that will produce pseudo echolocation clicks of similar frequency and source level of a real click.

Step 3: Test the spreading loss of sound power of the pseudo click device in order to see how far the click can travel. I intend to test spreading loss in areas of different bathymetry, because as sound propagates, sound energy is lost at different rates due to depth of the water. I will also map where whales sighted are foraging, in order to determine how variable depths are where foraging occurs. When testing for masking, the rate of spreading loss is essential in order to determine how far an echolocation signal can travel, which directly influences the range at which a killer whale can detect a fish. A range at which a killer whale can detect a food source is vital to my study because I am attempting to find out where motorboat noise could interfere with that range.

Step 4: Perform a masking experiment using my pseudo click device to measure where masking occurs.

PART 1:

In order to decide which frequency to set my pseudo echolocation clicks, I need to determine what the most common frequency clicks used for foraging are. According to the Au et al. (2004) study on free ranging resident killer whales off of Vancouver Island in Johnstone Strait, frequencies of echolocation clicks ranged from 20-80 kHz, with most of the sound energy in the spectra to be from 20-60 kHz. The Au et al (2004) study also modeled what an echo of a chinook salmon facing forward using a 50 kHz signal looked like, and concluded that, "the broad bandwidth of the echolocation signal provides a good range resolution capability." The higher frequency clicks will be able to detect smaller targets while lower frequency clicks detect larger targets (Au et al. 2004). Ford et al. (1998) found that of six species of salmon found in resident killer whale habitats, chinook salmon are the most common prey of the resident killer whales, most likely due to their high lipid content and large size. Preferred weight of prey chinook are between 3.7 and 8.1 kg (Ford et al.1998). The corresponding lengths of a chinook of those weights are from 0.6m-0.8m. Given that it is the swim bladder of a fish that a killer whale actually detects (Au et al 2004), it would be assumed that the clicks needed to detect the small organ would need to be of a high frequency. See *Figure 2*. I am going to aim to make the frequency of my pseudo click to be where the Au et al. (2004) study found most of the sound power in the frequency spectra to be at, which was between 20-60 kHz.

Fig 2 - Swim bladder of a salmonid species Courtesy http://www.pskf.ca/sd

Study Sight:

The study area was located in the waters surrounding San Juan Island in the Northwest corner of Washington State, commonly known as the Salish Sea, during the months of April through May of 2008.

Determining Frequencies and Source Levels from Southern Resident Echolocation Clicks:

Materials and Equipment :

To record echolocation clicks, a hydrophone array was deployed and towed from the *Gato Verde*, a 42-foot sailing catamaran powered by a bio-diesel/electric motor while in the presence of Southern Resident killer whales. See *Figure 3* for array set up. As the *Gato Verde* tows the array, the engine power can be switched to charged battery lasting up to two hours of silent movement in the water, which is most advantageous for recording underwater with acoustic devices.

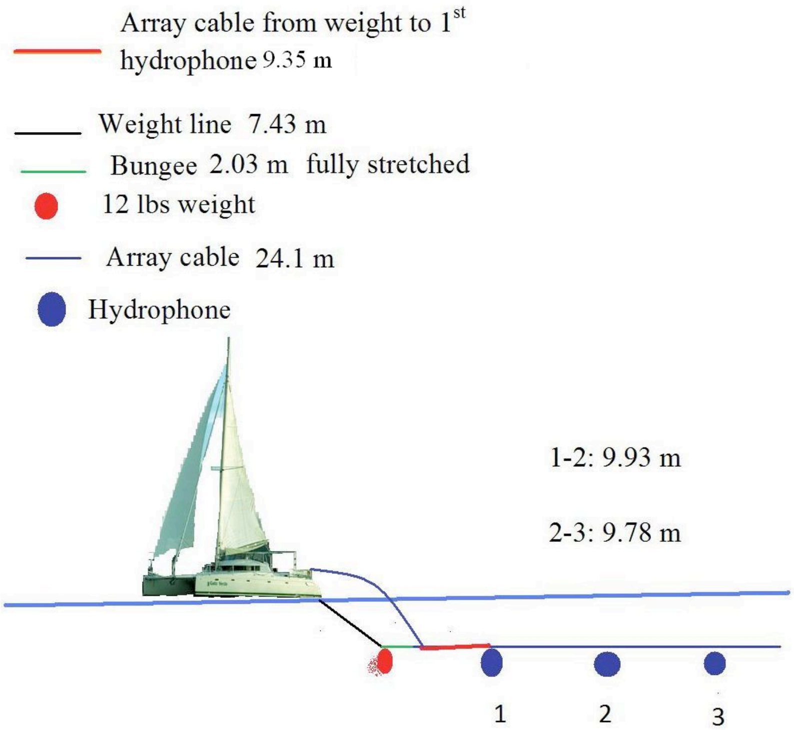

Fig 3 Courtesy Walk 2008

As the *Gato Verde* moves through the water, the linear array of three low frequency hydrophones is towed horizontal through the water. The weight line lowers the array in the water column and the bungee takes tension off the array cable. This help prevents surface noise in the recording. Hydrophone cables are laid out along the stern to avoid tension tapping of the weight lines.

On the port stern side corner of the *Gato Verde*, the horizontal array of three LONS low frequency hydrophones were towed, as shown in *Figure 3*. On the starboard stern side corner our single Cetacean Research Technology high-frequency hydrophone was also towed at the same depth, using a 10 lb weight. The CRT is aligned with hydrophone 1 on the portside array. The girth of the *Gato Verde* is 23 ft. This array set up allows us to both gather high and low frequency data while at the same time help better localize sound sources by avoiding the "mirror" effect of the hyperboloid measured of the distance a sound travels to the receiver.

Underwater sounds were recorded with two 702 Sound Devices, at 16 bit depth with sampling rate at 192,000 samples per second. Low frequency drag noise was filtered out with a low cut filter of 240 Hz 24 dB/oct. Our hydrophones were calibrated so that our recordings can be compared to other studies' data. This calibration allows us to find the sensitivity for each hydrophone and then compensate for that sensitivity to determine dB re 1μPa. Sensitivities that I used for this study for the CRT and hydrophones A, B, C, D of the LONS array (in corresponding order were 146, 151, 146, 143, and 143.

Frequencies of clicks were analyzed with the Beam Reach Sound Analyzer Program (v. June 2008) and saved into Excel to create frequency spectrums, using a Fast Fourier Transform (FFT) at a rate of 1024. Large files were broken up into one-minute wav files in order to better manage data analysis.

To calculate the source levels of echolocation clicks, I will localize the signals using the software Ishmael to plot out the signal and using trigonometry and the Pythagoras theorem to find the distance and bearing from the *Gato Verde*. Depending on the depth and location, I will either use Spherical, Cylindrical, or preferably my own measurements of spreading loss from my experiments.

Results:

A total of 11 days between 5-13-08 to 5-31-08 were recordings made of opportunistic sightings of Southern Resident Killer Whales, specifically only of J Pod. Of these 11 days, 6 of them were considered to contain files of foraging behavior. For this study, I determined foraging to be happening when I noted a frequent amount of click trains or rapid clicks, when the whales made frequent sudden lunges in the water, deep dives, change in direction, and were generally spread out as a group.

Of the 6 days of documented foraging, I analyzed 4 of those days using files only during times I observed foraging. 157 foraging clicks from the data analyzed by Spragg (2008) were used to find an average peak frequency for this study. For this study I term "peak frequency" to be at which frequency the most power of the sound is. Clicks which Spragg (2008) made frequency spectrums were randomly chosen from each minute of interest noted during whale observations. See *Table 1:*

Foraging Clicks		Highest	lowest	n=157
Average Peak:	19452.82	33843.75	11437.5	
Average dB:	102.51968	118.6	58.1	
Peak Median:	18375			
dB Median:	102.7			
Peak Mode:	17437.5			
dB Mode:	115.2			

Table 1: Average frequency of 157 foraging clicks, in Hz. Average sound power at peak frequency in dB re 1 mPa per square Hz.

The average peak frequency of the 157 foraging clicks was 19.5 kHz with a dB level of 102.52 dB re 1 mPa squared per Hz.

Source Level of Echolocation Clicks:

I attempted to localize a small sample of recorded echolocation clicks from our data. Clicks however, are very directional, and source level can only be accurately measured if the echolocation signal is faced within +or- 5˚ directly at the hydrophone (Au et al. 2004). There was documented incident on 5-13-08 of large male directly following us and echolocating on the hydrophone array as we recorded, but since the whale was most likely in our shadow zone of localizing (directly in front and in back of boat), and that there were a very large amount of clicks in that file to try to match up in the Beam Reach Analyzer Program with Ishmael, I determined our method of recording was not accurate enough to calculate source levels, and used data results from the Au et al. (2004) study, which recorded foraging killer whales but stationing directly in front of them while they traveled towards their array, and found average source levels of foraging echolocation clicks to be 195 to 210 dB re 1 μPa peak to peak. From some of the clicks that were able to be localized from this small sample, I was able to find a minimum range of 181m of how far the echolocation clicks could travel.

PART 2: Creating a Pseudo-Click Apparatus:

In order to practically measure how close a boat has to be in order to mask, I needed to have a method to either play back or mimic an echolocation click at a similar frequency and amplitude, of an echolocation click produced by a killer whale. According to Heard et al. (1997), "Sealed glass vessels…crushed under hydrostatic pressure have often been used as a safe, moderately broadband acoustic sources. Light bulbs have also been used as acoustic sources." (p.755). Once a light bulb dropped into the water reaches a certain depth, the pressure causes the light bulb to implode making a loud sound with a high amount of energy. Table 2 in Heard et al. (1997) gives at what depths different types of bulbs would implode, and the source levels of those implosions, ranging from 160-216 dB re 1 μpa @ 1m, which is within Au et al. (2004)'s reported source level range of clicks at 195 to 210 dB re 1 μPa peak to peak.

I initially tried to drop at 75 W Western Family light bulb in the Haro Strait on 4-30-08 (See *Figure 4*). Using a vertical array in the water column off the *Gato Verde* stern to calculate the source level, I detected no implosion noise in water of 152m depth. Other bulb types could have been explored or dropped at greater depths, but considering that I want to emit pseudo clicks at controlled depths in different habitats, I switched to another method of bursting a light bulb.

Fig 4
Initial method of attempting to implode a light bulb. Light bulb was attached to a heavy rock and dropped into the water.

Instead of just finding habitats deep enough for the light bulb to sink in order to burst, I found a way to burst the light bulb at any depth I chose by dropping a weight on a light bulb attached to a line. The line with the light bulb was lowered 21.6m into the water from the surface with a weight, and using another smaller weight with a hole in it, I let the holed-weight drop from the surface along the line until it burst the light bulb at the other end in the water column. *See Figure 5:*

Figure 5: Method of creating a pseudo echolocation click. The light bulb was lowered into the water column 21.6 m with a weighted-line and the smaller holed-weight (object held in hand) was dropped from the surface onto the bulb. The implosion created a loud high-frequency signal.

When experiments of light bulb implosions were being performed, a mandatory marine mammal watch consisting of constantly scanning the perimeter of the site for any marine mammals and checking the commercial whale watch radio station of any whales in the area was used in order to prevent any possible harassment or damage to marine mammal hearing.

There was some debris loss from imploding the light bulbs, but most of this was minimal consisting only of the small pieces of glass (which most likely were small enough to just form into sand), while the metal parts and tungsten of the bulb were hauled back in with the line. The only chemicals associated with a common incandescent light bulb are a small amount of Phosphorus.

Results: Comparison of the Pseudo Click to A Real Echolocation Click

Waveforms of echolocation clicks and light bulb implosions were generated in MATLAB for initial comparison. *See Figure 6 and 7:*

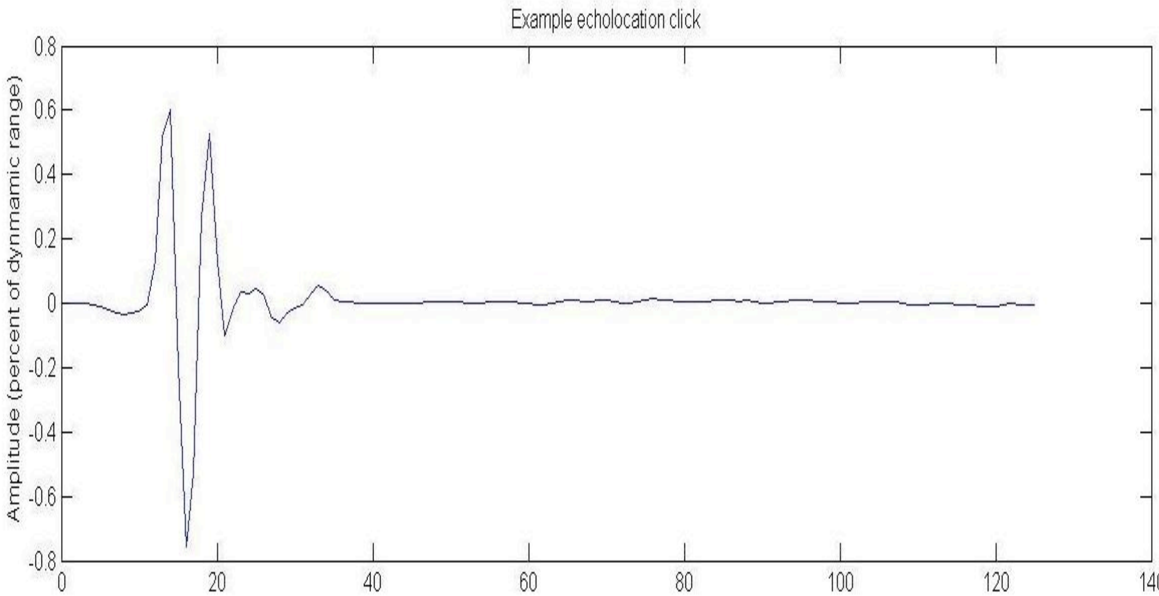

Figure 6: Waveform of an echolocation click. X-axis in is Micro Seconds

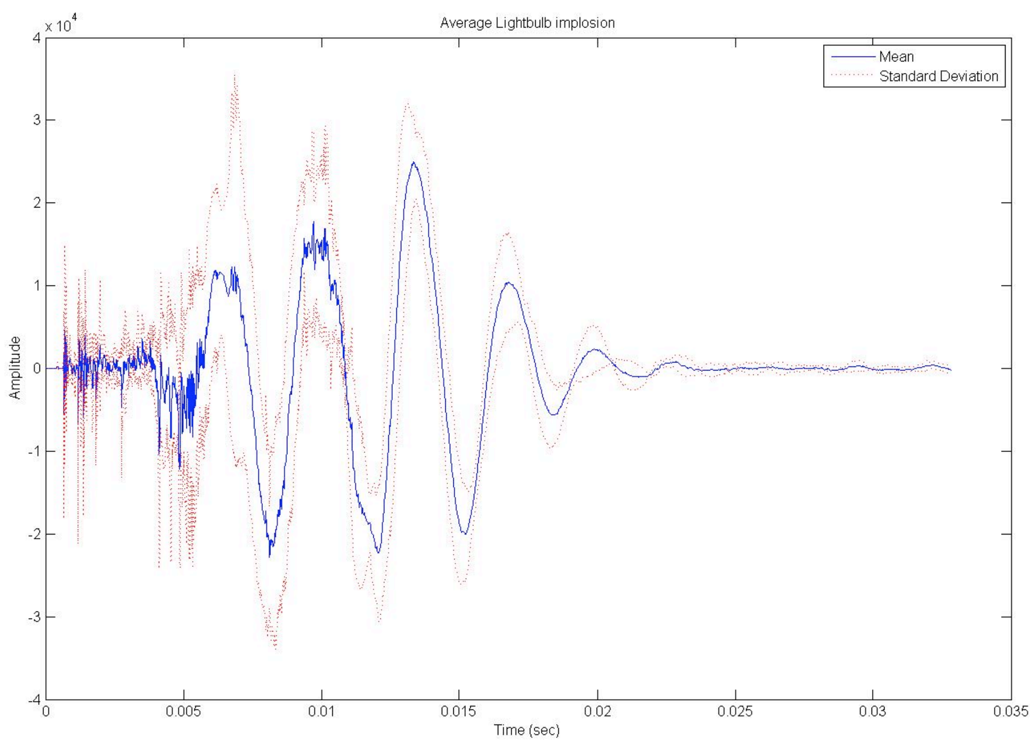

Figure 7: Waveform of average light bulb implosion, with standard deviation. X axis is in Seconds.

To initially calculate source level and analyze frequency, 5 light bulbs were lowered from the bow of the Gato Verde and imploded in deep waters of Haro Strait and the upper North West corner of San Juan Island. Implosions were recorded using the CRT at a gain setting of 22.0, lowered 5m into the water from the Gato Verde stern. Received levels were calculated using Peak to Peak measurements in the Beam Reach Sound Analyzer program, and converted into dB received by taking the 20log(x) (x = peak to peak value), then adding our sensitivity value of 146 to get a calibrated dB received level of Peak to Peak. To calculate source level, I used the spherical spreading loss equation TL= 20 log R, where transmission lost (TL) from the source is 20 times the Log base 10 of the distance from the source (R) (Richardson et al 1995). I used spherical spreading because the depths I recorded in Haro Strait were greater than 200m. The distance from the bow to the stern was 11.9m, but due to sea state and currents The line of the CRT cord and light bulb line were usually pushed out an angle with the water flow, so I used trigonometry to more accurately measure how far the light bulb implosion was from the receiver (the hydrophone). *See Table 2:*

Bulb	peak2peak	dB uncalibrated	dB re 1 microP	sensitivity	spreading loss	SL dB re 1 microP
1	19.44	25.77392521	171.77	-146	22.27887	194.05
2	18.91	25.53383058	171.53	-146	24.94965	196.48
3	19.3	25.71114618	171.71	-146	24.94965	196.66
4	17.23	24.72570555	170.73	-146	24.94965	195.68
5	18.66	25.41823279	171.42	-146	24.94965	196.37

Table 2: Source Levels Calculated for 5 light bulb implosions

The average source level of the light bulb implosions was 195.85 dB re 1 mPa Peak to Peak, which is in the range Au et al. (2004)'s range of foraging echolocation click source levels.

I also created frequency spectrums of the five light bulb implosions using an FFT rate of 1024. I found the peak frequency, or frequency containing the most sound power, and found the average. *See Table 3:*

Bulb Burst	peak frequency (Hz)	dB power	
1	30375	110.7089	average peak freq
2	28312.5	104.6706	28087.50
3	27750	105.4414	average dB power
4	31312.5	99.5378	103.66
5	22687.5	97.9183	

Table 3: Power levels in dB calculated for the 5 light bulb implosions

The average peak frequency of the light bulb implosions was 28.09 kHz. This average is 8.59 kHz greater than the average peak frequency I found for foraging clicks. The average dB of power in that frequency is 1.14 dB greater than the foraging click mean of 102.52 dB re 1 mPa square per Hz.

I also tried another method of finding an average peak frequency, and that was by creating a single spectrum of the single combined average light bulb implosions created in MATLAB. *See Figure 8:*

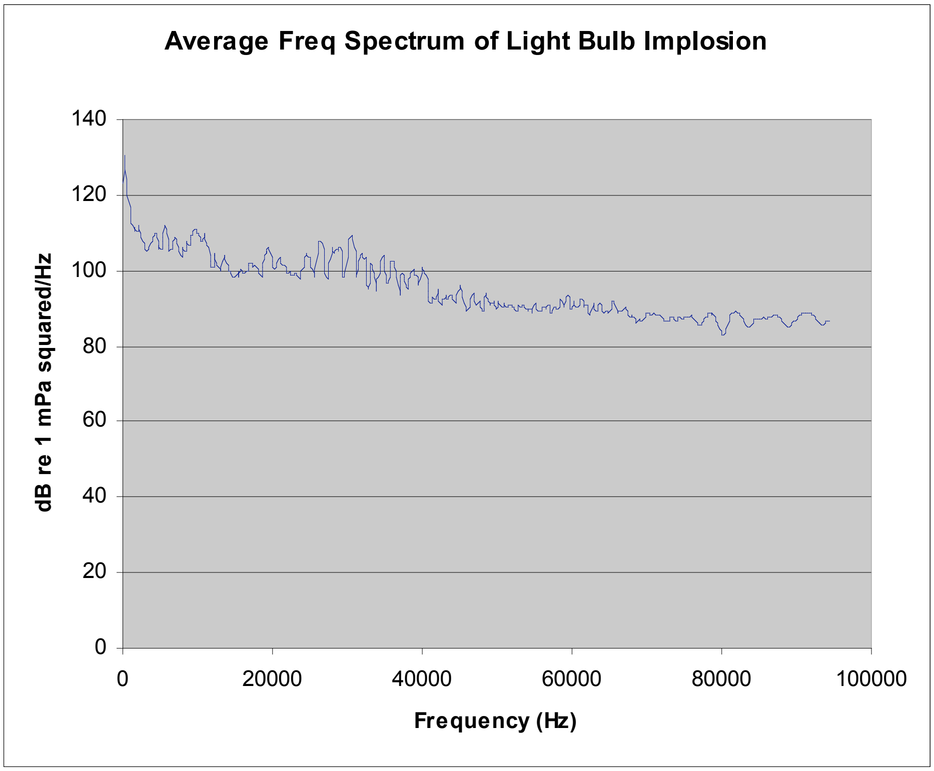

Figure 8: Frequency Spectrum (FFT rate 1024) of average light bulb implosion waveform

The peak frequency from this average-finding method resulted in an average peak frequency of 30.56 kHz, at a power of 109.1619 dB. This average peak frequency is 11.06 kHz greater than the foraging click peak frequency value, and 6.6419 dB in power greater than the foraging dB value.

<u>PART 3: Spreading Loss and Bathymetry</u>

To test for spreading loss of the light bulb implosion I set up the LONS hydrophone array as in *Figure 3,* but only used a linear four-channel portside array (an additional channel was towed from the array in *Figure 3* approximately 10m away from channel 3, with a total array system towing at 40m from the Gato Verde stern. The CRT was not used for these experiments because these experiments were solely for transmission loss measurements and not frequency measurements.

Bulbs were lowered 21.6m and imploded from our 4m inflatable dinghy, the *Gatito*, at 100 and 400m away from the bow of the Gato Verde (at a 12:00 bearing) as the Gato Verde moved <1.5 knots towards the dinghy in order to keep the array horizontal in the water column. Using the Gato Verde LCD Radar 1500 MKII and portable hand held radios, we were able to pinpoint exactly when the light bulb was 100m or 400m away and radio the dinghy to drop the weight on the light bulb. Three trials at both 100m and 400m were recorded for each site.

Results:

On 5-29-08 three bulbs were imploded at 100m and 400m away from the Gato Verde Bow in the Haro Strait (N48 34.279, W123 11.671) at a depth of >200m. At 400m away, there was a slight incline in depth up to 70m due the pushing currents, but this site is considered to be an area of deep depth.

Gains were lowered to 30.2 dB to prevent clipping. Files at Haro Strait were recorded at 192k with 16 bit depth. Received levels of each signal were calculated with Peak to Peak using the Beam Reach Analyzer software, and converted into dB by calculating the 20log10(p2p) and calibrated by adding the sensitivities of each hydrophone. An average spreading loss slope was calculated by plotting all received levels of each trial at 100m and 400m, with the x-axis distance scaled in Logarithmic value in order to have a linear regression line. *See Figure 9:*

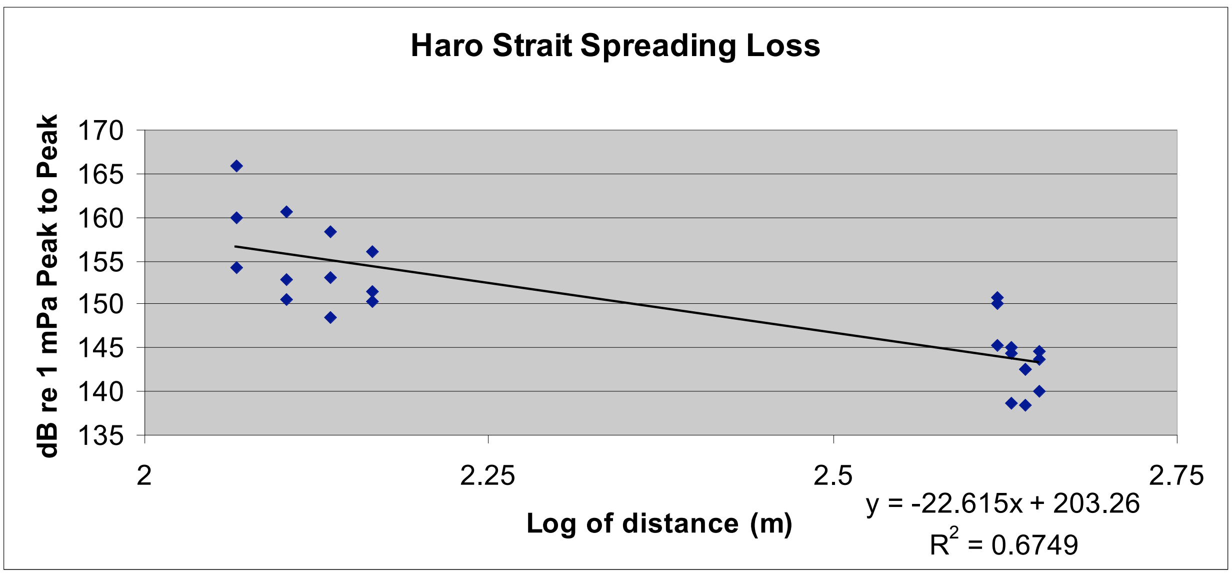

Figure 9: Linear regression line of transmission loss of light bulb implosion in Haro Strait from 100 to 400m (scaled in Log values on X-axis).

Transmission loss of the light bulb implosions in Haro Strait was Y=-22.615x + 203.26, with R^2 value of 0.6749, meaning the regression line represents 67.5% of the data. The average source level from this equation is 203.26 dB (at the Y intercept). If converted back into a Log scale, the transmission lost would be TL = 22.62 Log (R).

Additional Spreading Loss Experiments due to change in Bathymetry of SRKW habitats:

Sound spreads out differently as it propagates due to depth. If a water column is open and deep enough, a sound will spread spherically from its source. If the depth of water column is relatively shallow, the waves will reflect off the surface and ocean bottom. The sound then begins to propagate cylindrically. Sound propagation becomes even more complicated than these two demonstrated models when the change in ocean bathymetry is taken into account. With this in mind, I decided to look at the bathymetry of different areas of Southern Resident habitats in order to see how differently echolocation clicks may travel over distances due to change in bathymetry. *See Figure 10 and 11:*

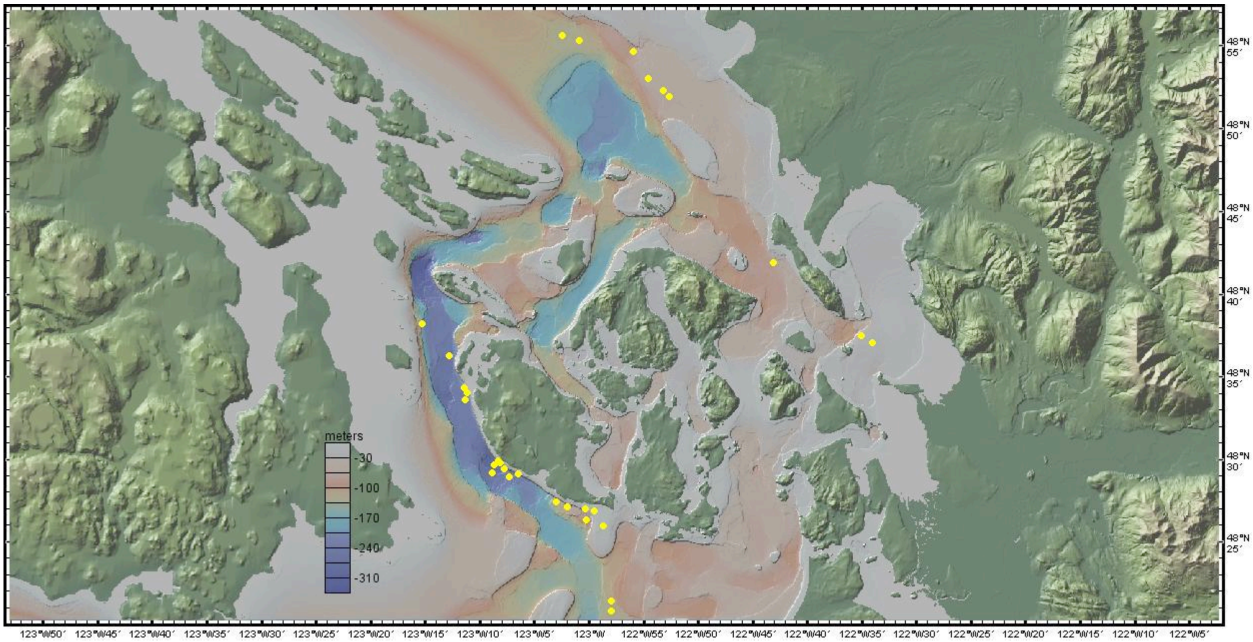

Figure 10: Plot of waypoints where foraging behavior was observed on a bathymetric map.

Figure x shows evidence of Southern Residents foraging in different depths. As stated depth and bathymetry directly influence the sound propagation of a signal, and therefore influences the range in which an echolocation click could travel and receive echoes back.

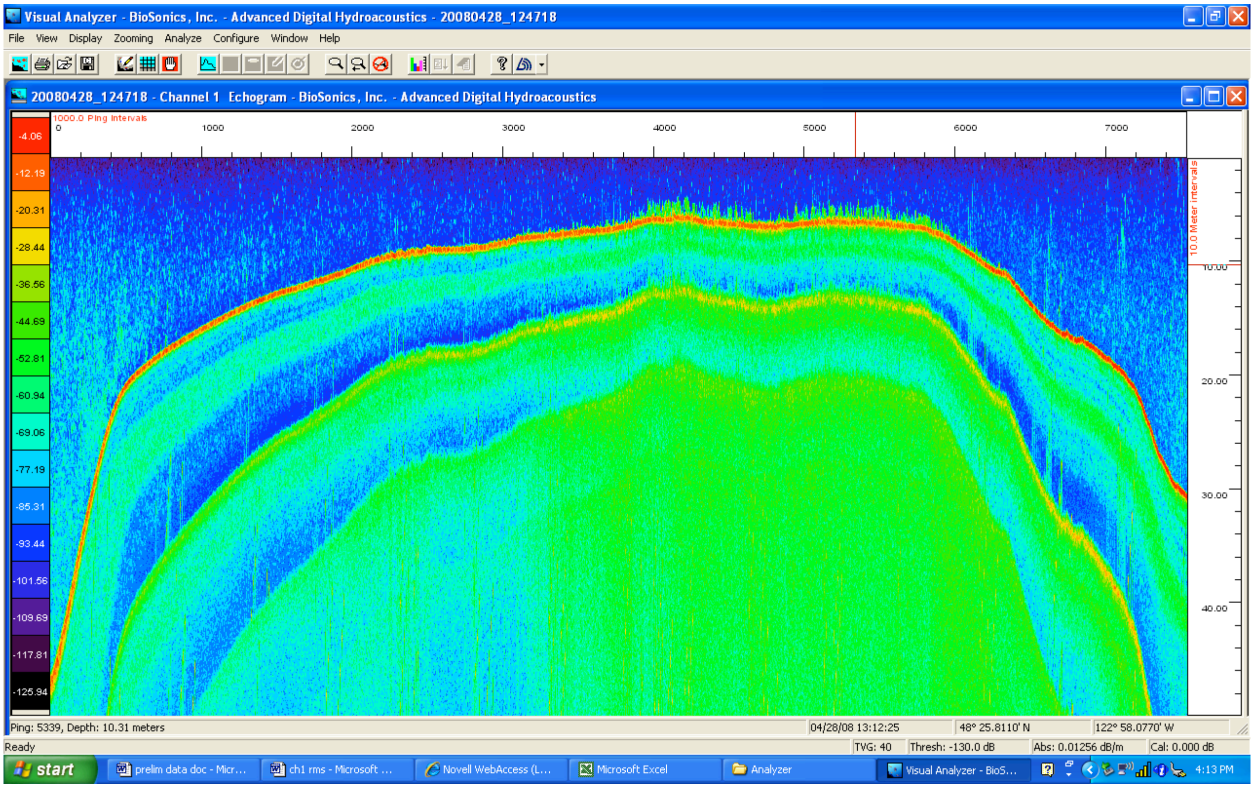

Fig 11: Bathymetry of Salmon Bank from plotted transect started at 48°26.0920' N 122°59.4480' W and ended at 48°25.8110' N 122°58.0770' W. It should also be noted that at 12:57 during the transect the Gato Verde slightly turned (at ~48°25.9590' N 122°58.4570' W) westward, so the transect is not a straight line but angled at the latter GPS point. X-axis is time, in unit of pings. Total time = 25 minutes (~7300 pings, and 292 pings a minute). Y-axis is depth, in meter units. Depth scale from 0-50m.

The bathymetric device Biosonics DT-X 200kHz scientific Echosounder was mounted on the inner aft port hull of the Gato Verde at 20 cm below the surface of the water. The Echosounder transmits a 200 kHz "ping" directly down into the water column, and the echo of each ping bouncing back up towards the surface is able to produce an image of the bathymetry directly below the vessel, with Visual Acquisition software. As the Gato Verde moves on a set course, a transect of a bathymetry can be logged.

Transmission loss at shallow depths:

Another spreading loss experiment was conducted at a shallow site due to the range of depths at which SRKW were observed to forage in. Salmon Bank was the initial site chosen, but since there was a frequent presence of Harbor Seals in the proximity, I conducted my experiment in Griffin Bay, on the Eastern side of San Juan Island, which had similar depths to Salmon Bank. Trials were performed the same as in Haro Strait, gains and array were set the same, except the sampling rate was set at 48k in order to have smaller files to work with.

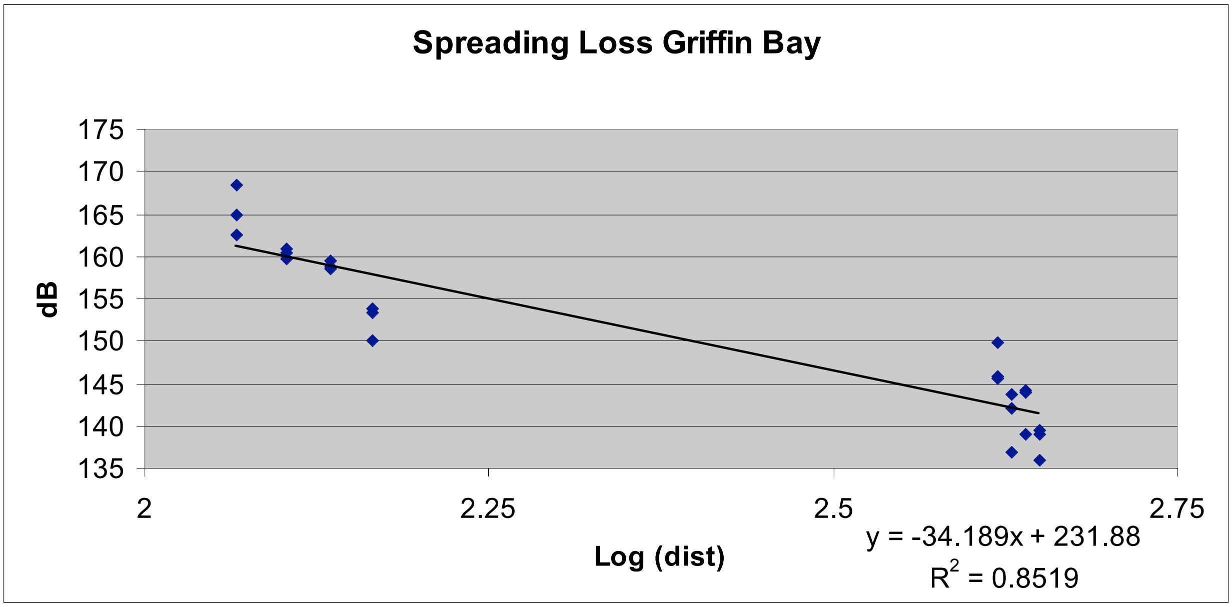

Figure 12: Spreading Loss of Light Bulb Implosion at Griffin Bay, an area of shallow depth in the San Juan channel.

Transmission loss of the light bulb implosions in Griffin Bay was Y=-34.189x + 231.88, with R^2 value of 0.8519, meaning the regression line represents 85.2% of the data. If converted back into a Log scale, the transmission lost would be TL = 34.189Log (R).

PART 4: Masking Experiment

The final step was to test the spreading loss of the light bulb burst, in order to see how far the sound could travel with different background noise levels. In calm open waters with minimum background noise, the signal of the pseudo click "S" was emitted from a rowboat 200m from the Gato Verde, or the Receiver "R" with the high frequency CRT set stationary on the portside stern to receive the signal. CRT gain was set at 22.0 and recordings sampled at 192k and 16 bit depth. Experiment was conducted in the Haro Strait, in approximately at the same location I did my spreading experiment in Haro Strait.

The noise source was created by the *Gatito*, a 4m inflatable dinghy with a single 18 HP outboard motor. Elaborating on the results of Hunt (2007)'s modeling for potential masking, I had the *Gatito* circle the omni-directional hydrophone at a cruising speed of 15 knots at 100 and 400m, which Hunt (2007) found that all motor types measured at those distances could potentially mask an echo of an echolocation click, in correspondence to the "Be Whale Wise" Marine Wildlife Guidelines for Boaters, Paddlers, and Viewers (Whale Museum 2007).

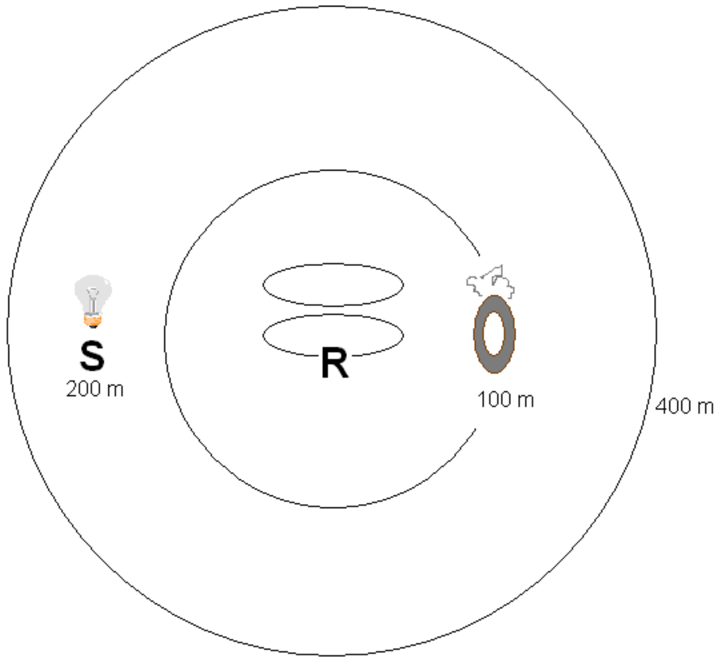

Figure 13: Diagram of masking experiment. The receiver "R" at the Gato Verde recorded the signal of the light bulb burst "S" 200m away. Trial 1 had the Gatito circling 15knots around the Receiver at a radius of 100m, and Trial 2 had the Gatito circling 15 knots at a radius 400m.

<u>Results:</u>

Frequency spectra were created for the light bulb burst signal, and the noise created at the 100 and 400m radius, and overlaid with the Szymanski ABR audiogram of a killer whale's hearing ability. *See Figure 14:*

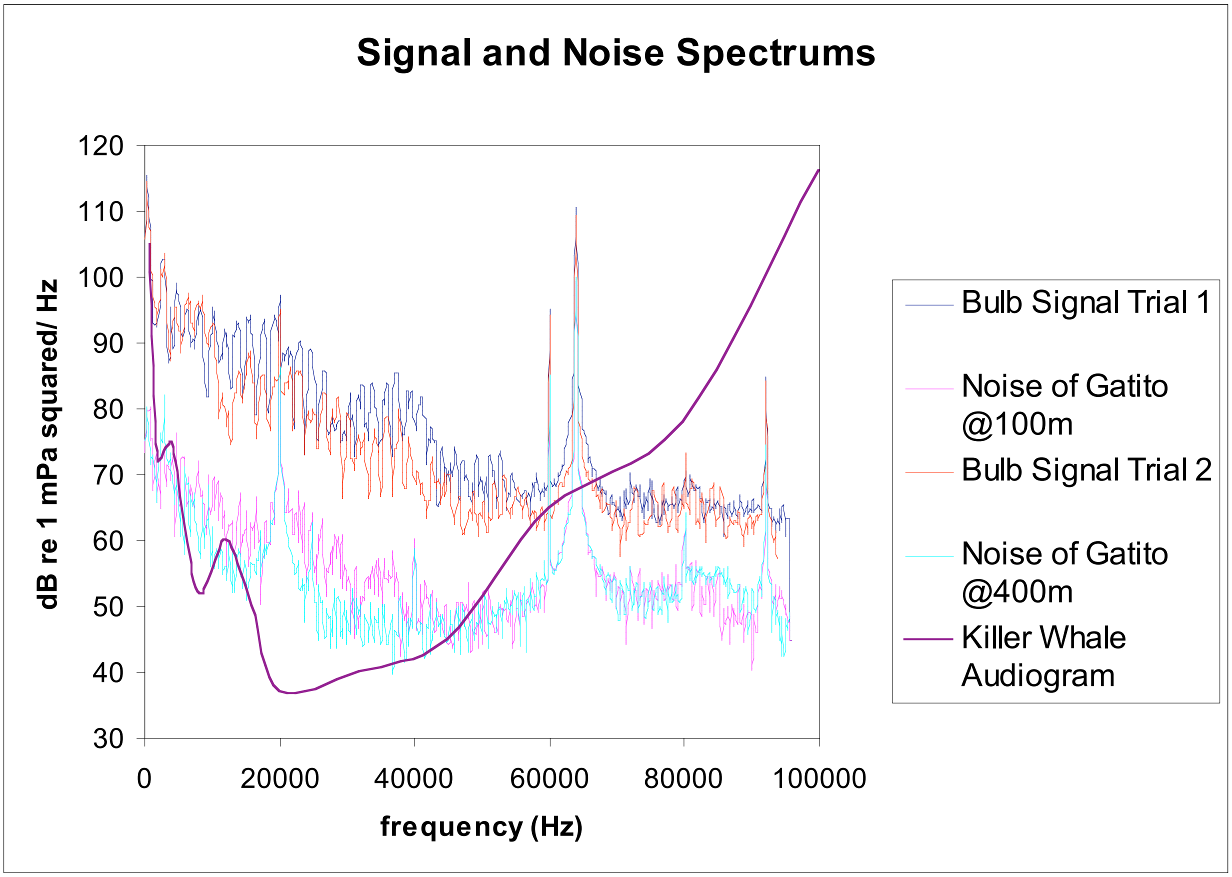

Figure 14: Frequency spectrums of Light bulb implosions (signal) during both masking trials, and of background noise made by inflatable motor-powered dinghy the Gatito circling recording device at 100 and 400m. The killer whale audiogram shows that all sound sources were audible to a killer whale.

A target sound needs to be at a certain level in loudness above the background noise in order for it to be detected. This concept is termed the Critical Ratio, and differs between species (Holt 2008). Killer whales have Critical Ratios that range from about 20 dB at 10 kHz to 40 dB at 80 kHz (Bain et al. unpublished data, cited in Bain and Dahlheim 1994). For my study I am using a Critical Ratio (CR) of 20 dB for a killer whale. This means that the signal of the light bulb burst must be 20 dB above the spectrum level of the noise in order for the killer whale to be able to detect it. In order to find out if a killer whale could detect the light bulb signal, I had to find out the Signal to Noise Ratio (SNR) of each trial of the masking experiment. It is also important to find the Critical Bandwidth (CBW), or the limit of the frequency spread of the noise in its ability to mask a signal at a particular frequency (Holt 2008), in order to properly interpret the SNR. As Holt (2008) states, “Sounds at frequencies outside the bandwidth of the auditory filter typically do not affect audibility unless the noise level is very high,” so I found a CBW at a central peak frequency of the light bulb signal at 1/6 of an octave and compared that same octave of the noise in order to get an accurate SNR.

I initially interpreted the central peak frequency (where the most sound power was at that frequency) to be near the average peak frequency of my light bulb implosions, which was at 19.5 kHz. The spectra that were produced however had some sort of interference (*See Figure x*), creating sharp peaks at about 20, 62, and 92 kHz (which still were evident even after decreasing the FFT rate to 64), and therefore I decided to find a CBW at a lower central peak which didn't have any interference.

The central frequency of the signal spectrum I chose was at 35.813 kHz, and the upper and lower bands I calculated at the 1/6 of an octave CBW were from 37.942 to 33.802.5 kHz. To calculate the SNR, I found the sum of the powers between the CBW for the light bulb signal, background noise of the dinghy traveling 100m away, and background noise of the dinghy traveling 400m, and converted those values back into dB by taking the 10 Log_{10} (sum) of each sum.

Signal Level	Noise Level @100m	Noise Level @400m
95.3295793	68.17576835	60.93091643

Table 4: dB levels of Light Bulb Burst Signal, and Noise at 100m and 400m away

The SNR is calculated by subtracting the noise from the Signal. When the *Gatito* was circling the hydrophone at a 400m radius, the SNR was 34.39866. When the *Gatito* was circling at a 100m radius, the SNR was 27.153811. The CR of a killer whale is 20 dB, and if the SNR is greater than that CR, that means the whale can detect the signal through the background noise.

From these calculations, both SNR's were greater than the killer whale CR, meaning a killer whale would be able to detect the signal and it was not masked.

I did some modeling using my spreading loss equation from Haro Strait (quite similar to spherical spreading) in order to figure out where the signal might actually be masked using the formula R= 10^(SL/20), where 20 is the CR, R is the radius, and SL is the source level of the signal. I found that the Gatito circling the Gato Verde at a radius of about 75m would have a SNR of 20.34, just at the threshold of the Killer Whale CR.

<u>DISCUSSION:</u>

My initial question was to find out if anthropogenic background noise created by the numerous boats surrounding killer whales in the Salish Sea possibly masks their echolocation signals when foraging. I went about this in a practical rather than modeling method, and while I may not have quite answered my initial question, I discovered that there are many factors that influence how and when masking might occur, and that over all it is a bit more complicated to determine what motor types and certain speeds and distances can mask a signal when the complexities of sound propagation are considered.

To go out testing for masking practically, I needed to create my own echolocation-click simulator, which proved to be the greatest limitation when it came to finding the answer to my question. I found that a light bulb implosion and a true echolocation click are comparable in that their mean peak frequencies and source levels are similar (with the results showing that the light bulb implosions actually have a higher mean peak frequency), but the frequency spectrums of the light bulb implosions did not always have a great a peak as echolocation clicks do, and I am skeptical of the mean peak frequency I found of the implosions. The waveforms (*Compare* *figures 6 and 7)* are also quite different, where the high frequency part of the implosion is where gas bubbles initially rush into the bulb, and the higher amplitude peaks are actually at a much lower frequency, according the findings of Heard et al. (1997). Further study of a comparison of a light bulb to an echolocation click could be analyzed by actually filming a bulb being imploded by my method in order to grasp a better understand of what the waveforms correspond to. Also, reloading time and efficiently of using light bulbs proved to be very time-consuming and situation dependent depending on the sea state (affected angle of line in the water) and marine mammals in the area (put experiments to indefinite halts).

The spreading loss I found in Haro Strait directly corresponded with Spherical spreading loss, which is understandable since Spherical spreading is used when modeling transmission loss in deep waters where there is little interference. Cylindrical spreading loss has been the model for transmission loss in shallow depths, meaning that sound can travel further since it has less of a volume to be absorbed, but my findings found the opposite of this trend. My spreading loss equation calculated from Griffin Bay was Y=-34.189x + 231.88 converted back into a Log scale of TL = 34.189Log (R). There are multiple reasons why this may have occurred, one being that the depth of Griffin bay was about 23m, and the bulb was lowered to a constant depth of 21.6m. Since the bulb was so close to the ocean floor, sound waves may have been directly loss as soon as the bulb may have burst. Also, my colleagues that imploded the light bulbs from the dinghy reported that as they were lowering the bulbs into the water column, at one point the weighted line hit a sea mound as we slowly drifted from our initial location. *See Figure 15:*

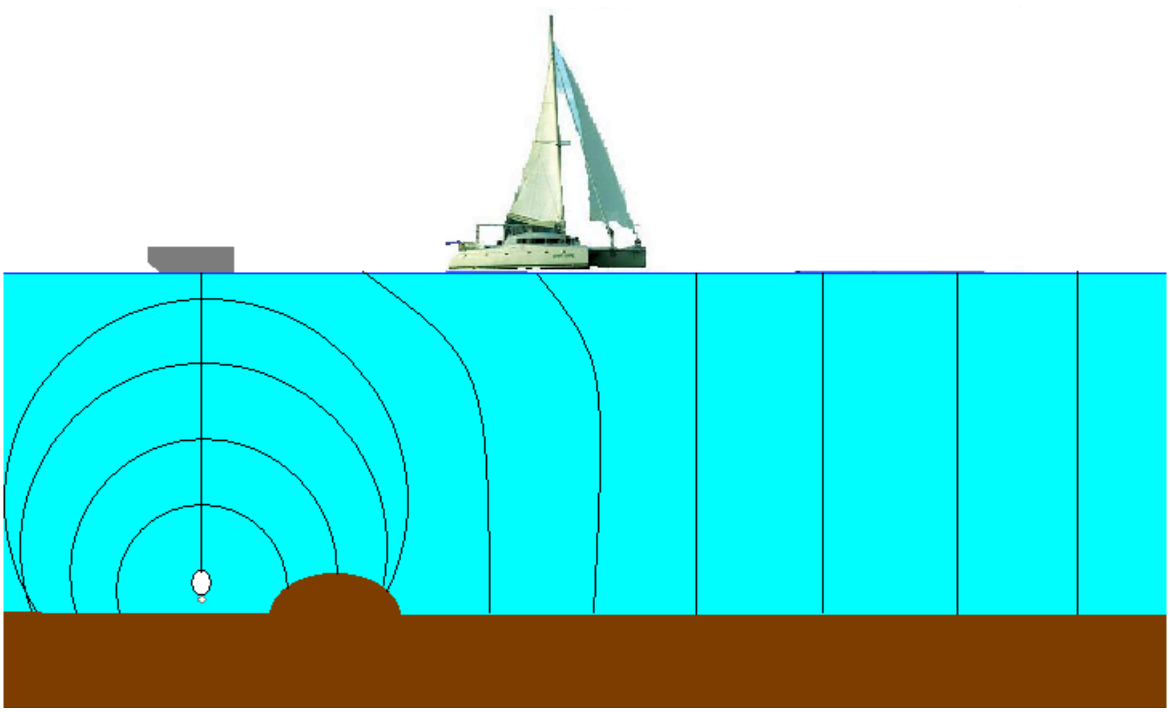

Figure 15: Light bulb implosion location at Griffin Bay, blocked by sea mound, with Gato Verde stationed at 100m to recorded spreading loss.

Figure 15 helps possibly explain why the received levels were initially louder at 100m at Griffin than they were in Haro Strait at 100m, and then dropped in value at 400m to create a steeper spreading loss slope. The sound waves may have been pushed upward by the sea mound and onto the array depending on the angle of the array at 100m, and when the boat moved to the 400m recording distance, the received levels were much smaller due to the interference of the sea mound.

Another factor that may have greatly influenced the received levels I measured were the sensitivities I used for each hydrophone. On 5-12-08 we attempted to calibrate our hydrophones using pure 500Hz, 1 kHz, and 2 kHz tones and using the Interocean System 902 which can give received levels of the pure tones it produces. Multiple colleagues analyzed the calibration data, finding varying sensitivities depending on which tone had been recorded and what program was used for analysis. Of the several sensitivities found, the ones I used for my experiment made the most sense when calculating controlled spreading loss, where channel 1 should have always been the largest received level, and channel two the second most, etc. Though I was able to find some conclusive spreading loss equations, I am also a bit skeptical of the sensitivities I used.

With the limited efficiency and time constraints of my pseudo-click device, I was only able to conduct one day of masking experiments. I found that my pseudo click can still be detected when a 18 HP inflatable dinghy travels by at a cruising speed and both 100 and 400m, and though I only modeling masking at 75m, I could easily test that masking by performing the experiment over and having the dinghy circle the hydrophone at 75m. Though this only a result for one particular motor type, if a more efficient pseudo-click device could be found, many more boats could be tested.

One very possible efficient way of testing for masking could be the use of a transducer such as the Biosonics Echosounder. When tilted horizontally in the water, the transducer creates a very directional beam of pings, and if a fish or other object/animal with an air bladder comes within the range of the ping, an "echo" or image is insonified onto the Visual Analyzer Software, much like the echo the whale would be interpreting if at the right frequency and amplitude. When the Gato Verde depth sounder was left on during Echosounder experiments, the high frequency pings it put out would interfere with the "echoes" the Echosounder logged as we performed bathymetry transects, obscuring the image on the computer screen.

If a transducer could be set to send out signals similar to a frequency of killer whale echolocation clicks (the Echosounder was only set stationary to 200kHz), boat drive-by experiments could be performed as the transducer insonified a target, and if the background noise caused interference in the image, masking could be documented and measured.

I still have questions yet to be answered about how motor boat noise can shorten the range at which echolocation signals can travel, but this study proves a point that further study on the complexities of sound propagation must be explored in order to find consistent distances where masking might occur before further revaluations of any adjustments of what "Be Whale Wise" guidelines should be. Distance and speed of vessel may be one factor affecting masking, but spreading loss, proven to change to do bathymetry (which is very complex in itself, without even factoring in oceanographic affects on sound propagation), could also be another factor in determining masking guidelines.

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