Investigating the Potential Effects of Shipping Traffic and Underwater Noise Pollution on Southern Resident Killer Whale Echolocation

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Abstract:

The Southern Resident Killer Whales (SRKW) are a distinct population of killer whales that live in the Salish Sea during the spring to fall months. These whales were listed as endangered by NOAA in 2005 and the Salish Sea was then designated as SRKW critical habitat. Haro Strait, the center of the critical habitat, is one of the most traveled shipping lanes in the Salish Sea, filling the underwater environment with noise pollution. Killer whales rely on underwater acoustics to forage, navigate, and communicate in their underwater environment. Increased levels in underwater noise have the potential to change the acoustic abilities of the Southern Resident killer whales. This study investigates the potential effects of shipping traffic on Southern Resident killer whale echolocation. To determine how ships affect the received level of sound, calibrated hydrophone recordings were made at 9 different waypoints around Haro Strait. Ship data was collected using an Automatic Information Systems (AIS) receiver. These recording samples and ship data samples were correlated using linear regression. A linear relationship was found between the minimum ship range and the received level of sound, suggesting that as ship range decreases, the received level of sound increases. Echolocation click rate was also compared to AIS ship data. Recordings, both real-time and archived, were analyzed using PAMguard Beta to count the clicks produced per minute. The click rates were then averaged for each half hour of recording and these averages were compared to their corresponding ship data using linear regression. No linear relationship was found between click rate and the number of ships, click rate and the minimum range of ships, or click rate and the speed of ships. Wilcox tests were done for all of these categories as well, and it was determined that none of the click rates were significantly different, regardless of the number of ships, speed of ships, and range of ships. Although the data collected during this study suggests the range, number, and speed of ships does not significantly change the click rate of SRKW's there is still potential for masking to occur. A masking model was created using data collected during this study that demonstrates the potential masking effects that killer whales may experience while using echolocation in the presence of ships.

Introduction:

The Southern Resident killer whales (SRKW) are a distinct population of killer whales that spend the spring to fall months in the northern inland waters of Northern Washington and Southern Vancouver Island, B.C. In 2005 the Southern Resident killer whale population was listed as endangered and the Salish Sea was designated as critical habitat for this population of whales. The recovery plan for the Southern Resident killer whales addresses three primary threats to the population recovery: limited availability of prey, exposure to contaminants from pollution, and disturbance from vessel traffic and noise (NOAA/NMFS 2008).

Vessel traffic and noise is a major concern to the recovery of the SRKWs because the whale watching vessels have a prevalent presence on the water and major shipping lanes run through the designated critical habitat environment. Killer whales rely on bioacoustics' communication, including echolocation, to navigate, forage, and communicate with one another (Ford 1989). Increases in underwater ambient noise levels have the potential to negatively affect these whales and their ability to use bioacoustics. If a killer whale were using echolocation in an area of high vessel traffic a variety of negative affects may occur, such as auditory threshold shifts, changes in behaviors (avoidance), increased energy expenditure, and masking, which may lead to changes in acoustic communication (Erbe 2002). It is possible that the received echo sound from a produced echolocation click may be masked, difficult to hear, due to the increased levels of ambient noise from passing vessel traffic. A study conducted in 2006 by Griffin and Bain suggests that masking of echolocation clicks is a significant problem for the Southern Residents. This study demonstrated that an increase of 12 dB in ambient noise levels could lead to an annual decrease in foraging space between 15% and 20%. Which also suggests a decreasing carrying capacity for these increasing noise levels and the subsequent avoidance behaviors from the killer whales is 18% to 23%.

Although the whale watch vessel traffic is still a concern in Southern Resident killer whale population recovery, many studies have been conducted on these types of interactions. However, few studies have investigated the potential affects that the nearby shipping lanes and shipping traffic may have on the Southern Resident killer whale's ability to use bioacoustics.

In 2005 Veirs and Veirs wrote a report to NOAA on their findings of the average sound pressure levels and ambient noise levels in Haro Strait. Their findings suggest that the noise levels in Haro Strait are dominated by shipping traffic. They also found that 1 ship passes through the Strait approximately every hour, adding 20-25 dB of noise with each passing.

Given what is known about marine mammals and underwater noise pollution, and the state of the noise pollution in the Southern Resident killer whale habitat this study aims to examine the potential affects of shipping traffic in respect to Southern Resident killer whale echolocation. This investigation aims to specifically address the following questions:

1. What factors of shipping traffic most affect the received level of sound at various locations near Haro Strait.
2. How do these same shipping factors affect Southern Resident killer whale echolocation, specifically echolocation click rate?
3. Is there potential for masking of echolocation clicks to be occurring in the designated critical habitat of the Southern Resident killer whales?

Methods

This study implements a three-part data collection and analysis with the ultimate goal of determining if a relationship exists between the Southern Resident killer whales' echolocation and shipping traffic in the Salish Sea.

<u>I. Determining ambient noise level in relation to shipping traffic</u>

The purpose of this portion of the study is to determine how shipping traffic affects the received noise level at various locations around Haro Strait, see below in Figure 1.

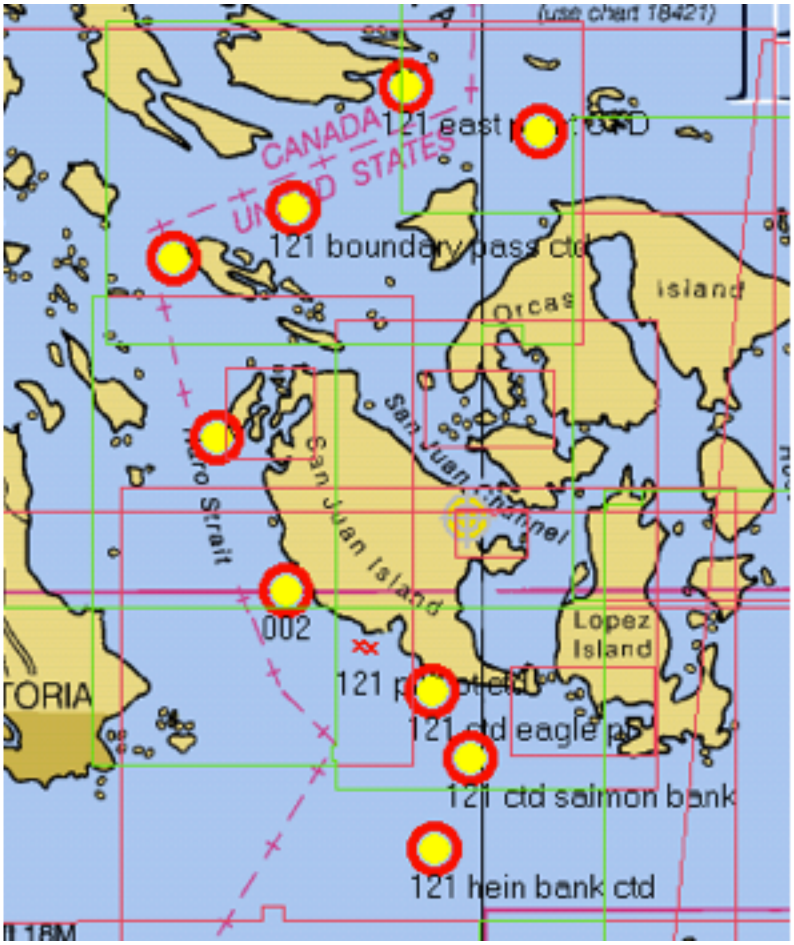

Figure 1:
Data collection waypoints near in the SRKW critical habitat

From Northeast to North to West to South:
West Bank
East Point
Boundary Pass
Turn Point Kellett Bluff
Lime Kiln
Eagle Point
Salmon Bank
Hein Bank

Calibrated hydrophone recordings

Calibrated hydrophone recordings were made at these 9 different waypoints during the data collection period of April 30th to May 24th. A minimum of two recordings was collected at each of the waypoints. Data collection was conducted from the Gato Verde, a 42' long catamaran. Recordings were made on a laptop using Audacity 2.0.0, recording from an InterOcean Systems Blue Box, Model 902 Acoustical Listening Calibration System. The blue box is vital to these recordings because the recording can be calibrated to the varying ambient noise level. The calibration tone was interjected into each recording at the start and finish for approximately 1-2 seconds. Audacity was used to contrast the calibrated gain setting to the recorded ambient noise level. The amount of difference in dB between the two will be used to calculate the received level, using the equation:

$$CGS - CD = RL$$

Where CGS is the Calibrated gain setting (dB), CD is the Contrast difference (dB) and RL is the Received level (dB).

AIS Vessel Data

Real-time ship data was collected using an Automatic Information Systems (AIS) receiver mounted on the catamaran. The receiver was connected to a computer which outputs ship data. Screen shots were taken at the start of each calibrated hydrophone recording to collect the AIS data. The receiver was set to pick up ship radar within a 26-nautical mile (nm) radius. This specific radius was chosen because it is approximately half the length of the region of interest, Haro Strait and the surround shipping lanes. Data collected was the name of the ship, the type of the ship, and the range of the ship and the ship speed over ground. Ship data was only collected if the ship speed over ground was above 0.1 knots. This was to ensure that ships, which may not be updating their navigational statuses, are not included as contributing to the received level. However, this could impact the data because some ships with low speeds may not have motors that are contributing to the received level of sound. They could be moving by other means, such as drifting or sailing. This potential error could explain some of the variability seen in the results. The ship data collected was then used to determine the number of ships present during each recording and the maximum, average, and minimum range of ships from the Gato Verde during the recordings as well as the maximum, average, and minimum ship speed over ground.

Received Levels in relation to AIS vessel data

The received levels and AIS ship data above were used to determine whether the number of ships or range of ships most affects received noise level. Using linear regression ship data was compared to the correlating received levels. A range threshold was determined by regressing a variety of ship ranges against received level. Along with the ship data, other factors that had the potential to affect the received level of sound, such as waypoint, day of the week, and time of day were also regressed against RL to account for any relationships that may be present.

II. Echolocation Click Rate in Relation to AIS Ship Data

This part of the study aims to look at the echolocation click rate of the Southern Resident killer whales compared to the number of ships, range of ships and speed of ships. For the purposes of this study, echolocation click rate is defined as clicks per minute.

Both real-time recordings and archived recordings were used for this study. Recordings were made on the Gato Verde and at the Lime Kiln Lighthouse.

Gato Verde Hydrophone Array Recordings

An array of hydrophones (Labcore 40's Array with peak sensitivity at 5 kHz) was used to record the SRKW acoustics. The hydrophone was towed from the aft starboard side of the Gato Verde so as to get the clearest recordings. Recordings typically began once the boat was positioned approximately 200 m to the front and side of the Southern Resident killer whales to ensure the quality of the recordings. The recording time continued for the length of the encounter. Real time recordings were made on May 4th during the field study that was conducted from April 30th to May 24th 2012. The archived recordings that were used in this study were made on September 21st and 27th by the fall 2011 Beam Reach class.

Lime Kiln Lighthouse Hydrophone Array Recordings

Acoustic recordings were made at Lime Kiln Lighthouse using Ishmael software. The hydrophone array at the lighthouse is stationary and consists of 4 hydrophones in.dfadsfjsdfj…. One real-time recording from the lighthouse array used in this study was made on April 27th, by the spring 2012 Beam Reach class. The archived recording used in this study from the lighthouse array was made on September 16th, 2011 by the fall 2011 Beam Reach class.

Acoustic Recording Analysis

This study analyzed a total of 368 minutes of acoustic recordings, both real-time and archived. All acoustic recordings (mentioned above) were analyzed using PAMguardBeta Version 1.10.00 December 2010 to determine the echolocation clicks per minute. A module, including sound acquisition, FFT spectrogram, and a click detector was created with specific settings. This module was used for each analysis to ensure that the click rates were being detected in a consistent manner. Click detection parameters that were changed for the purposes of this study are:

Grouping, Channel, Threshold, Minimum Click Separation, and Maximum Click Length. Grouping was set to no grouping, Channel was set to Channel 0, and detection threshold was set to 15.0 dB. The minimum separation of samples was set at 5,000 samples, and maximum click length, which was manually measured in Audacity, was set to 25 samples.

These standards were chosen based on a trial and error test that was used to weed out aspects of acoustic recordings that are not of interest for the purposes of this study. For example acoustic buzzing sounds produced by the killer whales resemble click trains, but are not of interest for this study. Thus the detection parameters had to be tested until there was an amount of clicks being detected that fulfilled the purposes of this study without picking up on other acoustic properties that were not of interest.

AIS Vessel Data II

AIS ship data was collected and analyzed to correlate with all of the above acoustic recordings. The overall data that was calculated from each collection of AIS ship data was: the number of ships, and the maximum, average, and minimum distances of these ships from the Gato Verde at the time of the collection.

AIS screen shots were taken using the same protocol mentioned previously in AIS Vessel Data I. These shots were taken every thirty minutes while recordings were being made aboard the Gato Verde using the hydrophone array in the presence of the SRKW's.

Siitech, a website database that logs AIS data, was used to obtain the ship data correlating with the archived acoustic recordings as well as recordings made using the Lime Kiln Lighthouse hydrophone array. Ships within an 8km radius were chosen to correlate with these studies.

Analyzing Click Rate in Respect to Shipping Traffic

The click rate and corresponding shipping traffic data were analyzed using, linear Regression and Wilcoxon tests. The click rates were divided into categories based on the number of ships present, the speed of ships, and the range of the ships. This allowed for testing between the click rate produced when no ships were present vs. 1 ship, and the click rate produced for when 1 ship was present vs. 2

ships being present, etc. The Wilcoxon test was chosen for analysis because the click rate data did not have normal distribution, so a t-test was not possible. The comparison between two (click rate) with different conditions (number of ships, speed of ships, range of ships) was the goal of this statistical analysis.

III: Modeling Potential Masking Effects of Ambient Noise on SRKW Echolocation Clicks

The final portion of this study focuses on demonstrating the potential masking effect of ship noise on Southern Resident killer whale echolocation clicks. The model takes into consideration the source level of the SRKW echolocation click, the two-way transmission loss of the click, the target strength (Chinook salmon), the received level of the echo, the received level of the ship noise (at the whale) and the range of the ship. This model is meant to demonstrate worst-case scenario with a received level greater than 130 dB due to close proximity of a ship. For the purposes of this model, masking was determined to occur if the received level of ship noise (at the whale) is greater in dB than the received level of the echo (at the whale) from the click that the whale produced.

The equations used in the making of this model were:

Sonar Equation : Source Level(SL) = Received Level (RL) + Transmission Loss (TL)

Echo Equation : Echo Level (EL) = SL – TL – Target Strength (TS)

(see locations of these variables in the model, Figure 2 below)

The RL and TL variables used in this model were obtained during the data collection period of this study. The received level (RL) came from a calibrated hydrophone and AIS sampling conducted at the Kellett Bluff waypoint. The RL calculated was ~133 dB with the average ship distance at approximately 1.3 km. The TL value was calculated from the results of a spreading experiment conducted by Dana Roberson, fellow Beam Reach Spring 2012 student. The spreading experiment was also conducted at the Kellett Bluff waypoint. Dana calculated the ~TL to be -17 dB. The following equation was used to calculate the transmission loss for this model

TL= 17 * LOG10(r)]

r = average range of ship

The source level of a killer whale echolocation click and the target strength of a Chinook salmon, for the purposes of this model, were estimated based off of calculations done by Au et. al. in 2004. The source level of the SRKW echolocation click for this model is 205 dB and the target strength of a Chinook salmon is 53. The target is assumed to be Chinook salmon because it is the known primary prey of the SRKW while in the summer range (Hanson et. al. 2010)

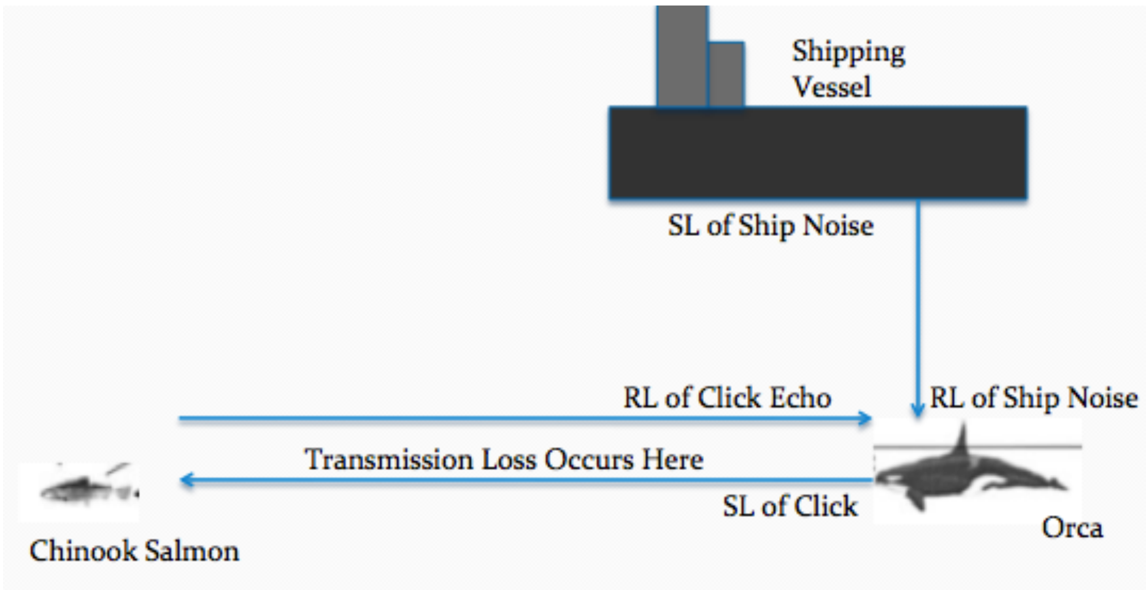

Figure 2: This model was used to determine the potential masking effects that a SRKW way may experience while using echolocation on a Chinook salmon in the presence of a very close ship.

Results:

I. Determining ambient noise level in relation to shipping traffic

The results from the calibrated hydrophone and AIS data demonstrate that there is a linear relationship between minimum ship range and the received level of sound. There was not a linear relationship between received level of sound and any other factors plotted. To test at which range this linear relationship is strongest, a variety of distances were plotted. A minimum ship range of 8km has the strongest linear relationship with the received level of sound, as calculated from the calibrated hydrophone recordings and corresponding AIS data used in this study (see Figure 3 below).

Plotting received level against the minimum ship range within the 8 km range threshold in respect to the number and speed of ships demonstrates that the number of ships and speed of ships do not seem to have a significant impact on the received level of sound. However, comparing these two graphs can explain specific outlier points that don't follow the linear relationship as well as the others. For example, figure 4 demonstrates received level of sound vs. the minimum range of ships in respect to the speed of ships. There are approximately 2 samples with a minimum ship range of 0.5 km, traveling within the speed range of 20-30km per hour, yet one has a RL of ~118 dB and the other has a RL of ~128 dB. This 10 dB difference is quite significant. If you compare these same two points again on the graph that plots received level v. the minimum ship range in respect to the number of ships, you will see that the sample with the lower RL of 118 dB has 2 ships present, where as the sample with the higher RL of 128 has 3 ships present. This suggests that although the number of ships and the speed of ships do not have linear relationships with received level of sound, they still have the ability to affect the received level within the 8km ship range.

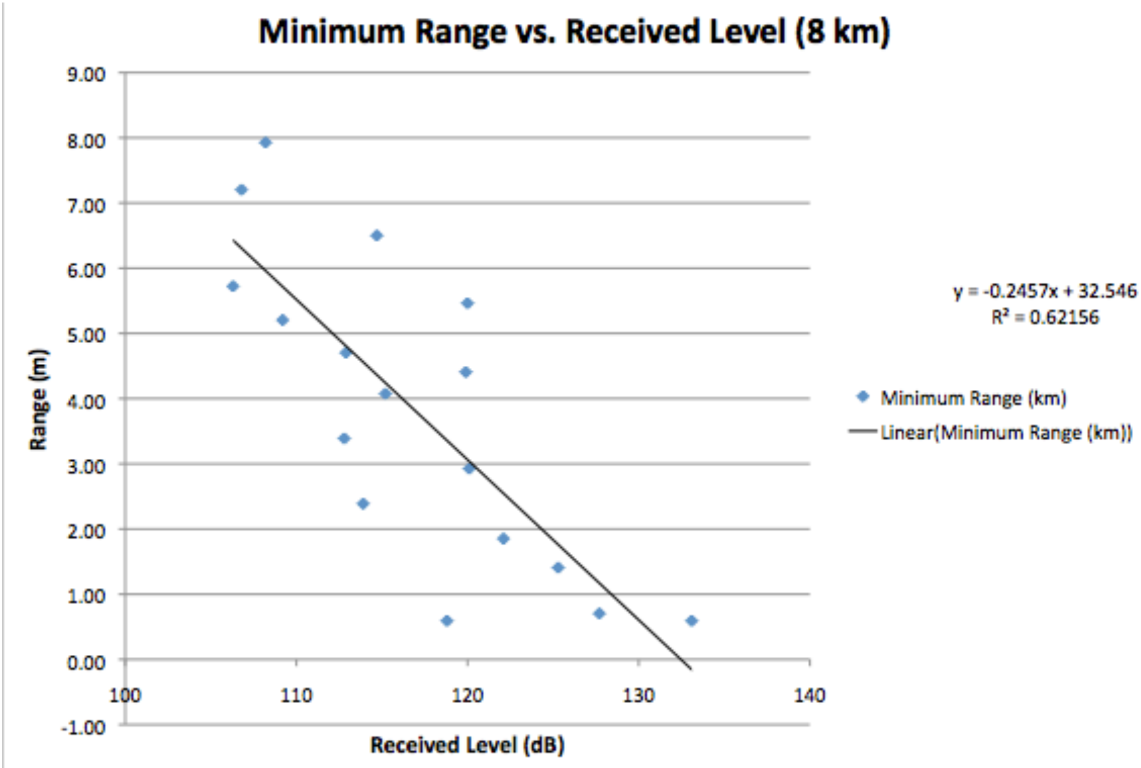

Figure 3:
This graph demonstrates the linear relationship between minimum ship range and the received level of sound to be strongest at 8 km with an R^2 value of ~0.6. This was stronger than the relationships between received level of sound and any other range of ships

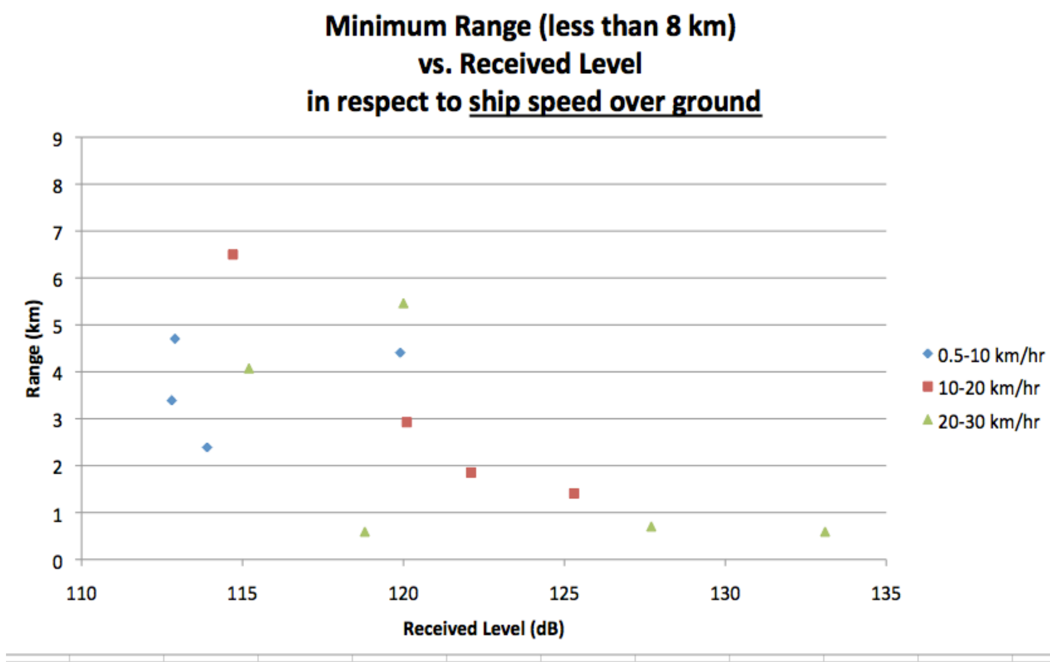

Figure 4: This graph plots the received level of sound (RL) vs. the minimum ship range in respect to the speed of ships. Notice the two points with similar speed and range, but different RLs.

Figure 5: This graph plots the received level of sound (RL) vs. the minimum ship range in respect to the number of ships. Notice the two points that demonstrated similar speed and range but different RLs on the previous two graphs. The higher RL has 3 ships present, were as the lower RL has only 2.

II. Echolocation Click Rate in Relation to AIS Ship Data

The results from linear regression demonstrate that there is not a linear relationship between click rates for the number of ships, speed of ships, and minimum range of ships present during the acoustic recordings (see Figure 5). The box plots for these data sets also suggest that the spread of the click rate data is not different. The results from the Wilcoxon test determined that there is not a significant difference in click rate in respect to the number of ships present, the minimum range of those ships or the speed of the ships (see figures 6-8).

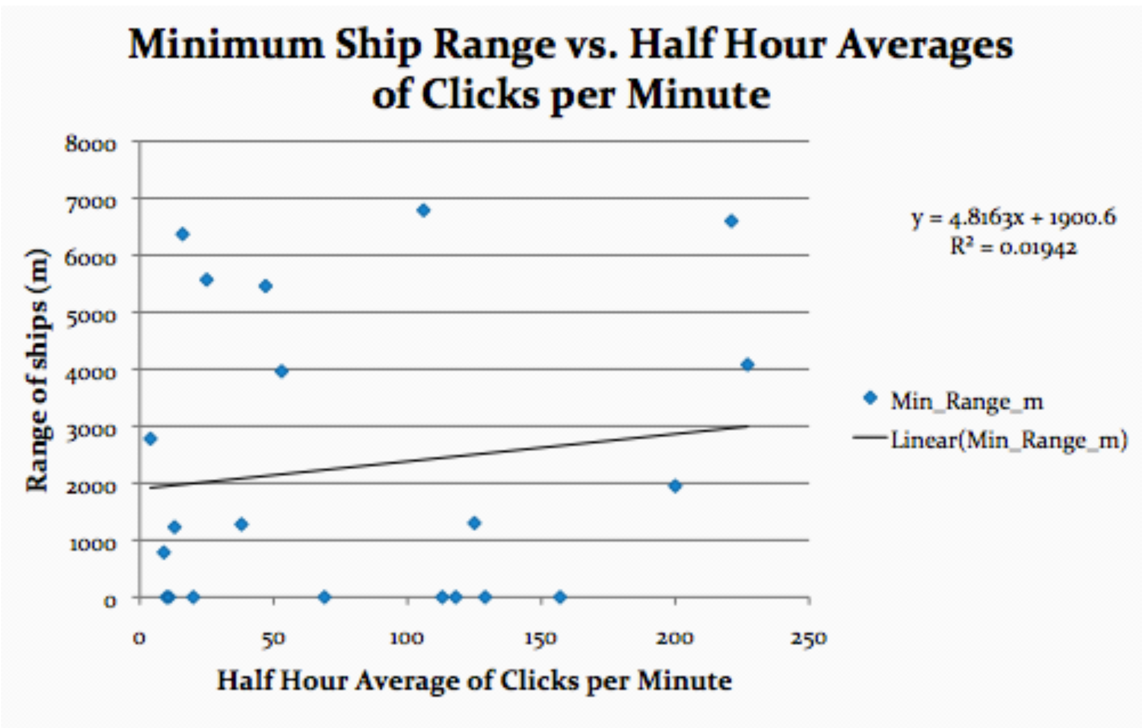

Figure 6:
This graph plots the minimum range of ships against the half hour averaged echolocation click rate (clicks per minute). It demonstrates that there is no linear relationship between minimum ship range and click rate in this data set.

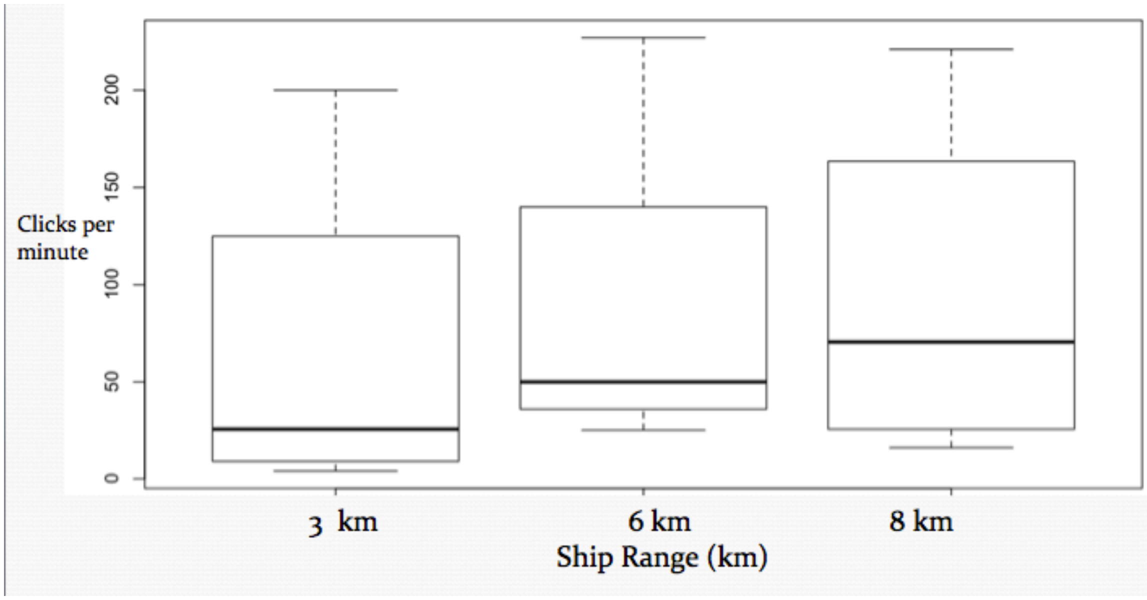

Figure 7: This box plot shows the echolocation click rate distribution for the minimum range ship categories of 3, 6, and 8 kilometers. The spread of the data does not look significantly different. Wilcoxon Test Results: click rate when ships are at 3km vs. click rate of ships at 6 km = 0.3524; click rate when ships are at 6km vs. click rate when ships are at 8km = 0.8857. There is no significant difference between click rates in regards to the distance of ships present.

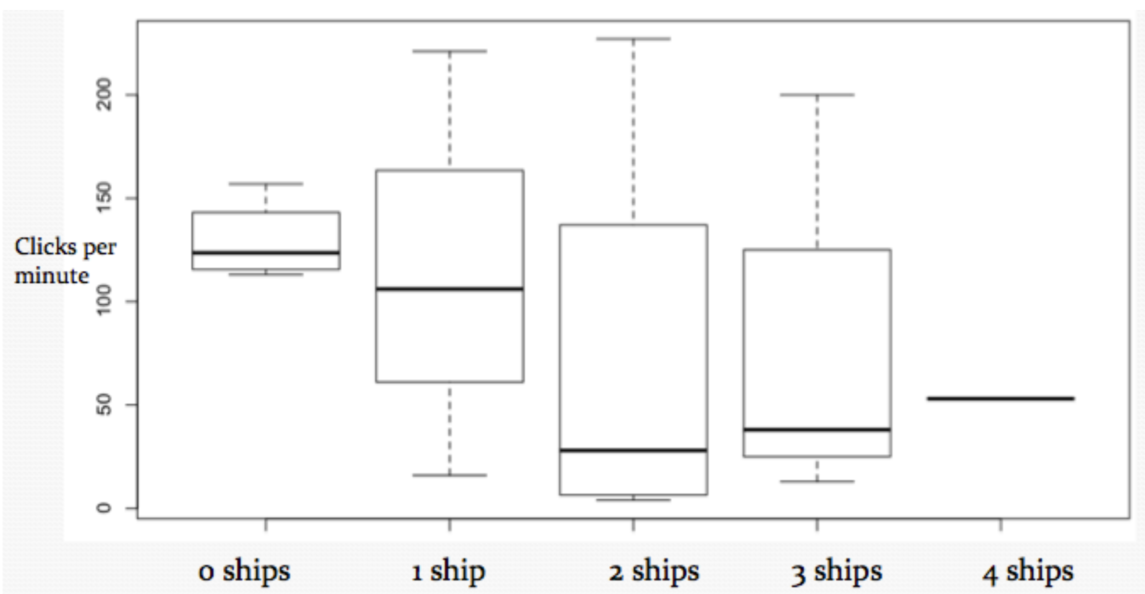

Figure 8: This box plot shows the different echolocation click rates in respect to the number of ships present. The spread of this data does not appear to be significantly different. The Wilcoxon Test results: click rate when 0 ships are present vs. click rate when 1 ship is present = 0.6286; 1 ship vs. 2 ships = 0.6286; 2 ships vs. 3 ships = 0.7302; 3 ships vs. 4 ships = 1. There was no significant difference between click rate and the number of ships present.

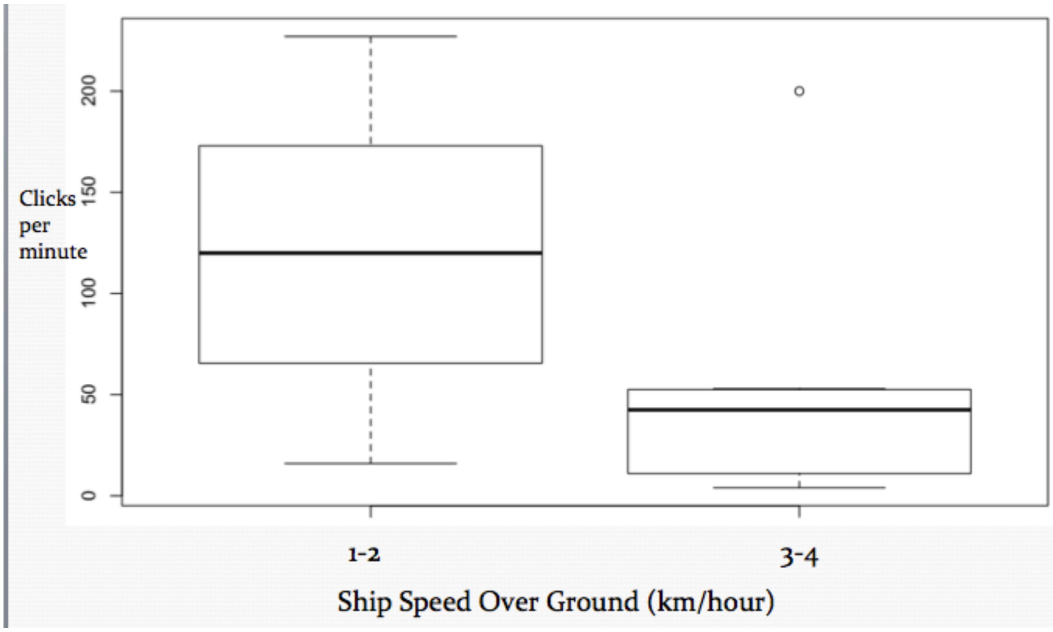

Figure 9: This box plot demonstrates the click rate in respect to the speed of ships present. The spread of the data does not appear to be significantly different. Wilcoxon test results: click rate for ships traveling 1-2 km/hr vs. click rate for ships traveling 3-4 km/hr p value = 0.1375. There is not a significant difference between click rates when ships traveling 1-2 km/hr vs. click rate when ships are traveling 3-4 km/hr.

III. Masking Model

The masking model created using data collected during this study period demonstrates that there may be masking of Southern Resident killer whale clicks occurring near the shipping lanes (see Figure 10).

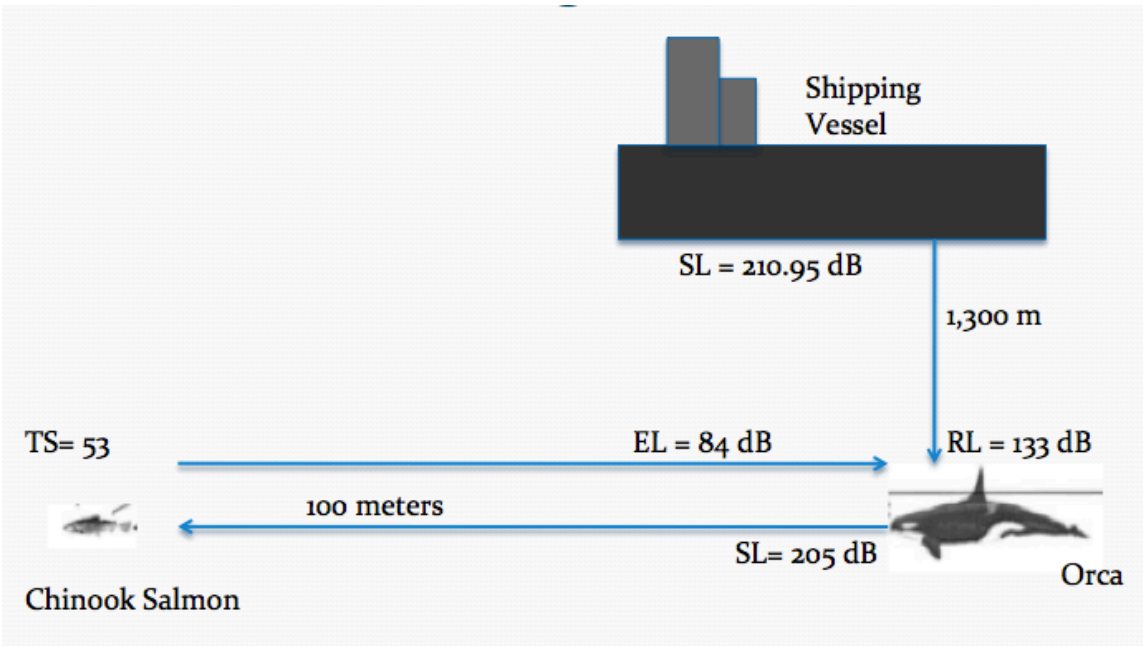

Figure 10: This masking model demonstrates that a ship ~ 1,300 meters away with transmission loss of -17 produces a received level of sound of ~133 dB. The source level of a killer whale click at 205 dB, a transmission loss of -17 and target strength of 53, 100 meters away, produces an echo level of 84 dB. 133 dB > 84 dB = Masking.

To determine at what point the EL is greater than or equal to the RL of ship noise the Sonar Equation and the Echo Equation were manipulated accordingly, changing the distance of the target strength from the killer whale. At 50 meters distance from the target the EL is 94 dB. At 5 meters distance from the target the EL is 128 dB.

Discussion:

The results from this study demonstrate that the received level of sound near Haro Strait is dependent on the range of the shipping traffic. It was found that the closer a ship's range to the location of the recording, the higher the received level of sound would be. A previous study done in 2005 by Veirs and Veirs suggested that the ambient noise levels of Haro Strait are dominated by shipping traffic. The data collected in this study adds to this information by demonstrating that the range of a ship has more of an effect on the ambient noise level than the number of ships in an area and the speed of those ships. The distance threshold of

Assuming that an increase in received level of sound would lead to a change in click rate, it could have been hypothesized that the echolocation click rate of Southern Resident killer whales would change in respect to the different factors of shipping traffic, specifically decreasing ship range. However, the data that was collected and analyzed in this study does not suggest that there is a significant difference in click rate in respect to the range of ships, number of ships, and speed of ships present. This could be due to the fact that a large amount of the shipping traffic operates in a low frequency, less than 20 kHz and the frequency of a SRKW echolocation click is typically between 20-60 kHz. Knowing this difference in frequency, it would be expected that shipping traffic wouldn't affect the killer whales' ability to use echolocation. However, not all ships are still operating in this low frequency range and the intensity of noise coming from the ships has the potential to still affect the Southern Resident killer whales' ability to use bioacoustics.

Click rate may be changing in respect to factors other than the range, speed, and number of ships present, such as: changes in behavioral state, the number of whales present, the number of echolocation targets present (i.e. the number of Chinook salmon in a given area), and the amount of smaller vessel traffic.

In Fall 2011 Beam Reach student Hayley Durance investigated SRKW echolocation click rate in respect to a foraging behavioral state vs. non-foraging behavioral states. The results from her study suggest that the change in click rate in respect to the behavioral state (foraging vs. non-foraging) were not significant. Further comparison of these click rates and fish finder data demonstrated that there was not a significant correlation between the percent of large target images and the click rate, however a trend appeared to occur that average click rate increased with the percent of large target images seen on the fish finder (Charla Basran, 2011). These two studies suggest that neither the behavior state nor the amount of targets (prey) present have a significant impact on the click rate. The behavioral observations for this study included categorizing behavioral states on sight. However, to get an unbiased observation, only surface behavior activities should be recorded, and post-data analysis should lead to determining the behavioral states observed (NOAA 2004).

Future investigations into the potential effects of shipping traffic on Southern Resident killer whale echolocation should include, surface behavior activity observations with the post-data analysis determination of behavioral states, whale counts so that there is an estimate of the number of whales present during each analyzed recording, general vessel counts along with the collected AIS data to get a better picture of all vessels in the area that could be contributing to the received level of sound.

Although the data collected in this study suggests that the range of ships, number of ships, and speed of ships present does not have a significant impact on Southern Resident killer whale click rate this is not to say that there is not still potential for masking to occur (see Figure 10). The received level of the ship noise (RL) at the whale is much greater than the received level of the echo (EL) at the whale. This indicates that there is potential for masking to occur in the scenario modeled. Manipulation of the equations showed that the Chinook salmon would have to be 50 meters from the whale producing the echolocation click for the echo level to be 94 dB. This means that at 50 meters distance the echo would be comparable to the quiet ambient noise level which is ~90-95 dB (no vessel traffic) (Veirs and Veirs 2005). If the Chinook salmon were only 5 meters from killer whale using echolocation the echo level at the whale would be 128 dB. This echo level is still less than the received level of ship noise, suggesting that even at 5 meters distance from the echolocation target, there is still potential for masking of the echolocation click.

It is important to recognize the threat that masking posses to the recovery of the endangered Southern Resident killer whales. Past studies have focused on the masking threat that smaller vessels, such as whale watch boats, pose to the whales. Masking can lead to changes in both acoustic communication and surface behavior activity. Both of these changes can increase the energy expenditure of killer whales (Williams *et. al.* 2002ab). The Southern Resident killer whales are also known to raise their calls 1 dB for each 1 dB increase in ambient noise, which also causes them to use more energy (Holt et. al. 2010). The ambient noise level in Haro Strait is dominated by the near constant shipping vessels that traffic through the region. Approximately 1 ship transits Haro Strait every hour with ~30 minutes of quiet in between ships. This puts the total shipping traffic at ~20 ships transiting Haro Strait each and every day of the year (Veirs and Veirs 2005). Regardless of the difference in frequency between shipping vessels and SRKW echolocation, the overwhelming presence of shipping traffic in Haro Strait and the Salish Sea and potential masking effects demonstrate that shipping traffic may pose a serious threat to the recovery of the Southern Resident killer whale population.

Conclusion:

The data collected in this study demonstrates that shipping traffic, specifically the distance of ships, affects the received level of sound near Haro Strait. The past studies done on SRKW communication, along with the model created for the purposes of this study, demonstrate that the Southern Resident killer whales may still be experiencing masking effects although the effects appear to not be reflected in a changing echolocation click rate. The potential effects of shipping traffic on the Southern Resident killer whales are a threat and further investigation into this issue is needed.

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