A study of the relationship between Southern Resident Killer Whale (*Orcinus orca*) echolocation click production and depth: A Beam Reach first

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INTRODUCTION

The killer whale (*Orcinus orca*) is the largest member of the Delphinidae family. Killer whales in the northeastern Pacific Ocean can be classified into three ecotypes that differ in morphology, genetics, behavior, foraging ecology, and acoustic repertoire (Baird 2000, Bigg et al. 1990). Resident killer whales feed on fish, primarily salmon, and travel in long-term stable groups (Ford et al. 1998). Transient killer whales feed on marine mammals and disperse from their maternal groups but continue to use their natal range (Baird 1994). Offshore killer whales eat fish, but little is known about their social organization or habitat use (Jones 2006).

The southern resident killer whales (SRKW) have a population of approximately 87 animals organized into three matrilineal pods. Between the months of May and November, the SRKW can be found in the Salish Sea, a geographic region that includes Puget Sound, the Strait of Juan de Fuca, and the Strait of Georgia, (K. Balcomb pers. comm). The SRKW were listed as endangered under the Endangered Species Act in 2005 (NMFS 2005). As part of this listing, the National Marine Fisheries Service (NMFS) designated the waters surrounding the San Juan Islands as critical habitat, and the SRKW's core summer habitat (NMFS 2006). The NMFS's Proposed Recovery Plan for Southern Resident Killer Whales (2006a) lists prey availability,

environmental contaminants, vessel effects, oil spills, disease, and cumulative effects of multiple chronic stressors as potential threats to the SRKW population.

The acoustic environment of the ocean is very important to all killer whales, as they use vocalizations to communicate, navigate, and forage for prey (Richardson et al. 1995). The killer whale vocal repertoire consists of whistles, calls, and clicks (Ford 1989). Whistles are highly variable tonal signals associated with social activity within groups. Calls are pulsed signals that function to coordinate group direction of movement and behavior state (Ford 1989, 1991). Clicks are short-duration, broadband signals that are used for echolocation by killer whales and other odontocetes (Au 2004). Killer whales use echolocation clicks to navigate obstacles when traveling and to track prey when foraging (Ford 1989, Barrett-Lennard et al. 1996).

Echolocation clicks are produced when an air stream is pushed dorsally through an odontocete's nasal system and the air stream causes a paire of connective tissue lips (phonic lips) to open and slap back together creating sound (Cranford et al. 1996, Au 2004). Echolocation clicks are projected from an odontocete's head in a highly directional beam (Richardson et al. 1995, Au 2004). Echolocation clicks produced by killer whales are between 80 and 120 μs in duration with bandwidths between 35 and 50 kHz. Most of the energy in the spectra is between 20 and 60 kHz (Au et al. 2004). Au et al. (2004) measured the echolocation signals of the northern resident killer whales and created a model of echo strength for whales foraging on chinook salmon (*Oncorhynchus tshawytscha*). Au et al. (2004) reported that the amplitude of the returning echolocation clicks was high enough that the killer whales should be able to detect chinook salmon at a distance of 100 m in high wind and wave conditions, and the broad bandwidth of their clicks should enable killer whales to perform fine target discrimination.

The SRKW selectively forage on chinook salmon when in the Salish Sea (Ford and Ellis 2006), and this may be a critical time for the SRKW, one during which they are particularly susceptible to human impact. The function and patterning of echolocation clicks have been studied in both resident and transient killer whale populations (Barrett-Lennard et al. 1996, Au et al. 2004, Deecke et al. 2004, Simon et al. 2007), but there is little or no information about echolocation and the SRKW in the literature. This study is an beginning step towards understanding SRKW echolocation. This step is taken with the ultimate goal of understanding the impacts of human activities on the success of SRKW foraging.

METHODS

Data Collection

I completed my research in Haro Strait, off of the west side of San Juan Island during week of October 7-13, 2007. The *Gato Verde*, a 42' catamaran was my research platform. I used a hydrophone array (Lab-Corr Systems, Olmpia, WA) to make my recordings. This hydrophone array consisted of four hydrophones spaced 10 m apart. The hydrophone array was connected to a four-channel intrumentation amplifier with *National Instrument*s analog to digital converters that was connected to a laptop running *OVAL* sound recording software (written for Beam Reach by V. Veirs).

When we encountered a group of SRKW, I asked the captain to situate the *Gato Verde* ahead and to the side of the whales' path of travel. If a direction of travel was not apparent, or if the whales were very spread out and/or frequently changing their direction of travel, I asked the captain to locate the between 100 and 400 meters from the whales, I asked the captain to stop the motors so the boat was stationary or drifting with the currents. *Gato Verde* in a position that was likely to be as close to the whales as the Be Whale Wise Guidelines allow (NOAA Fisheries

Northwest Region). The hydrophone array was deployed as depicted in Figure 1. To keep the

hydrophone array a close to vertical as possible as the *Gato Verde* drifted, I asked our captain to

make small adjustments to our position with the boat's nearly silent electric propulsion system.
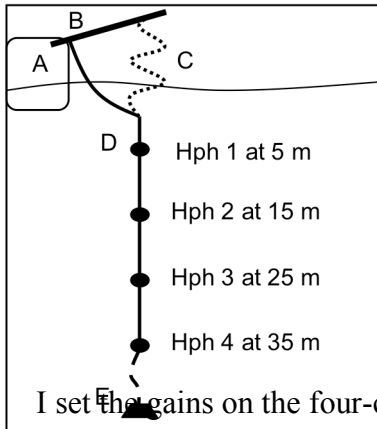

Figure 1. Vertical Deployment of Hydrophone Array

This diagram is not to scale. This deployment was set up at the stern of the starboard hull of the *Gato Verde* (A). An outrigger (B) was set up to prevent the array from tapping against the side of the boat. A 2 m bungee cord (C) was connected to the outrigger and to the hydrophone array (D) 5 m above the first hydrophone (Hph 1). A 12 lb weight attached to a rope anchored to the fourth hydrophone (Hph 4) in the array (E). The first hydrophone (Hph 1) was located approximately 5 m below the surface of the water, with the second (Hph 2) at 15 m, the third (Hph 3) at 25 m, and the fourth (Hph 4) at 35 m. The captain of the Gato Verde made small corrections with propulsion system to maintain the array's vertical positioning.

I set the gains on the four-channel amplifier and began recording if I heard calls or

echolocation clicks. I recorded continuously until the calls and echolocation clicks now longer

stood out clearly from the background noise, which typically occurred when the whales swam

away from the Gato Verde or when anthropogenic noise levels were high due to vessel noise

from ships and/or whale watching boats. While recording I took a GPS waypoint, noted the

weather and water conditions, and recorded my general impressions of the scene, including the

number boats in the vicinity and the behaviors of the whales. The OVAL recording program

divided the continuous recordings into one-minute segments, and for each segment I made note

of the presence of calls, echolocation clicks, and boat noise.

Data Analysis

I began my data analysis by attempting to localize echolocation clicks with

I.S.H.M.A.E.L. (April 15, 2005, U.S. Office of Naval Research and U.S. National Marine

Fisheries Service). When this analysis did not yield viable results, I abandoned this program and

used *Audacity* (Version 1.2.5, Sourceforge.net) to analyze echolocation click time of arrival

differences between hydrophone pairs. I opened a sound file in the waveform view, and located the all of echolocation click trains within the file (see Figure 2). I selected an echolocation click from the center of the first click train in the sound file, and continued analyzing clicks that were no less than 10 sec apart to avoid pseudoreplication, as I believe that 10 sec is sufficient time for an echolocating killer whale to change depths. If I analyzed a click within 10 sec of the end of a sound file, or if a sound file ended in the middle of a click train, I took this into account when beginning the analysis of the clicks in next sound file.
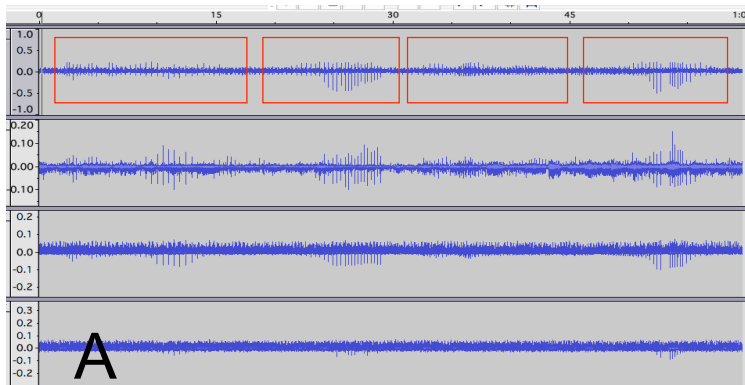

Figure 2. Examples of *Audacity* displays used for individual click analysis.
Display A shows echolocation click trains highlighted on the first channel. Display B shows three echolocation clicks with similar arrival signatures. Display C shows a single echolocation click. The first peaks of the click, used for time of arrival difference measurements, are highlighted in red in the third and fourth channels of the display.
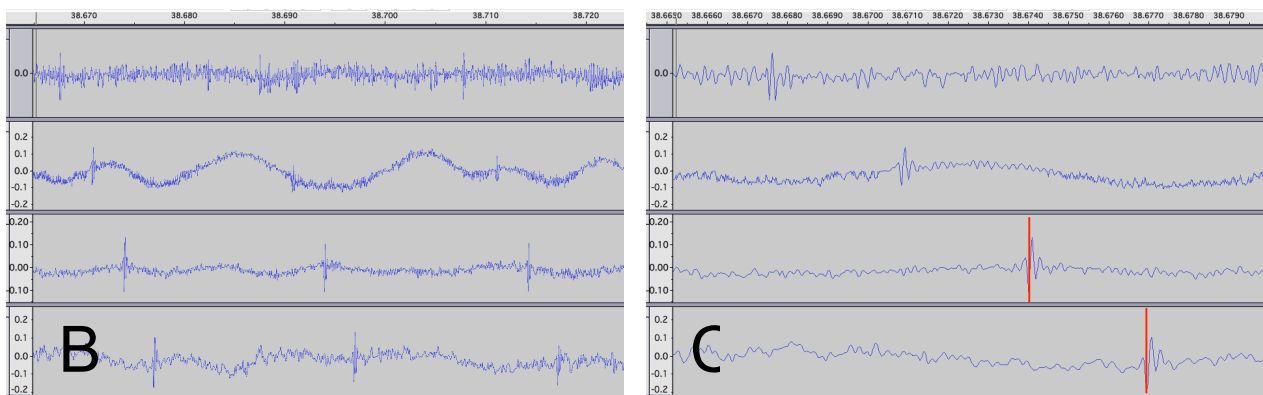
I used the "zoom in" command to expand my view until the screen was focused on a single click. I compared this single click to the clicks immediately preceding and following it to determine if they shared similar arrival signatures. If the click I selected did not share an arrival

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signature with its nearest neighbors, I did not include it in my analysis. I zoomed in on the first

channel until I could recognize the first peak of the click's waveform signal, and then aligned the

cursor with the center of this peak and recorded the time of arrival from the bottom of the

Audacity display. I repeated this procedure for the second, third, and fourth channels, though it

was frequently difficult to visually recognize echolocation clicks in the fourth channel. If I was

not able to visually recognize echolocations clicks in at least three of the channels, I skipped that

click train and moved to the next.

I used an *Excel* (Version 11.3.5, Microsoft) spreadsheet to organize and perform simple

analyses on my data. I calculated the time of arrival differences for neighboring hydrophone

pairs by subtracting the click arrival time recorded on the deeper hydrophone from the click

arrival time on the shallower hydrophone within the pair. I used these time of arrival differences

to group my data into shallow, middle, and deep categories with shallow clicks defined as those

that arrived at the shallowest hydrophone first, deep clicks defined as those that arrived at the

deepest hydrophone first, and middle clicks defined as clicks that arrived at one of the two

middle hydrophones first (see Figure 3). I then compared these data to two model dive profiles

(described below in the results section) and ran chi square tests were run to determine if the

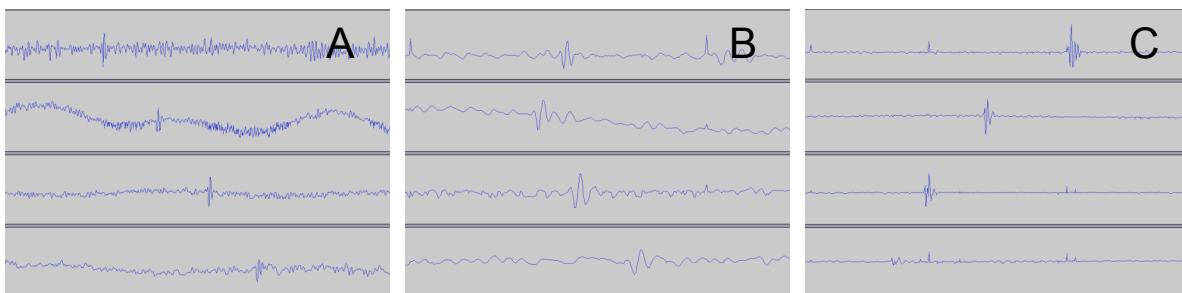observed data fit the values predicted by the models.

FIGURE 3. Time of arrival differences for clicks produced at different depths.
The horizontal and vertical scales are not constant in these images. Clicks that first arrived to the
shallowest hydrophone in the array were classified as shallow clicks (A). Clicks that arrived to one
of the middle hydrophones of the array were classified as middle (B). Clicks that arrived to the
deepest hydrophone of the array first were classified as deep clicks (C).

After completing a preliminary analysis of my data, I added the measures of click train length and number of clicks within a train to my analysis of 77 echolocation clicks (see Figure 4). I calculated the rate of clicking within each click train by dividing the number of echolocation clicks within a train by the length of that train, measured in seconds. I used a t-test to determine if there was a difference between click train length and clicking rate for the shallow and deep groups of clicks. I did not include the middle click group in my analysis due to the small sample size of this group.
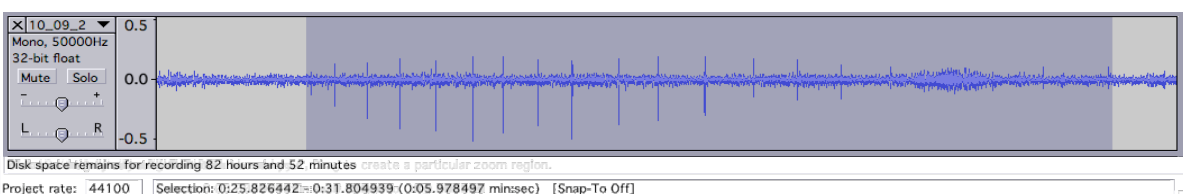

**Figure 4. A click train highlighted on one channel from the array.**
To determine the length of a click train, I zoomed in on a section of a sound file until I could clearly see individual echolocation clicks, and then used the cursor to highlight the section that contained the entire train. I recorded the length of the highlighted section, given in seconds, at the bottom of the *Audacity* display. I then counted the clicks within the highlighted section of the sound file. If click trains overlapped, and I was not able to separate clicks from the overlapping trains, I did not include clicks from those trains in my analysis. The click train in this figure is 5.98 sec long and contains 24 clicks.

RESULTS

I analyzed 165 individual echolocation clicks. Of these, 77 clicks fit in the shallow group, 15 fit in the middle group, and 73 fit in the deep group. The majority of echolocation clicks within one recording bout appear to fall into one of the groups, with very few clicks from the other two depth categories. Within click trains, nearly all of clicks appear to originate from the same depth category and have very similar visual signatures. No statistical analyses have performed to verify these general observations.

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Modeling of SRKW Dive Behavior and Echolocation Clicks:

Because little is known about the relationship between killer whale echolocation click production and dive behavior, I created and ran chi square tests on two simple models that describe possible relationships. Chinook salmon, the SRKW's favored prey (Ford and Ellis 2006) travel at an average depth of 25 to 64 m during the day, though they can dive to depths between 300 and 400 meters (Candy and Quinn 1999). While the SRKW spend 60-70% of their time between the surface and a depth of 20 meters (Baird 1994, Baird et al. 1998, 2005), they would likely have to dive deeper to forage for chinook salmon. In my first model, I used 44.5 m, the mean of the travels depths given by Candy and Quinn (1999) as the depth to which the SRKW would have to swim to catch chinook. In this model, I assumed that the SRWK swam at a constant speed and produced echolocation clicks at a constant rate. I also assumed that the SRKW did not linger at the surface or at depth, but instead dove and surfaced repeatedly (see Figure 6). My null hypothesis was that if the SRKW make echolocation clicks at a constant rate while swimming at constant speeds, and making repeated dives the observed distribution of clicks would match the distribution predicted by model one. Using the chi square test, I determined that the observed distribution of clicks was significantly different ($p < 0.001$, d.f. = 2) from the expected distribution described by model one, thus I was able to reject my null hypothesis (see Figure 5).
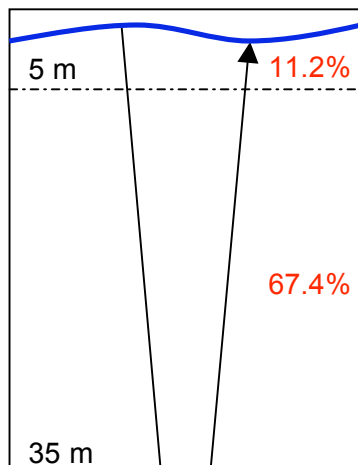
Group	Observed # of Clicks	Expected # of Clicks	χ^2	p <	d.f
Shallow	77	18.54	184.35	0.001	2
Middle	15	111.24	83.26	0.001	2
Deep	73	35.22	40.51	0.001	2
Total	165	165			

Figure 5. Diagram of Model 1 and results of chi square test
The red numbers in the diagram represent the percent of time the SRKW would spend in each depth category if they swam and constant speeds and made repeated dives without lingering at the surface or at depth. Shallow depths are < 5 m. Middle depths are 5-35 m. Deep depths are 35-44.5 m.

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During the summer of 2002, Baird et al. (2003) attached time depth recorders to eight

SRKWs and recorded over 79 hours of depth data. From this data, they found that an average of

only 2.4% of the SRKW's time was spent below 30 m in depth, but that 8-9% of velocity spikes

were recorded below 30 m. To Baird et al. (2003), this suggested that deep dives were important

for foraging. My second model incorporates a deep dive profile made by Baird et al. (2003) for a

dive made by whale L87 (see Figure 6). My null hypothesis for model two is that if the SRKWs

produce echolocation clicks at a constant rate while they are repeatedly making deep dives

following the dive profile created by Baird et al. (2003) and subsequently spending little time at

the surface, the observed distribution echolocation clicks will match the distribution of

echolocation clicks predicted by model two. Using the chi square test, I found that the observed

distribution of clicks was significantly different ($p < .02$, see Figure 6) from the expected

distribution predicted by Model 2, thus I am able to reject my null hypothesis.
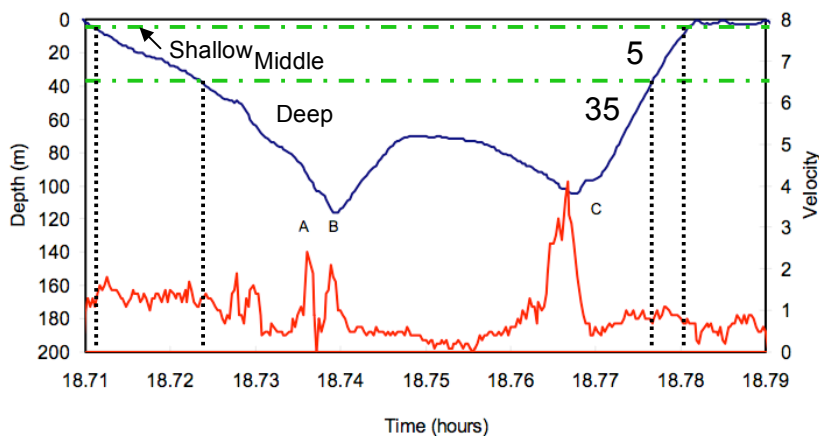
Figure 6. Diagram and chi square test for Model 2, adapted from a figure from Baird et al. (2003). The blue line is the dive profile of a single deep dive made by whale L87. The red line shows relative velocity of L87 during this dive. Shallow depths are < 5 m, middle depths are 5-35 m, and deep depths are > 35 m. Vertical dotted lines mark the point at which L87 entered a different depth category.

Group	Observed # of Clicks	Expected # of Clicks	χ^2	p <	d.f.
Shallow	77	24.06	116.46	0.001	2
Middle	15	37.81	13.76	0.02	2
Deep	73	103.13	8.80	0.0025	2
Total	165	165			

Analysis of Relationship Between Depth and Length of Click Trains and Clicking Rates

Because the number of clicks in the shallow category was nearly equally to the number of clicks in the deep category, I was interested in determining if there was a difference in the quality or total quantity of the clicks in each category. I measured the click train length and the number of clicks within the train for 77 clicks. From these values I calculated the clicking rate in clicks/sec for each train. If a click train was longer than ten seconds, more than one individual click was analyzed from that train, so long click trains are represented more than once in the data set. Of the 77 analyzed clicks, 40 were shallow and 37 were deep. Using a *t*-test for unequal variances, I determined that there was no significant difference between the shallow and deep categories for click train length or clicking rate (see Figure 7).

Click Train Length (sec)

	Sample size (n)	Mean	Standard Deviation
Shallow	40	5.66	7.06
Deep	37	6.53	6.72

t = -0.5508, p (2 tail) = 0.58, d.f. = 74.9

Clicking Rate (clicks/sec)

	Sample size (n)	Mean	Standard Deviation
Shallow	40	8.8	7.41
Deep	37	8.18	9.7

t = 0.3098, p (2 tail) = 0.76, d.f. = 67.2

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Figure 7. Results of *t*-tests for unequal variances for clich train length and clicking rate.

DISCUSSION

This study represents the first time a Beam Reach student deployed a four-element hydrophone array vertically to attempt to localize SRKW echolocation clicks at depth. The results of this study should be viewed in this light as new research often leads to more questions than answers. The two simple dive models in this study are examples of reaching into the literature to provide context for novel research. These models have faults, the greatest of which is that they are very simple and the behavior of intelligent social animals is usually very complex. With this in mind, I am not surprised that the distribution of echolocation clicks into the depth categories of shallow, middle, and deep was significantly different ($p < 0.05$) from the distributions predicted by the models. It is interesting to note that the observed distribution of echolocation clicks begins to approach the expected distribution predicted by Model 2, with $p < 0.025$ for the deep category $p < 0.02$ for the middle category, as compared to $p < 0.001$ for all three categories in Model 1. A study that combined dive profile data like those found by Baird et al. (2003) with bioacoustic recordings would provide the basis for developing more powerful models of foraging behavior.

The greatest surprise of this study was the small number of echolocation clicks observed in the middle category of 5-35 m deep, as it does not seem likely that the SRKW only echolocate very near the surface and at deeper foraging depths. I can hypothesize a number of reasons for these findings. The first is related to array geometry during data collection. It is difficult to know the actual underwater geometry of a hydrophone array, and bends in the line of the array

are likely to occur due to the pull of underwater current. During my data collection, there were times when the array was streaming 50° away from vertical due to current. Significant changes in the time of arrival differences recorded with the array can be expected when the geometry of the array changes. I did not correct for these changes in my analysis, so the observed distribution of clicks may favor one category over the others.

Because echolocation clicks are emitted from an ondontocete's head in a highly directional beam, and the intensity of the signal decreases as the angle away from the center of the signal increases (Richardson et al., 1995), obtaining accurate measurements of echolocation clicks produced by animals in the wild is difficult (Au 2004). This directional characteristic of echolocation clicks may play a role in the distribution of echolocation clicks observed in this study. With *Beam Reach*, we do not have a research permit, and we endeavor to carefully follow the *Be Whale Wise* guidelines (NOAA Fisheries Northwest Region) . This means that we are rarely directly in the path of the SRKW, and are usually parallel to or following their course of travel. Anecdotally, students listening to the hydrophone array in real time know when the SRKW are echolocating on the array because the received clicks become painfully loud, but it is hard to know if we are missing echolocation clicks made by animals that diving or swimming away from the array.

By analyzing click train length and clicking rate within click trains, I was hoping to provide some resolution to the nearly equal numbers of echolocation clicks observed in the shallow and deep categories, but my analysis revealed no statistically significant differences between the two categories for either of the measure. Put into context, these may not be surprising findings. Au et al. (2004) reported that killer whales should be able to detect chinook salmon at a distance of 100 m. This means that the SRKW could echolocate near the surface

when searching for chinook because the fish are traveling at average depths that are less than 64 m (Candy and Quinn 1999). An readily testable alternative hypothesis, is that the SRKW are using echolocation near the surface of the water to navigate and they are echolocating off of nearby whale watching vessels. Data supporting this hypothesis would show that the length of echolocation click trains and/or the clicking rate are higher when more boats are present.

While analyzing my data, I observed that some of the echolocation clicks had a secondary signal that cascaded down the array following the initial arrival of the click (see Figure 8). These secondary signals are from the reflection of the echolocation click off of the surface of the water. Researchers studying sperm whales have used these surface reflections as phantom hydrophones to localize the whales in three dimensions with a single hydrophone
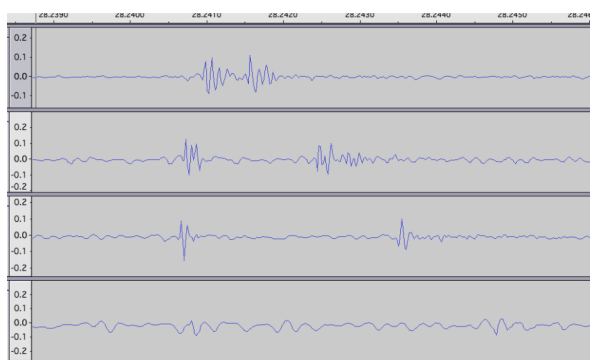

Figure 8. *Audacity* **display of a deep echolocation click with a surface reflection.**

(Tiemann et al., 2006) a horizontal towed array (Thode et al. 2002, Thode, 2004), and bottom-mounted hydrophones (Nosal and Frazer, 2007). Dr. Val Viers worked out the geometry of these surface reflections so that they could be used to localize the whale that produced the echolocation click, but because I do not have a firm grasp on the geometry, I elected to not include it here. Using surface reflections could a powerful tool for learning more about foraging behavior and echolocation click production.

This study provides the basic framework off of which many worthwhile studies could be created. Simply refining the methods and analysis used in this study would improve the quality of the data and allow for more careful modeling of echolocation click production. Other variables such as location, time of day, time of year, number of whales present, surface behavior of the whales, and/or number of boats present could be easily added to a study of echolocation click production. Because so little is known about the SRKW's use of echolocation, any additional study is valuable, and each new study will increase our understanding of these animals, which will in turn guide us in making informed decisions to reduce the negative impacts of human activities.

ACKNOWLEDGEMENTS

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