Investigating high frequency underwater vessel noise and potential masking of killer whale echolocation clicks

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INTRODUCTION

The killer whale (*Orcinus orca*) are the largest of the delphinids and are highly social creatures, travelling in matrilinial pods throughout their entire life span (Bigg et al. 1990 cited in Foote *et al.* 2004). The southern resident killer whale (SRKW) populations in the waters of southern British Columbia and northwestern Washington State were listed as endangered under the Endangered Species Act in November 2005. Population numbers in these waters are currently under threat from factors such as prey availability, environmental contamination, and vessel effects and sound (NMFS, 2006). Haro Strait on the western side of San Juan Island is the primary summer region for the SRKW, and is also a key shipping lane between Canada and the USA. Given the increase in commercial (cargo, ferry, whale watching) and recreational vessels over the past few decades, the SRKW's are subject to vessel disturbance, including the presence of vessels and associated underwater noise disturbance. Further potential underwater noise disturbances can be generated by dredging, seismic testing, sonar, construction and drilling (Richardson *et al.* 1995). Ambient noise generated in the underwater habitat is an area of much scientific concern, as killer whales use sound to communicate, navigate and detect prey. Vessel noise, at particular frequencies, may be masking the killer whale's ability to perform these tasks effectively. A report by the NRC reviewing marine mammal populations and ocean noise and determining when noise has biologically significant effects states that "there is currently not enough known about marine mammals or the impacts of anthropogenic sound upon them to conclusively demonstrate that there is or is not a link between exposure to sound and adverse effects on a marine mammal population" (Wright, 2006).

Given the social nature of killer whales and the fact that there are currently 87 individuals in the southern resident community (CWR, 2007), there is often a congregation of pods (J,K and L, or combination thereof) resulting in an abundance of boats around the whales. Foote *et al.* (2004) found that there is typically a fleet of 72 commercial vessels and an average of 22 boats following a pod during daylight hours. The whale watching industry in this region has increased dramatically over the last few decades: Foote *et al.* (2004) stated that from 1990 to 2000 the average number of vessels viewing the whales increased fivefold. According to Koski (2006) of Soundwatch, from 1998-2005, killer whales have consistently had 20 vessels within a half mile radius of their location. With increased boat traffic there is increased boat noise, and so it must be understood how and to what degree vessel noise underwater is affecting the killer whales' ability to perform audible tasks, particularly echolocation.

Killer whale calls consist of both high (fundamental range 5-12 kHz) and low (fundamental range 250-1500 Hz) frequency components (Bain & Dahlheim, 1994), with their most sensitive ranges between 18-42 kHz and a mean of 20kHz (Szymanski *et al.* 1999). Their echolocation clicks however have higher frequency spectrums. Au *et al.* (2003) found that killer whales have very broadband echolocation signals with centre frequencies 45-80 kHz and bandwidths 35-50 kHz.

A study by Erbe (2002) looked at underwater noise of whale watching boats and used an acoustic impact model to estimate zones around whale-watching boats where boat noise was audible to killer whales, where it interfered with their communication, where it caused behavioural avoidance and where it possibly caused hearing loss. It focussed on various vessel types and found that boat source level ranged from 145-169 dB re 1μPa @ 1m increasing with speed. Veirs (pers. comm. 2007b) states that 140 -170 dB re 1μPa @ 1m is a better representation of boat noise levels as hydrophone studies in past years have been with un-calibrated hydrophones. Different vessel types emit different spectrum levels (dB re 1μPa √Hz). For example, Veirs & Veirs (2007) found that over an 18 month period the maximum average background broadband noise for large commercial ships in Haro Strait, Puget Sound was 144 dB re 1μPa over 100 Hz – 15 kHz bandwidth. They also found that recreational vessels on average increased background noise 5 – 10 dB higher than the average of large commercial ships, but more importantly their frequency range is much higher (1 kHz - 15 kHz). Holt *et al.* (2007) studied noise effects on the call amplitude of southern resident killer whales and found that with increasing background noise, source level increased, ranging from 130-160 dB re 1µPa. Foote *et al.* (2004) studied whale-call response to masking boat noise and analysed primary calls of the SRKW pods in the presence of boat noise during three time periods (1977-81, 1989-1992 and 2001-2003). It was found that call duration across all three pods increased by 10-15% in the 2001-2003 period in comparison to the other time periods, thus indicating that killer whales may have adjusted their calls to compensate for increased vessel/ambient noise. It could also mean that the presence of vessels has meant the killer whales spread further apart and thus have had to make their calls longer to communicate with each other over longer distances.

The purpose of this study is to look at specific vessel types that frequent the waters of southern British Columbia and north western Washington State and determine the high frequencies at which sound propagates from the vessels travelling at certain speeds. I wish to expand on parts of the study done by Erbe (2002) and look at specific vessel types by speaking to the boat operators and hopefully getting them to travel at certain distances at certain speeds relative to the received level (hydrophone) and take high frequency recordings. Clearly this cannot be done for cargo ships or ferries so the research vessel will have to be placed in a position to enable this to be done. Erbe (2002) took opportunistic measurements of the vessels at rough distances and used a radar gun to detect speed. This study will aim to eliminate that error by taking measurements at known distances and speeds. Erbe (2002) suggests that it would be beneficial to do a more controlled study of single-boat noise at various speeds and operational modes. Hildenbrand *et al.* (unpublished data 2006) looked at vessel noise of specific whale-watching vessel types at various distances, although according to Veirs (pers. comm. 2007b) the study was done in poor sea conditions, thus giving results that were not entirely conclusive. By doing this study I hope to be able to be able to not only fill these data gaps, but also simulate what it would be like if a boat is travelling at a given distance from a group of whales, and examine the higher frequency spectrums of these vessels at various distances and speed. According to Veirs (pers. comm. 2007a), studies of boat noise using high frequency hydrophones has been little studied, if at all.

There has been much work on alteration of cetacean communication in response to masking boat noise (e.g. Au *et al.* 1985; Lesage *et al.* 1999; Foote *et al.* 2004; Morisaka *et al.* 2005), but these studies have typically been recorded using hydrophones that record in the lower frequencies (up to 50 kHz). Alteration of vocalisations in response to ambient noise has been evident in other species; a study by Slabbekoorn & Peet, (2003) found that urban great tits (*Parus major*) had a higher minimum frequency in the presence of ambient noise, thus preventing their calls to be somewhat masked by the consistent low frequency noise. Furthermore, social associations of killer whales have also been affected by vessel traffic. Ha (pers. comm. 2007) stated that there has been a statistically significant decline in social association among pods with increase in mean number of whale watch boats. It is known that echolocation clicks in killer whales range up to 80 kHz (Au *et al.* 2003) and so I wish to use high frequency hydrophones to take recordings up to those higher frequencies in both boat noise and echolocation clicks and infer to what degree the high frequency boat noise may be masking the higher frequency spectrum level echolocation clicks.

Recent laws passed in San Juan County state that no vessel must be closer than 100m to a group of Southern Resident Killer Whales, and those within 400m must operate at a "safe speed" (Ordinance No. 35 – 2007). A "safe speed" is defined in the 33 USC 2006 and the international regulations for preventing collisions at sea 1972 as "a speed at which one can take proper and effective action to avoid collision and be stopped within a distance appropriate to the prevailing circumstances and conditions" (CULS, 2007). More than 400m from the whales and a vessel may travel at any desired speed. I wish to examine the high frequency spectrums of various vessel types at distances of 100 and 400m from the received level. I also wish to record killer whale echolocation clicks and compare them to the frequency spectrograms of the boats. We know the hearing ranges of killer whales and where they are most sensitive (18 - 42 kHz), so determining the spectrum levels of various vessel types may aid in establishing stricter whale watch laws and what vessel types are having minimal noise impact on killer whale echolocation.

Expected outcomes

Given that certain vessels emit different frequency sounds in the upper and lower levels (i.e. large commercial ships dominate in the lower frequency [Hz] and smaller outboard motors in the higher frequencies [kHz], and the fact that studies of this noise have not really been studied using high frequency recorders (sampling at 192k up to 90kHz as opposed to 44.1k up to 40kHz) it is expected that the same kinds of patterns will be evident in the higher spectrums. Spectrum levels (dB re $1\mu Pa^2/Hz$) of these sounds will still dominate in the lower frequencies but the idea of the study is to look at the power spectrums of each vessel type at given distances, not look at source level, and focus on levels between 20-80kHz. Therefore, disregarding source levels, I hypothesise that:

- At 400m, outboard/inboard vessel motors operating at high rates of speed will dominate in the higher frequencies (>20kHz) over the sounds in the higher frequencies from large commercial vessels at the same distance
- A vessel powering at high speeds (>19 knots) at 100m will have a higher spectrum level (dB re $1\mu Pa^2/Hz$) than a vessel powering at 400m
- There will be a difference in spectrum levels between outboard, surface piercing, jet drive, and inboard vessel engine types

Similarly, source level in killer whale echolocation clicks will be very difficult to determine but examination of these clicks in the higher frequencies where they are dominant (45-80kHz according to Au *et al.* 2003) may overlap with vessel noise and thus masking may be apparent. Therefore, concentrating on spectrum levels between 30-80kHz, I hypothesise that masking of clicks will be more apparent in whale watching vessels than in large commercial vessels. I further hypothesise that all vessels travelling at high rates of speed (>19 knots) will mask clicks more than vessels travelling at slower speeds (<8 knots).

METHODS

Main method: Use of a high frequency hydrophone to record individual vessel noise at given distances and speeds and create power frequency spectrograms. Similarly, record killer whale echolocation clicks and create frequency spectrums.

A. Study area

The proposed study will take place in the Salish Sea surrounding San Juan Island, USA and southern Vancouver Island, Canada during the months of September and October, 2007. A high frequency hydrophone will be deployed from the *Gato Verde*, a 42 foot catamaran powered by a hybrid bio-diesel electric motor.

B. Materials

The investigation will require the following materials: C54 XRS/266 Cetacean high frequency (HF) hydrophone attached to a rope with a 12lb weight, connected to a 702 High Resolution Digital Audio Recorder, Logitech sound-cancelling headphones, Newcon Optik LRM 2000PRC laser rangefinder, portable VHF radio, floats/buoys and a portable radar reflector attached to a 5m man-overboard pole. Sound files will be analysed in Beam Reach Sound Analyser Program (v. Aug07a) created by Val Veirs, then transferred to Excel.

The vessel noise recordings are controlled experiments and will rely on the cooperation of boat operators. Various whale watch/boat operators will be contacted in the hope that they are willing to donate a small portion of their time to do drive-bys in order to make recordings. Taking measurements of ferries and large commercial ships will be done in a safe manner where the *Gato Verde* is positioned to take recordings as the ship passes by. Speed for these large vessels will be estimated at 20-30 knots and the assumption made that they are at a cruise level of acceleration, given that they are travelling Haro Strait transporting cargo or passengers.

C. Vessel types targeted

Vessel types targeted for this investigation are large (15-20m) whale watch vessels (surface piercing engines, jet drive engines, and inboard diesel engines), small-medium (8-10m) sized vessels (outboard engine), the *Gato Verde* hybrid bio-diesel/electric catamaran, Washington State Ferry, commercial/cargo ship (100-150m length), and a 4m inflatable dinghy.

D. Sampling methods

Due to the extremely high sampling rate (16 bit, 192k) of the HF recorder, boat noise samples will be recorded in 15-30 second clips, in order to allow for simpler analysis and efficient hard drive memory usage. Similarly, this will be done for echolocation clicks. As the primary purpose of this investigation is to determine vessel noise spectrums and echolocation clicks in the higher frequencies (up to 90 kHz), channels on the Digital Audio Recorder will be filtered to cut below 240 Hz 1/12 dB oct.

Controlled experiments will be done in calm open bodies of water to simulate whale travelling grounds and the related sound propagation in deeper waters (>15m), and where possible, where background noise is minimal and waters are calm (0.5-1m wind waves).

Controlled boat sampling

Vessels will travel at two speeds at 100 ±30m and 400 ± 30m from hydrophone. Speed 1, termed “Slow Motor”, where a vessel travels at a speed of 5-8 knots (required speed of travel when within 400m of killer whales in US waters). Speed 2, termed “Cruise”, travel speed of 20-30 knots, based on speed of whale watch boats travelling to or from a whale watch site measured in Erbe (2002).

The hydrophone will be weighted with a rope and deployed vertically to a depth of 7-12m. Using the floats and radar reflector attached to the man overboard pole, it will be placed overboard with the *Gato Verde* then positioned, using rangefinder, at desired distances (100m and 400m ± 30m from the buoys). The purpose of using these distances is to relate to the San Juan County Ordinance No. 35 – 2007. Communication with boat operators will be done via portable VHF radio asking them to accelerate at the desired speed (slow motor or cruise) using the buoys as a radius distance reference for the driver and circling the *Gato Verde* until a 15-30 second recording was made. Using the rangefinder, distances will be regularly ranged and noted at what time in recording to ensure driver was within ± 30m of hydrophone. Drive-bys will be repeated at the different speeds and distances but exact number will most likely differ between boat operators as time is a determining factor, as well as not being able to distinguish slow motor speed at 400m due to substantial background noise (SEE TABLE x in Results).

Large vessel sampling

Using the rangefinder, the hydrophone will be deployed and ready to record at a distance of 1000 ± 30m, as ship closes in on distance towards hydrophone. Using the rangefinder to determine the ship distance, 5-10 second recordings at 100 ± 30m intervals will be made from 1000m to 400 m from hydrophone. 400m is to be determined as the closest safe distance given the wake created by these vessels.

In the case of the *Gato Verde* catamaran, it has a top speed of around 6-7 knots, so I will compared its underwater noise at 100 and 400 ± 30m when using the bio-diesel engine vs. the electric motor.

Echolocation click sampling

When in the vicinity of killer whales, the hydrophone will deployed to a depth of 10-15m and opportunistic recordings of echolocation clicks will be made. These opportunistic recordings will be made when listening in real time, and when echolocation clicks are heard clearly. Numerous 10-20 second recordings will be made over the data collection period to get a broad spectrum of individual clicks to analyse and gain a representative mean frequency power spectrum of a southern resident killer whale echolocation click. Shorter sound file recordings will also allowed for simpler analysis.

E. Data analysis

Both vessel noise data and echolocation clicks will be analysed in the Beam Reach Sound Analyser Program (v. Aug07a) created by Val Veirs, and transferred into Excel for statistical analyses and graphical representation.

Vessel data

For each vessel sound clip recording, numerous 1-3 sec samples will be taken (depending on quality and length of recording) and frequency power spectrums created. Files will then be transferred into Excel to determine mean dB (re 1µPa^2/Hz) between certain frequencies (20-80kHz). These mean values will then be compared with the same vessel data at different speeds and distances, then further compared with means of other vessel types.

Echolocation data

Individual clicks in sound file recordings will be isolated and frequency spectrograms for each individual click will be created. An echolocation click database of clicks will be created and analysed to determine mean frequency spectrums. These spectrums between certain frequencies will then be compared with those of the individual vessel data and masking relationships, if any, may be inferred.

ANOVA will be used to measure statistical differences between means at particular frequency ranges of different vessels at the different distances and speeds. These vessel means at given frequency ranges will then be analysed against echolocation click means and possible masking inferred. Correlation and regression may also prove beneficial in determining relationships between individual vessel types and echolocation clicks

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