Variation in Southern Resident Killer Whale (*Orcinus orca*) Acoustic Signals in Relation to Environmental Factors

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INTRODUCTION

Killer whales (*Orcinus orca*) are one of the most widely distributed mammals in the world (Bigg et al. 1987; National Marine Fisheries Service 2008). They are the largest member of the *Delphinidae* family (Bigg et al. 1987; National Marine Fisheries Service 2008). There are three distinct ecotypes of killer whales in the North Pacific: transients, offshores and residents. Each ecotype is distinguishable by their behavior, diet, acoustics and their morphology (Ford et al. 2000; National Marine Fisheries Service 2008). They are genetically distinct and do not typically do not come into contact with each other, even though they have overlapping ranges (National Marine Fisheries Service 2008). This paper will focus on the third ecotype: the piscivorous residents, more specifically, the Southern Resident killer whales (SRKWs) that inhabit the Salish Sea. The SRKW community consists of related matrilines that associate into three pods (J, K, and L) and make up one acoustically distinct clan (J) (National Marine Fisheries Service 2008).

As with other resident killer whale populations, the SRKWs are highly vocal. Their acoustic signals are complex and unique from other residents and the other ecotypes (National Marine Fisheries Service 2008). An animal's ability to communicate is greatly dependent on its environment. They must overcome various hurdles dealing with sound loss and attenuation of sound in the medium that they are attempting to communicate in (Marler 1961). Many species have been shown to modify sound depending on different habitats and environmental constraints. The SRKWs inhabit the Salish Sea, which is a complex shallow-water environment (Jones and

Wolfson 2006). The varied bathymetry of the area leads to variations in sound propagation throughout the habitat (Jones and Wolfson 2006). I propose that the SRKWs will alter their acoustic signals based on the sound propagation of the area they are in. In areas where sound is attenuated more readily, phonation repetition rates will increase in an effort to be sure that information gets across. I propose that the whales will also shift the frequency distribution and peak frequencies of their calls to match the optimum frequency for maximum sound propagation in their environment.

Differences in phonations based on an animal's environment have been demonstrated for many species. It has long been known that birds have different dialects and display geographic variation (Morton 1975; Hunter and Kreb 1979; Lemon 1997). Hunter and Kreb (1979) showed that great tit (*Parus major*) songs vary significantly between habitats. Great tits living in open woodland habitats had songs with a larger frequency range, higher average frequency, and more notes than those living in forested areas (Hunter and Kreb 1979). According to the researchers, the decreased attenuation of lower frequency sounds in the densely vegetated forests allowed the lower frequency songs to propagate farther. The reduced number of notes observed in songs in forested habitats was believed to be a mechanism to limit distortion and the loss of information (Hunter and Kreb 1979).

Many species of bats are also known to alter their echolocation clicks depending on their environment. Free-tailed bats (*Tadarida*) display different echolocation signals in different situations (Simmons et al. 1978). Indeed, these bats utilize every kind of echolocation signal currently known to bats (Simmons et al. 1978). When foraging above the treeline, they use narrowband or constant frequency (CF) clicks (Simmons et al. 1978). These clicks generally have only one harmonic, and focus the energy of the click at the optimum frequency within the hearing range of the bats (Simmons et al. 1978). In contrast, when the bats are placed in a cluttered room or other areas where they need to constantly be aware of their surroundings, the bats use a brief, broadband frequency signal with a high repetition rate (Simmons et al. 1978). These signals have multiple harmonics, and are used to obtain quick, detailed information about their environment (Simmons et al. 1978). These same trends have been noted in many other species of bats, including *Myotis emarginatus*, *Pipistrellus pipistrellus*, *Nyctalus noctula,* and *Eptesicus fuscus* (Schumm et al. 1991; Pye 1967; Obrist 1995; Simmons et al. 1978).

Marine mammal environments can also limit the animals' sound production. Because sound attenuates much less in water than light, many marine animals use sound to communicate information (Richardson et al. 1995). The physics behind sound propagation is even more complex than in a terrestrial ecosystem. Bathymetry, slope, depth, currents, salinity, bottom type, bottom and surface interactions and the sound speed profile all play a role in how sound travels in the marine environment (Knobles et al. 2003).

The way sound moves through water is highly dependent on location and thus difficult to predict without understanding the environment. However, there are a few rules that hold true globally. One is that, in deep water, low frequencies experience little attenuation and are capable of traveling long distances (Kibblewhite and Denham 1971). Jensen and Kuperman (1983) provided further evidence for this phenomenon, and looked more closely at complex shallow water environments. In these environments, sound propagation gets more complex as sound waves come into contact with the surface and bottom much more frequently. Sound becomes prone to both spherical as well as cylindrical spreading, and bottom interactions become increasingly important (Jensen and Kuperman 1983). It was found that higher frequencies lose more energy to bottom interactions than low frequencies do (Jensen and Kuperman 1983;

Knobles et al. 2003; Richardson et al 2005). Although this has been found to be true in several different studies, at least one study conducted in shallow water environments in Hawaii found that *higher* frequencies traveled better (Mercado and Frazer 1999). This illustrates the complexity behind sound propagation in shallow water and how each case should be treated independently.

There are other variables as well that further complicate sound transmission. For one, sound travels differently over slopes in the ocean floor (Dosso and Chapman 1986; Richardson et al. 1995). When the sound waves propagate down-slope there is actually less attenuation (Dosso and Chapman 1986; Richardson et al. 1995). Higher frequencies in particular suffer much less attenuation when moving down-slope (Dosso and Chapman 1986; Richardson et al. 1995). However, the opposite is true when sound waves travel up-slope (Richardson et al. 1995). There are increased bottom reactions, leading to increase attenuation of the sound waves, especially at higher frequencies (Richardson et al. 1995). Sound waves that come at an angle to the slope tend to glance off of the bottom, while those that contact the bottom at a nearly perpendicular angle are usually absorbed by the bottom, making the angle of the slope important (Richardson et al. 1995, Val Veirs pers. comm.).

Currents can also have an effect on sound transmission. Attenuation of sounds increases with current (Kibblewhite and Denham 1971). In higher temperatures and pressures, the velocity of speed increases (Richardson et al. 1995). The increase in velocity of part of the sound wave as it encounters higher temperatures or greater pressures results in the bending, or refraction of the sound wave, further complicating transmission (Richardson et al. 1995). In addition, the bottom type further influences attenuation. Soft substrates absorb more sound, increasing attenuation of sound waves (Richardson et al. 1995).

While all of these features of the physical ocean environment potentially affect the propagation of sound produced by marine mammals, few studies have investigated whether marine mammals alter their signals based on the bathymetry of the area. Studies have shown, however, that members of the *Delphinidae* family do have the capability to adjust their echolocation clicks. A study done on a bottlenose dolphin (*Tursiops truncatus*) found that the dolphins can control the amplitude of their echolocation clicks (Moore and Patterson 1983). Another study by Moore and Pawloski (1991) trained a bottlenose dolphin to not only control the amplitude of their echolocation clicks, but also to control the peak frequencies of their clicks. It could be possible that cetaceans use this ability to alter their clicks based on the sound propagation in the environment that they're traveling through.

Several studies have also been done on cetaceans that showed adjustments in calls and echolocation clicks depending on ambient noise, which decreases the active space, or distance over which the signals travel (Richardson et al. 1995; Holt 2008). Humpback whales have been shown to increase their song durations when there was sonar in the area (Miller et al. 2000). A captive beluga whale (*Delphinapterus leucas*) as well as captive bottlenose dolphins that were moved from a quiet environment to an area with increased ambient noise shifted the peak frequencies and sound pressure levels of their clicks (Au et al. 1974; Au et al. 1985). Similar behavior has also been shown in killer whales. It has been shown that killer whales increase the amplitude of their calls in the presence of increased ambient noise due to vessel traffic (Holt et al. 2009). It has also been shown that killer whales have increased the duration of their calls over time, presumably because of increased ambient noise (Wieland 2007; Wieland et al. 2010). Again, this demonstrates that killer whales have the ability to alter their calls based on the ambient noise of their environment, making it feasible to assume that they may also adjust their calls in response to differences in sound propagation between areas of different bathymetry.

One of the only studies to explicitly compare sound propagation of the environment and cetacean acoustic signals was conducted by Mercado and Frazer (1999). They looked at humpback whale (*Megaptera novaeangliae*) songs in Hawaii and investigated sound propagation in their habitat. However, they simply compared the optimum frequency for maximum propagation through the environment to the frequencies that contained the most energy in humpback songs (Mercado and Frazer 1999). They did not look at whether the songs varied with the differences in sound propagation in relation to bathymetry.

The SRKWs would be an ideal population to study how vocalizations of marine mammals are affected by bathymetry. They are known for being very vocal (Veirs and Veirs 2005). There are three main sounds that are used by killer whales: clicks, whistles and pulsed calls (Ford 1987; Ford 1989). Clicks are used primarily for echolocation, and tend to be brief and varied (Ford 1989). The frequencies can either be narrow or broadband (Ford 1989). Killer whales also often use click trains made up of a series of clicks that can occur as fast as 300 clicks a second (Ford 1989). Killer whales also use whistles (Ford 1989; Thomsen et al. 2000). The function of whistles is largely unknown. What is known is that they are often a tone with few or no harmonics, although they do often have changes in frequency within the duration of the call (Ford 1989; Thomsen et al. 2000). Whistles can have a wide range of durations; Ford (1991) measured durations of 50 ms to 10-12 s and also found that they range in frequency from 1.5-18 kHz.

The final and most common type of vocalization produced by killer whales is pulsed calls (Ford 1989). These vocalizations are distinguished by high pulse-repetition rates. The pulses can vary in frequency and repetition rates (Ford 1989). Pulsed calls can also have two fundamental frequencies, and some also have a whistle component (Ford 1989; Ford 1991). Ford (1989) found that most of the energy in pulsed calls was concentrated between 1 and 6 kHz, but the high-frequency components extend to over 30 kHz. Killer whales produce three different types of pulsed calls (Ford 1989; Ford 1991). These calls are discrete, variable and aberrant calls (Ford 1989; Ford 1991). Discrete calls are repetitive, pulsed calls that have a distinctive structure that allows them to be recognized and categorized (Ford 1989; Ford 1991). Variable calls are non-repetitive calls that could not be categorized readily by structural cues (Ford 1989; Ford 1991). Ford (1989) described aberrant calls as calls that were similar to discrete calls, but were distorted or modified to the point that they couldn't be categorized into discrete categories.

Another factor that makes the SRKWs an ideal study population is the fact that their summer range lies in the area surrounding the San Juan Islands (National Marine Fisheries Service 2008). This area is complex and varied. Jones and Wolfson (2006) studied sound propagation of vessel noise in Haro Strait. They found that bathymetry played a significant role in how the sound propagates through the environment (Jones and Wolfson 2006). The glacier-carved Haro Strait is characterized by steep slopes and a relatively deep depth of up to 320 meters, while parts of Salmon Bank are less than 10 meters deep (McLellan 1927; Green 2010). Sound most likely propagates quite differently in each of these environments, which are both frequented by SRKWs. Because the SRKWs are exceptionally vocal, it will be possible to make adequate comparisons of calls between areas of different bathymetry.

METHODS

Data Collection:

Data will be collected from a 42' catamaran, the *Gato Verde,* for a five week study period from late April to late May. Data will be collected in two parts:

1. <u>Sound propagation in areas of different bathymetries</u>: The area surrounding the San Juan Islands will be divided into zones based on depth, relief, and bottom type. Representative sites from each of these zones will be selected (Appendix, Figure 1). All sound propagation experiments will be performed at slack tide. At each site, GPS coordinates will be taken from the *Gato Verde* and recorded. Temperature, conductivity and the sound speed vertical profile will be measured with a CTD, and other metadata such as weather, sea-state, and number of boats in the area will be recorded. Current velocity will be estimated by looking at current charts and using the knotmeter on the *Gato Verde.* While not providing an exact measurement of currents, the knotmeter will give a rough estimate. Therefore, current will be recorded as a range of 0 knots – 1 knot, 1 – 2 knots, 2 – 3 knots, and so on. These data will provide information critical to comparing the sound propagation between the environments, as all of these parameters have an effect on sound transmission and attenuation.

   The single hydrophone and "blue box" will be set up on the boat. The underwater speaker will be taken out on *Gatito,* the dingy. At least three people will be on the dingy: one driver, one person with the range finder to detect distance from the receiver, the *Gato Verde,* and one person to lower and pull up the speaker. An Apple Ipod will be hooked up to the speaker and used to broadcast the tone from the speaker. The tone used will be a 'chirp' created using Audacity 1.3 Beta (Unicode) software for a PC. The chirp will range in frequency from 400 hz to 6000 hz. *Gatito* will be driven out to a distance of 100 meters from the *Gato Verde;* distance will be confirmed using the laser range finder. The underwater speaker will be lowered into the water to an arbitrarily designated depth of three meters and the tone will be played. On the *Gato Verde,* one person will record the tone playing and play the 1 kHz calibration tone using the blue box. The calibrated gain settings (dB) will be recorded. Once this is recorded, the person on the *Gato Verde* will end and save the recording. The same procedure will be repeated for distances of 200 m, 300 m, and 400 m. These distances were picked because they most likely lie in the range that the killer whales will be from the *Gato Verde.* This procedure will then be repeated for each of the sites chosen.

2. <u>SRKW acoustic signals</u>: When killer whales are present, GPS coordinates will be taken with the hand-held GPS from the *Gato Verde* when we are within 400 meters of the whales. Calls and clicks will be recorded using a towed array of hydrophones. There will be an array of four Lab-Core hydrophones on one line, as well as one high frequency Single Cetacean Research Technology (CRT) hydrophone located on a separate line from the others (Appendix, Figure 2). The CRT will allow for accurate measures of all frequency components in calls and most in clicks. The four Lab-Core hydrophones will be located ten meters apart from each other, and the hydrophones will all be hooked up to two two-channel Sound Devices 702 recording units. All hydrophones will be appropriately calibrated before use. The strands will be weighted using a lead weight.

All recordings will be done at a speed of 2.5 knots. Metadata including date, time, GPS coordinates, the pod of whales present, group size, and range measured with a laser range finder will be measured. The behavior of the pod (foraging, socializing, resting, traveling or milling) will be determined using the guidelines described by the

NOAA Southern Resident killer whale behavior workshop (2004) and will be recorded. Foraging, which includes the pursuit and consumption of prey, is characterized by erratic swimming behavior, often at high speeds. The pod is often broken up into smaller subgroups (NOAA 2004). Socializing typically includes physical contact, and can include object play and percussive behaviors as well (NOAA 2004). There are no parameters defined for pod orientation and traveling speed (NOAA 2004). Resting is characterized by close contact and synchronous breathing (NOAA 2004). Any directional movement is very slow. Whales resting typically vocalize little or not at all. Traveling is defined as directional movement of the pod, while milling is when the whales are moving at a slow or medium pace in a nonlinear formation (NOAA 2004). They can be spread at any distance (NOAA 2004).

While observing, at least one team member will be taking photographs in order to allow for photographic identification of the whales. Another member will listen to the killer whale vocalizations with headphones attached to the recorders and record the vocalizations heard. This study will look at S1, S3, S4, and S10 calls, the four most common calls made by J Pod, the pod found most often in the Salish Sea this time of year. If any of these calls is heard, the time of the recording will be written down and the call name will be marked on the phonation data sheet created in Microsoft Excel. If clicks are heard, the time will also be recorded and "clicks" will be marked on the data sheet. Each day, the recorded vocalization files will be downloaded onto an external hard-drive as back-up.

Data Analysis:

Sound propagation: Sound propagation will be measured by estimating spreading. Wav sound files will be imported to the computer program Audacity 1.3 Beta (Unicode) for analysis. The computer used will be a Dell running on Windows XP. In Audacity, an analysis using the Contrast feature will compare the calibration tone to the recorded sound. This analysis will be performed at 1000 hz, 4000 hz, 10000 hz, and 20000 hz for each recording. The 10000 hz and 20000 hz analysis will be done on the harmonics of the tone, as the tone only extends to 6000 hz. This procedure will be repeated for each distance at each site. This will provide the received level in decibels. This received level will be plotted against the log of the distance the speaker was from the receiver using R 2.12.22 for Windows. A regression line will be plotted, which determines the source level of the signal projector. The equation of the regression line will be calculated in R. This equation will allow the type of spreading to be determined. Transmission loss will also be measured by using the equation: TL = Spreading factor*log10(Distance/ 1m reference distance).

SRKW acoustic signals: S1, S3, S4, and S10 calls will be looked at in this study. These are the four most common vocalizations made by J Pod. Clicks will also be looked at. The acoustic signals will only be analyzed if they are at least 3 dB above the background level. They will be binned into bouts of calls in an attempt to minimize the effect of possible stretches of silence. The call and click files will be analyzed using the program Raven Pro 1.3 running on Windows. For the calls, I will be looking at the repetition rate (number of times the call is used per minute in each bout of calls), minimum and maximum frequencies, frequency range, and the duration.

Harmonics will be counted, and the frequency of the strongest harmonic will be measured at the beginning, middle, and end.

For clicks, only the repetition rate will be analyzed. The repetition rate will be determined the same way as with calls. Raven provides a spreadsheet of this data that will be imported into Microsoft Excel. This data will be sorted by the location and physical features of the environment and further analyzed in R. This will tell us whether repetition rate of clicks and calls, call duration, call minimum and maximum frequencies, and call frequency range is significantly related to areas of different sound propagations. The behavior of the whales will also be overlaid on a bathymetry map to see if certain behaviors tend to occur more often over areas of particular bathymetry and perhaps contribute to any differences in acoustic signals that may be measured.

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APPENDIX

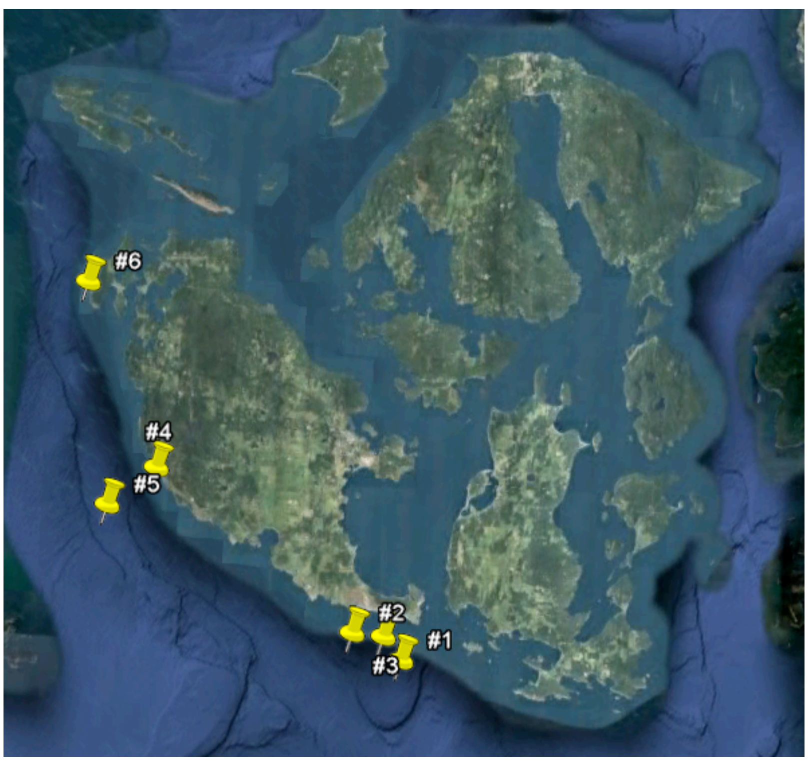

Figure 1. Proposed study sites to measure sound propagation. Sites #1, #2, and #3 are shallow water sites with sand/gravel bottoms. #1 and # 3 are low relief sites, while #2 lies on a slope. Site #4 is along a steep, rocky slope. Sites #5 and #6 are deepwater sites with rocky bottoms.

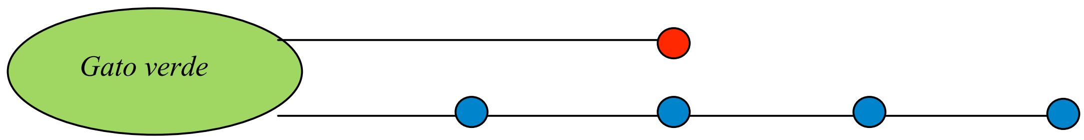

Figure 2. Diagram showing the hydrophone array towed behind the *Gato Verde*. The red hydrophone represents the high frequency CRT, while the four blue hydrophones are Lab-Core hydrophones.