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Marine Mammal Acoustic Monitoring and Habitat
Investigation, Southern California Offshore Region

by

John Hildebrand

November 2007

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**John Hildebrand
Marine Physical Laboratory
Scripps Institution of Oceanography**

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Executive Summary

This project tests the feasibility of using the SCORE range for the collection of marine mammal call data and develops techniques for predictive modeling of marine mammals within SCORE. The project aims to develop techniques for passive acoustic monitoring for marine mammals, and to model how oceanographic conditions affect marine mammal habitat.

The echolocation clicks of five species of dolphins found offshore of southern California are described and the use of clicks for species classification is investigated. The spectral and temporal properties are analyzed for the echolocation clicks from free-ranging short-beaked common (*Delphinus delphis*), long-beaked common (*D. capensis*), Risso's (*Grampus griseus*), Pacific white-sided (*Lagenorhynchus obliquidens*) and bottlenose (*Tursiops truncatus*) dolphins. Two of the species exhibit unique spectral peaks and notches when the complete click is analyzed. A nested ANOVA analysis indicates that spectral peaks and notches occurring between 24-35 kHz are distinct between the two species and exhibit low variation within each species. Additionally, two subgroups are distinguished within Pacific white-sided dolphin recording sessions, which may represent two populations that overlap in the southern California region. Bottlenose and common dolphin clicks do not exhibit consistent patterns of spectral peaks or notches.

To understand cetacean ecology and habitat, we conducted visual and acoustic line-transect surveys during four CalCOFI cruises in this contract period. The most commonly sighted mysticete species on surveys conducted between July 2006 and April 2007 were blue, fin, gray and sperm whales, whereas commonly sighted odontocete species were short-beaked common dolphins and Dall's porpoise. By integrating CalCOFI environmental and cetacean data, ecological models for cetacean habitat in the region offshore of southern California can be developed to improve predictive models for their presence in the SCORE range.

Background

A broad range of odontocetes (toothed whales) and mysticetes (baleen whales) are found in southern California waters and in the SCORE range in particular. Offshore of southern California is one of the better studied regions for cetaceans (eg. Barlow 1995); however, substantial uncertainty remains in the seasonal and annual abundance and distribution of the majority of marine mammal species present. Some odontocetes are found in southern California offshore waters throughout the year, whereas others migrate into the area on a seasonal basis. Short-beaked common dolphins are one of the most abundant odontocete species off California, though their abundance varies seasonally and annually as they move offshore and northward in summer months (Forney & Barlow 1998). An offshore population of bottlenose dolphins occurs during all seasons throughout the Southern California Bight (Forney & Barlow 1998). Risso's dolphins (*Grampus griseus*), Pacific white-sided dolphins (*Lagenorhynchus obliquidens*), northern right whale dolphins (*Lissodelphis borealis*) and Dall's porpoise (*Phocoenoides dalli*) exhibit a seasonal presence, moving into waters off California during cold-water months (November – April) and shifting northward to Oregon and Washington or offshore in warmer months (May – October) (Green *et al.* 1992, Forney *et al.* 1995, Forney & Barlow 1998). Several additional species inhabit southern California waters in all seasons or with unknown seasonal patterns. Among these are the sperm whale (*Physeter macrocephalus*), killer whale (*Orcinus orca*), Baird's beaked whale (*Berardius bairdii*), pilot whale (*Globicephala macrorhynchus*), false killer whale (*Pseudorca crassidens*), Cuvier's beaked whale (*Ziphius cavirostris*) and various other beaked whale species (*Mesoplodon spp.*).

Mysticetes (baleen whales) have been seen off southern California in all seasons, though particular species are more numerous during particular seasons. For instance, Blue (*Balaenoptera musculus*) and humpback (*Megaptera novaeangliae*) whales are present in greater numbers in the summer and fall as they migrate into the Southern California Bight (Forney & Barlow 1998, Larkman & Veit 1998, Calambokidis & Barlow 2004). Gray whales migrate southward through the region between November - February and northward in April – June (Poole 1984). Minke whale (*Balaenoptera acutorostrata*), fin (*Balaenoptera physalus*), and sei whale (*Balaenoptera borealis*) inhabit southern California waters in all seasons or with unknown seasonal patterns.

Acoustic monitoring for marine mammals has the potential to improve our understanding of marine mammal presence within the SCORE range. We have been using High-frequency Acoustic Recording Packages (HARPs) deployed adjacent to the SCORE range to monitor for marine mammal sounds. The advantage of this approach is that these data can cover a broad bandwidth of frequencies (10 Hz – 100 kHz) to allow more accurate classification of marine mammal sounds. Our second approach for marine mammal monitoring within SCORE has been to record a suite of SCORE installed hydrophones in collaboration with Dave Moretti (NUWC) and Curt Collins (NPGS), and use these data to better characterize the calls of marine mammals. The advantage of this approach is that it uses range assets, and that a large number (88) of sensors are available for localization of sounds over a broad region.

Acoustic call detection and classification by species is a key step in processing acoustic monitoring data. Recent advances in acoustic recording capabilities allow remote autonomous recordings with terabyte data storage (Wiggins and Hildebrand 2007). Manual analyses of these large datasets are prohibitive based on the time and costs for manual analysis. Reliable automated methods are needed for detection and classification of odontocete calls to allow rapid analysis of these large acoustic datasets. The calls of many baleen whale species are stereotyped and well known. Identification of stereotyped mysticete calls has been accomplished using

automatic detectors (e.g., Sirovic *et al.* 2004). Odontocete call identification is more difficult owing to their call complexity. Calls of some odontocetes, such as sperm whales, killer whales, and porpoises, are easily distinguishable (Weilgart 1990, Ford 1989, Evans *et al.* 1988). However, for most species the variation in and among call types is a topic of current research (Roch *et al.* 2007). Odontocete calls can be divided into three general categories: echolocation clicks, burst-pulsed calls, and whistles. Echolocation clicks are broadband, impulsive sounds which typically range between 10 and 150 kHz in many dolphin species (Au 1993). Burst-pulsed calls are rapid series of broadband clicks that are not individually distinguishable to humans, resulting in calls with a buzz-like, tonal quality (Murray 1998). These calls can range from 5-150 kHz and are thought to function for communicative purposes. Whistles are frequency modulated narrow-band calls that occur between 2-35 kHz. Whistles are thought to have communicative functions and it has been suggested that they may carry individual-specific information in some species (Caldwell 1990).

Objectives

This project tests the feasibility of passive acoustic monitoring of marine mammals in the SCORE range by conducting recordings using broadband acoustic recording packages and towed arrays and by examining a suite of SCORE installed hydrophones. The data from these recordings are being examined to assess the viability of automated call detection, classification by species, and localization. The goal of this work is to provide a means for acoustic monitoring of marine mammal presence within the SCORE range, so that range assets may be used for environmental compliance.

In collaboration with CalCOFI (California Cooperative Fisheries Investigation) and Cascadia Research Collective, we have been conducting visual and acoustic surveys for marine mammals in the southern California region. These data have yielded sighting and acoustic detection data on four cruises during the 2006-2007 project period. We report a summary of CalCOFI survey data below.

In collaboration with Cascadia Research Collective, we conducted a tagging program for baleen whales using an acoustic recording tag with suction cup attachment. These data provide calling rate and other behavioral information which can aid in species identification and interpretation of passive acoustic recording data. We report a summary of acoustic tag data collected during 2006-2007 below.

Results

Delphinid species classification using spectral properties of echolocation clicks

Melissa S. Soldevilla, Sean M. Wiggins, E. Elizabeth Henderson, Gregory S. Campbell, John A. Hildebrand and Marie A. Roch

INTRODUCTION

Accurate classification of recorded calls to species is needed for passive acoustic monitoring of wild cetaceans. Passive acoustic monitoring is increasingly being used for towed hydrophone line transect surveys (Barlow & Taylor 2005) and for remote, long-term monitoring of populations using autonomous instruments (Sirovic *et al.* 2004, Oleson *et al.* in press, Verfuss *et al.* 2007, Mellinger *et al.* 2004). Recent technological advances allow long-term recordings to reach higher bandwidths (Wiggins & Hildebrand 2007), which prompts research into use of higher frequency calls for species classification. Odontocete species regularly emit high frequency clicks and burst-pulsed calls, in addition to lower frequency whistles (Richardson *et al.* 1995), and usage of these call types varies with behavior state, geographic location and geometric spacing of conspecifics (Jones & Sayigh 2002, Nowacek 2005, Lammers *et al.* 2003). Advances have been made in classifying delphinid whistles to species (Oswald *et al.* 2003, Oswald *et al.* 2004, Roch *et al.* 2007), but little work has focused on classifying delphinid burst-pulses and clicks to species, particularly at frequencies greater than 24 kHz. While the clicks of porpoise, sperm whales and beaked whales are easily distinguishable from delphinid clicks based on time duration and peak frequency characteristics (Goold & Jones 1995, Madsen *et al.* 2005, Kamminga *et al.* 1996, Zimmer *et al.* 2005), delphinid clicks thus far have remained unclassifiable at the species level.

Five species of dolphins are commonly observed in the waters offshore of southern California. Short-beaked common and long-beaked common (*D. capensis*) dolphins are small dolphins (160-210 cm and 190-240 cm, respectively (Heyning & Perrin 1994)) typically sighted in offshore tropical and temperate waters in schools of hundreds to thousands of individuals (Gowans & Whitehead 1995, Gaskin 1992, Selzer & Payne 1988, Polacheck 1987, Evans 1974). They were only recently recognized as separate species. Pacific white-sided dolphins are small dolphins (230-250 cm) (Walker *et al.* 1986) endemic to cold temperate North Pacific waters (Green *et al.* 1992, Leatherwood *et al.* 1984) and observed in schools ranging between 10-1000 individuals (Leatherwood *et al.* 1984). The offshore population of bottlenose dolphins consists of medium-sized dolphins (290-310 cm) (Perrin & Reilly 1984) that are typically sighted in small groups (2-15) (Shane *et al.* 1986) throughout tropical and temperate waters (Forney & Barlow 1998). Risso's dolphins (*Grampus griseus*) are larger dolphins (400 cm) typically found in medium-sized groups (10-50) in tropical and temperate waters (Leatherwood *et al.* 1980, Kruse *et al.* 1999).

This study describes echolocation clicks for five species of dolphins from the southern California region. This is the first study to describe recordings from free-ranging short-beaked common, long-beaked common and Pacific white-sided dolphins. We compare the spectra of the initial click pulse to the spectra of clicks including reverberations, describe their spectral content and measure standard click features for comparison with other published results. In addition to the global peak frequency described by Au (1993), we describe local spectral peaks and notches and

show that two species of dolphins have a unique peak and notch structure. We quantify the intra- and inter-specific frequency variation of these peaks and establish that they represent invariant and distinctive features as required for species specificity (Nelson 1989, Emlen 1972), thereby demonstrating their value for species classification in passive acoustic monitoring.

MATERIALS AND METHODS

Our study area encompasses the region offshore of southern California extending from 32°42' N, 117°10' W along the coast to 35°50' N, 120°47' W and offshore to 29°51' N, 123°35' W and 33°23' N, 124°19' W (Fig.1). Recordings were obtained in the southern California neritic and pelagic waters between November 2004 and April 2007 (Fig. 1). Data are used from multiple

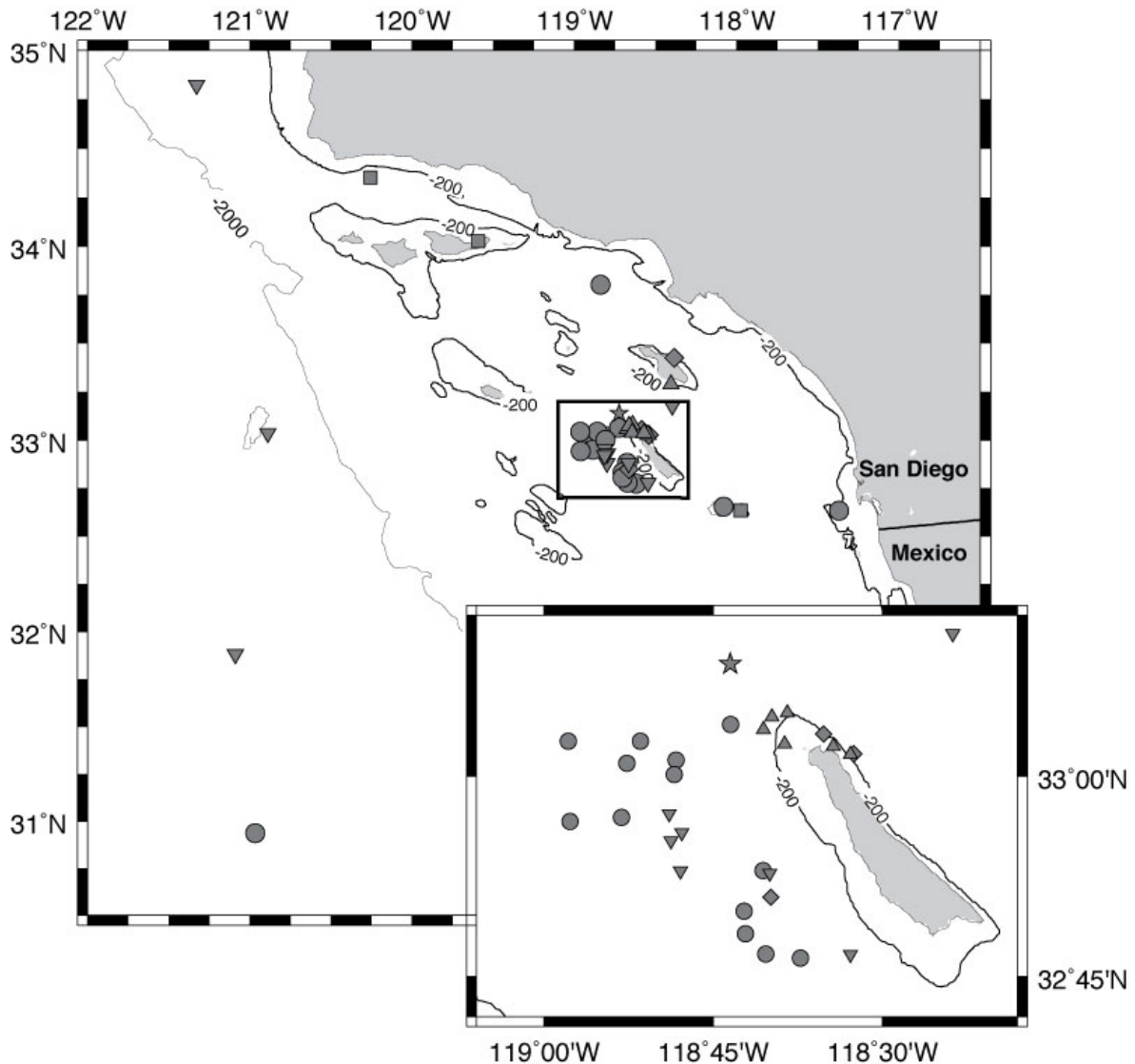


Fig. 1. Map of study area and delphinid recording locations offshore of southern California, USA. Coastline and 2000 m bathymetric contours are represented. Inset shows cluster of recordings from San Clemente Island. Symbols are: ● *Delphinus delphis*, ■ *Delphinus capensis*, ◆ *Grampus griseus*, ▼ *Lagenorhynchus obliquidens*, ▲ *Tursiops truncatus*

surveys: California Cooperative Oceanic Fisheries Investigations (CalCOFI) oceanographic surveys, San Clemente Island (SCI) small boat operations, Scripps Institution of Oceanography (SIO) instrumentation servicing cruises on the *R/V Robert Gordon Sproul*, and FLoating Instrument Platform (FLIP) moored observations.

Experienced marine mammal visual observers from Cascadia Research Collective identified dolphin schools to species, including mixed species groups. In addition, location, group size, presence of neonates and behavior were recorded. From all surveys, single species school recordings are used only if no other species were detected within 3 km. Following Oswald *et al.*'s (2003) whistle study, we consider this a conservative distance for species identification of clicks, as echolocation clicks are detectable to about 1 km (Philpott *et al.* 2007). Visual distinction of common dolphin schools to species is difficult and there is potential for misidentification between the two species when they are not clearly seen or photo-identified. We have used data for this study only when the identification by species was unambiguous.

As data in this study included all high-quality clicks, regardless of hydrophone position relative to the click production axis, we follow the method developed by Kamminga & Weirsma (1981) for analyzing clicks with reverberations. We compare spectra calculated from only the initial click pulse in the time-series to spectra calculated from the complete click including reverberations.

Signal analysis is performed with customized routines in *Matlab* (Mathworks, Natick, MA). An automatic click detection algorithm is run on all acoustic data to locate the clicks. In the spectral domain, calculated using a 1024 point Fast Fourier Transform (FFT) with 50% overlap and a Hann window, portions of data are selected as click candidates if they are 13 dB higher than the surrounding 3 seconds of noise over a minimum bandwidth of 10 kHz. A 15 ms segment of data is extracted for single clicks, while longer durations are extracted if multiple clicks are within 15ms of each other. These automatic detections are subsequently scanned by an analyst and false detections and burst-pulse calls removed. A finer resolution click detection algorithm is then performed which searches for the start and end point of each click. The signal is high-pass filtered at 3 kHz using a finite impulse response filter to remove any remaining flow noise caused by water flow around the towed hydrophone. The Teager energy (Kaiser 1990) for the extracted click data, including signal and surrounding noise, is calculated as:

$$E[x(t)] = x^2(n) - x(n+1)x(n-1). \quad (1)$$

Kandia and Stylianou (2006) demonstrate the utility of the Teager energy operator, a measure which provides nearly instantaneous energy tracking by using only 3 consecutive signal samples, for detection of sperm whale regular and creak clicks. For each click, a noise floor is defined at the 40th percentile of energy, based on empirical analysis of the data. All points whose Teager energy is 100 times greater than the noise floor are tagged and grouped as belonging to a single click if they are less than 500 μ s apart. Au (1993) determines the start and end points of symmetric on-axis click waveforms as the time at which the integral of the squared pressure over time increases no more than 1% as time increases. This approach needs to be modified to analyze off-axis clicks that have distorted asymmetric waveforms. The start and end points of clicks are determined as the time at which the integral of the Teager energy over time increases no more than 0.5% as time advances backwards or forwards from the peak amplitude of the initial click pulse (Fig. 2). Many clicks include reverberations which, because they follow less than 100 μ s after the initial pulse (<150 mm scale), are presumed to be from reflections within the head. Melon lengths of short-beaked common, Pacific white-sided and Risso's dolphins range from 150-185 mm and heights and widths range from 55-110 mm (Cranford *et al.* 1996). Oftentimes, the Teager energy of the 1st reverberation is greater than that from the initial pulse. Therefore,

rather than choosing the largest peak, the first of several large peaks is chosen. This method differentiates the initial pulse from the reverberations. To obtain the complete click, including reverberations, a 10-point running mean of the Teager energy is calculated and start and end points are determined as the first and last point that are 3 times greater than the noise floor.

The spectral characteristics of both the initial pulses and complete clicks are quantified using a 256-point FFT with a rectangular window. Signals used in the FFTs are calculated from the 256 points prior to the end of the initial pulse to exclude reverberations or from the 256 points after the start of the complete pulse to include reverberations. The boxcar window is necessary for analyzing the initial pulse since the window is not symmetrical around the click; this prevents

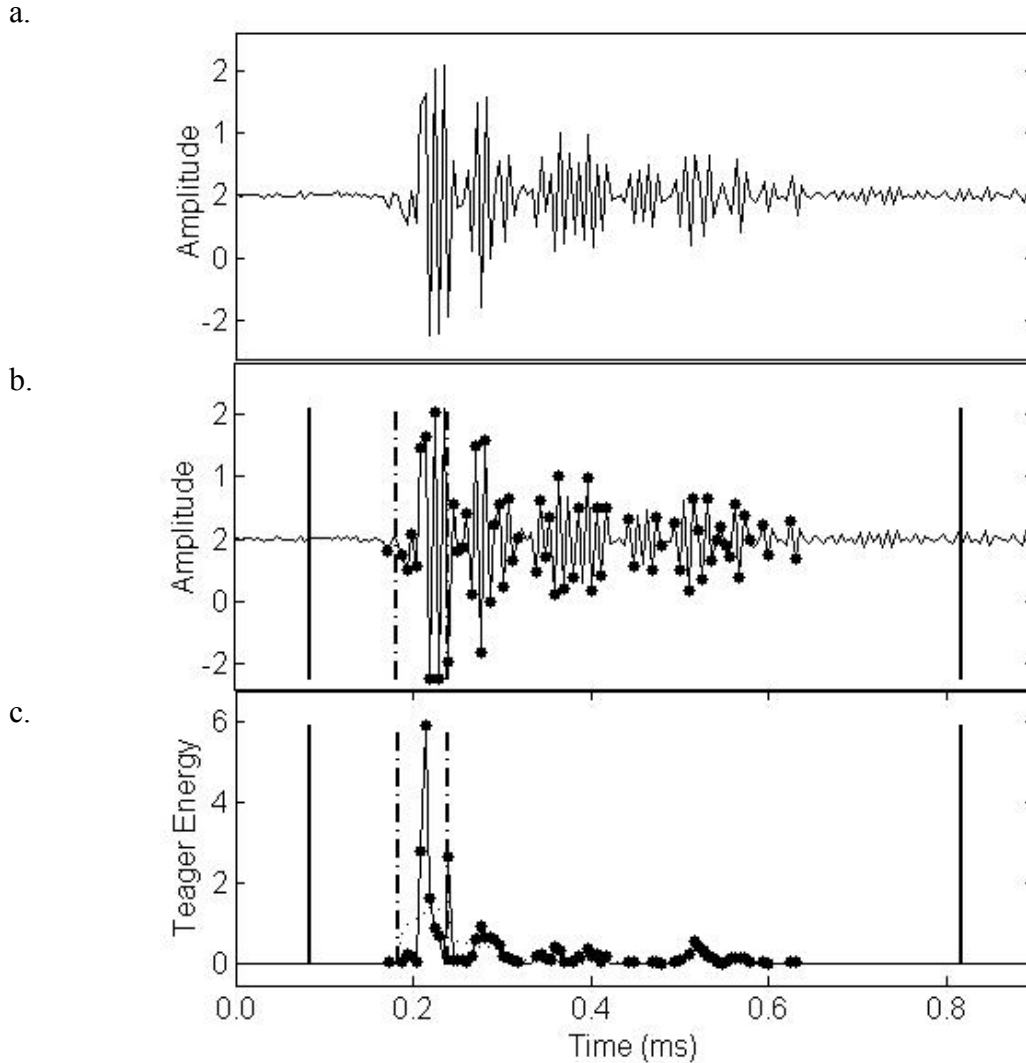


Fig. 2. Example waveform with corresponding Teager energy plot of a Pacific white-sided dolphin click. Note the reverberations present in the waveform. a) the click waveform b) the click waveform and denotations of initial pulse and complete click endpoints and points above Teager energy noise floor threshold, c) the Teager energy of the waveform and denotations of the initial pulse and complete click endpoints and points above the noise floor threshold. Dashed bars represent the time range of the initial click. Solid bars represent the time range of the complete click peak. Dots represent locations of points above the Teager energy noise floor threshold.

loss of the click signal at the tail end of the window. Furthermore, 256-point Hann-windowed spectra are calculated for the complete clicks which are more centered within the window. The rectangular-windowed data are used for spectral comparisons between the initial pulses and complete clicks, while the Hann-windowed data are used for analyzing detailed spectral characteristics of complete clicks to prevent edge effect problems caused by the FFT. The complete click spectra are similar between both windowing methods. For the remaining analyses, the spectral magnitudes are normalized between 0 and 1, and the mean and standard deviation of the normalized click spectra are calculated for each species. Additionally, concatenated spectrograms are created of all clicks analyzed for each species.

The original data lack the independence required for statistical analysis because click trains represent multiple clicks from one individual and individuals likely produce multiple click trains over a recording session. To prevent over-representation of one individual's clicks, single clicks are grouped into click trains if they are separated by less than 0.5 seconds; overlapping click trains, although likely to have been produced by different individuals, are grouped as a single train to reduce bias. A two stage selection process is used to sample click trains. In the first stage, click trains are sampled at random until twice the school size number of click trains is selected or until the set of click trains is exhausted. From each selected train, a single click is randomly chosen for use in analysis.

To examine spectral peak and notch structure and its variability in the frequency domain across clicks, the frequency location of consistent spectral peaks and notches is quantified for all clicks of each species. Variability exists among individual clicks, such that the frequency location of the peaks and notches may vary, the peak or notch may not exist at all, and additional peaks and notches may exist that are not consistent across clicks. To establish and select consistent peaks and notches for statistical analysis while avoiding circularity, clicks are randomly divided into two groups. Group one clicks are used to establish expected frequency ranges for consistent peaks and notches across all clicks of a species. For each group two click, locations of peaks and notches within these frequency ranges are quantified for statistical comparison among species.

To establish the frequency ranges of consistent peaks and notches, a regression-based peak and notch selection algorithm is run on the normalized Hann-windowed complete click spectra from group one. Regression order is set to 2 samples to smooth over smaller peaks and notches and a threshold is set at 2 dB. An average of 8 (range 0-20) each of peaks and notches are selected per click. These are combined across all clicks from group one for each species and a histogram is generated. The histogram is calculated such that each bin is 750 Hz wide to correspond with the FFT frequency resolution. To distinguish consistent peaks from the background noise of inconsistent peaks in the peak histogram, the peaks and notches from each individual click are randomly reassigned to frequency bins for each species, providing an estimate of background noise in each histogram. Expected count distributions from background noise histograms are compared to counts in the species histograms using a z-test (alpha 0.5, one-tailed) (Zar 1999). Groups of frequency bins greater than 15 kHz (to exclude overlapped whistles) with histogram counts significantly greater than histogram background noise are denoted as consistent peaks or notches. Univariate Gaussian curves (Huang *et al.* 2001) are fit to each species' histogram to obtain the mean and standard deviation of the frequency location of the consistent peaks and notches.

To examine differences in frequency location of peaks and notches among species, the peak/notch selection algorithm is run on normalized Hann-windowed complete click spectra from group two and statistical analyses are performed. Group two data are analyzed in reference to each of the consistent peaks and notches from group one as follows: for each click from group two, the peak

or notch nearest to the group one mean is selected if any peaks or notches exist within one standard deviation. To examine variability in peak and notch frequencies among and within species, nested ANOVAs (Zar 1999) are performed in SPSS 11.5 (SPSS, Inc., Chicago, IL). For each consistent peak and notch, a nested ANOVA is calculated examining the main effect of species differences in frequency location and the interaction effect of recording session nested within species. The nested ANOVA can only determine that differences exist among multiple comparisons; post-hoc tests were performed to determine which recording sessions were different using Tukey's method (Zar 1999).

For comparison with previous click studies, standard click measurements are made from rectangular-windowed click spectra, but they should be treated with caution as our recording system does not record the complete bandwidth of the clicks. The peak frequency is calculated as the frequency at which the spectrum reached maximum amplitude. The centroid frequency is defined as the point dividing the interpolated spectrum in halves of equal energy (Au 1993). The -3 dB and -10 dB bandwidths are calculated for the peak frequency, while the centralized root mean square bandwidth is calculated for the centroid frequency (Au 1993). The Q-value of each click is calculated as the centroid frequency divided by the centralized RMS-BW (Au 1993). Inter-click intervals are not calculated, as clicks often occur in overlapping trains in which individual click trains cannot be distinguished.

RESULTS

Concatenated spectrograms and mean spectral plots of clicks for the five dolphin species investigated reveal consistent spectral characteristics for both Pacific white-sided and Risso's dolphins (Fig. 3). Spectral peaks are centered near 22, 26-27, 33 and 39 kHz for Pacific white-sided dolphins, while the peaks are centered near 22, 25, 30 and 39 kHz for Risso's dolphins. These peaks are consistent for the majority of clicks across multiple recording sessions as well as for various hydrophone array configurations. No such pattern is evident for long-beaked common, short-beaked common or bottlenose dolphins (Fig. 3).

A comparison of the mean spectra from the initial pulse of the truncated clicks with the complete clicks for Pacific white-sided dolphins (Fig. 4) reveals that these spectral peaks only occur in the complete click. No consistent spectral pattern occurs when only the initial pulse is analyzed. Similar results were found for Risso's dolphin clicks. The spectral peaks are a result of reverberations, presumably caused by interference from multiple reflections within the head. The truncated click duration means ranged between 110-160 μ s for all five species of dolphins, while the complete clicks had longer durations, as expected, with means ranging from 400 – 670 ms. These clicks typically included several reverberations with the peaks of successive reverberations occurring less than 100 μ s apart.

The existence of consistent spectral peaks and notches in only two of the species is reinforced when comparing click counts of frequencies with peaks or notches from group one data. Only Pacific white-sided and Risso's dolphin clicks exhibit frequencies at which numbers of peaks and notches are greater than expected by chance. The remaining three species' clicks did not (Fig. 5). Univariate Gaussian mixture models fit to the peak histograms and notch histograms from Pacific white-sided and Risso's dolphin group one clicks provide estimates of means and standard deviations for each of the consistent peaks and notches.

For the two species, calculations of the percentage of clicks from group two data that have peaks or notches within the expected frequency ranges show that these consistent peaks and notches

occur in the majority of recorded clicks. The two species share similar spectral peaks at frequencies 22.2 and 37.3 kHz for Pacific white-sided dolphins and 22.4 and 38.8 kHz for Risso's dolphins. Risso's dolphins have two additional spectral peaks at 25.5 and 30.2 kHz and spectral notches at 19.6, 27.7, and 35.8 kHz, while Pacific white-sided dolphin clicks have spectral peaks at 26.6 and 33.7 kHz, and notches at 19.0, 24.5, and 29.7 kHz.

The species-specificity of click variables is tested using a nested ANOVA. ANOVA analyses indicate that click variables are distinct both between species and among recording sessions. The local frequency peaks around 22 kHz and notches around 19 kHz are not significantly different between species. Most other frequency peaks and notches are significantly different between species, with some peaks and notches varying among recording sessions. Post-hoc analyses reveal that while there are significant differences among recording sessions of Pacific white-sided dolphins, there also are consistencies present. In particular, the spectral peak at 26.6 kHz distinguishes two subgroups of recording sessions which are similar within the subgroup but significantly different from each other (Fig. 6). The mean peak location for subgroup A is 26.1 ± 0.7 kHz and is 27.4 ± 0.5 kHz for subgroup B. Only two of the 20 recording sessions show no significant differences from the remaining subgroups and inspection of spectra from these recordings shows both click types present. To exemplify the differences between these subgroups, clicks from recording sessions are divided into subgroups and concatenated spectrograms and mean spectra are generated (Fig. 7).

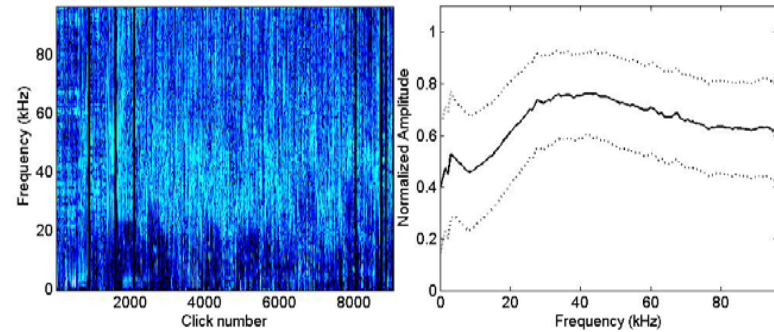
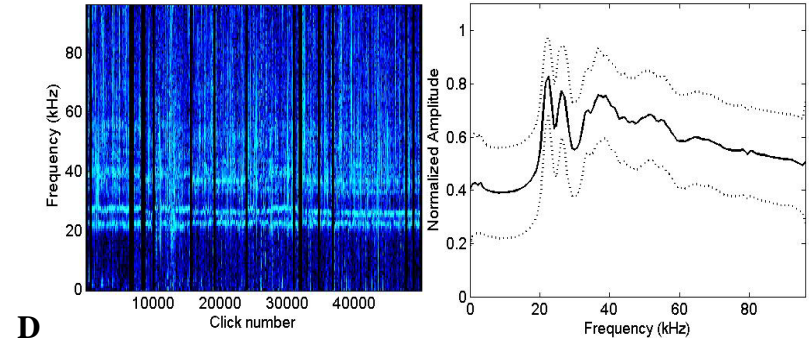
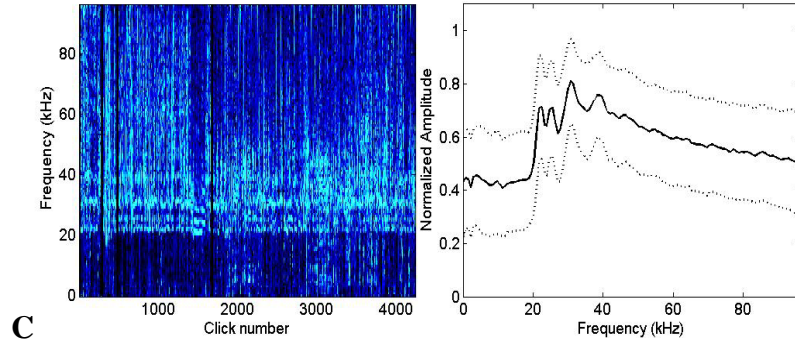
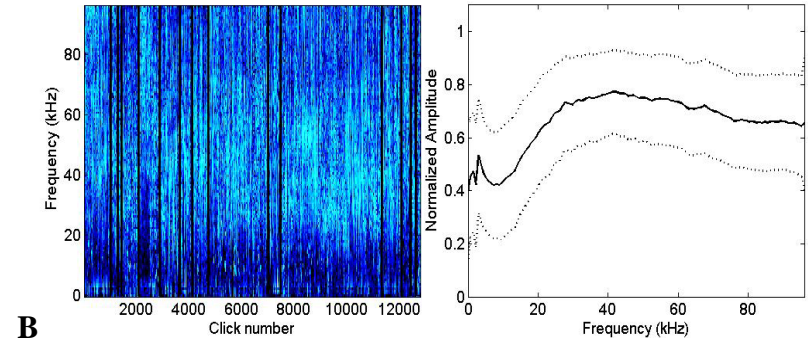
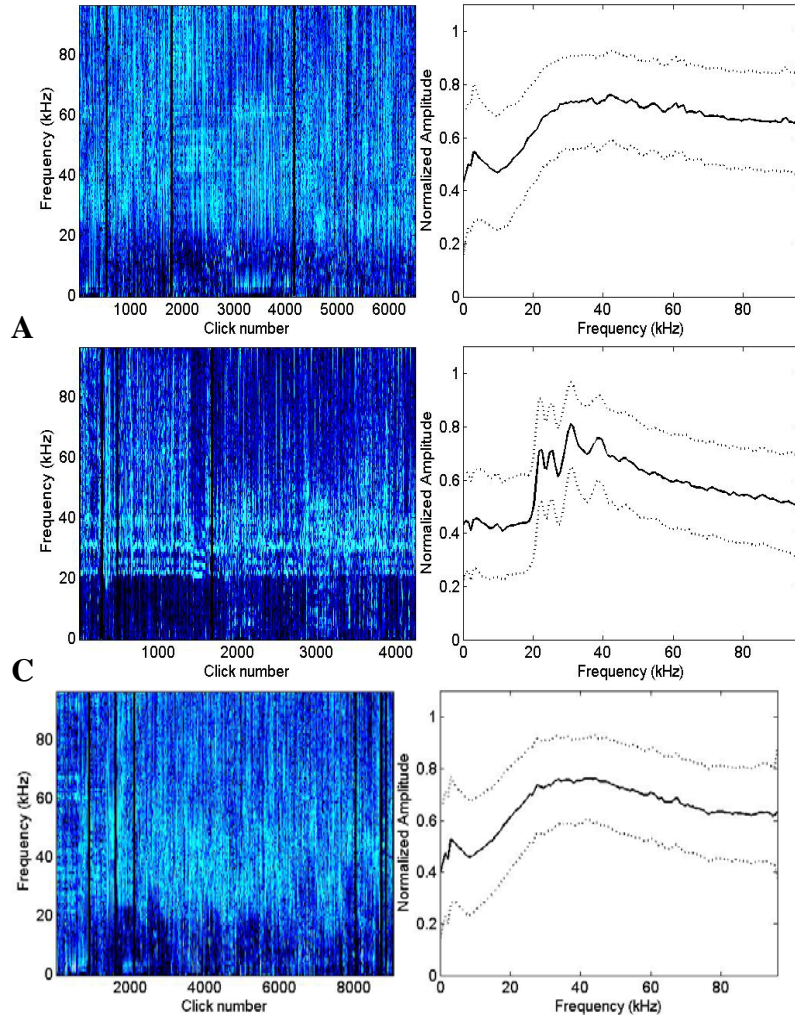


Fig. 3. Concatenated spectrograms and mean normalized spectral plots of complete clicks for each species using Hann-windowed data: a) *Delphinus delphis*, b) *Delphinus capensis*, c) *Grampus griseus*, d) *Lagenorhynchus obliquidens* and e) *Tursiops truncatus*. Spectral peaks are obvious for *G. griseus* and *L. obliquidens*. Black vertical lines in spectrograms represent breaks between recording sessions. For the mean normalized spectral plots, the solid line represents the mean and the dotted lines represent the standard deviation.

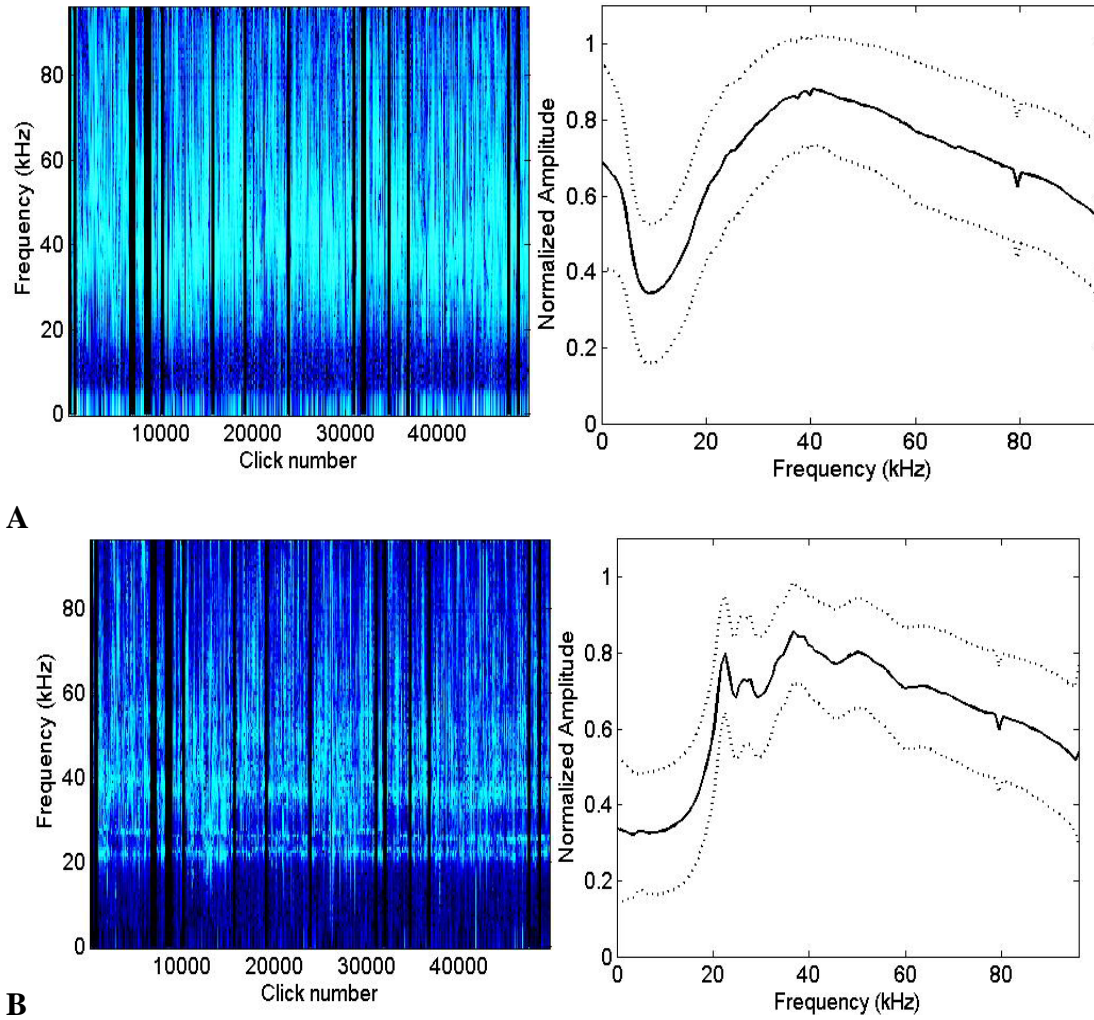


Fig. 4. Concatenated spectrograms and mean spectral plots for a) initial and b) complete pulses of *Lagenorhynchus obliquidens* clicks using rectangular-windowed data. These plots represent the same clicks; the only difference is the inclusion of reverberations in complete clicks. No obvious spectral peaks are apparent when only the initial pulse is analyzed. Black vertical lines in spectrograms represent breaks between recording sessions.

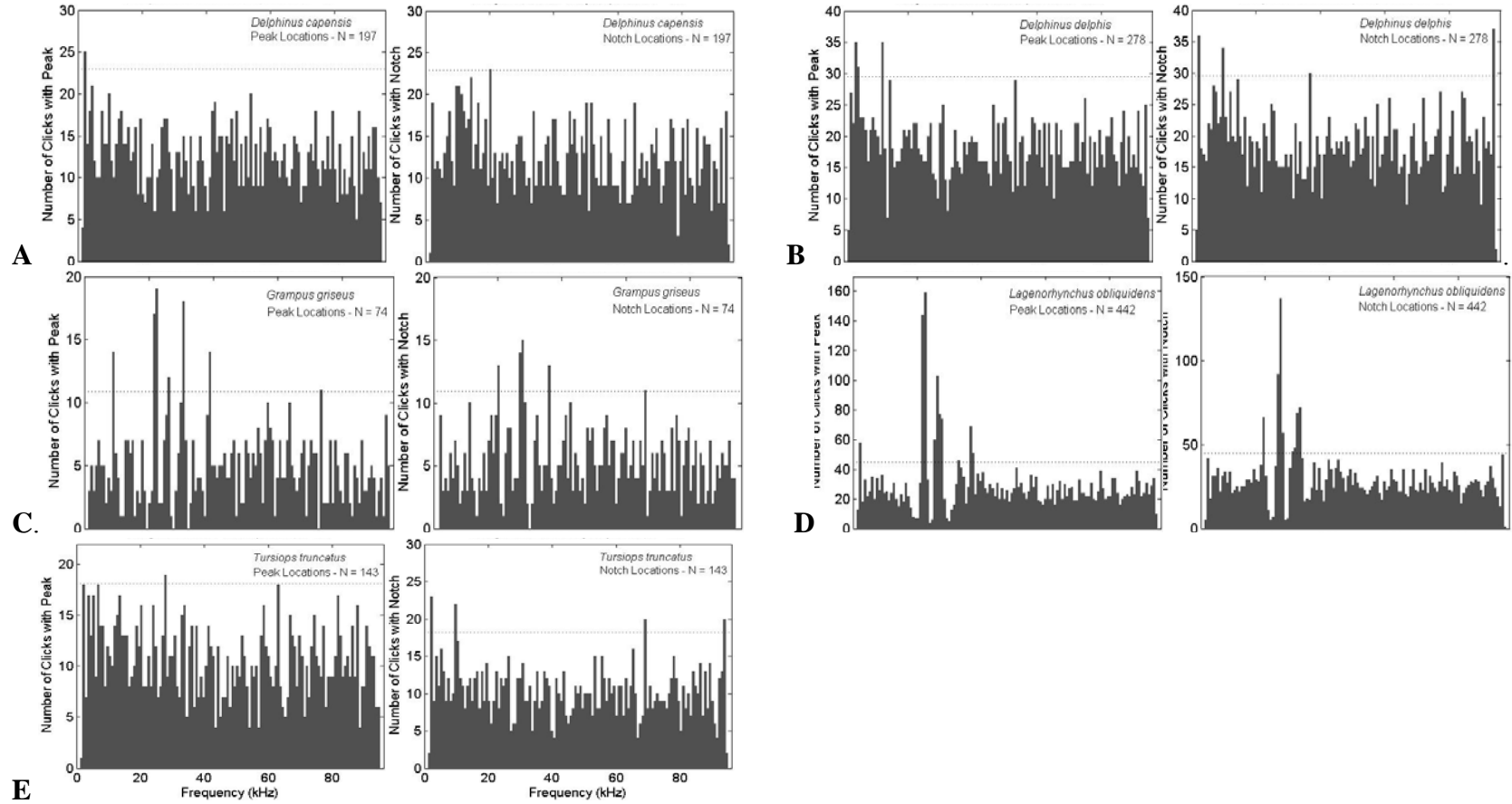


Fig. 5. Histograms of location of local frequency peaks (left) and notches (right) for a) *Delphinus capensis*, b) *Delphinus delphis*, c) *Grampus griseus*, d) *Lagenorhynchus obliquidens* and e) *Tursiops truncatus*. Each bar represents one 750 Hz FFT frequency bin. Dotted lines represent the upper boundary of histogram noise as determined from peak and notch randomization procedure. Groups of bars that rise above this line represent consistent peaks or notches that are analyzed further.

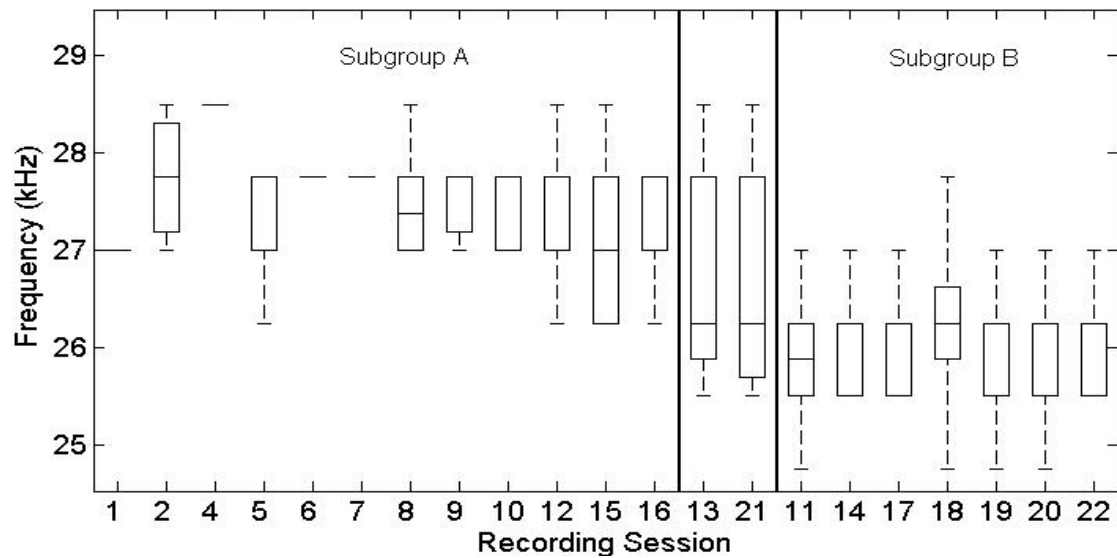


Fig. 6. Box plot of the frequency location of peaks around 26.6 kHz from each recording session of *Lagenorhynchus obliquidens*. Central lines represent the mean while surrounding boxes represent the 25th and 75th percentiles, whiskers represent the 95% confidence interval. Solid bars represent the distinction between subgroups of data as revealed by the Tukey post-hoc tests. Subgroup A and subgroup B are labeled. Recording sessions 13 and 21 were not significantly different from either of the two subgroups.

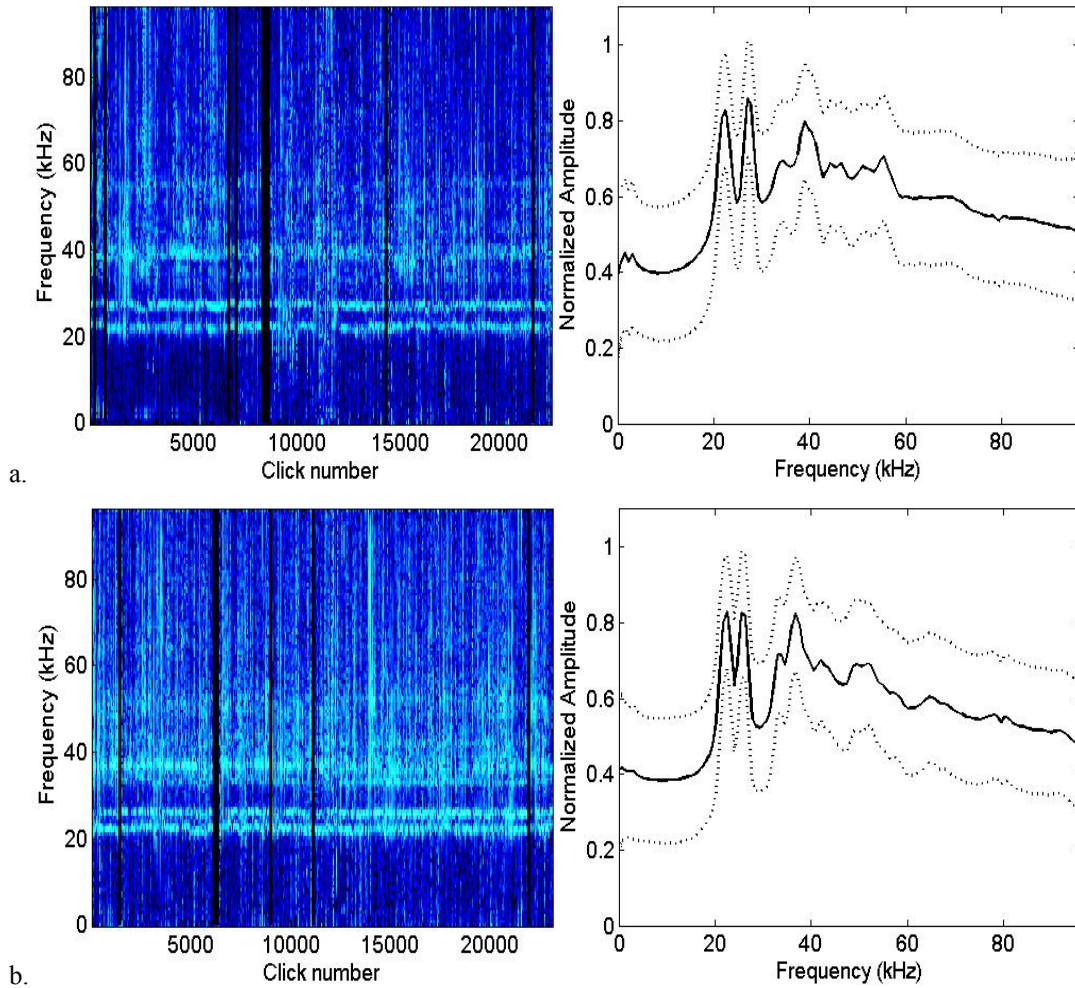


Fig. 7. Concatenated spectrograms and mean spectral plots for a) subgroup A and b) subgroup B of *Lagenorhynchus obliquidens* clicks using Hann-windowed data. Black vertical lines in spectrograms represent breaks between recording sessions. The consistency of spectral peaks and notches across recording sessions of each subgroup are apparent, as are the distinctions between clicks from the two subgroups.

DISCUSSION

Odontocete click classification of some species such as porpoise and sperm whales has been possible for many years; however, this study shows it is also possible for some species of dolphins which exhibit slightly different click spectral characteristics. This study indicates that detailed spectra of echolocation clicks obtained in the wild from passive acoustic monitoring can be used to identify some dolphins to species. Risso's dolphins and Pacific white-sided dolphins exhibit spectral peaks that are unique among the five species of dolphins recorded offshore of southern California. Autonomous acoustic recording packages have been deployed throughout this region and long-term spectral averages (Wiggins & Hildebrand 2007) of the data show echolocation click bouts exhibiting the same peak and notch structure as described above (Fig. 8). An automated classification scheme would be the ideal way to objectively classify the large amounts of acoustic data collected by these sea-floor instruments. Oswald *et al.* (2007)

have shown that automated methods can be used to classify dolphin whistles, and a classifier which used all call types produced by dolphins in the 5-24 kHz range suggests that clicks can be used to automatically classify dolphins (Roch *et al.* 2007). Automated classifiers that incorporate higher bandwidth click data are currently being developed by the authors. Different call types may be more prevalent during different behavioral states (Jones & Sayigh 2002, Nowacek 2005); therefore the incorporation of all delphinid vocalization types is important for identification of dolphins in a variety of behavioral states. Classification based on clicks can be particularly useful for those odontocete species which never or rarely whistle (Herman & Tavorla 1980). The ability to identify dolphin clicks to species will allow researchers to investigate long-term trends in their abundance and distribution patterns.

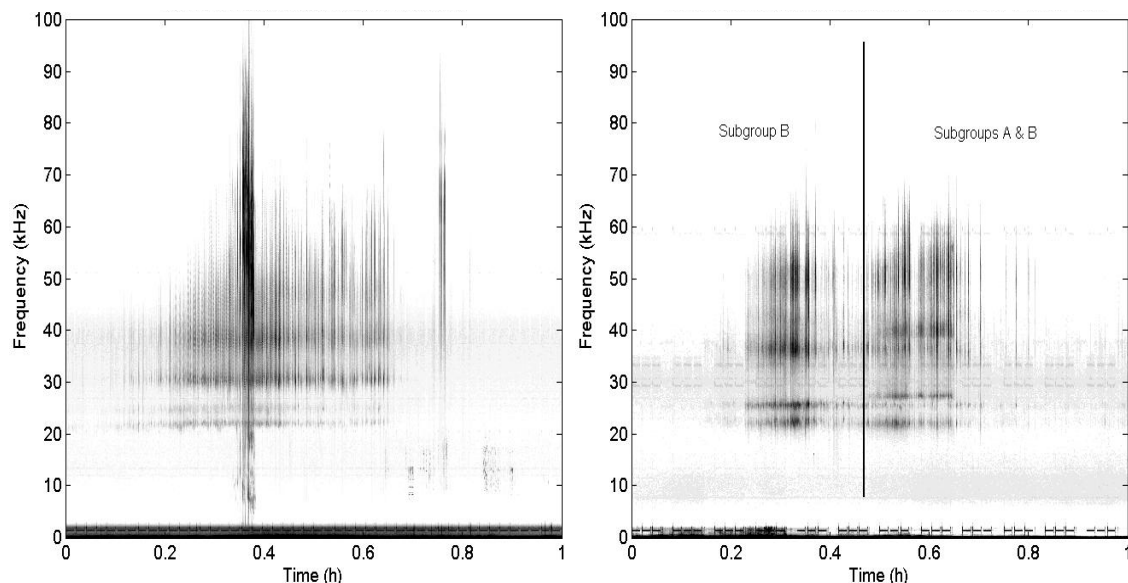


Fig. 8. Long-term spectral average of data from seafloor HARP instruments show echolocation bouts which exhibit similar spectral peak/notch structure to that found for (left) *Grampus griseus* and (right) *Lagenorhynchus obliquidens*, including both the 26 kHz and 28 kHz subgroup type clicks. Each plot shows 1 hour of data.

This species specificity of delphinid clicks has not been reported in previous studies focusing on the properties of the echolocation system. Prior studies have focused on on-axis clicks, which typically exhibit a single pulse (Madsen *et al.* 2004, Au 1993, Au 2004). Au *et al.* (1978) note that off-axis clicks are typically longer in duration due to multipaths which may be caused by reflections within the animal's head. While it is not possible to determine with certainty whether clicks are on- or off-axis in single hydrophone recordings of free-ranging odontocetes, one would expect the majority of clicks to be off-axis. Click data in this study contain reverberations where time delay is consistent with the propagation delay expected from reverberations in the melon. Spectral analysis comparing the initial click pulse to the complete click pulse suggests that, had we exclusively obtained on-axis clicks, this unique peak structure might not have been present. Madsen *et al.* (2004) examine the change in Risso's dolphin click spectra as a function of axis, and illustrate that spectral peaks and notches develop with increasing degree off-axis. Examination of their spectra for a click 10° off-axis suggests peaks at similar frequencies to those found here.

Call features which can be used by humans for species identification may also be important for species recognition by dolphins. In birds, terrestrial mammals, and fur seals, species recognition of calls is suggested to be relevant for mate attraction, mother-young attraction, territorial or threat calls, alarm calls, or feeding calls (Charrier & Sturdy 2005, chickadees; Page *et al.* 2001, hybrid fur seals; Wilczynski *et al.* 1999, tungara frogs). Offshore of southern California, Pacific white-sided and Risso's dolphins rarely

whistle compared to the other dolphins evaluated in this study, which suggests that clicks may be important in intraspecific communication as found in Hector's dolphin (Dawson 1991). The distinct spectral peak frequencies found in clicks from these two species may have evolved to facilitate species recognition. Pacific white-sided and Risso's dolphins overlap in habitat throughout the eastern North Pacific Ocean, occurring in shelf and slope waters from southern California through Washington (Green *et al.* 1992, Forney & Barlow 1998, Leatherwood *et al.* 1980, Leatherwood *et al.* 1984), and are sighted in mixed species groups (Green *et al.* 1992). Gotz *et al.* (2006) suggest rough-toothed (*Steno bredanensis*) dolphins eavesdrop on conspecifics' clicks, while Barrett-Lennard *et al.* (1996) discuss the potential sharing of information between conspecifics through interpreting echoes of clicks from group members. Species-specific features of clicks may be important in this context. Similar interspecific frequency shifts of calls have been found in sympatric short- and long-finned pilot whale whistles (Rendell *et al.* 1999). Seddon (2005) has shown that the evolution of mating calls in antbirds (*Thamnophilidae*) is concurrently optimized by two disparate processes, species recognition and adaptation to the signaling environment. Likewise, dolphin echolocation signals may have evolved to optimize both biosonar performance and species recognition.

The cause of the separation of Pacific white-sided dolphin recordings sessions into two subgroups based on click characteristics remains unknown. One possible explanation is that the different acoustic subgroups represent different populations of Pacific white-sided dolphins. Walker *et al.* (1986) show that two morphologically distinct populations of Pacific white-sided dolphin overlap in the southern California region, and are distinguishable by cranial measurements, particularly condylobasal length, a characteristic which could affect the sound production pathway. A genetic analysis of Pacific white-sided dolphin stock structure throughout the northeastern Pacific confirmed the existence of a Baja population and a California/ Oregon/ Washington population (Lux *et al.* 1997). These populations are not visually distinguishable (Walker *et al.* 1986), making visual field identification impossible. The ability to distinguish them acoustically could offer insight into their biology. Clicks from subgroup B were only recorded in October 2006 on the FLIP survey on the north end of San Clemente Island, while clicks from subgroup A were recorded on all surveys and throughout the entire region. Therefore, we suggest that subgroup A may represent the northern population while subgroup B may represent the southern population. Recordings from other areas in the eastern North Pacific and field studies incorporating acoustic recording with biopsy work could provide further answers on this prospect.

Similar to the species and population identity information found in the lower frequencies of the click, individual identity information may lie in spectral peaks at higher frequencies. Histograms in Fig. 7 show little variability at low frequencies, but high variability at higher frequencies. The lower frequencies (~20-40 kHz) correspond to a 3-8 cm scale for sounds traveling at 1500 m/s. At this scale, there is probably relatively little physical variation in the sound production pathway among individuals within a species. However the higher frequencies correspond to the 1 – 3 cm scale where individual variation is likely to be greater, resulting in intraspecific differences. A brief examination of overlapping click trains in a Pacific white-sided dolphin recording showed consistent peaks across presumed individual's clicks, with greater variation among individuals at frequencies above 60 kHz. The ability to distinguish individuals based on their calls and determine group sizes from recording sessions could provide an opportunity to estimate abundances of dolphin populations. Currently, determining the abundance of animals using passive acoustics remains a challenge to the bioacoustics field. Investigations into clicks from these species from different locations and captive studies examining individual differences in click spectra merit further study.

An intriguing question remains as to why some species of dolphins' clicks exhibit these spectral peaks while others do not. Researchers in the bioacoustics field have speculated many causes for interspecific call differences including phylogenetic constraints, size constraints, morphological differences, prey preferences, niche partitioning, and environmental variability including noise conditions (Kamminga *et*

al. 1986, Madsen *et al.* 2004, Wang *et al.* 1995, Dudok van Heel 1981, Oswald 2006). The occurrence of spectral peaks only in reverberant clicks and the consistency of those peaks within a species strongly suggest that they are due to interference from reflections within the head of the animal. This suggests that the morphology of the sound production pathways is important, including the monkey lip dorsal bursae (MLDB) complex, the melon, airspaces and skull. One morphological difference in the sound production pathways is that Pacific white-sided dolphins and Risso's dolphins have only slightly asymmetrical skulls and MLDB complexes, while bottlenose and common dolphins show strong asymmetry (Cranford *et al.* 1996). Perhaps the lack of asymmetry results in sound production organs producing clicks of similar central frequencies and amplitudes which result in the interference pattern observed, similar to beat structure for tonal sounds made up of two similar frequencies. Additional morphologic distinctions of the sound production path between these two species and the remaining three exist. Pacific white-sided and Risso's dolphins lack an extended rostrum or beak. Both species exhibit protrusions into the melon: a vertical cleft is present on the anterior surface of Risso's dolphin melon (White & Norris 1978); and a vertical connective tissue column is present in the central melon of Pacific white-sided dolphins (Cranford *et al.* 1996). These differences could also alter the sound production pathway and result in the click patterns this study presents.

Finally, it remains undetermined if the remaining three dolphins can be acoustically identified by higher frequency features in their clicks. The sample rate used in this study precludes the analysis of the full spectrum of delphinid clicks. Perhaps a higher sample rate may reveal distinct patterns within these species as Oswald *et al.* (2004) find for delphinid whistles. Another possibility is that the inclusion of whistles and burst pulses will be necessary to differentiate these species. Rankin *et al.* (2007) show distinct patterns of burst-pulse call production in northern right whale dolphins. Perhaps the incorporation of a quantitative description of burst-pulse production patterns as classification features will be useful for distinguishing other species. Additionally, computer learning techniques may be able to classify patterns that humans cannot easily distinguish.

CONCLUSIONS

The extension of acoustic species identification to higher frequencies shows promise for species classification and may enable researchers using passive acoustics to study temporal and spatial distribution and abundance patterns of delphinids. As the technology behind passive acoustic monitoring continues to advance, higher frequency sampling could provide recordings from less abundant and elusive species to determine if similar spectral patterns exist. Automatic classification algorithms could be developed to objectively distinguish delphinid species by their clicks, which, along with higher sample rate recordings, may allow all delphinid species to be classified by their clicks. Furthermore, the inclusion of all call types produced by delphinids could potentially strengthen the ability to classify periods of calling to species.

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Marine Mammal Monitoring during 2006-2007 CalCOFI Surveys

Melissa Soldevilla, Greg Campbell, Anne Douglas, John Calambokidis and John Hildebrand

INTRODUCTION

By incorporating visual and acoustic cetacean monitoring into the existing CalCOFI surveys, we can examine seasonal and inter-annual cetacean distribution patterns, develop delphinid acoustic identification capabilities, and integrate cetacean and environmental data to develop predictive ecological models of cetacean habitat. The CalCOFI platform enables us to sample on a spatial and temporal scale that has not previously been achieved, while incorporating both visual and acoustic monitoring reduces common biases present in single mode surveys. The combination of a strong cetacean sampling program with excellent CalCOFI environmental data will allow us to develop robust ecological models. This will help develop an understanding of their ecological role in the California current system and their interrelationships with their prey species. In this report, we describe the visual and acoustic survey methods that have been incorporated into CalCOFI cruises, and summarize results on cetacean visual and acoustic detection, distribution, and seasonality for four cruises from July 2006 to April 2007.

METHODS

Visual monitoring for cetaceans has been conducted on quarterly CalCOFI cruises since July 2004 using standard line-transect protocol. Visual observers watched during daylight hours when weather permitted while the ship transited between CalCOFI stations (Beaufort sea states 0-5 and visibility greater than 1 nm). A team of two observers searched for cetaceans in a 90° field of view from the bow to abeam of the ship alternating between 7 x 50 power binoculars and the naked eye. Because CalCOFI cruises were not always conducted on the same vessel, viewing conditions, such as ship speed and survey height varied by cruise (Table 1).

Table 1. Visual survey information for CalCOFI cruises during our 2006-2007 reporting period.

Cruise Date	Ship Name	Survey Speed (kt)	Observer Height (m)
Jul. 2006	R.V. New Horizon	10	8.1
Nov. 2006	R.V. Roger Revelle	12	12.0
Jan. 2007	David Starr Jordan	10	10.7
Apr. 2007	David Starr Jordan	10	10.7

A record of time, position, ship's heading and speed, viewing conditions (including sea state, wind speed and visibility) and observer identification was maintained and updated at regular intervals or whenever conditions changed. Information on all cetacean sightings was logged systematically, including distance and bearing from the ship, species identification and group composition, estimated group size and behavior. In all surveys during this reporting period, 25 x 150 power binoculars were used to improve species identification after sighting animals using lower power or no magnification.

Table 2. Visual detections of cetaceans over CalCOFI cruises from July 2006 – April 2007. Total number of schools sighted and total number of animals sighted per species for each trip.

Species	July 2006		November 2006		January 2007		April 2007		July 2006 – April 2007	
	# sight	# animals	# sight	# animals	# sight	# animals	# sight	# animals	# sight	# animals
Blue whale	11	16	3	4					14	20
Fin whale	7	7	8	11	1	2	1	2	17	22
Humpback whale	3	5	1	1			3	5	7	11
Sei whale							1	1	1	1
Minke whale	2	2			1	1	1	1	4	4
Gray whale					40	73	2	4	42	77
Sperm whale	4	12	1	4	2	3	3	6	10	25
Short-beaked common dolphin	36	1802	10	678	23	1488	2	193	71	4161
Long-beaked common dolphin	3	137	2	68			1	1800	6	2005
Common dolphin species	15	717	3	395	9	2638	5	1297	32	5047
Pacific white-sided dolphin			3	60	1	30	5	100	9	190
Risso's dolphin					2	292	4	73	6	365
Northern right-whale dolphin			1	45			2	35	3	80
Bottlenose dolphin			6	45	1	30	2	16	9	91
Dall's porpoise			1	1	10	53	15	78	26	132
Short-finned pilot whale	1	30							1	30
Killer whale	1	3							1	3
Cuvier's Beaked whale					1	1			1	1
Unidentified large whale	8	20	15	20	11	15	3	4	37	59
Unidentified small whale	1	4					2	2	3	6
Unidentified odontocete					1	2	1	1	2	3
Unidentified dolphin	7	172	5	162	7	480	2	4	21	818
Unidentified beaked whale					1	5			1	5
Total	99	2927	59	1494	111	5113	55	3622	324	13156

Acoustic monitoring for cetaceans during line-transect surveys is conducted using a towed hydrophone array. A 300 m lead wire connects the array to the vessel and the leading edge of the hydrophone is wrapped with 15 lbs of lead wire to submerge the array. Each pre-amplified element was band-pass filtered from 3 kHz to 100 kHz to decrease high-intensity, low-frequency flow noise and provide protection from signal aliasing at high frequencies. The multi-channel array data were digitized using a Mark of the Unicorn (MOTU) 896 sound system which recorded the data directly to a computer hard drive using the software program *Ishmael*. An acoustic technician listened to sounds received from the towed array while visually monitoring a scrolling spectrogram of the incoming sounds on a computer display.

Acoustic monitoring during CalCOFI stations was conducted with broadband AN-SSQ-57B sonobuoys. Sonobuoys are expendable hydrophones, sensitive from 20 Hz to 20 kHz, with radio data links for transmission of acoustic data to the ship. Sonobuoys were deployed one nautical mile before each daylight station to a depth of 30m and were recorded for the 2-3 hours. The received acoustic signal was digitized with a SoundBlaster SB0300 24-bit external soundcard and recorded directly to computer hard drive using *Ishmael*. An acoustic technician monitored the sonobuoy signals for cetacean calls using a scrolling spectrogram display. Mysticete calls, sperm whale clicks, and dolphin calls, including whistles, burst pulses, and the low frequency component of their clicks, could be recorded with this system. These data provide an expanded database of calls produced by a known, visually-identified species.

RESULTS

Visual sighting and school size data are summarized in Table 2 for all cetacean species. The most commonly sighted large whales were blue, fin, humpback, gray and sperm whales, while long- and short-beaked common dolphins, Pacific white-sided dolphins, northern right whale dolphins, bottlenose dolphins, and Dall's porpoise were the most commonly seen small cetaceans. Results from the visual surveys indicate that blue and fin whales were seen more frequently during summer and fall surveys, while Dall's porpoises and Risso's dolphins were seen more frequently during winter and spring.

DISCUSSION

Our preliminary results suggest patterns of seasonality and geographic distribution, which may eventually be interpreted as habitat preferences. Hydrographic, net tow, and acoustic backscatter data collected on the CalCOFI platform provide a unique opportunity to examine the distribution of cetacean species in the context of the entire ecosystem from physical forcing through zooplankton and fish, the primary prey of most cetaceans species. Our future investigations will focus on developing predictive habitat models to understand the role cetaceans play in the ecosystem off southern California.

The modeling of CalCOFI environmental and marine mammal occurrence data, combined with collection of new visual and acoustic distribution data, provide an ideal dataset for constructing marine mammal habitat models. We hope these models will enable researchers and managers to better understand ecological relationships in this marine system by providing improved abundance estimates and baseline distribution information for studying anthropogenic impact. The incorporation of visual and acoustic cetacean surveys to CalCOFI cruises allows us to examine seasonal and interannual distribution patterns on a finer temporal scale than has been achieved for previous surveys in the eastern North Pacific Ocean.

Project Publications

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- Kim, K. H., P. Hursky, M. B. Porter, J. A. Hildebrand, E. E. Henderson, and S. M. Wiggins. Automated passive acoustic tracking of dolphins in free-ranging pods. **Proceedings of the Eighth European Conference on Underwater Acoustics**, Edited by S. M. Jesus and O. C. Rodríguez Carvoeiro, Portugal 12-15 June, 2006.
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- M. S. Soldevilla, S. M. Wiggins, E. E. Henderson, G. S. Campbell, J. A. Hildebrand and M. A. Roch. Delphinid species classification using spectral properties of echolocation clicks. **Journal of the Acoustical Society of America** (submitted).

Abstracts

- Sean M. Wiggins, Chris Garsha, Greg Campbell, and John A. Hildebrand. High-frequency Acoustic Recording Package (HARP) for long-term monitoring of marine mammals. **Journal of the Acoustical Society of America** 120, 3015 (2006)
- Marie A. Roch, Melissa S. Soldevilla, Jessica C. Burtenshaw, E. Elizabeth Henderson, Sean M. Wiggins, and John A. Hildebrand. On the use of the Teager energy operator for the detection of clicks in free-ranging dolphins. **Journal of the Acoustical Society of America** 120, 3014 (2006)
- Catherine L. Berchok, Gerald L. D'Spain, and John A. Hildebrand. Reducing source localization errors: A visualization method to help guide the design, calibration, and use of widely separated acoustic sensor arrays. **Journal of the Acoustical Society of America**. 120: 2999 (2006)
- Melissa S. Soldevilla, Sean M. Wiggins, Annie B. Douglas, John Calambokidis, and John A. Hildebrand. Spatial and temporal patterns of dolphin occurrence off Southern California. Presented at the **CalCOFI Conference** December 2006
- Melissa S. Soldevilla, Marie A. Roch, Sean M. Wiggins, John A. Hildebrand. Spatial and temporal patterns in delphinid calling bouts offshore of Southern California. Presented at the **3rd International Workshop on Detection and Classification of Marine Mammals using Passive Acoustics**, Boston, MA July 24-26, 2007.
- E. M. Oleson, S. M. Wiggins, and J. A. Hildebrand. The impact of non-continuous sampling on cetacean acoustic detection probability. Presented at the **3rd Workshop on Acoustic Detection and Classification of Marine Mammals**. Boston, MA 24-26 July, 2007.
- Marie A. Roch, Melissa S. Soldevilla, Jessica C. Burtenshaw, Rhonda Hoenigman, Sean M. Wiggins, John A. Hildebrand. Comparison of machine learning techniques for the classification of echolocation clicks from three species of odontocetes. Presented at the **3rd Workshop on Acoustic Detection and Classification of Marine Mammals**. Boston, MA 24-26 July, 2007.

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