Measured Near-Surface, Bow Area, Underwater Cruise Ship Sound

Underwater sound levels of cruise ships measured over a wide range of aspects using near-sea-surface hydrophones at the U.S. Navy’s Southeast Alaska Acoustic Measurement Facility.
ABSTRACT

If a region of extraordinarily low sound levels ahead of the bow area of an advancing ship – an “acoustic null” – existed, this phenomenon could be a significant factor in collisions between large ships and whales. In fact, a number of investigators have hypothesized or reported the presence of such a null. In this study, the underwater sound levels from two cruise ships underway at speeds of 10 and 20 knots were measured at true bow aspect angles by hydrophones located 5, 10, and 15 feet below the sea surface at the U.S. Navy’s Southeast Alaska Acoustic Measurement Facility near Ketchikan, Alaska. These measurements showed no significant difference between bow and stern aspect radiated acoustic directivity. They also showed that received underwater ship sound level directionality did not differ significantly from an ideal omnidirectional acoustic source. For these reasons the results did not support the presence of an acoustic null unique to the region ahead of the approaching cruise ships. In addition, calibrated face-of-hydrophone sound levels showed that measurable acoustic energy existed ahead of the cruise ship at small angles representative of bow-on conditions, and at ranges in excess of 2000 and 3000 yards.
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ADMINISTRATIVE INFORMATION

This work was accomplished under an Interagency Agreement between the National Park Service and the Naval Surface Warfare Center, Carderock Division. The cruise ships involved were on-range as part of a separate acoustic measurement program accomplished under a Work for Private Parties Agreement.
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INTRODUCTION

Collisions between whales and large ocean-going ships are a conservation and management issue in many parts of the world (Kraus et al. 2005, Panigada et al. 2006). Scientists have wondered why baleen whales sometimes fail to avoid ships, given that ships produce underwater sound at frequencies and source levels that should be readily detectable by whales (Terhune and Verboom 1999, Nowacek et al. 2004). More than 200 cruise ship entries occur per year in Glacier Bay National Park. These ships carry visitors numbering in the hundreds of thousands into the Park each summer, which is also the prime season for humpback whale (*Megaptera novaeangliae*) activity in Glacier Bay and surrounding waters (Webb and Gende, 2015). Glacier Bay National Park initiated the present study in an effort to understand the physical acoustics of cruise ship and humpback whale encounters with the goal of preventing collisions between cruise ships and humpback whales.

Despite the fact that whales are usually successful at avoiding ships, whale-ship collisions occur worldwide, involving many species and many types of vessels. Humpback whales are the second most common species of whale to be lethally struck (Laist et al. 2001, Jensen and Silber 2003). Cruise ships accounted for 12.7% of 134 fatal whale strikes worldwide from 1930-2002 in which the type of vessel was known, although there are acknowledged biases and limitations to the data (Jensen and Silber 2003). In Southeast Alaska, the 89 definite whale strike records from 1978-2011 indicate that cruise ships accounted for 7% of all vessel strikes, but cruise ships and other large vessels were involved in the 25 known mortalities. Whales are at the highest risk of collision near the sea surface, due to proximity to vessels.

The acoustic environment near the ship and the whales’ auditory perception are likely two important factors in the occurrence of collisions. Understanding of baleen whale auditory capabilities, including sound localization, is poor, due to the practical difficulties in obtaining direct measurements from large free-ranging whales. Anatomical evidence suggests that baleen whale hearing is tuned for frequencies below 10 kHz (Ketten 2000, Southall et al. 2008) and characteristics of whale vocalizations suggest that humpback whales can hear in the frequency range of at least 20 Hz to 8 kHz (Richardson, et al. 1995).
Some investigators have suggested or reported that acoustic nulls (i.e., areas of drastically reduced sound levels), exist in the bow aspect sound fields of large vessels, and that such nulls might preclude marine mammals from detecting the approach of an oncoming vessel until it is too late to react (Terhune and Verboom 1999, Allen et al 2012). It has been postulated that these “acoustic shadows” may be due to a ship’s hull acting as an acoustic baffle between predominant stern area sound sources and areas forward of a ship’s bow, especially for ships where the propellers are located above the ship’s keel (Gerstein 2002). Others have observed omnidirectional behavior at low frequencies, yet slightly lower bow and stern aspect sound levels relative to beam aspect levels at mid-frequencies; the former due to the presence of the hull, and the latter due to acoustic absorption by bubbles in the wake of the ship (Arveson and Vendittis, 2000).

Given the background of the collision problem and the limited knowledge of the actual acoustic field near the sea surface in the area ahead of a cruise ship, the goal of this study was to empirically observe underwater sound levels at a point ahead of the bow of an oncoming cruise ship in an attempt to replicate the auditory experience of a whale near the surface and ahead of the ship. In cooperation with two cruise ships that volunteered to participate in this study, underwater sound pressures were measured by hydrophones located at three depths: 5, 10, and 15 feet below the sea surface. These data were examined to determine how measured sound levels changed as a function of time and bearing angle to the vessel. Since this study focuses on the near-surface sound fields of large ships, it adds significantly to current knowledge of the physical acoustics pertaining to encounters between whales and large ocean-going vessels. The results have the potential to inform as to which whale strike preventative measures are likely to be effective. They also should help to focus the discussion of, and future research into, the bioacoustics involved in these encounters.
ACOUSTIC MEASUREMENT APPROACH

These acoustic measurements were conducted in August 2004 at the U.S. Navy’s Southeast Alaska Acoustic Measurement Facility (SEAFAC) in Behm Canal near Ketchikan, Alaska, Figure 1, with cooperating cruise ships on two separate occasions. Water depth at this site is generally in excess of 1000 feet and the sound velocity profile in August consists of a layer of decreasing sound velocity, 4880 to 4830 feet/second, in the first 150 feet with a relatively constant velocity of 4840 feet/second below 150 feet.

Both ships navigated a GPS-defined, straight-line course and performed one pass-by test each at speeds of 10 and 20 knots. The acoustic measurements were accomplished using three shallow depth hydrophones that were deployed from a small unmanned, unanchored pontoon boat. A powered boat positioned, and then set adrift, the pontoon boat 100 yards to the side of the projected cruise ship course-line. The powered boat that positioned the pontoon boat then departed the area and went quiet before the acoustic test began. Figure 2 shows a typical pass-by measurement scenario with the pontoon boat adjacent to the cruise ship as it passed. Due to wind, current, and the fact that the pontoon boat was adrift, the pontoon boat location relative to the cruise ship course-line varied from test to test. As shown in Table 1, CPA (closest point of approach) ranges between the cruise ship and the measurement platform ranged from 35 to 336 yards. This geometry resulted in minimum bow aspect measurement angles of 5.5° or less, with 0° representing the measurement system directly in the path of the cruise ship. Hence, sound pressures were measured at small angles relative to the bow of the ship and the aim of replicating locations experienced by a whale nearly in the path of an oncoming vessel was achieved.

Table 1 – Cruise Ship Test Conditions

<table>
<thead>
<tr>
<th>Vessel</th>
<th>Speed (knots)</th>
<th>Shaft RPM</th>
<th>CPA to hydrophone (yards)</th>
<th>Range of angles measured (degrees)</th>
<th>Ship generator lineup</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>10</td>
<td>70</td>
<td>105</td>
<td>2.7 – 175.3</td>
<td>2 diesels</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>130</td>
<td>35</td>
<td>0.6 - 179.0</td>
<td>2 diesels, 1 gas turbine</td>
</tr>
<tr>
<td>B</td>
<td>10</td>
<td>70</td>
<td>153</td>
<td>3.8 – 171.7</td>
<td>3 diesels</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>112</td>
<td>336</td>
<td>5.5 - 172.0</td>
<td>4 diesels</td>
</tr>
</tbody>
</table>

0° = true bow, 90° = beam of ship presented to hydrophones, 180° = true stern
Angles are as measured to bow and stern of ship from the measurement hydrophones.
The range of angles and distances to the ship for each test are plotted versus time from CPA in Figures 3 and 4. Figure 3 shows that bow aspect measurements commenced at distances in excess of 2200 yards at 10 knots and 3500 yards at 20 knots to achieve the desired small bow aspect angles. Figure 4 shows that bearing angles between the measurement hydrophones and the ship changed rapidly near CPA, as would be expected for the close CPA ranges involved. Figures 5 and 6 show to-scale representations of the measurement angles and distances to aid in visualizing the measurement geometry. The ship size, in red, in these figures is also shown to-scale. Like Figure 4, these to-scale representations show that nearly bow-on measurement angles were achieved during the acoustic tests.

The arrangement of the shallow hydrophones that were deployed from the unmanned pontoon boat is shown in Figure 7. Three omnidirectional ITC-8201 hydrophones were deployed in a vertical string at depths of 5, 10, and 15 feet. The hydrophones and data acquisition system were calibrated over a frequency range from 10 Hz to 80 kHz. Sound pressure time series data from the hydrophones were recorded on a multi-channel digital recorder. All instrumentation was battery powered. During post-test data reduction, one one-third octave sound pressure spectrum was generated per second by a one-third octave analyzer from the start to finish of each test so that a time history of one-third octave sound pressure levels during the ship pass-by could be constructed.

The vessels that participated in this study were representative of many of the cruise ships that cruise Southeast Alaska. Both vessels were equipped with two inboard electric propulsion motors, diesel or diesel and gas turbine generators, and two propellers. Neither ship had podded propulsors. The radiated sound spectra of these ships were also typical of similarly equipped cruise ships in that the significant contributors to the sound pressure levels were acoustic energy from diesel generators, electric propulsion components, and propeller cavitation (Kipple, 2002). General specifications for each vessel are listed in Table 2.
Table 2 – Cruise Ship Specifications

<table>
<thead>
<tr>
<th>Vessel</th>
<th>Length (feet)</th>
<th>Tonnage</th>
<th>Draft (feet)</th>
<th>Propulsion type</th>
<th>Propeller type</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>963</td>
<td>91,600</td>
<td>27</td>
<td>Diesel/gas turbine electric</td>
<td>Constant pitch</td>
</tr>
<tr>
<td>B</td>
<td>777</td>
<td>60,900</td>
<td>26</td>
<td>Diesel electric</td>
<td>Controllable pitch</td>
</tr>
</tbody>
</table>

BACKGROUND INFORMATION

When assessing the significance of underwater sound levels, it is important to recognize that in-water sound levels are measured on a different scale than in-air levels, and that they represent different sound intensities than in-air sound levels. This difference means that the sound intensity of a 100 dB (relative to 20 micro Pascals) sound in air is not equal to that of a 100 dB (relative to 1 micro Pascal) sound in water. In part, this effect is due to the use of different reference pressures in airborne acoustics versus underwater acoustics. The difference in acoustic properties between air and water is also a factor. For this reason, the reader must resist the temptation to interpret underwater sound levels based on more familiar in-air decibel levels without accounting for the difference between the two scales.

In the absence of man-made underwater sound, the underwater ambient noise environment is usually dominated by wind-related, sea surface-generated sound. This sound source has been studied extensively and has long been recognized as a primary source of undersea ambient noise. The noise itself is due to wind agitation of the water surface and the resulting wave, turbulence, droplet, and bubble activity. Deep ocean wind-related underwater sound levels and their spectral dependence on sea state or wind speed have been established by a number of investigators. The widely recognized Knudsen wind noise spectra (Knudsen, 1948) show that wind-related noise levels increase by more than 20 dB when sea states progress from calm conditions to those associated with wind speeds near 30 knots.

Most of the underwater sound from cruise ships is typically attributable to generator engines, machinery, propulsion system components, and propellers. Because each class of vessel is equipped with different types of machinery, propulsion equipment, and propellers, the
narrowband and broadband sounds produced by each vessel class are characteristic of that class. Vessels of drastically different size are also acoustically distinguishable for similar reasons. The majority of the underwater sound energy from small craft with high-speed engines and high-speed propellers is concentrated at higher frequencies. On the other hand, large vessels typically produce substantial low frequency sound energy because of their size and large, slow speed engines and propellers. All vessels equipped with propellers have the ability to produce propeller cavitation noise. An additional important aspect of vessel underwater sound is that sound levels are typically speed dependent with levels generally, but not always\(^1\), increasing with increasing ship speeds.

RESULTS AND DISCUSSION

The cruise ship radiated sound pressure spectra that were measured by the shallow hydrophones are shown in one-third octave form in Figure 8 to illustrate the general spectral distribution of the radiated sound energy from each ship. These results show that, in general, the highest radiated sound levels occurred between 50 and 2000 Hz. They also show spectral character similar to previously measured cruise ship sound signatures (Kipple 2002) with peaks due to narrowband diesel-electric propulsion sources and broader energy distributions attributable to broadband propulsion-related noise. Each curve in Figure 8 represents an average of the levels measured at the three hydrophones (data from the 5, 10, and 15-ft hydrophones were averaged) and the levels are as-measured at the face of the hydrophone (i.e., they are not range corrected to account for spreading loss). The sound pressure spectra in Figure 8 were obtained by integrating the levels measured from just before acoustic CPA\(^2\) to just after acoustic CPA. The start and stop times for the integration were defined by the half-power (3 dB down) levels just prior to, and after, acoustic CPA. Integration times ranged from 16 to 21 seconds.

\(^1\) Cruise ship acoustic testing has demonstrated that ships with electric propulsion systems sometimes exhibit unusual speed dependence patterns that are attributable to non-linear behavior of their frequency converters.

\(^2\) The acoustic CPA is defined by the point in time where the highest acoustic levels are measured as the vessel passes by the hydrophones, see Figures 10 through 13.
No substantial depth dependence was observed between the 5, 10, and 15-ft hydrophone levels, as the variance between the 5, 10, and 15-ft hydrophone one-third octave band levels was generally less than 3 dB. A representative comparison of the 5, 10, and 15-ft one-third octave sound pressure spectra is shown in Figure 9. These curves were derived using the same integration process described above for Figure 8.

Cruise ship underwater sound levels for each pass-by test were plotted as a function of time in Figures 10 through 13 to assess the change in sound levels experienced by a hypothetical whale near the surface and ahead of the cruise ship, and to determine if a significant acoustic null existed ahead of the ship. The plotted acoustic levels represent a sum of all of the acoustic energy in the 50 to 2000 Hz frequency range. This range was chosen for two reasons: (1) because it generally corresponds to frequency ranges cited by various investigators that studied humpback whale reactions to sounds (Richardson, et. al. 1995), and (2) as stated above, this frequency range captures the highest level bands in the cruise ship one-third octave sound spectra shown in Figure 8\(^1\).

During the data reduction and analysis process, plots of the type shown in Figures 10 through 13 were also generated for band sums of the full measured spectrum, band sums of frequency ranges wider than 50 to 2000 Hz, and for select one-third octave bands that corresponded to significant spectral peaks in the cruise ship sound spectra. These plots showed sound level versus time patterns that were similar to those in Figures 10 through 13. The conclusion is that plots using other band sums that were not inordinately narrow, or even using peak one-third octave band levels, did not reveal significantly different outcomes with regard to the main conclusions reached here about radiated acoustic directivity patterns. This result should not be surprising since the levels of the peak one-third octave bands are typically the greatest contributors to the levels that result from band sums performed over a range of bands.

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\(^1\) Note that the one-third octave sound pressure spectra, like those shown in Figure 8, were not corrected for the well documented dipole effect (Arveson and Vendittis, 2000) that causes reduced face-of-hydrophone levels at low frequencies compared to source levels. Since this report is concerned with levels received at distance from the ship, face-of-hydrophone levels are represented in the sound spectra and in the discussion of the measured data.
For each of the plots in Figures 10 through 13, the red trace represents the time history of the 50 to 2000 Hz sound level as measured at the 5-ft hydrophone. The green trace shows the expected measured level for a hypothetical, omnidirectional acoustic point source traveling with the same track and speed as the ship and whose acoustic energy propagates according to spherical spreading laws (i.e., $20 \times \log_{10}(\text{range})$). The purpose of showing this trace is to provide a comparison to a source that has no special directivity and no unorthodox propagation properties. A dark blue trace is also included to show the bearing angle to the ship from the hydrophone over the course of the test. The scale for the bearing angle trace is on the right side of the graph, and the time scales on each plot are all 10 minutes in duration.

In general, these plots show that cruise ship sound levels build as the ship approaches, reach a maximum at a point called acoustic CPA, and then diminish as the range to the vessel opens. Bow aspect levels appear on the left side and stern aspect levels appear on the right side of the graphs. Note that the sharpness of the sound level peak depends on ship speed and CPA range. Hence the sharpest peak occurred for the Vessel A, 20-knot, 35-yard CPA test, Figure 11. The 10 and 20-knot, Vessel B sound level slopes (except for the isolated peak at CPA for the 20-knot test) in Figures 12 and 13 were fairly comparable because the long 336-yard CPA of the 20-knot test offset the effect of the higher ship speed.

These plots also show that acoustic CPA always occurred after the time corresponding to CPA of the bow of the ship (i.e., when the bearing angle was 90°). This result reflects that the portion of each ship responsible for the majority of the acoustic radiation trailed the bow by 11 to 33 seconds, as shown in Table 3, which merely indicates that most of the sound appeared to effectively emanate somewhat amidships as the ship passed by. Table 3 also lists the time required for each ship to pass by the sensors. It also lists a fraction of ship length value that was derived by dividing the time difference between bow CPA to acoustic CPA by the time for the entire ship to pass by (the ship length in seconds). This value represents the fraction of ship length that passed by the sensors before acoustic CPA occurred. For example, the position along the length of the ship that corresponded to acoustic CPA was at about 60% aft of the bow for Vessel A at 10 knots and Vessel B at 20 knots.
Table 3 – Vessel CPA Times and Time Between Bow and Acoustic CPA

<table>
<thead>
<tr>
<th>Ship</th>
<th>Speed (knots)</th>
<th>CPA range (yards)</th>
<th>Acoustic CPA time (hh:mm:ss)</th>
<th>Bow CPA time (hh:mm:ss)</th>
<th>Acoustic CPA to bow CPA time difference (sec)</th>
<th>Ship length (sec)</th>
<th>Fraction of ship length **</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>10</td>
<td>105</td>
<td>2:26:33</td>
<td>2:26:00</td>
<td>33</td>
<td>56.6</td>
<td>0.6 = 33/56.6</td>
</tr>
<tr>
<td>A</td>
<td>20</td>
<td>35</td>
<td>0:33:01</td>
<td>0:32:50</td>
<td>11</td>
<td>28.3</td>
<td>0.4 = 11/283</td>
</tr>
<tr>
<td>B</td>
<td>10</td>
<td>153</td>
<td>7:58:04</td>
<td>7:57:51</td>
<td>13</td>
<td>45.7</td>
<td>0.3 = 13/45.7</td>
</tr>
<tr>
<td>B</td>
<td>20</td>
<td>336</td>
<td>6:58:55</td>
<td>6:58:41</td>
<td>14</td>
<td>22.9</td>
<td>0.6 = 14/21.9</td>
</tr>
</tbody>
</table>

*Acoustic CPA time - bow CPA time

**(Acoustic CPA time - bow CPA time)/time for entire ship length to pass by in seconds (i.e., the fraction or amount of ship length that passed by the sensors before acoustic CPA occurred).

The fraction of ship length values ranged from 0.3 to 0.6. Some variability in these values is expected given that the point on each ship that appeared to radiate most of the acoustic energy probably varied from ship to ship, and varied based on ship speed. For example, at higher speeds one would expect this point to occur further aft since propeller related noise increases with speed and becomes more dominant compared to shipboard machinery noise. Note that this study was not intended to identify the acoustic radiation points of each vessel, and so the fraction of ship length values reported here should not be over emphasized. The main point is that the acoustic CPA occurred somewhat after bow CPA, as expected, but it never appeared to occur at the very stern of the vessels, as might be expected if one were to assume that the majority of vessel noise emanated directly from the propellers\(^1\) themselves. Note also that acoustic CPA timing based on sound amplitude alone is not a perfect method for localizing sources of radiated ship sound.

The primary purpose of the plots in Figures 10 through 13 was to quantify the acoustic energy that existed ahead of the approaching cruise ship. As such, they also provided a means of determining whether an acoustic null existed ahead of the ship. The plots showed that measurable acoustic energy from the cruise ships was in fact present well before the arrival of the ship at CPA. Even the lowest measured levels at the start of the tests (with the ship still 2200 to 3500 yards away) were 95 dB (re 1 microPa, 50-2000 Hz band level) or more, and were 10 dB or more above the ambient background noise level at the start of the test. Given that knowledge

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\(^1\) Certainly propeller cavitation noise originates at, and radiates from, a ship’s propellers. But other sources of acoustic noise (e.g., diesel generators and propulsion motors), exist and are located further forward.
of humpback whale hearing thresholds is incomplete and at least not widely agreed upon, it is not known whether the bow aspect sound levels would be sufficient for detection and localization of the ship on the part of a whale. Nevertheless, it is clear that measurable energy existed ahead of the cruise ship at small angles representative of bow-on conditions and at ranges in excess of 2000 and 3000 yards.

The plots in Figures 10 through 13 can also be examined for presence of any sort of acoustic null ahead of the ship. Presumably such a null would appear as unusually low levels at bow aspect angles compared to stern angles such that the pattern of rising and falling acoustic levels before and after CPA would appear asymmetric (i.e., favoring higher levels after CPA compared to before CPA). Visual comparison of the shapes of the measured sound level curves in Figures 10 through 13 show no indication of unusually low bow aspect levels relative to stern levels, nor any notable asymmetry (other measurement geometries, such as ship passing directly overhead of deeper hydrophones, might result in more significant bow or stern directivity).

A second series of plots was created to facilitate this type of before and after CPA comparison and to assess symmetry about the acoustic CPA point. In Figures 14 through 17 the sound level traces from Figures 10 through 13 were split into their before and after CPA segments and were then overlaid and plotted versus time relative to acoustic CPA time. In these plots the blue traces represent data prior to CPA and the red traces show levels after CPA. As in Figures 10 through 13, a green trace representing an omnidirectional source with spherical spreading is included for further comparison.

Comparison of the before and after CPA traces in these figures showed no substantial asymmetry between the before and after CPA trace pairs. For the most part these traces overlaid fairly closely and, if anything, the before CPA levels trended higher by 2 to 5 dB\(^1\) than the after

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\(^1\) At present the authors have no positive physical explanation for the slightly higher bow aspect levels in the two 20-knot tests, although the Vessel B 20-knot levels were probably controlled by the 80 Hz peak shown in Figure 8, and energy in this frequency region, if related to the electric propulsion system, would not necessarily be expected to be stern directive. Also, other investigators have cited the effect of wake bubbles in stern aspect sound absorption (Arveson and Vendittis, 2002) and presumably wake bubble presence would be greater at 20 knots.
CPA levels for portions of two of the tests – Vessel A at 20 knots, Figure 15 and Vessel B at 20 knots, Figure 17. These comparisons showed no evidence of an acoustic null ahead of the cruise ships, nor of any kind of notable directivity. If the hull of the ship acted as a significant acoustic baffle between the cruise ship’s acoustic sources and the shallow hydrophones located ahead of the ship, then levels at a point in the bow aspect portion of the plot should be substantially lower than those in the corresponding stern aspect portion of the plot. Figures 14 through 17 compare the bow and stern aspect portions of the sound level time histories directly, and bow aspect levels (i.e., those prior to acoustic CPA) were not lower than their corresponding stern aspect levels. These data show that, at least in Southeast Alaska in relatively deep water, there was no evidence of an acoustic shadow relative to an observer located near the surface of the water and near the path of each of the two large cruise ships tested here.

Further examination of the sound level traces in Figures 10 through 13 reveals that some of the traces were smoother than others in that they exhibited less short-term variation in level over the course of the test. In particular, the sound level time history for Vessel A at 20 knots in Figure 11 was noticeably smoother than the one for Vessel B at 10 knots, Figure 12. The peaks or spikes in plots like Figure 12 that cause the trace to appear variable over short time intervals (i.e., several peaks in the course of one minute) are indicative of constructive and destructive interference affecting measured levels due to multi-path propagation of dominant narrowband cruise ship sound components. Such narrowband components were particularly evident in the sound spectra of both vessels at 10 knots, but especially so in the case of Vessel B. They were responsible for the peaks at 50 and 100 Hz in Vessel B’s 10-knot sound spectrum in Figure 8. The sound spectra for both vessels contained significant electric propulsion tones at 10 knots.

1 An acoustic shadow could exist very near to the bow of a ship in a region so close to the approaching ship that one could not practically locate an off-ship hydrophone here. In fact, naval ship designers intentionally locate sonar sensors in the relatively quiet bow area of ships to isolate these sensors from own-ship noise. The designers take measures to quiet the bow area, including placement of an acoustic baffle behind the sonar sensors. Since sonar sensor performance is an important element of ship design, the acoustics of this arrangement have been studied. It is known that the shadow effect and forward extent of the zone are small when the size (width) of the baffle is small relative to the acoustic wavelength of interest (Loeser, 1999). Cruise ships have no intentionally placed acoustic baffle in the bow area of the ship, however the hull and various tanks could act as a baffle to some unknown (but probably small relative to a Navy ship) degree. This very near bow acoustic effect is not germane to the main thrust of this study.
The green traces in Figures 10 through 17 that represent a hypothetical omnidirectional source with spherical spreading compare remarkably closely to the measured sound level time histories. This agreement is another indication that nothing special in terms of source directivity and acoustic propagation was observed in the measured levels.

CONCLUSIONS

The near-surface underwater sound levels that were measured for two cruise ships over a full range of aspect angles from near-true bow aspect to stern aspect showed no significant bow aspect directivity indicative of an area of low acoustic energy, relative to corresponding stern aspect angles, ahead of the approaching cruise ships. Examination of the measured sound level time history plots about acoustic CPA showed that the bow and stern aspect sound levels and their rise and fall patterns were symmetrical with respect to angle from acoustic CPA. Also, comparison of these patterns with a hypothetical omnidirectional, spherically spreading, acoustic point source traveling the same path and speed of each ship showed little significant difference between the measured and hypothetical curves. Both of these results demonstrate that the measured cruise ship levels showed no special bow directivity patterns and no acoustic shadow ahead of the approaching ships, as one might expect if the ship’s hull were acting as an effective acoustic baffle between shipboard or propeller-centric acoustic sources, and the bow area forward of the ship.

However, the data do show that the bow of each cruise ship always “arrived” (or CPA’d) ahead of the acoustic CPA of the ship by 11 to 33 seconds. This result demonstrates that the primary source of acoustic energy on the ship was somewhat aft of the ship’s bow, which was not surprising. That said, from the perspective of a marine mammal located ahead of the ship, one must be careful not to read too much into this result, since in real-time the observer ahead of the ship only knows that sound levels are increasing. Only with the benefit of hindsight is it known that the peak sound level occurred after the CPA of the bow of the ship.
Also, as one would expect, the data show that sound levels ahead of the ship, while significantly higher than ambient background levels, were 20 dB or more below the peak levels at acoustic CPA. This result, along with the results from the aforementioned hypothetical point source, merely demonstrates that spherical spreading essentially accounted for the reduced sound levels ahead and astern of the ship (i.e., no special bow preferential sound reductions were observed ahead of the ship). Perhaps then, collisions sometimes occur due to the simple reason that a whale ahead of an approaching ship has limited time to detect, localize, and act correctly to avoid a ship, rather than the presence of an acoustic shadow ahead of an approaching vessel that would prevent the whale from detecting the vessel at all.

In summary, for the two ships tested, the two test speeds, the test measurement geometries, and the acoustic conditions of inland Southeast Alaska waters in summer, no area of significantly reduced bow area acoustic energy was observed other than what one would expect for normal spherical acoustic spreading. Given the authors’ experience with underwater sound measurements of numerous other Southeast Alaska cruise ships, the results reported here are expected to be representative of other large cruise ships. It is possible that the physical acoustic effects presented by other scenarios (e.g., substantially different water depths, sound velocity profiles, and vessel or propulsion types) could lead to results that differ from this investigation, but full exploration of a wide range of possible vessel-whale encounter scenarios is beyond the scope of this report.
REFERENCES


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