

## Background

Puget Sound is home to a unique population of killer whales (*Orcinus orca*) known as the "southern resident" community (henceforth the SRKW community). This population is composed of distinct matrilineal family units, or matrilines (Ford, *et al.*, 2000). Matrilines related by a common maternal ancestor are organized into a larger traveling group, or pod (Ford *et al.*, 2000), of which there are three in the SRKW community (Ford, *et al.*, 2000). SRKW pods currently range in size from 19 individuals (K pod) to 43 individuals (L pod), with the total population comprised of 87 individuals as of October 2007 (Center for Whale Research, unpubl. data). These animals specialize on Pacific salmon (*Oncorhynchus spp.*), particularly Chinook salmon (*Oncorhynchus tshawytscha*) (Ford and Ellis, 2006). The SRKW community centralizes annually around the San Juan Islands (Figure 1), in Washington State, between May and September (Bigg 1982, Center for Whale Research, unpubl. data). In 2003 the SRKW community was listed as "depleted" under the United States Marine Mammal Protection Act (MMPA) of 1972. The SRKW population was defined as a "distinct population segment" in 2005 under the terms of the United States Endangered Species Act (ESA) of 1973, and consequently listed as "endangered."

Acoustics play a significant role in navigation, social coordination and foraging within the SRKW community (Ford, 1989; Barrett-Lennard *et al.*, 1996; Ford, *et al.*, 2000; Miller, 2002). Three types of sounds are produced by killer whales: echolocation clicks, tonal whistles and pulsed calls (Ford, 1989). The SRKW community produces unique whistles used for long-range communication and socialization (Thomsen *et al.*, 2002). Like other members of family *Delphinidae*, killer whales rely on echolocation to find and catch prey, and to navigate (Barrett-Lennard, *et al.*, 1996). The most common vocalizations used by the SRKW community are pulsed calls, of which there are three varieties: discrete, variable and aberrant (Ford, 1989). Discrete calls are used primarily to maintain contact between individuals within groups, and make up a repertoire of stereotyped calls unique to each population (Ford, 1989; Ford *et al.*, 2000; Miller, 2002). Each pod in the SRKW community uses a unique primary call that comprises up to 52% of the pod's vocal activity (Hoelzel and Osborne, 1986). An example of the S3 stereotyped call is shown in figure 2.

The *Puget Sound Killer Whale ESA Recovery Plan* released by the NOAA Fisheries Service in 2008 cites various anthropogenic threats to the SRKW population, including vessel traffic and anthropogenic noise principally as obstacles to successful predation. Masking boat noise may also interfere with other vocal activities described above, having a negative effect on social cohesion and navigation (NMFS, 2008). According to theoretical models, underwater boat noise may affect communication among killer whales at a range of 1 to 14 km (Erbe, 2002; Bain and Dahlheim, 2004). Foote *et al.*, (2004) reported that SRKW call duration increases in the presence of boats. Similar lengthening of calls has been observed in humpback whales (*Megaptera novaeangliae*) in response to naval sonar (Miller, 2000). Increase in call intensity in response to elevated noise levels (i.e. interference with 'sidetones'/auditory feedback), known as the Lombard effect, has been demonstrated in a wide range of animals including Beluga whales on the St. Lawrence river (Scheifele *et al.*, 2005). Elucidating the nature and scale of impact to the SRKW community by vessel traffic via acoustic disturbance is thus an essential step in efforts to conserve this population.

Since the early 1990's the composition of the commercial whale watching fleet associated with the SRKW community has shifted from predominantly large, high-capacity/low-RPM, vessels to small, low-capacity/high-RPM, vessels (e.g. Zodiacs, popular among Canadian operators) (NMFS, 2008). Larger ships tend to contribute broadband noise at lower frequencies (100Hz - 15kHz), whereas smaller vessels (e.g. out-board driven vessels) contribute at higher frequencies (1kHz - 15kHz) (Veirs & Veirs, 2007). The discrete calls of killer whales have a fundamental frequency of around 1 – 10 kHz (Ford, 1987). The SRKW community experiences a wide range of exposure to vessel traffic, from large commercial freighters to small out-board driven Zodiacs. Because killer whale noise sensitivity increases with frequency to around 20kHz (Erbe, 2002) there is reason to believe that an increase in higher-frequency boat noise presents a higher level of acoustic stress to these animals than they have experienced previously. Alternatively, it is possible that larger low-RPM vessels, while generating the *majority* of their acoustic power at lower frequencies, still generate sound which dwarfs smaller high-RPM vessels at higher frequencies (Veirs, pers. comm.). Although these scenarios have been postulated in scientific and management literature, no empirical investigations of these issues have yet been conducted.

There are numerous examples of call-frequency responses to noise in a variety of animals. The frequency characteristics of calls made by southern right whales (*Balaena glacialis australis*) have been shown to be influenced by ambient noise characteristics (Clark, 1982). Beluga whales have been shown to increase the peak frequency of their echolocation pulses in the presence of snapping shrimp (Au, *et al.*, 1985). Thomas (1999) suggested that killer whales in Antarctica shift the frequencies of their calls to avoid competition with leopard seals (*Hydrurga leptonyx*) for acoustic space, and also showed that killer whales responded to leopard seal sounds by moving the frequency modulation (FM) points (detectable changes in the slope of the spectrogram; see figure 3) within their calls to frequency ranges outside of those most commonly used by leopard seals. Slabbekoorn and den Boer-Visser (2006) found that great tits (*Parus major*) increase the minimum frequency of their songs in urban settings to avoid masking at lower frequencies. These shifts did not occur in songs common to both urban and rural populations, but were synonymous with a shift in repertoire to songs that occur at higher frequencies (Slabbekoorn & den Boer-Visser, 2006).

## Proposed Research

This study will consider four distinct hypotheses. First, it will test the claim ( $H_1$ ) that an increase in the proportion of small, high-RPM vessels in the whale-watching fleet leads to an upward shift in the predominant frequency of boat noise. If this hypothesis is substantiated, it will affirm concerns that these vessels present an additional burden to the southern resident killer whales by increasing noise at frequencies to which these animals are more sensitive. This study will also consider the hypothesis ( $H_2$ ) that killer whales alter the frequency characteristics of their discrete calls to avoid masking by boat noise. If these animals are found to exhibit acoustic avoidance behaviour as hypothesized, it will substantiate the claim that current levels of boat noise interferes with the ability of killer whales to communicate. Finally, this study will determine whether these alterations occur in the ( $H_3$ ) composition of their repertoire based on call frequency, or ( $H_4$ ) the frequency characteristics of individual calls. Determining which of these alternatives best characterizes the frequency avoidance behaviour of these animals, if it is found to exist, will inform future studies and monitoring efforts. Given the established connections between communication, social structure and predatory success for killer whales, these results will empower managers to better prioritize conservation actions with regard to boat traffic.

## Methods and Analysis

Data collection will begin in late May and end in early August, 2008. Preparations will be made prior to and during data collection to expedite the statistical analysis of data at the end of the field season. The completion of analysis can reasonably be expected by the end of August, or early September, in time for participation in relevant poster sessions and/or symposia during the fall semester.

Recordings of killer whale calls in the presence and absence of various compositions of vessel traffic will be made using a single calibrated hydrophone and a solid-state digital recorder (24 bit/192kHz) from the decks of M/V *Olympas* and M/V *Glacier Spirit* during commercial day-trips from Port Townsend, WA. The use of calibrated instruments will ensure that the resulting data set will be useable for future studies, and opportunistic recordings and observations may be made to supplementing the efforts of other scientists in the field. Recording from a commercial platform will allow for the collection of data in quantities unattainable by other research strategies in the same time frame due to the ability of the commercial vessel to encounter whales in a wider range of areas and conditions than would be available to the smaller vessels currently used by scientists in the field.

Waveform audio format (a standard uncompressed lossless digital audio format) recordings generated by the solid-state recorder will be fed into RAVEN 1.2.1 (Cornell Lab of Ornithology) – running on a biology department laptop – for visualization and analysis. RAVEN enables the visualization and measurement of sound spectrograms for precise analysis (figure 4), and will be used to collect all relevant acoustic data. Statistical tests will be conducted in SPSS 14.0 in University of Puget Sound computer labs.

The frequency characteristics of discrete whale calls which this study will consider will include the fundamental frequency, peak frequency (frequency of highest intensity), minimum/maximum

frequencies and FM points of each call, after Thomas (1999). Boat noise frequency characteristics considered will include peak frequency and predominant frequency (defined as the median of frequencies within a 20dB power drop from the peak frequency) of noise. Ambient boat noise will be characterized according to the noise-state immediately preceding the call with which it is paired.

**H<sub>1</sub>: An increase in the proportion of small, high-RPM vessels in the whale-watching fleet present at an encounter leads to an upward shift in predominant boat noise frequency.**

**A<sub>1</sub>:** The predominant frequency of boat noise will be compared to the number of outboard-propelled vessels present at each recording using a simple linear regression analysis. This test attempts to capture the actual result of the historical increase in the proportion of high-RPM outboard-driven vessels in the fleet. Intermediate factors (e.g. time spent repositioning between viewings, as a function of boat speed and acceleration) may influence this effect. Because the vessels in question must be present in order for these factors to come into play, however, the effect of these factors is proportional to the number of these vessels present within the fleet. An answer to this basic question about the overall effect of zodiacs in the fleet will allow researchers to perform more refined analyses of the intermediate factors described above.

**H<sub>2</sub>: Killer whales alter the frequency characteristics of their discrete calls to avoid masking by ambient boat noise.**

**A<sub>2</sub>:** Based on this hypothesis, the frequency characteristics of whale calls should vary significantly between noise environments with different predominant (or peak) frequencies. To test this prediction, call frequency metrics will be compared between ranges of predominant boat noise frequencies. As shown in figure 5, the predicted shift in whale call frequency characteristics may not necessarily behave as a linear function of the predominant boat noise frequency, thus a regression analysis will not adequately demonstrate a positive outcome. By defining groups within the data set up according to ranges of predominant boat noise frequency (e.g. comparing call-frequency metrics between noise environments with predominant frequency of 0-2kHz and 4-6kHz) it will be possible to compare the frequency characteristics of whale calls across noise environments using a t-test (or similar analysis), after Slabbekoorn and den Boer-Visser (2006). In addition to the likelihood of a non-linear response in call-frequency metrics, it is possible that calls will straddle the predominant noise frequency rather than being simply higher or lower, as in Thomas (1999). If this is found to occur for a particular predominant noise frequency range the corresponding data will be divided into independently-analyzed sets at the minimum between them (Figure 5). A one-way ANOVA will be used, with planned comparisons between each of the boat noise predominant frequency ranges (and sub-sets, if they exist), and between each such range and the no-boat-noise environment.

**A<sub>3</sub>:** Thomas (1999) showed that killer whales changed the frequency ranges of the FM points in their calls so that they would not overlap with competing leopard seal calls. If the same is to be said of these whales in response to boat noise, it is necessary to demonstrate not only that the FM metric varies between noise environments, but that the FM points within an environment do not overlap with the predominant frequency of noise. The Wilcoxon sign-rank test will be used to test whether there is a difference between the FM metric and the predominant frequency of boat noise within each noise frequency range (and sub-set, as above, if they exist). The same tests will be run using the other chosen call-frequency metrics.

**H<sub>3</sub>: Killer whales alter the composition of their repertoire based on call frequency characteristics to avoid masking by boat noise.**

**H<sub>4</sub>: Killer whales alter the frequency characteristics of specific calls to avoid masking by boat noise.**

Slabbekoorn and den Boer-Visser (2006) found that great tits exhibited a frequency-response to masking in urban noise, but that this response consisted in a change in repertoire rather than changes within calls themselves. To examine this possibility in killer whales the data set will be divided according to stereotype, according to Ford (1987), and the following analyses will be conducted.

**A<sub>4</sub>:** The A<sub>2</sub> analysis (above) will be conducted within individual stereotyped call categories.

A<sub>5</sub>: The proportion of different stereotyped calls used will be compared between noise environments, as in A<sub>2</sub>, using a Chi-square test.

If the hypothesized change in overall frequency characteristics of calls between acoustic environments is due to a change in the composition of the whale's repertoire,

If call-frequency characteristics are found to vary between noise environments within individual stereotyped call categories (A<sub>4</sub>) then H<sub>4</sub> will be corroborated. If this is not the case, however, and both the call-frequency characteristics of calls overall (A<sub>2</sub>) and the proportion of stereotyped calls used vary between noise environments, then H<sub>3</sub> will be corroborated.

### **Additional Considerations**

One concern is that the acoustic information received by the hydrophone, being removed from the vocalizing animal by a certain distance, might be skewed by sound spreading and other physical factors. The worry is that the whale may experience a different sound state than what is received at the hydrophone, skewing the results. Researchers have been able to minimize this kind of systemic error by ensuring close proximity to both the animals under study and the noise-producing vessels, thus minimizing sound loss by spreading and absorption; Scheifele *et al* (2005) was able to effectively quantify a Lombard effect – a measurement based entirely on call and noise amplitude, which is far more severely affected by the factors discussed above than are the metrics of this study – in Beluga whales using this methodology. For this reason, measurements will only be taken when the animals under study are within 400 meters of the recording hydrophone.

It is important to note that recording calls in the absence of boat noise, although it would add to the power of the analyses conducted here, is not necessary to corroborate or falsify the hypotheses tested in this study. Puget Sound Express vessels are often the first on-scene with the whales at the beginning of the day, and frequently an entire encounter with the animals takes place in the absence of other boats. Thus it is reasonable to expect that recordings in the absence of boats is quite feasible. Additionally, no-boat-noise recordings may be available from Dr. Veirs or from the Lime Kiln archives at the Whale Museum on San Juan Island. As this study looks for a change in the frequency characteristics of the whale's calls in response to a *change* in the frequency characteristics of boat noise, however, the possibility that such recordings may not be made in sufficient quantities does not diminish the ability of the study to produce meaningful results.

Physical data such as water temperature, sea state, time of day, location (GPS coordinates) and the relative arrangement of boats and whales will be recorded in order to standardize data analysis. To avoid the influence of naturally occurring ambient noise due to elevated sea state, only recordings made at sea-state 3 (Beaufort scale) or less will be included in analyses. When possible, the identities of individuals and/or groups in an encounter will also be recorded, however the hypothesis does not depend on this information as a call-frequency response is expected to exist across all pods. As killer whale vocalizations are largely social in nature, it is possible that changes in call-frequency characteristics might arise due to altered behavior due to the presence of vessels. A description of behavior (foraging, traveling, playing, resting) will be noted at the time of each recording to control for this potential alternative mechanism.

This study will address some of the immediate concerns of conservation managers and bioacoustic scientists attempting to understand the relationship between boat noise and the southern resident killer whales. It will elucidate the actual effects of the recent increase in the proportion of high-RPM vessels in the commercial whale-watching fleet. It will also determine whether the hypothesized shift in predominant boat noise frequency as a result of this increase elicits a frequency response in the calls of these animals. If such a response is found, it will provide compelling evidence for the claim that current levels of boat noise threaten the ability of the southern resident killer whales to communicate by masking their calls.

## Works Cited

- Au, W.W.L., Carder, D.A., Penner, R.H. and Scronce, B.L. 1985. Demonstration of adaptation in beluga whale echolocation signals. *Journal of the Acoustical Society of America* **77**:726-730.
- Bain, D. E. and Dahlheim, M. E. 1994. Pages 243–256 in Loughlin, T. R., editor. *Marine Mammals and the Exxon Valdez*. San Diego: Academic Press.
- Barrett-Lennard, L.G., Ford, J.K.B. and Heise, K.A. 1996. The mixed blessing of echolocation: differences in sonar use by fish-eating and mammal-eating killer whales. *Animal Behaviour* **51**:553-565.
- Bigg, M. 1982. An assessment of killer whale (*Orcinus orca*) stocks off Vancouver Island, British Columbia. *Report of the International Whaling Commission* **32**:655-666.
- Clark, C.W. 1982. The acoustic repertoire of the southern right whale: A quantitative analysis. *Animal Behavior* **30**:1060-1071.
- Erbe, C. 2002. Underwater noise of whale-watching boats and potential effects on killer whales (*Orcinus orca*), based on an acoustic impact model. *Marine Mammal Science* **18**(2):394-418.
- Foote, A.D., Osborne, R.W. and Hoelzel, A.R. 2004. Whale-call response to masking boat noise. *Nature* **428**:910.
- Ford, J.K.B. 1987. A catalogue of underwater calls produced by killer whales (*Orcinus orca*). British Columbia, Canada Data. Report of Fish and Aquatic Science. No. 633.
- Ford, J.K.B. 1989. Acoustic behavior of resident killer whales (*Orcinus orca*) off Vancouver Island, British Columbia. *Canadian Journal of Zoology* **67**:727-745.
- Ford, J.K.B. 1991. Vocal traditions among resident killer whales (*Orcinus orca*) in coastal waters of British Columbia. *Canadian Journal of Zoology* **69**:1454-1483.
- Ford, J.K.B. and Ellis, G.M. 2006. Selective foraging by fish-eating killer whales *Orcinus orca* in British Columbia. *Marine Ecology Progress Series* **316**:185-199.
- Ford, J.K.B., Ellis, G.M. and Balcomb, K.C. 2000. Killer whales: the natural history and genealogy of *Orcinus orca* in British Columbia and Washington State. 2nd ed. Vancouver, B.C.: UBC Press.
- Hoelzel, A. R. & Osborne, R. W. 1986. Killer whale call characteristics: implications for cooperative foraging strategies. Pages 373–403 in Kirkevold, B. and Lockard, J. S., editors. *Behavioral biology of killer whales*. New York: Alan R. Liss.
- Kemp, A. 2007 Sequential structure analysis in the vocal repertoire of the Southern Resident Killer Whale *orca*. Beam Reach Marine Science and Sustainability School.
- Miller, P.J.O. 2002. Mixed-directionality of killer whale stereotyped calls: a direction of movement cue? *Behavioral Ecology and Sociobiology* **52**:262-270.
- Miller, P.J.O., Biassoni, N., Samuels, A. and Tyack, P.L. 2000. Whale songs lengthen in response to sonar. *Nature* **405**:903.
- National Marine Fisheries Service. 2008. Recovery Plan for Southern Resident Killer Whales (*Orcinus orca*). National Marine Fisheries Service, Northwest Region, Seattle, Washington.
- Scheifele, P.M., Andrew, S., Cooper, R.A., Darre, M., Musiek, F.E., Max, L. 2005. Indication of a Lombard vocal response in the St. Lawrence River beluga. *The Journal of the Acoustical Society of America* **117**:1486-1492.
- Slabbekoorn, H. and den Boer-Visser, A. 2006. Cities change the songs of birds. *Current Biology* **16**(23):2326-2331.
- Thomas, J. 1999. An "acoustic niche" for antarctic killer whale and leopard seal sounds. *Marine Mammal Science* **15**(4):1351-1357.
- Thomsen, F., Franck, D. and Ford, J.K.B. 2002. On the communicative significance of whistles in wild killer whales (*Orcinus orca*). *Naturwissenschaften* **89**:404-407.
- Veirs, S., & Veirs, V. (2007) 18 months of ambient underwater sound levels in Haro Strait, Puget Sound. Presentation given at American Acoustical Society conference, Hawaii, 2006.