Observations of potential acoustic cues that attract sperm whales to longline fishing in the Gulf of Alaska

Aaron Thode[a)]
Marine Physical Laboratory, Scripps Institution of Oceanography, San Diego, California 92093-0205

Janice Straley
University of Alaska Southeast, Sitka, Alaska 99835

Christopher O. Tiemann
Applied Research Laboratories, University of Texas at Austin, P.O. Box 8029, Austin, Texas 78713-8029

Kendall Folkert
P.O. Box 6497, Sitka, Alaska 99835

Victoria O'Connell
Alaska Department of Fish and Game, Sitka, Alaska 99835

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Sperm whales (*Physeter macrocephalus*) have learned to remove fish from demersal longline gear deployments off the eastern Gulf of Alaska, and are often observed to arrive at a site after a haul begins, suggesting a response to potential acoustic cues like fishing-gear strum, hydraulic winch tones, and propeller cavitation. Passive acoustic recorders attached to anchorlines have permitted continuous monitoring of the ambient noise environment before and during fishing hauls. Timing and tracking analyses of sperm whale acoustic activity during three encounters indicate that cavitation arising from changes in ship propeller speeds is associated with interruptions in nearby sperm whale dive cycles and changes in acoustically derived positions. This conclusion has been tested by cycling a vessel engine and noting the arrival of whales by the vessel, even when the vessel is not next to fishing gear. No evidence of response from activation of ship hydraulics or fishing gear strum has been found to date. © *2007 Acoustical Society of America.* [DOI: 10.1121/1.2749450]

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I. INTRODUCTION

Sperm whales (*Physeter macrocephalus*) are distributed throughout the world's oceans and are considered an endangered species in U.S. waters.[1–6] The current population in the North Pacific is unknown, although acoustic recordings from bottom-mounted recorders suggest a year-round presence.[7] While females and immature individuals are known to reside at low latitudes,[6] adult males are known to travel and forage at higher latitudes in both hemispheres.[6,8–12] The diet of these deep-diving animals primarily consists of various species of cephalopods, based on an analysis of stomach contents.[6,13–19] However, in certain regions fish seem to comprise part of the diet as well,[4,6,15,18,20] including the eastern Gulf of Alaska,[19] but it is unknown what fraction of this population's diet consists of fish.

The sperm whale is the largest marine mammal known to depredate on human fishing activities. While the vast majority of reports of cetacean depredation involves killer whales, pilot whales, and other smaller odontocete species,[21–24] depredation activities by sperm whales have received increasing coverage in scientific literature.[21–23,25–29] This species has been associated with fishing operations, particularly demersal longline operations, in a number of locations around the globe,[6,21,25–27] including Norway, Greenland, eastern Canada (Labrador and Newfoundland), Chile, and the Falkland Islands. Although quantitative data are not available, anecdotal accounts suggest an increasing trend in sperm whale depredation.

In the eastern Gulf of Alaska (GOA) an active longline fishery for sablefish *Anoplopoma fimbria* (also called blackcod and butterfish) continuously occurs from late February through mid-November. Sablefish occur on the continental slope and most commercial longliners fish for this species in water depths between 400 and 1000 m. The continental shelf off the Kruzof and Baranof islands is very narrow; consequently, these sablefish grounds are relatively close to shore, within 12 to 20 miles (Fig. 1). In the GOA, depredation of longline gear set for sablefish by sperm whales has been occurring since at least 1978 in the domestic U.S. fishery, and observers on Japanese longline vessels in the Gulf of Alaska reported depredation occurring in the mid 1970s. This fishery occurred year-round until the early 1980s, when fleet expansion resulted in a shortened season. By 1994, the entire quota was caught in 10 days. In 1995 individual fishing quotas were implemented, reducing overall effort while maintaining an 8.5-month open season. This extended season apparently provided more opportunities for sperm whales to depredate longline gear, and by 1997 reports of depredation had increased substantially. A domestic sablefish survey in

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[a)] Electronic mail:athode@mpl.ucsd.edu

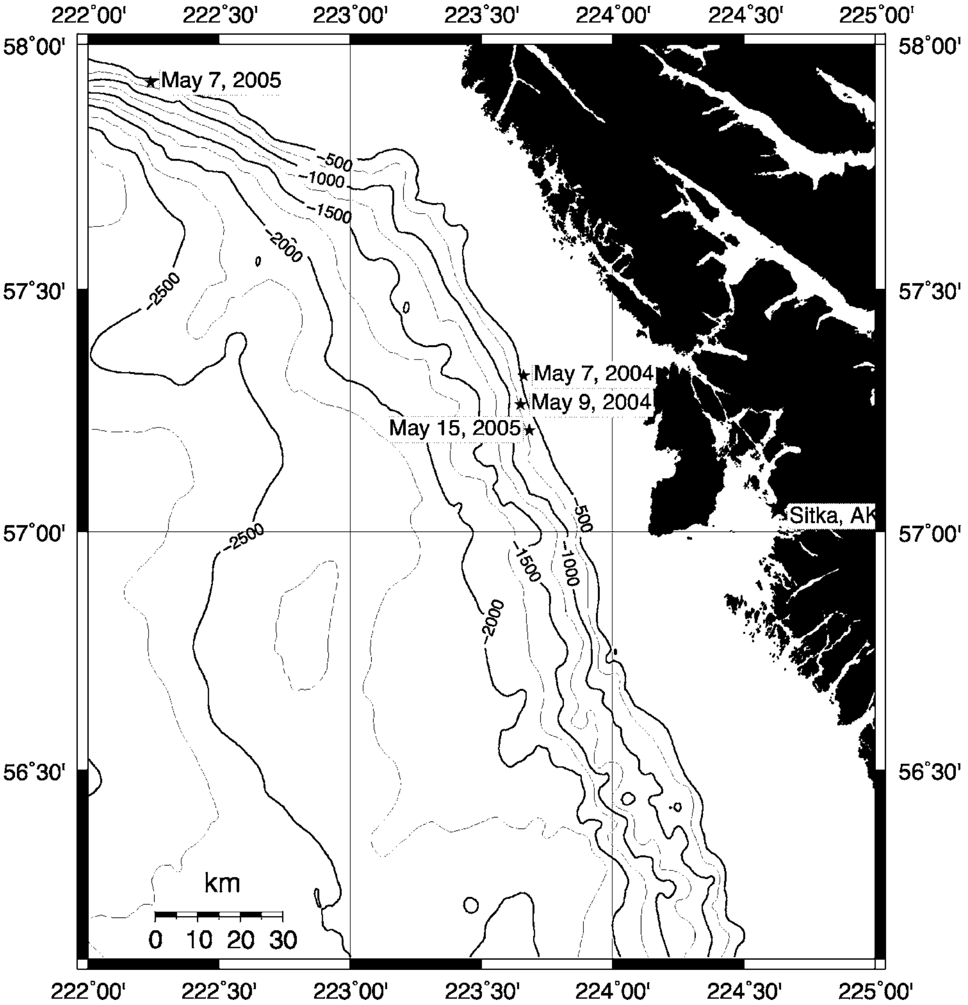

FIG. 1. Locations of four experimental sites discussed in the paper. All sites are along the continental slope off Sitka, AK. Bathymetry contours are in meters, with 250-m intervals.

the GOA looked at catch rates from 1999 to 2001 for all sets with sperm whales present; they compared boats with and without evidence of depredation and found a 5% lower catch rate in boats with depredation.[29]

While local Sitkan longliners have observed sperm whales following fishing vessels to deployment sites, they also often observe whales arriving after a haul begins, raising the question as to whether the animals are responding to distinctive visual or acoustic cues inadvertently produced by the activity. An example of a potential visual cue is the flocking of tens to hundreds of seabirds to a fishing haul site, and popular hypotheses for acoustic cues have included propeller cavitation, activation of auxiliary hydraulic systems to haul gear, echosounders, and strum noise produced by the vibration of the taut gear line as it is hauled out of the water. To our knowledge little to no acoustic monitoring has been conducted to observe or test potential acoustic cues for most marine mammal species, with the exception of Refs. 30 and 31.

While much of their foraging behavior cannot be observed directly, sperm whales are acoustically active underwater, and during a single dive one individual can make thousands of impulsive sounds called "clicks"[32–34] over a typical 45-min length dive. Measurements in other areas of the world have found that about 10–15 min before returning to the surface, an animal typically falls silent.[18,35] Thus passive acoustic monitoring of an animal's vocalizations can yield an estimate of the animal's dive cycle, even if the animal is not observed at the surface. Other statistics on the sounds' rhythm and internal characteristics can be collected as well. Furthermore, under certain circumstances these clicks generate multipath returns from the ocean surface and bottom that can be used to derive an animal's depth and range from the hydrophone, provided that the ocean depth is known. The technique has been previously used in the Gulf of Mexico to track the dive profiles of female sperm whales,[36] as well as in the Mediterranean Sea.[37] A companion paper discusses how this multipath can be used to track sperm whales off Sitka.[38]

This natural acoustic activity has provided an opportunity to observe correlations, and in some cases direct effects, of various types of potential acoustic cues on the acoustic activities of whales in the vicinity. Section II describes how demersal longline deployments can be converted into noninvasive listening posts by attaching compact autonomous passive acoustic recorders to the anchorlines of the deployment, and then discusses acoustic data analysis and tracking procedures. Section III describes the circumstances behind three independent encounters of sperm whales with instrumented longline gear sets between 2004–2005, of which two permitted some form of "controlled cue" hypothesis testing.

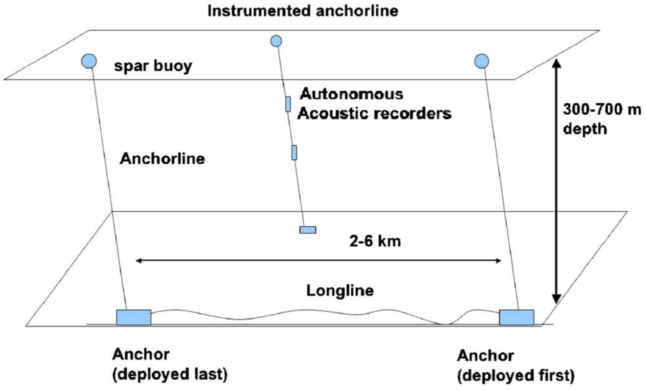

FIG. 2. (Color online) Schematic view of longline deployment, including instrumented anchorlines deployed separately from longline.

Finally, Sec. IV discusses the cumulative evidence for and against various hypothetical acoustic cues.

II. EXPERIMENTAL PROCEDURE

A. Equipment and deployment

Acoustic data presented here were collected from autonomous acoustic recorders, or "Bioacoustic probes," designed and built by Greeneridge Sciences Inc.[39] These instruments could sample acoustic data at sampling rates of 100 Hz to 20 kHz, using an HTI-96-MIN/3V hydrophone (typical sensitivity of -172 dB $re:1\ \mathrm{V}/\mu\mathrm{Pa}$) and storing the data to 1 GB of flash memory with 16-bit precision. For the data presented here, the data sampling rates varied between 8192 and 20105 Hz. The unusual sampling rates are a consequence of the low-level hardware requirements of the electronics. Additional auxiliary measurements of pressure, temperature, and acceleration on two axes were sampled once a second and also stored to memory. Four AAA batteries were found to provide sufficient energy to fill the memory. All components except for the hydrophone were inserted into a transparent acrylic pressure case with a Delrin end-plug, manufactured by Cetacean Research Technology in Seattle, WA. The resulting length and diameter of each recorder is 25 cm and 5 cm. The hydrophone is connected to the internal electronics via a Subconn underwater connector.

Figure 2 shows a schematic of a demersal longline deployment, once a vessel has left the area. The longline itself lies along the ocean bottom over a typical distance of a few nautical miles, typically at depths between 300 and 700 m. At each end of the longline a 35-kg anchor is used to fix the ends, and from each anchor an "anchorline" rises to the surface, attached to a spar buoy. To recover the line, the fishing vessel transits to the upstream buoy, and a deckhand pulls the anchorline over a set of rollers mounted on the side, wrapping the anchorline around a hydraulic winch, which then pulls the anchor and longline off the floor. As the hydraulic systems on these vessels are typically only activated just before a haul begins, the acoustic tones made by such a system have been a popular hypothesis for a potential acoustic cue. Once the anchor has been retrieved, the vessel attempts to drift with the current, while continuing to winch the longline aboard. Often the vessel captain has an auxiliary set of steering controls next to the rollers, which he/she will use to engage the engine during a haul in order to permit fine-scale control of the vessel.

During a typical instrumented deployment, two autonomous recorders are attached to a third anchorline, deployed before beginning the actual longline deployment, and recovered once the haul is complete. The instrumented anchorline is generally deployed within 1 km of the upstream anchorline, with recorder depths between 100–200-m depth, as far from the ocean surface as practical given the structural strength of the pressure cases. Given the large scope of the anchorlines, the actual deployment depths can vary considerably and must be logged from the pressure transducers. Flow noise was an initial concern, but it was found that continuous flow noise was only significant at frequencies below 50 Hz, although one significant exception will be discussed in Sec. III E. Visual observers record all major vessel and bird activities sighted from either the longlining vessel or from a small sport fishing vessel chartered for the day, and auxiliary acoustic data have been recorded from a hydrophone deployed 10–20 m beneath the bow of the fishing vessel.

B. Single-hydrophone analysis

Once acoustic data from an encounter have been transferred to hard disk in WAV format, three low-level acoustic analyses are performed on the data: sperm whale click detection, interclick interval (ICI) estimation, and source sound exposure level rate (SASELR) estimation of the fishing vessel acoustic output.

To detect sperm whale clicks the acoustic software analysis program ISHMAEL (Ref. 40) scans the record using the "energy detection" feature and activates a MATLAB script to process each detection. ISHMAEL computes the audio spectrogram, "equalizes" the spectrogram levels by subtracting a time-averaged background noise spectrum, and then integrates the squared modulus of the pressure spectrum between 100 Hz to 80% of the Nyquist frequency of a given recording.[7] Whenever this integrated value exceeds a threshold of 1.5, the MATLAB script logs the pulse time, amplitude, and duration. Upon completion of an ISHMAEL run, a second MATLAB script then consolidates the detection data into histograms of click rate. The effects of acoustic multipath were removed, to first order, by accepting only pulses that were not followed by another pulse within 0.2 s. Some acoustic multipaths can arrive later than 0.2 s after the main pulse, but the detection threshold would be set so that these weaker arrivals are generally not detected. However, some multipath arrivals are still accepted by the detector, so the click counts here may be biased toward an overcount.

Another useful parameter that could be automatically extracted from the raw acoustic data is the interclick interval, or the interval between two consecutive direct path click arrivals from the same sperm whale. The ICI is automatically estimated for each detected click by hypothesizing a range ICI values between 0.1 and 2 s, and then examining the subsequent time series to determine whether pulses are present at three predicted times after the click in question.[41] Best estimates were obtained whenever multipath arrivals were first removed from consideration, as discussed previously. The ICI can be useful in distinguishing sperm whale clicks from other random pulsive sounds.

Finally, to characterize the acoustic output of the fishing vessel, the square modulus of the sound-pressure level is integrated between frequency ranges dominated by vessel noise when sperm whale clicks were absent, which in this paper will be between 250 and 1000 Hz. The integrated levels were then averaged over 5 s to produce an estimate of what is defined here as the "average sound exposure level rate" (ASELR), with units of uPa^2. In more common terminology the ASELR is the ensemble-averaged "power spectral density level" (PSDL),[42] integrated over a given frequency bandwidth. This term ASELR is used here because this quantity is not really an acoustic intensity or power measurement, as a true measurement of acoustic intensity requires an independent measure of the acoustic particle velocity.[43] Instead, if the ASELR is multiplied by a time interval, one obtains a bandlimited quantity defined as a "sound exposure level," (SEL) or "energy flux density," which has been argued to be a biologically significant metric of the acoustic field.[44]

As the GPS position of the fishing vessel relative to the instrumented anchorline is known to within 10 m (0.1% of typical vessel range), the received ASELR can be corrected for vessel slant range to produce an estimated "source level" SEL at 1-m range, or SASELR, with units of uPa^2 @ 1 m. The SASELR permits fundamental changes in the vessel acoustic signature to be separated from simple changes in vessel translational position. In all figures that follow the SASELR will be plotted, using a spherical spreading assumption if the slant range is less than the ocean depth, and using a cylindrical spreading assumption if the slant range is greater than the water depth. For the latter case the SASELR is defined to be $2\pi RD^*$ ASELR, where R is the vessel's horizontal range from the instrument and D is the local water depth.

C. Acoustic tracking procedures

Whenever feasible, one of two types of acoustic tracking is conducted. For situations where the bottom bathymetry is well characterized out to ranges of 2 km from the recorder, the relative arrival times of the acoustic multipath can be used to estimate the 3D position of the whale over time. This analysis, which is featured in Sec. III C, is the subject of a companion paper.[38]

Unfortunately, accurate bathymetry information is often not available, so in one of the 2005 deployments to be discussed, an alternative array geometry used two instrumented anchorlines deployed 4.9 km apart, at opposite ends of a longline deployment. The autonomous recorders were activated and time-synchronized before and after the deployment, and a linear clock drift was assumed to derive the time offset at all times in between. After processing each station's data stream using the pulse detection procedure outlined above, "direct path" detections were designated whenever the arrival in question is not preceded by another detection within a time $t_{\min}$. The selected direct-path arrivals were then matched between the stations by comparing the ICI patterns at both stations, using N direct-path detections following the pulse in question, and using a time tolerance of 25 ms for matching the arrivals.[45] For instruments spaced 4.9 km apart, good values of $t_{\min}$ and N were 0.4 s and 16, respectively. The resulting relative time-of-arrival (TOA) values fix the whale position to a locus of points that form an "isodiachron,"[46] which becomes a hyperboloid surface if a homogeneous sound speed is assumed throughout the water mass. Even if the sound of the vessel cannot be recorded on both stations, given a vessel's GPS position an "effective" vessel TOA can be computed and plotted against the TOA of whale clicks, and some information about changes in the animals' position relative to the vessel can be inferred. If two recorders are deployed at the same location, but at different depths, then false matches can be eliminated by comparing whether the TOA estimates from each recorder for a given click match to within 0.5 s. This latter technique is used in Sec. III E.

III. RESULTS

A. Overview

Passive acoustic measurements of sperm whale depredation activity began in 2004, with an initial goal of observing and identifying potential acoustic cues produced by hauling longliners. Sec. III B describes near-field measurements of acoustic signatures of the engine and hydraulic systems of a fishing vessel, taken on 7 May 2004, and Sec. III C discusses the first complete acoustic observations of two sperm whales arriving in the vicinity of a longline haul on 8 May 2004.

By 2005 potential acoustic cues had been identified, and the level of coordination and cooperation between the SEASWAP fishermen and researchers had reached a level where limited hypothesis testing became feasible during opportunistic encounters at sea. Sec. III C discusses how a potential hydraulic cue was tested during an 8-h sperm whale encounter on 7 May 2005, while Sec. III D describes the results of an engine cue test conducted on 15 May 2005, utilizing two instrumented anchorlines to permit crude localization estimates. All 2004 and 2005 encounters took place close to the continental shelf break near Sitka (Fig. 1).

B. Acoustic signatures of a fishing vessel

On 7 May 2004 the 58-ft. fishing vessel KELLEY MARIE volunteered to approach an instrumented anchorline during a time when no whales were present, engage and disengage the engine, and then activate the hydraulic system that is used to power the haul winch. The engine was a 6-cylinder diesel with 250 horsepower, and the propeller had five blades. Figure 3 shows a spectrogram (of the square modulus of acoustic pressure in units of power spectral density, or dB $re:1$ uPa^2/Hz) of the propeller cavitation noise and winch hydraulic system as the vessel passed within 10-m horizontal range of a 100-m-deep hydrophone mounted on the anchorline, sampling at 15 019 Hz. At 10 s the vessel put the engine in neutral, and at 22 s the ship's hydraulics were activated, producing the tone visible at 190 Hz. The broadband cavitation signal from the ship's propeller is also clearly visible,

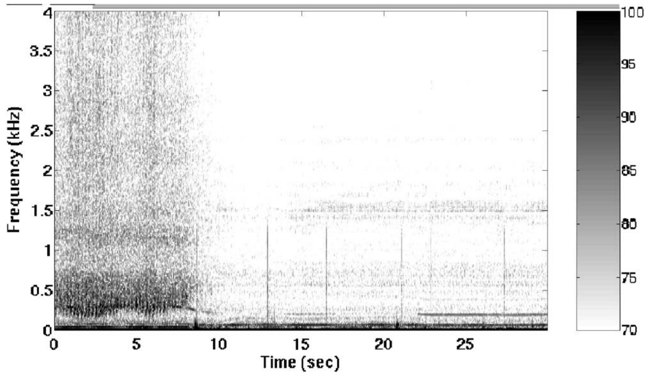

FIG. 3. Spectrogram of F/V KELLY MARIE, measured at 13:21:14, 7 May 2004, at a depth of ~100 m directly underneath the hull, using FFT size of 1024 with 25% overlap. The gray scale shows the square modulus of the acoustic pressure in units of power spectral density (dB *re*: 1 uPa^2/Hz). Cavitation noise from the propeller is visible between 0 and 10 s, and the hydraulic system to power the hauling winches has been activated at 22 s, generating the 190-Hz tone visible in the spectrogram. The thin vertical lines between 0 and 1.25 kHz are not sperm whale clicks.

with the largest spectral density levels lying between 250 and 1000 Hz, but with significant detectable levels past 4 kHz. (The vertical lines between 0–1.25 kHz are not sperm whale sounds). The measured ASELR for the engine cavitation was 110 dB *re*: 1 uPa^2 between 250 and 1000 Hz, and 95 dB *re*: 1 uPa^2 for the hydraulic system between 150 and 250 Hz, yielding effective signal-to-noise ratios of 20 and 6 dB, respectively. A predicted spherical spreading transmission loss of 44 dB yields respective SASELR values of 153 and 139 dB *re*: 1 uPa^2 @ 1 m. Interference effects from the Lloyd's mirror phenomenon have been ignored in the transmission loss computation, but simultaneous measurements by a second hydrophone at 195-m depth generates the same SASELR values to within 3 dB.

C. Acoustic measurements of sperm whales approaching a hauling vessel

The first acoustic measurements of sperm whales interacting with a hauling longliner began the morning of 9 May 2004, during a longline recovery by the F/V COBRA off a local promontory at the edge of the continental shelf. The previous day the COBRA had deployed the gear and departed to let the longline "soak" overnight. At 07:55 the next morning an instrumented anchorline was deployed in 460-m-deep water, 1.6 and 1.5 km from the two original anchorlines, with two recorders attached at 83 and 155 m depth. If one were east of the deployment looking west, one would see a similar deployment geometry as shown in Fig. 2. After slowly circling the area for an hour, the vessel retrieved the first anchorline buoy at 9:04, and by 9:16 the buoy anchor was on deck. The fish haul began immediately afterward, but sperm whales were not sighted until 10:08, when a sperm whale surfaced approximately 50 m away from the vessel, followed 3 min later by a second whale surfacing. Both animals dove around the vessel vicinity until the recovery of the second anchorline buoy at 11:00, and then proceeded to follow the vessel back toward the instrumented anchorline. The COBRA then drifted for 2 h before finally hauling the instrumented longline around 13:00.

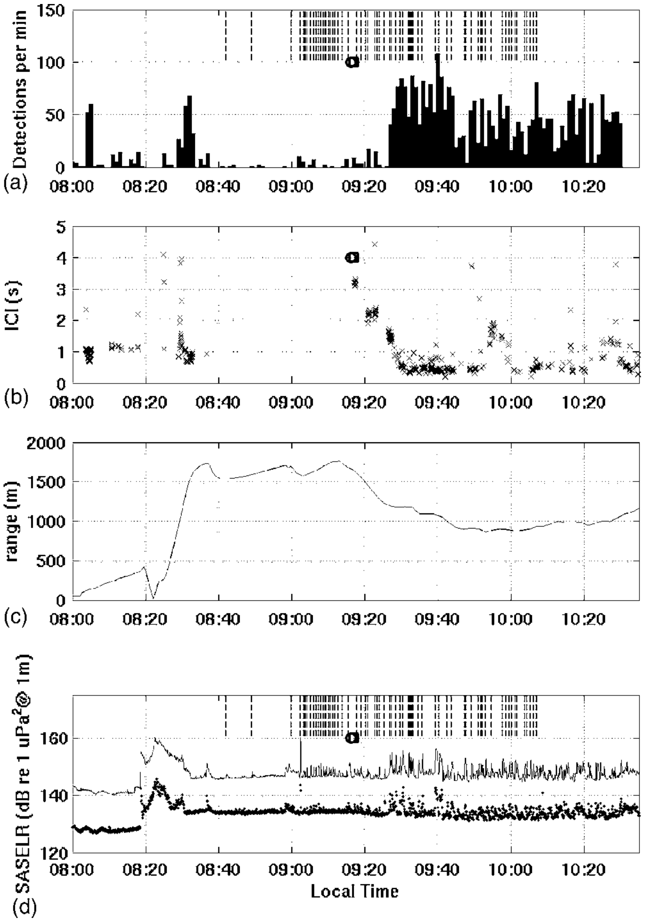

FIG. 4. Beginning of 9 May 2004, encounter, between 8:00 and 10:30 AM. (a) Histogram of pulsive sounds detected per minute. Vertical dashed lines indicate presence of acoustic signatures of an engine engaging and disengaging the propellor. The circle indicates time at which an anchor is dropped on deck (anchorline on board), and the square indicates the start of substantial sperm whale acoustic activity at 09:17:01; (b) ICI of sperm whale sounds detected on the instruments; (c) horizontal range of fishing vessel from instrumented anchorline buoy; (d) source-averaged sound exposure level rate (SASELR), in units of dB *re*: 1 uPa^2 @ 1 m, averaged over 5-s intervals, integrated between 250 and 1000 Hz (solid line) and 150 and 250 Hz (dashed line, shifted −10 dB for clarity). Received levels have been adjusted by measured vessel slant range to produce effective source levels at 1-m range.

The acoustic record of the beginning of the encounter, displayed in Fig. 4, shows substantial sperm whale acoustic activity. Subplot (a) shows a histogram of sperm whale clicks detected per minute, computed as described in Sec. II B, by integrating the squared pressure modulus between 500 and 7500 Hz (sampling frequency 15 019 Hz, 256-pt FFT, 1/16 overlap), and using a preset threshold of 1.5 in ISHMAEL.

Subplot (b) shows an estimate of the interclick interval (ICI) derived via the procedure in Sec. II B. From both the ICI and detection plots, it is clear that within minutes of the instruments' entering the water, sperm whale activity was detected in the area (8:05 AM). The sounds lasted for 2 min, had no acoustic multipath, and had a steady ICI of about 1 s. Five minutes of sperm whale clicks were also detected around 8:30, also with an ICI of about 1 s. These ICIs are typical of natural sperm whale foraging behavior found in

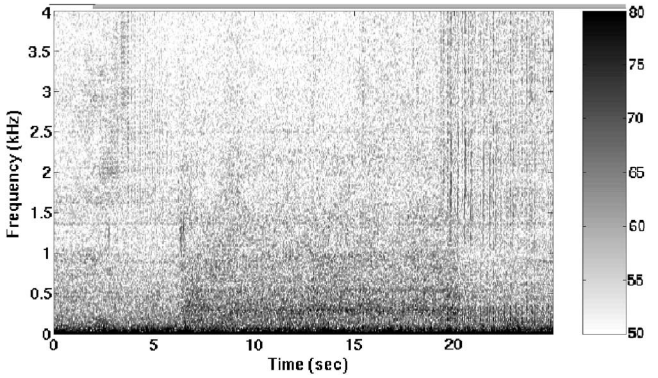

FIG. 5. Example of "engine cycling" as fishing vessel fine-tunes its position relative to the longline, during a time (9:51:03) that the vessel is closest to the acoustic recorder during the haul (900-m range). The engine is engaged at 6 s and disengaged at 20 s, generating broadband cavitation noise visible up to 4 kHz. Sperm whale clicks are visible between 1 and 4 kHz throughout the figure.

this area and at other high-latitude locations.[18,47] The lack of multipath indicates that the animals are greater than the few-kilometers range.

Subplot (c) shows the range of the vessel from the instrumented anchorline, and thus from the hydrophones' approximate position, while subplot (d) displays the estimated SASELR of the received acoustic field at 155-m depth, with the solid line representing integrated square pressure between 250 and 1000 Hz. The SASELR levels have been derived from the vessel range from the instrumented longline shown in (c), assuming a cylindrical spreading transmission loss, which seems to adequately model the propagation environment in that the final SASELR curve remains at a steady level between 9:00 and 10:20 even as the vessel range decreases from 1800 to 900 m. The dotted line represents the SASELR measured between 150 and 250 Hz, the region where a hydraulic winch tone would be expected. The exact time that the hydraulic system was switched on was not noted, but it was approximately 9:00 AM, a few minutes before the first anchorline retrieval, and the system remained on until the end of the haul. However, the SASELR over the hydraulic frequency band shows no sudden, permanent jump at this time, and a careful review of the acoustic record around 9:00 AM confirms the absence of any distinctive hydraulic signature at 1.6-km detection range.

However, an interesting feature in the SASELR appears as the vessel begins to haul the anchorline at 9:04. The 250-Hz–1-kHz curve displays a series of short-duration peaks that change the SASELR by 3–5 dB between 9:05 and 9:20. (The cycling continues after this time, but numerous sperm whale clicks contaminate the SASELR curve.) The short-term peaks beginning at 9:05 arise from a particular method of handling the vessel in order to keep the winched longline vertical. Generally a longliner tries to keep the engine in neutral and drift with the current while hauling the line. Often, however, due to snags, currents, or delays in gaffing fish, the line will begin to angle underneath the hull of the vessel. Under this circumstance the engine is briefly engaged for 5–10 s to swivel the vessel around the line, the result being a cavitation bubble cloud. Figure 5 shows an example of what a spectrogram of this signal appears like, taken at 9:51:03, or 34 min after substantial sperm whale activity has begun, and when the vessel is 900 m from the instrumented anchorline. Figures 4(a) and 4(d) use vertical dashed lines to mark discrete times when this activity occurs while hauling the anchorline.

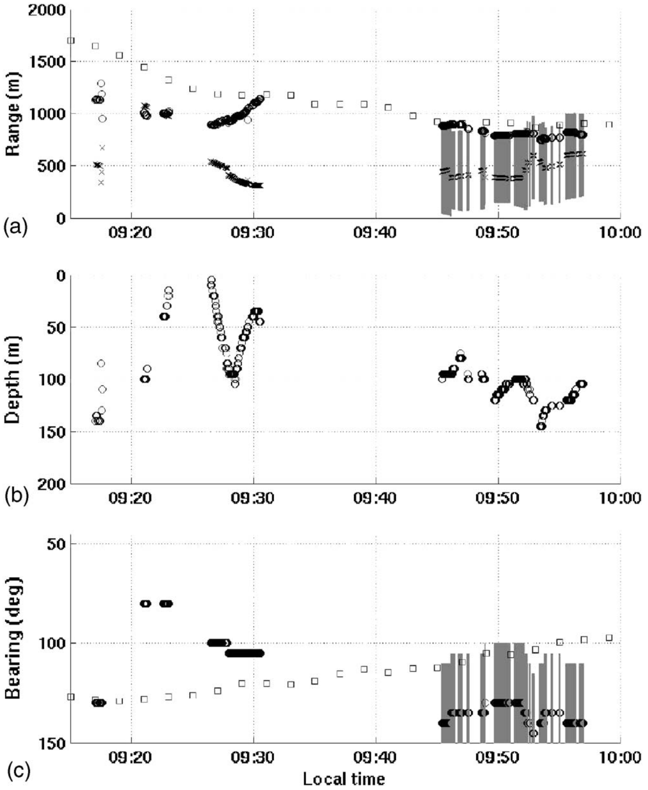

FIG. 6. (a) range; (b) depth, and (c) bearing of sperm whale clicks (circles) relative to instrumented anchorline, between 9:15 and 10:00. Bearings are with respect to true north. Subplots (a) and (c) also show the fishing vessel range and bearing (squares), respectively. Subplot (a) also displays the derived horizontal separation between sperm whale and vessel (crosses). Gray regions indicate bounds of uncertainty in whale azimuth and horizontal distance from vessel after 9:45, due to lack of bathymetry variation vs. azimuth in that region. The sperm whale clicks before 9:20 seem to be from an animal different than the one clicking after 9:20.

At 9:16:14 the anchorline has been completely recovered, and the anchor that is attached to one end of the longline has been dropped on deck, producing an audible tone detected on the recorders 1800 m away (marked by a circle in the subplots). At 9:17:01 sperm whale clicks are again detected (black square in the subplots), but the clicks display two important differences from the sounds previously detected around 8:05 and 8:30.

First, there are considerable amounts of time-separated multipath present in the signal, enough to permit tracking of an animal in range and depth. Figure 6 shows the range, depth, and bearing of the clicks derived from this multipath, relative to the hydrophones, using data analyzed in Ref 38. The range and bearing of the F/V COBRA are also displayed, as well as the derived horizontal separation between whale and vessel. The clicks detected at 9:17 seem to arise from a different whale at a different spatial location than those made after 9:20, since the best-fit bearing for the former sounds is nearly 130 deg, and the latter 80 deg. If the sounds were made by the same animal, it would have had to cover 790 m in 4 min, or 3.3 m/s (6-knot) mean speed, inconsistent with the speeds and directions derived after 9:20. However, later bearing estimates suggest that after 9:20 an animal is converging on the location of the fishing vessel, arriving about 300 m north of the vessel at 9:31, when the echolocation clicks stop for a few minutes. A second track obtained after 9:45 finds that the range of the whale and the fishing vessel lies within 50 m, but unfortunately the bathymetry profiles lying between an azimuthal arc of 100–150 deg are sufficiently similar such that the whale's azimuth can only be determined as being somewhere between the gray bars in subplots (a) and (c). Thus, while the whale may also be at the same azimuth as the vessel, the convergence of the whale and vessel positions cannot be proved.

The second difference between the clicks detected before 9:17 and those afterward is that the ICI for the latter is very high—3.4 s when the sounds begin [subplot (b) of Fig. 4]. Over the next 10 min, bouts of clicking are detected with minutes of silence in between, and the ICI steadily decreases, until at 9:26 continuous clicking starts and the ICI drops to 0.5 s or less for the rest of the encounter.

Finally, note that after 9:26 the sperm whale clicks contribute significant energy to the SASELR function in Fig. 4(d), at a level at least 3–6 dB greater than the cavitation sounds of the fishing vessel. The visual sighting of the whales by the vessel by 10:00 indicates that relative SASELR levels between vessel and whale can be justifiably compared in this manner. The fact that whales around a vessel can produce SASELR levels greater than the vessel itself has implications to be discussed in Sec. V.

D. Testing hydraulic and engine cues on a single whale around an anchorline

In 2005 potential acoustic cues began to be tested during opportunistic encounters. The first testing opportunity arose on 7 May 2005, when the F/V COBRA (the same vessel as in Sec. III C) traveled to the Spenser Spit, approximately 60 nautical miles northeast of Sitka (Fig. 1). After deploying a longline at 20:11, the COBRA moved about 1 km away to deploy an instrumented anchorline ("buoy 1") by 21:11. At 21:22 a sperm whale was sighted swimming directly toward the vessel, and within minutes was circling around the vessel at a radius of less than 50 m. The COBRA set its engines into neutral and began drifting, dropping an additional instrumented anchorline (buoy 2) at 22:10, 1.1 km from buoy 1. As night fell at 22:52 whale was observed to be swimming in circles around buoy 2, occasionally diving within 20 m of the spar buoy.

For several hours the vessel continued to drift away from the instrumented anchorlines. At 02:49 the following morning the COBRA finally engaged its engines to move toward buoy 2, and when the spar buoy was sighted in the sodium lamps, the engines were placed into neutral at 3:09. At 3:35 the whale was sighted in front of the vessel's sodium lamps, but visual contact was lost as the vessel drifted away from buoy 2 once again. The situation seemed auspicious for testing various acoustic cues, so at 4:19:25 the winch hydraulics were engaged for 3 min while leaving the engines in neutral. Finally, at 4:45:20 the propeller was re-engaged and the vessel moved back to buoy 2 to mimic a longline recovery.

Figure 7 summarizes the acoustic behavior of this lone animal throughout the night, as measured from a recorder sampling at 8.192 kHz on buoy 1. (Unfortunately, the recorder on buoy 2 failed to record.) Subplot (a) shows the number of acoustic detections per minute logged by the sensor, using a spectral integration range between 500 and 3.5 kHz.

Between 22:00 to shortly after 23:00 the time intervals of vocal activity versus silence are short and irregular. However, by 23:15 the animal had settled into a pattern of long intervals of vocal activity averaging 38 min, followed by an average of 16 min of silence. Shortly before 3:00, just after the COBRA's engines had been engaged and the vessel was moving back to buoy 2, the cycles of acoustic activity and silence become irregular once again. At 3:55 the animal seems to resume an extended cycle of acoustic activity, which is not interrupted by the activation of the vessel's hydraulic system at 4:19 (marked by black circle). From Fig. 7(c) one notes that transitions to "normal" dive cycle behavior (23:10 and 3:58) correspond to times when the vessel drifts more than 800 m away from buoy 2.

Subplot (b) quantifies this discussion by plotting the "acoustic cycles" of the sperm whale over this time period. An acoustic cycle is defined here as the time interval between acoustic gaps, where a gap in turn is defined as a period of time where the number of acoustic detections averaged over a 3-min interval is less than 30 clicks per minute (i.e., an ICI greater than 2 s). As mentioned in the Introduction, acoustic cycles are associated with the start of the dive cycle and an animal's foraging time at depth. The periods of silence correspond roughly with the animal's ascent and rest at the surface (e.g., Refs. 18, 35, and 48).

Subplot (b) also quantifies the variance in natural acoustic cycles measured from sperm whales in this area, using recordings of natural acoustic activity of sperm whales collected on 8 and 11 May 2004, and 25 April 2005, yielding measurements of 15 complete natural acoustic cycles. The median of this natural distribution is 25 min, and is plotted as a horizontal line in subplot (b), along with two dashed lines that indicate one standard deviation of 11 min above and below this median.

One sees that, after the initial encounter with the whale early in the evening, the observed acoustic cycles lie at or above the median acoustic times recorded under natural conditions until shortly after 3:00, the time at which the boat's engines have been engaged and disengaged. Once the engine has been disengaged and the vessel is within 100 m of the buoy, the animal displays five acoustic cycles of 10 min or less, before reverting to acoustic cycles consistent with both its earlier behavior and the other results from naturally foraging animals. Neither the hydraulic activation nor second engine engagement are associated with consistently short acoustic cycles.

The SASELR source level between the 250-Hz and 1-kHz band has been computed in Fig. 7(d). As the vessel's engines are disengaged most of the night, much of the acous-

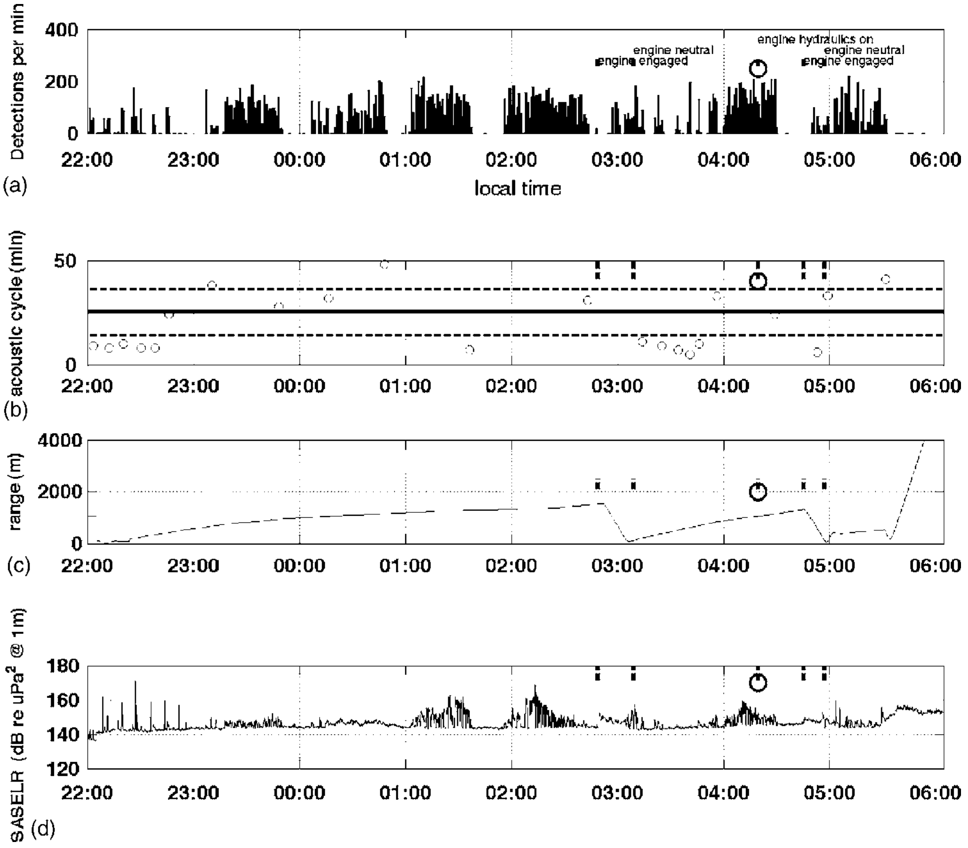

FIG. 7. 7 May 2005, overnight encounter, between 21:00 and 6:00 local time. Local time in hours and minutes is plotted on the *x* axis. (a) Histogram of pulsive sounds detected per minute. Vertical dashed lines indicate times at which boat engine was engaged and disengaged, as well as a time that the ship hydraulics were activated for 3 min, with the engine set in neutral (04:19:25). A black circle marks the time of the hydraulic system test. (b) Duration of sperm whale acoustic cycle in minutes (see the text for definition). Circles display the start time and duration of a cycle, the horizontal solid line indicates the median acoustic cycle culled from acoustic measurements of natural foraging behavior in the area, and the horizontal dashed line indicates the standard deviation of the natural acoustic cycles; (c) horizontal range of fishing vessel from instrumented anchorline buoy (buoy 2); (d) SASELR (dB *re*:1 uPa^2 @ 1 m) averaged over 5-s intervals, integrated between 250 and 1000 Hz (solid line) and 150 and 250 Hz (dashed line).

tic energy detected is actually associated with the sperm whale. However, it can be seen that at the two times when the boat engine is engaged the SASELR jumps 6 dB above the ambient noise background. As in Sec. III B, no hydraulic acoustic signal was detected at 1-km range either via the SASELR plot or visual or aural monitoring of the data.

E. Testing of engine cues on multiple whales with multiple acoustic sensors

On 15 May 2005, 8 days after the previous section, another whale encounter with the COBRA took place, providing an opportunity to test whether the vessel cavitation noise initially observed in Sec. III B is associated with changes in vocal behavior. Furthermore, two instrumented longlines were deployed simultaneously, permitting relative time-of-arrival measurements and thus providing a rudimentary acoustic tracking capability over long distances, as discussed in Sec. II C. Figure 8 shows a map of the deployment geometry off the continental shelf, in an area only a few kilometers away from the first encounter discussed in Sec. III B. At 10:50 an instrumented anchorline (buoy 1) was dropped with one recorder attached at 92-m depth, and from 11:15 to 11:55 a longline was deployed beginning from a location (anchor 1) 640 m south from buoy 1, and ending at anchor 2. The COBRA then deployed a second instrumented anchorline (buoy 2) 1.2 km east of anchor 2 at 12:40, with two recorders attached at approximately 100-and 200-m depth, respectively. Buoy 2 was thus 4.9 km NW from buoy 1. Both instrumented anchorlines had a lead weight attached beneath the recording instruments to prevent substantial inclination of the recorders, in order to permit more predictable deployment depths.

The COBRA then traveled 3 km to the NE to make a detailed bathymetry map of the area where the encounter in Sec. III B occurred, finishing by 15:30 (labeled “Survey 15:30” in Fig. 8). The vessel then traveled back to buoy 1 at 6 knots, passing within 400 m of buoy 1. At 16:08 the vessel put its engine in neutral and began to drift. Throughout the morning and afternoon no whales had been sighted, but a hydrophone dropped overboard at 16:10 detected sperm whale clicks at 16:13, and a decision was made to cycle the engine to simulate a haul, while keeping the hydraulic system off. The engine cycling began at 16:17:30 when the vessel was 1.1 km away from anchor 1 (labeled “Engine test” in Fig. 8). At 16:21:57 a sperm whale surfaced 20 m away from the vessel, and began a dive at 16:29:06. By 16:30 two whales had been sighted next to the vessel, and by 16:37 the first albatross were sighted approaching the vessel. The engine cycling continued until 16:48, when the vessel re-engaged the engines and started to move toward anchor 1, now about 1.6 km away, to begin a haul of the anchorline. Over 100 albatrosses had settled by the vessel by 17:10, marking the first large aggregation of birds encountered during the test, and thus the first time a potential visual cue was available. Once the haul began at least three distinct sperm whales had been identified.

Figures 9 and 10 display the relative time-of-arrival (TOA) measurements of sperm whale acoustic pulses between buoys 2 and 1, using the methods discussed in Sec. II C. Mapped over the data is the modeled vessel TOA, which is not derived from the acoustic record, but computed

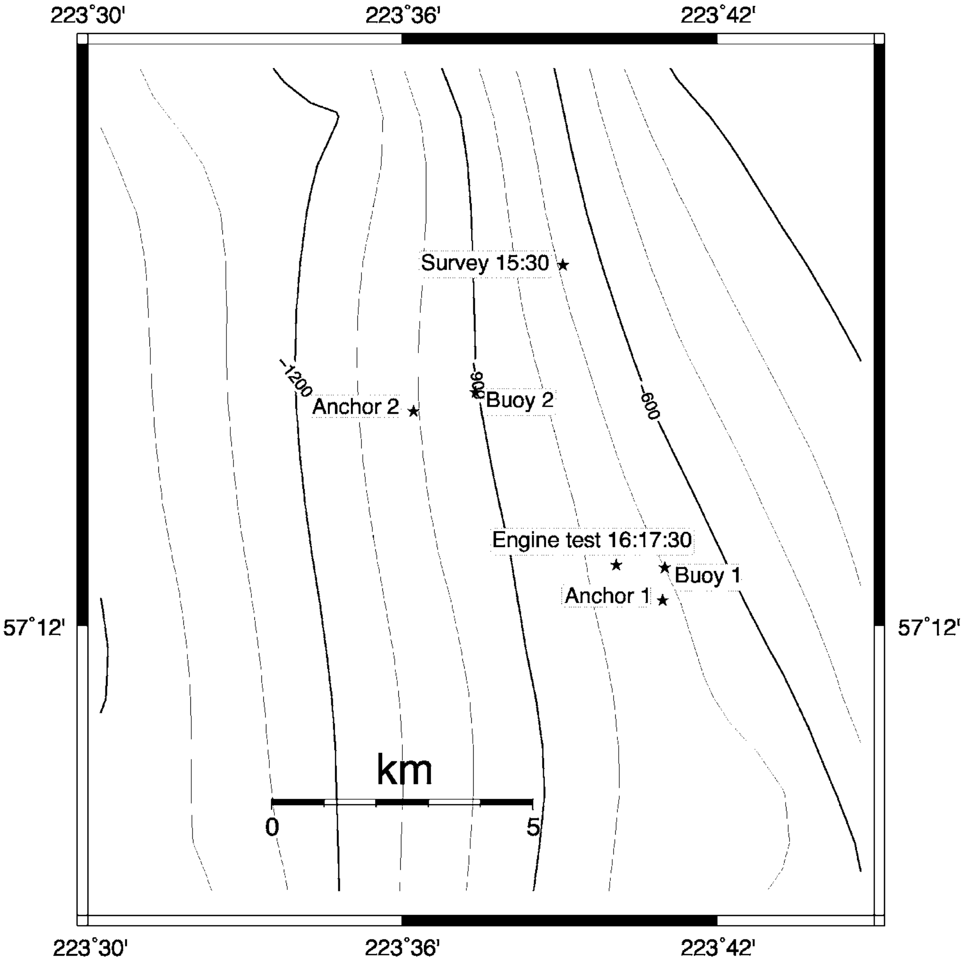

FIG. 8. Bathymetry map of region surrounding engine cycling test on 15 May 2005. A "buoy" marks an instrumented longline, and the "anchor" points mark the ends of the longline deployment. The publicly available bathymetry shown here is only accurate at 200-m depths or less due to the low spatial resolution of the data in this region.

from the COBRA's GPS log. Positive TOA values indicate that the sound source is closer in range to buoy 2, which lies north of buoy 1, and will be interpreted as a "northerly" location in Fig. 8.

While sperm whales were not visually sighted until 16:21, the raw detection data indicate that sperm whale clicks were detected on the southern buoy 1 by 11:41:26. After buoy 2 had been deployed at 12:40, consistent TOA measurements become possible and two whales are detected near buoy 1 (TOA of −2 to −3 s in Fig. 9), passing south of the buoy at 13:45, since only locations south of buoy 1 could

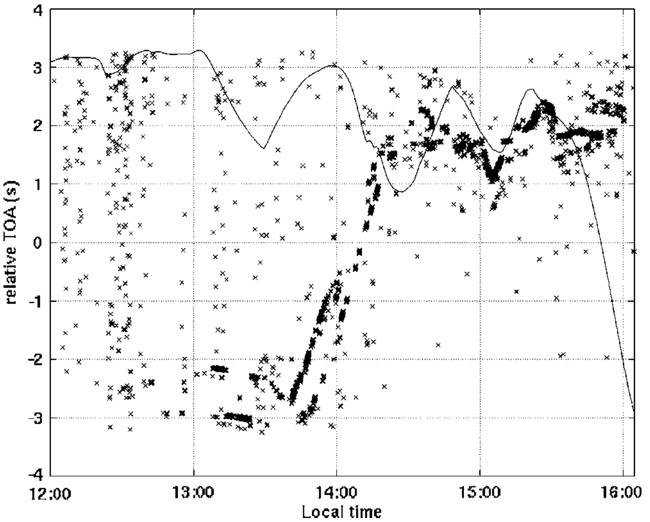

FIG. 9. Relative time-of-arrivals (TOA) of direct-path sperm whale clicks on buoy 1 relative to buoy 2. A positive TOA is defined as a signal that arrives on buoy 2 before buoy 1, i.e., a "northerly" bearing. The solid black line is the computed TOA for the fishing vessel.

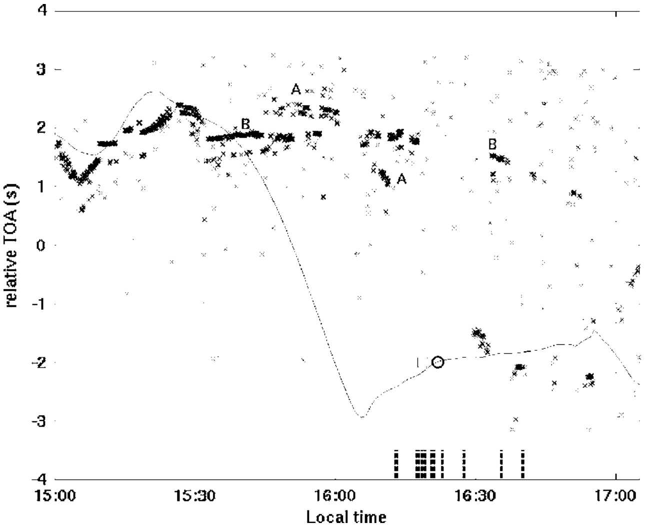

FIG. 10. Same as Fig. 9, but for times between 15:00 and 17:00. Vertical hashed lines represent deliberate cycling on the engine, with the square representing the first test, and the circle representing the first visual sighting of a whale next to the vessel. The gap in TOA activity seem between 16:00 and 16:10 is due to masking of sperm whale sounds by boat engine noise.

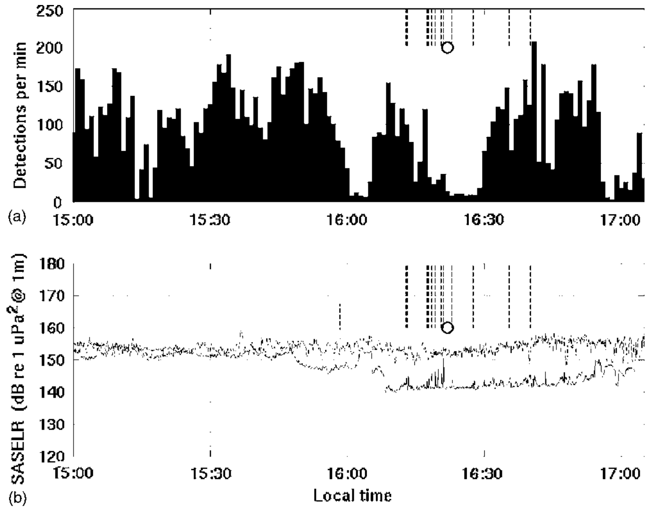

FIG. 11. 15 May 2005, test of engine cycling as an acoustic cue. (a) Sperm whale click detections per minute vs time—note the gap from 16:00 to 16:05 reflects masking of the sperm whale signals by vessel noise, not lack of acoustic activity. Dashed lines represent engine cycling events, while the black circle indicates time of first visual sighting of sperm whale 20 m from vessel; (b) SASELR corrected for vessel range, computed over the 250–1000-Hz frequency band for buoy 1 (black line) and buoy 2 (dashed line). The latter curve is substantially contaminated by acoustic "knocking" on the hydrophone.

produce TOA values of -3. The animals moved north at an estimated 2 m/s (4.7 km in 37 min) toward the vessel location, until the vessel and animal TOA merge at 14:50. From that time to 15:30, the whales' and vessel's TOA mirror each other, suggesting that the whales were either following or somehow coordinating their movements with the fishing vessel as it conducted its bathymetry survey, located at the label "Survey 15:30" in Fig. 8.

Figure 10 shows the TOA data from 15:00 through 17:00, and Fig. 11 shows a single-hydrophone analysis from buoy 1 over the same time period, viewed in terms of pulse count and COBRA SASELR. Unfortunately, there were substantial impulsive "knocking" sounds on buoy 2 that precluded automated detection analysis in Fig. 11(a), and substantially contaminates the SASELR curve for buoy 2 in Fig. 11(b).

At 15:00 the COBRA was still north of the set, traveling in a large circle mapping bathymetry, but shortly thereafter it left the area and traveled rapidly south to buoy 1. By 16:04 the vessel has passed close to buoy 1 at 6 knots, generating substantial acoustic noise, as can be seen from the SASELR plot in Fig. 11(b). Note that when the vessel was underway at full speed, its adjusted SASELR is 25 dB above background levels in the 250-Hz to 1-kHz range. The noise is sufficiently intense to mask sperm whale click detections over the time period from 16:00 to 16:05 in the pulse detection histograms in Fig. 11(a) and the TOA detections in Fig. 10. The reason that the absence of detections is known to be due to masking, and not absence of whale activity, is that sperm whale activity is still detected on buoy 2 during this time.

Once the COBRA's engine had been set to neutral by 16:08, the background noise subsided and buoy 1 detected sperm whale activity again. As the deliberate engine cycling began, all sperm whale acoustic activity ceased on both stations, as shown in Figs. 10 and 11(a). The commencement of the engine cycling can be seen as vertical lines in Fig. 10 and as 6–10-dB spikes in the SASELR curve in Figs. 11(a) and 11(b). The visual sighting of a whale next to the vessel is shown as a circle in both figures, and fluke shots confirm the presence of two individuals after this time. These whales must be different than the acoustic active whales near buoy 2 in Figs. 9 and 10, and thus four whales were in the area by this time. At the same time two additional animals were floating next to the vessel, with both animals diving at 16:29 and 16:33. The dive cycles were short—7 min or less, and the two animals' dive cycles are apparently staggered—thus, there are no clear gaps of silence in the pulse detection record.

The key observations from this encounter can be summarized as follows:

(1) Between 13:00 and 15:30 two whales traveled at least 5 km from the south and mirrored the fishing vessel's movements, bypassing the gear deployment.
(2) All sperm whale acoustic activity tapered off during the engine cycling test, as is visible in Figs. 10 and 11.
(3) Two initially nonvocalizing animals surfaced next to the vessel within 10 min of starting the engine cycling.

IV. DISCUSSION

The three encounters described above provide cumulative insight into what sperm whales do and do not respond to with regard to acoustic cues. Below we review the list of potential acoustic cues and summarize the evidence for and against each candidate.

A. Hydraulics

Before this study began, the narrow-band acoustic tones produced by the hydraulics were a popular candidate for a distinctive acoustic cue that could be exploited by whales, as the hydraulic system for the winch is typically never activated until shortly before a haul begins, and would thus be a distinctive signature. Indeed, as Fig. 3 illustrates, the signal can clearly be detected underwater when a vessel is 100 m away in calm ocean conditions.

During all of our actual acoustic encounters, however, no hydraulic signature was ever detected through either the automated SASELR computations or direct monitoring of the acoustic data from instruments as close as 1-km range, even though the flow noise levels of the instruments between 100–200 Hz were sufficiently low to presumably permit such detection. Furthermore, the activation of the hydraulic system without engaging the engine in Sec. III D prompted no apparent changes in the acoustic pulse rate or dive cycle of the lone sperm whale in the anchorline vicinity (Fig. 7). Finally, during the activity recorded in Sec. III E no hydraulic systems were activated until after 18:00, yet sperm whale positions are clearly mirroring the vessel's movements before then, and whales were visually sighted next to the vessel by 16:20. These combined observations suggest that the vessel hydraulic system is not a primary acoustic cue for attracting sperm whale attention.

B. Fishing gear strum and echosounders

Another hypothesis for an acoustic cue is that longline fishing gear would produce an acoustic signal as it "strums" while hauled under tension. Once again, direct monitoring of the acoustic record for all deployments indicates no evidence of a distinctive acoustic waterborne signature generated by fishing gear under tension. However, if the gear were producing sounds at very low frequencies, say 50 Hz or below, it is conceivable that such a signal could be buried in the flow noise recorded on the instrument. However, during at least two encounters in Secs. III D and III E, sperm whale reactions to the fishing vessel were noted even when the longline was not being hauled; indeed, the vessel was at least 1–2 km distant from the closest surface expression of the gear in both cases. Thus, acoustic strum from fishing gear seems to be an unlikely candidate for an acoustic cue for these encounters.

Similarly, echosounder signals are generally not detected in the data unless the vessel is less than 50 m from the vessel. Statistical analysis by the SEASWAP project has found no difference in encounter rate between vessels with and without echosounders. Since the frequency range of most echosounders lies in the kilohertz range, they would not be expended to propagate great distances compared to the other acoustic cues discussed here.

C. Birds and other visual cues

A large concern throughout this effort was distinguishing acoustic cues from potential visual cues such as the arrival of seabirds scavenging on the fishing haul. During a haul hundreds of birds can surround the vessel, including the northern fulmar (*Fulmarus glacialis*), the black-footed albatross (*Phoebastria nigripes*), and various species of gulls. In principle these bird flocks could be visually detected miles away. While the visual acuity of dolphins is excellent,[49] little is known about the visual capabilities of the sperm whale above water.

Fortunately, birds were not a significant confounding factor in two of the three encounters above. All the measurements in Sec. III D took place without the presence of birds as no longline was actually hauled, and most of the observations were recorded at night. Also, in Sec. III E the visual observers noted whales surfacing by the vessel at least 15 min before more than three birds had circled and settled by the COBRA. Thus, birds cannot be discounted as a potential visual cue for the animals, but in the context of these observations they were not a significant cue.

D. Cavitation noise from propeller

From the first acoustic observations conducted in 2004, it was apparent that the cavitation noise generated by changes in the propeller rotation speed produced a significant broadband acoustic signature that could be detected kilometers away. These changes occur via engaging the engine from neutral, or to a lesser extent via changes in vessel shaft speed. In all three encounters documented here, the act of engaging the propeller from a neutral state increased the SASELR by 6–10 dB between 250 to 1000 Hz and produced a detectable signal on a single hydrophone from 1 to nearly 2-km range, with a signal-to-noise ratio (SNR) of at least 6–10 dB. Even in a spherical-spreading environment, a worst-case propagation scenario, a signal with 10-dB SNR at 1 km would propagate 3 km before it merges with the measured ambient background noise spectrum. Measurements on buoy 2 from Sec. III E suggest that the cavitation signals do not propagate further than 5-km range in 600–700-m-deep water.

The act of engaging and disengaging the ship's propeller provides a distinctive acoustic cue for a longline haul, and sperm whale acoustic activity seems to alter in response to these cues. As Figs. 4(d) and 11(b) illustrate, the fact that a hauling vessel needs to engage and disengage its engine frequently makes a distinctive mark in the received acoustic data between 250 and 1 kHz. In the encounter described in Sec. III C, after an initial period of silence large amounts of sperm whale acoustic activity were detected 15 min after these signatures began, and derived acoustic tracks in Fig. 6 reveal that at least one whale was converging on the vessel location within 15 min of the start of the engine cycling activity. In Sec. III E deliberate engine cycling was associated with a complete cessation in acoustic activity from two sperm whales, and 4 min after the cycling began a third whale surfaced within 50 m of the COBRA. At this time the COBRA was over 1 km from the nearest anchorline spar buoy (anchor 1).

Section III C also suggests that engaging the engine to move the vessel from a drifting state produces an acoustic signature that is perceptually significant to sperm whales. The only observed disruptions in the animal's dive cycle that night, as inferred from the acoustic activity record, took place when the drifting vessel engaged its engines and traveled back to an instrumented anchorline. While the effect of the vessel's lights cannot be discounted, the lights should have been visible at a range of 1.5 km and thus would have been present as a constant stimulus the entire night. The TOA trajectories of the two whales before 15:30 in Sec. III E also suggest that vessel engine noise is sufficient to attract whales that are at least 5 km away.

V. CONCLUSION

Beginning with passive observation and then advancing to hypothesis testing, acoustic monitoring of depredating sperm whales off Sitka has gathered evidence that cavitation noise arising from the ship's propeller is the best candidate for a distinctive acoustic cue that causes changes in the behavior of sperm whales in the area, and hydraulic system and fishing gear signatures have at most a secondary role. In particular, the tendency of vessels to cycle their engine as they conduct a haul produces a distinctive signature that is projected to propagate 4–8 km under the conditions measured here, and this signature is associated with the interruption of sperm whale acoustic activity, the convergence of animals toward the vessel, and the surfacing of animals next to the vessel. Whales also seem to respond to situations when a vessel is transitioning from drifting to transiting.

A natural question to ask would be whether knowledge of acoustic cues could be practically applied to reduce depredation encounters with vessels. Given the well-known ability of marine mammals to habituate quickly to sounds intended to discourage depredation (e.g., Refs. 50 and 51), it would be easy to conclude that any change in fishing activity strategy to alter acoustic cues would be a temporary situation at best.

However, knowledge of acoustic cues opens up a variety of strategies, including reducing cue detection range, evaluating whether passive acoustic monitoring for sperm whales from fishing vessels is a viable avoidance measure, and faking cues to decouple the association of a cue with fishing activity. Even a set of actions that causes a delay in the response time of the animals can help reduce losses.

An animal cannot react to an acoustic cue that it does not hear, so any activity that reduces the intensity of a distinctive sound will reduce the volume of water over which an animal can detect a cue. A signal reduction of 6 dB translates into a factor of 4 reduction in intensity, or a halving of the detection radius under spherical spreading conditions, and greater reductions in less attenuating environments. Thus, reducing noise levels would potentially reduce the number of animals detecting the sound. Local fishermen have been advised not to linger in an area where gear has been deployed, and particularly not to drift in the same area as a haul, as well as to conduct "circle hauls" or other techniques that minimize the number of times engines need to be disengaged while fishing.

Figure 11(b) in Sec. III E also shows that the acoustic signature of a vessel is difficult to extract from a receiver 100–200-m depth at 5-km range, while the TOA plots in Figs. 9 and 10 demonstrate that sperm whale acoustic signals can propagate beyond that distance, a result consistent with previous observations of sperm whale detection distance during acoustic surveys.[52] There is thus a possibility that fishing vessels could acoustically monitor an area for the presence of sperm whales before deploying or retrieving gear. Practical experience in deploying cabled hydrophones indicates that, if an HTI-96 min hydrophone can be dropped to at least 20-m depth underneath an idling vessel, sperm whales can be detected to at least a couple of kilometers range in Beaufort 3 conditions. Further work would be needed to determine whether a fishing vessel could detect a sperm whale at a greater distance than a sperm whale could detect a fishing vessel.

Knowledge of acoustic cues also raises the possibility that they can be faked, thus introducing an element of risk in a whale's decision to expend time and energy investigating a cue. For example, at present if a sperm whale hears engine cycling from a fishing vessel, it is almost guaranteed to encounter a haul if it responds, which apparently more than compensates for the energy loss sustained in traveling to the site, and the opportunity cost of forgoing natural foraging activity during that transit time. From a game-theoretical perspective this is an optimal strategy,[53] and from the perspective of behavioral theory depredation behavior is strongly positively reinforced. Even if the cue changes, but still unambiguously indicates the presence of fishing activity, the animal would quickly habituate and continue its behavior.

Suppose, however, that the acoustic cue remains the same, but the consequences of responding to that decision are altered. For example, what if fishing vessels make a habit of cycling their engines at random, or cycling engines around "decoy" anchorlines? In this situation the presence of the acoustic cue no longer guarantees an encounter with a longline haul, and the whale faces a potential energy loss when responding to the action. From a game-theoretical perspective,[53] if the whale is a "rational" decision maker then one can see how a widespread adoption of faking cues by a fishing fleet might eventually disassociate the cue from an actual haul, if the negative consequences of responding to a cue, in terms of lost time and effort, are large enough. Of course whales, like people, may not be rational decision makers. In comparative psychology it has been long noted that intermittent schedules of reinforcement can condition stronger behavioral responses than a consistent reward schedule.[54,55] However, the effectiveness of "extinction" or "negative reinforcement" in deconditioning undesirable behaviors has also been well-documented in the same literature. The key unknown factor is what opportunity cost an animal faces when responding to a faked cue. If there is little to no "punishment" in terms of lost time and energy when responding to a faked cue, then from both a game theory and learning theory perspective the behavior may continue and even strengthen. However, if the cumulative punishment accrued from lost feeding opportunities were large enough, then the conditions for an extinction or negative reinforcement learning model might exist.

Thus, the ability of animals to habituate quickly to changes in acoustic stimuli does not negate the importance of identifying acoustic cues that attract the animals, because efforts to reduce the detection range of these cues and to produce "false cues" might be effective long-term strategies in reducing depredation, or at least delaying the response of animals to fishing activity.

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[1] H. Whitehead, "Estimates of the current global population size and historical trajectory for sperm whales," Mar. Ecol.: Prog. Ser. **242**, 295–304 (2002).

[2] T. Lyrholm and U. Gyllensten, "Global matrilineal population structure in sperm whales as indicated by mitochondrial DNA sequences," Proc. R. Soc. London, Ser. B **265**(1406), 1679–1684 (1998).

[3] Y. Cherel and G. Duhamel, "Antarctic jaws: Cephalopod prey of sharks in

Kerguelen waters," Deep-Sea Res., Part I **51**(1), 17–31 (2004).

[4] A Berzin, *Kashalot (The Sperm Whale)*. (U.S. Dept of Commerce, National Technical Information Service, Springfield, VA, 1971).

[5] M. E. Gosho, D. W. Rice, and J. M. Breiwick, "The sperm whale, *Physeter macrocephalus*," Mar. Fish. Rev. **46**(4), 54–64 (1984).

[6] D. W. Rice, in *Handbook of Marine Mammals*, edited by S. H. Ridgway and R. Harrison (Academic, London, 1989), Vol. **4**, pp. 177–233.

[7] D. K. Mellinger, K. M. Stafford, and C. G. Fox, "Seasonal occurrence of sperm whale (Physeter macrocephalus) sounds in the Gulf of Alaska, 1999–2001," Marine Mammal Sci. **20**(1), 48–62 (2004).

[8] P. B. Best, in *Behavior of Marine Animals*, edited by H. E. Winn and B. L. Olla (Plenum, New York, 1979), Vol. **3**, pp. 227–289.

[9] D. K. Caldwell, M. C. Caldwell, and D. W. Rice, in *Whales, Dolphins, and Porpoises*, edited by K. S. Norris (University of Califronia Press, Berkeley, 1966), pp. 677–717.

[10] N. Jaquet, "How spatial and temporal scales influence understanding of Sperm Whale distribution: A review," Mammal Rev. **26**(1), 51–65 (1996).

[11] H. Whitehead, M. Dillon, S. Dufault, L. Weilgart, and J. Wright, "Non-geographically based population structure of South Pacific sperm whales: Dialects, fluke-markings and genetics," J. Anim. Ecol. **67**(2), 253–262 (1998).

[12] T. Lyrholm, O. Leimar, B. Johanneson, and U. Gyllensten, "Sex-biased dispersal in sperm whales: contrasting mitochondrial and nuclear genetic structure of global populations," Proc. R. Soc. London, Ser. B **266**(1417), 347–354 (1999).

[13] M. B. Santos, G. J. Pierce, P. R. Boyle, R. J. Reid, H. M. Ross, I. A. P. Patterson, C. C. Kinze, S. Tougaard, R. Lick, U. Piatkowski, and V. Hernandez-Garcia, "Stomach contents of sperm whales *Physeter macrocephalus* stranded in the North Sea 1990–1996," Mar. Ecol.: Prog. Ser. **183**, 281–294 (1999).

[14] K. Evans and M. A. Hindell, "The diet of sperm whales (*Physeter macrocephalus*) in Southern Australian waters," ICES J. Mar. Sci. **61**(8), 1313–1329 (2004).

[15] T Kawakami, "A review of sperm whale food," Sci. Rep. Whales Res. Inst. **32**, 199–218 (1980).

[16] K. M. Fristrup and G. R. Harbison, "How do sperm whales catch squids?," Marine Mammal Sci. **18**(1), 42–54 (2002).

[17] K. Das, G. Lepoint, Y. Leroy, and J. M. Bouquegneau, "Marine mammals from the Southern North Sea: Feeding ecology data from delta C-13 and delta N-15 measurements," Mar. Ecol.: Prog. Ser. **263**, 287–298 (2003).

[18] H. Whitehead, *Sperm Whales: Social Evolution in the Ocean* (University of Chicago Press, Chicago, 2003).

[19] T. Okutani and T. Nemoto, "Squids as the food of sperm whales in the Bering Sea and Alaska Gulf," Tokai Regional Fisheries Laboratory, Report No. 18, 1964.

[20] M. R. Clarke and N. Macleod, "Cephalopod remains from sperm whales caught off Iceland," J. Mar. Biol. Assoc. U.K. **56**, 733–750 (1976).

[21] C. P. Nolan and G. M. Liddle, "Interactions between killer whales (*Orcinus orca*) and sperm whales (*Physeter macrocephalus*) with a longline fishing vessel," Marine Mammal Sci. **16**(3), 658–664 (2000).

[22] M. G. Purves, D. J. Agnew, E. Balguerias, C. A. Moreno, and B. Watkins, "Killer whale (*Orcinus orca*) and sperm whale (*Physeter macrocephalus*) interactions with longline vessels in the patagonian toothfish fishery at South Georgia, South Atlantic," Ccamlr Sci. **11**, 111–126 (2004).

[23] R. Hucke-Gaete, C. A. Moreno, J. Arata, and Blue Whale Ctr, "Operational interactions of sperm whales and killer whales with the Patagonian toothfish industrial fishery off Southern Chile," Ccamlr Sci. **11**, 127–40 (2004).

[24] E. A. Zollett and A. J. Read, "Depredation of catch by bottlenose dolphins (*Tursiops truncatus*) in the Florida king mackerel (*Scomberomorus cavalla*) troll fishery," Fish. Bull. **104**, 343–349 (2006).

[25] J. R. Ashford, P. S. Rubilar, and A. R. Martin, "Interactions between cetaceans and longline fishery operations around South Georgia," Marine Mammal Sci. **12**(3), 452–457 (1996).

[26] D. Capdeville, "Interaction of marine mammals with the longline fishery around the Kerguelen Islands (Division 58.5.1) during the 1995/96 cruise," Ccamlr Sci. **4**, 171–174 (1997).

[27] E. F. González, *presented at the XXI Congreso de Ciencias del Mar*, Chile, 2001.

[28] P. S. Hill, J. L. Laake, and E. Mitchell, "Results of a pilot program to document interactions between sperm whales and longline vessels in Alaska waters," U.S Department of Commerce, Report No. NOAA TM-NMFS-AFSC-108, 1999.

[29] M. F. Sigler, C. R. Lunsford, and J. M. Straley Marine Mammal Sci. (in press).

[30] G. R. McPherson, P. Turner, C. McPherson, and D. Cato, "Predation of large marine mammals (family *Delphinidae*) on longline and dropline target species. Phase I. Pilot study of the acoustic mechanism of predation, and development of a three dimensional acoustic tracking system." Australian Fisheries Management Authority and Eastern Tuna Management Advisory Committee, Department of Primary Industries, Queensland., Report No. QI 02105, 2002.

[31] G. R. McPherson, C. Clague, P. Turner, C. R. McPherson, A. Madry, I. Bedwell, and D. H. Cato, *presented at the Proceedings of Acoustics 2004*, Gold Coast, Australia, 2004.

[32] J. C. Goold and S. E. Jones, "Time and frequency-domain characteristics of sperm whale clicks," J. Acoust. Soc. Am. **98**(3), 1279–1291 (1995).

[33] L. V. Worthington and W. E. Schevill, "Underwater sounds heard from sperm whales," Nature (London) **180**, 291 (1957).

[34] W. A. Watkins, "Acoustic behaviors of sperm whales," Oceanus **20**, 50–58 (1977).

[35] L. A. Douglas, S. M. Dawson, and N. Jaquet, "Click rates and silences of sperm whales at Kaikoura, New Zealand," J. Acoust. Soc. Am. **118**(1), 523–529 (2005).

[36] A. Thode, D. K. Mellinger, S. Stienessen, A. Martinez, and K. Mullin, "Depth-dependent acoustic features of diving sperm whales (*Physeter macrocephalus*) in the Gulf of Mexico," J. Acoust. Soc. Am. **112**(1), 308–321 (2002).

[37] W. M. X. Zimmer, M. P. Johnson, A. D'Amico, and P. L. Tyack, "Combining data from a multisensor tag and passive sonar to determine the diving behavior of a sperm whale (*Physeter macrocephalus*)," IEEE J. Ocean. Eng. **28**(1), 13–28 (2003).

[38] A. Thode, C. Tiemann, J. Straley, K. Folkert, and V. O'Connell, "Three-dimensional localization of sperm whales using a single hydrophone," J. Acoust. Soc. Am. **120**(4), 2355–2365 (2006).

[39] W. C. Burgess, "The bioacoustic probe: A general-purpose acoustic recording tag (A)," J. Acoust. Soc. Am. **108** (5, Pt. 2), 2583 (2000).

[40] D. K. Mellinger, "ISHMAEL 1.0 User's Guide," NOAA/PMEL Tech. Mem., Report No. PMEL-120, 2002.

[41] A. Thode, "Three-dimensional passive acoustic tracking of sperm whales (*Physeter macrocephalus*) in ray-refracting environments," J. Acoust. Soc. Am. **18**(6), 3575–3584 (2005).

[42] W. M. Carey, "Sound sources and levels in the ocean," IEEE J. Ocean. Eng. **31**(1), 61–75 (2006).

[43] National Research Council Ocean Studies Board, *Ocean Noise and Marine Mammals* National Academies, Washington, D.C., 2003.

[44] P. T. Madsen, "Marine mammals and noise: Problems with root mean square sound pressure levels for transients," J. Acoust. Soc. Am. **117**(6), 3952–3957 (2005).

[45] A. Thode, "Tracking sperm whale (*Physeter macrocephalus*) dive profiles using a towed passive acoustic array," J. Acoust. Soc. Am. **116**(1), 245–253 (2004).

[46] J. L. Spiesberger, "Geometry of locating sounds from differences in travel time: Isodiachrons," J. Acoust. Soc. Am. **116**(5), 3168–3177 (2004).

[47] M. Wahlberg, "The acoustic behaviour of diving sperm whales observed with a hydrophone array," J. Exp. Mar. Biol. Ecol. **281**(1–2), 53–62 (2002).

[48] S. Watwood, P. J. O. Miller, M. Johnson, P. T. Madsen, and P. Tyack, "Deep-diving foraging behaviour of sperm whales," J. Anim. Ecol. **75**(3), 814–825 (2006).

[49] R. L. Pepper, Jr., and V. Simmons, "In-air visual acuity of the bottlenose dolphin," Exp. Neurol. **41**(2), 271–276 (1973).

[50] D. A. Hanan, L. M. Jones, and R. B. Read, "California sea lion interaction and depredation rates with the commercial passenger fishing vessel fleet near San Diego," CalCOFI Report 30, 122–126 (1989).

[51] T. A. Jefferson and B. E. Curry, "Acoustic methods of reducing or eliminating marine mammal-fishery interactions: Do they work?," Ocean Coastal Manage. **31**(1), 41–70 (1996).

[52] J. Barlow and B. L. Taylor, "Estimates of sperm whale abundance in the northeastern temperate Pacific from a combined acoustic and visual survey," Marine Mammal Sci. **21** (3), 429–445 (2005).

[53] J. W. Bradbury and S. L. Vehrencamp, *Principles of Animal Communication* (Sinauer Associates, Sunderland, MA, 1998).

[54] John Hall, *Classical Conditioning and Instrumental Learning: A Contemporary Approach* (JB Lippincott, Philadelphia, 1976).

[55] http://www.animalbehaviour.net/PosReinforcement.htm, reviewed 15 May 2007.