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

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I. INTRODUCTION

The killer whale, (*Orcinus orca*) are the largest of the delphinids and are highly social creatures, travelling in matrilineal 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 north western Washington State were listed as endangered under the Endangered Species Act in November 2005. There are currently 87 individuals in the Southern Resident community (CWR, 2007), comprising of three pods; J, K and L. Population numbers in these waters however 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 SRKWs 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 that killer whales are highly social creatures, and the fact that there are currently 87 individuals in the southern resident community, 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 may be affecting the killer whales' ability to perform audible tasks. If particular vessel types at certain speeds and certain distances are found to mask echolocation clicks at certain frequencies, then this will have implications on a killer whales' ability to forage and navigate, and may ultimately impact populations.

A killer whale vocal repertoire consists of pulsed calls, whistles, and echolocation clicks (Griffin & Bain, 2006). Echolocation involves a killer whale emitting a signal (a "click"), and listening for an echo that contains information about the surfaces that reflect the signal (Bain & Dalheim, 1994). In a study examining echolocation signals of free-ranging killer whales and modelling for foraging for Chinook salmon, Au *et al.* (2003) found that the returning signal from an echolocation click can be reduced by as much as 75 dB, depending on initial target strength and sea state. Killer whale vocalisations consist of both high (fundamental range 5-12 kHz) and low (fundamental range 250-1500 Hz) frequency components (Bain & Dalheim, 1994), with their most sensitive ranges between 18-42 kHz and a mean of 20 kHz (Szymanski *et al.* 1999, see Figure 1). Their echolocation clicks however have very broadband signals with centre frequencies 45-80 kHz and bandwidths 35-50 kHz. Therefore in order to effectively study echolocation signals in relation to boat noise, a device that can measure in these higher frequencies is necessary.

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 $1\mu Pa^2/Hz$). 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 (and their propulsion systems) that frequent the waters of southern British Columbia and north western Washington State and determine the high frequency spectrums at which sound propagates from these vessels travelling at certain speeds and certain distances. I wish to expand on parts of the study done by Erbe (2002) by focussing on specific vessels and their propulsion types by gaining the cooperation of the boat operators and have them travel at certain distances at certain speeds relative to the received level (hydrophone) and take high frequency underwater recordings. Clearly this could not be done for cargo ships or ferries so the *Gato Verde* research vessel was placed in a position to enable this to be done safely. 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, hence the reason for this type of experimentation. Hildebrand *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 high 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. This study will also aid in creating underwater noise signatures for different vessel types, which will be important not only for the individual boat operators, but may aid in future safe whale watch guidelines.
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 40 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 have centre frequencies that 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 boat noise may be masking echolocation clicks. More importantly, I wish to look at what degree the boat noise is masking an orca's ability to receive the echoes from these clicks.

On September 11, 2007 San Juan County, USA passed "An Ordinance Regulating The Operation of Vessels in Proximity to the Southern Resident Killer Whales, an Endangered Species, and Establishing Penalties for the Violation Thereof" based on the current 'Be Whale Wise Guidelines' for boaters (NMFS, 2006b). The ordinance states 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" (see Appendix 2; 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 spectra 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 spectrums of the different vessel types. Figure 1 shows an audiogram of the physiological threshold of a killer whale (simplified from Szymanski *et al.* 1999), so understanding the hearing range of killer whales and where they are most sensitive (18 – 42 kHz), and being able to determine the spectrum levels of various vessel types, may aid in establishing stricter whale watch laws and identifying vessel types/propulsion systems that are having lesser or greater noise impact on a killer whale's use of echolocation.

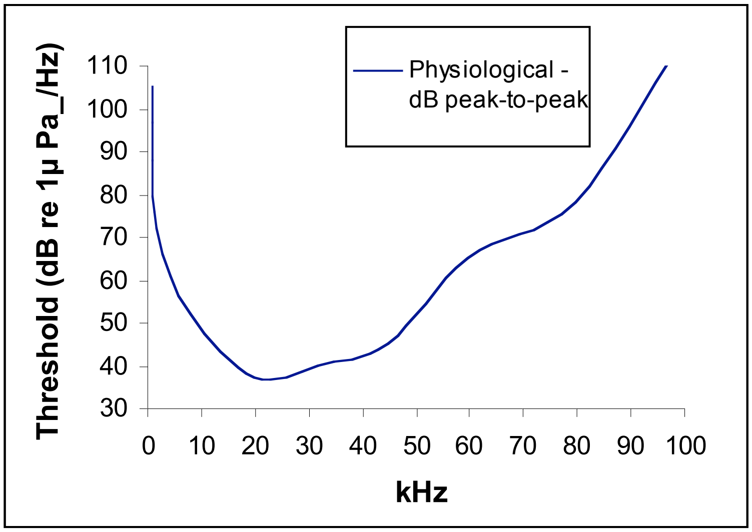

Figure 1. Killer whale audiogram showing physiological threshold (simplified from Szymanski *et al.* 1999)

A. Expected outcomes

Different vessel types will emit underwater sound that dominates at certain frequencies (i.e. large commercial ships tend to dominate in the lower frequency [Hz] and smaller outboard motors in the higher frequencies [kHz]. The fact that studies of this noise have not been examined in detail using high frequency recorders (sampling at 192k up to 90kHz as opposed to 44.1k up to 20kHz) it is expected that similar relationships will still be evident at these lower frequencies (<20kHz), but it will be interesting to examine what the spectrums look like at frequencies greater than 20kHz. It is important to note the killer whale audiogram (Figure 1), as this will be the basis for comparison in determining which vessel types (at different distances and speeds) have spectra that dominate in the 18-42 kHz range. The purpose of this study is to look at the power spectra and received level (dB re $1\mu Pa^2/Hz$) of each vessel type at given distances and speeds (relating to County Ordinance Laws) and not look at source level. Therefore, disregarding source levels, I hypothesise that a vessel cruising (>19 knots) at 400m will have a higher mean spectrum level and received level than a vessel slow motoring at 100m. Furthermore, there will be a difference in spectrum and received levels between outboard, surface piercing, jet drive, and inboard vessel propulsion types.

As defined by Bain & Dalheim (1994) "masking is a term used to describe any impairment in an animal's ability to detect a signal." Therefore, examination of a mean spectrum of received echolocation clicks, related to the killer whale audiogram, will help determine what vessels may be masking an orca's ability to detect an echolocation signal at certain frequencies. I hypothesise that masking of echolocation clicks, at both 100m and 400m, will be more apparent in vessels cruising (>19 knots) than vessels slow motoring (<8 knots).

II. 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 a mean received frequency spectrums.

A. Study area

This investigation took place in the Salish Sea (48º29'N, 123º7'W) surrounding the west side of San Juan Island, USA and southern Vancouver Island, Canada during the days of September 10th to October 13th, 2007 (Figure 2). A C54 XRS/266 Cetacean high frequency hydrophone was deployed from the *Gato Verde*, a 42 foot catamaran powered by a hybrid bio-diesel electric propulsion system.

Figure 2. Map indicating study site in the Salish Sea

Source: http://www.sanjuancountyfair.org/img/sji-map.jpg

B. Materials

The investigation required 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. The hydrophone and rope were looped onto a 2m outrigger pole that protruded from the starboard stern of the research vessel. Other equipment used: 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 were analysed in the Beam Reach Sound Analyser Program (v. Aug07a) created by Val Veirs, then transferred to Excel.

The vessel noise recordings are controlled experiments and relied on the cooperation of boat operators. Various whale watch/boat operators were contacted and were willing to donate a small portion of their time to do drive-bys in order to make recordings. Business names of whale watch operators measured have not been identified in this paper. Taking measurements of ferries and large commercial ships was done in a safe manner where the *Gato Verde* was positioned to take recordings as the ship passes by. Speed was estimated for these large vessels to be 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 measured

Vessel types measured for this investigation were categorised into the following, based on propulsion type: Surface Piercing, Jet Drive, Twin IB 400HP BioDiesel, Twin IB Diesel, and Twin OB 150HP. (NB: HP refers to Horse Power, Twin mean there are two engines of stated HP, IB represents Inboard and OB represents Outboard. These terms will be used interchangeably throughout this paper). Other vessels measured were the *Gato Verde* hybrid bio-diesel/electric catamaran, a Washington State Ferry, a commercial/cargo ship and a 4m inflatable dinghy. (See Appendix I for individual vessel specifics).

D. Sampling methods

Due to the extremely high sampling rate (16 bit, 192k) of the HF recorder, boat noise samples were recorded in 15-30 second clips, in order to allow for simpler analysis and efficient hard drive memory usage. Similarly, this was 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 were filtered to cut below 240 Hz 1/12 dB oct.

Controlled experiments were 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 was minimal and waters were calm (0.5-1m wind waves). Background noise recordings were taken for each controlled experiment in order to be filtered out during data analysis.

Controlled boat sampling

Vessels travelled at two speeds at 100 ± 30m and 400 ± 30m from hydrophone. Speed 1, termed "Slow Motor" (SM), 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" (C), 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).

Hydrophone was weighted with a rope and deployed vertically off the outrigger to a depth of 7-12m. Using the floats and radar reflector attached to the man overboard pole, it was 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 Section 3 of the San Juan County

Ordinance No. 35 – 2007 (see Appendix II). Communication with boat operators was done via 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 were regularly ranged and noted at what time in recording to ensure driver was within ± 30m of hydrophone. Drive-bys were repeated at the different speeds and distances but exact number differed between boat operator as time was the determining factor, as well as not being able to distinguish slow motor speed at 400m due to substantial background noise (See Table 1). For actual speed and RPM of vessels see Appendix I.

Large vessel sampling

Using the rangefinder, hydrophone was deployed and ready to record at a distance of 1000 ± 50m, as ship closed in on distance towards hydrophone. Using the rangefinder to determine the ship distance, 5-10 second recordings at 100 ± 50m intervals were made from 1000m to 400 m from hydrophone. 400m was determined the closest safe distance given the wake created by these vessels.

In the case of the *Gato Verde* catamaran, it had a top speed of around 6-7 knots, so I 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 was deployed to a depth of 10-15m and opportunistic recordings of echolocation clicks were made. These opportunistic recordings were made when listening in real time, and when clicks were heard clearly. Numerous 10-20 second recordings were made over the data collection period to get a broad spectrum of received level of individual clicks to analyse and gain a representative mean frequency power spectrum of what a southern resident killer whale echolocation click. Shorter sound file recordings also allowed for simpler click identification and analysis.

E. Data analysis

Both vessel noise data and echolocation clicks were analysed in 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 2-15 second samples were taken (depending on quality and length of recording), background noise was filtered out, and using Fast Fourier Transform (FFT), frequency power spectrums created. Files were then transferred into Excel to determine a mean value at given frequencies (kHz) and dB (re 1µPa^2/Hz). These mean spectrum values were then compared with the same vessel data at different speeds and distances, then further compared with mean spectrums of other vessel types. A mean received level (dB re 1µPa^2/Hz) was calculated for each vessel type at each speed and distance. This was done by referring to a calculated calibration curve that had been conducted on the HF recorder during the data collection period (See Appendix III). Each vessel at Slow Motor 100m and Cruise 400m were plotted on the same spectrum for ease of comparison. A test for two paired samples was performed on dB received of Slow Motor at 100m versus Cruise at 400m. The killer whale audiogram was overlayed on the vessel spectrograms and used to determine which vessels at Slow Motor 100m and Cruise 400m can be heard by an orca at certain frequencies.

Echolocation data

Individual echolocation clicks in sound file recordings were isolated and frequency spectrum values for each individual click were created. An echolocation click spectrum, based on a mean of 101 received clicks recorded over the data collection period by different whales at different distances was created. This spectrum was then modified to simulate the loss of signal that an orca receives, and this spectrum was then compared with those of the individual vessel data and examined to determine at what frequencies certain vessels may be masking an orca echolocation click. The audiogram was also overlayed on the click spectrum and used to determine if there is a relationship between orca hearing sensitivity and the frequency range at which an echolocation click dominates. A mean received level for the click spectrum was also calculated.

III. RESULTS

Figures 3-7 show the frequency power spectrums of Twin Inboard 400HP BioDiesel, Twin Inboard Diesel, Twin Outboard 150HP, Surface Piercing, and Jet Drive propulsion types, respectively. Figures 2-5 show that Cruise (C) at 100m is prevalent above the other speeds and distances by 10-40 dB, and dominant between 0-40 kHz at around 70-80 dB. These figures follow the general pattern (in decreasing dB) of Cruise 100m, Cruise 400m, Slow Motor 100m and Slow Motor 400m. Figure 7 however shows a different spectra pattern. It is evident that there are discernible peaks at 20, 40, 60, 80 and 100 kHz that are 15-20 dB above the general spectrum shape, and Slow Motor 140m appears to have the highest spectrum level over all frequencies. Furthermore, Cruise 100m appears to show a lower spectrum level than both SM 140m and C 400m. The background file in this figure also has these peaks, although at much lower dB. Figure 3 also shows peaks at 40, 60 and 80 kHz. This consistent, although irregular pattern in Figure 7 when compared with the frequency spectra of other vessels, seems to be inferring more than what a typical Jet Drive underwater signature may look like (see Discussion for possible explanations), therefore it was eliminated from further vessel comparisons. Figures 4 and 6 show Slow Motor at 100m and 400m spectra that are very similar, i.e. within 3-5 dB of each other. This is also evident in Figure 5, although Cruise at 400m is also within 3-5 dB of SM 100m and 400m.

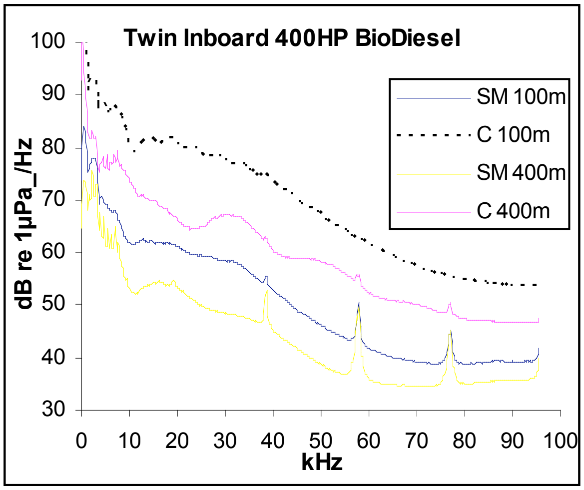

Figure 3. Frequency spectrogram of a Twin Inboard 400HP BioDiesel vessel

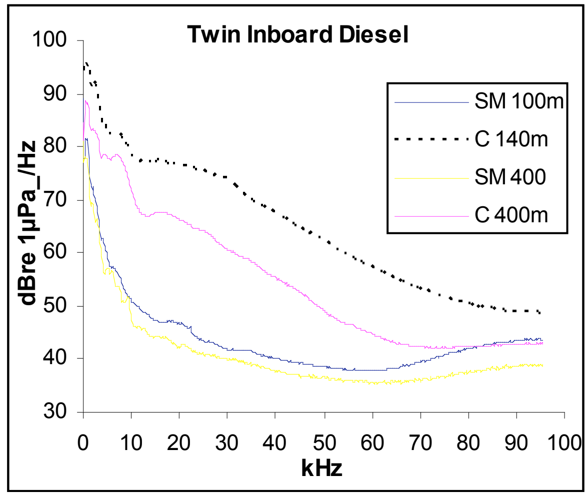

Figure 4. Frequency spectrogram of a Twin Inboard Diesel vessel

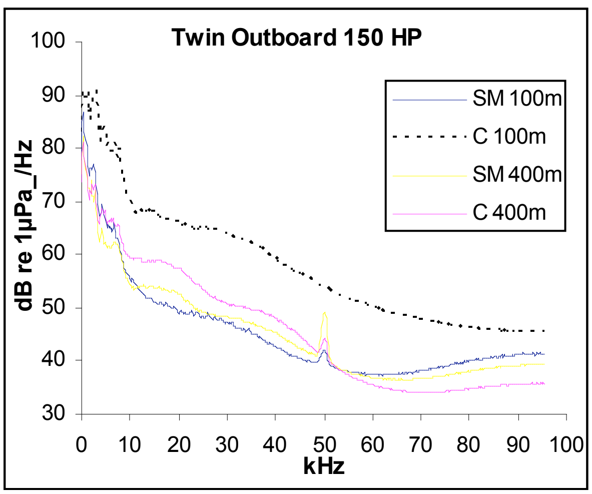

Figure 5. Frequency spectrogram of a Twin Outboard 150HP vessel

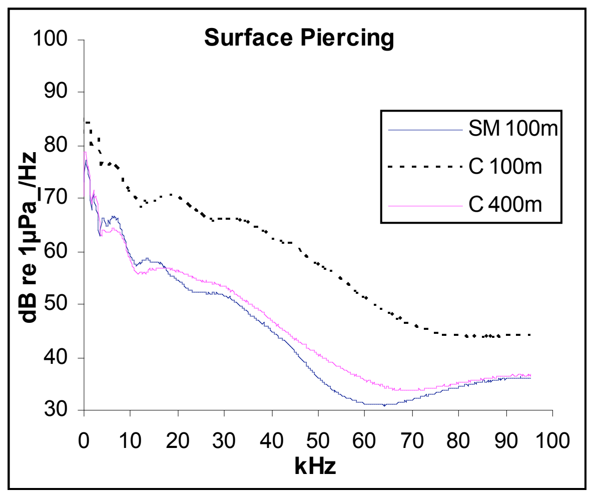

Figure 6. Frequency spectrogram of a Surface Piercing vessel

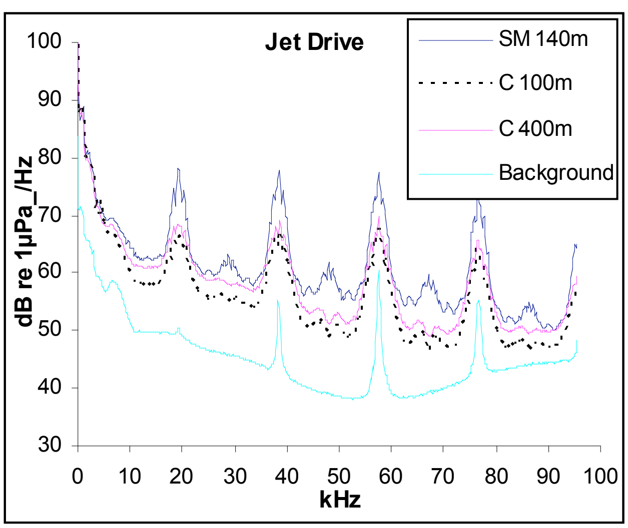

Figure 7. Frequency spectrogram of a Jet Drive vessel

Table 1 displays the mean received level (dB re 1µPa²/Hz) for each vessel type at each distance. These figures relate to Figures 3-7, in that the higher the spectrum levels of each speed at distance in relation to each other, generally the higher the mean RL (received level). For example, Figure 6 shows a Surface Piercing vessel having a Cruise 100m spectrum consistently 15-20 dB above Slow Motor 140m and Cruise 400m, over all frequencies. When referred to in Table 1, it is evident that the mean RL for Cruise 100m is 120.1 dB, which is 10 dB greater than SM 140m and C 400m, which are 109.2 and 110.2, respectively. Similarly, Figure 5 shows a Twin Outboard 150HP vessel at C 100m, SM 400 and C 400 having very similar spectrum levels, and when referred to in Table 1, the RL is 115.5 dB, 110.8 dB, and 111.5 dB respectively. Jet Drive RL is inconsistent in comparison with other vessel RL, stating that Cruise 400m RL is less than 1 dB difference to Cruise 100m, whereas the difference in RL for other vessel types at these distances is 8-14 dB.

		Received Level (RL) dB (re 1µPa²/Hz)			
Vessel type	**Total N (# of sec)**	**Slow Motor 100m**	**Cruise 100m**	**Slow Motor 400m**	**Cruise 400m**
Twin IB 400HP BioDiesel	51	115.6	134.7	108.5	127.8
Twin Inboard Diesel	51	111.6	129.3 (140m)	108.8	121.6
Twin OB 150HP	60	115.5	125.2	110.8	111.5
Surface Piercing	30.5	109.2	120.1	NM	110.2
Jet Drive	22	109.2 (140m)	120.1	NM	120.9

Table 1. Comparison of vessel RL at different speeds and distances

*NM = Not Measured

A test for Two Paired Samples was performed on the received level (RL) on vessels stated in Table 1 in order to test the null hypothesis that a boat cruising at 400m does not have a higher received level than a vessel slow motoring at 100m. This test was chosen as there was a prediction that Cruise RL at 400m would in fact be larger than Slow Motor RL at 100m. Results of this test indicated a p(1-tail) value of 0.069, concluding that we cannot reject the null hypotheses, and that there does in fact appear to be no difference between the two speeds. Mean values for Slow Motor 100m and Cruise 400m were 112.2 dB and 118.4 dB, respectively. Descriptive statistics for this test can be viewed in Table 2, and represented graphically in Figure 8. Although statistically there is no difference between RL of SM 100m and C 400m across all vessel types, Figure 9 gives a graphical representation of each individual vessel type and their RL at these speeds/distances. It should be noted that three out of the five vessel types have a difference in RL of 10 dB or greater (i.e. C 400m > SM 100m). Twin OB 150HP however has a SM 100m that is in fact 4 dB higher than C 400m.

In general, there does appear to be somewhat of a difference in spectra and received level of these five vessel types, so one may reject the null hypotheses that there is no difference. However, this was not proven statistically and therefore cannot be implied.

	Slow Motor 100m	Cruise 400m
Mean Received Level (dB re 1µPa²/Hz)	112.22	118.4
Standard Deviation	3.19	7.41
Standard Error of Mean	1.43	3.31

Table 2. Descriptive statistics for vessel RL at Slow Motor 100m and Cruise 400m

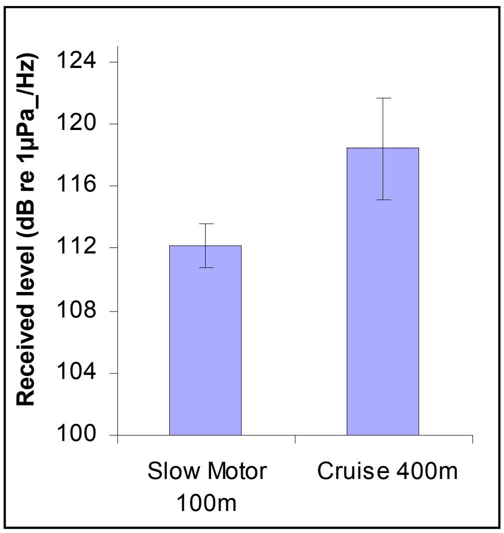

Figure 8. Comparison of mean vessel RL at Slow Motor 100m and Cruise 400m, displaying standard error bars

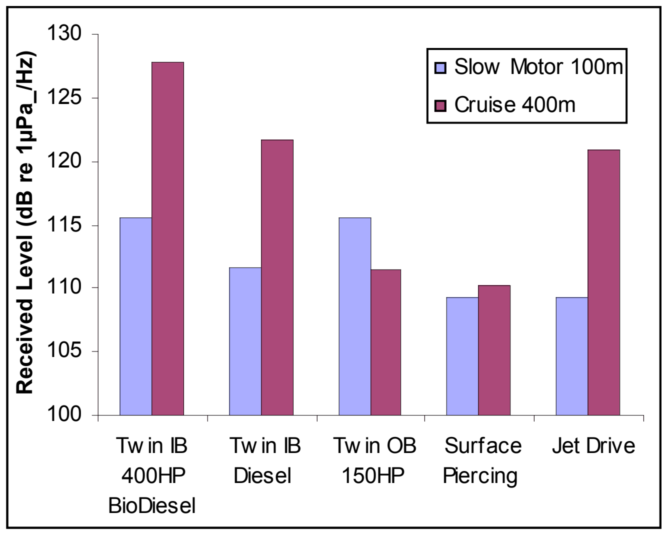

Figure 9. Comparison of individual vessel RL at Slow Motor 100m and Cruise 400m

The *Gato Verde* catamaran had a maximum speed of around 6-7 knots under electric and generator power, so it was measured and classified under the 'Slow Motor' speed of acceleration. Figure 10 shows the *Gato Verde* frequency spectrogram, and it is evident that when travelling using the Generator or Electric Motor at 100m, the spectrums are almost identical, and this is supported with a mean RL value of 107.4 and 109.2, respectively. These values are virtually identical to Surface Piercing and Jet Drive vessels at SM 100m, and within 4-6 dB of the Twin IB 400HP BioDiesel, Twin IB Diesel, and Twin OB 150HP travelling at SM 100m. Frequency spectrograms of a Washington State Ferry (WSF) and a cargo ship (CS) travelling at cruising speed at 450m and 900m. It appears that at 10-30 kHz, a WSF at 450m is almost 10 dB louder than a cargo ship at both 900m and 450m. Table 3 shows the mean RL for both the WSF and cargo ship at these distances. A WSF appears to be

8-11 dB higher than a cargo ship at both distances. These spectrums and RLs appear to be similar to the ones stated in Figures 3-7 and Table 1.

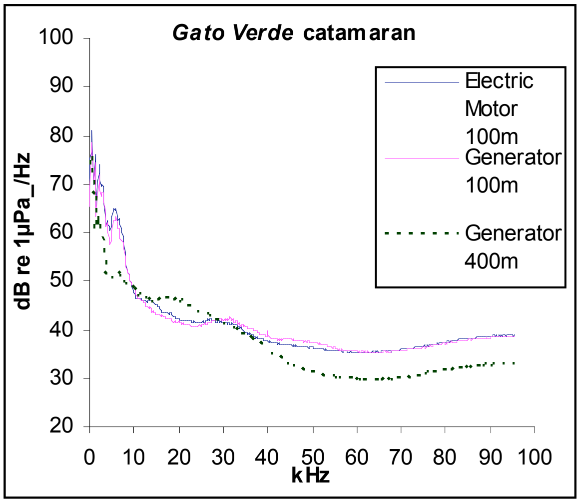

Figure 10. Frequency spectrogram of the *Gato Verde* catamaran

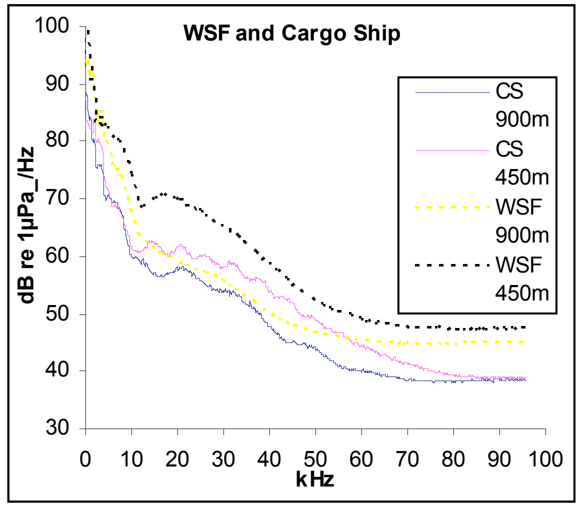

Figure 11. Frequency spectrograms of a Washington State Ferry and a cargo ship

		Received dB	Level (re 1µPa²/Hz)
Vessel type	**Total N (# of sec)**	**Cruise 450m**	**Cruise 900m**
Washington State Ferry	12	129.0	125.8
Cargo Ship	3.3	118.3	118.0

Table 3. Comparison of RL in a Washington State Ferry vs. a cargo ship

Figure 12 shows a single echolocation click spectrum (± 1SD) that is the mean of 101 clicks recorded over various days by different individuals at different distances. This mean click had a RL of 134.4 dB, with a mean standard deviation of 9.9 dB. The click spectrum ranges from 60-90 dB up to 70 kHz, which is comparable (up to 30 kHz) to Cruise 100m of all vessel types measured at this distance, but significantly (15-20 dB) greater than vessels travelling at SM 100m and 400m, and C 400. Figure 12 also shows the spectrum of the echo of a click, which was calculated to be 40 dB less than the RL of a click (according to target strength loss of a click in Au *et al.* 2003). The killer whale audiogram is also displayed, and shows sensitivity of 50 dB at 10-50 kHz, with the greatest sensitivity at around 40 dB at 20 kHz. The echo of a click spectrum crosses the audiogram at around 15 kHz 45 dB, and 40 kHz 40 dB.

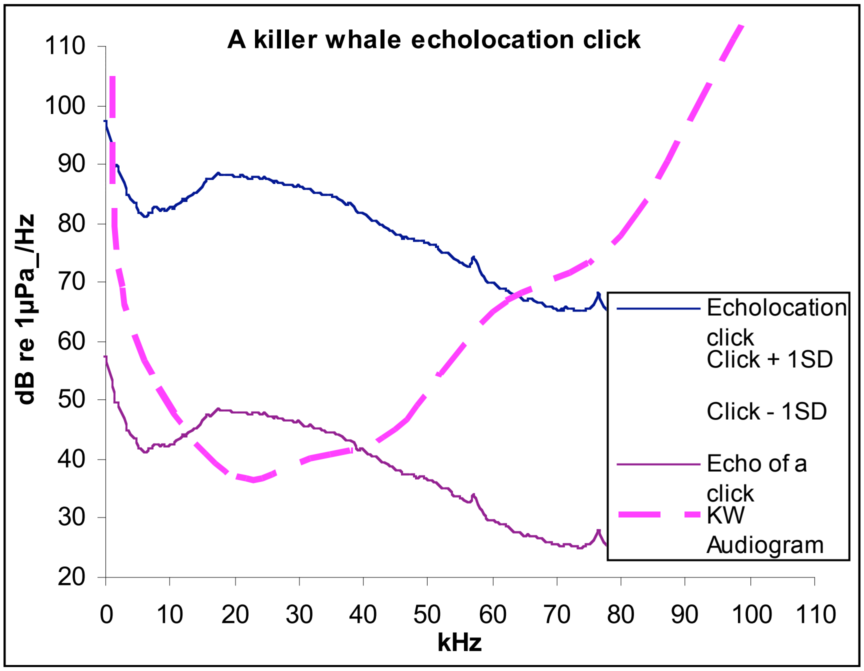

Figure 12. A killer whale echolocation click (± 1SD) based on a mean of 101individual clicks, and the echo of a click (less 40dB of click mean), overlayed on a killer whale audiogram

Comparison of each vessel type Slow Motoring at 100m is displayed in Figure 13. It is evident that all vessel types, according to the audiogram, are within the hearing range of a killer whale. The Twin IB 400HP BioDiesel vessel appears to have the highest frequency spectrum, around 5 dB or greater above other vessel types from 10-70 kHz. The RL however of this vessel at this speed and distance is identical to that of the Twin Outboard 150HP (115.6 vs. 115.5 dB). Surface Piercing, Twin OB 150HP, Electric Motor and Twin IB Diesel have spectrums that are all within 10 dB of each other. The mean echolocation click appears to be greater than 20 dB above all vessel types from 10-100 kHz.. Examination of the echo of a click spectrum however reveals that the Electric Motor (*Gato Verde* catamaran) and Twin Inboard Diesel are the only vessels that are lower, by as much as 5 dB.

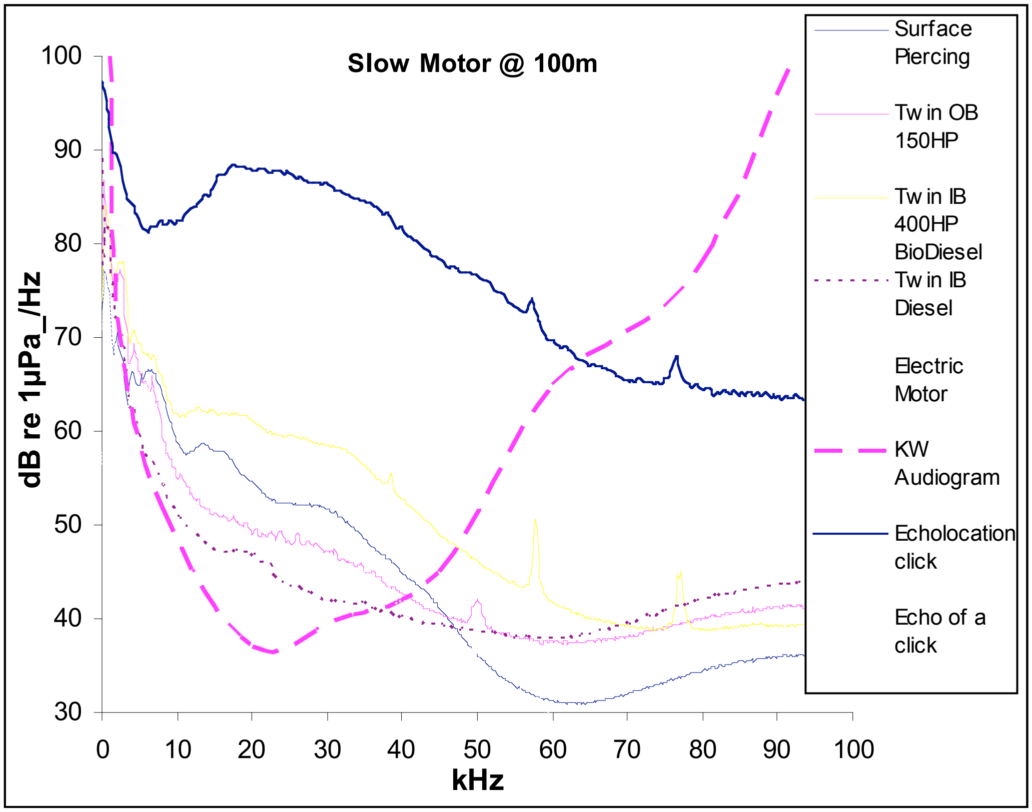

Figure 13. Comparison of vessel types Slow Motoring at 100m against killer whale echolocation clicks and audiogram

Comparison of each vessel type Cruising at 400m is displayed in Figure 14. Similarly to Figure 13, it is again evident that because all vessel spectrums are above the audiogram, they can be heard by a killer whale. The Twin IB 400HP BioDiesel vessel again appears to have a higher frequency spectrum (around 5 dB or greater) than other vessels, but this is evident above 30 kHz (c.f. above 10 kHz in Slow Motor 100m). According to Table 1, the lowest mean RL for Slow Motor 100m is the Surface Piercing vessel at 110.2 dB, with the Twin OB 150HP having the next lowest RL at 111.5 dB. However, upon viewing Figure 14, it is evident that the Surface Piercing vessel does not consistently have the lowest spectrum level across all frequencies. It is in fact up to 5 dB greater than the dinghy at 20 kHz. The dinghy was actually calculated to have the lowest overall mean RL at Cruise 400m, 109.3 dB, but the spectrum for this vessel is 5-10 dB higher than both the Surface Piercing and Twin OB 150HP between 50-90 kHz. The mean echolocation click spectrum is again 15-20 dB higher than any other vessel at 10-100 kHz. The echo of a click spectrum however is below all vessels by a minimum of 4 dB at 20 kHz. This observation then supports the hypothesis that masking of clicks is more apparent if a vessel is Cruising at 400m than if it was Slow Motoring at 100m, as two vessels (Electric Motor and Twin IB Diesel) had spectrum levels below the echo of a click spectrum at Slow Motor 100m.

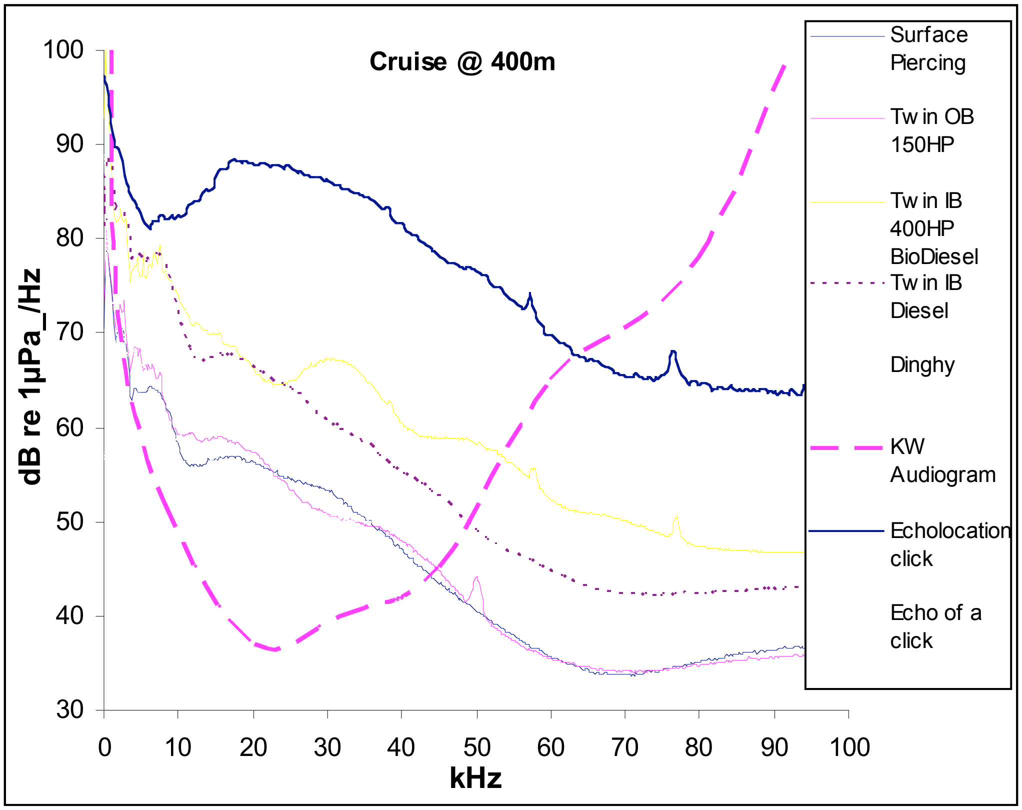

Figure 13. Comparison of vessel types Cruising at 400m against killer whale echolocation clicks and audiogram

IV. DISCUSSION

The general trend in comparison of vessel spectra shows that Cruise 100m has the highest spectrum across all frequencies. This can be expected as it is of the distance closest to the hydrophone, and is travelling at high speeds. Slow Motor 400m across all vessel spectra was shown to have the lowest spectrum across all frequencies, and again this can be expected as it is a vessel travelling at slow speeds, propeller rotation is low (c.f. travelling at high speeds when propeller rotation is higher) and it is further from the hydrophone. This is not however the case for the Jet Drive vessel (Figure 7). This figure shows that SM 140m spectrum level is around 5 dB higher than C 100m, which is very unlikely given the pattern evident in Figures 3-6. Figure 7 also appears to have peaks at consecutive 20 kHz intervals, from 0-100 kHz. When this spectrum was compared with that of another jet drive vessel spectrum from Hildebrand *et al.* (unpublished data 2006) this peak at these frequencies was not evident. This pattern is also evident in the Twin Inboard 400HP BioDiesel SM 100m, SM 400m and C 400m spectrums (Figure 3). It is believed that this is caused by an external factor and is not an indication of the underwater noise signature of this vessel type. This is concluded by the fact that the background noise also displays these peaks, and it was sampled after the vessel was >3nm away, so it was deemed a characteristic of the electrical system of the research vessel and thus an interference, thus no real conclusions can be made about jet drive propulsion, and further analysis of this vessel type was not conducted. A peak is evident at 50 kHz across all spectrums in Twin OB 150HP, and this may be due to a characteristic of the propeller type.

When making comparison of the spectrum levels and mean RL of the vessel types in this investigation, it must be understood what a difference in dB means. dB is a measure of the energy in a sound, and for the purpose of this investigation it was represented as dB (re $1\mu Pa^2/Hz$), a common classification in acoustic journals. To the human ear, 6dB is perceived as a doubling in sound, or twice the wave amplitude. A doubling in energy/power of a sound however is represented by 3 dB. Whether it is a 3 dB or a 6 dB difference between vessel spectra or RL, it is unknown how this is perceived by a killer whale, it may in fact not be a doubling at all. Examination of the differences in received levels of all vessels at Slow Motor 100m and Cruise 400m showed no significant difference, therefore the null hypothesis could not be rejected. However, the p(1-tail) value was 0.06, which suggests somewhat of a difference between the two, and examination of Figure 9 supports this idea. Three out of five vessels had a difference of greater than 10 dB (I.e. Cruise 400m > Slow Motor 100m), so further sampling of this may in fact find a significant difference. The *Gato Verde* at Electric Motor 100m and Generator 100m had a RL difference of less than 2 dB. One would expect the Electric Motor to have a lower dB, when in fact the opposite was true. Perhaps because the generator is louder above water it would hold the same relationship for underwater, but because this was not the case, it may suggest that propeller noise is all that is being distinguished. The Washington State Ferry and cargo ship spectrums and RLs in this investigation are not an ideal representation of what the underwater signatures of these vessels actually are. They were recorded early on in the data collection period when hydrophone deployment was still being troubleshot and subsequent sound file analysis revealed recordings that were of poor quality, hence the small sample size, N (# of seconds used). Furthermore, there are different sized ferries and cargo ships that frequent the Haro Strait/Spieden Channel and the particular cargo ship measured in this investigation had a low dB (118) compared to others heard opportunistically during the data collection period. Therefore this value is not an entirely true representation of a cargo ship spectrum or RL, but it makes a good reference when comparing with other vessel types measured. N (# of sec used) varied within sound file recordings in this investigation, primarily due to interference or distortion, therefore the most audible sections of an individual sound file were used to create the spectra and RLs.

The individual echolocation clicks used to create the echolocation click mean were a variety of clicks picked from separate files recorded on numerous days over the entire data collection period, and were from different individual orcas. The distance from where the whale was that produced these clicks is unknown, but all clicks analysed were of different amplitude (dB) and so are a good representation of what an echolocation click being emitted from an orca looks like. This notion is supported by the frequency spectra of echolocation clicks displayed in Au *at al.* (2003) that show clicks having a bimodal distribution and dominating in the 10-60 kHz range. Upon viewing Figure 12 it can be noticed that this click mean also has a somewhat bimodal distribution between 10-50 kHz. It should be noted that this click mean represented in Figure 12 is a mean received level click, as the assumption was made that all clicks recorded were either from whales echolocating on or close to the hydrophone. The mean RL of a click was 134.4 dB, but this is a representation of the energy emitted by an orca, not the energy returning after the click has reflected off the surface or object it was echolocating on. Au *et al.* (2003) also found that the signal strength lost from an emitted killer whale click after it had reflected off a surface was in the vicinity of 40-60 dB at 50 kHz. For example, if an orca emitted a series of clicks onto a salmon with energy of 140 dB, then the signal strength it would receive back after it had bounced off the salmon would be in the vicinity of 80-100 dB. Based on this figure, the assumption was made that an echo of a click (after a click had bounced off a surface/object) would be 40 dB less than the mean received echolocation click across all frequencies. This echo of a click is also represented in Figure 12.

The killer whale audiogram (Figure 1) shows the physiological threshold hearing sensitivity of an orca underwater (simplified from Szymanski *et al.* 1999). It was derived from two captive killer whales that had probes attached to their melons to measure auditory brainstem response when emitted signals of different amplitude and frequency. It is the only study of its kind that has been conducted and is thus widely used in the scientific community. It shows a killer whale hearing is sensitive from 18-42 kHz, and most sensitive at 20 kHz. Examination of Figure 12 shows a relationship between the killer whale audiogram and an echolocation click. The most power in a click is between 10-40 kHz, which is where an orca is most sensitive. Based on this relationship, we can then determine at what points the echo of a click overlaps the audiogram (15 kHz 45 dB and 40 kHz 40 dB) and therefore make the assumption that any vessel with a spectrum level above the echo of a click is masking the ability of an orca to receive a signal back from an object or surface it has sent out a signal to. Figures 13 and 14 combine echolocation click spectrum and the audiogram with vessels travelling at Slow Motor 100m and Cruise 400m, and from these figures, a number of relationships can be observed. Firstly, in both figures, the mean echolocation click is 15-25 dB higher than any vessel spectra from 10-100 kHz. This can be expected as the power of a click emitted by a killer whale needs to have a lot of energy in order to bounce back and be received. In Figure 13, all vessel spectra appear to be within 15 dB of each other, but only two vessels, Electric Motor (the *Gato Verde* catamaran) and Twin Inboard Diesel are below the echo of a click spectrum. We can therefore conclude that all other vessels (Twin Inboard 400HP BioDiesel, Twin Outboard 150HP and Surface Piercing), when at Slow Motor 100m, have the potential mask the ability of a killer whale to hear the echo of a click. In Figure 14, all vessel spectra are again within 15 dB of each other, but are all above the echo of a click spectrum, and thus have the potential to mask an echolocation click echo. These results support the hypothesis that a vessel travelling at higher speeds will potentially mask a click more than a vessel travelling at slow speeds. Certain vessels appear to have a higher spectrum levels than others, but when a comparison is made of the RL, this may show otherwise. For example, at Slow Motor 100m, the Twin IB 400HP BioDiesel vessel appears to have the highest frequency spectrum, around 5 dB or greater above other vessel types from 10-70 kHz, however, the RL of this vessel at this speed and distance is identical to that of the Twin Outboard 150HP (115.6 vs. 115.5 dB). One must therefore conclude that although in Figures 13 and 14, certain vessels may appear to be masking other vessels and clicks, overall, their received level may be very different, so according these frequency spectrums, it is very hard to infer which vessel types would mask clicks more than others. Furthermore, a big assumption is made that the audiogram calculated from captive orcas is the same as the hearing sensitivity of a wild orca. It should be noted that one of the individuals from which this audiogram was derived was believed to be partially deaf, which further negates the use of this audiogram as a true representation of a killer whale's hearing sensitivity. The controlled boat sampling for this experiment was conducted in relatively calm, open bodies of water with minimal background noise, and background noise was taken into consideration for vessel sampling and filtered out. On a busy day out in the Haro Strait with many whale watch boats and public boats out viewing the whales, the cumulative background noise may be comparable, or even higher than individual vessel dB, so individual vessel RL would not be audible to an orca.

A. Improvements and future research

There are many areas in which this investigation could be improved. Firstly, more recordings of vessels on different days are needed. The mean spectral and RL values for this investigation were taken from one sound file (i.e. one single drive-by at each speed and distance). Although sampling was at a very high rate (192k), separate sound files on separate days are needed to avoid pseudoreplication. Calculation of a more representative mean echolocation click could also be done by sampling more clicks. Further controlled experiments of various vessel types travelling at various distances could be done to determine source level of each vessel. From this a database of various vessel/propulsion types could be built and used to help determine at what distance for certain vessels slow motoring at 100-400m is equal to a vessel cruising further away. This, along with conducting ANOVAs could be done on different vessel type RL's to determine differences amongst vessel types and this could then have implications for whale watch laws/guidelines. For example, it may be found that surface piercing vessels can motor slowly at 400m but an inboard diesel has to start motoring slowly at 800m as that is the distance at which it has an equivalent RL to a surface piercing vessel. There are a variety of factors that can affect the underwater noise signature of a vessel. For example, engine vs. propeller noise. Engines in two vessels may be identical, but if the propellers are different, then the underwater noise signature may be different as it is the propeller that creates the cavitations underwater and produces sound. Further studies could test this and determine what factors affect the sound produced by a vessel underwater. This may then be used in outfitting propulsion types in existing vessels to minimise noise impact on whales.

B. Conclusion

The purpose of this investigation was to examine, at high frequencies, different vessel types at different speeds/distances to determine which vessels may be masking echolocation clicks. From the results of this investigation, it was difficult to infer which propulsion types appear to be different from each other (as this was hard to quantify) and which appear to be having minimal impact on a killer whale's ability to emit and receive an echolocation click. In general, all vessel types have the potential to mask echolocation signals, although some more noticeable than others. Through technological advancement, further study of different propulsion types on vessels, and gaining a better understanding of the sensitivity of wild killer whale hearing, we can minimise our noise impact on the Southern Resident killer whales and thus aid in conserving their populations for the future.

Acknowledgements

I would like to thank the Beam Reach Marine Science and Sustainability School for giving me this great opportunity and to all the staff for their assistance and guidance throughout the program. Thanks must go to the boat operators for their cooperation and donating their time to drive-by the hydrophone, to the whale watch operators of Victoria, Canada and San Juan Island for aiding us in finding the whales throughout the program, to Giles (Debbie), to the Whale Museum in Friday Harbor, to Ken Balcomb and the Center for Whale Research, to Kari Koski and Soundwatch, to Team VaTo, and to everyone else that I met and helped me out throughout this program, you know who you are. I'm very appreciative. Cheers.

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APPENDIX I
Individual vessel details/specifics

Vessel name in paper	Propulsion System	Speed (knots) & RPM	Vessel type	Dimensions (metres)	Comments
Jet Drive	Twin 340 Ultra-waterjets powered by D-9 Volvo Diesels	SM: 7 knots, 750RPM Cruise: 25 knots, 2400RPM	Aluminium mono-hull	Length: 13 Beam: 4	Deep V type with 19° of deadrise - cuts through water very efficiently even in choppy conditions
Twin IB 400HP Diesel *IB = Inboard	Cummins QSL9, 400HP each. Gears: ZF 1.53:1 reduction ratio. 4 blade Nibral, 58.4 x 68.6cm props	SM: 7 knots, 700RPM Cruise: 19.5 knots, 1850RPM	Mono-hull	Length: 14 Beam: 4.4	Boat displacement: 29 tons Biodiesel fuelled
Twin OB 150HP *OB = Outboard	Twin 4-stroke YAMAHA 150HP outboards	SM: 6-7 knots, 1600RPM Cruise: 19-21 knots, 3700RPM	Coastal Runner 3600 Glacier Bay catamaran	Length: 8	Twin catamaran hulls for smooth ride and stability
Surface Piercing	Arneson ASD12 surface drives with five-bladed Nibral 35-inch by 37-inch props. Twin Caterpillar 3406E diesels Gears: TwinDisc MGX5114 2:1, electronically controlled	SM: 5-7 knots, 675RPM Cruise: ~25 knots, 2150RPM	All-aluminium RHIB-derivative with double-walled sides plus buoyancy collar	Length: 19 Beam: 5.5	Welded aluminium to provide extra stability
Twin IB Diesel	Diesel engines (Specifics unknown)	SM: 6-8 knots, 800RPM Cruise: 19 knots, 2050RPM	Mono-hull	Length: >20	
Gato Verde catamaran	2 x 9000W Electric Motors, charged by a 20HP biodiesel generator	SM: 5.9-6 knots Cruise: Not possible RPM N/A	Sailing catamaran	Length: 13 Beam: 7	Hybrid biodiesel-electric plug-in system
Dinghy	Single 18HP outboard	SM: 4-7 knots Cruise: 18-20 knots RPM unknown	Inflatable	Length: Beam:	
Washington State Ferry (WSF)	Twin 2500HP Diesel-Electric	Speed: >20 knots RPM unknown	Auto/Passenger Ferry	Length: 95 Beam: 22	
Cargo Ship	Unknown	Speed: >20 knots RPM unknown	Bulk carrier	Length: >150 Beam:>60	Vessel name: 'Giorgos Monrovia'

APPENDIX II

(Taken from Ordinance No. 35-2007. Complete version available at:
<http://www.co.san-juan.wa.us/News/vesselwhaleord_final.pdf>

Section 3. **Unlawful activity in proximity to the southern resident killer whale.**

A. Except as provided in Section 3(B) of this ordinance, it is unlawful for any person subject to the jurisdiction of the State of Washington to commit, attempt to commit or cause to be committed the following acts within the marine waters of San Juan County with respect to the southern resident killer whale (*Orcinus orcas*):

1) Knowingly approach, by any means, within 100 yards in any direction of any killer whale; or

2) Knowingly allow a vessel or other object to remain in the apparent path of an oncoming killer whale thereby resulting in a killer whale surfacing within 100 yards in any direction of the vessel or object; or

3) Knowingly place a vessel or other object within 100 yards in any direction of the killer whale; or

4) Fail to yield to a killer whale; or

5) Fail to disengage the transmission of a vessel that is within 100 yards in any direction of any killer whale; or

6) Operate a vessel in excess of a slow, safe speed when such vessel is within 400 yards of any killer whale. “Safe speed” has the same meaning as the term is defined in 33 USC 2006 and the international regulations for preventing collisions at sea 1972, *See* 33 USC Section 1602.

7) Feed a killer whale.

B. The following exceptions apply to the conduct described in Section 3(A) of this ordinance, but any person who claims the applicability of an exception has the burden of proving the exception applies:

1) The vessel is required to use the Vessel Traffic Services (VTS) in the waters of or adjacent to San Juan County; or

2) The person is operating a vessel pursuant to and in a manner consistent with a permit issued by the National Marine Fisheries Service, or similar authorization; or

3) The master or operator reasonably determines that compliance with the distance requirement of this ordinance will threaten the safety of the vessel, the vessel’s crew or passengers, or is not feasible due to vessel design limitations, or because the vessel is restricted in its ability to maneuver due to wind, current, tide, or weather.

4) The person operating the vessel is lawfully engaged in actively setting, retrieving or closely tending commercial fishing gear. For purposes of this subsection, “commercial fishing” means taking or harvesting fish or fishery resources to sell, barter or trade. “Commercial fishing” does not include commercial sport fishing boats used for charter operations or sport fishing; or

5) The person was operating a public vessel in the course of official duty for local, state, or the federal government; or

6) The person was operating a vessel in a manner consistent with a treaty with Native Americans or foreign nations.

APPENDIX III

Calibration of a C54 XRS/266 Cetacean high frequency hydrophone

On 24th September, 2007, calibration of a C54 XRS/266 Cetacean high frequency (HF) hydrophone was performed in the waters 200m offshore western San Juan Island (approx. 2-3km north of Lime Kiln Lighthouse). A known calibrated hydrophone was taped to the HF hydrophone and deployed to a depth of 5m off the port stern of the *Gato Verde* catamaran. The calibrated hydrophone was attached to a Marantz Digital Audio Recorder, the HF to a 702 High Resolution Digital Audio Recorder. An underwater ballet speaker was deployed off the starboard stern also to a depth of 5m. A single S1 killer whale call was emitted continuously from the speaker in order to record and calibrate the HF hydrophone. The calibrated hydrophone box (preamp) was set to an appropriate dB scale (relative to sound level emitted from speaker) and the HF Gain setting was adjusted to compensate for this (see Table 1). The 702 HR Digital Recorder had the Gain Range set to 'Low', Low Cut Enabled and 240Hz 1/12 octave dB eliminated (i.e. received levels below 240Hz were filtered out of recording). The reason for this setting is that we wish to obtain a calibration for the settings that will be used for the scientific investigation.
A total of six, synchronised, 15 second recordings were made at five different gain settings on the HF Recorder and the Marantz. For each Marantz recording a short calibration tone (Table 1) from the calibrated hydrophone box was emitted. The purpose of this cal-tone is to use the synchronous recordings of the Marantz and the HF Recorder and match the sound files to determine an actual received level (dB). Once the corresponding sound files have been examined using the appropriate software - Beam Reach Sound Analyser Program (v. Aug07a) created by Val Veirs, then a Sensitivity rating for each Gain setting can be calculated using the software. The Sensitivity for each Gain setting can be observed in Table 1.

Calibration Scale/Tone (dB)	HF Recorder Gain	Sensitivity
150	20	-95
150	26	-91
130	29	-89
130	36	-81

Table 1. Calibration of a HF hydrophone showing a known calibrated scale/tone at different HF Recorder Gain settings with calculated Sensitivity.

Once the Sensitivity for each Gain setting on the HF Recorder has been calculated, a calibration curve can then be created, and this can be viewed in Figure 1. From the four data points plotted a trendline has been fitted, and subsequent line equation and R^2 value.

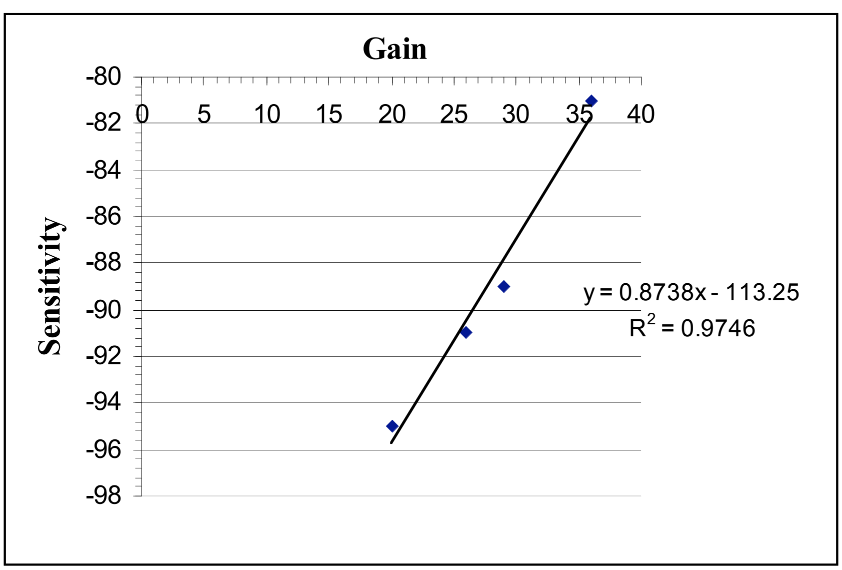

Figure 2. Calibration curve of the C54 XRS/266 Cetacean HF hydrophone

The purpose of creating a calibration curve for the C54 XRS/266 Cetacean HF hydrophone is to determine the actual received level (dB re 1µPa $^2/\sqrt{Hz}$) of an underwater sound at any given Gain level on the 702 High Resolution Digital Audio Recorder. Gain can be substituted into the equation of the line the to determine the Sensitivity, and this number is then put into the Beam Reach Sound Analyser (v. Aug07a) to determine actual received level. Calibration enables recordings on the HF to be comparable with levels stated in other peer-reviewed scientific articles.