ResearchGate

See discussions, stats, and author profiles for this publication at: https://www.researchgate.net/publication/314240353

Estimation of minke whale abundance from an acoustic line transect survey of the Mariana Islands

Article *in* Marine Mammal Science · March 2017

DOI: 10.1111/mms.12397

CITATIONS
17

READS
310

4 authors:

Thomas Norris
Bio-Waves Inc.
31 PUBLICATIONS 1,027 CITATIONS
SEE PROFILE

Kerry Dunleavy
Bio-Waves Inc.
5 PUBLICATIONS 17 CITATIONS
SEE PROFILE

Tina Yack
EcoSound Bioacoustics
29 PUBLICATIONS 310 CITATIONS
SEE PROFILE

Elizabeth Ferguson
Ocean Science Analytics
16 PUBLICATIONS 29 CITATIONS
SEE PROFILE

Some of the authors of this publication are also working on these related projects:

NAVFAC marine mammal monitoring program View project

Density Classification & Localization Workshop View project

All content following this page was uploaded by Elizabeth Ferguson on 27 December 2017.

The user has requested enhancement of the downloaded file.

Marine Mammal Science

MARINE MAMMAL SCIENCE, 33(2): 574–592 (April 2017)
© 2017 Society for Marine Mammalogy
DOI: 10.1111/mms.12397

Estimation of minke whale abundance from an acoustic line transect survey of the Mariana Islands

THOMAS F. NORRIS, KERRY J. DUNLEAVY, TINA M. YACK,[1] ELIZABETH L. FERGUSON,[2]
Bio-Waves, Inc., 1106 2nd Street, #119, Encinitas, California 92024, U.S.A.

ABSTRACT

The minke whale is one of the most abundant species of baleen whales worldwide, yet is rarely sighted in subtropical waters. In the North Pacific, they produce a distinctive sound known as the "boing," which can be used to acoustically localize individuals. A vessel-based survey using both visual and passive acoustic monitoring was conducted during the spring of 2007 in a large (616,000 km^2) study area encompassing the Mariana Islands. We applied line transect methods to data collected from a towed hydrophone array to estimate the abundance of calling minke whales in our study area. No minke whales were sighted, but there were hundreds of acoustic detections of boings. Computer algorithms were developed to localize calling minke whales from acoustic recordings, resulting in over 30 independent localizations, a six-fold increase over those estimated during the survey. The two best estimates of abundance of calling minke whales were determined to be 80 and 91 animals (0.13 and 0.15 animals per 1,000 km2, respectively; CV = 34%). These are the first density and abundance estimates for calling minke whales using towed hydrophone array surveys, and the first estimates for this species in the Mariana Islands region. These are considered minimum estimates of the true number of minke whales in the study area.

Key words: minke whale, *Balaenoptera acutorostrata*, passive acoustics, density estimation, Pacific, Mariana Islands, marine mammals.

The common minke whale (*Balaenoptera acutorostrata*) is the second smallest species of baleen whale but the most abundant, with a wide distribution from the ice-edge to the tropics (Jefferson *et al*. 1993, 2015). In tropical and subtropical areas in the North Pacific, they typically occur individually or in small groups of two to three animals, produce inconspicuous blows, and remain at the surface for very short periods of time. Due to these characteristics, visual survey methods are not well-suited for surveying and detecting minke whales in these regions.

During the winter and spring seasons in the North Pacific Ocean, minke whales produce a unique type of call known as the "boing" (Rankin and Barlow 2005). Boings are complex, amplitude modulated calls that last 3–5 s with a peak frequency near 1.5 kHz. The function of the boing is unknown, but is possibly an acoustic display that plays a role in courtship and reproduction similar to that in other species of

[1]Current address: EcoSound Bioacoustics, LLC, 9423 Saint Andrews Drive, Santee, California 92071, U.S.A.

[2]Corresponding author (e-mail: eferguson@bio-waves.net).

baleen whales (Croll *et al.* 2002, Herman *et al.* 2013) and the closely related population of dwarf minke whales (*Balaenoptera acutorostrata* subspecies) in the Great Barrier Reef off of NE Australia (Gedamke *et al.* 2001). Based on seafloor recordings, a peak in calls detected around the Hawaiian island of O'ahu typically occurs between February and March (Thompson and Friedl 1982, Oswald *et al.* 2011) when courtship and breeding would be expected to occur. Regardless of the function of boings, they are a distinctive sound that can be easily detected and localized using towed hydrophone arrays (Rankin and Barlow 2005, Norris *et al.* 2012, Martin *et al.* 2013). In this paper, we provide information about the density, abundance, and distribution of calling minke whales, estimated using passive acoustic data collected during a line transect survey of the Mariana Islands in the western North Pacific Ocean.

Line transect survey methods are based on "distance sampling" theory (Buckland *et al.* 2001) and are well developed for estimating density and abundance of marine mammals using visual observation data (Holt 1987, Buckland *et al.* 2004). Line transect methods require measurements of the perpendicular distances of animals from the survey track, but are relatively robust to unbiased measurement errors (Marques 2007). The perpendicular distance data are then used to model a "detection function," in order to estimate the "effective strip width" that is used in the formula to estimate density and abundance (Buckland *et al.* 2004). The detection function models the probability of sightings (or acoustic localizations, in our case) as a function of increasing perpendicular distance from the survey trackline. One important assumption of line transect methods is that all animals located along the trackline are detected. This is often referred to as "$g(0) = 1$" (Buckland *et al.* 2004).

The same analytical approach that is used for visual-based line transect surveys can be applied to acoustic data of animal locations estimated using a towed hydrophone array system. This requires estimating perpendicular distances of vocalizing animals from the trackline. Towed hydrophone arrays are now commonly used during vessel based surveys of marine mammals (Rankin *et al.* 2008*a*, Van Parijs *et al.* 2009).

When using a towed hydrophone array system, a method of localization known as "target motion analysis" is typically used to localize marine mammals (Leaper *et al.* 1992, Barlow and Taylor 2005). This method involves estimating the location of a "target" (*i.e.*, a sound source) based on the convergence of sequential bearings that are calculated using data processed from a narrow aperture, dipole hydrophone array (*i.e.*, two hydrophones that are closely spaced). When target motion analysis is used for localizing marine mammals it requires that individual animals are calling relatively frequently, are solitary or occur in small, tightly clustered groups, and are stationary, or are moving slowly relative to the speed of the survey vessel. Target motion analysis has been used effectively for localizing sperm whales (*Physeter macrocephalus*), beaked whales, and some species of porpoise, and for acoustic-based abundance estimation of these and other species of marine mammals using line transect survey methods (Barlow and Taylor 2005, Gerrodette *et al.* 2011, DoN 2015). However, this technique has not yet been used for acoustic-based density estimation for baleen whales.

Various other methods have been used to localize baleen whales using towed hydrophone array systems. For example, Clark and Fristup (1997) used other localization methods with a long-baseline towed hydrophone array to conduct surveys of blue (*Balaenoptera musculus*) and fin (*Balaenoptera physalus*) whales in the Southern California Bight. Croll *et al.* (2002) used beamforming methods to survey and monitor fin whales in the Sea of Cortez, but made no attempt to estimate densities of animals. These localization methods require larger and more expensive hydrophone arrays, and more complex software and processing systems. We chose to use target motion analysis for localization and line transect methods for the abundance estimation, as the former is relatively simple to implement and the latter approach is well accepted for abundance estimation.

In the winter and spring of 2007, the first large-scale systematic survey for marine mammals in the Mariana Islands was conducted as part of an effort to survey the U.S. Navy's Mariana Island Range Complex[3] (MIRC) (DoN 2007, Fulling *et al.* 2011). This survey was conducted in order to generate reliable estimates of marine mammal density in the MIRC study area for use by Navy resource managers and planners. The MIRC region includes a chain of volcanic islands and atolls, a large U.S. Navy base, and the deepest underwater trench in the world, the Mariana Trench (DoN 2005). The study area was approximately 616,000 km^2. Combined visual and acoustic monitoring were conducted using line transect survey methods; however, only the visual sighting data were used to estimate density and abundance for some species of marine mammals (Fulling *et al.* 2011). Because there were no sightings of minke whales during the survey, it was not possible to estimate distribution, density, or abundance for minke whales from the visual survey data. During the survey, 29 "unique acoustic detections" of minke whales were made, of which only five were localized (DoN 2007). Unique acoustic detections were considered an approximation of independent detections of animals. Since the time of that survey, new semiautomated acoustic processing computer algorithms have been developed to more efficiently and effectively estimate localizations and perpendicular distances for use in line transect density and abundance analyses (Norris 2012). The objective of our study was to postprocess and analyze the recorded acoustic data in order to estimate the density and abundance of calling minke whales in the MIRC study area.

Methods

Field Methods

A 56.5 m offshore supply ship (the M/V *Kahana*) was used to conduct line transect surveys of marine mammals in the Mariana Islands in the winter/spring of 2007 (Fulling *et al.* 2011). The 236 metric ton ship was powered by twin Caterpillar D399 engines. It was outfitted with two "big-eye" (25 × 150 Fujinon) binoculars mounted on the flying bridge for marine mammal observers to search for and locate animals.

A hydrophone array was towed approximately 400 m behind the stern of the vessel during daylight hours. The hydrophone array consisted of two hydrophone elements and preamplifiers, potted in polyurethane, with 3 m separation between them. The hydrophone array had an effective (*i.e.*, useable) frequency response from approximately 200 Hz to 50 kHz. The two channels of acoustic data from the hydrophone array were transmitted as analog signals up the electrical tow cable to the acoustics room located in a shipping container on the back deck of the vessel. Both channels were passed through a low pass filter system (Alligator Technologies, AAF-1 model) with a corner frequency fixed at 48 kHz for antialiasing. A tunable high-pass filter (Krohn-Hite model 3382) was used to reduce flow noise and vessel self-noise, as well as to add any gain necessary to match the signal levels on both channels. This eight-

[3]This area is a subregion of the area now called the Mariana Islands Training and Testing Area (MITT).

pole filter provided selectable input gains to 50 dB as well as two filter types (Butterworth or Bessel). The Butterworth filter was typically used with the specific corner frequencies of the filters set by the acoustic operator, between 100 Hz and 500 Hz, to reduce low frequency vessel and sea noise conditions as needed to better listen to and view the spectrograms of incoming data. Corner frequencies and gain settings were logged by the operator whenever they were changed.

A multichannel digital audio interface (MOTU Traveler Mk-1) was used to digitize the incoming analog hydrophone signals at a sample rate of 96 kHz at 24 bit resolution. This allowed an effective audio range of up to 48 kHz and a dynamic range of 144 dB. The digitized audio signals were then passed to a desktop computer for further signal processing and recording.

A custom built PC desktop computer system was used to run the bioacoustic analysis software program *Ishmael* (Mellinger 2001) in real time. *Ishmael* was used for real-time spectrographic display, processing, and recording of the acoustic data from the towed hydrophone array. Two-channel recordings (*i.e.*, one channel from each hydrophone) were saved in WAV file format at a sampling rate of 96 kHz. Durations of recording files were limited to 10 min to allow easier file management and postprocessing of data. *Ishmael* was also used for near real-time calculation of bearings to signals for localization (Mellinger 2001). Bearings estimated using *Ishmael* were sent to a separate laptop computer that was connected *via* ethernet to the desktop computer. *Whaltrak II* software[4] was used to plot the bearings, the ship's track and current location, and other relevant information in a window with a map display. Bearing plots were used to estimate locations of vocalizing animals (or compact groups of animals) using methods commonly referred to as "target motion analysis" (Leaper *et al*. 1992).

When possible, localizations were estimated in real-time during the survey. Localization estimates were based on the convergence of bearing lines plotted on a map in a window of *Whaletrack II*. The latitude and longitude of each localization were saved in a Microsoft Access database. If the point of localization could not be reliably estimated (*i.e.*, because the bearings lines did not converge precisely enough), but the bioacoustics operator considered it to be an independent acoustic encounter (*i.e.*, the encounter was believed to be from a single animal), it was assigned an identification number to designate it as a "unique encounter." The unique encounters were used as an approximation of the minimum number of independent acoustic encounters with animals that occurred during the survey.

Postprocessing

Following the survey, a preliminary review of the acoustic summary data was conducted to assess how many independent "acoustic encounters" (*i.e.*, unique acoustic detections) occurred for each species. This information was used in the final survey report (DoN 2007). Acoustic encounters were defined using both quantitative and qualitative criteria. For example, the amount of time that had passed between boing detections, whether the bearings for boings converged, and consistency of source bearing angles (*i.e.*, if they were coming from apparently different source locations). Any comments made by the bioacousticians in the logbook were reviewed to determine whether an acoustic encounter was independent. This information was used in the

[4]Developed by Dr. G. Gailey at Texas A&M University, Galveston, TX; currently at Cascadia Research Collective, Olympia, WA.

final survey report to provide an estimate of the minimum number of independent minke whales that were acoustically encountered during the survey (DoN 2007).

At the time of the field study and the field report, there was insufficient funding available to conduct a more comprehensive analysis of the data, such as density estimation for minke whales. Due to the limited processing techniques available for passive acoustic data at this time, such an analysis would have required a manual approach to reprocessing the acoustic data. Several years later we developed computer algorithms that allowed for more efficient, semiautomated detection and localization of boings, with intermediate data outputs that could be easily imported into distance sampling software for further analysis. Therefore, the density estimation analysis was delayed until these more efficient processing and analysis methods became available.

The following steps were used to reprocess all the acoustic and ancillary data. Boings were detected using an automated call detector (developed by D. Mellinger, Oregon State University/Pacific Marine Environmental Laboratory) using the bioacoustic program *Ishmael*. The boing detector was run on all acoustic data recorded during the survey. All automated detections were visually reviewed and confirmed by a trained data analyst to identify and remove false detections. All verified detections were then imported into a database for additional processing. This database, along with the original Microsoft Access database (from *Whaletrack II*) from the field survey, were used as the two main inputs for the localization analysis.

The original acoustic WAV files recorded during the survey and the postprocessed database of automatically detected boings were analyzed further using a custom developed Matlab program called *Boinger* (written by Ricardo Antunes, St. Andrews University and Michael Oswald, Bio-Waves, Inc.). This program was developed in order to efficiently review each boing detected from the large number of acoustic WAV files and also to estimate perpendicular distances from the trackline to calling animals. These "distance data" were then used as inputs to the density estimation analysis program, *Distance* (Version 6; Thomas *et al.* 2010*a*). Data analysts used *Boinger* to automatically plot bearings to the sound source for each boing. Maps of potential localizations were plotted for visual review by the data analysts (Fig. 1, 2). Each boing was analyzed further by calculating the dominant signal component (DSC) values in *Boinger* (see bottom-left panel of Fig. 1) (Martin *et al.* 2013, 2014). The DSC is the peak frequency within a particular frequency band in the call, and is unique to individual minke whales (Martin *et al.* 2013) over the short periods of times used in localization and tracking individuals (Martin *et al.* 2014). A graph of the cross correlation function (used by the algorithm to estimate the time delay of signal arrival between two hydrophones) was reviewed by the data analyst to provide information about the relative errors in the bearing angle estimation (Mellinger 2001). The general shape of the cross-correlation function provides information about the fit of the cross-correlation between the same signal being compared from the two hydrophones. For example, if there was a sharp peak in the function, it was considered a high quality cross-correlation. Alternatively, if the correlation had an ambiguous or relatively low peak, or if it had multiple peaks at similar heights, it was considered a poor quality cross-correlation, and the bearing was excluded from the analysis. Each bearing was reviewed and only good quality bearings were included in the localization analysis. *Boinger* used these "analyst approved" bearings for the final localization estimate. The geographic location was estimated by calculating the mean location of the geographic coordinates of all the intersection points for each bearing pair used. The final output of *Boinger* included times and angles of bearings, georeferenced positions of localizations, maps of the ship track, and the perpendicular distance (hereafter distance data) of acoustic localizations to the ship trackline. Finally, the distance data were imported into the software program *Distance* for density and abundance estimation analysis.

There is an inherent left/right ambiguity in acoustic localizations estimated from towed hydrophone arrays that is due to the two dimensional, linear design of any towed hydrophone array system. For the localization methods most commonly used in towed array systems, the animal is assumed to be located on a plane at the same depth of the towed array. This simplification results in two possible solutions to every localization. Furthermore, because the ship was not always traveling in a perfectly straight line and the array was not always streaming directly behind the ship (*i.e.*, perfectly coincident with the ship-track), the estimated perpendicular distances to the trackline from the left and right solutions for localizations were not always equidistant. It is not possible to resolve this left/right ambiguity without having detailed information about the exact heading or location of the towed hydrophone array. In these cases, the mean value of the left and the right perpendicular distance was used to approximate the perpendicular distance from the trackline. In cases in which the ship turned or deviated significantly from the planned ship track, it was sometimes possible to resolve which side the animal was on (*e.g.*, when bearing lines

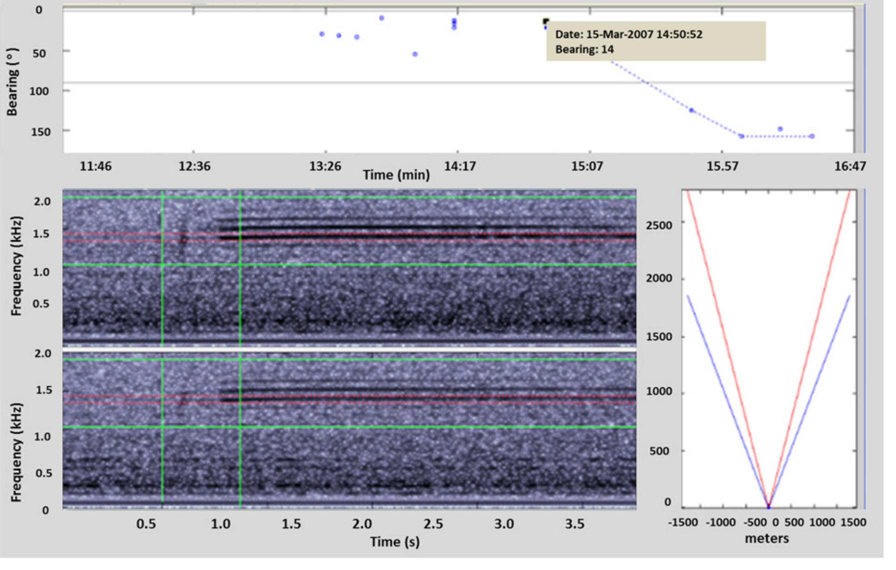

Figure 1. Example of a bearing *vs.* time display (top panel) and a spectrogram *vs.* time display (bottom panel) from the matlab algorithm *Boinger*. The top panel depicts a bearing *vs.* time display in which a series of bearings calculated from boings are plotted (in this case about 518 min of data). The bottom panel includes two spectrograms, one from each hydrophone channel of the towed hydrophone array. A single boing is evident starting at approximately 0.6 sec. and continuing to the end of the spectrogram (a short upsweep followed by series of tonal bands located between the green horizontal lines). The panel on the bottom right is a plot of the bearing calculated in the field (red) and the bearing calculated using *Boinger* (blue) (note the presumed error in the field estimated bearing). The Dominant Signal Component (DSC; a frequency-windowed peak frequency value) is calculated within the user specified band between the two horizontal green lines overlaying the spectrograms. The broken red lines indicate the expected range of the DSC value (based on Martin *et al.* 2013) to allow the user to decide if there is an "atypical" DSC value present.

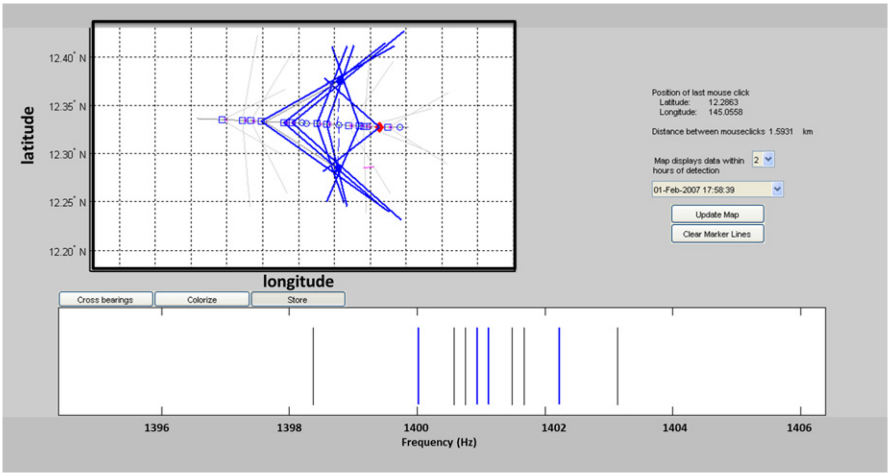

Figure 2. Example of the *Boinger* localization and Dominant Signal Component (DSC) value window. Top panel depicts a localization plot of sequential bearings to a calling minke whale, with good quality localizations shown in blue. Shaded gray lines in the top panel represent bearings to boings that were not selected for use in the localization. The associated DSC values are displayed in the bottom panel, with vertical lines in blue, indicating that the DSC values from this localization are clustered within a few Hz of each other (centered approximately around 1,401 Hz). Combined, this information suggests that the boings and associated bearings are likely from the same animal.

converged only on one side of the ship's track). In such cases, the perpendicular distance for the side where bearing lines converged was used.

Density Estimation

The distance sampling analysis program *Distance* was used to determine detection functions, encounter rates, and effective strip widths in order to estimate the density and abundance of calling minke whales. The following formula was used for abundance estimation (Buckland *et al*. 2001):

$$\hat{N} = \frac{nsA}{2wL\hat{P}_a\hat{g}_0},$$

where $\hat{N}$ is the estimated abundance, n is the number of animals acoustically localized, s is the animal group or cluster size, A is the area of the study area (km^2), w is the strip width surveyed on each side of the survey trackline, L is the total length of on-effort trackline surveyed, $\hat{P}_a$ is the average probability of detecting an animal between distance 0 and w, and $\hat{g}_0$ is the probability of detecting an animal at distance of 0. For this study, both s and $g(0)$ are assumed to equal 1.

Given the assumptions that s and $\hat{g}_0 = 1$, the formula can be simplified to:

$$\hat{N} = \frac{nA}{2wL\hat{P}_a}.$$

Frequency histograms of the perpendicular distances to minke whales were created and visually inspected. Prior to analysis, distances beyond 20 km were removed (*i.e.*, the data were right truncated). Right truncation is a standard approach used in distance sampling analysis to improve the fit of the detection function model and reduce potential bias in the detection probability estimate (Buckland *et al.* 2001). We also applied left truncation using a 1 km cut-point (*i.e.*, removing distance data <1 km) to reduce the potential bias related to the low number of observations in the first bin (*i.e.*, distances closest to the trackline) (Thomas *et al.* 2010*b*). The rationale for taking this approach was to address the possibility that animals were reducing their calling rate in response to the survey vessel (and therefore were not detectable near the trackline), or were not detectable along the survey track ahead of the survey vessel due to limitations of towed hydrophone arrays to accurately obtain bearings directly ahead of the array (Rankin *et al.* 2008*b*).

Several types of detection function models were fit to the data to estimate the probability distribution of distances from the trackline. Detection function models that were tested included key functions with added adjustment terms for additional flexibility (Buckland *et al.* 2001). We used the conventional distance sampling in the program *Distance* to fit Hazard-Rate and Half-Normal models with and without adjustment terms. Akaike's Information Criterion (Akaike 1973) was used for selection of the best-fit model for both the right truncated and left truncated models. For all final models, variance estimates and confidence intervals were obtained using a nonparametric bootstrap to resample lines (n = 999) within strata as described in Buckland *et al.* (2001).

Distribution Analysis

The estimated water depth of each minke whale acoustic encounter was derived from ETOPO2 2 minute global relief data using ARC GIS tools (version 10.1, ESRI, Inc.). A Global Moran's I test in ARC-GIS was used to evaluate spatial autocorrelation of the acoustic encounters over the bathymetric gradient.

Results

Postprocessing

Over 700 h of acoustic recordings were processed using *Ishmael* (for automatic detection of boings) and *Boinger* (to obtain localizations). This resulted in 30 independent minke whale localizations, representing a six-fold increase over the five localizations obtained in the field, but just one more than the 29 unique detections estimated as independent acoustic encounters in the final report (DoN 2007).

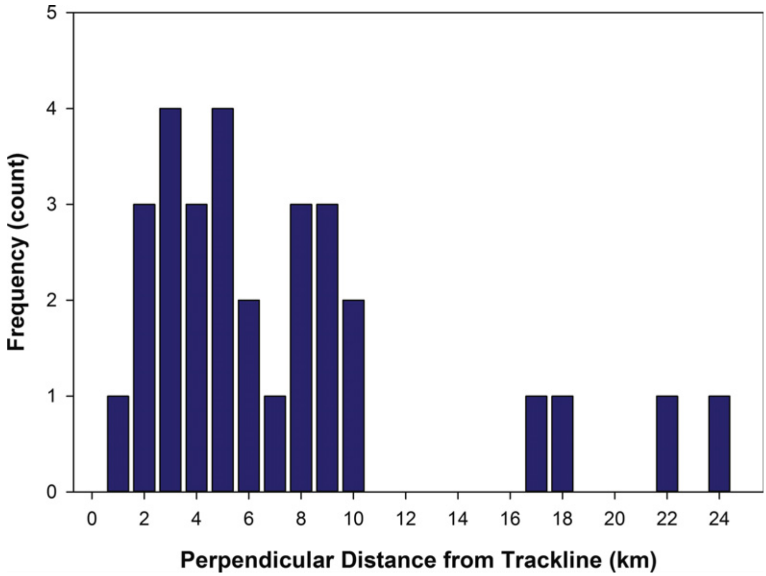

Figure 3. Histogram of the perpendicular distances of localizations to the trackline (1 km bins) with counts of each localization on the *y*-axis. Note the decreased number of localizations that occur in the first bin (1 km) relative to bins two through five. This pattern can be caused by animals that are either avoiding the vessel as it approaches, or are reducing (or ceasing) vocalizations.

Abundance and Density Estimates

The frequency histograms of the perpendicular distances indicates a lower number of detections in the first two distance bins that are closest to the trackline compared to the next three distance bins (Fig. 3). To account for this unusual distribution, detection functions were modeled for two possible scenarios: (1) animal movement away from the trackline/survey vessel and (2) a reduction in vocalization rate for animals near the survey vessel (trackline), and/or a limitation of the towed hydrophone array to detect animals in front of the vessel (along the trackline). These two scenarios were considered the most likely explanations for the unusual frequency distribution of distances (Janik and Thomas 2012, Norris *et al.* 2012).

For Scenario 1, data were right truncated at 20 km to increase robustness of the model fit. Left truncation was not used in this model. The best fit model was a Half Normal Key function (Fig. 4). The resulting abundance estimate for calling minke whales in the study area using this detection function was 80 (95% CI 41–155; ESW = 9.1 km; Table 1) and density was 0.13 animals per 1,000 km^2 (CV = 34%). This estimate is based on the assumption in Scenario 1, that calling animals redistribute (*e.g.*, move away) when the survey vessel passes nearby.

For Scenario 2, all distance values <1 km were deleted (*i.e.*, left truncated) and values at a distance of greater than 20 km were removed (*i.e.*, right truncated) in order to increase robustness of the model fit. The best fit model for the detection function was a Half Normal Key function (Fig. 5). Left truncation was used to eliminate any bias in the detection function due to the possibility that some animals were present, but were not vocalizing (or decreased vocalization rates enough to avoid localization)

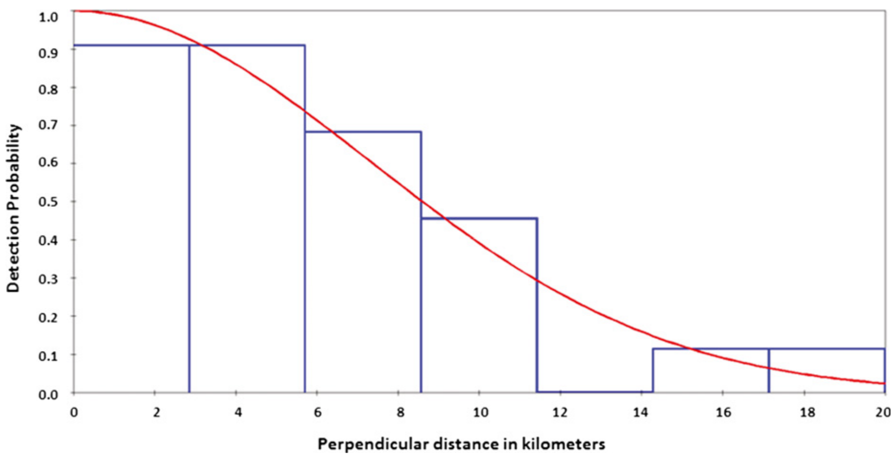

Figure 4. Probability of detection (vertical axis) and detection function modeled for Scenario 1 (which assumes avoidance movements by animals near the survey vessel). The best fitting model was the half normal key function. Right truncation at 20 km was applied to allow for a more robust model fit. Note that these data are binned differently (*i.e.*, multiple bins were combined) compared to the data in Figure 3.

Table 1. Summary of acoustic-based abundance (N) and density (D) estimates for calling minke whales using the software program *Distance* are provided with the associated coefficient of variation (CV) and estimated strip width (ESW). The two scenarios are the same as presented in the results; Scenario 1 assumes animal avoidance of the survey vessel (See Results for details). Scenario 2 assumes a reduction in vocalization rates near the survey vessel or trackline.

Scenario	*N*	95% CI	*D*	CV (%)	ESW (km)
1	80	41–155	0.13	34	9.1
2	91	48–176	0.15	34	7.7

Note: *N* = estimated abundance, *D* = estimated density (animals per 1,000 km^2), CV = coefficient of variation, ESW = effective strip width.

due to the presence of the research vessel, or could not be detected due to their location directly ahead of the survey vessel where the towed hydrophone array is less likely to pick up their sounds. For Scenario 2, the abundance estimate of calling minke whales in the study area was 91 (95% CI 48–176, ESW = 7.7 km) and the density was 0.15 animals per 1,000 km^2 (CV = 34%; Table 1). This is a difference of only 11 animals from the Scenario 1 estimate. The 95% CIs for the two possible estimates overlap and we leave it up to the reader to decide which estimate is most appropriate for their question or management needs. It should be noted that these estimates should be considered a minimum of the true number of animals present as it only represents animals that are calling for a long enough period of time to localize, and it does not include animals that may have responded to the survey vessel, or were not detectable due to limitations of the towed hydrophone array system used.

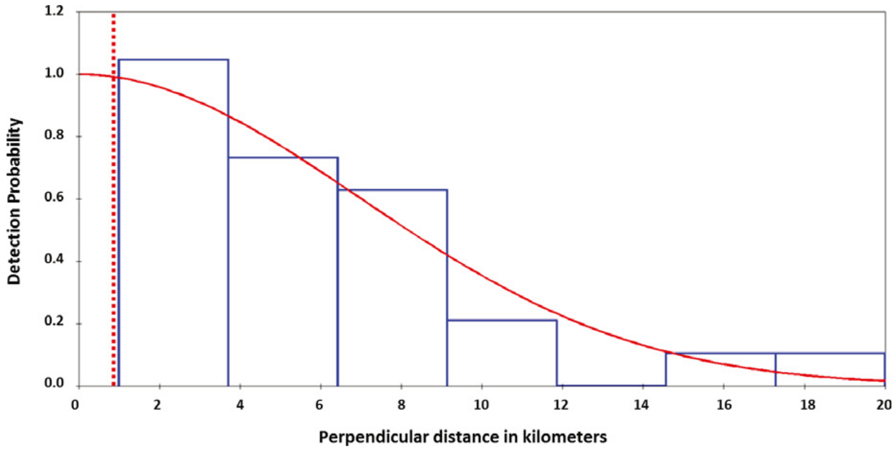

Figure 5. Probability of detection (vertical axis) and detection function modeled for Scenario 2. This scenario assumes a reduction in calling behavior of minke whales near the trackline. The best fitting model was the half normal key function. Left truncation was used at 1 km to remove bias associated with reduced calling rates. The dashed red line indicates the left truncation point. Note that these data are binned differently (*i.e.*, multiple bins were combined) compared to the data in Figure 3.

Distribution

Minke whales were more likely to be detected in deep water (>1,000 m), with the highest number of encounters occurring in ocean depths between 3,000 and 7,000 m (Fig. 6). A Global Moran's I spatial autocorrelation test showed that minke whale encounters were clustered with respect to ocean depths (Moran's I Index = 1.35, Z-score = 7.97, $P < 0.01$).

Discussion

Acoustic methods have the ability to detect and locate vocally active marine mammals underwater, and therefore are more likely to detect some species of baleen whales relative to visual methods (Clark and Fristrup 1997, Rankin and Barlow 2005). There are also advantages to using passive acoustic methods for identifying important habitat for species of marine mammals with low densities (Rogers *et al.* 2013). Due to the elusive and inconspicuous nature of minke whales in subtropical waters, in addition to the poor sighting conditions that are pervasive in the Mariana Islands and the study area (DoN 2007, Fulling *et al.* 2011), it is unlikely there would ever be a sufficient number of sightings from a visual line transect survey in this region to reliably estimate minke whale abundance. We therefore chose to use well established line transect survey methods coupled with passive acoustic methods utilizing towed hydrophone arrays to estimate abundance of calling minke whales in our study area. Using new computer algorithms to efficiently postprocess these data, we were able to greatly increase the number of localizations over six-fold from those determined in the field, allowing enough samples to statistically estimate density and abundance of calling minke whales. The two best estimates of the abundance of calling minke

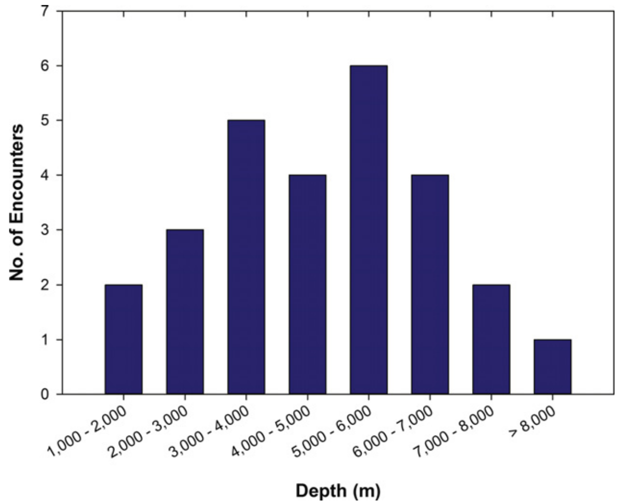

Figure 6. Depth distribution of acoustic encounters with minke whales showing the number of minke whale acoustic encounters (*y*-axis) that occurred in each depth gradient bin (*x*-axis).

whales were determined to be 80 and 91 animals (or a density of 0.13 and 0.15 animals per 1,000 km2, respectively; CV = 34%) in the relatively large (616,000 km^2) study area. These should be considered minimum estimates of the true number of animals present as they only represents animals that are actively calling for an extended period of time and do not include animals that may have responded to the survey vessel, or were not detectable due to limitations of the towed hydrophone array system used. Martin *et al.* (2013) used fixed seafloor arrays to estimate between 0.18 and 1.17 calling minke whales per 1,000 km^2 in their much smaller 3,780 km^2 study area off the island of Kauai, Hawaii. The density varied in relation to Navy training activities that occurred in the area, with approximately 0.74 calling animals per 1,000 km^2 occurring before training activities commenced. The results of our study provide the first density estimates for this visually elusive, but acoustically active species of baleen whale in the large MIRC study and Navy testing area. This is also the first line transect based estimate of minke whale abundance using data collected from a towed hydrophone array system.

The majority of acoustic encounters occurred near, but not directly over the deepest regions of the Mariana Trench (Fig. 7). The distribution of these encounters relative to water depth revealed some obvious and interesting patterns (Fig. 6). First, all animals were detected in water depths greater than 1,000 m. There was a bimodal peak in the distribution with peaks at 3,000–4,000 m and 5,000–6,000 m with an average depth of approximately 5,000 m. Further inspection of the map of localizations (Fig. 7) indicated that animals were not distributed near islands nor along the axis of the Mariana Trench (which include the deepest water depths in the world), but instead were mostly distributed along the relatively steep walls of the Mariana Trench. These preliminary analyses indicate that minke whale habitat associations in this study may be driven by static features such as water depth and bathymetry slope. Additional, more detailed analysis of these and other related environmental data will be required to further elucidate and verify these preliminary findings. A quantitative analysis of these data using a multivariate analysis of physiographic and oceanographic variables or using a habitat modeling approach would yield more insights into the strength of these associations (Redfern *et al.* 2008; Becker *et al.* 2010, 2012; Forney *et al.* 2012). Additional passive acoustic sampling of the region using autonomous recorders, sonobuoys, or using towed arrays deployed from vessels of opportunity might also allow more data to be collected in a cost effective manner to increase the encounter rate and sample size for such an analysis.

Several caveats, biases, uncertainties and potential violations of the assumptions for line transect distance sampling methods should be considered when interpreting the results of this study. First, it should be noted that these estimates were made for calling individuals. Therefore, the estimates must be considered minimum estimates of the true number of animals present in the study area. Minke whale calling rates are known to be variable. Based on previous passive acoustic studies off the Hawaiian Islands, minke whales appear to have at least two vocalization modes: slow calling (approximately one call every 5–6 min; Thompson and Friedl 1982), and fast calling (about two calls per min; Rankin and Barlow 2005). Calling rates for both of these vocalization modes were high enough so as not to miss detections or localizations of animals at the survey speeds (8–10 knots) that were used during our survey. Therefore the assumption that $g(0) = 1$ should not be violated based on calling rates alone. Other possibilities such as, a reduction in calling in response to vessels and biases in the detection and localization capabilities of towed arrays are considered in greater detail below.

There is also a known seasonality of calling activity of minke whales. There is no published information about seasonality of minke whales for the MIRC study area, but based on data collected from seafloor hydrophones around the Hawaiian Islands, minke whale boings are detected from late fall to late spring with peaks in calls detected typically during February through March (Thompson and Friedl 1982, Oswald *et al.* 2011). Our survey was conducted from mid-January to mid-April. If it is assumed that seasonal patterns for minke whales in our study area are similar to those in the Hawaiian Islands, then any seasonal effects on our abundance estimate should be reduced because the surveys were conducted during the expected seasonal peak in calling. Further investigation is needed to confirm the seasonal peak in calling in the Mariana Islands.

In other species of baleen whales, such as humpback whales (*Megaptera novaeangliae*), acoustic displays are produced exclusively by males, primarily during the winter/spring season, and most likely related to courtship and breeding (Darling 1983, Darling *et al.* 1983, Herman *et al.* 2013). Based on sex information from other species of baleen whales that sing or produce acoustic displays (Winn *et al.* 1973, Darling *et al.* 1983, Croll *et al.* 2002, Oleson *et al.* 2007), we consider it possible, even likely, that only male minke whales are producing boings. However, we do not have information about the ratio of vocalizing to nonvocalizing animals or the sex of calling animals. Therefore, we did not attempt to correct for the occurrence of nonvocalizing animals which were not detectable in our study.

Based on inspection of frequency histograms for detection distances of calling animals (Fig. 3), it is apparent that there is a gap in the number of detections near the trackline. This has several implications. The most problematic is that $g(0)$, the probability that all animals on the trackline are detected, is likely not equal to one (*i.e.*, some animals on or very near the trackline are not being detected). If all animals near the trackline are detected, the expected shape of the distribution of the number of perpendicular localizations from the survey trackline should be a half-bell or sigmoidal shaped curve with the greatest number of animals occurring near the

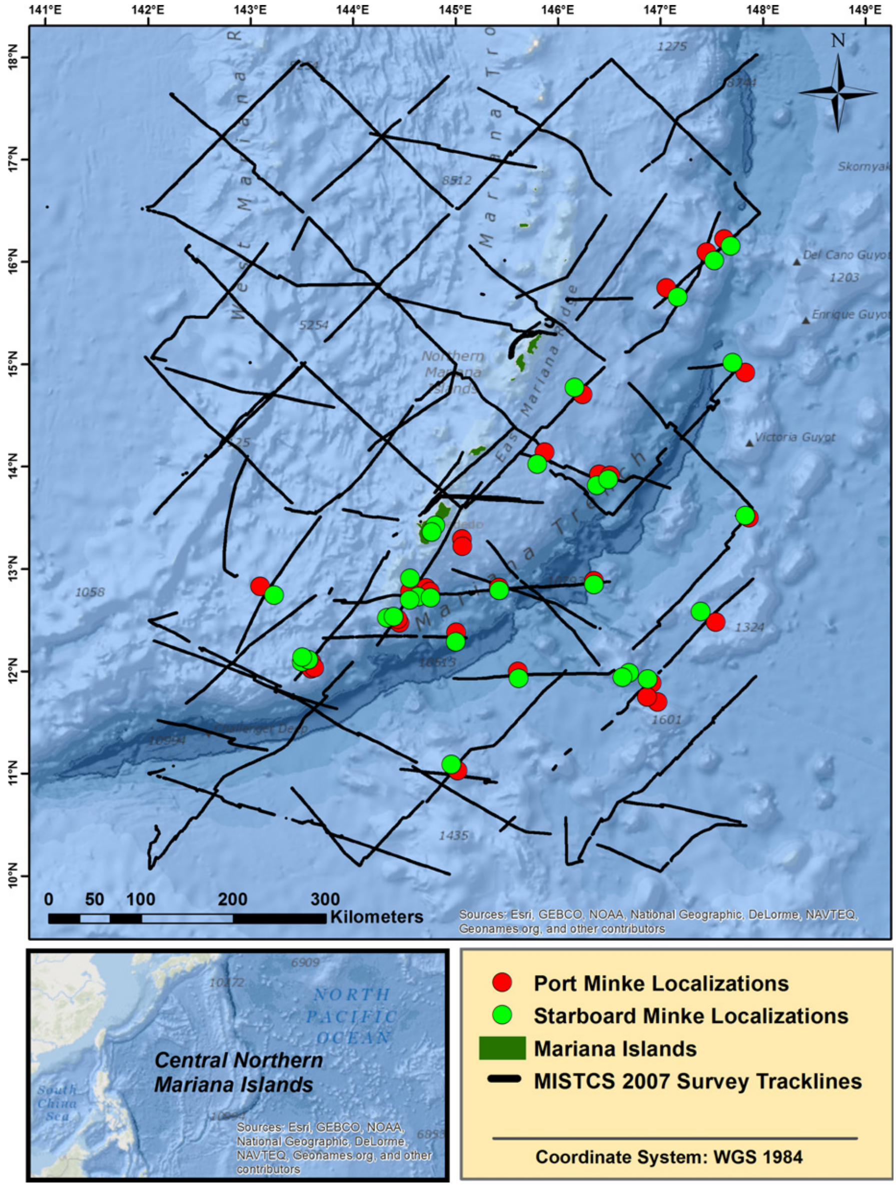

Figure 7. Map of the study area (top box) with ship tracks (black segments) and minke whale acoustic encounters along the trackline. The bottom left box indicates the Central Northern Mariana Island region where this survey took place. The port (red circles) and starboard (green circles) localizations are plotted for each acoustic detection, unless the left/right ambiguity was resolved when the ship turned, in which case a localization on only one side is plotted.

trackline, and fewer animals detected as the distance away from the trackline increases (Buckland *et at*. 2001). The assumption that $g(0) = 1$ is a fundamental assumption of line transect methods. In practice, this assumption is often violated, usually resulting in the true population size being underestimated (Thomas *et al.* 2002).

One possibility to explain the gap in localizations in the shoulder of the detection function is that animals are avoiding the survey vessel by moving away. This type of evasive movement of animals in response to the survey vessel is known to occur for some species of cetaceans (Au and Perryman 1982). This first possibility was modeled as Scenario 1 (Fig. 4). A second possibility is that animals reduce their calling rates when the survey vessel passes nearby. A third possibility is that the array is unable to detect animals near, or ahead of the trackline. For example, it has been demonstrated that for small bearing angles (*i.e.*, those <15° off the trackline) towed hydrophone arrays using cylindrical hydrophone elements and a small aperture have a limited ability to detect sounds ahead of the ship (Rankin *et al.* 2008*b*). The second and third possibilities would have a similar effect of reducing the number of animals of animals that are detected near the trackline, resulting in an underestimation of the true abundance. Therefore, we considered both these possiblities as Scenario 2 and modeled a single detection function with left truncation (Fig. 5). We have addressed what we believe to be the two main biases related to three possible explanations for the gap in detections near the trackline by modeling two separate detection functions for these two scenarios in the analysis, with the results not differing significantly (Table 1). We leave it up to the reader to decide which scenario is best for their management, research or other needs. More work is needed to investigate which of these scenarios is true. Acoustic data logger tags, location tags, passive acoustic tracking, or ideally some combination of these techniques can be used to elucidate these potential issues.

For the purposes of this analysis, it was assumed that the group size of all acoustic localizations was equal to one. There is only limited evidence to confirm this, but based on our experience, and those of our colleagues, we consider this assumption to be valid. We are aware of only four sighting events in the North Pacific in which minke whales were coincidentally localized using passive acoustic methods, and all consisted of single animals (Rankin and Barlow 2005, Rankin *et al.* 2007, Norris 2009, Norris *et al.* 2012). It is possible that two calling animals could be co-located, and therefore could not be easily differentiated from each other spatially using acoustic localization techniques. However, in this case one might expect calls to overlap, or at least occur with repetition rates that can be differentiated, which does not occur. Nor do we see animal tracks merging or splitting from two animals, albeit the resolution of localizations from towed array data might not be sufficient to see this on small scales (<100 m). After thousands of hours of effort with towed hydrophone arrays, boings almost never overlap in time. When they occur within a few seconds of each other (as sometimes occurs with counter-calling animals) there is usually a difference in the bearings and received call intensity to the alternating calls, indicating that they are being produced by different animals from different locations. However, considering the methods we used to collect and analyze the data, it is not possible to determine whether more than one individual was calling from exactly the same location, thus further research will be necessary to confirm our assumptions.

There are several ways in which the aforementioned biases associated with acoustic based line transect density estimation for minke whales can be addressed in future research. First, improvements to towed hydrophone arrays and localization methods will allow improved localization of calling animals as well as incorporation of localization errors into the density estimation analysis. Improvements should include integration of additional sensors such as accelerometers (for pitch and yaw) and magnetometers (for heading) to allow more precise location and orientation of the towed array to be determined. This will improve the precision of the resulting localization estimates of calling marine mammals. Second, acoustic tags could be deployed on animals during the study to provide useful information about vocalization rates and movements of animals relative to survey vessels. If combined with biopsy and sex data (*e.g.*, using skin samples collected incidentally from tags, or from biopsy samples), sex ratio biases with respect to vocalization rates could also be obtained. The possibility of determining movements and calling behaviors of animals in response to vessel presence can be examined using existing seafloor hydrophone systems and data to conduct detailed analysis of animal tracks (*e.g.*, Helble *et al.* 2015) in relation to vessel movements. Third, a potential decrease in calling in response to vessel presence could be explored using acoustic data collected from sonobuoys and/or fixed seafloor hydrophones that have sufficient temporal and spatial coverage to track and monitor vocalization rates of individuals as the survey vessel passes nearby. Such studies are being carried out with minke whales and other species on a Navy instrumented hydrophone range off the island of Kauai.[5] Acoustic tag data with controlled studies using vessel playbacks or passes could also be used to study these possible responses (Johnson and Tyack 2003). There have been only a few successful tag attachments to minke whales using acoustic data logger tags (*e.g.*, D-tags): two in the Antarctic (Friedlander *et al.* 2014, Risch *et al.* 2014) and one in the Southern California Bight (Southall *et al.* 2014). Ongoing improvements in tagging and passive acoustic tracking technologies and techniques should soon allow this approach to be used more readily in the future.

Acknowledgments

The field survey and analysis effort was funded by the U.S. Navy, Pacific Fleet *via* a subcontract to Bio-Waves, Inc. from Geo-Marine. Analysis was funded by NAVFAC Pacific *via* contract CON-005-4394-009 to HDR, under which Bio-Waves was subcontracted. Support for the Boinger algorithm development was provided in part by ONR. We would like to acknowledge all bioacoustic field personnel, especially Alyson Azzara and Laura Morse, and many others who assisted us, especially the marine mammal observer team, oceanographers, and the crew of the M/V *Kahana* who helped with operating and monitoring acoustic equipment in the field. We thank Julie Rivers for her support of the original research and reviews of this manuscript. We thank Ricardo Antunes for his help with developing *Boinger* for postprocessing data to obtain localizations from individuals. Steve Martin provided important feedback and numerous discussions on minke whale bioacoustics and behaviors. Dave Mellinger and Steve Martin provided various versions of minke whale boing auto detectors used in the analysis. Len Thomas and Tiago Marques provided important expert advice on the analysis. Julie Oswald and Robyn Walker helped with manuscript reviews, technical editing, and formatting of the manuscript.

[5]Personal communication from Steve Martin, National Marine Mammal Foundation, 2240 Shelter Island Drive, San Diego, CA 92106 and Tyler Helble, SPAWAR Systems Center Pacific, 53560 Hull Street, San Diego, CA 92152, 10 March 2015.

Literature Cited

Akaike, H. 1973. Information theory and an extension of the maximum likelihood principle. Pages 267–281 *in* B. N. Petran and F. Csàaki, eds. International Symposium on Information Theory. 2nd edition. Acadèemiai Kiadi, Budapest, Hungary.

Au, D., and W. Perryman. 1982. Movement and speed of dolphin schools responding to an approaching ship. Fishery Bulletin 80:371–379.

Barlow, J., and B. L. Taylor. 2005. Estimates of sperm whale abundance in the northeastern temperate Pacific from a combined acoustic and visual survey. Marine Mammal Science 21:429–445.

Becker, E. A., K. A. Forney, M. C. Ferguson, D. G. Foley, R. C. Smith, J. Barlow and J. V. Redfern. 2010. Comparing California Current cetacean-habitat models developed using in situ and remotely sensed sea surface temperature data. Marine Ecology Progress Series 413:163–183.

Becker, E. A., K. A. Forney, M. C. Ferguson, J. Barlow and J. V. Redfern. 2012. Predictive modeling of cetacean densities in the California Current ecosystem based on summer/fall ship surveys in 1991–2008. U.S. Department of Commerce, NOAA Technical Memorandum NMFS SWFSC-499. 47 p.

Buckland, S. T., D. Anderson, K. Burnham, J. Laake, D. L. Borchers and L. Thomas. 2001. Introduction to distance sampling: Estimating abundance of biological populations. Oxford University Press, Oxford, U.K.

Buckland, S. T., D. Anderson, K. Burnham, J. Laake, D. L. Borchers and L. Thomas. 2004. Advanced distance sampling. Oxford University Press, New York, NY.

Clark, C. W., and K. M. Fristrup. 1997. Whales '95: A combined visual and acoustic survey of blue and fin whales off Southern California. Report of the International Whaling Commission 47:583–600.

Croll, D. A., C. W. Clark, A. Acevedo, B. R. Tershy, R. S. Flores, J. Gedamke and R. J. Urban. 2002. Only male fin whales sing loud songs. Nature 417:809–811.

Darling, J. D. 1983. Migrations, abundance, and behavior of Hawaiian humpback whales, *Megaptera novaeangliae*. Ph.D. dissertation, University of California, Santa Cruz, CA. 147 pp.

Darling, J. D., K. M. Gibson and G. K. Silber. 1983. Observations on the abundance and behavior of humpback whales (*Megaptera novaeangliae*) off West Maui, Hawaii, 1977–79. Pages 201–222 *in* R. Payne, ed. Communication and behavior of whales. Westview Press, Boulder, CO.

DoN (Department of the Navy). 2005. Marine resources assessment for the Marianas Operating Area - Final report. Contract number N62470-02-D-9997, CTO 0027. Prepared for Pacific Division, Naval Facilities Engineering Command, Pearl Harbor, HI.

DoN (Department of the Navy). 2007. Marine mammal and sea turtle survey and density estimates for Guam and the Commonwealth of The Northern Mariana Islands - Final Report. Contract Number N68711-02-D-8043. Prepared for U.S. Navy, Pacific Fleet, Naval Facilities Engineering Command, Pacific, Honolulu, HI.

DoN (Department of the Navy). 2015. From clicks to counts: Using passive acoustic monitoring to estimate the density and abundance of Cuvier's beaked whales in the gulf of alaska (GoA). Prepared by T. M. Yack, T. Norris, E. Ferguson, S. Coates and B. K. Rone for Assistant Secretary of the Navy. Submitted to Naval Facilities Engineering Command Pacific, Pearl Harbor, Hawaii, under Contract No. N62470-10-3011, Task Order 22, issued to HDR, Inc., San Diego, CA. 31 August 2015. 43 pp.

Forney, K. A., M. C. Ferguson, E. A. Becker, *et al*. 2012. Habitat-based spatial models of cetacean density in the eastern Pacific Ocean. Endangered Species Research 16:113–133.

Friedlaender, A. S., J. A. Goldbogen, D. P. Nowacek, A. J. Read, D. Johnston and N. Gales. 2014. Feeding rates and under-ice foraging strategies of the smallest lunge filter feeder, the Antarctic minke whale (*Balaenoptera bonaerensis*). The Journal of Experimental Biology 217:2851–2854.

Fulling, G. L., P. H. Thorson and J. Rivers. 2011. Distribution and abundance estimates for cetaceans in the waters off Guam and the Commonwealth of the Northern Mariana Islands. Pacific Science 65:321–343.

Gedamke, J., D. P. Costa and A. Dunstan. 2001. Localization and visual verification of a complex minke whale vocalization. Journal of the Acoustical Society of America 109:3038–3047.

Gerrodette, T., B. L. Taylor, R. Swift, S. Rankin, A. M. Jaramillo-Legorreta and L. Rojas-Bracho. 2011. A combined visual and acoustic estimate of 2008 abundance, and change in abundance since 1997, for the vaquita, *Phocoena sinus*. Marine Mammal Science 27: E79–E100.

Helble, T. A., G. R. Ierley, L. D. Gerald and S. W. Martin. 2015. Automated acoustic localization and call association for vocalizing humpback whales on the Navy's Pacific Missile Range Facility. Journal of the Acoustical Society of America 137:11–21.

Herman, L. M., A. A. Pack, S. S. Spitz, E. Y. K. Herman, K. Rose, S. Hakala and M. H. Deakos. 2013. Humpback whale song: Who sings? Behavioral Ecology and Sociobiology 67:1653–1663.

Holt, R. S. 1987. Estimating density of dolphin schools in the eastern tropical Pacific Ocean by line transect methods. Fishery Bulletin 85:419–434.

Janik, V., and L. Thomas. 2012. Supplement to final report to Office of Naval Research by Norris, T. 2012. The ecology and acoustic behavior of minke whales in the Hawaiian and other Pacific Islands. Final Report to Office of Naval Research. Award Number. N0001409-10-534. 7 pp.

Jefferson, T. A., S. Leatherwood and M. A. Webber. 1993. Marine mammals of the world. FAO Species Identification Guide. Food and Agricultural Organization of the United Nations, Rome, Italy.

Jefferson, T. A., S. M. A. Webber and R. Pitman. 2015. Marine mammals of the world: A comprehensive guide to their identification. 2nd edition. Academic Press/Elsevier, San Diego, CA.

Johnson, M. P., and P. L. Tyack. 2003. A digital acoustic recording tag for measuring the response of wild marine mammals to sound. IEEE Journal of Oceanic Engineering 28:3–12.

Leaper, R., O. Chappell and J. Gordon. 1992. The development of practical techniques for surveying sperm whale populations acoustically. Report of the International Whaling Commission 42:549–560.

Marques, T. A. 2007. Incorporating measurement error and density gradients in distance sampling surveys. Ph.D. dissertation, University of St. Andrews, St. Andrews, U.K. 203 pp.

Martin, S. W., T. A. Marques, L. Thomas, *et al*. 2013. Estimating minke whale (*Balaenoptera acutorostrata*) boing sound density using passive acoustic sensors. Marine Mammal Science 29:142–158.

Martin, S., C. Martin, C. Matsuyama and E. Henderson. 2014. Minke whales (*Balaenoptera acutorostrata*) respond to navy training. Journal of the Acoustical Society of America 137:2533–2541.

Mellinger, D. K. 2001. Ishmael 1.0 user's guide. NOAA Technical Memorandum OAR-PMEL-120. National Oceanic and Atmospheric Administration, Pacific Marine Environmental Laboratory, Seattle, WA.

Norris, T. 2009. The ecology and acoustic behavior of minke whales in the Hawaiian and other Pacific Islands. Annual Report to Office of Naval Research. Award Number N00014-10-1-0429. 7 pp.

Norris, T. 2012. The ecology and acoustic behavior of minke whales in the Hawaiian and other Pacific Islands. Final Report to Office of Naval Research. Award Number N00014-10-1-0429. 10 pp.

Norris, T., S. Martin, L. Thomas, *et al*. 2012. Acoustic ecology and behavior of minke whales in the Hawaiian and Mariana Islands: Localization, abundance estimation, and characterization of minke whale "boings". Pages 149–153 *in* A. N. Popper and A. Hawkins, eds. The effects of noise on aquatic life. Springer, New York, NY.

Oleson, E. M., J. Calambokidis, W. C. Burgess, M. A. McDonald and J. A. Hildebrand. 2007. Behavioral context of call production by Eastern North Pacific blue whales. Marine Ecology Progress Series 330:269–284.

Oswald, J. N., W. W. L. Au and F. Duennebier. 2011. Minke whale (*Balaenoptera acutorostrata*) boings detected at the station ALOHA cabled observatory. Journal of the Acoustical Society of America 129:3353–3360.

Rankin, S., and J. Barlow. 2005. Source of the North Pacific 'boing' sound attributed to minke whales. Journal of the Acoustical Society of America 118:3346–3351.

Rankin, S., T. N. Norris, M. A. Smultea, C. Oedekoven, A. M. Zoidis, E. Silva and J. Rivers. 2007. A visual sighting and acoustic detections of minke whales, *Balaenoptera acutorostrata* (Cetacea: Balaenopteridae), in nearshore Hawaiian waters. Pacific Science 61:395–398.

Rankin, S., J. Oswald and J. Barlow. 2008*a*. Acoustic behavior of dolphins in the Pacific Ocean: Implications for using passive acoustic methods for population studies. Canadian Journal of Acoustics 36:88–92.

Rankin, S., J. Barlow and J. Oswald. 2008*b*. An assessment of the accuracy and precision of localization of a stationary sound source using a two-element towed hydrophone array. U.S. Department of Commerce, NOAA Technical Memorandum NOAA-TM-NMFS-SWFSC-416. 29 pp.

Redfern, J. V., J. Barlow, L. T. Ballance, T. Gerrodette and E. A. Becker. 2008. Absence of scale dependence in dolphin-habitat models for the eastern tropical Pacific Ocean. Marine Ecology Progress Series 363:1–14.

Risch, D., N. J. Gales, J. Gedamke, L. Kindermann, D. P. Nowacek, A. J. Read and A. S. Friedlaender. 2014. Mysterious bio-duck sound attributed to the Antarctic minke whale (*Balaenoptera bonaerensis*). Biology Letters 10:20140175.

Rogers, T. L., M. B. Ciaglia, H. B. Klinck and C. Southwell. 2013. Density can be misleading for low-density species: Benefits of passive acoustic monitoring. PLoS ONE 8:e52542.

Southall, B., J. Calambokidis and J. Barlow, *et al*. 2014. Biological and behavioral response studies of marine mammals in Southern California, 2013 ("SOCAL-13") final project report. Available at http://sea-inc.net/assets/pdf/SOCAL13_final_report.pdf.

Thomas, L., S. T. Buckland, K. P. Burnham, D. R. Anderson, J. L. Laake, D. L. Borchers and S. Strindberg. 2002. Distance sampling. Page 544 *in* A. H. El-Shaarawi and W. W. Piegorsch, eds. Encyclopedia of environmetrics. John Wiley & Sons, Ltd., West Sussex, U.K.

Thomas, L., S. T. Buckland, E. A. Rexstad, *et al*. 2010*a*. *Distance* software: Design and analysis of Distance Sampling surveys for estimating population size. Journal of Applied Ecology 47:5–14.

Thomas, L., V. Janik and T. F. Norris. 2010*b*. The ecology and acoustic behavior of minke whales in the Hawaiian and Pacific islands. Office of Naval Research Year-end report. Award Number: N000140910489. Submitted to Office of Naval Research, Arlington, VA.

Thompson, P. O., and W. A. Friedl. 1982. A long term study of low frequency sounds from several species of whales off Oahu. Hawaii. Cetology 45:1–19.

Van Parijs, S. M., C. W. Clark, R. S. Sousa-Lima, S. E. Parks, S. Rankin, D. Risch and I. van Opzeeland. 2009. Management and research applications of real-time and archival passive acoustic sensors over varying temporal and spatial scales. Marine Ecology Progress Series 395:21–36.

Winn, H. E., W. L. Bischoff and A. G. Taruski. 1973. Cytological sexing of Cetacea. Marine Biology 23:343–346.

Received: 5 August 2015
Accepted: 25 November 2016

View publication stats