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 work together in cooperative groups in order to find schools of fish to feed on, and 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. 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 bandwidths 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. Erbe (2002) found that 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 of boat noise.

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*.

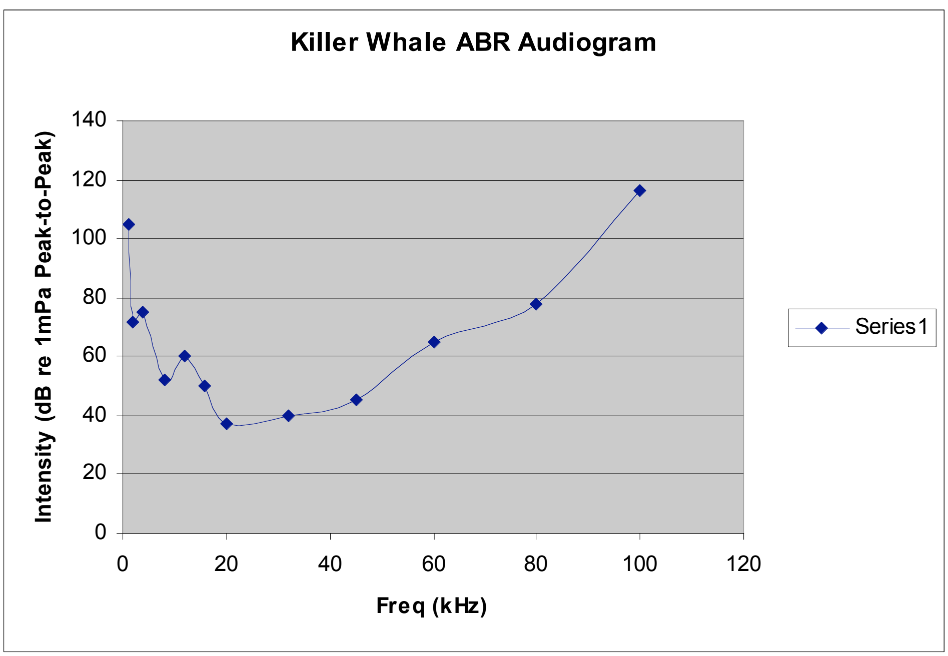

Fig 1 *adapted from* Szymanski et al. (1999)

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.

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 echolocation click frequencies with harmonics ranging over 100 kHz (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

Instead of creating a model to estimate potential masking, I will document masking by making "pseudo" echolocation clicks of similar frequency and source levels of wild killer whale clicks.

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 Au et al. (2004), frequencies of echolocation clicks ranged from 20-80 kHz (Au et al. 2004). The higher frequency clicks will be able to detect smaller targets while lower frequency clicks detect larger targets (Wood per. com 2008). 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 (Au et al 2004). Given that it is the swim bladder of a fish that a killer whale actually detects (Wood per. com 2008), it would be assumed that the clicks needed to detect the small organ would need to be of a high frequency. See *Figure 2*. Au et al. (2004)'s study found target strengths of a chinook salmon to be at 50 kHz using digital radiographs, so I am going to aim to make the frequency of my pseudo click to be at 50 kHz.

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

Study Sight:

The study area will be 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.

<u>Determining Frequencies and Source Levels from Southern Resident Echolocation Clicks</u>:

Materials and Equipment :

To record echolocation clicks, a hydrophone array will be 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.

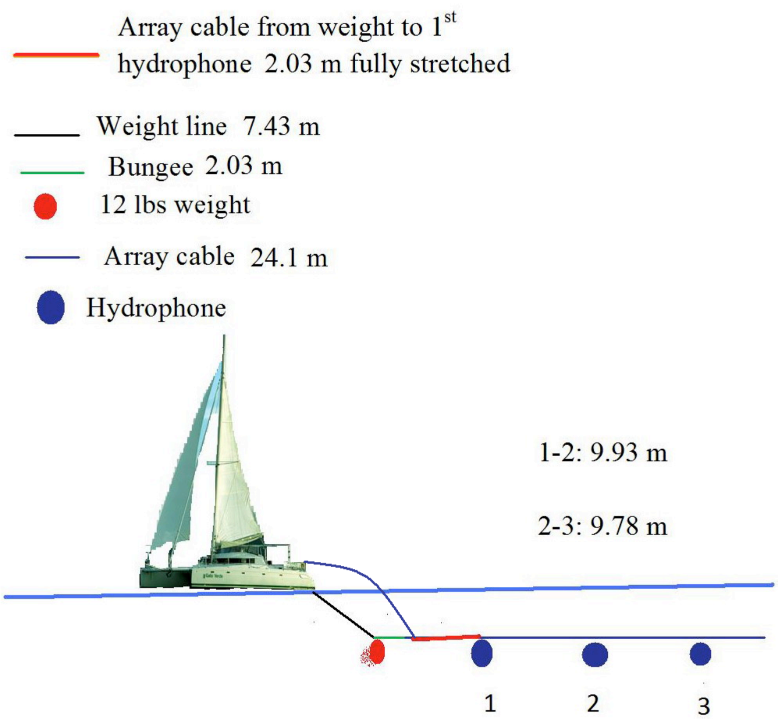

Fig 3 Courtesy Walk 2008

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 low frequency hydrophones will be towed, as shown in *Figure 3*. On the starboard stern side corner our single Cetacean Research Technology high-frequency hydrophone will also be 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 will be recorded with two 702 Sound Devices, at 16 bit depth with sampling rate at 192,000 samples per second. Low frequency drag noise will be filtered out with a low cut filter of 240 Hz 24 dB/oct. Our hydrophones will be 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.

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*. Frequencies of clicks will be analyzed with the Beam Reach Sound Analyzer Program (v. Oct 18th 2008) and saved into Excel to create frequency spectrums and to test means statistically.

Measuring Masking: Creating a Pseudo-Click Apparatus

In order to practically measure how close a boat has to be in order to mask, I need 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.

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 Southern Resident killer whale habitats deep enough for the light bulb to sink in order to burst, I attempted to burst the light bulb at any depth I chose by dropping a weight on a light bulb attached to a line. For my first test I lowered a light bulb into the water with a weight. Using another smaller weight with a hole in it, I let the holed-weight drop from the dock along the line until it burst the light bulb at the other end. In order to prevent glass debris left in the water, I surrounded the bulb with a small mesh netting to collect the broken glass.

I used a hydrophone array with one high frequency CRT hydrophone and 3 lower high frequency hydrophones. See *Figure5 :*

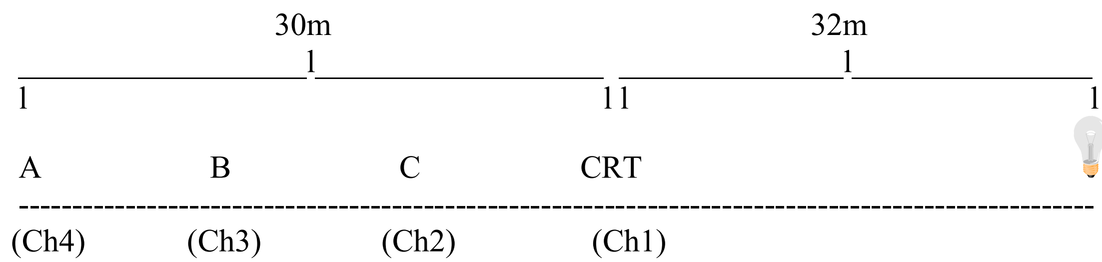

Fig 5
Placement of hydrophone along the dock. The light bulb and weight were deployed at one end of the dock, and the array lowered parallel to the dock. The first channel was deployed 32m from the bulb, with the array stretching 30m to the other end resulting in the last channel being 62m away from the bulb. The four channels were evenly spaced.

Using the linear array along the Friday Harbor Laboratory dock, I lowered the light bulb about 5m deep into the water, 32m away from the closest hydrophone (CRT – ch1) and 62m away from the furthest hydrophone (A – ch4). The total length of the set array was 30m, with each array evenly spaced apart 10m. The array was lowered 1m into in the water column. The water column along the FHL docks is fairly shallow (mean low tide of 10ft). Sampling rate was at 192 Hz, 16 bit depth. Gains were lowered on the first two channels to prevent clipping. Gains from ch1-ch4 were: 20.4 dB, 25.1 dB, 37.7 dB, and 36.7 dB.

Using data from ch.1, I analyzed the data from the short blast using the Beam Reach Sound Analyzer, transferring the data to excel to create a spectrum for the blast:

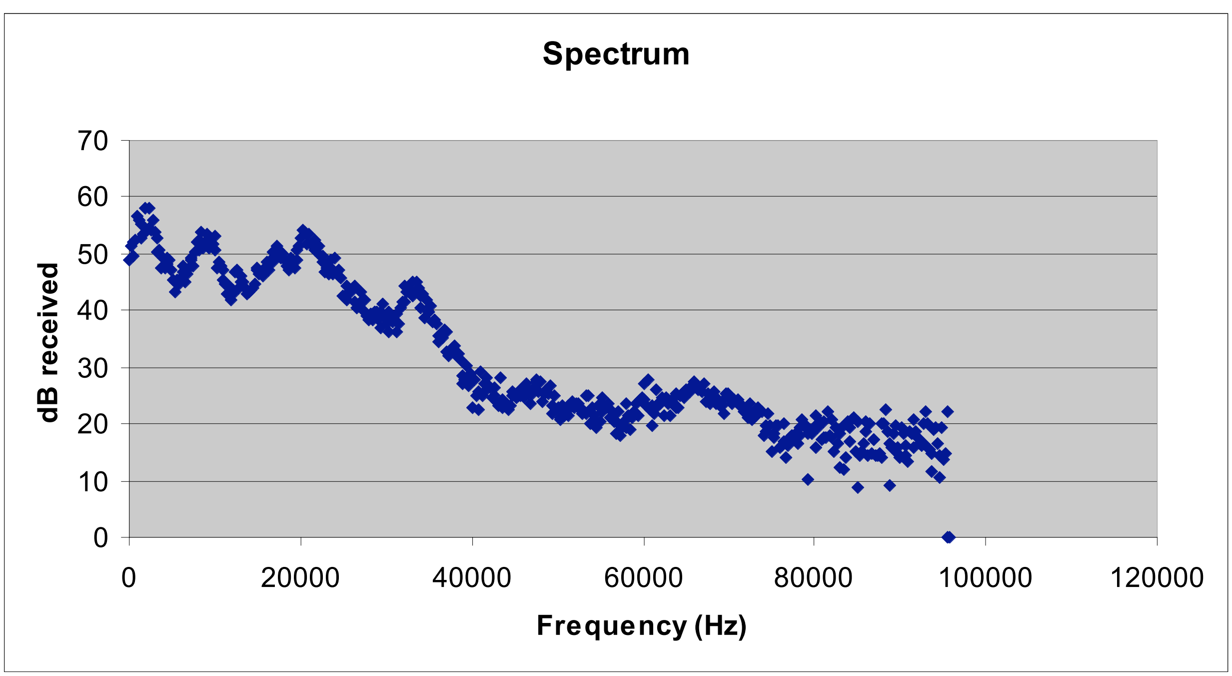

Fig 6

Using data I collect recording actual killer whale echolocation clicks, I will compare the mean frequencies, amplitude, and spectrums to the data I collected bursting a light bulb in order to accurately access if this pseudo click mechanism is a good representation of a real click.

The next step to create my masking experiment required me to find the attenuation of the light bulb burst in order to see how far my pseudo could travel, and help me find the source level. To measure attenuation of the sound produced by the light bulb I used the array described in *Figure 5*. In order to calculate the spreading loss, I calculated the RMS of each channel using the Beam Reach Sound Analyzer Oval Software (v. Oct18th 2007) and converted it to dB received by using the equation: dB re 1 μpa = 20log10(RMS) + sensitivity. I then subtracted the sensitivities from our hydrophone calibration on 4-29-08, adjusting the sensitivities due to the changes I made in each channel's gain. (I lowered ch1 and ch2 8 dB from our normal gain settings to prevent clipping). See *Table 1*

Table 1

	RMS	Class recorded sensitivities	Class gain settings	Gain adjusted	Experiment gains	Adjusted sensitivity	RMS converted to dB	dB received - adjusted sensitivity
Ch1	0.2	-143	28.4	lowered 8 dB	20.4	-151	-13.979	137.021
Ch2	0.18	-147	33.1	lowered 8 dB	25.1	-155	-14.8945	140.1055
Ch3	0.17	-145	37.7	stayed the same	37.7	-145	-15.391	129.6089
Ch4	0.16	-149	36.7	stayed the same	36.7	-149	-15.917	133.082

To calculate an equation for spreading loss, I plotted the log of the distance of each hydrophone from the sound source versus the dB re 1 μpa. *See Table 2*

Table 2

hydrophone	distance from sound source	log of distance	dB re 1 μPa @ 1m
ch1 CRT	32m	1.505	137.021
ch2 C	42m	1.623	140.1055
ch3 B	52m	1.716	129.6089
ch4 A	62m	1.792	133.082

After plotting the log of the distance of each hydrophone from the sound source versus the dB re 1 μPa I calculated a linear regression line of the slope. See *Figure 7:*

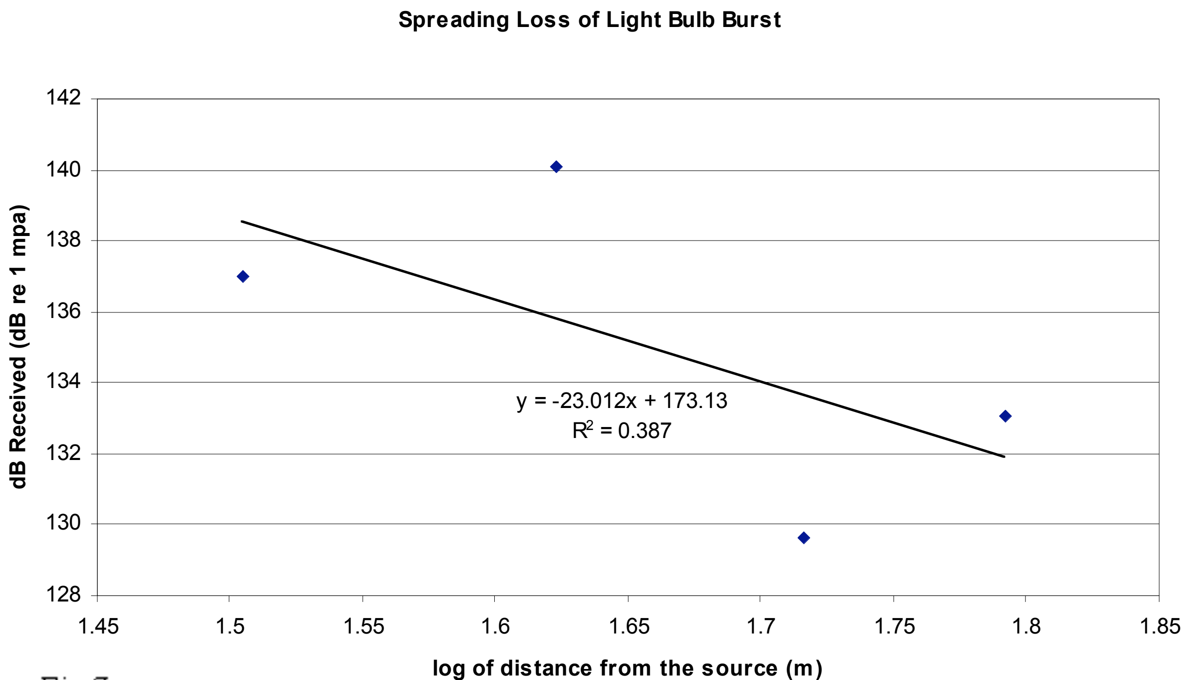

Fig 7

The slope I found for spreading lost of the light bulb burst was y = -23.012x + 173.13. The dB level of the sound decreases as it spreads. At Y = 0 would be the limit of the distance the sound can travel because at that point dB re 1 µpa is equal to 0. At 0 distance from the source, the dB re 1 µpa is equal to 173.13 dB, which is the source level of the bulb burst.

I also wish to measure spreading loss in different Southern Resident killer whale habitats, specifically due to the differences in bathymetry. 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.

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. I will also break a light bulb in these habitats, similar to the array set up in *Figure 5* to calculate each spreading loss equation.

The final step in the masking experiment is to then 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" will be emitted from a dinghy, with the high frequency CRT set stationary on the *Gato Verde* to receive the signal. Distances of the receiver "R" from the source will be determined by the distances found for each pseudo click to travel in different bathymetric habitats. Elaborating on the results of Hunt (2007)'s modeling for potential masking, I will attempt to use a motor boat cruising at 400 m, which Hunt (2007) found that all motor types measured could potentially mask an echo of an echolocation click, and also test slow motoring speeds at 100 m in correspondence to the "Be Whale Wise" Marine Wildlife Guidelines for Boaters, Paddlers, and Viewers (Whale Museum 2007). I will use a laser range finder to measure and report via radio the distances of the dinghy and motorboat. For the sake of timing and planning within the short number of field days, I will use one of the small motor boats most available to the *Gato Verde* to be piloted by our own crew and used whenever needed rather than schedule multiple boats with each specific type of engine. If possible I intend to use a either a motorboat with a twin inboard 400HP Biodiesel or surface piercing engine, which Hunt (2007) found to most likely potentially mask at slow motors speeds at 100 m and cruising speeds at 400 m. See *Figure 8*:

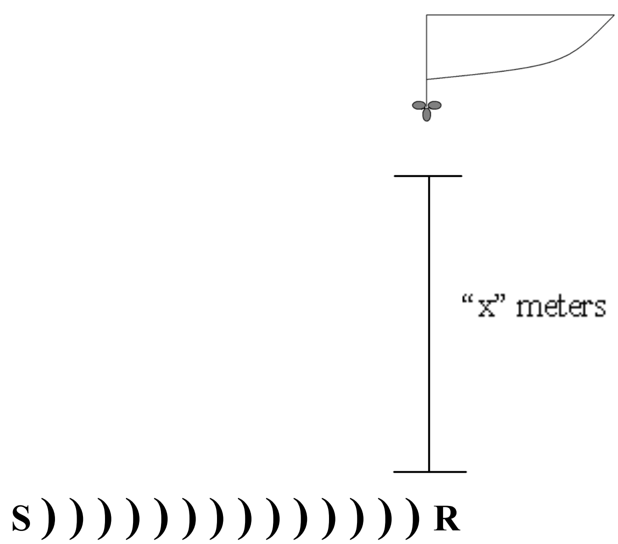

Fig 8 – "S" is the Signal, "R" is the Receiver. The motorboat will be placed at *x* distance away from the receiver and signal.

With the advantage of piloting our own boat, the exact point where the receiver detects the source can be found. By moving the boat closer or farther from the hydrophone, the point where the Signal to Noise Ration (SNR) is greater than 0 can be found using the critical bandwidth (CBW) assumed for boat noise. I am assuming a $1/6^{th}$ an octave for the CBW of boat noise.

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