Marine Physical Laboratory of the Scripps Institution of Oceanography University of California, San Diego

Joint Institute for Marine Observations
Report on cooperative agreement NA17RJ1231:

Whale Watch Vessel Ambient Noise in the Haro Strait

John A. Hildebrand
Marine Physical Laboratory, Scripps Institution of Oceanography
University of California San Diego, La Jolla, CA 92093-0205

Mark A. McDonald
WhaleAcoustics
11430 Rist Canyon Road, Bellvue, CO 80512

John Calambokidis
Cascadia Research Collective
218-1/2 West Fourth Ave. Olympia, WA 98501

Ken Balcomb
Center for Whale Research
PO Box 1577, Friday Harbor, WA 98250

MPL TM-490
August 2006

Acknowledgements

This project was a collaborative effort between the Scripps Institution of Oceanography of the University of California San Diego, Cascadia Research Collective, Whale Acoustics LLC, the Whale Research Center, and NOAA National Marine Fisheries - Northwest Fisheries Science Center.

Acoustic studies were the primary concern of the Scripps Institution of Oceanography, with John Hildebrand as the project principal investigator, and Sean Wiggins as the co-principal investigator. Chris Garsha and Graydon Armsworthy provided assistance with acoustic instrumentation, field data collection. Nadia Rubio assisted with acoustic data processing. Additional Scripps staff members that helped with this project were Allan Sauter, Kevin Hardy, and Harry Lam.

Small boat operations and coordination with whale watch vessels were the primary concerns of the Cascadia Research Collective, with John Calambokidis as the principal investigator, and additional help provided by Erin Falcone, Randy Luper, Kyla Graham, and Chantal Huijbers.

Whale Acoustics LLC, with Mark McDonald as the principal investigator, provided instrumentation and field assistance with this project and also played a primary role in the vessel noise analysis, instrument calibration, and report production. Dinny Falkenburg assisted in the field and provided digital photography for the vessels under study.

The Center for Whale Research, with Ken Balcomb as the principal investigator, provided detailed local knowledge research setting and of the whale watch industry, logistical support for the field operations, and use of the Sea Hunt as a platform for acoustic measurements.

David Bain, from the University of Washington, collaborated in visual tracking of vessels and marine mammals. Jody Smith assisted with the theodolite tracking and other field logistics.

The NOAA National Marine Fisheries, Northwest Fisheries Science Center, provided support for this project, with Linda Jones as the project lead, and Brad Hanson as the primary field and logistical coordinator.

We thank all the above named organizations and individuals for support of this work.

Introduction

This report provides a partial analysis of Haro Strait whale watching vessel noise data collected during fieldwork conducted May 28th to 31st, 2004 under contract to the NOAA Northwest Fisheries Science Center. The goal of this project was to measure representative calibrated noise levels of whale watching vessels and commercial shipping vessels operating in the Haro Strait and to examine differences in noise between vessel types. The Haro Strait is the site of high levels of vessel activity, both from the whale watching industry and from commercial vessel traffic.

One outcome of this work will be a better evaluation of the potential impact of vessel noise on southern resident killer whales. The Haro Strait is an important habitat for southern resident killer whales, a population designated as an endangered species owing to declines in their numbers. By characterizing the noise of vessels operating in the Haro Strait, the potential for noise to impact killer whales will be better understood.

Two concerns related to the impact of noise on marine mammals are behavioral impacts and masking noise. Behavioral impacts may range from short-term changes in activity to complete displacement from key habitat. Masking occurs when noise interferes with the animals' ability to communicate with conspecifics, or to use echolocation for foraging or other functions. Killer whale communication whistles are centered at about 8 kHz (Thomsen, 2001) and the average intensity of stereotyped whistles is 153 dB re 1 μPa at 1 m (Miller, 2006). Their echolocation clicks are centered near 50 kHz on axis (although off-axis frequency peaks may be lower) and source levels are 194-225 dB re 1 μPa at 1 m on axis (Au et al., 2004).

For this analysis we present calibrated noise measurement of five vessels encountered in the Haro Strait. Field noise data were collected for a total of fifteen vessels under controlled conditions, and for a larger number measured under opportunistic conditions. Analysis of the complete vessel dataset will be the topic of future study. Four of the vessels considered in this preliminary study were small boats used for whale watching; one vessel was a large commercial container ship.

The noise produced at low frequencies (below 1 kHz) by the vessels examined in this study is thought to be due both to cavitation (bubble creation and collapse) and rotating machinery. Above 5 kHz the noise comes almost entirely from cavitation of the vessels' propellers or bubble creation by jet drives.

High levels of ambient noise encountered in the Haro Strait hampered the ability of our study to separate the noise of individual vessels from others operating in the vicinity. This was the case both for vessel that were cooperating with our study and operating under controlled conditions, and those that we measured opportunistically. We recommend that future noise measurements for whale watching vessels operating in the Haro Strait should be conducted in an isolated setting, to allow better characterization of vessel noise generation under a wider range of operating conditions.

Geographic Setting

This study was conducted in the Haro Strait, which spans the international border between the United States and Canada. San Juan Island, in Washington State, forms the eastern (US) side, whereas Vancouver Island (Canada) forms the western side of Haro Strait (Figure 1). The area off Limekiln Lighthouse on the west coast of San Juan Island, was the site for our study.

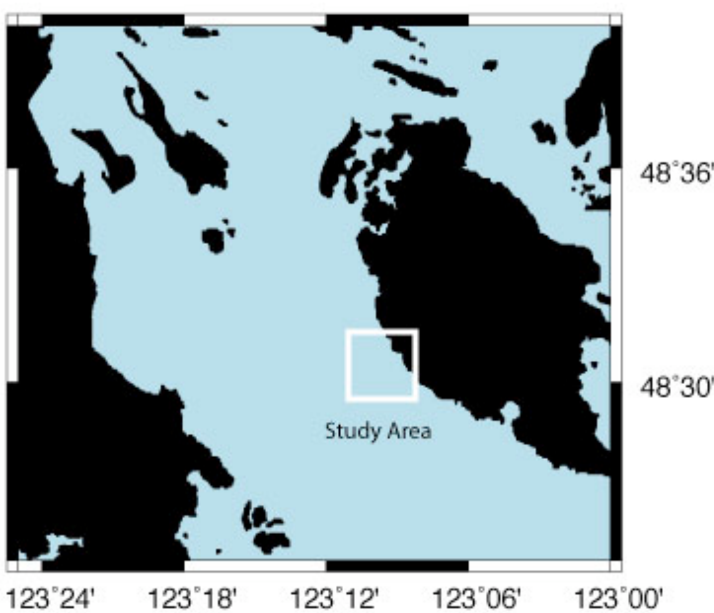

Figure 1. Noise study area in the Haro Strait, adjacent to Limekiln Lighthouse on the west coast of San Juan Island.

Methods

Our study was conducted under the ambient conditions of the Haro Strait. We deployed recording hydrophones from a small vessel, and then recorded noise either under a controlled protocol, or under opportunistic passage of vessels operating in the Haro Strait.

1. Equipment

Acoustic recording equipment was operated from the Sea Hunt, a small research vessel operated by the Center for Whale Research (Ken Balcomb), which was allowed to drift with no engines operating, while noise-generating vessels were located nearby. Three acoustic receivers were deployed: (a) vertical hydrophone array, (b) broadband hydrophone, and (c) sonobuoys. All acoustic receivers were suspended beneath the Sea Hunt, while the electronic equipment used to record the acoustic data were operated inside the Sea Hunt cabin.

a. Vertical Hydrophone Array (60-1000 Hz)

The low frequency (60 to 1000 Hz) recording system consisted of a four hydrophone vertical array, illustrated in Figure 1. The elements of this hydrophone array were obtained from a SSQ-77A sonobuoy, having been re-configured so that they could be operated on a multi-conductor wire. Calibration of the vertical hydrophone system was conducted at the U.S. Navy facility, TRANSDEC as detailed in a calibration report (McDonald, 2006a). The recorder used was a National Instruments Sound Card, interfaced with a custom version of the Ishmael software (mobysoft.com), sampling at 50 kHz.

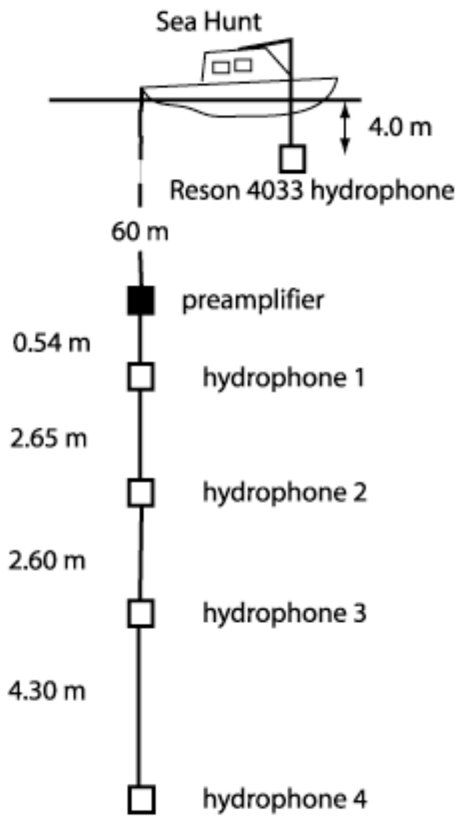

Figure 1. Schematic diagram of the depths of vertical hydrophone array elements and broadband hydrophone (Reson 4033) used in the preparation of this report. All distances are in meters.

The reason for using a vertical array when making vessel noise measurements is because tonal sounds such as produced by rotating machinery on ships will result in nulls and peaks in the sound field, corresponding to constructive and destructive interference of the sound and its sea surface echo. If hydrophones are spaced more than a few fractions of a wavelength apart, it is possible to detect the magnitude of these nulls and peaks, making a more accurate measurement. At higher frequencies (above 1000 Hz), hydrophones removed from the sea surface by more than a few wavelengths are not appreciably affected by these interference patterns, and a single hydrophone is sufficient.

b. Broadband hydrophone (1000 to 75,000 Hz)

A broadband hydrophone was suspended at shallow depth, and recorded by a high frequency recording system. This system consisted of a Reson 4033 hydrophone with 10 m cable, attached to an UltraSoundGate charge amplifier and Avisoft-UltraSoundGate 116 recorder sampling at 500 kHz with the "Avisoft Recorder" software interface. The hydrophone cable was suspended from a fishing rod to reduce vertical motion and the hydrophone was suspended at a depth of 4.0 m. These recordings have a 16 bit dynamic range and the level was adjusted with 20 dB and 42 dB attenuators when needed to keep vessel noise within the dynamic range of the recording system. Calibration of the system was conducted from 1 kHz to 75 kHz at the U.S. Navy TRANSDEC facility as detailed in the calibration report (McDonald, 2006b).

c. Sonobuoys

One DIFAR (directional) sonobuoy of type 53D and one broadband sonobuoy of type 57B were deployed each to a depth of 27.4 m (90 feet) during the whale watching vessel monitoring. These data are not analyzed in this report, thus no further details of these recordings are given.

d. Expendable bathythermographs

Temperature profiles were measured each day using radio linked expendable bathythermographs (type AN-SSQ-36). If propagation analyses were to be conducted these XBT data could be used to compute vertical sound speed profiles to be used in the acoustic propagation models.

2. Protocol

A set of whale watching vessels cooperated with this study and these boats were measured according to a protocol at a range near 200 m at idle, at normal cruise speed (> 10 knot) with a closest approach near 200 m and during rapid acceleration from a stop near 200 m range (Figure 2). Ranges and speeds were obtained during the tests using laser range finders and tracks recorded by a GPS unit, which was handed off to each participating vessel for the tests and returned. Range corrections were made to compute calibrated noise spectra. The laser ranges were considered more accurate than the GPS ranges, but the GPS was used to document cruise speeds and to verify the range data. Each vessel was also photographed with a digital camera.

Additional vessels which were not cooperating with the study were measured opportunistically as they passed by our research site, using laser range finding and the radar on the Sea Hunt. In this analysis, the only vessel in this category is the commercial container ship the *Hanjin Marseille* whose speed and position were measured using the Sea Hunt radar and laser range finding.

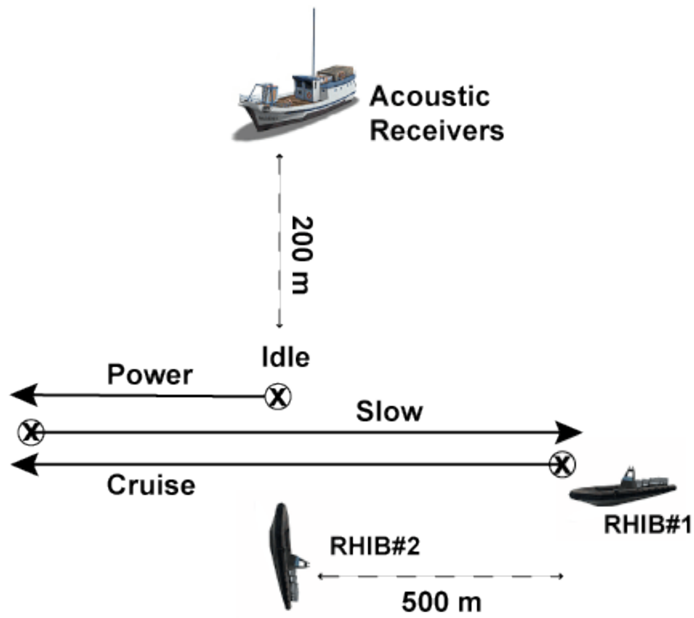

Figure 2. Schematic of controlled protocol for measurement of noise from whale watching boats. Two RHIBs were used to provide location references for boat movement. The whale watching boat began at RHIB#1, and proceeded to pass near RHIB#2 at cruise (> 10 knot) speed. A passage was then conducted at slow (4 knot) speed. The boat was held at idle at approximately 200 m range, and then executed a power acceleration to full speed.

3. Analysis and Acoustic Propagation Loss

The noise pressure spectra were computed using custom software written in the MATLAB programming language. Each spectra represents a 10 second average of the noise level. In the case of power up, this ten second interval was chosen to include the most intense sound pressure level interval, as judged by visual observation of a spectrogram. All spectra are presented in frequency bins of 1-Hz width.

The noise source spectra presented in this report are all corrected to a range of 1 m from the source. The whale watching vessels being analyzed were near enough and the water depth great enough that spherical spreading losses were used to account for differences in range and thereby compute source levels. Absorption coefficients were computed from the equation of Ainslie and McColm (1998).

Results

In this section we present noise spectra from four whale watch vessels collected under a controlled protocol and one commercial container ship collected opportunistically. Vessels parameters and operating conditions are listed in Table 1.

Table 1. Vessel parameters and operating conditions examined in this study.

Name	Size (feet)	Propulsion	Date Time	Protocol	Sea State	Cruise Speed (kts)	Distance CPA (m)
Annie Mae	28	Outboard	5/31/04 12:30	Controlled	2	17	207
K-KO	29	Outboard	5/29/04 16:30	Controlled	1	24	177
Mercury	38	Jet drive	5/29/04 16:15	Controlled	1	31	219
Olympas	50	Propeller	5/31/04 13:00	Controlled	3	23	199
Hanjin Marseilles	950	Propeller	5/30/04 10:40	Opportunistic	2	21	442

Conditions during these tests ranged from sea-state 1 to 3, and we do not consider these differences to be an important factor in the final noise measurements. Rather, the main impediment to collecting accurate vessel noise data was the abundance of other vessels in the operations area. For the controlled measurements, none of the noise data collected while the vessels were at idle were significantly different from background noise. This is not to say that it is impossible to detect the idling vessel in the spectra, but these data were generally dominated by other more distant ships. For this reason, we do not consider the data that we collected to be an accurate measurement of the real ship noise under idle conditions. Under the other controlled operating conditions, cruise and power acceleration, the vessel noise data were generally above the ambient.

1. Annie Mae

The Annie Mae is a 28' fiberglass mono-hull with twin 90 Hp four stroke outboards that is operated as a six-passenger whale watch vessel (Figure 3). The acoustic measurements took place in sea state 2 conditions, with no other vessels in the local vicinity on May 31st at about 12:30 PM.

Figure 3. The Annie Mae is a six-passenger whale watch boat with twin 90 Hp four stroke outboard engines.

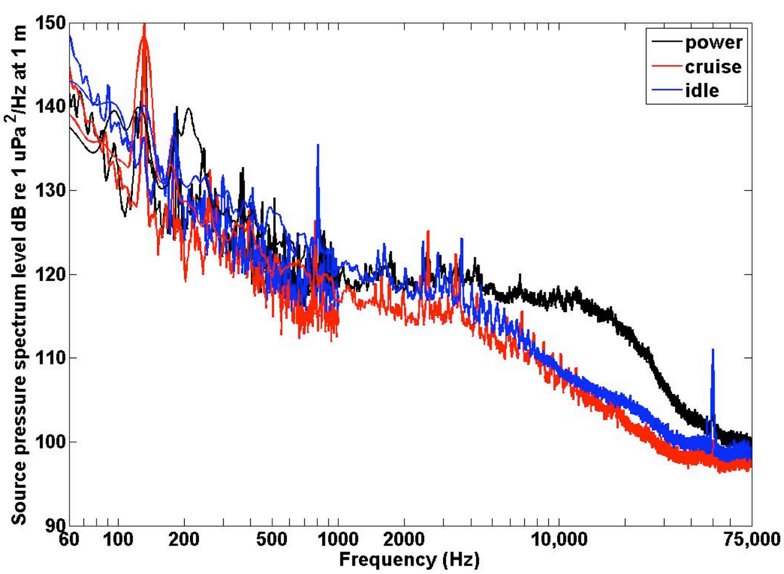

Figure 4. Annie Mae source spectral levels (dB re: $\mu Pa^2/Hz$ @ 1 m). The spectral peak at 50 kHz in the idle data is an echosounder. The vertical array uppermost hydrophone is plotted to 1 kHz and overlaid by the broadband hydrophone data, which extends to 80 kHz. The power-up noise data at 8-30 kHz show as much as 10 dB increase over background noise levels.

The Annie Mae executed a pass at 17 knot cruise speed, with a minimum range of 207 m from the Sea Hunt (time 12:30:07). The vessel then held station nearby (200 m range) under idle conditions. Subsequently a two-engine power acceleration was conducted at a range of 178 m (time 12:41:20). Source noise spectra are shown in Figure 4 and corrected for vessel-to-hydrophone range using spherical spreading and absorption losses.

In the Annie Mae noise spectra (Figure 4), only the power up measurement is noticeably above ambient noise levels, emerging from the noise between 3 kHz and 50 kHz, as expected from propeller cavitation noise. The Annie Mae idle noise data collected at 200 m range and cruise data collected at 207 m were not significantly different from background noise on this day at this time (sea state 2).

The power up test occurred at 178 m and provided measurable noise spectra level results between 4-60 kHz. In the band 4-15 kHz the Annie Mae source level averaged about 118 dB re: 1 μPa^2 /Hz @ 1m, which resulted in as much as 10 dB noise increase over the prevailing ambient noise at the range of 178 m. The noise is likely a result of cavitation from the engine propellers.

2. K-KO

The K-KO is a twelve-passenger whale watching boat with a 29 foot aluminum mono-hull which was recorded under the controlled protocol on May 29th at about 4:30 PM in sea state 1 conditions (Figure 5). The K-KO is powered by twin 225 Hp Mercury EFI outboard motors, and it was operated at 24 knots for the cruise test, with a minimum range of 177 m. The K-KO idle test took place at 126 m, and power acceleration at 125 m.

Noise spectra for the K-KO are shown in Figure 6. The idle measurement can again be assumed to represent approximate background noise levels rather than a true source level. Noticeable increases in noise source spectra from the K-KO can be seen from 100 to 350 Hz during cruise and power up and cavitation noise is evident above 10 kHz during the cruise test.

Figure 5. K-KO is a twelve-passenger whale watching boat with twin 225 Hp outboards.

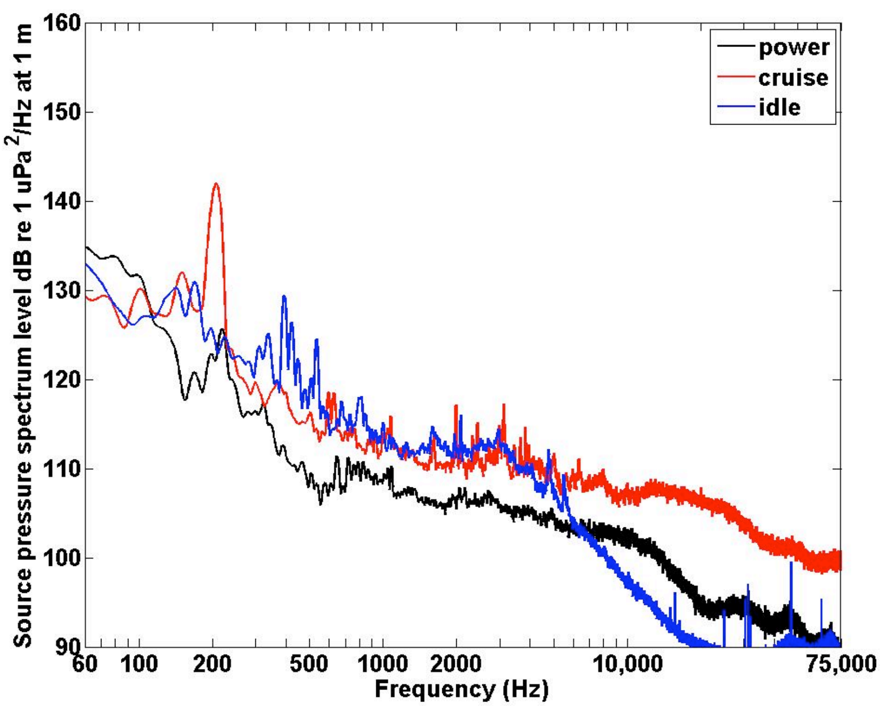

Figure 6. K-KO source spectral levels (dB re: $\mu Pa^2/Hz$ @ 1 m). These data are from the broadband hydrophone.

3. Mercury

The Mercury (since renamed the Island Whaler) is a 38' aluminum catamaran whale watching vessel with jet drives (Figure 7). Measurements took place in sea state 1 conditions on May 29th near 4:15 PM. The cruise speed for the Mercury during this test was 31 knots. The minimum vessel range during the cruise speed approach was 219 m. Idle measurements were made at 297 m, and the power acceleration was conducted at 350 m.

The Mercury source spectra shows detectable bubble (cavitation) noise, but no measurable rotating equipment noise (Figure 8). Less than 10 dB of difference is seen between the idle and power acceleration noise conditions.

Figure 7. The Mercury is a 38' aluminum catamaran with jet drives.

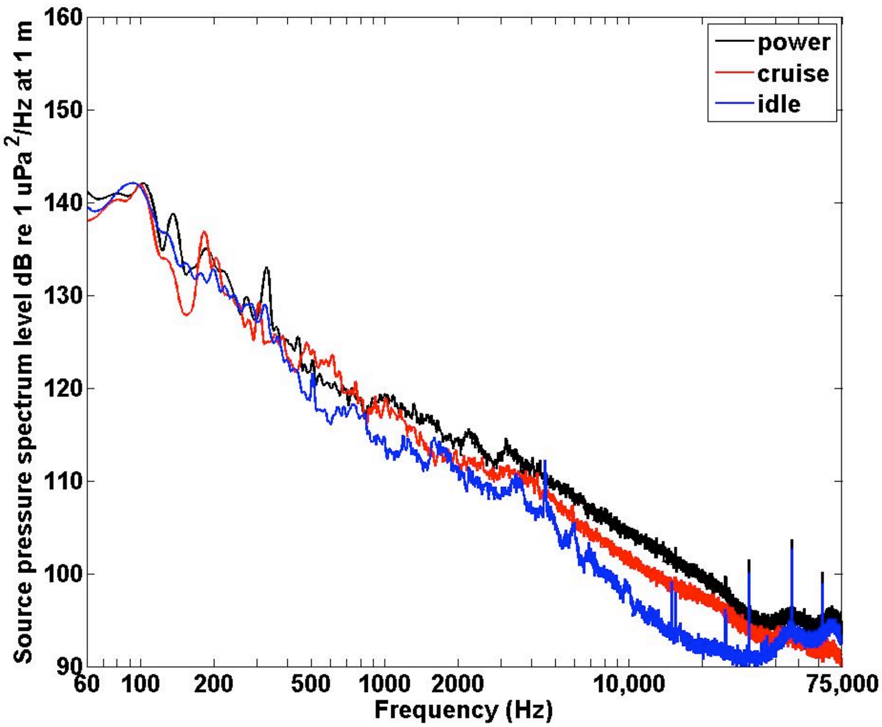

Figure 8. Mercury source spectral levels (dB re: $\mu Pa^2/Hz$ @ 1 m). These data are from the broadband hydrophone.

4. Olympas

The Olympas is a 50 foot monohull whale watching vessel (Figure 9). Recording took place in sea state 3 conditions near 1:00 PM on May 31, 2004. The cruise speed for the Olympas testing was 23 knots, and the minimum range was 199 m. The power acceleration measurement was at 134 m by the laser range finder, and the idle measurement at 200 m.

The Olympas produced the highest noise levels (Figure 10) from a whale watching vessel in this analysis, with significant noise from about 120 Hz to the upper frequency limit of the recordings. Ample rotating machinery noise is seen as noise peaks for selected frequencies between 200 Hz and 2000 Hz. As much as 20 dB of additional noise are seen for the cruise and power conditions relative to the idle at frequencies above 2 kHz, probably related to cavitation noise.

Figure 9. The Olympas is a 50 foot monohull whale watching vessel.

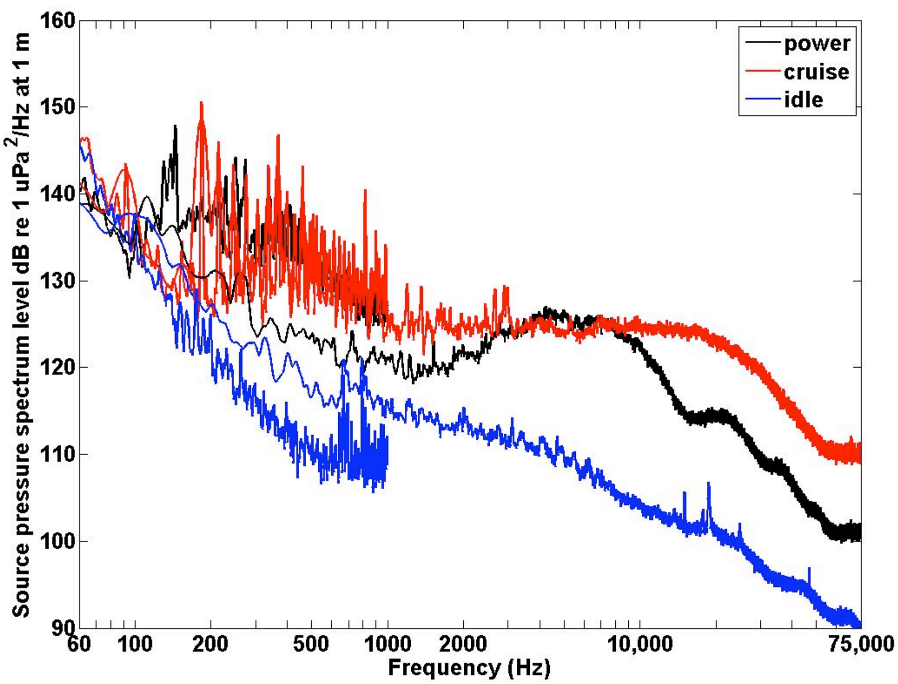

Figure 10. Olympas source spectral levels (dB re: μPa^2/Hz @ 1 m). Vertical array data are plotted 60-1000 Hz and broadband hydrophone data from 60 – 75,000 Hz. The offsets at 1000 Hz between recordings systems may be related to slight time offsets in the two recording systems.

5. Hanjin Marseilles

The Hanjin Marseilles is a commercial container vessel which passed by at a steady speed of 21 knots with a closest point of approach of 442 m. As is evident from the waterline markings in the photo in Figure 11, the vessel is not fully loaded. The Hanjin Marseilles is a 289.5 meter (950 foot) Korean container ship built in 1993. She is rated at 4024 TEU (20 foot container equivalents) and 62,681 DWT (dead weight tonnes) which makes her among the largest ships built in 1993 when the Panama Canal vessel width limit (32.2 m) was considered as a limit to practical ship size. Significantly larger vessels are in operation now. The rated cruise speed is 24 knots and the rated draft is 13 meters. Recording took place on May 30th about 10:40 AM in sea state 2 conditions.

Figure 11. The container ship Hanjin Marseilles cruising at 21 knots.

Computed source spectral levels for the Hanjin Marseilles are shown in Figure 12. A source level of 165 dB re: $\mu Pa^2/Hz$ @ 1 m is seen at low frequency (60 Hz) as the propellers were a beam to the hydrophone array. The sawtooth pattern in the spectra from 8 kHz to 75 kHz may be due to modulation effects within the cavitation noise as discussed by Ross (1976).

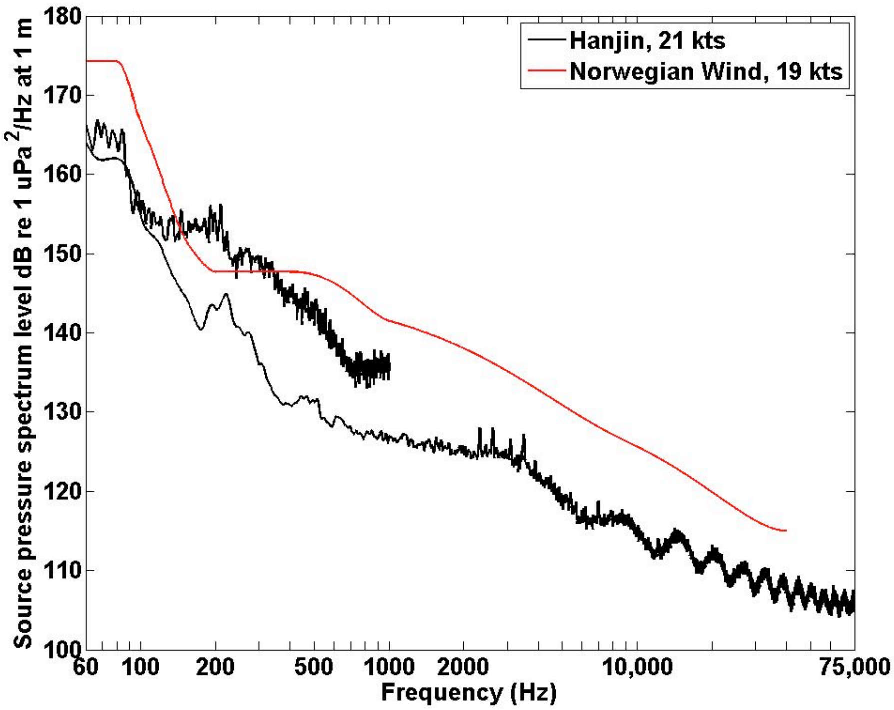

Figure 12. Hanjin Marseilles source spectral levels (dB re: μPa^2/Hz @ 1 m) measured as the propellers passed the hydrophones at 442 m range. The spectra from 60 to 1000 Hz is from channel one of the vertical array, the 60 – 75,000 Hz spectra from the broadband hydrophone. The beam aspect source level of the Norwegian Wind, a 230 m cruise ship traveling at 19 kts (Kipple, 2002) is plotted for comparison. The Norwegian Wind data is converted from third octave band levels, thus appears smoother.

At low frequency, there is a greater difference in computed source level from one minute to the next, than is seen from one hydrophone to the next, presumably due to propagation differences and aspect ratio of the sound source (Figure 13). The highest source level of 180 dB re: μPa^2/Hz @ 1 m was observed 3 minutes after the vessel passed a beam of the hydrophone array.

The received sound pressure level of the Hanjin Marseilles (Figure 14) is compared to ambient background noise level before the arrival of the vessel and to a reference sea state noise level (Urick 1983). The presence of the Hanjin Marseilles elevated the ambient noise levels at the measurement site by as much as 30- 40 dB across a broad band of the spectrum.

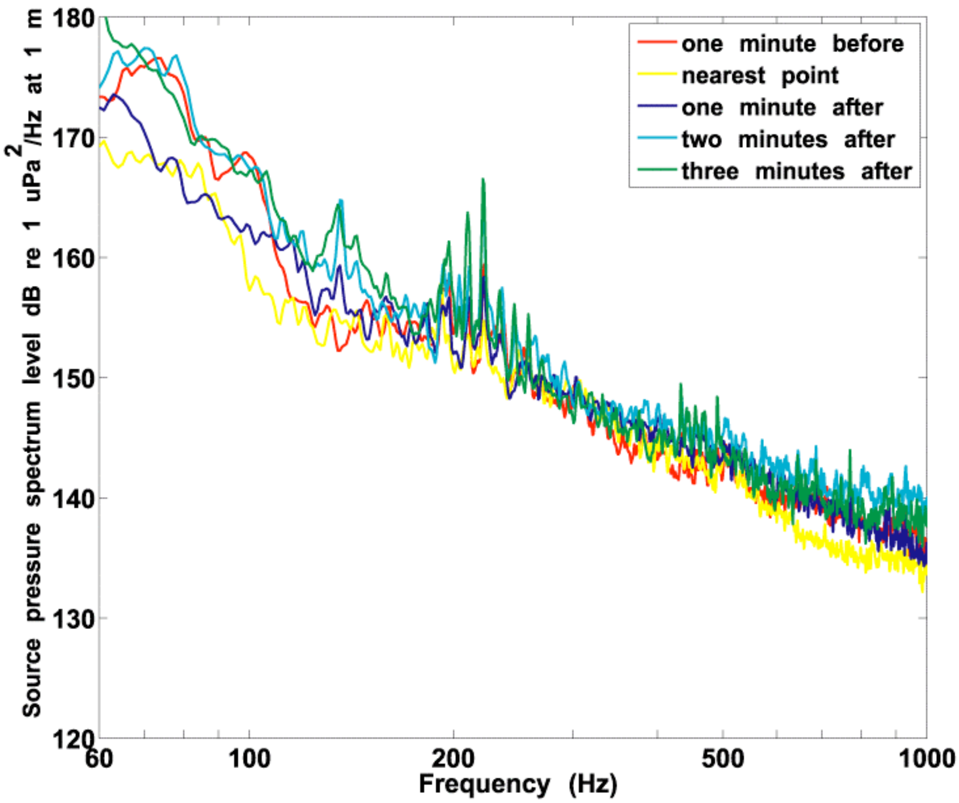

Figure 13. Computed source spectral levels (dB re: μPa^2/Hz @ 1 m) of the Hanjin Marseilles are shown at various times as it passes our measurement site at a speed of 21 knots with a closest point of approach of 442 meters. Data are from channel one of the vertical array.

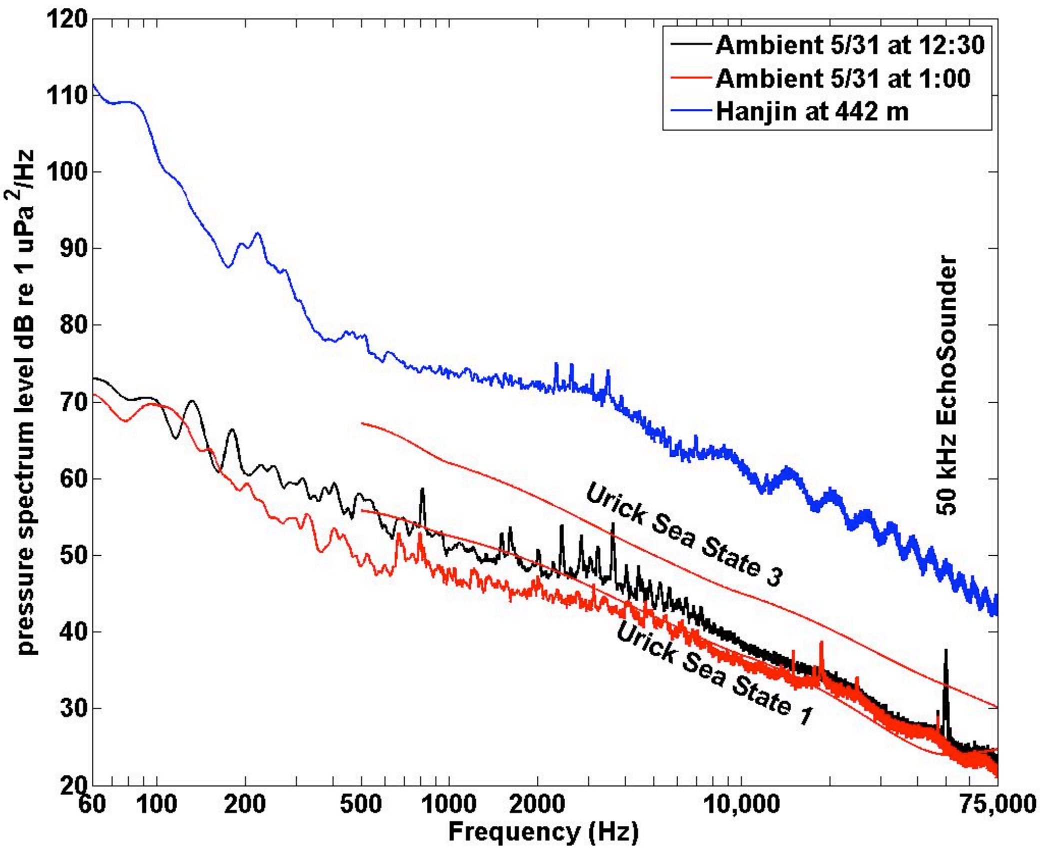

Figure 14. Received pressure spectrum level of the Hanjin Marseilles at 442 m compared to background ambient noise levels in sea state 2 at 12:30 increasing to sea state 3 at 1:00 and the deep water ambient levels of Urick (1983) for sea states 1 and 3.

Discussion

1. Interference from other vessels

Measurement of whale watching vessel source levels at idle when near 200 m was not possible at the Lighthouse Kiln measurement site because of high background noise levels. The computed idle source levels are therefore only maximum sound pressure level spectra. Commercial vessels traffic more than one mile distant often produced spectral lines at rotating equipment frequencies stronger than any of the whale watching vessels at idle during any of the tests. At higher frequencies, echosounders from unidentified vessels often produced strong lines at 50 kHz and 80 kHz.

The background ambient noise levels due to the many other vessels make this a poor site for calibrated measurements of individual vessel noise. Commercial vessels are within sight at the study location about sixty percent of the time (Val Viers, unpublished report) and smaller vessels were nearly always present on the holiday weekend when this work was conducted. However, the site did have the advantage of being a typical location where vessels interact with whales.

2. Vessel Comparisons

Source spectral levels at cruise speed are compared for each of the vessels in this study in Figure 15. The Mercury, the jet drive vessel, was the quietest at high frequencies. The Mercury is unusually quiet for its size and speed, with bubble (cavitation) noise less than 5 dB above background levels when operated at cruise speed at 219 m, and there is no appreciable rotating equipment noise. The anomalously low underwater noise levels for this size vessel are presumably due to the jet drive system. Above about 3 kHz the K-KO and Annie Mae have noise levels that appear to be 5-10 dB higher than the Mercury. Rotating machinery noise at selected frequencies is evident for both of these vessels. The Olympas, the largest whale watch vessel, had significant rotating machinery noise at 200 Hz to 2000 Hz and at high frequencies produced the highest sound pressure levels measured for any vessel in this study. As much as 30 dB noise difference is seen between the Mercury and the Olympas when operating at cruise speed. The Hanjin Marseilles has significantly higher source level at low frequency (< 200 Hz) than the smaller vessels. However, it is noteworthy that this commercial container ship produced significant levels of noise at high frequencies (> 2000 Hz), having a higher source level than all studied whale watch vessels except for the Olympas.

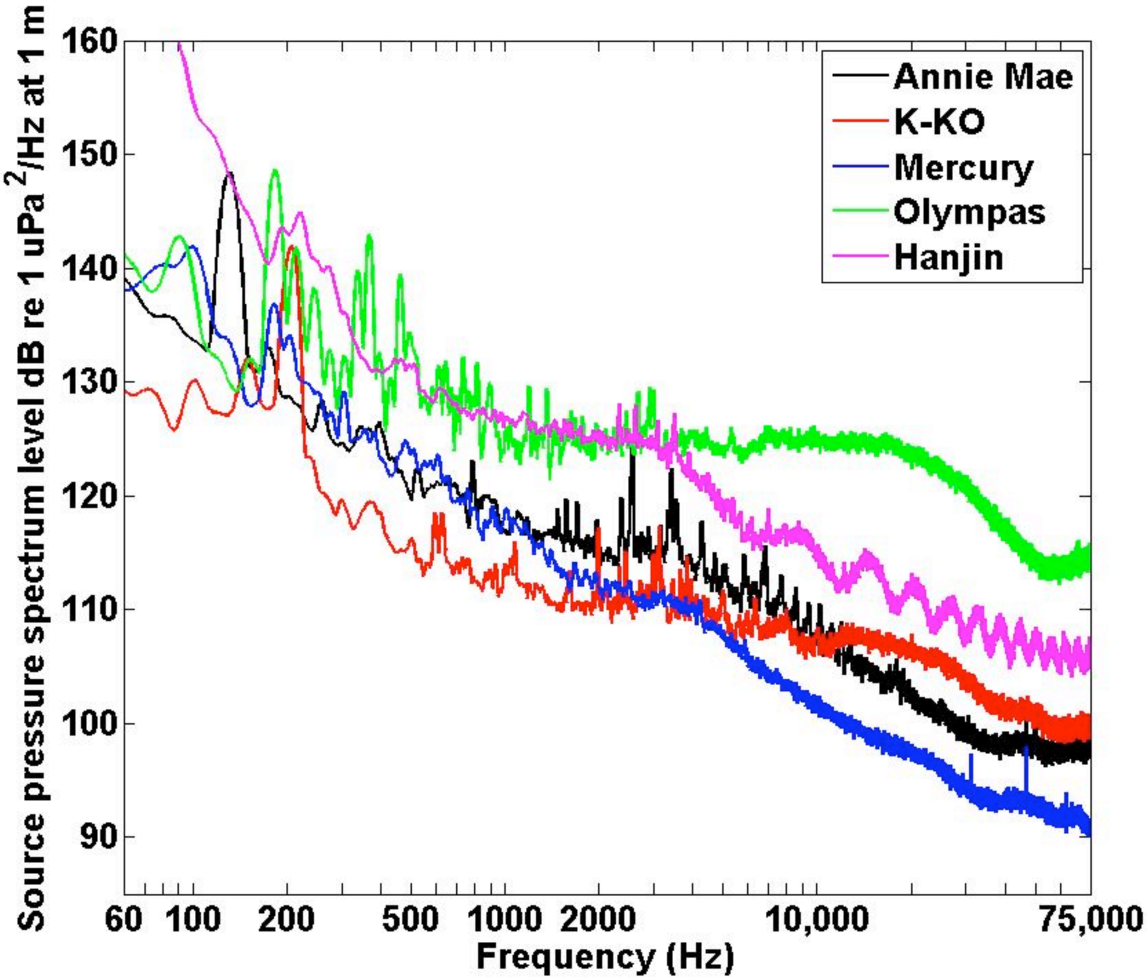

Figure 15. Source spectral levels (dB re: $\mu Pa^2/Hz$ @ 1 m) at cruise speed are compared for each of the vessels in this study, as recorded on the broadband hydrophone system.

3. Killer Whale Relevance

Killer whale hearing peaks at about 20 kHz and is thought to be poor below 1 kHz based on auditory evoked potential studies (Szymanski 1999). As shown by Gerstein et al. (1999), such work needs to be critically evaluated in the context of the problem being addressed. The problem of superimposing a killer whale hearing audiogram on background noise spectra is complex. Erbe (2002) produced such a plot, but the complexities of hearing perception make it difficult to translate what is measured in the audiogram to background noise spectra, and such a comparison deserves greater discussion and error evaluation than can be provided in this report.

The results of our study suggest that noise from whale watching and commercial vessels in the Haro Strait could have significant impact on killer whale echolocation ability. Under cruise and power acceleration operating conditions, whale watch vessels were capable of increasing the ambient sound levels by 20 dB at about 200 m range. The most relevant frequencies for whale watching vessel masking of killer whale echolocation appear to be from 5 kHz to 100 kHz. A baseline killer whale echolocation study by Au *et al*. (2004) could be used to calculate the detection range reduction for killer whales echolocation on salmon, induced by whale watching vessel noise. Assuming spherical acoustic propagation loss and omni-directional sources, a 20 dB increase in background noise may be expected to reduce echolocation detection range by an order or magnitude, although the details of killer whale echolocation need to be factored into this calculation.

Future Work

While work has been published on vessel noise, on masking zones, and salmon detection range for killer whales, no one has brought these concepts together. Previous thinking on whale watching vessel noise has focused on rotating equipment noise and the behavioral response of killer whales, rather than on cavitation noise and its potential masking effect on killer whale echolocation.

The analyses in this report suggest that jet drive vessels have lower cavitation noise than propeller driven vessels of similar size, a perhaps not surprising result. This could become an important result if killer whale echolocation masking is shown to be an issue for whale watching vessels.

Neither of the above two topics can be placed in perspective in the Haro Strait without considering the impact of the large commercial vessels (container ships, etc.) which are within sight in the Haro Strait more than half the time. A study of background ambient noise related to commercial shipping would be helpful in placing the above topics in context.

Recent studies sponsored by Glacier Bay National Park have measured noise levels from a wide variety of vessels, ranging from aluminum outboard skiffs (14 ft) to cabin cruisers (65 ft) using a portable system deployed in Glacier Bay (Kipple, 2003). A separate report for Glacier Bay National Park analyzed 6 cruise ships over frequencies from 40 Hz to 50 kHz using the Navy measurement facility near Ketchikan (Kipple, 2002). Integration of the National Park Service measurements with those we have collected in the Haro Strait could begin to provide a generic correlation between vessel parameters and expected noise levels.

References

Ainslie MA and McColm JG, 1998 A simplified formula for viscous and chemical absorption in sea water, J. Acoust. Soc. Am., 103, 1671-1672.

Au WWL, Ford JKB, Horne JK and Newman-Allman KA, 2004 Echolocation signals of free-ranging killer whales (Orcinus orca) and modeling of foraging for chinook salmon (Oncorhynchus tshawytscha), J. Acoust. Soc. Am., 56, 1280-1290.

Erbe C. 2002 Underwater Noise Of Whale-Watching Boats and Potential Effects on Killer Whales (*Orcinus orca*), Based on an Acoustic Impact Model. Mar. Mamm. Sci. 18:394-418.

Gerstein ER, Gerstein L, Forsythe SE and Blue JE 1999 The underwater audiogram of the West Indian manatee (*Trichechus manatus*), J. Acoust. Soc. Am. 105: 3575–3583.

Kipple, B 2002 Southeast Alaska cruise ship underwater noise, Naval Surface Warfare Center, Technical Report NSWCCD 71-TR-2002/S74, Oct. 2002. 92 pp.

Kipple, B and C. Gabriele 2003 Glacier bay watercraft noise, Naval Surface Warfare Center, Technical Report NSWCCD-71-TR-2003/522, February 2003. 54 pp.

McDonald, MA 2006a Calibration of Haro Vertical Array Recording System at Pt. Loma Transducer Evaluation Center (TRANSDEC). Manuscript.

McDonald, MA 2006b Calibration of UltraSoundGate Recording Systems at Pt. Loma Transducer Evaluation Center (TRANSDEC). Manuscript.

Miller PJO. 2006 Diversity in sound pressure levels and estimated active space of resident killer whale vocalizations. Journal of Comparative Physiology A: Neuroethology, Sensory, Neural, and Behavioral Physiology 192: 449-459.

Ross D, 1976 Mechanics of Underwater Noise, Pergamon Press, New York, 375 pp.

Szymanski MD, Bain DE, Kiehi K, Pennington S, Wong S and Henry KR 1999 Killer whale (*Orcinus orca*) hearing: Auditory brainstem response and behavioral audiograms, J.

Acoust. Soc. Am. 106:1134–1141.

Thomsen F, Franck D and Ford JKB 2001 Characteristics of whistles from the acoustic repertoire of resident killer whales (*Orcinus orca*) off Vancouver Island, British Columbia, J. Acoust. Soc. Am. 109: 1240-1246.

Urick RJ 1983 Principles of Underwater Sound, McGraw-Hill, New York .