An Analysis of Acoustic Data from the Mariana Islands Sea Turtle and Cetacean Survey (MISTCS)

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Task Order #002
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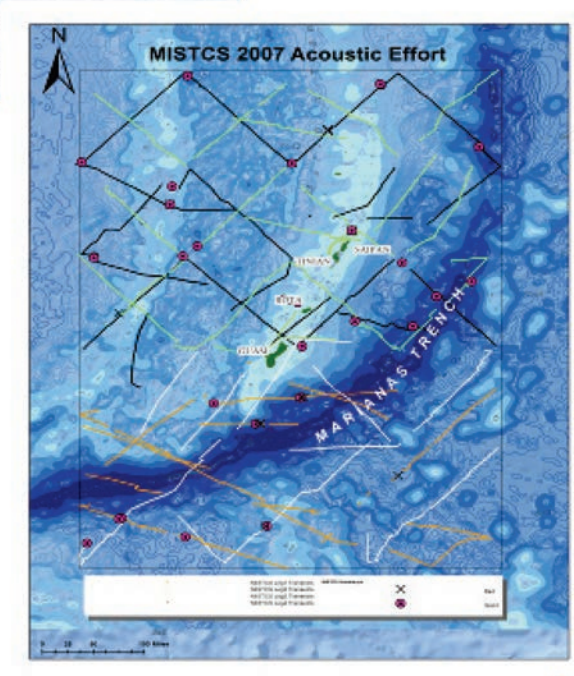

Prepared for:

Commander, Pacific Fleet,
Pearl Harbor, HI.

Submitted to:

NAVFAC Pacific
258 Makalapa Dr.
Suite 100
Pearl Harbor, HI 96860,

Under Contract No.:

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issued to ***HDR, Inc***.

Prepared by:

***Bio-Waves Inc*.**
144 West D St, Suite 20
Encinitas, CA 92024

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Prepared for:
Commander, Pacific Fleet
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NAVFAC Pacific
258 Makalapa Dr.
Suite 100
Pearl Harbor, HI 96860

Prepared by:

Thomas F. Norris, Julie Oswald, Tina Yack,
Elizabeth Ferguson, Cory Hom-Weaver,
Kerry Dunleavy, Shannon Coates
and Talia Dominello.

Bio-Waves Inc.
144 West D St, Suite 20
Encinitas, CA 92024

March 26, 2012.
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Acronyms and Abbreviations

AIC	Akaike Information Criteria
CART	classification and regression tree
CI	confidence interval(s)
DFA	discriminate function analysis
DSC	Dominant Signal Component
EEZ	Exclusive Economic Zone
ESA	Endangered Species Act
ETP	eastern tropical Pacific
HI	Hawaiian Islands
HICEAS	Hawaiian Islands Cetacean and Ecosystem Assessment Survey
hr(s)	hours
Hz	hertz
kHz	kilohertz
km	Kilometer(s)
km^2	square kilometers
LFA	Low frequency active
LTSA	Long-Term Spectral Average
m	meter(s)
MIRC	Mariana Islands Range Complex
MISTCS	Mariana Islands Sea Turtle and Cetacean Survey
MRA	Marine Resources Assessment
NM	nautical mile(s)
NOAA	National Oceanic and Atmospheric Administration
PAM	passive acoustic monitoring
PICEAS	Pacific Islands Cetacean and Ecosystem Assessment Survey
PMRF	Pacific Missile Range Facility
ROCCA	Real-time Odonotocete Call Classification Algorithm
S	Sighting
Sec	second(s)
SNR	Signal-to-Noise Ratio
STAR	*STenella* Abundance Research

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Background

During 2007, the first large-scale survey for marine mammals and sea turtles -- the Mariana Islands Sea Turtle and Cetacean Survey (MISTCS) -- was conducted in the Navy's Mariana Islands Range Complex (MIRC; DoN 2007, Fulling et al. 2011). The survey region encompassed approximately 584,800 square kilometers (km^2) and was a rectangle bounded by 18° – 10° N and 142° –148° E. The survey used standard line-transect methodology and also included passive acoustic monitoring (PAM) using a towed hydrophone array system. This was the first systematic survey of marine mammals conducted in this region of the North Pacific, and the sei whale (*Balaenoptera borealis*) that was not considered to likely occur in the area (see DoN 2005) was encountered during MISTCS.

The PAM component of the survey was effective in detecting some species (e.g., humpback whale and minke whale [*Megaptera novaeangliae* and *Balaenoptera acutorostrata*, respectively]) that were infrequently (or never) visually detected, and for other species (e.g., sperm whale [*Physter macrocephalus*] and small groups of delphinids), increased detection rates when visual sighting conditions were poor. More than 65 percent of survey effort was conducted in Beaufort sea states of 5 or higher during the 3-month cruise (DoN 2007). Towed-array survey effort was conducted for 70 out of 71 (99 percent) potentially surveyable days at sea for a 762 hours (hrs) and 11,478 kilometers (km) of total acoustic survey effort. This resulted in an average of 10.9 hours /day of acoustic survey effort over the entire survey period. In addition, over 50 sonobuoys were deployed; 36 were monitored and/or recorded successfully. These sonobuoys had a relatively high failure rate since they were acquired for the cruise past their expiration date (battery life). Bioacoustic signals for 12 species of cetaceans were recorded from both the towed array and sonobuoy data. This was the first time they were documented at sea (i.e., other than from stranding records) in the Northern Mariana Islands region for several species.

In this report, we present a detailed analysis of several species of cetaceans that were acoustically detected during the MISTCS. Only preliminary results of these encounters were presented in the cruise report for MISTCS (DoN 2007). Recordings of minke whale, sperm whale, sei whale (*Balaenoptera borealis*), humpback whale, and several species of dolphins (including larger delphinids, such as the "blackfish") were analyzed in detail to provide more comprehensive information on the occurrence and aspects of these species' ecology and behavior. The main goals of these analyses were to: (1) provide acoustically-derived density estimates when feasible (e.g., minke whales); (2) estimate an acoustically-derived 'detection function' (e.g., sperm whales); (3) describe and compare acoustic signals for some species and populations for which limited information is available (e.g., sei whales and humpback whales); and (4) assess the success of automated classification algorithms for several species of delphinids. This report is divided into five sections: **Section 1** is an assessment of the abundance of calling minke whales; **Section 2** is a classification of recorded whistles; **Section 3** is an evaluation of the sperm whale encounter; **Section 4** is an analysis of humpback whale song; and **Section 5** addresses sei whale vocalizations.

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Section 1. An Assessment of the Abundance of Calling Minke Whales Using Towed Array Passive Acoustic Data and Line-transect Methods

1.1 Background

Although they are one of the most abundant species of baleen whales worldwide, the minke whale is rarely sighted in subtropical and tropical waters. As noted by Rankin and Barlow (2005), minke whales are the smallest of baleen whales and are typically found as individuals or in small groups of two to three. The minke whale produces inconspicuous blows and surfaces for short periods of time. High sea states also reduce the probability of sighting minke whales. Other factors that are not yet understood may also be driving the low sighting rates in these waters. Like most baleen whales, the minke whale is believed to migrate to warm waters in the winter and spring, probably to engage in reproductive activities. Before MISTCS, winter/spring distribution and abundance of minke whales in the subtropical waters of the Western North Pacific was relatively unknown. Based on the Navy's Marine Resources Assessment (MRA) for the Mariana Islands (DoN 2005), minke whale occurrence was considered to be 'rare' in the Mariana Islands Range Complex (MIRC). In fact, prior to the MISTCS, there were no verified records for this species in the MIRC and surrounding regions, even though the MIRC is within the known distribution range for this species. The MRA states that "there is a low or unknown occurrence of the minke whale from the coastline (excluding harbors and lagoons) to seaward of the Marianas study area and vicinity" (DoN 2005). Since the MISTCS, there have been a few additional acoustic detections, mostly in the vicinity of the Marianas Trench, using sonobuoys and towed hydrophone array methods similar to those used on the MISTCS (Oleson and Hill 2010).

During the 2007 MISTCS survey, there were 29 'unique acoustic detections' of minke whales, five of which were acoustically localized (see Figure 4-4 and Table 3-8 in DoN 2007). A type of call known as the 'boing' that is unique to minke whales, was used to determine the presence of minke whales (Rankin and Barlow 2005). Boings are complex amplitude modulated calls that last 3 to 5 seconds with a peak frequency near 1.5 kilohertz (kHz). For MISTCS, unique acoustic detections were considered to be independent encounters with animals (i.e., different animals). Both quantitative information, such as bearing angles and time interval between detections, and qualitative information such as relative amplitude of calls and the degree differences in bearing angles were used to determine unique detections. Five acoustic localizations that were made during the survey were included in the 29 unique detections; however, the remaining 24 detections did not include localizations. Because of the limited number of localizations, and the lack of analytical tools available at the time for post-processing of acoustic detections of minke whales, abundance estimates were not calculated in the final cruise report (DoN 2007) nor in subsequent analyses of abundance (Fulling et al. 2011).

Line-transect survey and analytical methods are relatively well developed for estimating abundance of marine mammals using visual sighting data (Holt 1987). These methods are based on a broader theory known as Distance Sampling (Buckland et al. 2001). Line-transect methods assume accurate measurements of the perpendicular distances of animals from the survey-track, although they are relatively robust to some types of measurement error (Marques 2007). These distances, and other data, are used to estimate a detection function, which is one of the main components of the abundance estimation formula. The detection function describes the decreasing probability of sightings (or acoustic localizations) as a function of increasing perpendicular distance from the survey trackline (i.e., fewer animals are detected as one ‘looks’ further out from the trackline).

The same analytical approach that is used for visual-based line transect surveys can be applied to acoustic data collected from marine mammals using a towed hydrophone array. To do this requires acoustic localization of individuals or groups of calling animals in order to obtain the perpendicular distances from the trackline that are used to model the detection function. A method of localization known as ‘target motion analysis’ (originally developed by the Navy to track submarines and ships) is commonly used to localize marine mammals with a towed hydrophone array (Leaper et al. 1992; Barlow and Taylor 2005). This method estimates the location of a ‘target’ using successive bearings (**Figure 1-1**). Target motion analysis assumes that animals are calling often, are solitary (or occur in small, tightly clustered groups) and are stationary (or move slowly relative to the survey vessel speed). This approach has been used with dipole towed hydrophone arrays to locate sperm whales and small porpoises acoustically for line-transect abundance estimation (Barlow and Taylor 2005; Gerrodette et al. 2011). To our knowledge, this approach has never been applied to estimate baleen whale abundance from towed arrays, although alternative approaches have been described for blue and fin whales (*Balaenoptera musculus* and *Balaenoptera physalus*, respectively) (Clark and Fristrup 1996). We use an approach similar to that of Barlow and Taylor (2005) (without group size estimation from visual data) to estimate the density and an abundance of calling minke whales in the MIRC area. The caveats and assumptions for this approach will be discussed in relation to our preliminary findings.

1.2 Methods

Details on the towed-array system are presented in DoN (2007). All channels of analog acoustic data from the hydrophones were passed through a low-pass filter system (Alligator Technologies, AAF-1 model) with a 48 kHz corner frequency (for anti-aliasing). A tunable high-pass filter (Krohn-Hite model 3382) was used to reduce flow and self-vessel noise thereby increasing the effective dynamic range of the system. Corner frequencies of the high pass filter were set between 100 Hz and 500 Hz, depending on noise conditions. A PC digital audio interface (MOTU Traveler Model) was used to digitized the filtered hydrophone signals (@ 96 kHz sample rate) and pass them to a desktop computer via a fire-wire cable.

Towed hydrophone array recordings were analyzed using the program *Boinger*, which was a MATLAB program developed by St. Andrews University and Bio-Waves Inc. under Office of Naval Research (ONR) sponsorship (Norris et al. 2011). The purpose of using Boinger was to review and re-process all boings recorded and detected in the field and use automatic detection methods during post-processing in order to localize minke whales better. The resulting distances from the trackline were then imported into a program (e.g., *Distance*) for line-transect abundance estimation. Modifications were made to the existing version of *Boinger*, so that the Microsoft Access database (Whaletrack II) used during MISTCS survey to datalog and map acoustic data could be used as one of the main inputs for localization analysis. Acoustic .wav files recorded in the field from the two-element towed array were also used as inputs. Other modifications to *Boinger* were made to allow input of boings that were automatically detected by post-processing files using Ishmael software (using automatic boing detectors developed by D. Mellinger, Oregon State University/Pacific Marine Environmental Laboratory). Ishmael is a bio-acoustic data-acquisition, display and processing program that can be used in the field and for post-processing data from hydrophone arrays (Mellinger 2001).

The modified version of *Boinger* used in this study allowed a data analyst to quickly review and analyze acoustic data from MISTCS by sequentially processing each boing detected and saving results and localization maps for further review (**Figures 1-2A to 1-2C**). In addition, other features such as the Dominant Signal Component (DSC) and the cross-correlation function were reviewed by the data analyst in order to attempt to differentiate multiple individuals when they occurred. The DSC is the peak frequency of a particular frequency band in the call. The cross correlation function is used to calculate the bearing between the two hydrophones in the array (Mellinger 2001). The output of *Boinger* included times, geo-referenced positions of localizations, the perpendicular distance of acoustic localizations to the ship trackline and maps of the ship track and localizations (**Figure 1-2C**).

The automated boing detector was run on all .wav files recorded during the MISTCS cruise using the program Ishmael. All automated detections were visually reviewed and confirmed by a trained data analyst to identify and remove false detections. The verified detections were then imported into the database that *Boinger* reads to locate boings from the .wav files. The outputs of the detector included the filename and the relative times of the detections.

Both the detections of boings made in real-time (i.e., during the survey) using the program Ishmael, and the automatic detections made during post-processing were used as inputs to *Boinger*. These data were processed by data analysts who reviewed and saved all possible localizations. All localizations were ranked based on a variety of qualitative and quantitative characteristics, including the quality of the localization, the number of bearing lines used in a localization, the level of clustering of DSC values from the bearings used, and the ‘tightness’ of the convergence of the bearing lines. This information was saved to a spreadsheet. Maps of localizations were saved and printed out for a final review by a senior data-analyst (T. Norris) for a final decision on whether or not to include in the line-transect analysis.

Due to the linear configuration of the towed hydrophone array, there is a left/right ambiguity inherent in the localization. Because the ship was not usually traveling in a perfectly straight line and the array was always streaming directly behind the ship (i.e., coincident with the ship-track), the left and right side perpendicular distances from the trackline to the localizations were not always the same. In these cases, the mean of the two distances was used as an approximation of the true distance. 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 converged only to one side). In such cases, only the perpendicular distance for the localization on the ‘good’ side was used.

The perpendicular distances estimated using *Boinger* were used as inputs to the distance sampling analysis program *Distance* (Version 6; Thomas et al. 2010a). *Distance* was used to estimate detection functions, encounter rates, effective strip widths and ultimately, the density and abundance of calling minke whales in the MISTCS study area using the line-transect formula for density (modified for abundance below) from Buckland et al. (2001):

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

The fixed (known) variables in this equation are:

A = area of the MISTCS survey area (584,800 km^2)
L = total length of on-effort trackline surveyed (6,324 km)
n = number of animals acoustically localized (30)

The estimated variables are:

w = strip width surveyed on each side of the survey trackline (i.e., the truncation distance)
P_a = the average probability of detecting an animal between 0 and w.

Variables and function with assumed values:

s = animal group or cluster size for this study s is assumed to equal 1.
g(0) = the probability of detecting an animal at distance = 0 (i.e., on the trackline) - for this study, g(0) is assumed to equal 1.

(Deviations from the assumptions will be addressed in the discussion).

Given that S and g(0) = 1, the formula can be simplified to:

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

Before models were tested in *Distance*, frequency histograms of the perpendicular distances were inspected to determine if there were any problems with the data. Various cut points for the histograms were tried in combination with ‘right truncation’ to eliminate ‘outliers’ (i.e., detections that did not contribute to the overall expected shape of the function) and improve the fit and, therefore, the robustness of the model. ‘Left truncation’ was applied at various distances to remove localization data near the trackline, but based on visual inspection of the histograms and advice by outside experts on Distance Sampling (e.g., L. Thomas, CREEM, St. Andrews, UK) 1 km was chosen as the appropriate distance for left truncation. This step was taken to reduce the bias associated with possible reduction in vocalization rates near the trackline (Thomas et al. 2010b). The rationale for this step will be explained in greater detail in the discussion.

Final models were chosen based on a comparison of the Akaike Information Criteria (AIC) value for various models, as well as the coefficient of variation (CV) of the abundance estimate (lower was considered better for both). AIC measures the relative fit for different models (Buckland et al. 2001).

Abundance and density (abundance divided by the total study area sizes) were estimated after selection of the best model for the detection function. CVs and Confidence Intervals (CIs) were automatically calculated in *Distance* using the analytical method.

1.3 Results

The Ishmael automatic detector and *Boinger* program were used to efficiently review over 700 hrs of recordings from MISTCS. After post-processing the data using *Boinger*, 30 localizations were estimated. This total consisted of 25 more localizations than originally were made *in-situ* during the cruise. A map of localization indicates that most detections were distributed near, but not in, the deepest regions of the Mariana Trench (**Figure 1-3**).

Inspection of the frequency histograms of the perpendicular sighting distances reveals a decrease in detection near the trackline (**Figure 1-4**). Two scenarios were modeled for the detection function: 1.) Animal movement away from the trackline and; 2) Vocal rate reduction near the trackline.

For Scenario #1 (animal movements away from the trackline), a Uniform Key function with a Cosine Series expansion model was chosen as the best fit (**Figure 1-5A**). No right or left truncation was used but 4-km cut-points for the histograms were manually selected. The abundance estimate for calling animals in the MISTCS study area was 333 (95 percent C.I. 201 – 552) calling animals. This estimate assumes that all animals calling remain present when the vessel passes nearby, but that animals just redistribute relative to the trackline.

For Scenario #2 (reduction in vocal rates near the trackline), a Uniform Key function with a Cosine Series expansion model was also chosen. In this model, 5 percent of the largest values (at the far right on the histogram) were truncated as well as all values less than 2 km on the left side of the histogram (**Figure 1-5B**). This was necessary to reduce any bias in the overall detection function shape that was caused by animals that were present, but not vocalizing due to some effect caused by presence of the research vessel. The abundance estimate for the MISTCS study area for Scenario #2 was 540 (95 percent C.I. 299 – 975) calling animals (**Table 1-1**). This estimate assumes some animals go undetected (or under-detected) as the vessel passes nearby, and thus attempts to correct for this by removing those animals (distributed near the trackline) from the detection function analysis.

1.4 Discussion

Presently there are no estimates for minke whale abundance or density in the MIRC or surrounding areas in the tropical western North Pacific. Because there were no sightings made of minke whales during MISTCS, minke whales were not included in the recent abundance estimates resulting from this effort (Fulling et al. 2011). Due to the elusive nature of minke whales in subtropical waters and the poor sighting conditions that are pervasive in the MIRC area, it is unlikely there will ever be enough sightings to estimate minke whale abundance using visual data.

Several caveats and deviations from the assumptions required for line-transect sampling methods and data analysis should be considered before using these data. First, it is clear that g(0), the probability that all animals on the trackline are detected, is not equal to one (i.e., some animals on or very near the trackline are not being counted). This is apparent based on visual inspection of the first bin (1 km) of the histogram of perpendicular localization distances from the tracklines (**Figure 1-4**). This fundamental assumption of line-transect methods must be met for abundances to be considered unbiased (Buckland et al. 2001). However, in practice this assumption is often violated (e.g., due to animal responses to the survey platform or inability to see some animals on the trackline) or ignored resulting in the true population being underestimated.

The reduced numbers of localizations near the trackline is likely caused by three (non-mutually exclusive) possibilities:

1. Acoustic methods are negatively biased with respect to their ability to detect and localize animals near the trackline (due to a directional beam-pattern for the array).
2. Animals are moving away from the survey vessel when it is nearby (i.e., evasive movements).
3. Animals are reducing their vocalization rates when the vessel is nearby.

The first possibility can occur due to what is known as ‘end-fire’ for towed hydrophone arrays. End-fire is a reduction in sensitivity in regions directly in front of and behind the hydrophone array (i.e., along the axis of the cable). It is usually caused by a receiving beam pattern for the hydrophone array elements that is not omni-directional. This is often the case for cylindrical elements that are often used in towed hydrophone arrays. In addition, physical obstruction of sound waves can be caused by the hydrophone cable, components in the hydrophone array, the research vessel or bubbles generated by cavitation from the propeller of the research vessel. The result of these obstructions is that the hydrophone does not have a clear path to ‘look’ directly forward and/or backward. This occurs for most towed hydrophone arrays, but generally is limited to small angles (less than 10 -15 degrees) along the axis of the hydrophone array (Rankin et al. 2008). This situation can easily be corrected for in the analysis (via left truncation of data) if the angles, or regions, of poor localizations are known or can be estimated.

The second possibility occurs when animals avoid the vessel when it is nearby. This possibility is difficult to verify without being able to track animals. Preliminary analysis of acoustic data collected from minke whales using fixed seafloor hydrophones at the Pacific Missile Range Facility (PMRF) in Hawaii indicated that at least some animals moved away from a relatively quiet motor-sailing vessel used to conduct surveys in the area (S. Martin, SPAWAR Systems Center Pacific, San Diego, CA, unpublished data). Further information is needed to verify this effect. Fortunately, line transect methods are relatively robust to this effect as the detection function can account for movement of animals away from the trackline if the effect on the frequency histogram distribution of perpendicular distances is not too severe.

The third possibility, a reduction in vocalization rates when the vessel is nearby, is one that we consider very likely to be occurring. However, this possibility is difficult to assess without being able to track animals when they reduce or cease vocalizing. This situation can be problematic for line-transect abundance estimation because it results in an underestimate of animals. However it can be corrected for by 'left truncating' the perpendicular distance (localization) data. Collecting data to verify this possibility will probably require tagging animals and tracking them at the same time. Alternatively, vocalization rates could be compared before, during, and after the vessel passes animals that were initially vocalizing, assuming they do not move away. We have analyzed some preliminary towed array data that indicate a decrease in vocalization rates, but the situation appears to be complex (Norris et al. 2011).

Even with these caveats, we believe that the abundance estimates we present here are relevant because some of the issues and biases can be addressed. For example, left truncation of the histogram of distance data can reduce or eliminate the bias associated with a reduction in vocalization rates (Thomas 2010b). Evasive movements can be examined with existing seafloor hydrophone data and more detailed analysis of towed-hydrophone array data. Or additional acoustic data could be collected from sonobuoys and/or fixed seafloor hydrophones with sufficient temporal and spatial coverage to track and monitor vocalization rates of individuals as the survey vessel passes nearby. Tracking data collected using either passive acoustic methods or via electronic tagging might also provide information on vocalization rates that can be used for correction factors. This situation is not as problematic as it seems as many line-transect surveys have some biases that must be accounted for or considered (e.g., for many species $g(0) \neq 1$) and solutions to these problems exist (e.g., Schweder et al. 1996).

For the purposes of this analysis, we 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 detecting and tracking numerous species we believe this assumption to be valid. Vocalizations almost never overlap and when they occur closely in time (e.g., within a few seconds of another call) the second individual is usually several hundreds to thousands of meters away. Similar results have been determined based on passive acoustic tracking of multiple individuals from the PMRF hydrophone arrays (S. Martin, SPAWAR Systems Center Pacific, San Diego, CA, pers. comm.). It is possible (even likely) that non-vocalizing individuals are associated with or occur nearby vocalizing individuals, but this effort does not attempt to assess or correct for the occurrence of non-vocalizing animals. Future efforts in which animals are tagged or tracked might allow this possibility to be studied, but this was well beyond the scope of the current study.

Other issues that should be examined are the segmentation of tracklines (in the case of MISTCS, due in part by bad weather and sea conditions disrupting effort). Density surface modeling might be a more effective type of line-transect estimation if the segmentation is too severe or if the effort is biased (Buckland et al. 2004). Density surface modeling treats the encounter rate component in the distance formula as a model based problem, as compared to the design-based approach that is used in conventional distance sampling, as we did in this study. Other methods of modeling abundance and distribution that include covariates and habitat features might improve the accuracy of estimates or allow predictive assessments of occurrence, distribution and habitat preference. Acoustic data will be essential for such efforts, since it is unlikely that sufficient visual data will ever be available for minke whales.

1.5 Conclusions and Recommendations

The estimates provided in this report are probably biased but we consider these limitations acceptable given the alternative (i.e., no estimates for minke whales in the study site). Coefficients of Variation for both scenario estimates were under 30 percent, which is substantially lower than those for density estimates of all other species in the same area that were made using visual data (e.g., most CVs were greater than 50 percent for estimates in Fulling et al. 2011). We would recommend using the lower estimate (i.e., scenario #1 estimates) for any management needs concerning permitting for takes or deleterious impact as this is the more conservative estimate. For management needs, modeling impacts, or other effects on minke whales, we would recommend using the larger (i.e., scenario #2 estimates) as this would provide the most conservative approach.

Future efforts should examine vocalization rates as this is perhaps the main variable that affects the population estimates provided here. For example, gender biases relative to vocalization rates of minke whales are unknown, but might be expected to favor, or be exclusively limited to, males given what is known about other species in the genus *Baleanoptera* (e.g., blue and fin whales). Given that we think that the MISTCS study area is likely to be a wintering area, it is important to collect more information about these poorly understood aspects of minke whale biology. Finally, the effects of survey vessel noise and other anthropogenic noise (e.g., sonar and explosive noise) need to be studied further in order to obtain better population estimates and understand if noise is negatively affecting this elusive and acoustically sensitive species.

Any plans to conduct future surveys and monitoring should also consider how to optimize collection of passive acoustic data. Vessel types for towed array surveys should be an important consideration during survey planning. For example, any survey planning to incorporate passive acoustic methods (i.e., either towed arrays and/or sonobuoys) should use a vessel that is quiet and preferably diesel-electric powered. The quality of the electrical power source for the acoustic research equipment should also be considered. If AC power onboard the survey vessel is not ‘clean,’ then a high-quality inverter connected to an isolated battery bank should be considered, or alternatively, audio equipment should be directly powered via DC current using batteries. A small, high quality generator dedicated to powering only the acoustic equipment is another alternative.

If autonomous recording devices are used, their placement should consider the distribution of minke whales as determined from this and future studies. Finally, efforts to improve and automate analysis of passive acoustic data, for detection, localization, and data analysis should be undertaken to improve the efficiency and accuracy of data analysis. For example, the program *Boinger* should be developed further to make it more efficient and effective for post-processing data. This would include allowing more information to be used to asses if different animals are being localized; e.g., by colorizing bearing based on DSC values, providing animation or playback capabilities, and providing semi-automatic bearing and localization capabilities. The cost of developing automated programs is relatively small relative to the cost of collecting and post-processing data in real-time.

For visually elusive species like the minke whale, passive acoustics is probably the only method available to effectively survey the population and obtain abundance estimates, even if for the time being it might only represent a proportion of the overall population. Future studies undoubtedly will shed light on aspects such as vocalization rates and the effects of the survey vessel on the behaviors of minke whales. Additionally, passive acoustic data collection will be one of the few methods that will be able to effectively survey, monitor, and assess effects of man-made activities on marine mammals in remote areas such as MIRC and will likely be an important component for any such efforts.

1.6 Tables and Figures

1.6.1 Tables

Table 1-1. Summary statistics for acoustic-based abundance/density estimate for calling minke whales using the software program *Distance*. The two scenarios are the same as presented in the results; Scenario #1 assumes animal movement away from the trackline. In this scenario neither right nor left truncation is done. Scenario #2 assumes a reduction in vocal rates near the trackline. In this scenario left truncation (at 1 km) is done to remove any bias due to the lower probability of detecting animals close to (< 1km) the trackline. (Details of analysis 36 and 37 available in *Distance* project folder.)

Scenario	N	95 percent CI	D	Percent CV	d.f.
#1 (analysis 36)	345	208-572	.0005923	25	29.26
#2 (analysis 37)	394	238-652	0.000676	25	29.07

1.6.2 Figures

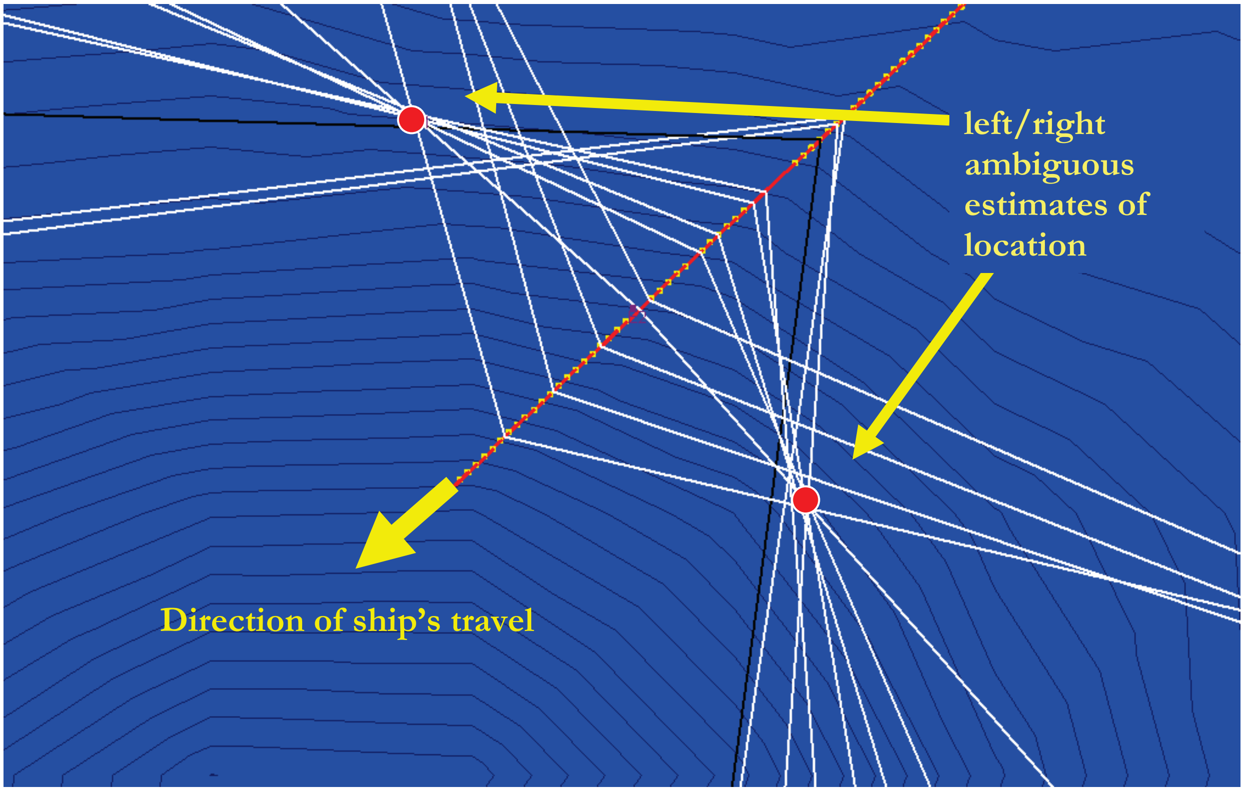


Figure 1-1. An example of the 'target motion analysis' method of localization used for minke whales. Sequential bearing lines from the towed hydrophone array to a vocalizing animal converge as the vessel passes the animal. This method assumes that the animal is relatively stationary compared to the vessel speed. Also note the left/right ambiguity caused by the linear configuration of the hydrophone array.

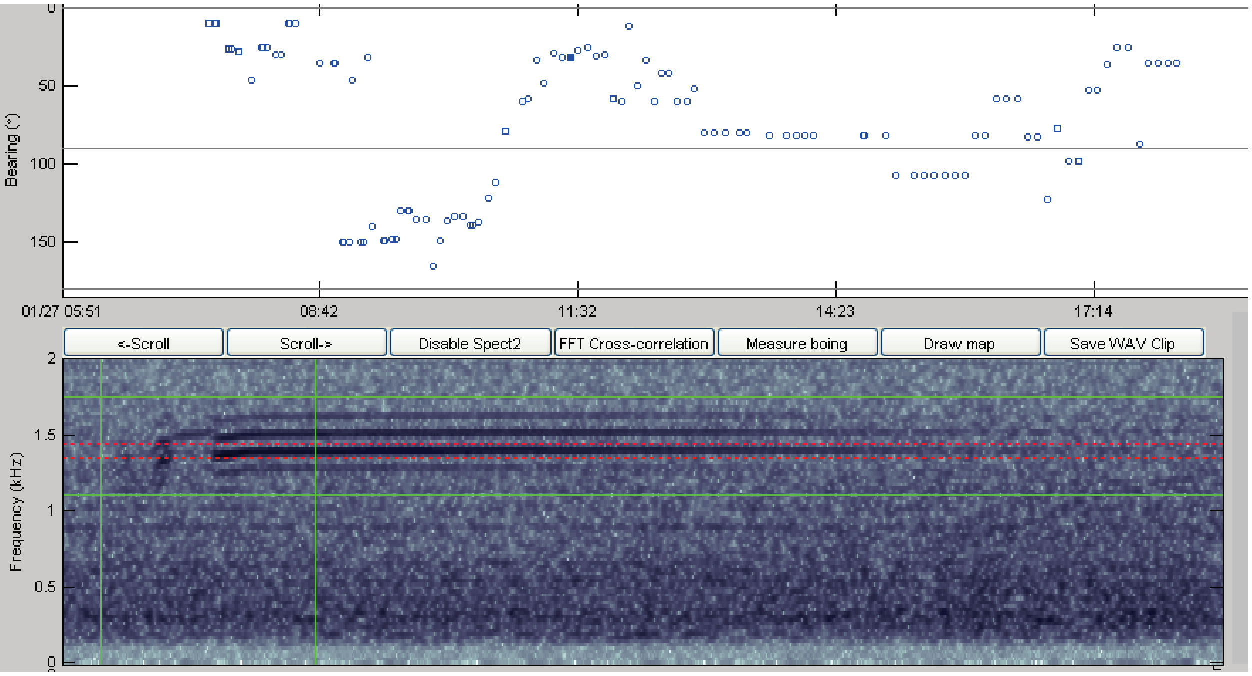


Figure 1-2A. Example of a bearing vs. time display (top panel) and a spectrogram vs. time display (bottom panel). The top panel depicts a series of boings over time (in this case about 18 minutes) and the bottom pane is an individual boing that is being processed in *Boinger*. Boings are selected by clicking on open circles in top panel (imported from Ishmael's auto-detection output) which results in *Boinger* loading the corresponding boing from a .wav file. The data analyst then moves the horizontal green lines to window the appropriate part of the boing to measure the FFT cross-correlation (used to calculate the bearing); and the horizontal green lines to measure the DSC of the boing. The tabs at the top of the spectrogram depict the different measurements and other options possible in Boinger. The Dominant signal component is the peak frequency of the signal that occurs within the band of the 2 horizontal green lines. The broken red lines indicate the expected range of the DSC value to allow the user to decide if there is an 'unusual' DSC present.

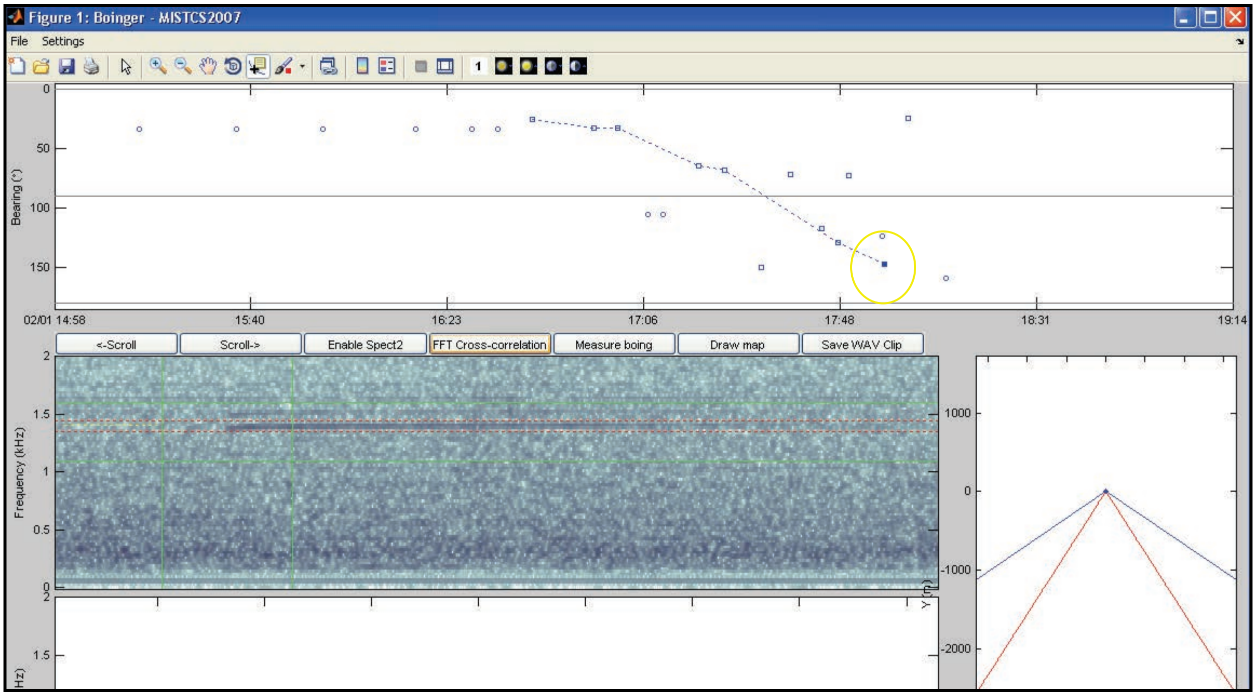
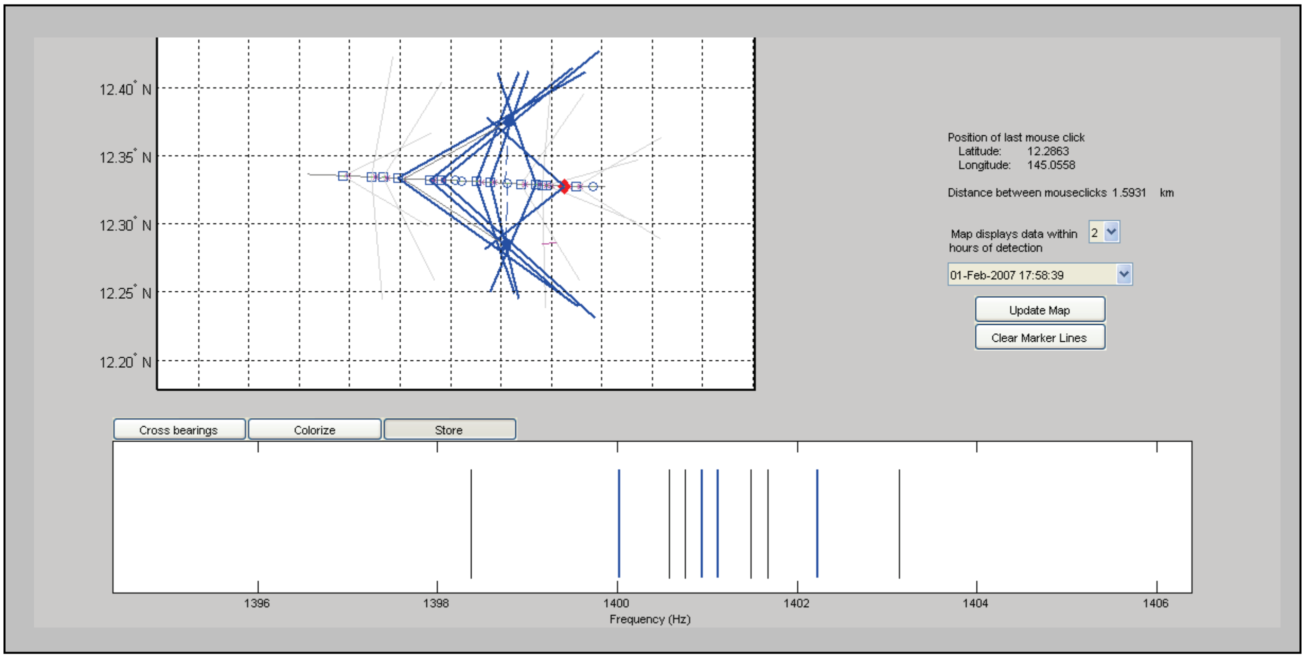


Figure 1-2B. An example of a good bearing vs. time track (top panel) for an individual whale that is being localized. The bearing for the last boing (solid blue square inside yellow circle in top panel) is plotted in blue on the panel on the lower right. This panel depicts the bearing measurement made in the field (red lines) and the one made using *Boinger* (blue lines). Once the bearing is reviewed and compared to the bearings obtained in the field, the data analyst can then save the bearing and plot it on a map to localize the calling animal (see next figure).



Position of last mouse click
Latitude: 12.2863
Longitude: 145.0558

Distance between mouseclicks 1.5931 km

Map displays data within 2 hours of detection

01-Feb-2007 17:58:39

Figure 1-2C. Example of a good localization (top panel). DSC values (bottom panel) of bearings used in the localization are depicted by the blue vertical lines which in this case are clustered within a few Hertz (Hz) of each other, indicating that boings that are being used for localization bearings are likely from the same animal. There are likely several vertical lines overlaid on top of each other, thus not the same number of blue lines in the bottom panel as bearing lines in the top map.

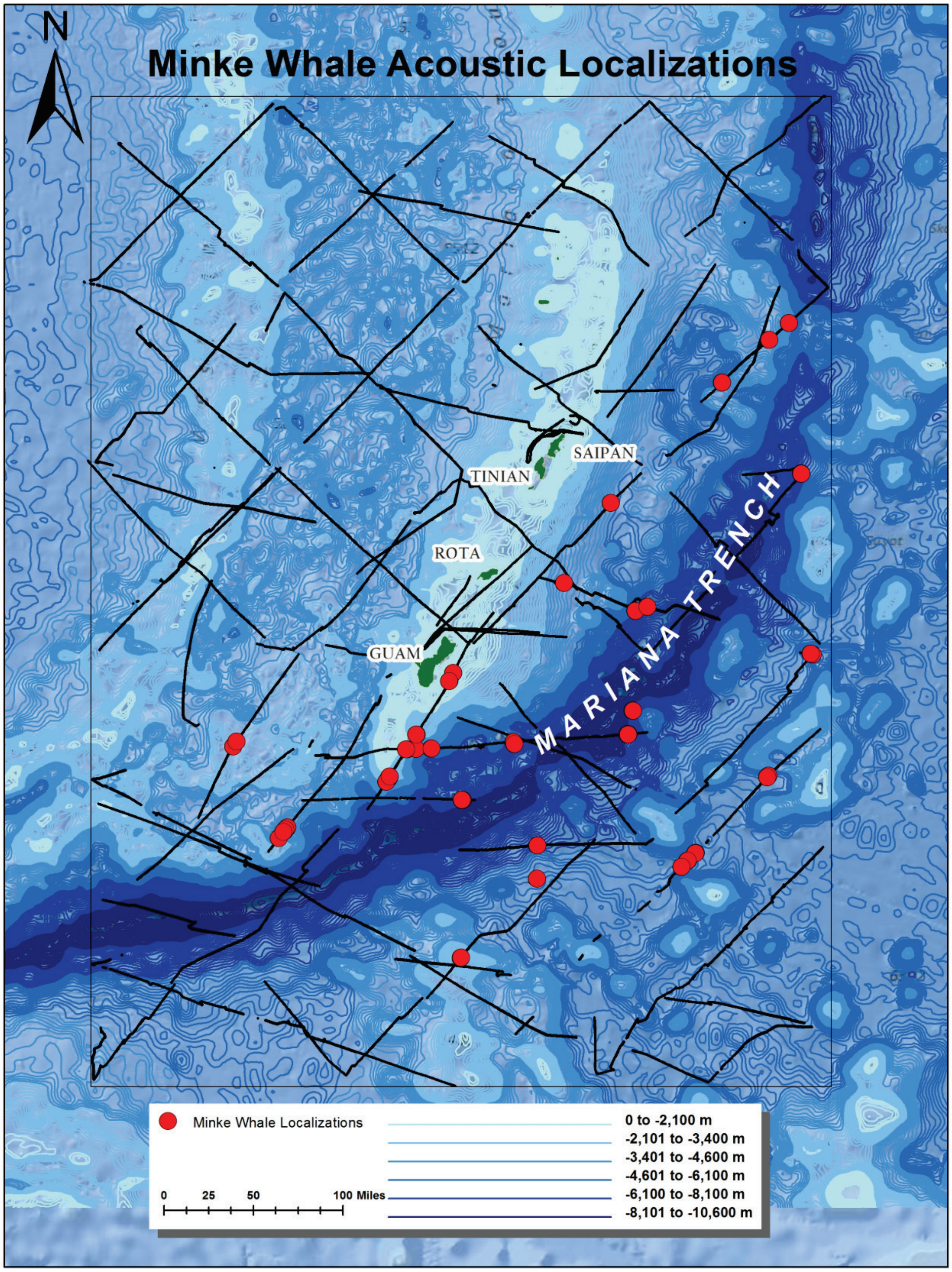


Figure 1-3. Map of the MISTCS study area (gray box) with ship tracks (dark blue segments) of minke whale post-processed acoustic localizations. Left-right ambiguous localizations are indicated by a pair circles with both port (red) and starboard (green) locations.

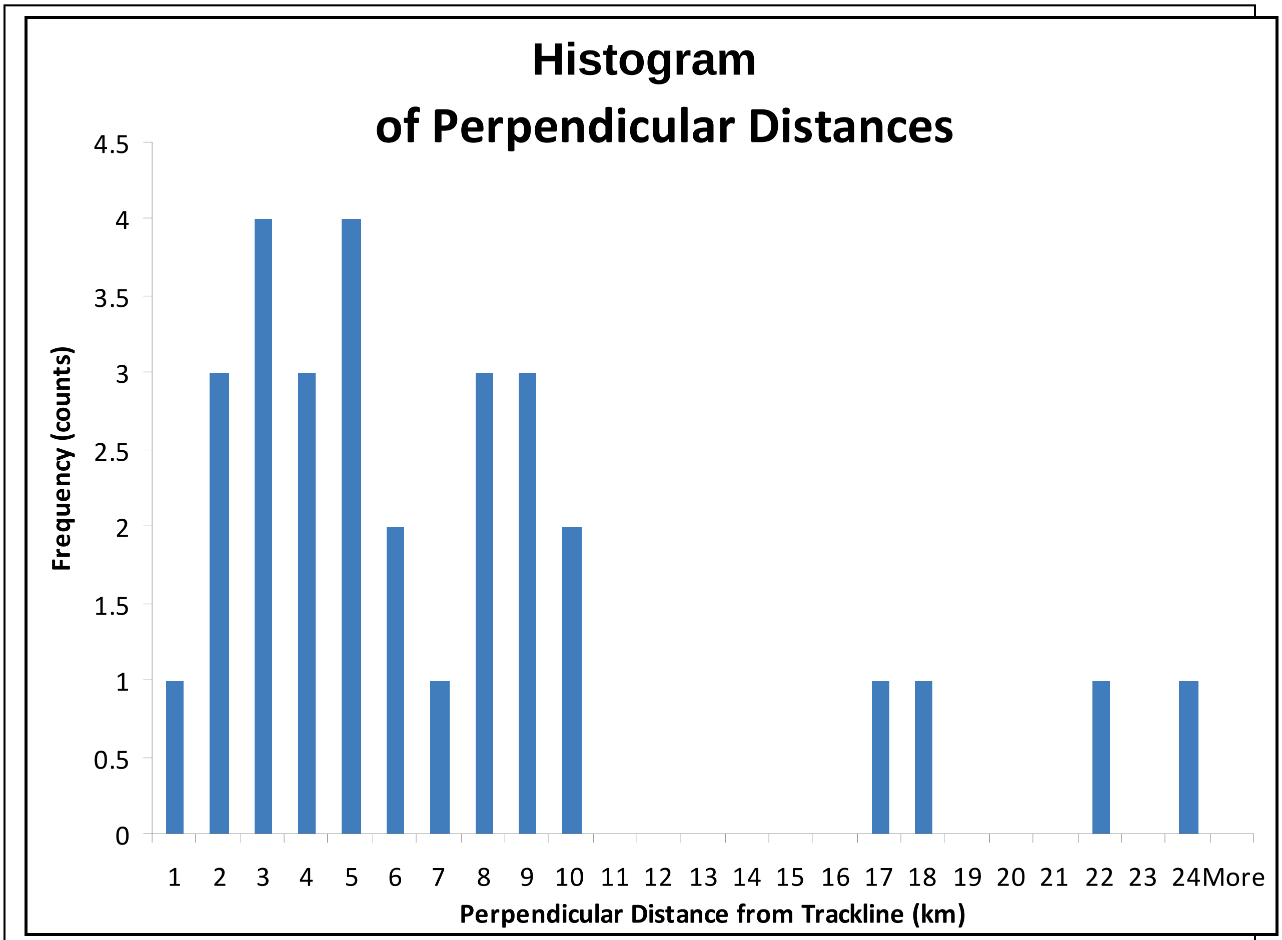


Figure 1-4. Histogram of distances of localization perpendicular to the trackline (1 km bins). Note the significant reduction in localizations that occur in the first bin (1 km). This indicates that animals are either avoiding the vessel as it approaches, or are reducing (or ceasing) vocalizations.

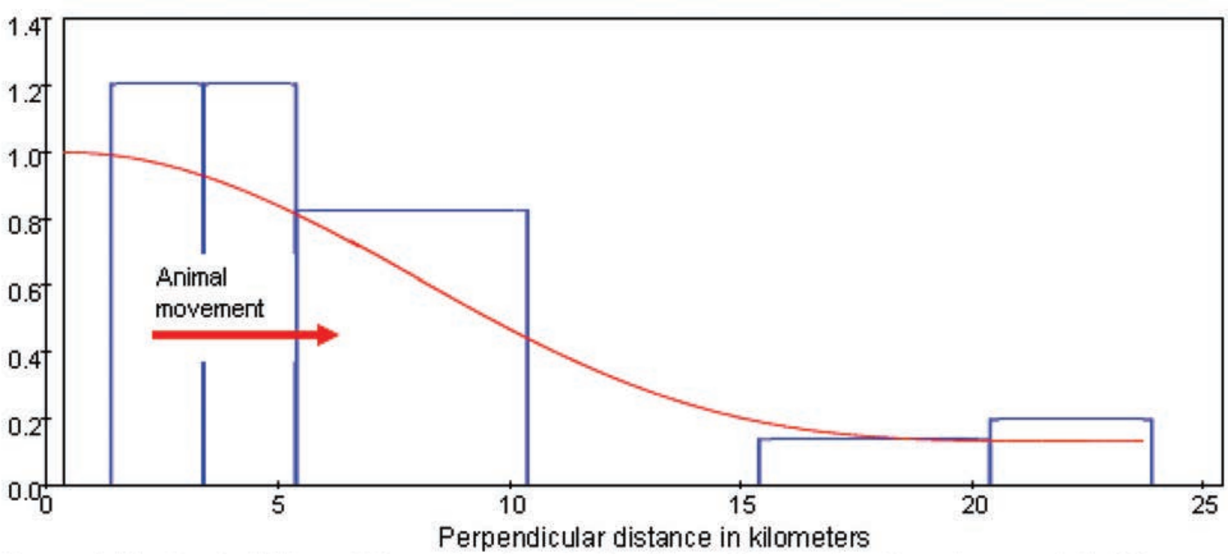


Figure 1-5A. Probability of detection (vertical axis) and detection function modeled for Scenario #1 which assumes evasive movement away from (research vessel at) trackline. Best fit was the Uniform Key function plus a Cosine Series expansion. No truncation was used. (analysis #36 in *Distance* Project Folder)

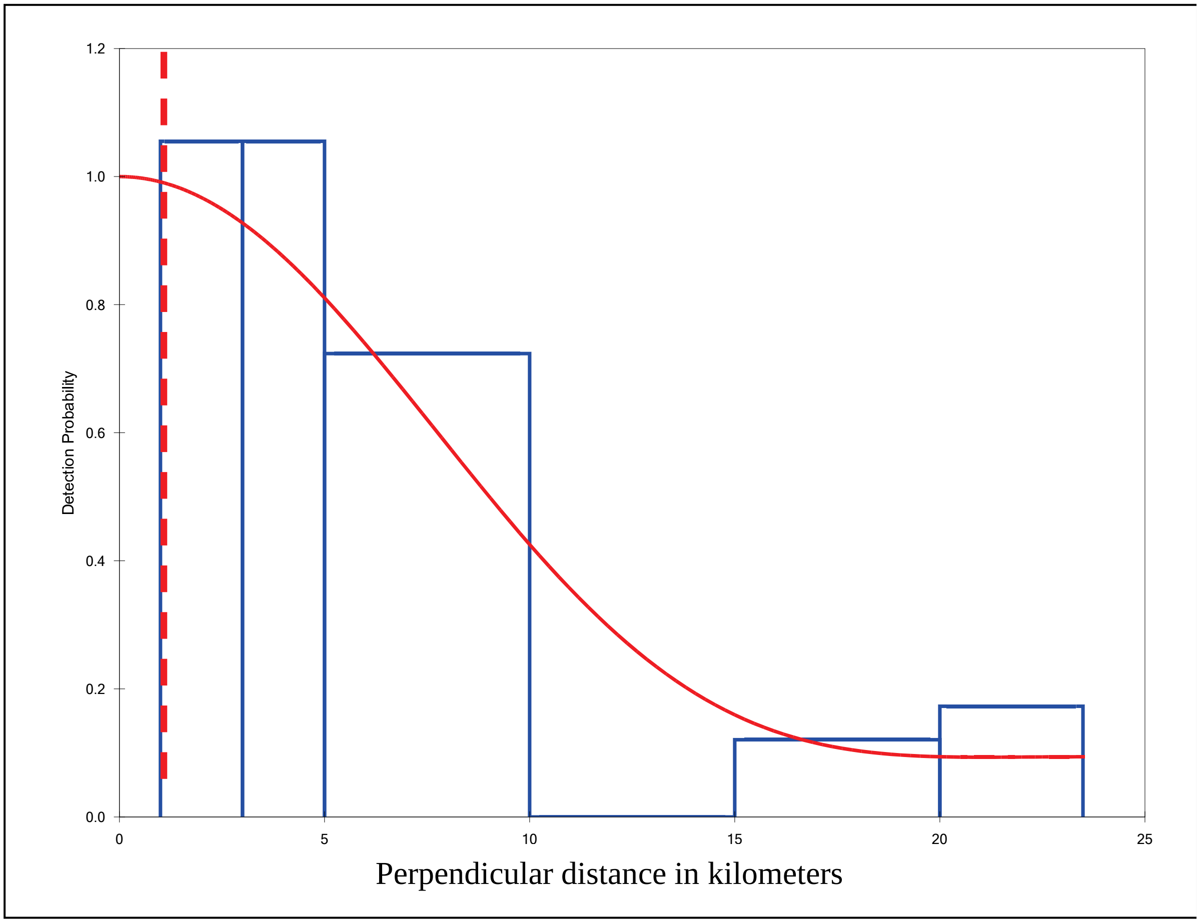


Figure 1-5B. Probability of detection (vertical axis) and detection function modeled for scenario #2. This scenario assumes a reduction in calling behavior (probably due to the vessel) near the trackline. Best fit was the Uniform Key Function plus Cosine series expansion. Left truncation was used at 1 km to remove bias due to reduced calling rates. Dashed red line indicates right truncation point. (Analysis # 37 in *Distance* project folder)

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Section 2. Classification of Whistles Recorded During the MISTCS 2007 Cetacean Survey

2.1 Background

The sounds produced by delphinids are varied and can be divided into three general categories: echolocation clicks, burst pulses and whistles. Echolocation clicks are short, broadband pulses that are used for navigation and object discrimination (Au 1993). These pulses have peak frequencies that vary from tens of kHz to well over 100 kHz (Norris and Evans 1966; Au 1980). Burst pulses are broadband click 'trains' with very short inter-click intervals. These clicks are repeated at such high rates that the click train, rather than the individual clicks, is audible (Watkins 1967, Herzing 2000). Burst pulses are thought to play a role in both social interactions and echolocation tasks. Whistles are continuous, narrowband, frequency modulated signals that often contain harmonic components. They range in duration from several tenths of a second to several seconds (Tyack and Clark 2000). The fundamental frequency of whistles generally ranges between 2 kHz and 20 kHz, although whistles with fundamental frequencies extending to almost 30 kHz have been reported for several species (Lammers et al. 2003, Oswald et al. 2004). Whistles are thought to function as social signals (Janik and Slater 1998, Herzing 2000, Lammers et al. 2003).

Due to the relatively long duration and frequency modulated nature of whistles, many features can be measured from these types of signals. Whistles are thought to be social signals and therefore have the potential to carry important information. In addition, whistles are relatively omni-directional and their mid- to high- fundamental frequencies (ranging from approximately 5 to 25 kHz) generally propagate well underwater (Rankin et al. 2008). These characteristics make whistles well-suited for studies of species-specific traits and, in particular, for acoustic species identification. The identification of delphinid species using whistles is a topic that is receiving more attention as passive acoustic methods have come into widespread use and acceptance for monitoring marine mammals (e.g., Matthews et al. 1999; Rendell et al. 1999; Oswald et al. 2007; Roch et al. 2007; Gannier et al. 2010).

Recently, Oswald et al. (2007) developed software called Real-time Odontocete Call Classification Algorithm (ROCCA) that allows for the acoustic identification of delphinid whistles occurring in the eastern tropical Pacific (ETP) Ocean. The original classification algorithm used in ROCCA included visually validated acoustic recordings from eight species, was based on linear discriminant function analysis (DFA) and classification and regression tree analysis (CART), and correctly classified 46 percent of schools to species (Oswald et al. 2007). Recent modifications to ROCCA include the use of a random forest analysis in place of DFA and CART. The development of ROCCA is discussed in further detail in **Section 2.2.1** of this report. A near-real-time version of ROCCA has recently been incorporated into the bio-acoustic software program PAMGUARD (Gillespie et al. 2008). This software can be used for real-time acoustic monitoring and post-processing of marine mammal acoustic data.

During a combined visual and acoustic cetacean abundance survey that took place in the waters around Guam and the Northern Mariana Islands (DoN 2007), whistles were frequently detected.

These acoustic detections were not always coupled with visual observations. As a result, many acoustic detections were not identified to species. This survey took place in a very large area that is difficult to study due to its remote location and its poor sighting conditions as a result of high Beaufort sea state. Therefore, very little data exist on the occurrence and distribution of delphinids in this study area. The ability to acoustically identify species (or any taxonomic level) that were not sighted (referred to in this report as 'non-sighted acoustic detections') will provide important information regarding the occurrence and distribution of delphinid species in the MISTCS study area. This information can then be used to help assess habitat characteristics, general patterns of distribution, population characteristics, and responses to possible anthropogenic impacts such as naval training exercises.

In this study, we developed a random forest classifier for whistles recorded using a towed hydrophone array during the MISTCS. A Random Forest is a collection of decision trees. Each tree is grown using binary partitioning of the data, based on the value of one variable at each branch or node. Randomness is injected into the tree-growing process by basing the decision of which variable to use as a splitter at each node on a random subsample of all variables (Breiman 2001). Each whistle is run through every tree in the forest, and is then classified as the species that the greatest number of trees 'voted' for. We applied this classifier to the acoustic detections that were not visually sighted during the cruise.

2.2 Methods

2.2.1 Random Forest classification models

The ETP whistle classification algorithms used by ROCCA were created using random forest classification models. Several random forest classification models were created using a database of 1,864 whistles (**Table 2-1**) recorded during five combined visual and acoustic cetacean abundance surveys in the ETP and the waters surrounding the Hawaiian Islands (HI). These five month surveys included *STenella* Abundance Research (STAR) surveys in 2000, 2003, and 2006, Hawaiian Islands Cetacean and Ecosystem Assessment Survey (HICEAS) in 2002, and Pacific Islands Cetacean and Ecosystem Assessment Survey (PICEAS) in 2005 (**Figure 2-2**). As HICEAS and PICEAS were located more in the central than eastern Pacific, the combined dataset will be referred to as the ETP/HI in this report for convenience. See Oswald et al. (2007) for detailed survey methods.

To create classifiers, whistles produced during visually validated, single species encounters were detected manually by a trained bio-acoustic technician (ROCCA does not currently contain an automated whistle detector). The technician noted the start time of all whistles occurring during each acoustic encounter. If more than 35 whistles occurred during an acoustic encounter, 35 of the whistles were randomly selected for analysis. This was done to reduce the risk of over-sampling groups or individuals. ROCCA was then used to extract time-frequency contours from the selected whistles and then to measure 56 features from each contour (in addition to containing classification algorithms, ROCCA also has the capability to extract and measure time-frequency contours from tonal signals), as described in Oswald et al. (2007). The 56 features measured automatically from each whistle contour using ROCCA are described in **Appendix A**. Descriptive statistics for a subset of these variables are presented in **Table 2-2**. The 56 measured features were collectively grouped into "feature vectors" for each whistle. These feature vectors were then used to create several different random forest classification models. The first model classified all whistles down to species. Subsequent models were based on groups of species (ex. 'blackfish', '*Stenella* species,' etc.). Species were grouped based on the confusion matrix produced by the first random forest model. For each classification model, different subsets of the 56 features were tested to find the feature vector that yielded the best tradeoff between the number of features included and the percentage of whistles correctly classified.

To create the random forest models, the data were first sub-sampled so that there were equal sample sizes for each species or group of species. This avoided one class swamping the data and skewing the results. To determine the number of trees and the feature set to use for each model, a random forest analysis was repeated 100 times on the sub-sampled data. The output for each analysis included out-of-bag error estimates (Breiman 2001) for forests consisting of 1 up to 1,000 trees. To calculate out-of-bag error, each tree was grown using approximately two-thirds of the data. The remaining one-third of the data was used as test data. These test data were the 'out-of-bag' data and were used to evaluate the performance of the tree. The out-of-bag error estimates were averaged over all 100 runs to create a plot as shown in **Figure 2-3**. The point at which the out-of-bag error curve began to asymptote was considered to be the number of decision trees to include in the random forest because after this point, little gain was made in classification success with the addition of more trees.

Another output of the random forest analysis is the Gini variable importance index (Breiman 2001). The Gini variable importance index provides a measure of how strongly each variable contributes to the model predictions. The optimal subset of variables to include in each random forest was determined based on this importance index. Variable importance was averaged over all 100 runs described above. Different sets of variables were tested for each random forest model based on the variables that were shown to be most important to the model predictions.

Once the number of trees and the set of variables to include had been determined for a random forest model, all of the data were randomly divided into two equal subsets. One subset was used to train the random forest model and the other was used to test it. The datasets were then switched so that each dataset was used as both a test and a training dataset, and every whistle in the full dataset was classified. Data were divided such that all whistles from a single acoustic detection were in only one subset. This avoided whistles produced by one group or individual being in both the test and train datasets and artificially inflating correct classification scores.

In this study, a whistle was considered to be "strongly classified" if the percentage of trees voting for the predicted class exceeded a user-determined 'strong whistle threshold' (Oswald et al. 2011). Any whistle that was not strongly classified was omitted from the analysis. The choice of strong whistle threshold was based on maximizing the percentage of whistles correctly classified while minimizing the number of detections that could not be classified due to the omission of weakly classified whistles. The strong whistle threshold was determined individually for each random forest model that was tested and ranged from 35 to 50 percent.

Several random forest models were created and tested. The first model classified whistles to species. Eight species were included in this model (false killer whale [*Pseudorca crassidens*], short-finned pilot whale [*Globicephala macroryhnchus*], bottlenose dolphin, pantropical spotted dolphin [*Stenella attenuata*], spinner dolphin [*Stenella longirostris*], striped dolphin [*Stenella* *coeruleoalba*] and short-beaked common dolphin [*Delphinus delphis*]). These species were included based on a list of species expected to occur in waters off Guam and the Mariana Islands (Fulling et al. 2011). Although short-beaked common dolphins are considered rare in the MISTCS study area, it is important to include them in the classifier. If not included, this species would be missed altogether and it would be impossible to investigate their occurrence in the MISTCS study area. Based on the confusion matrix produced by the eight species model, several other models were also tested. These included, but were not limited to:

1. A model that grouped false killer whales and short-finned pilot whales into a ‘blackfish’ class and classified all others to species.
2. A model that contained a blackfish class, a ‘medium-sized delphinid’ class (bottlenose and pantropical spotted dolphins) and classified the others to species.
3. A model that contained a blackfish class, a medium-sized delphinid class, a small delphinid class (spinner, striped and short-beaked common dolphins) and a rough-toothed dolphin class.

Classification success of each random forest model was evaluated by examining the percentage of individual whistles and overall detections that were correctly classified (by reference to visual species identifications), as well as the ‘error reduction’ provided by each classification model. Error reduction provides an unbiased measure of the performance of the classifier and is calculated as follows:

$$(((100 - \text{chance rate}) - (100 - \text{observed rate}))*100)/(100 - \text{chance rate})$$

It is a measure of how a classifier performs compared to the correct classification rates expected by chance alone (Bachorowski and Owren 1999). For example, for a five-class classifier, one would expect 20 percent of cases to be classified correctly simply by chance alone. If the classifier classifies 70 percent of cases correctly, then the classifier has reduced classification error from 80 percent to 30 percent. In order to evaluate the actual magnitude of this chance relative to chance, the error reduction is calculated. In this example, the error reduction is equal to 62.5 percent, meaning that the classifier has reduced error by 62.5 percent relative to what was expected by chance alone.

Patterns in misclassifications were also evaluated by examining confusion matrices for each classifier. Confusion matrices were created based on strongly classified whistles only. Two confusion matrices were produced; one for individual whistles and one for overall detections. Detections were classified based on the percentage of trees voting for the predicted species for all whistles combined within that detection.

2.2.2 Classification of MISTCS whistles

Whistle contours recorded during both sighted and non-sighted acoustic detections that were made using a towed hydrophone array during MISTCS were extracted and measured using ROCCA. Only detections (both sighted and non-sighted) that occurred more than 3 nautical miles (NM) from any other visual or acoustic detection were included in the analysis. This helped to ensure that the whistles analyzed were produced by the school in question and not by any other school in the area. Whistles recorded during MISTCS in the waters around Guam and the Northern Mariana Islands, where species identity was confirmed visually, were used to test the accuracy of the different classifiers created using ETP data. Acoustic detections that were not coupled with visual sightings or observations (non-sighted acoustic detections) were then run through the most accurate classifier in order to determine which species, or groups of species, were detected acoustically but not visually during the MISTCS.

2.3 Results

2.3.1 MISTCS whistle classification

Whistles were recorded during a total of 80 acoustic detections. Of these, 36 (45 percent) detections were matched to visual sightings (**Table 2-3, Figure 2-4**) and 44 (55 percent) were acoustic-only detections (**Figure 2-5**). A total of 1,122 whistles were measured from acoustic-only detections, ranging from 1 to 50 whistles per detection. Summary statistics describing the whistles of species that were detected both visually and acoustically are provided in **Table 2-4**, where the variables included were chosen to allow comparisons with previously published research.

2.3.2 Random Forest analysis

The confusion matrices for the eight-species random forest model created using ETP/HI data are shown in **Table 2-5**. Several random forest models that contained classes of combined species were created based on this confusion matrix. Species that were commonly misclassified as each other were grouped together (ex. false killer whales and short-finned pilot whales). In an attempt to classify the greatest number of taxa to species, different models were tested, each containing a greater number of species groupings (see **Tables 2-6 to 2-8** for examples). Correct classification scores for these models are given in **Tables 2-6 to 2-8**. The model consisting of four classes (blackfish, medium-sized delphinids, small delphinids, and rough-toothed dolphin), 500 trees, and a strong whistle cutoff of 50 percent gave the best results (**Table 2-8**). Overall, 70 percent of detections were correctly classified using this model, compared to 50 percent, 52 percent, and 53 percent for the eight, seven and six class models, respectively. For all models, different feature vectors were tested based on the variable importance scores. In all cases, using all 56 variables gave the best classification results.

2.3.3 Classification of whistles recorded during MISTCS

When the whistles from the MISTCS acoustic detections that included visual confirmation of species identity (**Figure 2-4**) were run through the four different random forest models created from the ETP data, the model consisting of four classes (small delphinids, medium-sized delphinids, blackfish, and rough-toothed dolphin) gave the highest correct classification scores (**Table 2-9**). Consequently, this was the model used to classify whistles recorded during non-sighted acoustic detections (**Figure 2-5**). The percentage of trees voting for each species provides a measure of the certainty of the classification, with 25 percent expected to “vote” for each class based on chance alone. The percentage of trees voting for the predicted class ranged from 38 percent to 93 percent (**Table 2-10**). This was significantly greater than chance alone for every detection (chi-square test, $p<0.001$), suggesting that classifications were made based on real differences in the classes and not simply based on chance alone. Our confidence in the predicted species increases with the percentage of trees voting for that species. Based on our experience with this type of analysis, we consider a prediction to be relatively certain when the percent of trees voting for the predicted species is greater than 60 percent.

Another measure of the certainty of the classification is the distribution of tree votes among species. If the percentage of trees votes are similar for more than one class (e.g.,. if 45 percent of trees voted for ‘medium delphinid’ and 38 percent of trees voted for ‘small delphinid’), the classification can be considered less certain than if the votes are overwhelmingly in favor of a single species or class. When more than 60 percent of trees voted for the predicted species, it was rare that another species had a similar percentage of tree votes (**Table 2-10**). All blackfish and rough-toothed dolphin classifications were considered relatively certain, based both on the percent of trees voting for the predicted species and on the distribution of tree votes. Sixty percent of small delphinid classifications and one out of the three medium delphinid classifications were considered relatively certain based on the distribution of tree votes among species (**Table 2-10**).

Over half (56 percent) of non-sighted detections were classified as blackfish (**Figure 2-6**). The next most common predicted class was small delphinids. Both medium-sized delphinids and rough-toothed dolphins were also represented in the non-sighted detection subsample. Two of the non-sighted acoustic detections could not be classified because they each contained only one whistle of sufficient quality for analysis, and that whistle did not meet the strong whistle cutoff threshold when it was run through the classifier.

2.4 Discussion

Correct classification scores were higher overall for the four-class random forest model (**Table 2-8**) than they were for the eight-class random forest model (**Table 2-5**). This is partially due to there being fewer categories in the four-class random forest model. The likelihood of correct classification simply by chance alone increases as the number of classes decreases. However, the improvement is also partially because the classes in the four-class random forest model were created based on confusion matrices. Species that were commonly confused as each other were grouped into classes (such as ‘blackfish’ or ‘small delphinid’). Eliminating these sources of confusion led to improved classification success. For example, the confusion matrix in **Table 2-5a** shows that for short-finned pilot whales, 37 percent of whistles were correctly classified as short-finned pilot whales, while 49 percent of whistles were misclassified as false killer whales. Short-finned pilot whale whistles were rarely classified as anything else. Similarly, 70 percent of false killer whale whistles were correctly classified and 21 percent of false killer whale whistles were misclassified as short-finned pilot whales. These misclassifications are likely due to the similar frequency characteristics in whistles produced by these two species (**Table 2-2**). Short-finned pilot whale and false killer whale whistles are also less complex than many whistles produced by other species (i.e. the whistles have few inflection points and steps, and cover a narrow frequency range). The fact that these two species were most commonly misclassified as each other led to grouping them into one ‘blackfish’ class in subsequent classification models. Grouping these species into a ‘blackfish’ class also makes sense evolutionarily, as false killer whales and short-finned pilot whales are more closely related to each other than they are to the other delphinids included in the random forest.

Other species groupings included a 'small delphinid' class and a 'medium delphinid' class. The small delphinid class included spinner, striped and short-beaked common dolphins, and these species were commonly misclassified as one another. All of the species within the small delphinid class had similar frequency characteristics, likely leading to some of the confusion among these classes. Spinner and striped dolphins are in the same genus (*Stenella*), which may contribute to similarity among their whistles, but more research needs to be done before this can be stated conclusively. Spinner dolphin whistles were especially likely to be misclassified as not only striped and short-beaked common dolphins, but also as bottlenose, pantropical spotted, and rough-toothed dolphins (**Table 2-5**). Spinner, bottlenose, and pantropical spotted dolphins are the three species in the analysis with the highest maximum frequencies. As maximum frequency was the most important variable in the random forest, similar maximum frequencies explain at least some of the misclassification among these species. The fact that spinner dolphin whistles were also misclassified as rough-toothed dolphins is a little more difficult to explain. Qualitatively, rough-toothed dolphins commonly produce whistles with relatively flat slopes and several steps. Spinner dolphins also occasionally produce whistles that fit that description. It is possible that these whistles are distinctive to rough-toothed dolphins and when another species produces them, they are automatically classified as rough-toothed dolphin whistles. This would be an interesting and valuable avenue of future research.

The two species in the 'medium delphinid' class (bottlenose and pantropical spotted dolphins) had similar minimum and maximum frequencies and similar body sizes. Ding et al. (1995a) and Matthews et al. (1999) both found a negative correlation between body length and frequency characteristics of whistle contours for nine odontocete species. Frequency variables were important features in all of the random forest classifiers tested in this study, and so grouping species based on body size seemed reasonable. Based on the Gini variable importance index, maximum frequency was one of the most (if not the most) important variables in all of the random forest models tested here. Other frequency variables also ranked near the top of the variable importance index, including: mean frequency, center frequency, beginning and ending frequency and frequency at one-fourth, one-half, and three-fourths of the duration. Other variables that were consistently important in the random forest were variables related to the slope of the whistle, such as mean slope, and mean negative slope.

It is interesting to note that although rough-toothed dolphins were not grouped with any other species in any model, the percentage of their whistles correctly classified was higher for the four class random forest than it was for the eight class random forest. This is likely because most misclassified rough-toothed dolphin whistles were misclassified in the eight-class model as either short-finned pilot whales or false killer whales (**Table 2-5a**). Grouping short-finned pilot whales and false killer whales into one 'blackfish' class resulted in a more distinct class, as evidenced by the high correct classification score for this class. The increased distinctiveness of this class also resulted in fewer rough-toothed dolphin whistles being misclassified as blackfish.

Correct classification scores were generally higher for detections than they were for individual whistles. This was especially true for short-beaked common dolphins, where 22 percent of individual whistles were correctly classified compared to 40 percent of detections (**Table 2-6**). This can be explained by the method used to classify detections. For individual whistles, the whistle was classified as the species that the greatest number of trees voted for. To classify a detection, the number of trees voting for each species was summed over all of the whistles within that detection. For short-beaked common dolphins, the number of votes for the correct species was often lower than, but still close to, the number of votes for the predicted species. The predicted species varied, however, from whistle to whistle. Because of this, when votes were summed over all whistles, short-beaked common dolphin had the highest number of votes more often than it did for individual whistles.

Most (56 percent) of the non-sighted acoustic detections that occurred during the MISTCS were classified as blackfish. Based on results from the ETP training dataset (95 percent of blackfish schools classified correctly, **Table 2-8**) and on results of running MISTCS-sighted acoustic detections through the four-class random forest model (100 percent of blackfish schools classified correctly, **Table 2-9b**), we have a high degree of confidence in the non-sighted blackfish classifications.

During the MISTCS, one school of melon-headed whales (*Peponocephala electra*) was sighted and after running the whistles recorded during that sighting through the four-class random forest model, the acoustic detection was correctly classified as blackfish. This suggests that the blackfish class could be considered representative of whistles from other species of blackfish and not only applicable to short-finned pilot whales and false killer whales. The whistles recorded during the encounter with melon-headed whales had similar characteristics to those recorded from short-finned pilot whales and false killer whales (i.e., the whistles were relatively low frequency, had few inflection points and steps, and had a narrow frequency range). However, it is important to note that this analysis is based on only one detection of a group of melon-headed whales. Additional visually-confirmed acoustic detections of this and other blackfish species (e.g., pygmy killer whale, *Feresa attenuata*) are necessary in order to determine if these results will hold for other species of blackfish.

It is plausible that most non-sighted acoustic detections were blackfish, as these species often travel in small sub-groups and surface inconspicuously (Barlow and Rankin 2007), making them difficult to detect visually in high Beaufort sea states such as those often encountered during MISTCS. In addition, blackfish are very active acoustically (Barlow and Rankin 2007) and produce whistles that are relatively low frequency and, thus, propagate efficiently under water. All of these characteristics of blackfish whistles make them well suited to acoustic detection and classification methods. During two unrelated visual and acoustic cetacean surveys by the National Oceanic and Atmospheric Administration (NOAA) that took place within the Hawaiian Exclusive Economic Zone (EEZ) and adjacent waters south to Palmyra and Johnston atolls, there were twice as many acoustic detections of false killer whales as there were visual detections (Barlow et al. 2004, 2008; Barlow and Rankin 2007, Barlow et al. 2008).

The percentages of schools correctly classified in both the ETP test data and the MISTCS sighted acoustic detection dataset were not quite as high for the other three classes (small delphinids, medium delphinids and rough-toothed dolphins) as they were for the blackfish class. However, they were all significantly greater than expected by chance alone (**Tables 2-8 and 2-9b**). In addition, the proportion of trees voting for the predicted class was significantly greater than chance for every non-sighted acoustic detection (**Table 2-10**). Based on this and on the distributions of tree votes among species, we believe that the non-sighted acoustic detection classification results can be considered very reliable for these groups as well.

It is important to note that the classifier used to identify whistles recorded in the waters surrounding Guam and the Northern Mariana Islands was created using data collected in the ETP and the waters surrounding the Hawaiian Islands. Geographic variation has been found in the whistles of some species (e.g., Baron et al. 2008, Morisaka et al. 2005, Rendell et al. 1999, Ding et al. 1995b), and so it is possible that a classifier created using whistles collected in the MISTCS study area would produce better results. We were unable to fully test the classifier on whistles collected during MISTCS because not every species included in the classifier was represented in the dataset of MISTCS recordings with visual confirmation of species identity (as expected, short-beaked common dolphins were not observed). In addition, species that were represented in the MISTCS dataset had relatively small sample sizes (i.e. independent detection events). Because of this, we were unable to statistically compare the descriptive statistics presented for the ETP and MISTCS datasets. Such a comparison would provide another means for evaluating how accurately a classifier created using ETP data can predict species in recordings collected around Guam and the Northern Mariana Islands. Larger sample sizes would produce results that could be generalized with a higher degree of confidence.

While classifying whistles to a group of species such as ‘small delphinid’ or ‘blackfish’ is useful, it would be beneficial to be able to classify whistles to species with a high degree of confidence. Extensive work has been conducted to develop species-specific classifiers for delphinid whistles (e.g., Matthews et al. 1999, Rendell et al. 1999, Oswald et al. 2007, Roch et al. 2007, Gannier et al. 2010). To create a species-specific classifier for the MISTCS study area would require visually validated recordings from every whistling species that could be encountered in this area. A large enough sample size to provide both training and test data would also be required. In addition, although the set of variables used to classify whistles to four classes worked well, these may not be the optimal variables for classifying whistles to species. Additional or alternate variables that can be measured from tonal signals should be explored in order to find a set that may allow for more detailed classification. Variables related to the relative intensities of different frequencies may prove useful, as well as variables that describe the overall form of an acoustic encounter (such as the number of whistles recorded, the amount of overlap among whistles in the time domain, and the time between subsequent whistles).

2.5 Conclusions and Recommendations

Of all of the classifiers that were tested, the four-class (small delphinids, medium delphinids, blackfish, rough-toothed dolphins) classifier produced the best results. When this classifier was applied to non-sighted acoustic detections that occurred during MISTCS, most (56 percent) were classified as blackfish. The ability to identify detections that did not have concurrent visual observations makes it possible to obtain information that has been unavailable until now on the distribution and occurrence of species.

While the results of this study provide important information, the ability to identify detections to species, rather than to groups such as “small delphinids” or “blackfish” would be advantageous. In addition, while we were able to test the classifier on some species recorded in the Guam/Mariana Islands study area, we were not able to test it on every species, as visually validated recordings do not exist for every species that may be encountered in the study area. The inability to fully test the classifier on data collected in this study area leaves gaps in our knowledge. With additional visually validated recordings from the Guam and Mariana Islands study area, we would be able to fully test the ETP/HI classifier and determine whether it is truly applicable to these data. In addition, the collection of visually validated data would allow us to include whistles from this study area into the ETP/HI classifier, or if necessary, to create an entirely new classifier containing only whistles from this study area. Comparisons of the whistles produced by species found in both the ETP/HI and the Guam/Mariana Islands study area would also allow us to determine whether a new classifier needs to be created. When the classifier can be fully tested and optimized, it will provide a tool for analyzing data collected using towed hydrophone arrays, seafloor mounted acoustic recorders and sonobuoys. The ability to identify species on recordings that do not include concurrent visual observations will allow species occurrence and distribution data to be collected in a more comprehensive, efficient and cost effective way.

Future research should include efforts to improve the performance of the classifier. Several approaches should be investigated. First, an examination of the characteristics of whistles that are strongly classified for each species could illuminate variables that are important and distinctive to different species. Similarly, an investigation of whistles that are weakly classified could highlight problems and provide insight into why misclassifications occur. Second, additional or alternate features should be explored for inclusion in the classification analysis. The feature vector used here may not be the optimal vector for classification of delphinid whistles. Other variables such as amplitude of whistles, density of whistles and overlap among whistles could provide greater separation among species. In addition, analysis methods other than spectrographic analysis (such as wavelet analysis) could provide entirely different feature vectors that may provide greater classification success. Finally, alternate classification methods should be explored. The use of classification algorithms such as artificial neural networks, hidden Markov models and support vector machines in conjunction with, or instead of, random forests could lead to higher correct classification scores.

Although it was not possible to classify all whistles to species, even classifying them to broader categories has provided new and important information that is useful in understanding the occurrence and distribution of cetaceans in the MISTCS study area. Due to the remote location of this study area, as well as the challenging visual survey conditions typically encountered in the region, there is a paucity of information on species occurrence and distribution. The ability to identify the presence of “small delphinids,” “medium delphinids,” “blackfish,” and rough-toothed dolphins provides information that can be used to plan future vessel surveys, aerial surveys, and locations of fixed PAM installations. Furthermore, predictive habitat and spatial models could benefit from any additional information about the distribution and occurrence of delphinids in the MISTCS study area. Finally, this project represents a step forward in the development of a classifier specific to the MISTCS study area. A classifier specific to this area will provide an effective tool that can be used to analyze data collected in the future using passive acoustic methods, especially fixed PAM installations and recorders, as these recordings rarely have visual observations that are associated with them.

2.6 Tables and Figures

2.6.1 Tables

Table 2-1. Number of whistles and number of schools that whistles were recorded from for each delphinid species in the ETP whistle dataset.

Species	# of whistles	# of schools
Bottlenose dolphin (*Tursiops truncatus*)	155	8
Short-beaked common dolphin (*Delphinus delphis*)	226	20
False killer whale (*Pseudorca crassidens*)	309	9
Short-finned pilot whale (*Globicephala macrorhynchus*)	109	12
Pantropical spotted dolphin (*Stenella attenuata*)	297	18
Rough-toothed dolphin (*Steno bredanensis*)	145	12
Striped dolphin (*Stenella coeruleoalba*)	452	36
Spinner dolphin (*Stenella longirostris*)	170	15

Table 2-2. Summary statistics (means and standard deviations) for a subset of the variables measured from whistles recorded in the ETP. The variables included in this table were chosen to allow comparison with previous research. Frequency variables are given in Hz and duration is in seconds.

Species		Begin Hz	End Hz	Minimum (Min) Hz	Maximum (Max) Hz	Frequency Range	Duration	# of Steps	# of Inflection Points
Short-finned pilot whale	Mean	5466.4	6879.6	4673.3	7867.5	3194.2	0.5	0.3	0.9
	SD	3347.4	4466.5	2444.5	4831.0	3328.9	0.3	1.1	2.0
False killer whale	Mean	5902.5	6463.1	5423.2	7132.0	1708.8	0.4	0.0	0.9
	SD	1387.7	1599.2	1220.0	1627.2	1343.3	0.2	0.1	0.9
Pan tropical spotted dolphin	Mean	10106.3	15345.6	8496.3	18119.9	9624.2	0.7	2.7	1.1
	SD	4214.9	5938.1	2582.5	5147.9	5334.1	0.4	3.5	1.2
Striped dolphin	Mean	11439.1	12268.1	8870.6	15279.9	6408.2	0.6	1.7	1.6
	SD	4096.9	3476.2	2308.1	3414.9	3250.8	0.3	2.6	2.3
Spinner dolphin	Mean	12975.3	13674.6	10688.1	16307.8	5625.8	0.6	0.9	1.7
	SD	4706.2	4719.5	3326.1	4815.4	3859.2	0.4	1.8	2.9
Rough-toothed dolphin	Mean	7885.4	8234.8	6631.9	9764.7	3132.9	0.7	1.5	3.0
	SD	3156.2	2806.4	2157.5	2824.3	1919.0	0.3	1.9	2.9
Bottle- nose dolphin	Mean	12298.4	11486.2	8446.0	16998.9	8550.8	0.9	1.2	2.0
	SD	5765.3	5484.3	2666.0	5561.1	5357.2	0.6	2.3	2.0
Short-beaked common dolphin	Mean	12333.6	12484.6	8677.9	15590.6	6915.0	0.7	2.1	1.8
	SD	4996.2	4539.5	2756.7	4606.0	4126.0	0.4	2.5	2.0

Table 2-3. Number of acoustic detections in the MISTCS study area that were matched with visual observations by species, as well as the number of whistles measured for each species.

Species	# of detections	# of whistles measured
Short-finned pilot whale	2	67
False killer whale	8	400
Melon-headed whale	1	50
Pantropical spotted dolphin	12	199
Striped dolphin	9	257
Spinner dolphin	1	50
Rough-toothed dolphin	1	4
Bottlenose dolphin	2	57

Table 2-4. Summary statistics (means and standard deviations) for a subset of the variables measured from whistles recorded during MISTCS sighted acoustic detections. The variables included in this table were chosen to allow comparison with previous research. Frequency variables are given in Hz and duration is in seconds

Species		Begin Hz	End Hz	Min Hz	Max Hz	Frequency Range	Duration	# of Steps	# of Inflection Points
Short-finned pilot whale	Mean	5100.3	5360.5	4556.0	5937.0	1381.1	0.4	0.1	1.0
	SD	3784.9	3386.7	3305.3	3677.5	1442.8	0.2	0.4	1.3
False killer whale	Mean	6823.1	7098.5	6041.1	7916.1	1875.0	0.4	0.2	2.3
	SD	1710.8	1963.4	1511.3	1751.5	1592.8	0.2	0.6	2.5
Melon-headed whale	Mean	8737.5	8852.8	7394.1	10042.5	2648.4	0.5	0.3	1.7
	SD	3396.1	3608.6	2914.3	3558.9	2186.5	0.3	1.2	1.6
Pantropical spotted dolphin	Mean	10905.2	13797.5	9741.5	16393.1	6651.5	0.6	0.1	1.1
	SD	3995.1	5894.5	3078.3	6431.2	4922.0	0.3	0.3	1.2
Striped dolphin	Mean	9669.6	11024.9	8301.6	12612.3	4310.7	0.6	0.3	1.7
	SD	3645.1	4450.1	2596.1	4773.8	3604.8	0.3	1.2	2.0
Spinner dolphin	Mean	14085.9	13605.9	11281.9	20037.2	8755.3	0.9	0.0	1.9
	SD	3831.0	3818.2	2569.3	2959.5	3189.5	0.3	0.1	1.6
Rough-toothed dolphin	Mean	4921.9	5355.5	4722.7	5578.1	855.5	0.1	0.3	0.5
	SD	597.8	594.6	508.3	357.0	505.4	0.0	0.5	0.6
Bottle-nose dolphin	Mean	8718.8	9024.7	8278.1	9409.1	1131.0	0.5	0.0	2.1
	SD	3093.1	3124.1	2888.1	3267.0	766.0	0.2	0.0	1.7

Table 2-5. Confusion matrices (percentages of classification) for (a) individual whistles and (b) detections. Percent of whistles or detections correctly classified are in bold and underlined. Eight-species random forest model was trained and tested using ETP data, and consisted of 800 trees and 56 variables. Results are based on a strong whistle threshold of 35 percent.

Actual species	% classified as								
	Bottle-nose dolphin	Short-beaked common dolphin	False killer whale	Spotted dolphin	Pilot whale	Rough-toothed dolphin	Striped dolphin	Spinner dolphin	n
(a). Individual Whistles									
Bottlenose dolphin	**51**	4	3	20	2	7	5	8	74
Short-beaked common dolphin	8	**40**	2	11	0	11	7	21	63
False killer whale	1	2	**70**	0	21	4	0	2	98
Spotted dolphin	16	20	3	**42**	0	1	4	14	81
Short-finned pilot whale	1	1	49	1	**37**	3	5	3	98
Rough-toothed dolphin	3	3	13	0	10	**65**	3	3	68
Striped dolphin	0	18	3	5	0	6	**58**	10	73
Spinner dolphin	12	18	5	17	3	12	13	**20**	76
(b). Detections									
Bottlenose dolphin	**63**	12	12	0	0	0	0	13	8
Short-beaked common dolphin	6	**41**	0	12	0	6	18	17	17
False killer whale	0	0	**89**	0	11	0	0	0	9
Pantropical spotted dolphin	13	13	7	**47**	0	0	0	20	15
Short-finned pilot whale	0	8	58	0	**26**	8	0	0	12
Rough-toothed dolphin	9	0	9	0	9	**64**	9	0	11
Striped dolphin	0	25	4	8	0	13	**42**	8	24
Spinner dolphin	15	15	0	8	8	8	15	**31**	13

Table 2-6. Percent of individual whistles and detections that were correctly classified and error reduction analysis using ETP test data. The random forest consisted of 7 classes, 700 trees and 56 variables. The 'blackfish' class contained false killer whales and short-finned pilot whales. Correct classification scores were calculated using a strong whistle threshold of 35 percent. Overall, 48 percent of individual whistles and 52 percent of detections were correctly classified using this model. Correct classification expected by chance was 14.3 percent.

Species	% of whistles correctly classified	Error reduction	n	% of detections correctly classified	Error reduction	n
Bottlenose dolphin	53	45	104	63	57	8
Short-beaked common dolphin	22	9	87	40	30	18
Blackfish	87	85	142	84	81	19
Pantropical spotted dolphin	43	34	92	50	42	16
Rough-toothed dolphin	63	57	106	67	62	12
Striped dolphin	43	34	90	41	31	31
Spinner dolphin	28	16	123	21	8	14

Table 2-7. Percentages of individual whistles and detections that were correctly classified and error reduction using ETP test data. The random forest consisted of 6 classes, 700 trees and 56 variables. The 'blackfish' class contained false killer whales and short-finned pilot whales, the 'medium-sized delphinid' class contained bottlenose and pan-tropical spotted dolphins. Correct classification scores were calculated using a strong whistle threshold of 35 percent. Overall, 52 percent of individual whistles and 53 percent of detections were correctly classified using this model. Correct classification expected by chance was 16.7 percent.

Species	% of whistles correctly classified	Error reduction	n	% of detections correctly classified	Error reduction	n
Medium-sized delphinids	54	45	104	52	42	25
Short-beaked common dolphin	28	14	112	47	36	19
Blackfish	84	81	141	100	100	18
Rough-toothed dolphin	68	62	111	50	40	12
Striped dolphin	47	36	100	44	33	32
Spinner dolphin	30	16	125	25	10	12

Table 2-8. Percentages of individual whistles and detections that were correctly classified and error reduction using ETP test data. The random forest consisted of 4 classes, 500 trees

and 56 variables. The "blackfish" class contained false killer whales and pilot whales, the "medium-sized delphinid" class contained bottlenose and pan-tropical spotted dolphins and the 'small delphinids' class contained spinner, striped and short-beaked common dolphins. Correct classification scores were calculated using a strong whistle threshold of 50 percent. Overall 72 percent of individual whistles and 70 percent of schools were correctly classified using this model. Correct classification expected by chance was 25 percent.

Species	% of whistles correctly classified	Error reduction	n	% of detections correctly classified	Error reduction	n
Medium-sized delphinids	62	49	115	60	47	25
Small delphinids	62	49	122	57	43	47
Blackfish	91	88	128	95	93	19
Rough-toothed dolphin	71	61	101	67	56	12

Table 2-9. Correct classification scores (percent cc = percent correctly classified) and error reduction (error reduct) for individual whistles and detections recorded during acoustic detections that had visual confirmation of species identity. Results are given for individual whistles ("whistles" columns) and overall acoustic detections ('detections' columns) a) the eight class random forest model contained eight species and correct classification expected by chance was 12.5 percent. The seven-class model contained six species and a 'blackfish' class and correct classification expected by chance was 14.3 percent. b) The six class model contained four species, a blackfish class and a "medium-sized delphinid" class and correct classification expected by chance was 16.7 percent. The four class model contained blackfish, medium-sized delphinids, small delphinids and rough-toothed dolphins and correct classification expected by chance was 25 percent.

a) Eight and seven class random forest model.

Species	Eight class model						Seven class model					
	whistles			detections			whistles			detections		
	% cc	error reduct	n	% cc	error reduct	n	% cc	error reduct	n	% cc	error reduct	n
Bottlenose dolphin	8	-5	37	0	0	2	9	-6	46	0	0	2
Short-beaked common dolphin	n/a	0	0	n/a	n/a	0	n/a	n/a	0	n/a	n/a	0
False killer whale	60	54	287	100	100	8	see blackfish class					
Pantropical spotted dolphin	37	28	154	58	52	12	22	9	172	36	25	11
Short-finned pilot whale	70	66	60	100	100	2	see blackfish class					
Rough-toothed dolphin	0	0	3	0	0	1	0	0	4	0	0	1
Striped dolphin	8	-5	128	13	0.5714	8	34	23	193	56	49	9
Spinner dolphin	32	22	37	0	0	1	33	22	46	0	0	0
Blackfish	n/a	n/a	n/a	n/a	n/a	n/a	69	64	456	100	100	11
Medium delphinid	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Small delphinid	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

b) Six and four class model.

Species	**Six class model**						**Four class model**					
	whistles			**detections**			**whistles**			**detections**		
	% cc	**error reduct**	**n**	**% cc**	**error reduct**	**n**	**% cc**	**error reduct**	**n**	**% cc**	**error reduct**	**n**
Bottlenose dolphin	see medium delphinid class						see medium delphinid class					
Short-beaked common dolphin	n/a	n/a	0	n/a	n/a	0	see small delphinid class					
False killer whale	see blackfish class						see blackfish class					
Spotted dolphin	see medium delphinid class						see medium delphinid class					
Pilot whale	see blackfish class						see blackfish class					
Rough-toothed dolphin	0	0	4	0	0	1	0	0	4	0	0	1
Striped dolphin	21	5	159	44	33	9	see small delphinid class					
Spinner dolphin	32	18	75	50	40	2	see small delphinid class					
Blackfish	73	68	376	100	100	10	74	65	388	100	100	11
Medium delphinid	29	15	191	54	45	13	38	17	222	57	43	14
Small delphinid	n/a	n/a	n/a	n/a	n/a	n/a	42	23	233	60	47	10

Table 2-10. Predicted species and the percentages of trees voting for each class for non-sighted acoustic detections. Predicted species based on the four-class random forest model with a 50 percent strong whistle threshold. "Ambig" means that the detection could not be classified because there were no strong whistles present. Detection ID is the identification number assigned to the acoustic detection during MISTCS. The class receiving the highest percent of tree votes is indicated in bold. Cases where the classification can be considered relatively certain are highlighted in yellow or blue. Yellow denotes cases where the percent of tree votes is greater than 60 percent and blue denotes cases where the classification can be considered relatively certain based on the distribution of tree votes. Codes in the "predicted species" column are: Md = medium-sized delphinid, Sd = small delphinid, Bf = blackfish, and Sb = rough-toothed dolphin.

Detection id	# whistles	# strong whistles	Predicted species	% tree votes			
				Medium delphinid	Small delphinid	Black-fish	Rough-toothed dolphins
A007_S999	30	27	Bf	2.8	4.4	**81.5**	11.3
A015_S999	5	5	Sb	5.9	23.2	9.4	**61.6**
A019_S999	15	14	Bf	0.4	1.0	**90.1**	8.4
A020_S999	20	9	Md	**45.6**	38.5	4.3	11.6
A023_S999	21	19	Sd	40.3	**55.5**	0.3	4.0
A025_S999	16	9	Sd	20.4	**38.1**	30.5	11.0
A027_S999	30	22	Sd	23.3	**39.4**	7.0	30.3
A036_S999	10	6	Sd	40.5	**46.3**	1.6	11.6
A037_S999	1	0	Ambig	0.0	0.0	0.0	0.0
A042_S999	1	1	Bf	26.2	14.4	**50.4**	9.0
A043_S999	10	5	Sb	6.9	27.8	20.8	**44.6**
A044_S999	30	30	Bf	1.5	2.3	**78.8**	17.4
A047_S021	48	39	Bf	3.9	7.4	**71.2**	17.5
A049_S026	25	20	Bf	8.1	21.7	**50.5**	19.7
A052_S999	30	27	Bf	3.3	5.3	**69.4**	22.0
A056_S999	7	5	Bf	22.1	14.7	**57.3**	6.0
A059_S999	9	7	Sb	4.9	14.3	18.4	**62.5**
A065_S999	50	42	Bf	4.0	10.0	**56.7**	29.3
A085_S042	50	45	Bf	3.9	4.9	**73.8**	17.4
A086_S999	30	15	Sd	32.0	**53.1**	6.9	8.0
A099_S999	18	10	Sd	30.8	**59.0**	2.1	8.1

Detection id	**# whistles**	**# strong whistles**	**Predicted species**	**% tree votes**			
				Medium delphinid	**Small delphinid**	**Blackfish**	**Rough-toothed dolphins**
A100_S999	50	41	Bf	3.0	6.0	**72.5**	18.5
A101_S999	50	19	Sd	33.8	**57.1**	1.5	7.6
A102_S999	30	22	Bf	4.0	3.8	**79.2**	13.0
A104_S999	48	38	Bf	2.8	4.3	**79.0**	13.9
A112_S999	30	23	Sd	22.9	**45.9**	11.4	19.8
A126_S999	16	14	Bf	2.1	3.6	**81.0**	13.3
A127_S074	30	23	Bf	2.1	4.1	**79.5**	14.2
A129_S999	7	3	Bf	5.3	5.5	**73.7**	15.6
A136_S089	50	45	Bf	2.6	4.2	**76.7**	16.5
A149_S999	14	11	Sd	36.4	**50.4**	8.3	4.9
A168_S999	9	6	Sb	3.1	20.5	5.3	**71.1**
A169_S999	4	4	Md	**63.3**	35.4	0.2	1.1
A180_S999	50	41	Bf	3.5	4.5	**76.8**	15.3
A187_S999	8	8	Bf	0.4	3.6	**76.2**	19.9
A194_S999	13	6	Bf	7.8	11.6	**53.4**	27.2
A196_S999	17	17	Bf	4.9	8.6	**79.8**	6.7
A205_S999	50	44	Bf	4.0	5.2	**66.8**	24.0
A212_S999	50	38	Bf	3.4	6.4	**73.5**	16.7
A999_S028	1	0	Ambig	0.0	0.0	0.0	0.0
A999_S053	3	3	Bf	0.6	0.6	**93.3**	5.5
A999_S999a	14	12	Bf	2.7	4.5	**78.6**	14.3
A999_S999b	9	9	Bf	6.2	10.5	**61.3**	22.0
A999_S999c	30	25	Sd	27.5	**52.2**	8.6	11.7
A999_S999d	19	17	Md	**52.6**	42.0	1.3	4.1

2.6.2 Figures

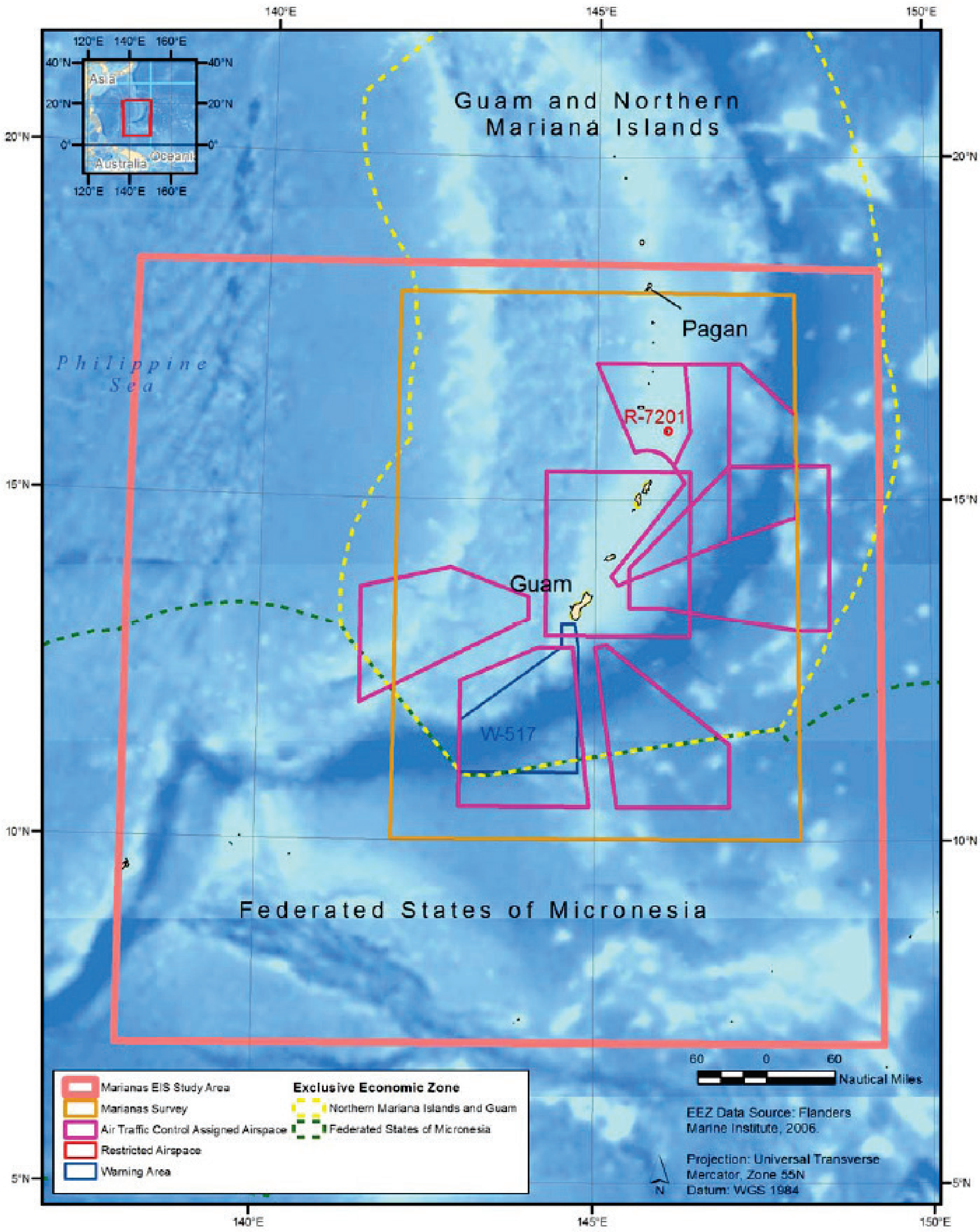

Figure 2-1. MISTCS study area (tan colored box) and Mariana Island EIS study area (peach colored box) including the Commonwealth of the Northern Mariana Islands (from Don 2007).

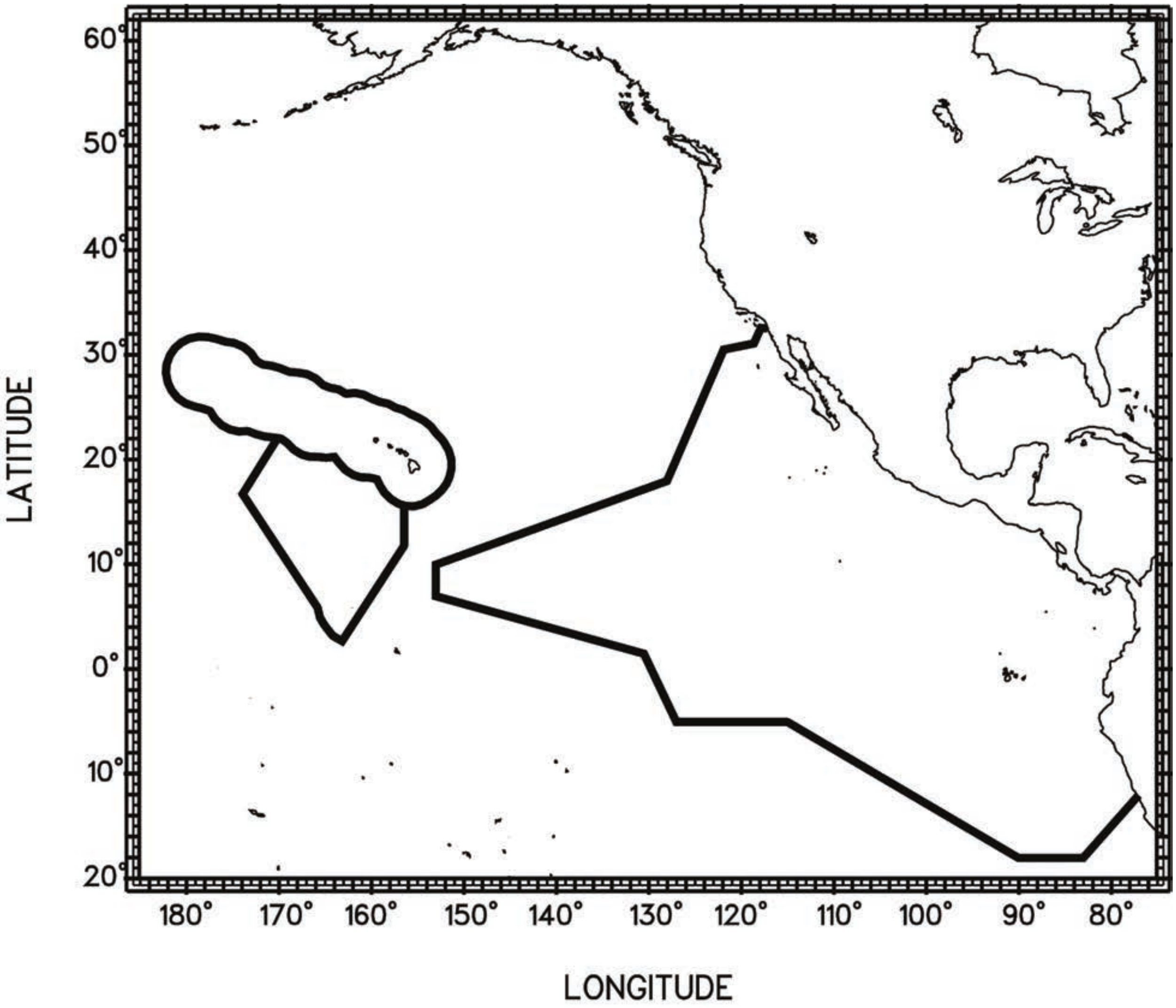

Figure 2-2. Pacific Ocean study area boundaries for the STAR 2000, 2003, and 2006, HICEAS 2002 and PICEAS 2005 visual and acoustic marine mammal abundance surveys.

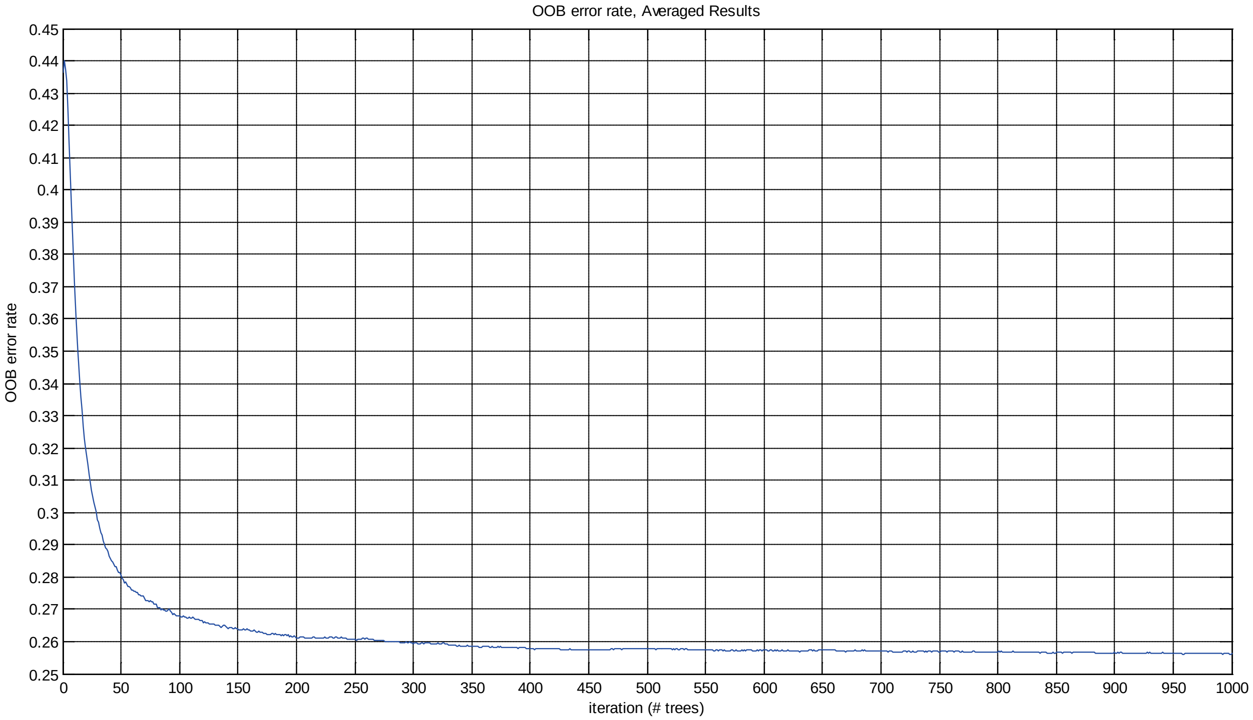

Figure 2-3. Out-of-bag error rate vs. number of trees in the random forest.

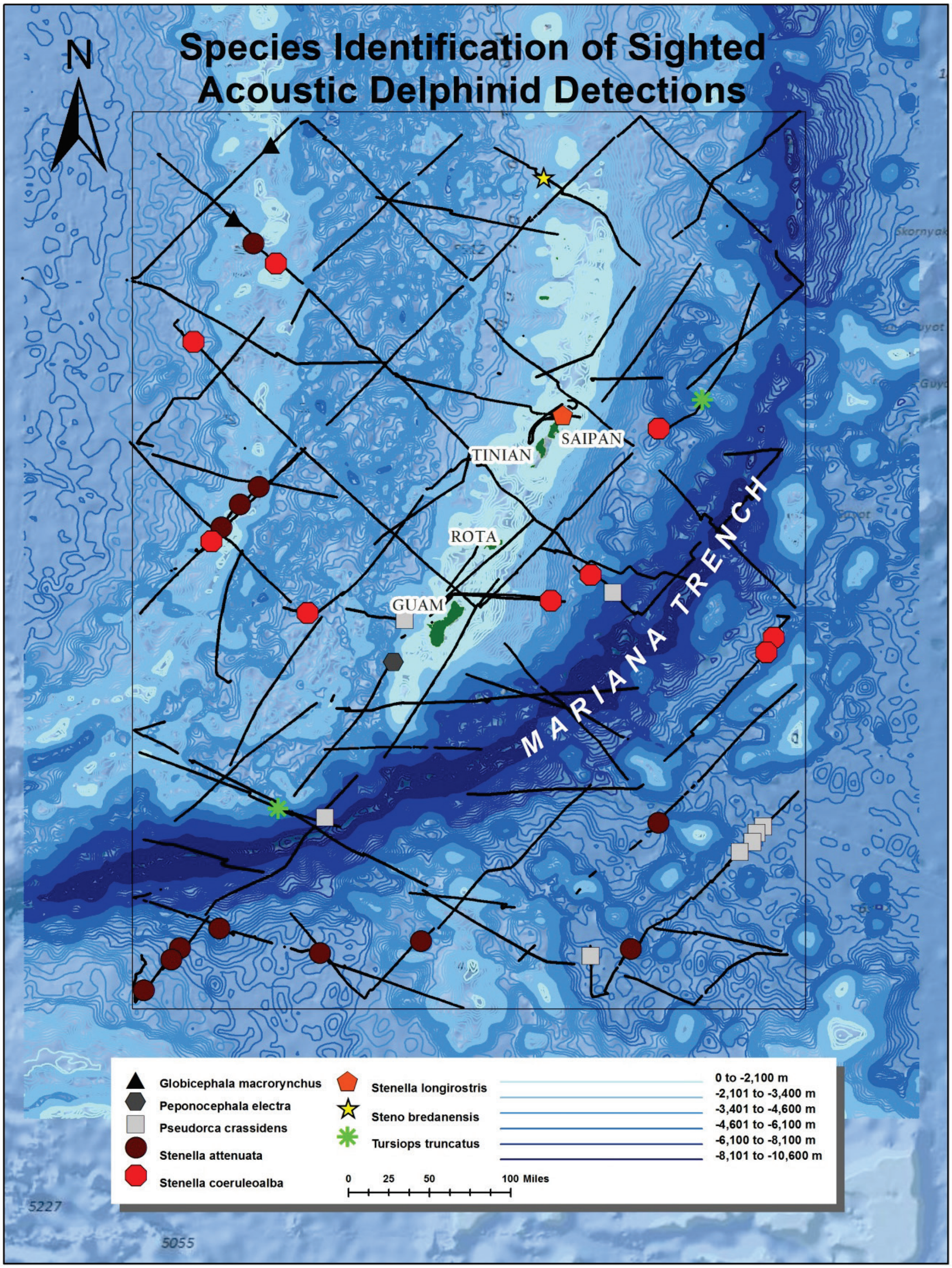

Figure 2-4. Sighted delphinid detections.

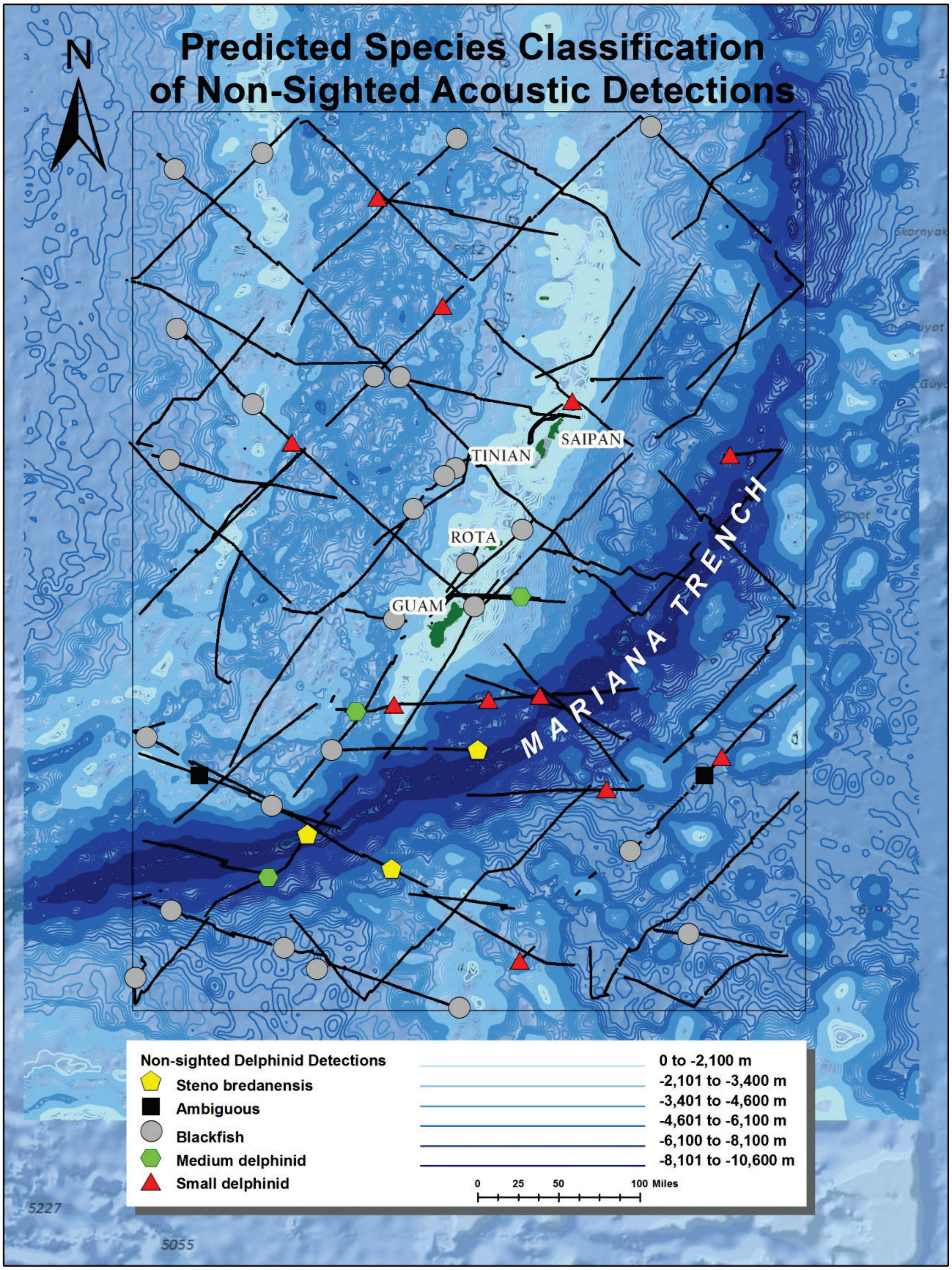

Figure 2-5. Predicted delphinid detections.

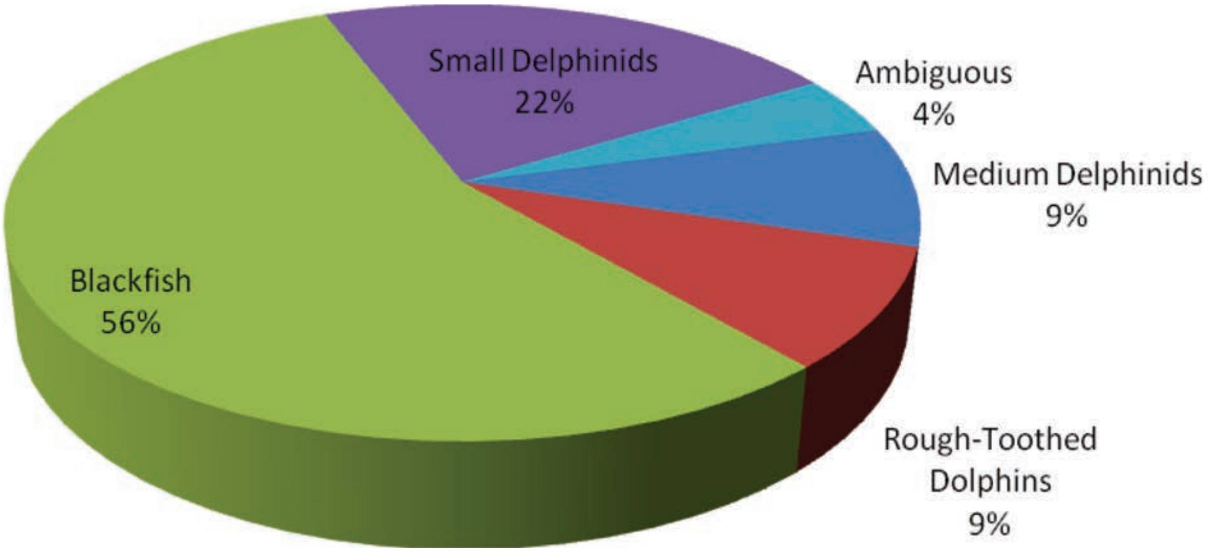

Figure 2-6. Distribution of species predictions for non-sighted acoustic detections. Predicted species are based on the four-class random forest model with a 50 percent strong whistle threshold. "Ambiguous" means that the detection could not be classified because there were no strong whistles present.

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2.8 Appendix A – Variables measured by ROCCA

Variable	Explanation
begsweep	slope of the beginning sweep (1 = positive, -1 = negative, 0 = zero)
begup	binary variable: 1=beginning slope is positive, 0=beginning slope is negative
begdwn	binary variable: 1=beginning slope is negative, 0=beginning slope is positive
endsweep	slope of the end sweep (1 = positive, -1 = negative, = 0 zero)
endup	binary variable: 1=ending slope is positive, 0=ending slope is negative
enddwn	binary variable: 1=ending slope is negative, 0=ending slope is positive
harms	binary variable: 1=harmonics are present, 0=harmonics are absent
beg	beginning frequency (Hz)
end	ending frequency (Hz)
min	minimum frequency (Hz)
dur	duration (seconds)
range	maximum frequency - minimum frequency (Hz)
max	maximum frequency (Hz)
meandc	mean duty cycle (Measured from the waveform. Proportion of time that the signal exceeds a threshold amplitude)
meandc_quart	mean duty cycle of the first quarter of the whistle
meandc_2quart	mean duty cycle of the second quarter of the whistle
meandc_3quart	mean duty cycle of the third quarter of the whistle
meandc_4quart	mean duty cycle of the fourth quarter of the whistle
mean freq	mean frequency (Hz)
median freq	median frequency (Hz)
std freq	standard deviation of the frequency (Hz)
spread	difference between the 75th and the 25th percentiles of the frequency
quart freq	frequency at one quarter of the duration (Hz)
half freq	frequency at one half of the duration (Hz)
threequart	frequency at three quarters of the duration (Hz)
centerfreq	(minimum frequency+(maximum frequency-minimum frequency))/2
rel bw	relative bandwidth: (max freq - min freq)/center freq
maxmin	max freq/min freq
begend	beg freq/end freq
cofm	coefficient of frequency modulation: take 20 frequency measurements equally spaced in time, then subtract each frequency value from the one before it. COFM is the sum of the absolute values of these differences, all divided by 10000
tot step	number of steps (10 percent or greater increase or decrease in frequency over 2 contour points)

Variable	Explanation
tot inflect	number of inflection points (changes from positive to negative or negative to positive slope)
max delta	maximum time between inflection points
min delta	minimum time between inflection points
maxmin delta	max delta/min delta
mean delta	mean time between inflection points
std delta	standard deviation of the time between inflection points
median delta	median of the time between inflection points
mean slope	overall mean slope
mean pos slope	mean positive slope
mean neg slope	mean negative slope
mean absslope	mean absolute value of the slope
posneg	mean positive slope/mean negative slope
perc up	percent of the whistle that has a positive slope
perc dwn	percent of the whistle that has a negative slope
perc flt	percent of the whistle that has zero slope
up dwn	number of inflection points that go from positive slope to negative slope
dwn up	number of inflection points that go from negative slope to positive slope
up flt	number of times the slope changes from positive to zero
dwn flt	number of times the slope changes from negative to zero
flt dwn	number of times the slope changes from zero to negative
flt up	number of times the slope changes from zero to positive
step up	number of steps that have increasing frequency
step dwn	number of steps that have decreasing frequency
step.dur	number of steps / duration
inflect.dur	number of inflection points / duration

Section 3. Evaluation of Sperm Whale Encounters During the MISTCS 2007 Cetacean Survey

This report section replaces placeholder text contained in the original version, submitted 01 October 2012.

3.1 Introduction

Sperm whales inhabit all major ocean basins from the tropics to the polar regions (Rice 1989). Presently, this species is listed as 'endangered' under the Endangered Species Act (ESA) and 'depleted' under the Marine Mammal Protection Act. Currently, there is no widely accepted abundance estimate for the worldwide population of sperm whales, although extrapolation of regional estimates suggests a worldwide population of between 200,000 and 1,500,000 individuals (NMFS 2010). The National Oceanographic and Atmospheric Administration’s (NOAA) stock assessments surveys indicate an estimated population of 6,919 (Coefficient of Variation [CV] = 0.81) sperm whales in the Hawaiian Islands EEZ (Barlow 2006) and 22.7 in the eastern tropical Pacific Ocean (Wade and Gerrodette 1993; Carretta et. al. 2011). There are no estimates provided in the NOAA Stock assessment of the western Pacific Ocean population; however a marine mammal survey sponsored by NAVFAC Pacific resulted in an estimate of 705 (CV = 0.604) animals within the relatively large (584,800 km^2) Mariana Islands Range Complex (MIRC) study area (Fulling et al. 2011).

The sounds most commonly produced by sperm whales are relatively distinctive and consist of broadband (100 Hz to 25 kHz) click trains. These click trains are frequently characterized by evenly spaced pulses of decaying amplitude, with a varying pulse repetition rate (Backus and Schevill 1966). All sperm whales, including adult males, females and juveniles, typically produce 'regular' echolocation clicks that have a 0.5 to 1.0–second (sec) inter-click interval and centroid frequency of 15 kHz (Madsen et al. 2002). Sperm whales produce 'regular' clicks (also referred to as ‘usual’ clicks) for the purposes of underwater navigation and to scan for prey during dives (Weilgart and Whitehead 1988; Whitehead 2003). Mature males produce high amplitude clicks with slow inter-click intervals (i.e., greater than 2-sec separation between clicks), known as 'slow' clicks. These 'slow' clicks have been documented to have source levels of up to 223 dB re: 1 μPa @ 1 m (Møhl et al. 2000). Sperm whales also produce stereotyped patterns of 3 to 40 broadband clicks, termed 'codas,' that typically occur within a period of 3 sec or less (Watkins and Schevill 1977). Coda production is strongly linked to social behaviors, as these types of sounds have been detected during bouts of social behavior at the surface, as well as following periods of dispersed foraging (Best 1979; Whitehead and Weilgart 1991; Schulz 2008). These vocalizations are typically produced by sperm whales existing in social units, which Whitehead (2003) defined as "sets of whales who live and move together over periods of years.” Documentation of similar vocal repertoires in social units that are geographically isolated have led researchers to believe that sperm whales occur in culturally linked populations defined as ‘vocal clans’ (Rendell and Whitehead 2003a; Whitehead 2003)

Codas can be classified into several types according to the number and temporal pattern of the clicks they contain. Coda repertoires are unique for different sperm whale social units, which typically consist of adult females, calves and juveniles. Coda repertoires have been referred to as dialects and can be assigned to a vocal clan, a larger type of social group that has been used to define sperm whale population structure (Rendell and Whitehead 2005; Marcoux et. al. 2006). The sperm whale clan consists of sets of sperm whale social units that use the same dialect. Rendell and Whitehead (2003a) identified five vocal clans across the eastern Tropical Pacific (ETP) and South Pacific Oceans. Their research indicates that the three dominant vocal clans in the ETP and South Pacific are the regular, '+1 and short clans which are defined by the predominant coda type (i.e., the most frequently occurring type of coda) represented in the repertoire. Rendell and Whitehead (2003b) statistically established that a vocal clan can produce a variety of coda types, but that the most commonly occurring coda type (e.g., regular type) determined clan association despite the group's location. Regular coda types consist of 5, 7 or 8 equally spaced clicks, +1 coda types consists of codas with an extended last interval (e.g. 5+1, 6+1, etc.), and short coda types consist of 3 or 4 clicks that exhibit variable patterns, such as regularly spaced or 1–3 extended interval clicks (e.g., 4R, 4+1+1). The regular clan is the most commonly encountered clan off the Galápagos Islands, although it has also been documented off of northern Chile and the coast of Ecuador. The +1 clan has only been documented within the offshore waters of Ecuador and off the Galápagos Islands. Weilgart and Whitehead (1997) observed that of the three clan groups, the less frequently encountered short clan has the greatest geographic distribution, ranging from the central to the eastern South Pacific Ocean, and encompassing the region from the Galapagos Island to Easter Island and Christmas Island.

The Northern Mariana Islands were once well-known year-round whaling grounds for sperm whales, as evidenced by whale catches from 1750 to the early 1900s (Townsend 1935). Since then, there has been very limited information about sperm whale occurrence in this region (reviewed in DoN 2005). An extensive 3-month line transect survey of a large (584,800 km^2) study area centered on the Mariana Islands (MISTCS) was conducted in winter/spring of 2007 (DoN 2007). During this survey, 23 sperm whale groups were visually observed and group sizes were estimated (Fulling et al. 2011). Of these, 11 groups were used for estimating density (1.23/1,000 km^2) and abundance (705) (Fulling et. al. 2011). Unfortunately, the uncertainty associated with the estimate was relatively high (CV = 0.604), primarily due to the high uncertainty associated with the group size estimate component (CV = 0.402) of the density estimation formula. During the same cruise, more than 60 unique acoustic encounters of sperm whales were reported during real-time monitoring at sea. Unique acoustic encounters are used as an approximation for independent groups encountered (DoN 2007).

Sperm whales dive for extended periods of time and can be easily missed by visual observers, especially if they are solitary, in small groups, or occur during poor sighting conditions. However, sperm whales vocalize nearly continuously during foraging dives (which is the most common diving behavior), and can easily be detected and localized with passive acoustic methods, such as target motion analysis using a towed hydrophone array (Leaper et al. 1992; Gillespie 1997). Localizations are estimated positions to a vocalizing marine mammal or group of marine mammals. Using a two-element hydrophone array towed behind a survey vessel (TOA), differences of the same signals detected at each hydrophone can be used to calculate bearings to vocalizing animals. Target motion analysis (a method of localization originally developed by the Navy to track enemy vessels) is then used to localize the calling animal by sequentially estimating bearings to a vocalizing animal. Over time, these bearing usually converge at the source location. This point of convergence of bearing angles is then used to calculate the perpendicular distance from the trackline to the sound source (i.e., the vocalizing animal or group of animals). In order for this method to work for precisely locating marine mammals, it is assumed that animals are calling frequently, are solitary or occur in small, tightly clustered groups, and are stationary or moving slowly relative to the speed of the survey vessel.

Although some sperm whale acoustic encounters were localized during the survey, it was not possible to localize every sperm whale encounter in real-time in the field (n = 25 field localizations of 61 encounters). This was, in part, due to conflicting priorities based on the multi-species nature of the survey and other constraints (e.g., data-logging efforts) which in many cases precluded obtaining localizations in real-time.

Line transect survey and analytical methods are relatively well developed for estimating abundance of marine mammals using visual sighting data (Holt 1987). Line transect methods are a subset of a broader theory known as Distance Sampling (Buckland et al. 2001). These methods require accurate measurements of the perpendicular distances of animals from the survey track. These distances are then used to estimate a 'detection function.' The detection function is one of the most important components of the line transect formula. Simply put, the detection function describes the decline in the probability of sightings or acoustic localizations as a function of increasing perpendicular distance from the survey trackline (i.e., fewer animals are sighted as distance from the trackline increases because more are missed). A curve is usually modeled to the probability of perpendicular sighting distances or localizations for use in the abundance estimation. The same analytical approach used for visual-based line transect surveys also can be applied to acoustic data. This approach has been used recently to estimate abundances of sperm whales and small porpoises by using both acoustic and visual data collected from line transect surveys (Barlow and Taylor 2005; Gerrodette et al. 2011).

The primary goal of post-processing and re-analysis of acoustic data gathered during MISTCS (DoN 2007) was to conduct a thorough analysis of localizations for sperm whale encounters and estimate detection functions that could be later used in line transect abundance/density estimation. A secondary goal of the post-processing effort was to identify, characterize, and classify sperm whale codas detected during the cruise. Comparison of coda types identified from the MISTCS study area to those identified in other areas can provide insight to the population structure of sperm whales in the MISTCS study area.

3.2 Methods

3.2.1 Data Review and Post-Processing

Recordings were initially reviewed using the MATLAB-based program Triton (www.cetus.ucsd.edu) to create Long Term Spectral Averages (LTSAs) of the recordings (**Figure 3-1**). LTSAs were manually reviewed to identify periods that contained sperm whale clicks events. These periods were further reviewed using XBAT software (www.xbat.org) in order to verify sperm whale click events and obtain accurate start and end periods for each sperm whale acoustic encounter.

Each sperm whale acoustic encounter period was then post-processed using PAMGuard software (Gillespie et al. 2008). PAMGuard provides a flexible and easy-to-use suite of detection, localization, data management, and display modules. An automated sperm whale click detector was configured in PAMGuard and each encounter was run separately to obtain 'click files' (i.e., waveforms and spectrums of clicks) and generate a Microsoft Access database table of click detections. Prior to PAMGuard processing, GPS logs corresponding to each encounter period were added to the Access database and provided to PAMGuard to allow for accurate bearing angle estimation relative to the ship track.

3.2.2 Distance Analysis

Click files initially generated during PAMGuard post-processing were further analyzed using Rainbow Click software (Gillespie and Leaper 1996). Rainbow Click provided time/bearing and map displays of clicks, which were used to assign click trains to individual animals in order to create tracks or events for each encounter period. Each event was used to represent an individual whale's track, and was subsequently logged to an Access database. Next, these data were processed using custom-written MATLAB algorithms to estimate perpendicular distances from the trackline for each animal/event. This step involved using 'target motion analysis' in which bearings to individual clicks were estimated and a least squares fit algorithm was applied to identify the point of convergence of sequential bearing angles with the lowest error. This point was used to estimate the perpendicular distance of the animal from the trackline (**Figure 3-2**) (e.g., Lewis et. al. 2007; Swift et al. 2009). Simultaneously, detection events were classified into two categories of click types based on the inter-click-interval (ICI); regular (ICI < 2 sec) or slow (ICI > 2 sec) (Barlow and Taylor 1995). In this context, the term regular click refers to regular interval between successive clicks, and should not be confused with regular coda types described earlier. The regular and slow click types were categorized because the detection ranges for these two click types are very different.

As clicks were processed, each localization event was qualitatively assessed for recording quality and given a score between 1 and 5, with 1 being the best and 5 being the worst. Comments describing the quality of the event and the fit of the least-squares estimate of the localization (e.g., perpendicular distance to the trackline) were recorded for each localization event. Some events were considered too poor in quality to be used, either because too few bearings could be obtained or the signal strength of clicks was too low to obtain reliable bearings. Localization events that were given a quality score of 5 were excluded from the detection function analysis. All remaining localization events were compiled into an excel database. Histograms were created of the perpendicular distance from the trackline for both the regular and slow click categories. These histograms were reviewed before detection functions were generated.

Perpendicular distances for all sperm whale events and corresponding transect ID and transect line lengths were imported into the program *Distance* (6.0 release 2; Thomas et al. 2010) for estimating the best detection function. Several models (i.e., different curves) of the probability distribution of distances from the trackline were compared for best fit to the data. The best fit model was determined by the lowest Akaike Information Criteria (AIC) and CV values. Models were fit for three click type categories, all clicks combined, regular clicks only, and slow clicks only. Because abundance estimation was beyond the scope of this study, only the detection functions were estimated.

3.2.3 Coda Analysis

Sperm whale codas were detected using both aural and visual reviews of the sperm whale acoustic encounters using Adobe-Audition and XBAT software. Once detected, codas were clipped from original .wav files and saved for a more detailed review by a data analyst. Coda types were categorized based on descriptions from peer-reviewed literature (Weilgart and Whitehead 1997; Rendell and Whitehead 2003a). Vocal clan repertoires (indicating a vocal clan type) were then determined for each acoustic encounter based on the most frequently occurring type of coda.

3.3 Results

3.3.1 Localization Results

A total of 103 sperm whale acoustic encounters were localized during post-processing. Of these, 91 encounters were determined to be of sufficient quality to include in subsequent analysis. These consisted of 54 encounters of the regular click type (ICI < 2 sec) and 37 encounters of slow clicks type (**Table 3-1; Figure 3-3**). Histograms of the perpendicular distances to the trackline for regular and slow click types were produced (**Figures 3-4 and 3-5)**. These figures show the difference in the distribution of the perpendicular distances to the trackline for the regular and slow click types (**Figure 3-4**) and both click types combined (i.e., slow + regular clicks) (**Figure 3-5**).

3.3.2 Detection Function Results

The program *Distance* was used to fit Hazard Rate key function models (with a series expansion) to the perpendicular distance data for both the regular and slow clicks localization events (**Figures 3-6 and 3-7**). Other models were tested (e.g., uniform and half-normal); however, we determined that the Hazard Rate model had the lowest AIC values for both click types. In addition, the Hazard Rate models had relatively low CVs with the fewest parameters, and thus were chosen as the best-fit model. The best-fit model also included 5 percent right truncation, which is generally considered acceptable for this type of analysis.

3.3.3 Coda Results

Codas were detected in 13 out of 60 (22 percent) of sperm whale acoustic encounters (**Table 3-2**). Comparison of codas types found in the MISTCS encounters to coda types described in the literature for eastern Pacific Ocean sperm whales revealed similarities in coda repertoires. Coda types identified within the repertoires of these groups included evenly spaced or regular codas (e.g., 5R, 6R), extended last interval +1 codas (e.g. 5+1), and 'short codas' with varied inter-click intervals (e.g., 4R, 4+1). Vocal clans produce a mixture of coda types within their repertoires and the majority (85 percent) of acoustic encounters produced regular coda types. Of the 13 acoustic encounters in the MISTCS dataset, 9 encounters produced regular codas as the predominant coda type, and thus were classified to the regular clan. One encounter primarily consisted of short codas, and in two encounters, equal numbers of +1 and regular coda types were identified and, as such, were considered ambiguous clan types (**Table 3-2**). Examples of the short and regular coda types identified in this study are shown in **Figures 3-8 and 3-9**.

3.4 Discussion

3.4.1 General Geographic Distribution Trends

Based on a qualitative assessment of the localizations plotted on a map (**Figure 3-3**), the distribution of sperm whales appears clustered in three main regions of the study area: the northeast, central and southwest portions, respectively, with only 23 localizations located in the trench and offshore regions. The central cluster may reflect a preference by at least some animals to inhabit waters near islands.

Sperm whales that were acoustically detected produced both slow clicks and regular clicks, with some groups producing codas patterns similar to those found vocal repertoires of eastern Pacific vocal clans. Codas are produced primarily by social units, which consist of long term associations of whales that most often consist of adult females and juveniles. These matrilineal social units commonly occur around other island regions (e.g., the Galapagos Islands, eastern Caribbean Islands) (Weilgart and Whitehead 1997; Marcoux et al. 2006; Whitehead and Rendell 2004). As such, a similar occurrence of matrilineal social units was expected near the Mariana Islands. Coda production within the central cluster of this study area suggests that these encounters consist predominantly of matrilineal social units. However, the reason for the higher concentrations of sperm whale encounters near islands is unclear. Further spatial and habitat analysis and modeling will be necessary to further elucidate these patterns. Density Surface Models (using *Distance*) and Generalized Additive Models are among the types of approaches that should be considered for a more detailed habitat modeling analysis.

3.4.2 Acoustic Localization Post-processing Analysis

We used semi-automated post-processing methods to obtain perpendicular distances from the trackline for individuals, which was difficult to do manually during the survey (i.e., in real-time) given the software limitations that existed in 2007. Post-processing of the acoustic data collected during the MISTCS from the towed hydrophone array resulted in an additional 31 high quality acoustic encounters than were not identified in real-time during the cruise. From the 61 acoustic encounters of sperm whales in the field, only 25 localizations were made *in situ*. The semi-automated methods used resulted in 91 distinct localizations of individual sperm whales. Post processing allowed for the localization of individual animals with a 1 degree bearing resolution. These additional localizations from post-processing represented a 260 percent increase in total localizations relative to the original total of *in situ* localizations.

Visual inspection of the frequency histograms of counts for slow and regular click perpendicular distances to localizations revealed different shapes of the distributions for these two vocalization types (**Figure 3-4**). For example, the histogram for regular clicks had a small shoulder (evident in the similar number of counts in the first two bins) beyond which the numbers of counts dropped off quickly with increasing distance from the trackline. For slow click localizations, there was a dramatic decrease in counts in the first few bins (i.e., localizations close to the trackline), suggesting either vessel avoidance or possibly a decrease or cessation in vocalizations when the vessel was nearby. The greater range and more gradual drop-off in the number of counts versus perpendicular distance in the histogram for slow clicks is most likely due to the greater ranges over which high amplitude slow clicks can be detected relative to regular clicks using acoustics methods. The slow clicks which are believed to be produced by adult males (Weilgart and Whitehead 1988), have greater source levels (i.e., they are louder) and also contain relatively greater energy in lower frequencies than regular clicks. This allows the slow clicks to propagate and be detected over greater distances of up to several tens of kilometers relative to regular clicks (Barlow and Taylor 1995; Madsen et al. 2002).

The dramatic differences in the shapes of these two histograms justified fitting separate detection function models to the two click types (**Figure 3-4**). Barlow and Taylor (2005) fit detection functions to both the pooled and stratified (by click type) localizations and determined that "AIC values were consistently lower for the stratified analyses so these estimates were favored.” In cases in which stratification of distance data is possible, a more precise abundance estimate can be determined by decreasing uncertainty in the detection function. Our histograms for both the regular and slow clicks appear qualitatively similar to those presented in Barlow and Taylor (2005); however, they selected the half-normal key function as the best fitting model, whereas we used a Hazard Rate 'key function' model to fit a curve to both regular and slow click types, with hermite polynomial series expansion or with a simple polynomial expansion used respectively for regular and slow click types (**Figures 3-6 and 3-7**). The choice of models is based on the best fit as indicated by the lowest AIC scores and CVs (Thomas et al. 2010). The Hazard Rate model was chosen in this case based on these criteria.

Because there was enough perpendicular distance data to reliably fit detection functions to both slow and regular clicks types separately, we believe that a stratified approach is desirable. However, a comparison of the uncertainty in resulting density estimates using both pooled and stratified data will allow the best approach to be determined quantitatively.

One difference between the Barlow and Taylor (2005) study and our study, is that they estimated localizations to *groups of animals* for the regular clicks, not to individuals, as we did. However, recent improvements in acoustic methods now allow for perpendicular distance estimates to individuals. Our approach to localize all individuals and obtain detection functions was based on a study conducted by Lewis et al. (2007). This approach will allow for acoustic only based density estimates.

The detection functions developed herein can be used for an acoustic-based estimate of abundance for sperm whales in this region. If necessary, a combined visual/acoustic-based estimate can also be conducted with minor additional effort. The additional localization data we were able to provide will allow development of spatial models (e.g., density surface modeling) and habitat models of sperm whales to improve our understanding of sperm whale distribution and expected habitat use in the Northern Mariana Islands region.

3.4.3 Coda Analysis

This qualitative assessment of the predominant coda types within each the 13 coda-producing acoustic encounters indicated the occurrence of regular, short, and possibly the +1 vocal clans in the MISTCS study area. These vocal repertoires are known to be produced by vocal clans occurring in the eastern Pacific Ocean (Weilgart and Whitehead 1997; Rendell and Whitehead 2003a). The two ambiguous coda events described here require further analysis to identify whether these groups predominantly produce regular or +1 coda types (i.e., if these two events reflect repertoires similar to the regular or +1 vocal clans). To confirm that the vocal repertoires detected in our study are representative of the vocal clans documented in the eastern tropical Pacific Ocean, a comparative statistical analysis is required. A quantitative assessment of these vocalization events was beyond the scope of this project, but recommended for future analyses.

Due to the culturally-linked populations thought to exist for this species, coda dialects are not geographically isolated for the three dominant vocal clans described in the Pacific Ocean, which suggests that each population may span wide ranges of the equatorial Pacific Ocean (Rendell and Whitehead 2003a; Rendell and Whitehead 2005). For example, as previously mentioned, the short vocal clan has been identified as having the largest distribution of all vocal clans based on observations of this vocal clan type in the Galapagos Islands, off the coast of Ecuador, and in the south Pacific Islands (Weilgart and Whitehead 1997). The presence of social units belonging to this vocal clan in the western Pacific Ocean would more than double the documented range of distribution. Implications for range of the regular vocal clan would be even greater given the presence of social units in the western Pacific Ocean, as social units belonging to this vocal clan have previously only been encountered in the eastern tropical Pacific Ocean. Little is documented regarding the extent of vocal clans within the central or western equatorial Pacific Ocean. The occurrence of vocal repertoires similar to those produced by sperm whales in the eastern Pacific Ocean provides previously undocumented evidence of a possible link between eastern and western Pacific Ocean social units.

Our findings provide initial evidence that the short and regular vocal clans may have a much greater distribution that previously known. To date, most of the work assessing coda repertoires in the Pacific Ocean basin has been conducted in the eastern South Pacific and off the Galápagos Islands. Our results provide new evidence that sperm whale vocal clans in the Northern Mariana Islands have similar vocal repertoires to vocal clans in the eastern Pacific Ocean. Vocal clan association is currently the most effective method for characterizing sperm whale stocks within the Pacific Ocean (Mesnick 2001; Rendell et. al. 2012). The new information provided here about vocal clans can be used to better characterize population structure of sperm whales in the Northern Mariana Islands, and potentially across the Pacific Ocean basin.

3.5 Conclusions and Future Research

Based on the large number of additional acoustic localizations of sperm whales that resulted from post-processing the MISTCS acoustic dataset, an acoustic-based estimate of sperm whale abundance is now feasible. However, additional analysis effort using this dataset will be required to estimate sperm whale abundance in the MISTCS study area. Sufficient localizations were obtained to fit detection functions to both regular and slow clicks, an important result. As such, improved estimates (relative to the visual based estimate by Fulling et al. 2011) should be possible by reducing the variance in both the encounter rate and by obtaining a better (stratified) estimate of the detection function for regular and slow clicking individuals. There are two approaches to abundance estimation that could be taken: (1) an acoustic only-based approach, using both the slow click and regular click detection functions; and (2) a combined visual and acoustic abundance estimate using information from both data sets. The second approach will require deriving an acoustic detection function to *groups of animals* and also using visual estimates of group size in the line transect formula. Given that it is possible to obtain localizations to all individuals acoustically detected, we recommend an analysis using the first approach.

The additional work necessary for the first recommended approach is minimal because the line transect data are already processed and saved in a *Distance* project folder. For the acoustic-only abundance estimate we would assume that perpendicular distances were acquired for all individuals encountered along the trackline, which is feasible give that approximately one degree bearing resolution was available to distinguish individual event tracks. Under this assumption, the standard distance sampling equations can be used to estimate density and, therefore, do not require a group size estimate. Density estimates should be provided from this approach along with detailed methods and a summary and discussion of results. It is also recommended that bio-statisticians with expertise in line transect data and analytical methods (e.g., scientists from CREEM or the NMFS-Southwest Fisheries Science Center) be involved in an advisory capacity for density estimate efforts using this data.

The improved acoustic localization data also will help to better estimate the distribution of sperm whales in the western tropical Pacific population. The apparent non-uniform spatial clustering of localizations in certain regions lends itself to be used in more robust spatial analysis in which oceanographic features may be correlated with sperm whale distribution. In situ oceanographic data (e.g., sea surface temperature and chlorophyll-a) were collected as part of MISTCS (DoN 2007) and could be used in addition to satellite oceanographic data for this analysis. Using this data, acoustic-based habitat models for sperm whales could be produced for the study area.

The preliminary results of the coda review provide new insights into the sperm whale social units occurring within this region of the western Pacific Ocean. The presence of the short and regular vocal clans identified from the acoustic encounters in this dataset can be used as putative indicators of sperm whale stock structure for this region (Marcoux et al. 2006). To our knowledge, the vocal repertoires identified herein provide the first information on the occurrence of vocal clans in the western Pacific Ocean. The vocal repertoires identified through this qualitative assessment suggest a potential cultural and acoustic link to vocal clans found in the eastern tropical Pacific Ocean. This new information greatly extends the known range for the regular and short vocal clans. A more detailed analysis of these codas using multivariate statistical methods described by Rendell and Whitehead (2003b) is required to provide a quantitative assessment of coda types and corresponding vocal repertoires for each encounter.

The most recent 5-year evaluation by NMFS for sperm whales identified that an important component of sperm whale recovery is to more accurately determine population size, distribution and population structure in order to better evaluate the status of this species (NMFS 2009). We recommend further analysis of codas, spatial analysis and habitat modeling using the localization data, and finally acoustic-based abundance estimates. The results herein and subsequent future analysis of this data provide new information on sperm whale population structure and distribution and abundance for this region. This information will be needed for better resource management and conservation efforts for sperm whales in the MIRC area.

3.6 Tables and Figures

3.6.1 Tables

Table 3-1. Sperm whales localizations as determined from post-processing analysis.

Date	Perpendicular Distance (m)	Latitude (N)	Longitude (E)	Click Type
1/19/2007	4669.8	10.986	145.294	Slow
1/21/2007	761.1	10.169	147.122	Regular
1/21/2007	858.5	10.184	147.115	Regular
1/26/2007	8870.2	12.744	145.861	Slow
1/26/2007	2946.9	12.866	146.062	Slow
1/31/2007	11494.2	12.185	142.676	Slow
2/8/2007	40663.1	18.396	147.863	Slow
2/8/2007	6364.8	18.081	147.941	Slow
2/8/2007	3970.1	17.931	147.872	Regular
2/8/2007	1849.6	17.989	147.857	Regular
2/8/2007	1260.2	17.984	147.861	Regular
2/8/2007	215.6	17.972	147.872	Regular
2/8/2007	3849.5	17.942	147.778	Regular
2/8/2007	34721.5	17.891	147.322	Slow
2/8/2007	48699.5	17.279	146.581	Slow
2/8/2007	8637.6	17.528	147.207	Regular
2/8/2007	38764.9	17.149	146.562	Slow
2/8/2007	15599.9	16.966	146.676	Slow
2/8/2007	16745.4	16.925	146.608	Slow
2/8/2007	9629.1	17.081	146.913	Regular
2/9/2007	11478.6	17.376	145.569	Slow
2/9/2007	398.2	17.501	145.596	Regular
2/9/2007	2.4	17.506	145.596	Regular
2/9/2007	823.9	17.497	145.579	Regular
2/9/2007	1504.3	17.510	145.574	Regular
2/9/2007	1423.6	17.489	145.600	Regular
2/9/2007	3472.5	17.372	145.709	Slow
2/12/2007	1022.1	17.038	145.144	Regular
2/12/2007	307.1	17.048	145.150	Regular
2/12/2007	555.1	17.052	145.147	Regular
2/12/2007	10235.2	17.089	145.407	Slow
2/12/2007	492.4	17.051	145.149	Regular
2/12/2007	13107.6	16.946	145.065	Slow
2/12/2007	6352.7	16.960	145.289	Regular
2/12/2007	2179.6	17.046	145.252	Regular
2/12/2007	1660.3	17.013	145.237	Regular

Date	Perpendicular Distance (m)	Latitude (N)	Longitude (E)	Click Type
2/12/2007	2734.3	17.005	145.230	Regular
2/12/2007	2352.8	17.008	145.232	Regular
2/14/2007	1339.3	15.390	146.046	Regular
2/14/2007	959.9	15.385	146.047	Regular
2/14/2007	1146.9	15.384	146.051	Regular
2/14/2007	4720.4	15.289	146.076	Regular
2/14/2007	2623.3	15.405	146.046	Regular
2/14/2007	3271.5	15.413	146.044	Regular
2/17/2007	8284.2	15.662	144.647	Regular
2/17/2007	10582.4	15.614	144.945	Slow
2/17/2007	27677.8	15.229	144.988	Slow
2/17/2007	9138.0	15.529	145.184	Slow
2/17/2007	6192.6	15.360	145.359	Regular
2/17/2007	27429.3	15.612	145.683	Slow
2/17/2007	1325.2	15.337	145.539	Regular
2/17/2007	500.5	15.326	145.583	Regular
2/17/2007	5078.5	15.366	145.679	Slow
2/17/2007	1299.1	15.344	145.579	Regular
2/17/2007	1423.4	15.319	145.575	Regular
2/17/2007	745.2	15.337	145.584	Regular
2/18/2007	16822.5	15.057	145.710	Slow
2/18/2007	6405.7	15.099	145.619	Slow
2/21/2007	24975.0	14.426	145.215	Slow
2/21/2007	34146.7	14.307	145.245	Slow
2/21/2007	19727.8	14.827	145.382	Slow
2/21/2007	12228.8	14.836	145.298	Slow
2/21/2007	10864.4	14.792	145.309	Slow
2/21/2007	9052.7	14.791	145.007	Slow
2/21/2007	1452.9	14.855	145.104	Regular
3/9/2007	9519.0	12.549	147.166	Slow
3/16/2007	16713.6	10.497	143.900	Slow
3/16/2007	2225.2	10.441	143.778	Regular
3/17/2007	9310.7	11.052	142.717	Slow
3/17/2007	2825.3	10.974	142.710	Regular
3/17/2007	5124.8	10.929	142.647	Slow
3/17/2007	1114.7	10.890	142.667	Regular
3/18/2007	1135.8	10.558	142.410	Regular
3/18/2007	243.4	10.559	142.430	Regular
3/18/2007	2924.8	10.537	142.446	Regular
3/18/2007	1578.8	10.551	142.445	Regular
3/18/2007	1412.1	10.537	142.431	Regular
3/18/2007	37202.7	10.244	142.615	Slow

Date	Perpendicular Distance (m)	Latitude (N)	Longitude (E)	Click Type
3/18/2007	24455.2	10.733	142.274	Slow
3/18/2007	2232.0	10.422	142.285	Regular
3/18/2007	12058.8	10.238	142.296	Slow
3/18/2007	5681.7	10.218	142.210	Regular
3/18/2007	21107.1	10.318	141.832	Slow
3/18/2007	34891.3	10.208	142.530	Slow
3/26/2007	7558.2	16.935	147.698	Slow
3/26/2007	12735.7	17.002	147.696	Slow
3/30/2007	4372.4	16.309	142.378	Regular
3/30/2007	5071.5	16.368	142.447	Regular
3/31/2007	223.1	15.621	146.099	Regular
3/31/2007	100.4	15.624	146.092	Regular
3/31/2007	75.2	15.630	146.090	Regular
3/31/2007	1020.2	15.617	146.095	Regular
3/31/2007	196.8	15.632	146.092	Regular
3/31/2007	252.5	15.638	146.086	Regular
4/2/2007	1597.1	15.716	145.787	Regular
4/2/2007	5873.7	15.660	145.754	Regular

Table 3-2. Summary of sperm whale coda repertoires identified in the MISTCS 2007 dataset.

Date	Detection	Predominant Coda Type
2/8/07	75	Short
2/9/07	79	+1 or Regular
2/17/07	106	Regular
2/17/07	109	Regular
2/18/07	N/A	Regular
2/21/07	124	Regular
2/21/07	125	Regular
3/16/07	163	Regular
3/18/07	174	+1 or Regular
3/18/07	177	Regular
3/18/07	181	Regular
3/31/07	200	Regular
4/10/07	211	Unknown

3.6.2 Figures

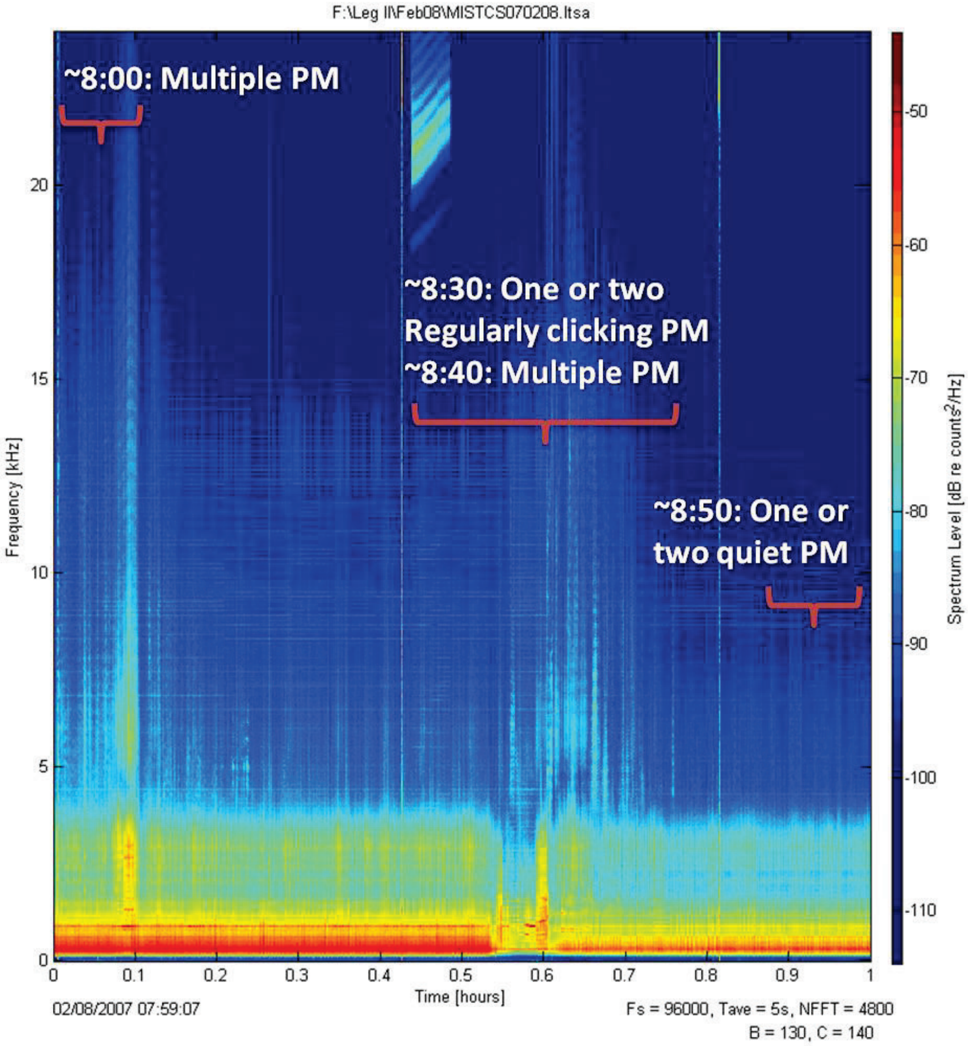

Figure 3-1. LTSAs, used to review MISTCS 2007 dataset (PM in this figure stands for the scientific name of sperm whale *Physeter macrocephalus*).

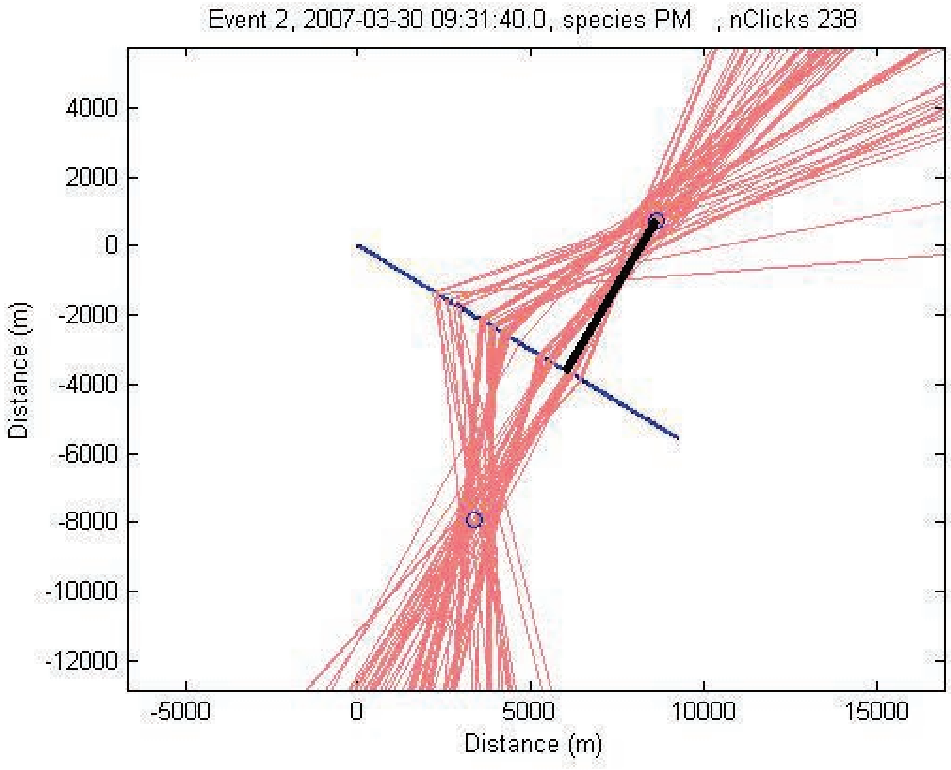

Figure 3-2. Localization point for an individual sperm whale as determined in post-processing analysis. The blue line represents the ship's trackline and the red lines indicate the left/right bearings to individual sperm whale clicks. Using target motion analysis methods when only one towed-hydrophone array is deployed results in the left right ambiguity that can only be definitively resolved when the ship turns; a straight trackline results in identical bearings on either side of the ship. As the bearings converge, a localization for the acoustic detection is determined and the distance to the trackline is measured. If the left/right ambiguity is not resolved, an average of the two distances is calculated and used in detection function calculation. The black line leading to the blue circle in this figure identifies the least squares perpendicular distance estimate for this event.

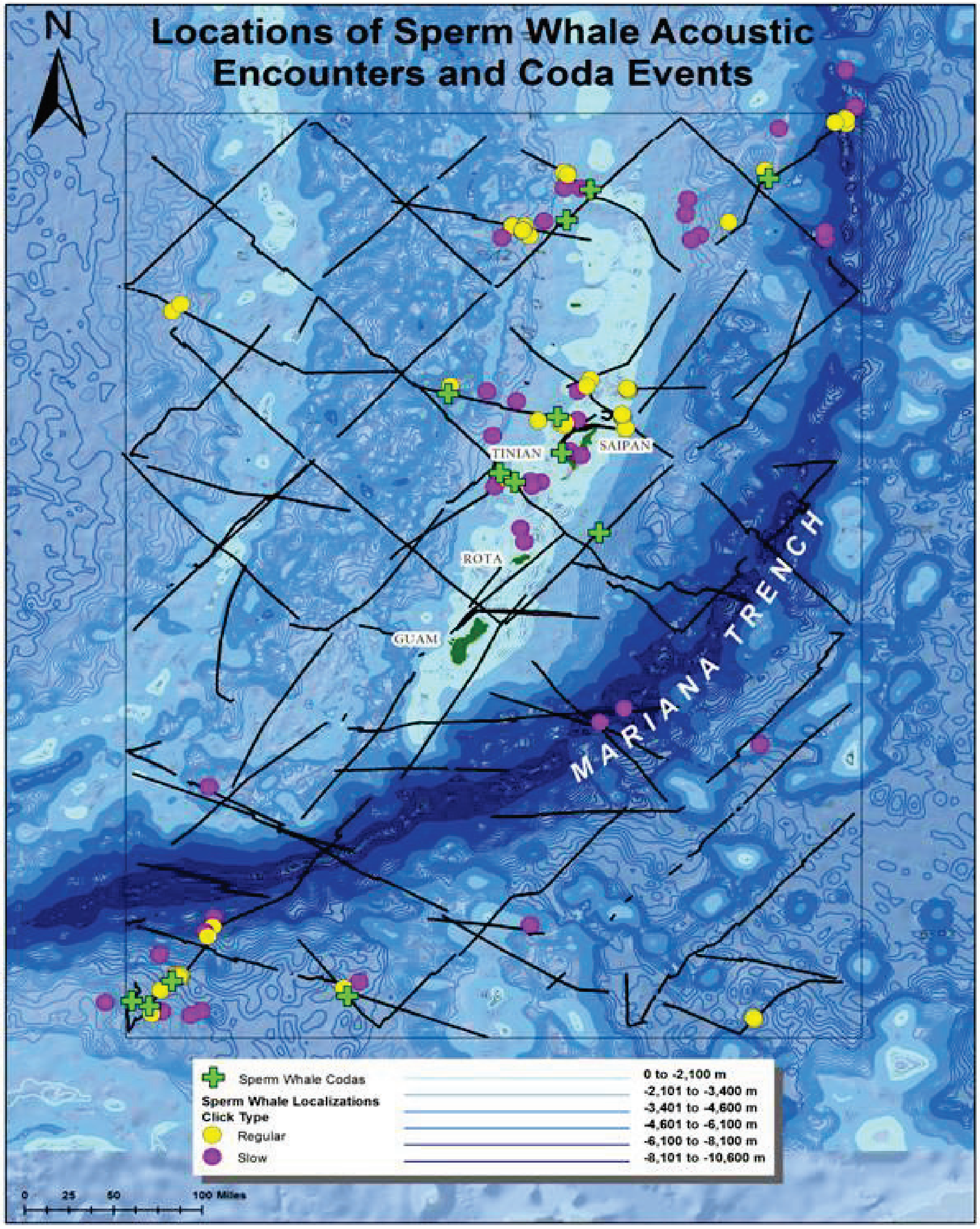

Figure 3-3. MISTCS 2007 sperm whale acoustic encounters and coda events occurring in and around the Northern Mariana Islands region. Regular clicks (yellow circles), slow clicks (magenta circles), and regular clicking groups that produced codas (green crosses) are represented. Ship tracklines are represented by black lines.

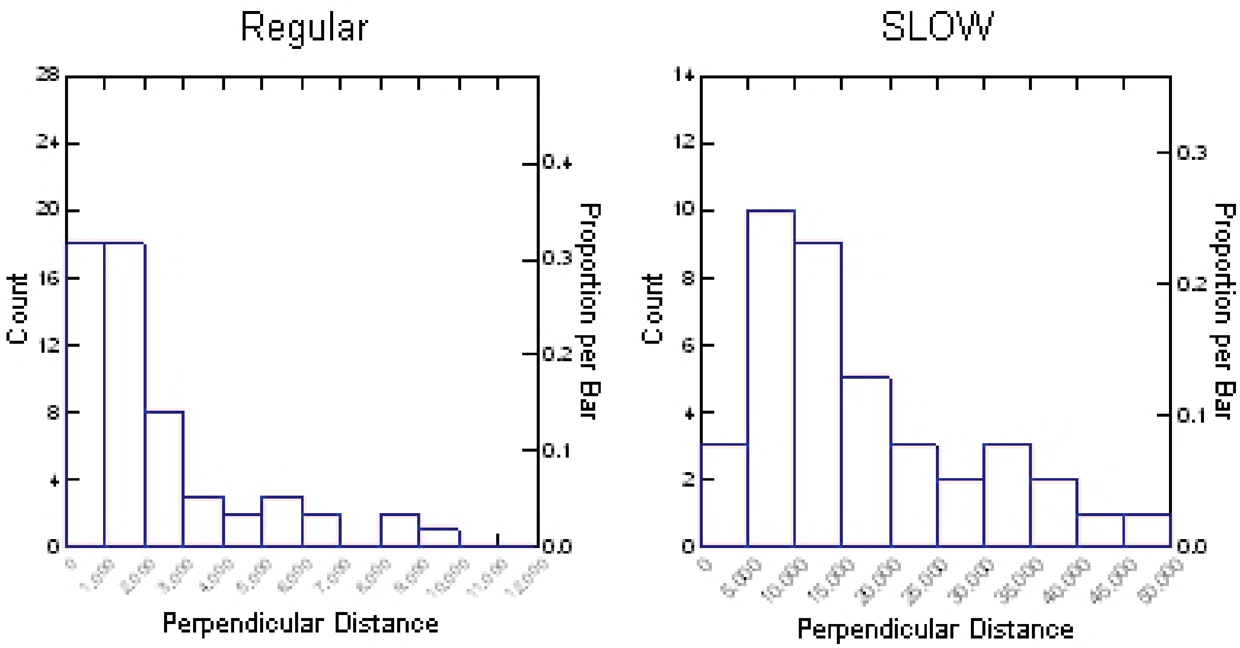

Figure 3-4. Histograms showing perpendicular distances (m) from the trackline of sperm whale localizations categorized by click type; regular (ICI < 2sec) or slow (ICI > 2sec).

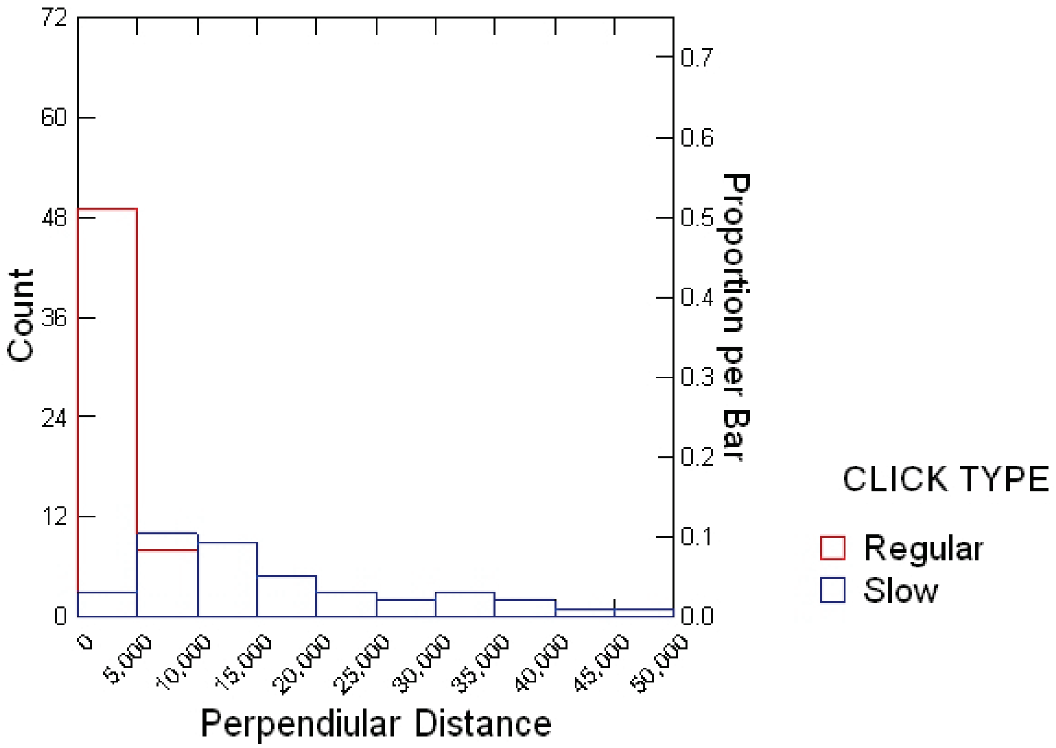

Figure 3-5. Histograms showing perpendicular distances (m) from the trackline of sperm whale localizations with both click types combined; regular clicks (in red-see first two bins; ICI < 2 sec) and slow clicks (in blue; ICI > 2 sec).

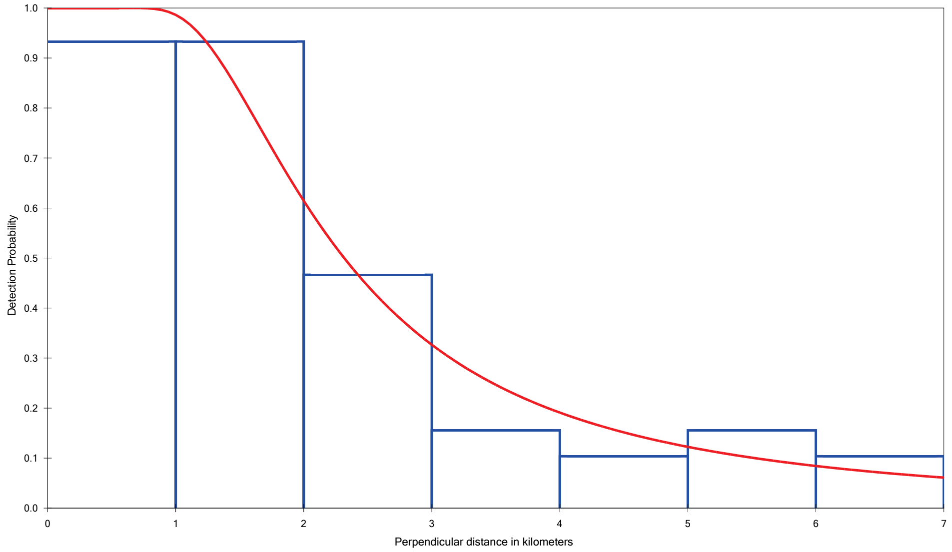

Figure 3-6. Detection function for regular sperm whale click localizations. The best model fit was a Hazard Rate 'key function' with hermite polynomial series expansion (See Buckland et al. 2001 for details on detection model shapes and choice). AIC = 180.66; CV of Density Estimate = 0.227. One km bin width/cut points used. Right truncation was used on 5 percent of data.

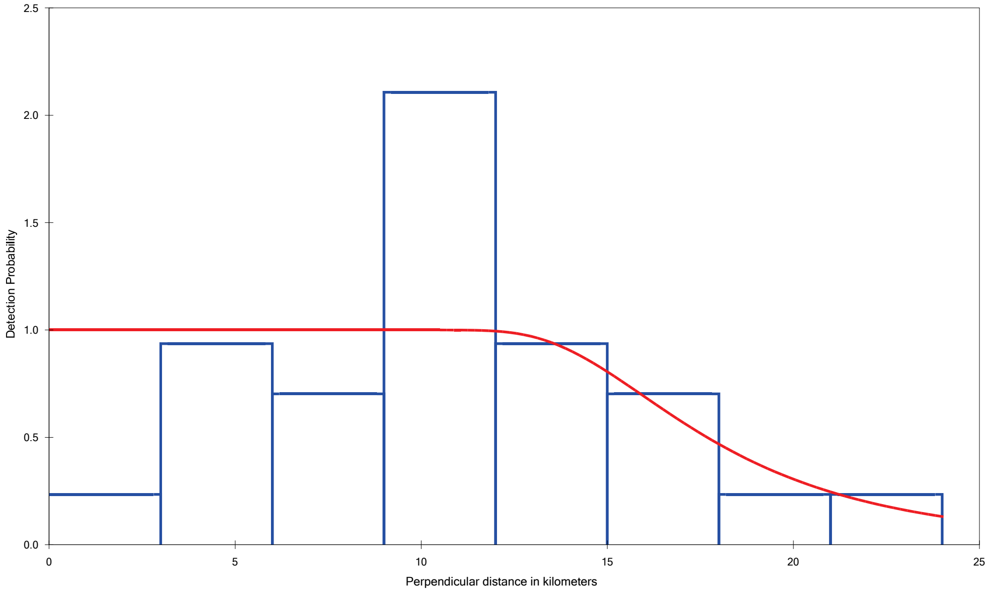

Figure 3-7. Detection function for slow sperm whale click localizations. The best model fit was Hazard Rate 'key function' with a simple polynomial expansion (See Buckland et al. 2001 for details on detection model shapes and choice). AIC 107.7; CV of Density Estimate 0.244. Three km bin width/cut points used. Right truncation was used on 5 percent of data.

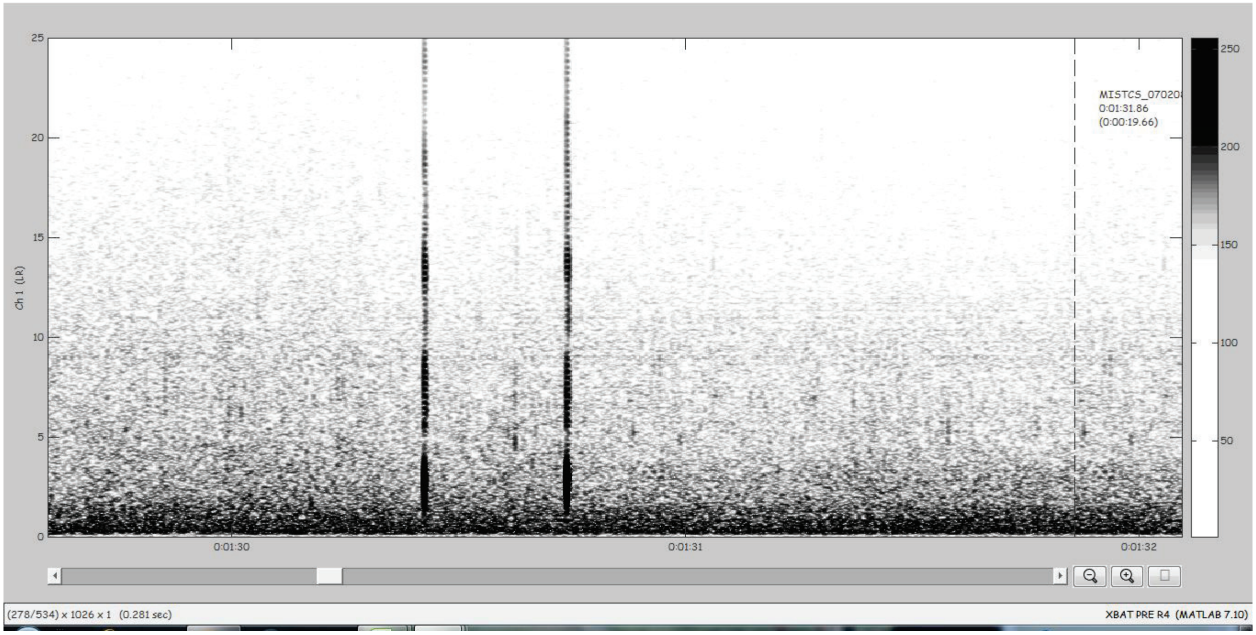

Figure 3-8. Example of a short coda type.

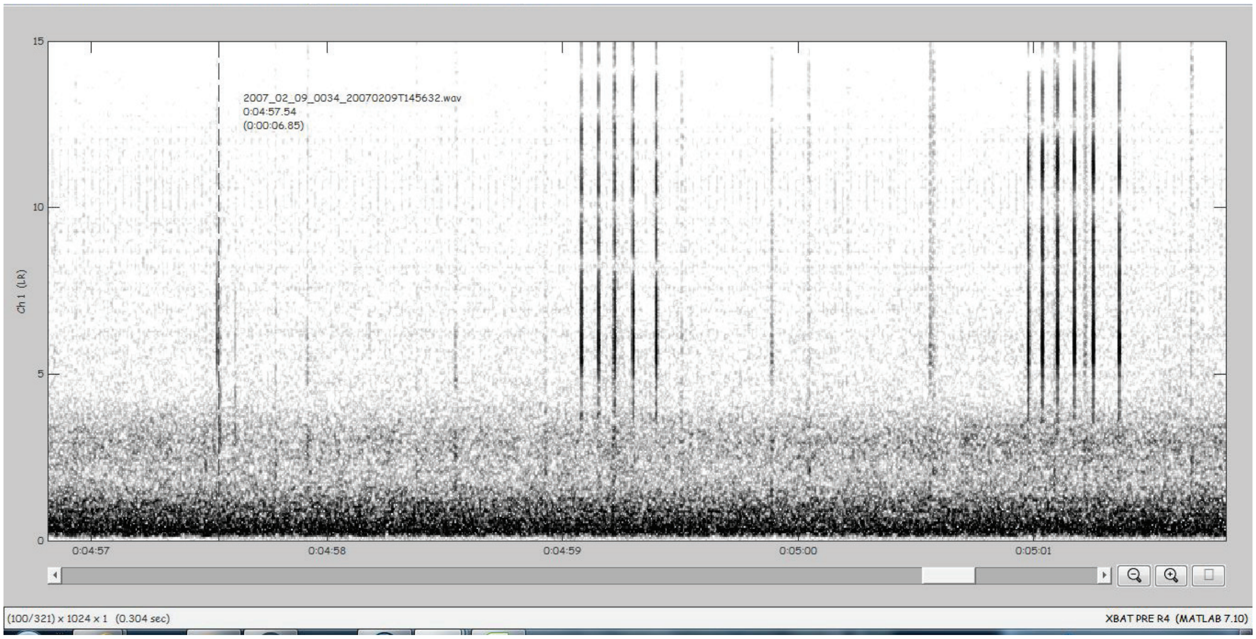

Figure 3-9. Example of a regular coda type.

3.7 Literature Cited

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Section 4. Humpback Whale Song Review and Comparison

4.1 Introduction

Humpback whales (*Megaptera novaeangliae*) were once very abundant in the North Pacific but were decimated to just over a thousand animals after years of commercial whaling (Gambell 1976; Johnson and Wolman 1984). Based on records from whaling logbooks from the 1750s to early 1900s numerous whales were taken from the Mariana Islands (**Figure 4-1;** Townsend 1935). Since this time, there have been very limited reliable reports of humpback whales in the Northern Mariana Island area. The Mariana Islands MRA states that 'there is a low or unknown occurrence of humpback whales from the coastline (excluding harbors and lagoons) in the Mariana study area and vicinity (DoN 2005). Darling and Mori (1993) conducted a limited survey listening for humpback whales off Saipan and concluded that 'humpback whales were not seen regularly so far south.' They interviewed residents and cited a newspaper article in which a group of three animals was photographed off Saipan in February 1991, indicating that the winter range may extend into this region. There have been just a handful of other sightings of humpback whales in the Northern Mariana Islands in the past 20 years, including a cow/calf pair off Rota and a group of six at the entrance to Apra Harbor, the main harbor in Guam. All these sightings occurred in January and February from the early to mid 1990s (Eldredge 2003) suggesting that this indeed is a winter/spring breeding area.

During the MISTCS line-transect survey, humpback whale songs were acoustically detected on several days over the course of the 3-month survey period (DoN 2007). A night-time acoustic survey off the islands of Saipan and Tinian on 18 February 2007 resulted in an acoustic localization of a singing animal and eventually led to a visual encounter of several animals soon after daybreak (DoN 2007; Morse et al. 2007). Identification photographs were taken and behavioral observations were made of animals in what appeared to be a surface active group as evidenced by tail-slapping, breaching, and chin-slapping behaviors (DoN 2007; Fulling et al. 2011).

This report presents the findings of a more thorough review of humpback song detections, with an emphasis on those that were recorded off Saipan and Tinian as those were the best quality recordings available. A main goal was to do a comparison of these songs with humpback whale songs recorded in Hawaii during a similar time period in the same season.

4.2 Methods

Towed hydrophone array and sonobuoy recordings were made during the winter/spring MISTCS line-transect cruise (for a detailed description of methods, see DoN 2007). Acoustic detection records were compiled from the MISTCS cruise final report and the original acoustic field database. Audio recordings were reviewed aurally (headphones) and visually (scrolling spectrographic display) to identify recordings the presence of humpback whale songs.

.Wav files were reviewed by examining spectrograms using both Adobe Audition and Triton software. To facilitate processing efficiency and optimize frequency settings for the review, all recordings were down-sampled from 96 kHz to 10 kHz. Triton software (www.cetus.ucsd.edu) was used to create long-term spectral averages (LTSAs) of .wav files using 5-second time bins and 10 Hz frequency bins. LTSA files were reviewed by an experienced bioacoustician to identify humpback whale songs for periods in which they were noted in the database and final MISTCS report. Periods with possible song were then reviewed in greater detail using the 'expand' feature in Triton's LTSA to view the corresponding .wav files as a spectrogram (900 FFT points, 60 percent overlap, maximum frequency=2,500 Hz). Sound files were also using the spectral display (i.e. spectrogram; 512 FFT size) display in Adobe Audition. A qualitative 1-5 scale was used to rank the song quality (1=low quality song and 5=high quality song) and background noise intensity (1=low background noise and 5=high background noise). Start and end times of song periods were logged in Triton. The dates and time periods were imported from Triton into an Excel spreadsheet. The relative quality of the songs, and relative level of background noise of all songs (as 10minute .wav files), file names and other relevant information was saved in an Excel spreadsheet to provide a summary of information.

Representative examples of each phrase type that could be qualitatively identified by the data analyst were clipped and saved as .wav files. Spectrograms for each phrase type were made using the same settings (5-sec time bins and 10 Hz frequency bins, with a 10 kHz sampling rate and 900 FFT) so that they could be visually compared (**Figure 4-2**).

The same procedure was conducted for phrases from a sample of humpback whale song (courtesy of Adam Pack, University of Hawaii, Hilo) recorded on 18 February 2007 from the main Hawaiian Island of Maui (**Figure 4-3**). Humpback whale song phrases from MISTCS were then qualitatively compared to those from Hawaii to identify which phrase types were common (**Figure 4-4**).

4.3 Results

Over 120 hours of recordings were reviewed from over 12 days of effort in which humpback whale songs (or possible humpback whale songs) were noted in the acoustic logs. From these recordings, humpback whale songs were identified on 5 separate days, for a total of approximately 5.5 hours of song. The periods of song were then plotted on a map of the survey area to show relative location of the singers (**Figure 4-5**). Of the songs reviewed, approximately 1.5 hours were of sufficient quality for comparative analysis. Much of the data recorded were of too low quality (i.e., low signal/noise) that they were not useful for comparison to the Hawaii song sample (**Table 4-1**).

Only two phrase types from the MISTCS cruise were identifiable (**Figures 4-6 and 4-7**). Unfortunately, the song sample from Hawaii had severe clipping (i.e. the sound levels exceeded the recording system dynamic range resulting in artifacts in the recording e.g. **Figure 4-4**), which resulted in difficulty in identifying the phrase types. In spite of these issues, we were able to identify one phrase type that was shared between the MISTCS Saipan/Tinian sample and the Maui, Hawaii sample (**Figure 4-3**).

Also of interest, we noted the occurrence of mid-frequency sonar activity (14 February 2007) during one of the periods in which humpback song was also recorded. Upon a more detailed review of the spectrograms, it was evident that the sonar signals overlapped with humpback whale songs units during the sonar activity (**Figure 4-8**). No further review of these data was conducted.

4.4 Discussion

Due to low signal-to-noise ratios, the song samples from the MISTCS were not of sufficient quality to identify more than a few phrases types making a comprehensive comparison to songs from other areas less meaningful. Furthermore, the song sample obtained from the Main Hawaiian Islands included sections with ‘clipped’ signals resulting in occasional artifacts in the spectrograms of phrase types. For some signals, this made qualitative assessment of phrase types difficult. In spite of these difficulties, we were able to identify two phrase types from the MISTCS recordings made off Saipan/Tinian one of which was similar to a phrase types identified from the songs recorded off the Hawaiian island of Maui. This suggests at least some acoustic interchange is occurring between Hawaii and the Mariana Islands. This result is not unexpected because, humpback whales in the North Pacific are believed to consist of one population with animals mixing on the breeding areas, but maintaining some fidelity and segregation at coastal feeding areas in the north (Calambokidis et al. 2008).

Singing and surface active behaviors such as tail slapping and chin breaching that were observed during the visual encounter near Saipan are common for humpback whales inhabiting winter breeding areas. The occurrence of singing and surface active behaviors we observed during the mid-February encounter suggests that the nearshore waters around Tinian and Saipan were being used by at least a few humpback whales that were engaging in courtship behaviors. This might implicate the Northern Mariana Islands as a possible winter breeding area. At one time, humpbacks were relatively common in the Northern Mariana Islands region during winter and spring, as is evident from the records of whaling kills (Townsend 1935). Based on the limited, but new information collected during the MISTCS cruise, it is possible that humpback whales are now re-occupying a former breeding site. However, additional effort to monitor singing activity and the occurrence of surface active groups is needed to verify this.

Interestingly, Calambokidis et al. (2008) suggested the likely existence of an undiscovered wintering area used by whales that feed in the Bering Sea, off the Aleutian Islands and off the Commander Islands. Based on long-term acoustic monitoring of humpback whale songs, some researchers have suggested that the Northwestern Hawaiian Islands could be this undiscovered area (Lammers et al. 2011). Alternatively, it is also possible that the Mariana Islands, Micronesia, the Philippines and other subtropical islands in the western Pacific that remain poorly surveyed could be part of this undiscovered wintering area.

From 2000 to 2003, small vessel surveys were conducted in the Philippines to investigate the current status of humpback whales in the area, and their relationship to other humpback whale populations in the western and central North Pacific (Acebes et. al. 2007). The study site was located in the Babuyan Islands, north of Luzon Island. Recordings of songs and other data were collected during the survey. A comparison of song themes from the Philippines to those recorded in Hawaii indicated that nine unique themes were identified in songs from both Hawaii and the

Philippines, with seven of these themes common in both regions. The similarity of song suggests that humpback whales in the Philippines mix, at least to some degree, in order to exchange song information with whales in Hawaii. It might be expected that a similar level of mixing is occurring between the Mariana Islands, Hawaii and Philippines, however, better samples of songs will be needed to confirm this.

Results of the recent Structure of Populations, Levels of Abundance and Status of Humpback Whales in the North Pacific (SPLASH) photographic-identification study indicate that the western-most feeding and wintering areas are distinct from the rest of the North Pacific (Calambokidis et al. 2008). The results also suggest that there is a very low level of interchange between Asian wintering or feeding areas and those in the central and eastern North Pacific (Calambokidis et al. 2008). However, a few occurrences of animals moving between islands of Hawaii; the Revillagigedos and mainland coast of Mexico; and Ogasawara and Okinawa, Japan have been documented during these photographic identification studies (Calambokidis et al. 2008). Fluke photographs from MISTCS were compared to the SPLASH database; however, no matches were made (Rivers et al. 2007).

4.5 Conclusions and Recommendations

Vessel-based surveys conducted in 2010-2011 jointly by the Navy and NMFS have not resulted in any humpback whale sightings (Oleson and Hill 2010; HDR 2011; Ligon et al. 2011; Hill et al. 2012). In addition, acoustic data have been collected from autonomous acoustic recording devices, but these data are still being analyzed. Additional PAM, especially in nearshore areas of the Northern Mariana Islands (e.g., Guam, Saipan and Tinian) is needed to collect better quality samples of humpback whale song. Acoustic monitoring of humpback whale songs can provide remotely collected information on the relative abundance, seasonal trends, migration routes and important breeding habitat for humpback whales in the Northern Mariana Islands region. Autonomous recorders, sonobuoys, and towed array monitoring all have the capability to provide this information (Norris et al. 1999; Au et al. 2000; Lammers et al. 2011).

High-quality recordings of individual humpback whale songs are necessary in order to compare humpback whale songs from the Marianas Islands to songs from other areas. This type of analysis will provide indication of movements of animals and more importantly exchange of cultural information between areas (Cerchio et al. 2001; Darling and Sousa-Lima 2005). Garland et al. (2011) recently demonstrated that song information can be spread rapidly in a unidirectional manner over ocean-basin wide scales. Identifying the level and rate of song exchange is important for identifying and better defining stocks of this depleted species of whale that appears to be re-inhabiting areas impacted by whaling activities.

Finally the effects of Navy activities and sonar on humpback whales acoustic behaviors should be examined. An occurrence of mid-frequency active sonar activity recorded simultaneously with humpback whale singing was identified during our review of songs (**Figure 4-8**). Low frequency active (LFA) sonar has been observed to affect humpback whale songs (Miller et al. 2000), and we have observed and recorded at least one occurrence in which a singing humpback whales ceased singing during the onset of intense mid-frequency sonar near PMRF (T. Norris, Bio-Waves, unpublished data). In several other cases no changes in singing behaviors were observed when sonar intensity was low or infrequent. Autonomous recorder data is most likely to pick up sonar events and these data should be analyzed to give an indication of whether and how sonar might affect humpback whale singing behaviors and relative occurrence.

4.6 Acknowledgements

We would like to acknowledge Laura Morse, Alyson Azzara for their efforts at sea and with preliminary data analysis. Adam Pack (University of Hawaii-Hilo) provided the humpback song sample from Hawaii. The observer and marine mammal survey team from MISTCS provided field assistance locating and photographing animals in the surface-active group encountered off Saipan/Tinian.

4.7 Tables and Figures

4.7.1 Tables

Table 4-1. Summary of Humpback Song Detections and Relevant Attributes.

Date (all 2007)	Total Song/Day (hh:mm:ss)	Leg	Song Detection ID #*	Mean Song Quality**	Mean Noise**
7 Feb	1:13:05	II	TA 67	3.05	3
14 Feb	1:23:00	II	TA 97	2.26	3
17 Feb	0:22:50	II	TA 110	3.5	3.75
18 Feb	1:45:05	II	TA 213***	3.38	3.06
18 Feb	0:24:00	II	SB 214***	4.33	4
2 Apr	0:29:00	II	TA 201	1.91	4
Totals	**05:37:00**	n/a	**Means**	**3.07**	**3.46**

*TA=Towed Array, SB=Sonobouy
** Refer to methods for ranking system
*** Detection #SB214 is most likely the same animal(s) as detection as TA213

4.7.2 Figures

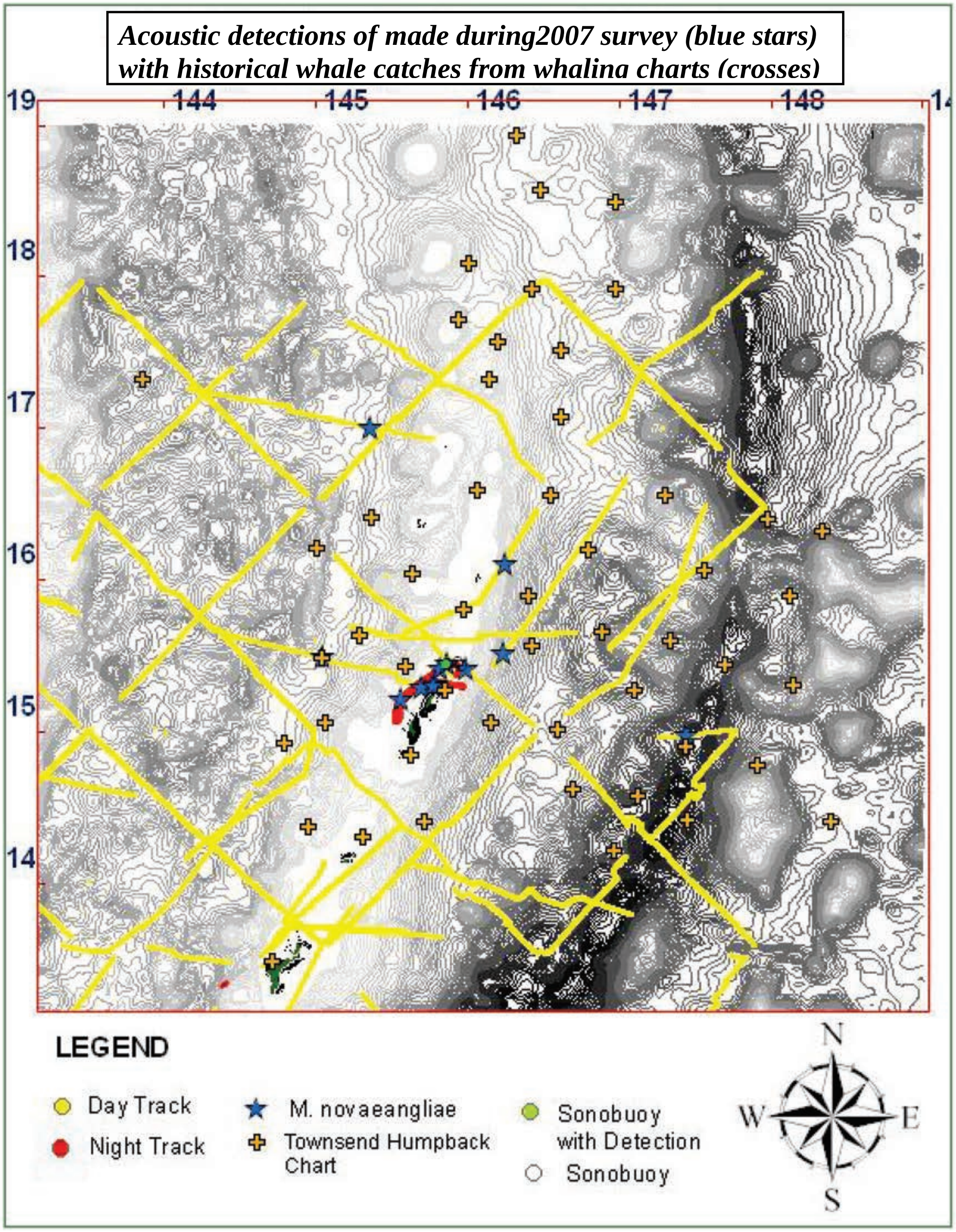

Acoustic detections of made during2007 survey (blue stars) with historical whale catches from whalina charts (crosses)

Figure 4-1. Locations of humpback whale kills (orange crosses) from 1750s-1920s (adapted from Townsend 1935) overlaid on the MISTCS study area with survey trackline (yellow) and humpback whale song acoustic detections by towed hydrophone array (blue stars) and sonobuoys (green star).

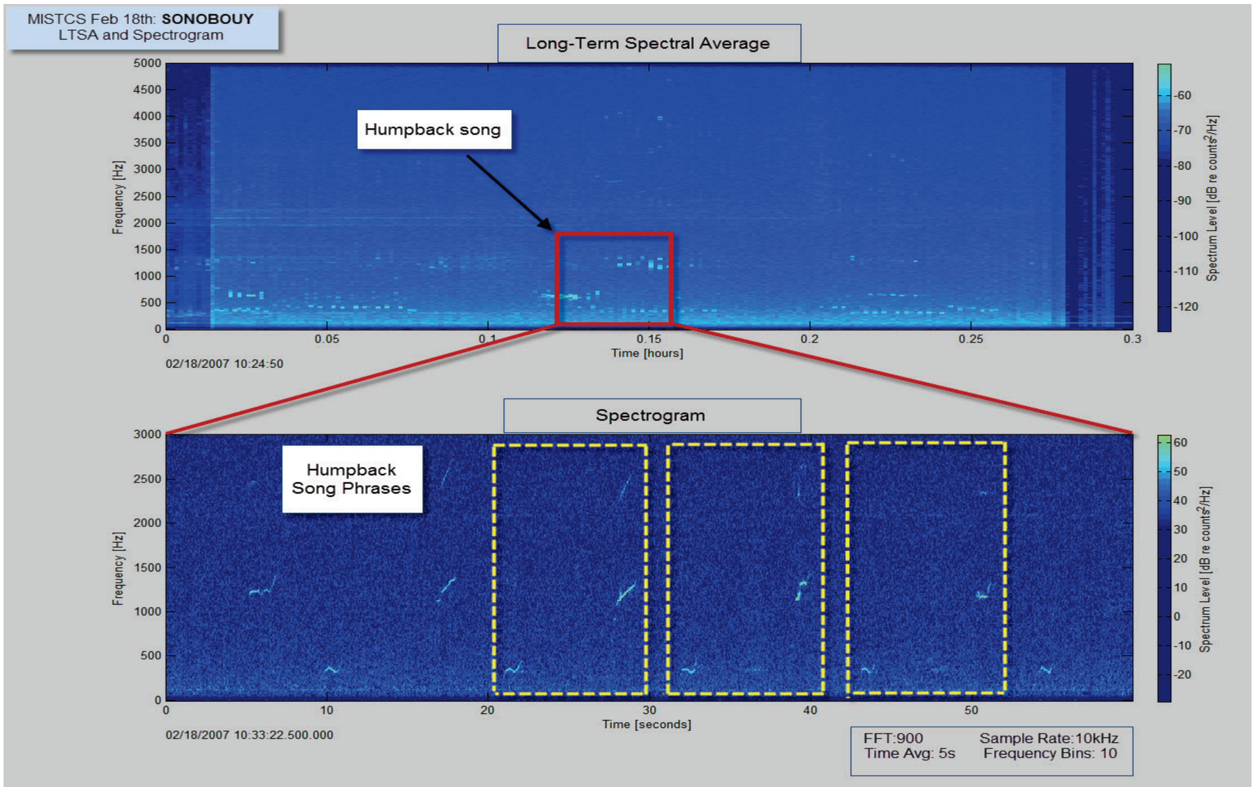


Figure 4-2. LTSA (top panel) and a corresponding spectrogram of boxed (red) selection (bottom panel). The three boxes (broken yellow line) indicate a single phrase type.

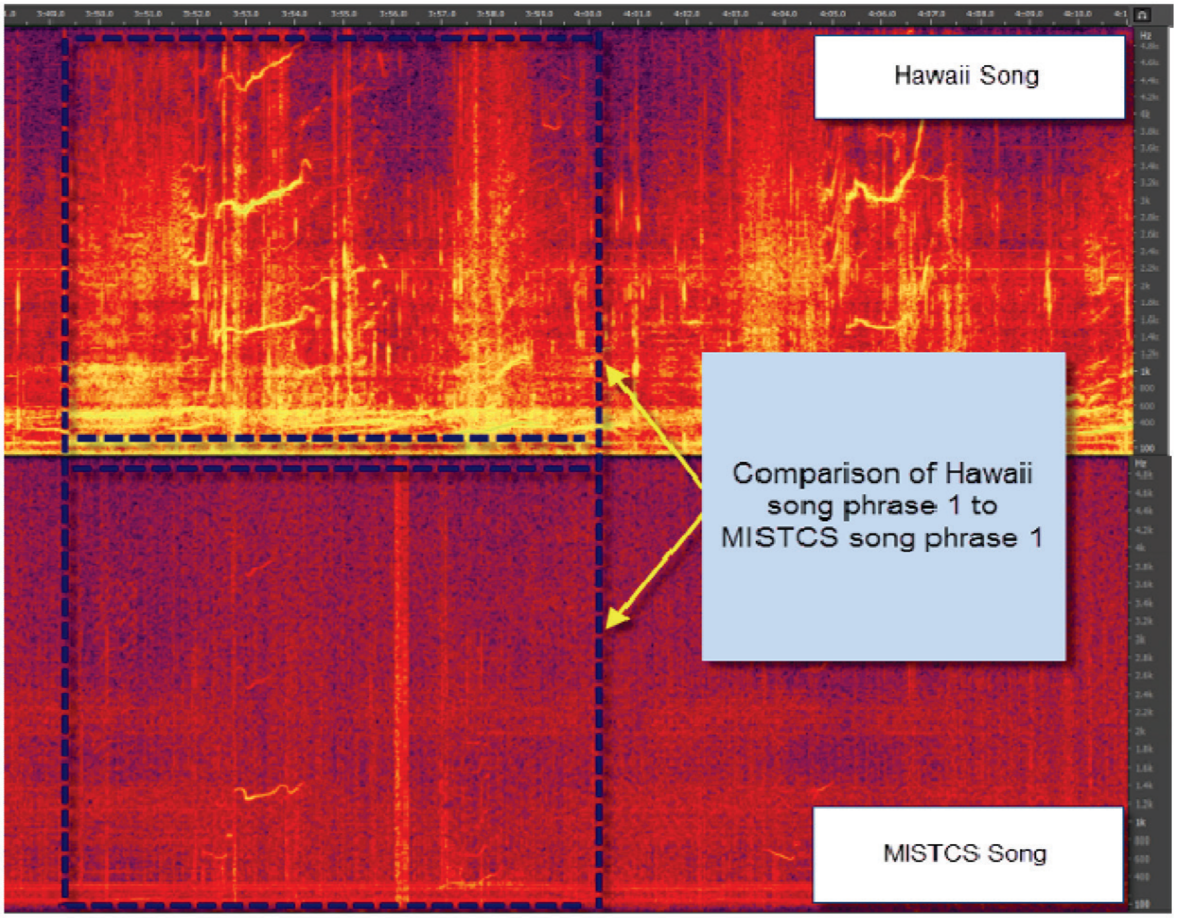
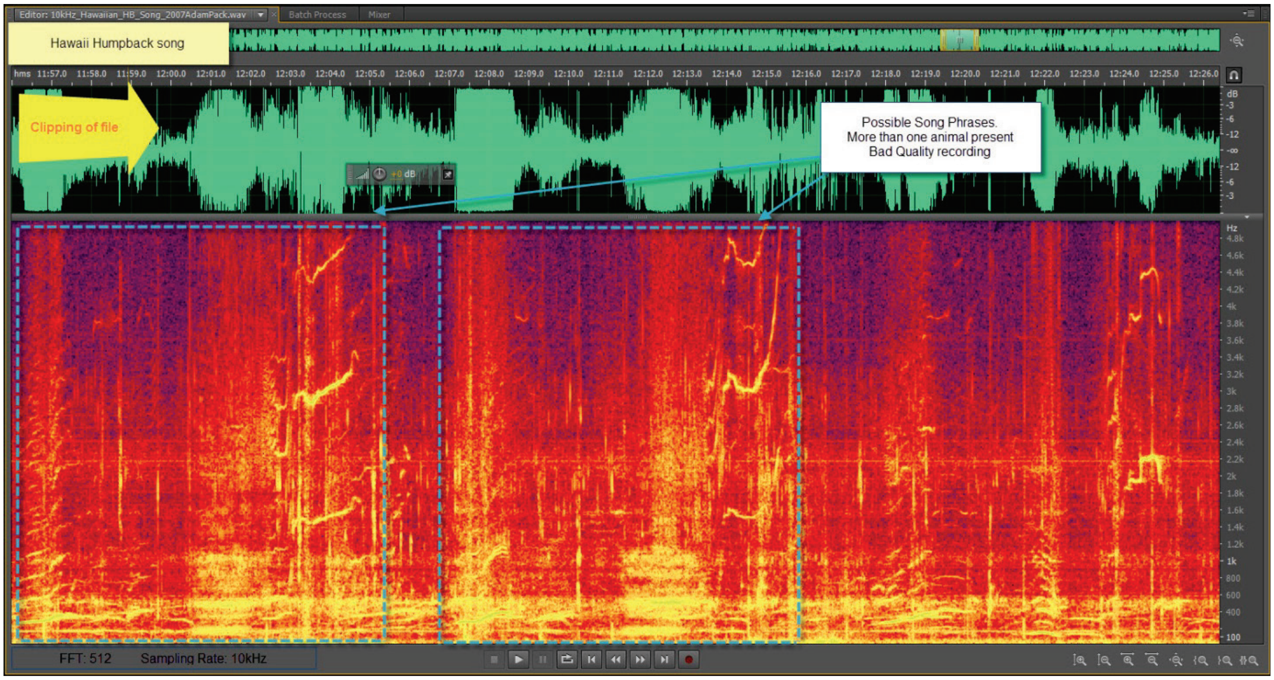


Figure 4-3. Song Comparison: Hawaii song phrase (top), MISTCS song phrase (bottom). Due to quality issues with both the Hawaii song (with more than one animal singing, and clipping of .wav form), and the MISTCS song (poor signal-to-noise ratio), this was the only shared phrase type that we could identify for both locations.


Hawaii Humpback song

Clipping of file

Possible Song Phrases.
More than one animal present
Bad Quality recording

FFT: 512 Sampling Rate: 10kHz

Figure 4-4. Hawaii humpback whale song spectrogram. Poor quality recording due to clipping of .wav form. Two animals present making it difficult to distinguish individual phrase types.

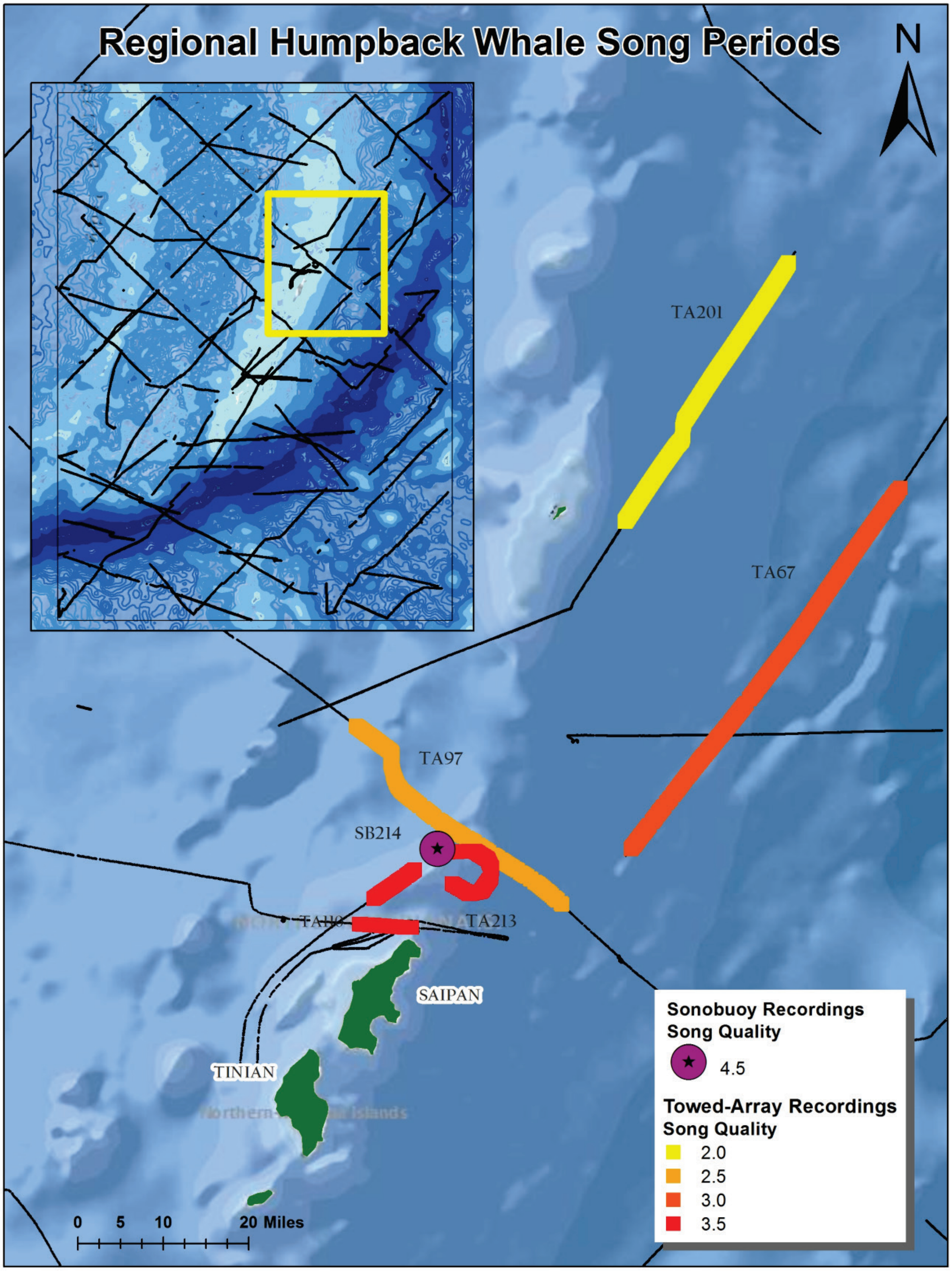


Figure 4-5. Map of humpback whale song intensity and locations near Saipan and Tinian Islands.

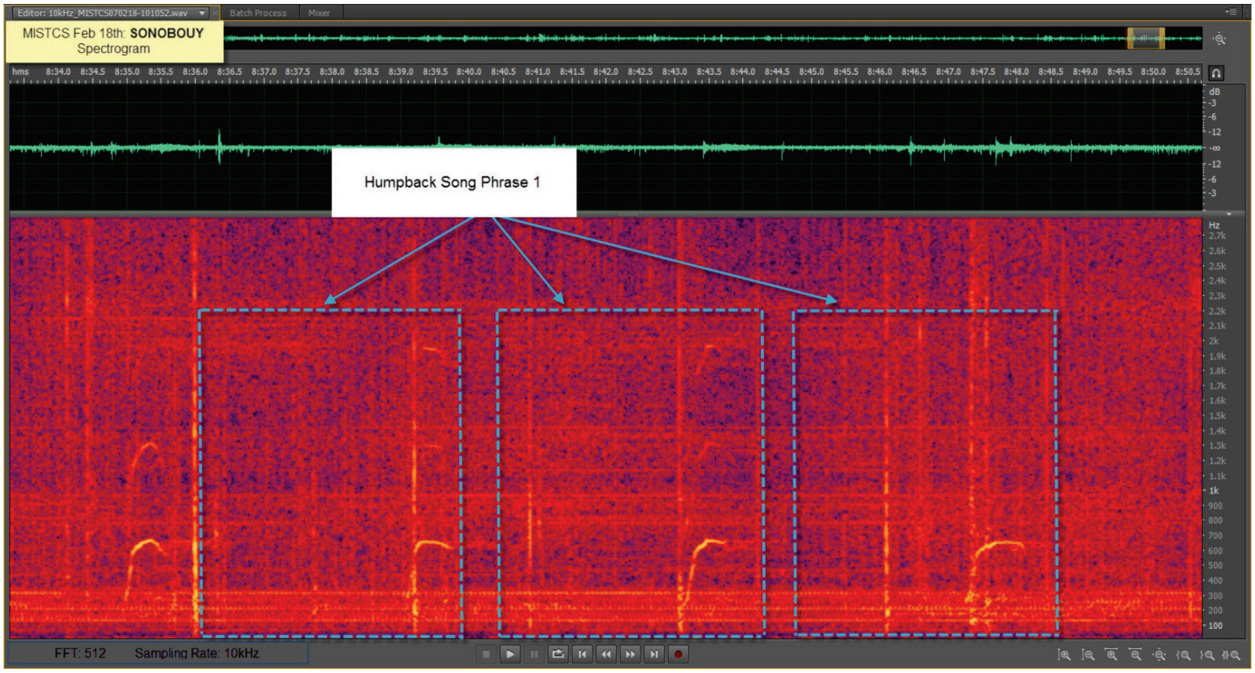


Figure 4-6. Spectrogram of humpback whale song phrase type # 1 from MISTCS. (sonobouy recording)

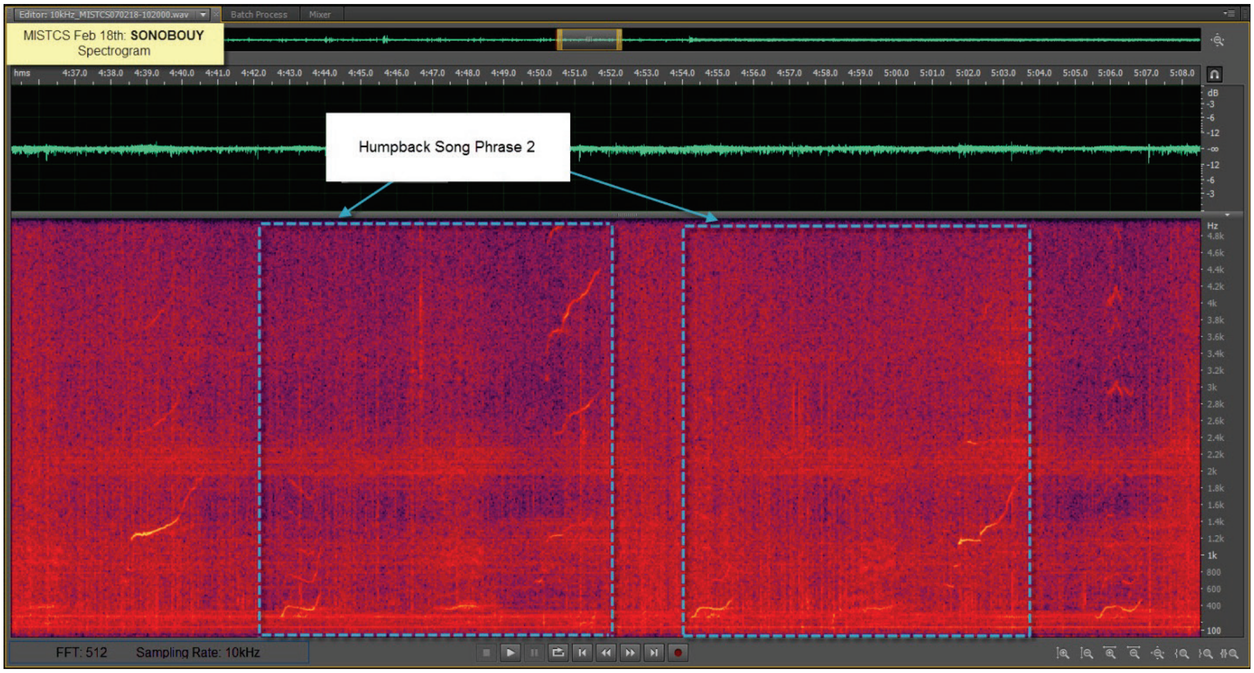


Figure 4-7. Spectrogram of humpback whale song phrase type # 2 from MISTCS. (sonobouy recording)

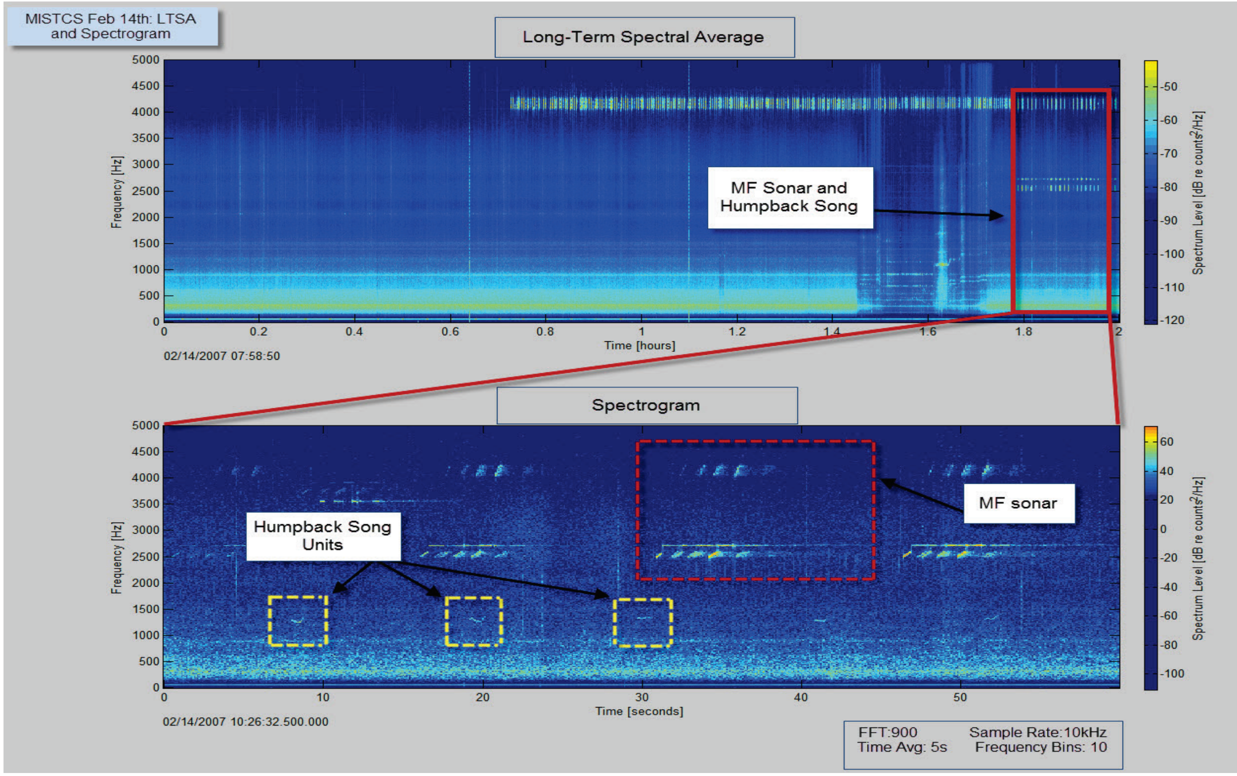


Figure 4-8. LTSA (top panel) and corresponding spectrogram of selection (bottom panel) depicting mid- frequency sonar and concurrent humpback whale song.

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Section 5. Characterization of Sei Whale Vocalizations from MISTCS 2007 Encounters

5.1 Introduction

The sei whale is a cosmopolitan pelagic species found in subtropical, temperate, and sub-polar oceanic waters worldwide (Horwood 1987). Individuals are thought to occur primarily in deep water along slopes and shelf breaks (Horwood 1987). Little is known about the distribution and movement of this species and the population has not been defined adequately. For management purposes, in western and Hawaiian U.S. territorial waters, the sei whale is divided into two stocks: the Hawaiian Stock and the Eastern North Pacific Stock (NMFS 2011). The last population estimate for sei whales in the North Pacific of 42,000 was conducted over 30 years ago and used a variety of different methods based on the history of whale catches and trends in sighting rates for sei whales in the North Pacific (Tillman 1977). There have not been any direct estimates of sei whale abundance in the entire (or eastern) North Pacific based on sighting surveys. A 2002 shipboard line-transect survey of the entire Hawaiian Islands EEZ resulted in a summer/fall abundance estimate of 77 (CV=1.06) sei whales (Barlow 2003). The sei whale is currently listed as endangered under the ESA and the International Union for Conservation of Nature’s Red List. A final recovery plan was recently released (NMFS 2011). The recovery plan proposes a three-tiered recovery strategy including: 1) continuation of international whaling regulation; 2) determination of population size, population trends, and population structure using opportunistic data combined with PAM; and 3) continuation of stranding response and affiliated data collection (NMFS 2011).

The sei whale is one of the least studied species of the genus *Balaenoptera*, thus little is known about their vocal behavior. Sei whale vocalizations have been described in only a handful of peer-reviewed publications (**Table 5-1**). Vocalizations have been described for sei whale encounters in four geographic regions: the Antarctic Peninsula (Gedamke and Robinson 2010; McDonald et al. 2005), Nova Scotia (Knowlton et al. 1991; Thompson et al. 1979), the Hawaiian Islands (Rankin et al. 2007; Smultea et al. 2010), and New England (Baumgartner and Fratantoni 2008; Baumgartner et al. 2008). Call descriptions have ranged from 40 to 3,500 Hz in frequency and 1.0 to 1.5 sec in duration. Sei whale vocalizations recorded from off the New Jersey coastline tended to consist of low frequency (<100 Hz) downsweeps and chirps (Newhall et al. 2009). Off the coast of eastern Canada, frequency-modulated sweeps and pulses have been described (Knowlton et al. 1991; Thompson et al. 1979). The frequency range of these calls extends from the low hundreds of Hz to mid-frequency values from 1.5 to 3 kHz. The only description of calls available in the Hawaiian Islands region is of a low frequency (<100 Hz) downsweep (Rankin and Barlow 2007) similar to some calls characterized from the Atlantic Ocean (Newhall et al. 2009; Baumgartner et al. 2008). The most dynamic documented vocalizations are those collected in the Southern Ocean; these calls range from 170 to 700 Hz and consist of a "frequency stepping" that was encountered in both studies (Gedamke and Robinson 2010; McDonald et al. 2005). There is no description of sei whale vocalizations recorded in the western Pacific Ocean, which is likely due to the elusive behavior of the species and limited survey effort in this region.

Several species of baleen whale were encountered during MISTCS, including Bryde's, sei and humpback whales, in addition to sightings of several unidentified species (DoN 2007). Through an extensive literature review, we determined that the characteristics of vocalizations from these other species were distinctly different from those of sei whale calls described in the literature. In addition to known species, we also investigated the recently recognized species known as Omura's whale (*Balaenoptera omurai*). *Balaenoptera omurai*, formerly classified as a small Bryde's, is now considered a separate species in the family Balaenopteridae (Wada et al. 2003). When originally classified (based on skeletal morphology), specimens collected from the Solomon Islands and Eastern Indian Ocean were treated as a small form of Bryde's whale, because of a relatively reduced body size at sexual maturity when compared with measurements of known Bryde's whale. This smaller type is found in and around the coastal southeastern North Pacific waters. Because this is a newly distinguished species, there are no known acoustic recordings of Omura's whale. Because the habitat of Omura's whale overlaps with other species in the family Balaenopteridae, more research is needed to be able to differentiate its distinct vocal repertoire.

Sei whale occurrence had not been previously confirmed in the MIRC prior to MISTCS 2007 (DoN 2005), however, during MISTCS, this species was the second-most frequently observed species (DoN 2007, Fulling et al. 2011). During the MISTCS, three sightings of sei whales were recorded, during which simultaneous acoustic detections of calls were made from the towed array (**Table 5-2**). The acoustic detections occurred after visual observers initially sighted the animals (and in some cases, the survey vessel approached the whales to verify species identity). Calls were produced sporadically and call durations were brief (generally < 2 sec). No sightings or acoustic detections of other species were made in the two hours preceding or following these events, except in one instance where an unidentified rorqual was sighted at a distance of > 3 km. Sixteen visual detections of sei whale were documented throughout MISTCS, although no real-time acoustic detections were attributed to 13 of these encounters by bioacousticians on-effort. The goal of this analysis was to review acoustic recordings taken during the MISTCS cruise to: (1) characterize calls of sei whales, which occurred during sightings of sei whales; (2) evaluate calls that occurred during sightings of undetermined species that could have been sei whales; and (3) compare sei whale calls described in the literature from other geographic areas to calls measured in this study.

5.2 Methods

Known acoustic detections that were associated with sightings (*n*=3) were reviewed to determine if an automated detector could be developed to post-process the acoustic dataset. Spectrogram template detectors for three call types were developed using XBAT software (www.xbat.org) and tested on a subsample (*n*=5) of sonobuoy recordings. Due to the diverse nature of sei whale vocalizations recorded during MISTCS, a detector (which in XBAT is designed to be used with stereotyped calls) was not feasible to implement. Therefore, all towed-array and sonobuoy recordings with associated sei whale visual sightings were reviewed by an experienced bio-acoustician both aurally, with headphones, and visually by inspecting a spectrographic display. XBAT software was used to review and annotate all recordings. For visual sei whale detections that were not accompanied by acoustic detections in the field, we reviewed the 30 minutes of acoustic data prior to and after each sighting to look for calls. This review was only conducted for sei whale sightings that existed independently from sightings of other species (*n*=10). Additionally, we reviewed all sonobuoy recordings (*n*=33) to look for sei whale vocalizations.

Sei whale calls were logged and clipped into short .wav files using XBAT. Clipped .wav files were then decimated to 12 kHz using *Adobe Audition* software. Decimation is a process in which the sample rate of the signal is reduced to allow quicker analysis and better frequency resolution at lower frequencies in the spectrogram. After files were decimated they were loaded into *Osprey*, a custom MATLAB program that is used to automatically measure a suite of variables from marine mammal calls (Mellinger and Bradbury 2007). All calls were assigned a quality value (1-3) subjectively, based on their signal-to-noise ratio (SNR) with 1 = the lowest SNR and 3 = the highest SNR. In Osprey, a measurement box was drawn around the call to extract and calculate a variety of frequency, time, and amplitude measurements (**Figure 5-1**). Measurements were then logged to a database for further analysis. Several variables were selected to characterize the vocalizations (low frequency [Hz], upper frequency [Hz], duration[s], bandwidth [Hz], peak frequency [Hz] and signal to noise [SNR; dB]). These measurements were based on the entire signal included in the measurement box. *Osprey* also identifies and logs the low and high frequency as the upper and lower limits of the selection box, which we used to approximate the range of frequency represented by the calls. Calls with extremely poor quality were excluded from the analysis. Calls associated with sighting (S) #063 all occurred within an hour of another distant unidentified rorqual. Although we are not able to definitively claim that the calls are from S#063, these calls were detected within 20 minutes of the sei whale being sighted 50 m from the ship; the relative intensity and SNR of the calls thus lead us to believe that it was associated with the closer sei whale detection rather than the unidentified rorqual detected 30 minutes after calls and 3.7 km away from the ship. As calls were reviewed, they were assigned to a subjective call type category based on their spectrographic representation - Type 1A, 1B, 2, 3, 4, 5A, 5B and 6, respectively. These call types were then compared to those described in the sei whale literature (**Table 5-1**).

5.3 Results

Thirty-two calls were identified and analyzed from towed-hydrophone array and sonobuoy recordings; all calls identified from the towed-hydrophone array were associated with a sighting (*n*=6). Calls identified from sonobuoy recordings were attributed to sei whales if a possible sei whale was detected prior to or during deployment and/or the call matched a type identified from the review of the towed-hydrophone array recordings (**Table 5-2**). Several calls identified from both towed-hydrophone array and sonobuoy recordings were not measured due to poor quality, often caused by engine noise and/or electrical interference on the audio signal. The geographic locations of all sei whale encounters categorized as combined acoustic and visual (*n*=6), visual only (*n*=10), or sonobuoy detections (*n*=5) are shown in **Figure 5-2**. The call types (Type 1 through 6) were used to categorize all sei whale vocalizations from the dataset. Between one and 10 calls were assigned to each representative type (**Table 5-3**). The suite of measurements are described for each call type in **Tables 5-4 to 5-10** and visually represented in spectrograms in **Figures 5-3 to 5-20**.

- Type 1 A calls (*n*=7) were characterized by their slight frequency-modulated (FM) downsweep and had a mean minimum frequency of 834 Hz, a mean maximum frequency of 1,517 Hz, a mean duration of 0.8 sec, a mean bandwidth of 682 Hz, and a mean peak frequency of 991 Hz.
- Type 1 B calls (*n*=2) were comprised of calls with a slight (FM) downsweep centered around 1 kHz and a mean minimum frequency of 914 Hz, a mean maximum frequency of 1,078 Hz, a mean duration of 0.3 sec, a mean bandwidth of 164 Hz, and a mean peak frequency of 1,031 Hz.
- Type 2 calls (*n*=2) are FM short signals, with a mean minimum frequency of 949 Hz, a mean maximum frequency of 1,640 Hz, a mean duration of 0.2 sec, a mean bandwidth of 691 Hz, and a mean peak frequency of 1,042 Hz.
- Type 3 and Type 4 calls only contained one representative each. Both are longer tonal signals that are described in greater detail in the discussion.
- Type 5A and 5B are complex frequency ‘stepped’ signals that either increase or decrease, respectively, in frequency as a function of duration. Type 5A calls (*n*=3) had a mean minimum frequency of 863 Hz, a mean maximum frequency of 1,582 Hz, a mean duration of 0.3 sec, a mean bandwidth of 718 Hz, and a mean peak frequency of 1,047 Hz. Type 5B calls (*n*=8) had a mean minimum frequency of 826 Hz, a mean maximum frequency of 1,642 Hz, a mean duration of 0.6 sec, a mean bandwidth of 897 Hz, and a mean peak frequency of 902 Hz.
- Type 6 calls (*n*=4) were characterized by slight upsweeps and had a mean minimum frequency of 850 Hz, a mean maximum frequency of 1,125 Hz, a mean duration of 0.4 sec, a mean bandwidth of 275 Hz, and a mean peak frequency of 973 Hz.

5.4 Discussion

The MISTCS 2007 sei whale encounters occurred primarily in the central and southern region of the study area, ranging from the island of Tinian to the southeast corner of the study area. A higher concentration was found in the southeast corner and along the Mariana Trench (**Figure 5-2**). The 32 sei whale vocalizations recorded during the survey included acoustic characteristics not previously described elsewhere. The distinctive features of the recorded calls were difficult to measure due to their variability and the poor signal-to-noise quality of some of the recordings at the relevant frequencies. The spectrograms of these calls still provide qualitative representation of call characteristics which might be more diagnostic than quantitative measurements, therefore, both are provided.

Post-processing of the sei whale calls successfully allowed us to identify and attribute three additional sei encounters with acoustic detections (N=7 calls). Additionally, review of the sonobuoy recordings provided an additional three sei whale encounters and seven attributed calls. These were probably missed during the real-time monitoring probably because so little is known of sei whale vocal behavior, and bio-acousticians in the field did not know what types of calls to look for. This review will be useful to other researchers who will be collecting acoustic data, or have recordings from this area and can now search for the calls types described here.

Sei whale calls from this survey were categorized into eight ‘unique types’ previously discussed. Type 1A calls were grouped based on their slight FM downsweep from approximately 1,000 to 840 Hz. These calls generally included a second, less intense downsweep in the band between 2.5 and 2 kHz (**Table 5-4, Figures 5-3 to 5-7**). Similar to these calls were Type 1B vocalizations, which consisted of a slight downsweep centered at 1 kHz. There was not a secondary band present in this call type (**Table 5-5, Figures 5-8 and 5-9**). While the literature describes downsweep calls that occur in association with sei whale vocalizations, those were frequencies below 100 Hz (Baumgartner et al. 2008; Baumgartner and Fratantoni 2008; Newhall et al. 2009; Rankin and Barlow 2007).

Call type 2 is a short, frequency modulated call that occurs between 1,000 and 1,200 Hz that does not appear similar in spectrographic representation or contour to other documented calls (**Table 5-6, Figure 5-10**).

Call type 3 is represented by only one call and contains three (possibly harmonic) segments between 900 and 3,200 Hz (**Table 5-7, Figure 5-11**). These segments consist of an approximate 1-second long tonal element immediately followed by a short (>.0.5-seconds) frequency modulated element. This call is similar in frequency range with the calls described off Nova Scotia.

Call types 5A and 5B are complex vocalizations that contain overlapping frequency "steps" centered at one or more frequencies. These calls were separated into two groups because type 5A increases from low to higher frequencies, whereas 5B decreases in frequency (**Tables 5-8 and 5-9**, **Figures 5-13 to 5-19**). All of these calls are centered at approximately 1,000 Hz with some of the bands extending to 3,500 Hz. Although the frequency range of the Type 5A and 5B calls do not coincide with those encountered in the Southern Ocean, the qualitative characteristic of the frequency "stepping" is evident; Type 5A and 5B calls are somewhat similar to the frequency range of those collected off Nova Scotia. It should be noted that the frequency stepping in these calls contains more overlap and frequency modulation than those described in the Southern Ocean.

Finally, Type 6 calls represent a more ‘stereotypical baleen whale call’ as it consists of a slight upsweep from 850 to 1,100 Hz (**Table 5-10, Figure 5-20**). Upsweeps are not mentioned in the literature, although they are typical of calls from other baleen whale species (e.g., fin whales, etc.)

The MISTCS 2007 dataset contained extensive electrical noise (due to a short in the main power system that was providing power to the acoustic system). This was especially true in the beginning of Leg I when the majority of sei whale calls were recorded. This noise was particularly strong in the low frequency range (below 500 Hz), which precluded localization of calls in the field or post-processing. This might have also resulted in missed detections of calls below approximately 500 Hz, or mischaracterization of calls with energy below 500 Hz during the survey. Although localizations were not possible during the survey, we still have high confidence that the calls analyzed here were produced by sei whales because they all occurred coincident to, or within a short time period of, visually confirmed sei whales, and no other visual or acoustic encounters were made within approximately 5 km during the relevant time period.

5.5 Conclusions and Recommendations

The vocalizations described here include call characteristics that have not been previously described from recordings of sei whales in other regions. It is recommended that these findings be submitted for a peer-reviewed publication. Our findings indicate greater variability in the vocal repertoire of sei whales than previously documented. These descriptions should aid in the analysis of other passive acoustic data, especially those collected remotely without associated visual information, such as from autonomous recorders, gliders, and seafloor hydrophones. Additional research is required to obtain a better understanding of the vocal repertoire of sei whales both in the Marianas and in other areas in the North and western North Pacific. Additional effort should be directed toward obtaining validated recordings of sei whales, behavioral information related to calls rates and call types, and if possible photo-identification and genetic (i.e., biopsy) samples. Future research including combined acoustic, behavioral, genetic and sighting data collection may lead to a better assessment of stock structure, distribution and abundance in the western North Pacific Ocean. Additionally, it may be possible to dedicate further effort to development of automated detectors for each call type, but it was not feasible for this effort due to small sample size.

5.6 Tables and Figures

5.6.1 Tables

Table 5-1. Summary of known sei whale studies and vocal descriptions compiled from literature reviews.

Location	Study Period	General Description	Frequency Range & Call Duration	Methods	Author
Cape Cod, MA	2006-2007 (Spring)	Low frequency, downsweeps, single calls, pairs and triplets occasionally detected	<100 Hz, 82 to 34 Hz over 1.4 s	Autonomous recorders (MARUs), 70 hrs of visual and acoustic observations. Used synthetic kernel for auto detections. Localized w/in 3 km.	Baumgartner et al. 2008
SW Gulf of Maine	May 2005 (Feeding)	Low frequency, downsweeps, single calls, pairs and triplets occasionally detected	<100 Hz, 82 to 34 Hz over 1.4 s	Array of autonomous ocean gliders	Baumgartner and Fratantoni 2008
Southern Ocean near Antarctic Peninsula	2003 (summer)	Low freq, tonal, FM, broadband calls; “growls” or “whooshes”. Multi-part frequency step in-between. No temporal pattern in calling.	200-700Hz: avg freq 433 ± 192 Hz, over 0.45 s	Seafloor recorders in 3,000 m of water, 2 sonobuoys (DIFAR/Omni). DIFAR 305 m, omni at 27 m. Photo ID within 200 m of ship.	McDonald et al. 2005
Mid-Atlantic continental shelf off New Jersey coast	2006	Low freq, downsweep chirps	NA	Hydrophones on vertical array from 13 m to bottom	Newhall et al. 2009
North of Hawaiian Islands	November 2002	Low freq, Downsweep	<u>Call 1</u>: 100-44 Hz over 1.0s <u>Call 2</u>: 39-21 Hz over1.3s	NA	Rankin and Barlow 2007
B/W Nova Scotia and Newfoundland	NA	Mid freq, Long bursts	1.5-3.5 kHz: 0.7s long bursts of 7-10 metallic pulses (peak freq=3kHz)	NA	Thompson et al. 1979
Antarctic Peninsula	Jan – Feb 2006	Frequency “stepping” from 170-570 Hz	170 – 570 Hz	Acoustic sonobuoy survey	Gedamke & Robinson, 2010
SW Nova Scotia	1986-1989 (Fall)	Mid freq	1.4-2.6 s midfreq vocals, consisted of 2 bouts of 10-20 freq-modulated 1.5-3.5kHz sweeps separated by 0.4-1 s	32 opportunistic recording sessions	Knowlton et al. 1991

Table 5-2. Summary of all calls identified in association with either a visual sighting, or unique acoustic detection. Quality is a relative measure based on a scale of 1 through 3 with 1 being the lowest SNR and 3 being the highest.

Date	Array/SB	Visual ID	Clip_ID	Quality	Preliminary Type
1/20/2007	Array	S#003 & Acoustic	20070120_8_3_0005.wav	3	1A
1/20/2007	Array	S#003 & Acoustic	20070120_8_3_0006.wav	2	2
1/20/2007	Array	S#003 & Acoustic	20070120_8_3_0007.wav	2	1A
1/20/2007	Array	S#003 & Acoustic	20070120_8_3_0008.wav	2	3
1/20/2007	Array	S#003 & Acoustic	20070120_8_3_0010.wav	1	1B
1/20/2007	Array	S#003 & Acoustic	20070120_8_3_0012.wav	1	1B
1/20/2007	Array	S#003 & Acoustic	20070120_8_3_0016.wav	2	1A
1/20/2007	Array	S#003 & Acoustic	20070120_8_3_0017.wav	2	1A
1/20/2007	Array	S#003 & Acoustic	20070120_8_3_0018.wav	1	6
1/21/2007	Array	S#005 & Acoustic	MISTCS_20070121_0001.wav	2	4
2/19/2007	Array	S#063 & Acoustic	MISTCS_20070219_0001.wav	3	5B
2/19/2007	Array	S#063 & Acoustic	MISTCS_20070219_0002.wav	2	5A
2/19/2007	Array	S#063 & Acoustic	MISTCS_20070219_135738_0001.wav	2	1A
2/19/2007	Array	S#063 & Acoustic	MISTCS_20070219_140000_0001.wav	1	5A
2/19/2007	Array	S#063 & Acoustic	MISTCS_20070219_140000_0002.wav	1	5B
2/19/2007	Array	S#063 & Acoustic	MISTCS_20070219_140000_0003.wav	2	5A
2/19/2007	Array	S#063 & Acoustic	MISTCS_20070219_140000_0004.wav	1	5B
2/19/2007	Array	S#063 & Acoustic	MISTCS_20070219_141000_0002.wav	2	5B
2/19/2007	Array	S#063 & Acoustic	MISTCS_20070219_141000_0003.wav	2	5B
3/26/2007	Sonobuoy	No Sighting	070326_0026_010652.826.wav	1	6
3/26/2007	Sonobuoy	No Sighting	070326_0034_012142.927.wav	2	No Match
4/8/2007	Sonobuoy	No Sighting	070408153100_0001_000754.342.wav	2	1A
4/9/2007	Sonobuoy	Possible S#143	070409_142800_0001_000050.933.wav	1	1A
4/9/2007	Sonobuoy	Possible S#143	070409_142800_0004_001103.022.wav	1	6
4/9/2007	Sonobuoy	Possible S#143	070409_142800_0005_002339.586.wav	1	1A
4/10/2007	Sonobuoy	No Sighting	070410_195000_0013_000630.017.wav	1	6
2/1/2007	Array	S#030	Sei Whale 134848_0001_000018.726.wav	1	1A
2/1/2007	Array	S#030	Sei Whale 135000_0001_000048.741.wav	2	1A
2/1/2007	Array	S#030	Sei Whale 135000_0002_000124.997.wav	2	2
2/20/2007	Array	S#068	Sei Whale_0001_000610.223.wav	2	5B
2/21/2007	Array	S#073	Sei Whale_0001.wav	2	5B
2/21/2007	Array	S#073	Sei Whale_0002.wav	1	5B

Table 5-3. Summary of the number of clipped sei whales calls classified to one of eight qualitative types (1A – 5B). The total number of clipped calls measured and the number of calls that were associated with a sighting are given for all calls and each type, respectively.

Sei Whale Call Summary		
Category	**Total Samples**	**Total Associated with Sighting**
All	32*	25
Type 1A	10	7
Type 1B	2	2
Type 2	2	2
Type 3	1	1
Type 4	1	1
Type 5A	3	3
Type 5B	8	8
Type 6	4	1

*One call could not be matched to a type

Table 5-4. Measurements of sei whale calls categorized as "Type 1A". The statistical average, median, standard deviation (Std. Dev.) and 10-90th percentile values are provided for each of the six descriptive measures.

Type 1A				
Measurement	**Mean**	**Median**	**Std. Dev.**	**10-90th Percentile**
Minimum Frequency (Hz)	835.0	867.2	145.7	(666.8 - 954.5)
Maximum Frequency (Hz)	1517.0	1230.5	527.5	(1051.2 - 2240.6)
Duration (s)	0.8	0.6	0.5	(0.34 - 1.7)
Bandwidth (Hz)	682.0	503.9	531.8	(70.3 - 1333.6)
Peak Frequency (Hz)	991.4	1019.5	69.0	(890.6 - 1057.0)
SNR (dB)	15.3	16.1	2.8	(11.9 - 18.7)

Table 5-5. Measurements of sei whale calls categorized as "Type 1B". The statistical average, median, Std. Dev. and 10-90th percentile values are provided for each of the six descriptive measures.

Type 1B				
Measurement	**Mean**	**Median**	**Std. Dev.**	**10-90th Percentile**
Minimum Frequency (Hz)	914.1	914.1	49.7	(885.9 - 942.2)
Maximum Frequency (Hz)	1078.1	1078.1	49.7	(1050.0 - 1106.3)
Duration (s)	0.3	0.3	0.1	(0.22 - 0.29)
Bandwidth (Hz)	164.1	164.1	0.0	(164.1 - 164.1)
Peak Frequency (Hz)	1031.3	1031.3	33.1	(1012.5 - 1050.0)
SNR (dB)	11.9	11.9	2.2	(10.7 - 13.2)

Table 5-6. Measurements of sei whale calls categorized as "Type 2". The statistical average, median, Std. Dev. and 10-90th percentile values are provided for each of the six descriptive measures.

Type 2				
Measurement	**Mean**	**Median**	**Std. Dev.**	**10-90th Percentile**
Minimum Frequency (Hz)	949.2	949.2	66.3	(911.7 - 986.7)
Maximum Frequency (Hz)	1640.6	1640.6	778.9	(1200.0 - 2081.3)
Duration (s)	0.2	0.2	0.0	(0.18 - 0.21)
Bandwidth (Hz)	691.4	691.4	712.6	(288.3 - 1094.5)
Peak Frequency (Hz)	1043.0	1043.0	49.7	(1014.8 - 1071.1)
SNR (dB)	14.1	14.1	2.6	(12.6 - 15.6)

Table 5-7. Measurements of sei whale calls categorized as "Types 3 and 4". The measured values are provided for each of the six measures.

Measurement	Type 3	Type 4
Minimum Frequency (Hz)	832.0	714.8
Maximum Frequency (Hz)	3035.2	1160.2
Duration (s)	1.9	3.5
Bandwidth (Hz)	2203.1	445.3
Peak Frequency (Hz)	937.5	890.6
SNR (dB)	19.1	14.5

Table 5-8. Measurements of sei whale calls categorized as "Type 5A." The statistical average, median, standard deviation (std. dev.) and 10-90th percentile values are provided for each of the six descriptive measures.

Type 5A				
Measurement	**Mean**	**Median**	**Std. Dev.**	**10-90th Percentile**
Minimum Frequency (Hz)	863.3	855.5	13.5	(855.5 - 874.2)
Maximum Frequency (Hz)	1582.0	1535.2	564.0	(1141.4 - 2041.4)
Duration (s)	0.3	0.3	0.1	(0.23 - 0.37)
Bandwidth (Hz)	718.8	679.7	551.8	(285.9 - 1167.9)
Peak Frequency (Hz)	1046.9	1054.7	35.8	(1017.2 - 1073.4)
SNR (dB)	14.6	15.4	2.7	(12.3 - 16.5)

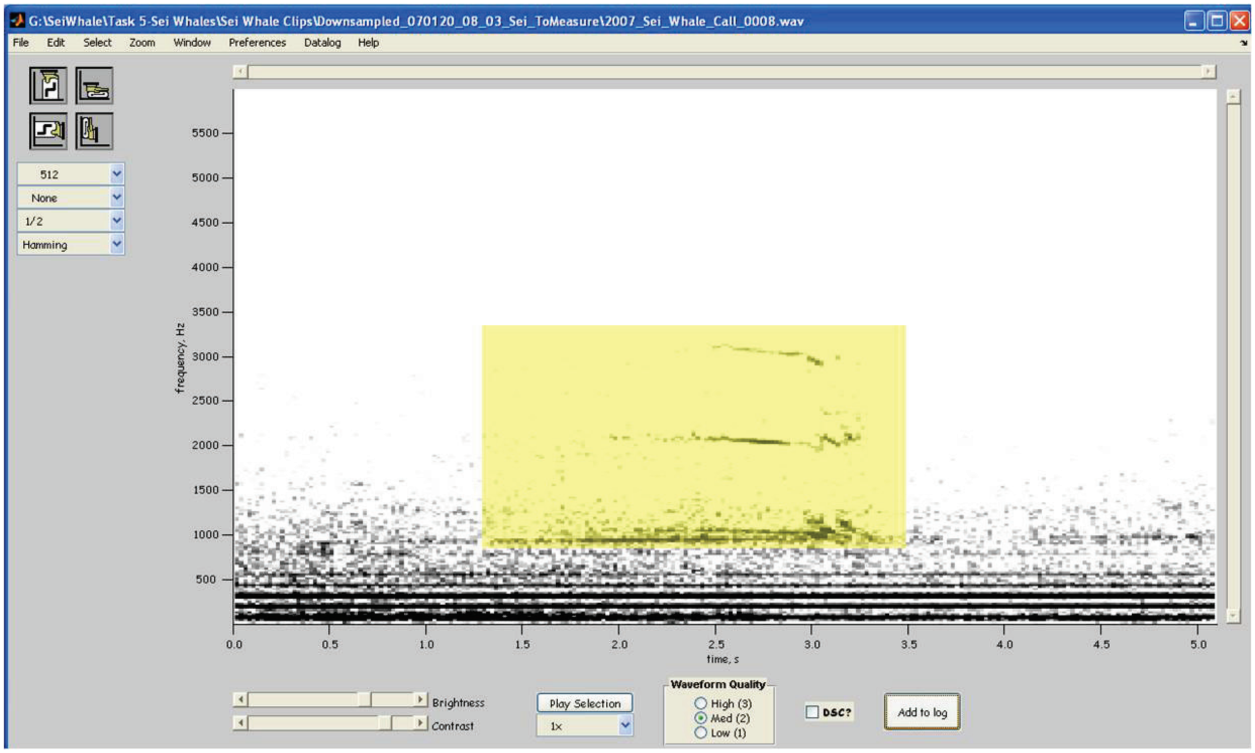
Table 5-9. Measurements of sei whale calls categorized as "Type 5B". The statistical average, median, Std. Dev. and 10-90th percentile values are provided for each of the six descriptive measures.

Type 5B				
Measurement	**Mean**	**Median**	**Std. Dev.**	**10-90th Percentile**
Minimum Frequency (Hz)	826.2	843.8	55.8	(764.1 - 876.6)
Maximum Frequency (Hz)	1642.1	1546.9	705.8	(1037.7 - 2294.5)
Duration (s)	0.6	0.6	0.2	(0.39 - 0.78)
Bandwidth (Hz)	815.9	773.4	728.0	(165.2 - 1453.1)
Peak Frequency (Hz)	902.3	896.5	14.0	(890.6 - 917.6)
SNR (dB)	16.9	17.4	3.5	(12.6 - 20.39)

Table 5-10. Measurements of sei whale calls categorized as "Type 6". The statistical average, median, Std. Dev. and 10-90th percentile values are provided for each of the six descriptive measures.

Type 6				
Measurement	**Mean**	**Median**	**Std. Dev.**	**10-90th Percentile**
Minimum Frequency (Hz)	849.6	873.0	76.8	(776.9 - 903.5)
Maximum Frequency (Hz)	1125.0	1119.1	131.5	(1007.8 - 1246.9)
Duration (s)	0.4	0.2	0.3	(0.16 - 0.66)
Bandwidth (Hz)	275.4	234.4	98.3	(217.9 - 365.6)
Peak Frequency (Hz)	972.7	984.4	40.6	(935.2 - 1000.8)
SNR (dB)	9.6	9.8	2.3	(7.37 - 11.57)

5.6.2 Figures



G:\SeiWhale\Task 5-Sei Whales\Sei Whale Clips\Downsampled_070120_08_03_Sei_ToMeasure\2007_Sei_Whale_Call_0008.wav

Waveform Quality
○ High (3)
● Med (2)
○ Low (1)

☐ DSC?

Figure 5-1. An example of a measurement box for a sei whale call in *Osprey*. The spectrographic display shows frequency (Hz) along the y-axis and time (sec) along the x-axis with amplitude reflected as color intensity. The dark bands along the bottom of the figure are attributable to electric noise present in the system.

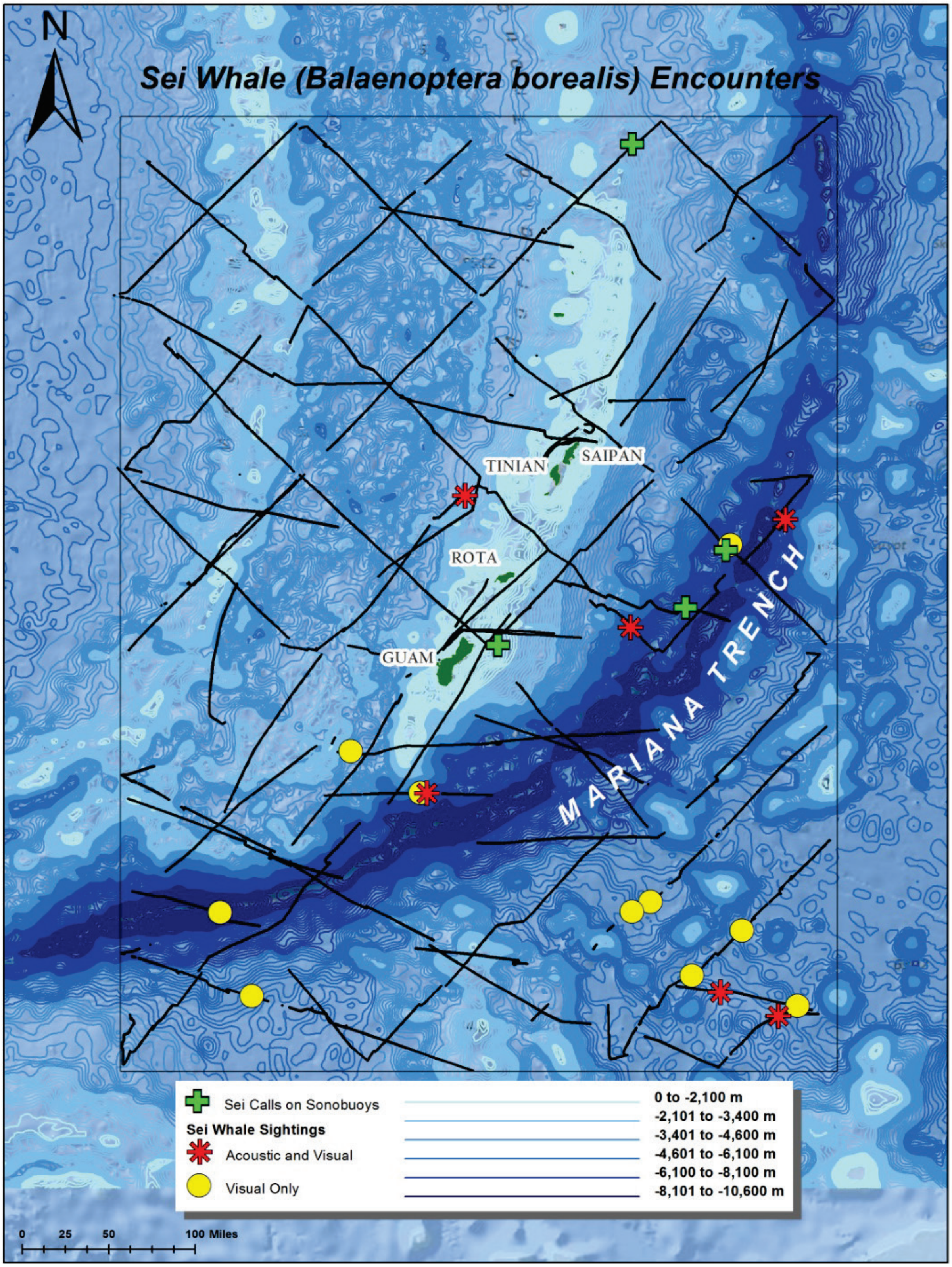


Figure 5-2. Locations of MISTCS 2007 sei whale encounters categorized as combined acoustic and visual (red star), visual only (yellow circle) or sonobuoy (green cross).

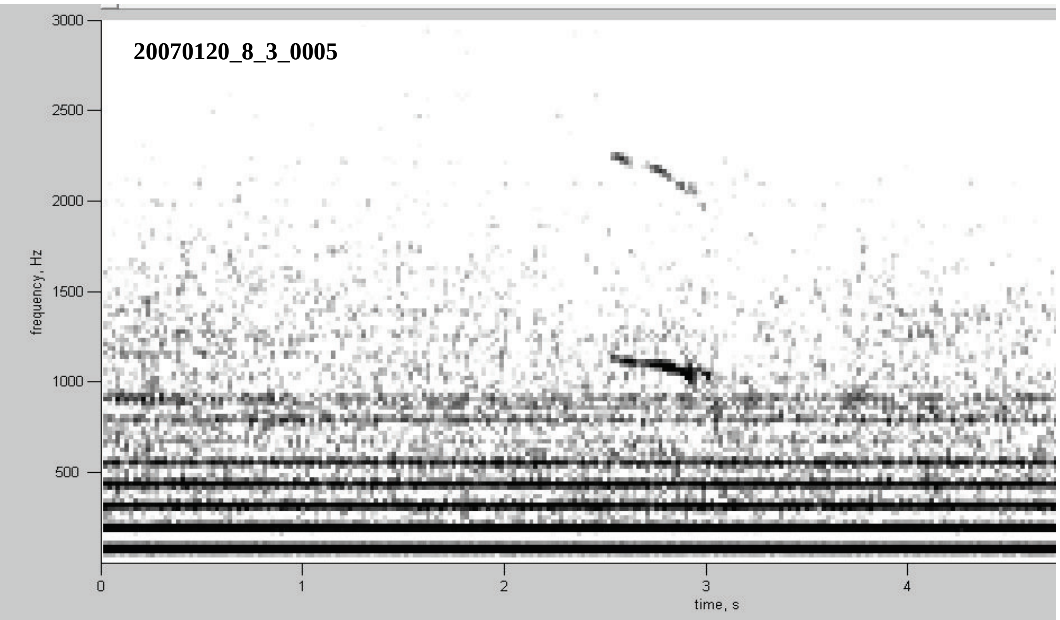


Figure 5-3. Example of Type 1A sei whale call spectrographic display showing frequency (Hz) along the y-axis and time (sec) along the x-axis with amplitude reflected as color intensity. The dark horizontal banding pattern is due to electrical noise from the research vessel's power supply. This noise only occurred during the beginning of the first leg, when, unfortunately, most of the recordings of sei whale calls were made.

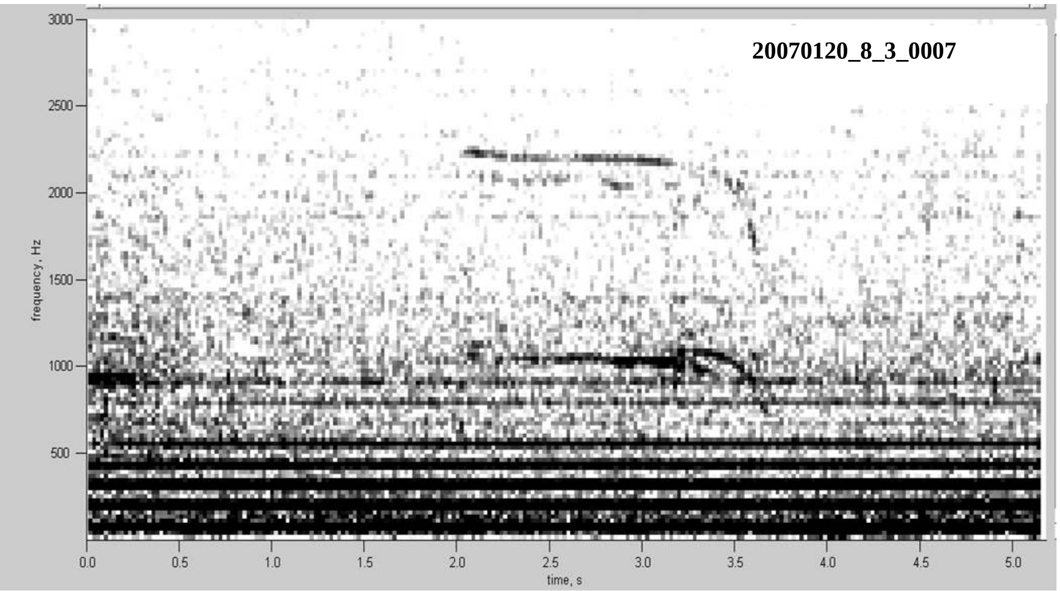


Figure 5-4. Example of Type 1A sei whale call spectrographic display showing frequency (Hz) along the y-axis and time (sec) along the x-axis with amplitude reflected as color intensity.

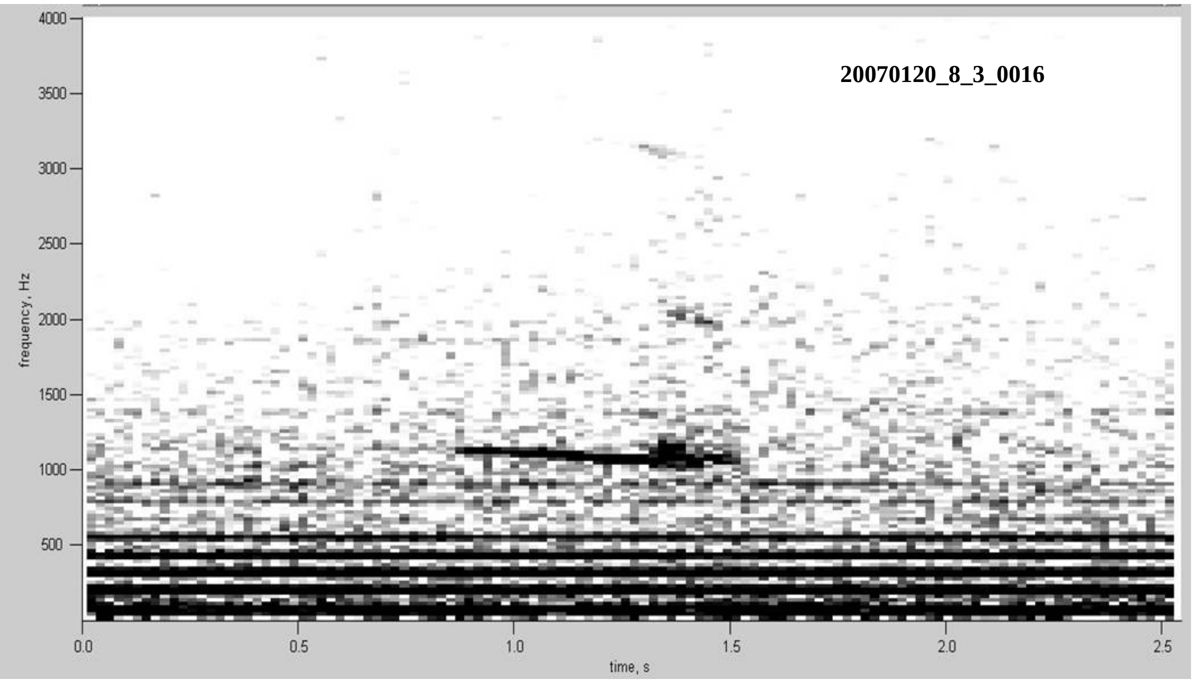


Figure 5-5. Example of Type 1A sei whale call spectrographic display showing frequency (Hz) along the y-axis and time (sec) along the x-axis with amplitude reflected as color intensity.

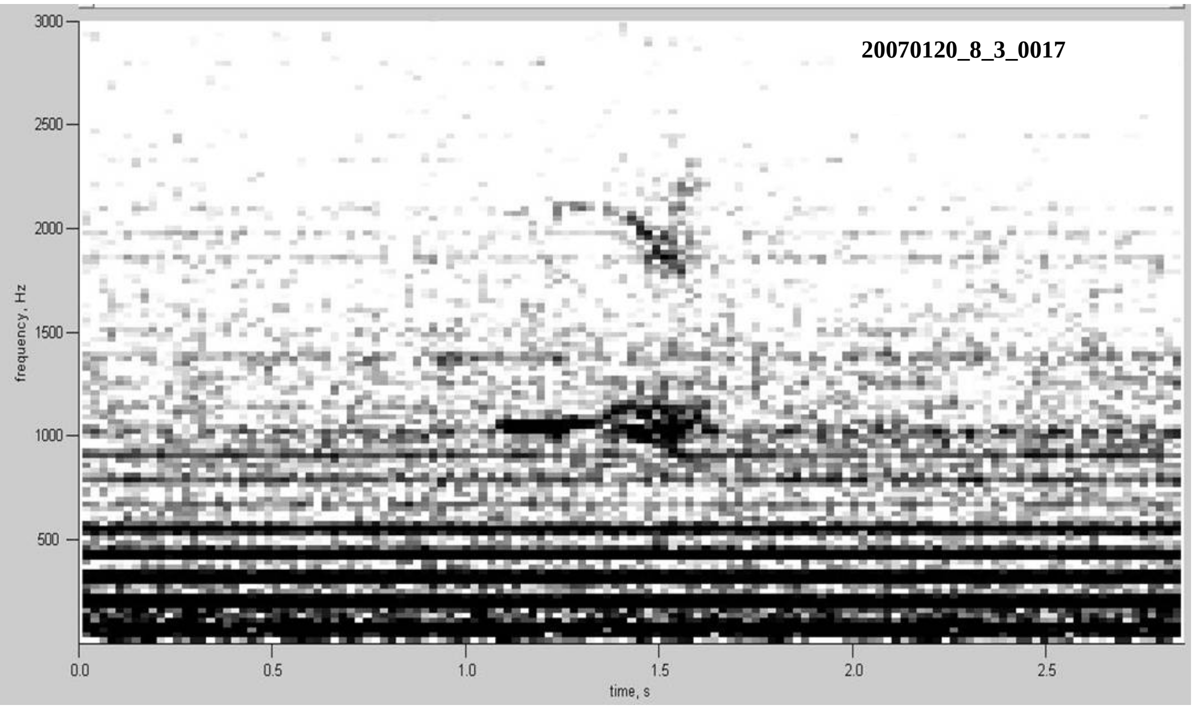


Figure 5-6. Example of Type 1A sei whale call spectrographic display showing frequency (Hz) along the y-axis and time (sec) along the x-axis with amplitude reflected as color intensity.

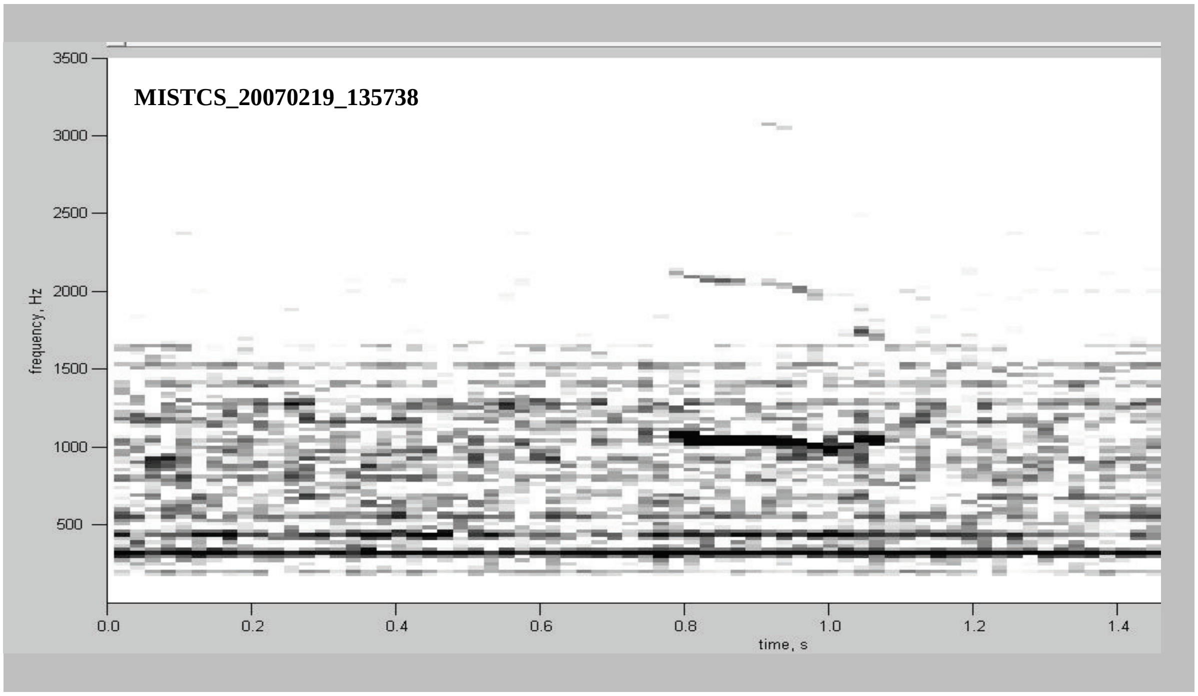


Figure 5-7. Example of Type 1A sei whale call spectrographic display showing frequency (Hz) along the y-axis and time (sec) along the x-axis with amplitude reflected as color intensity.

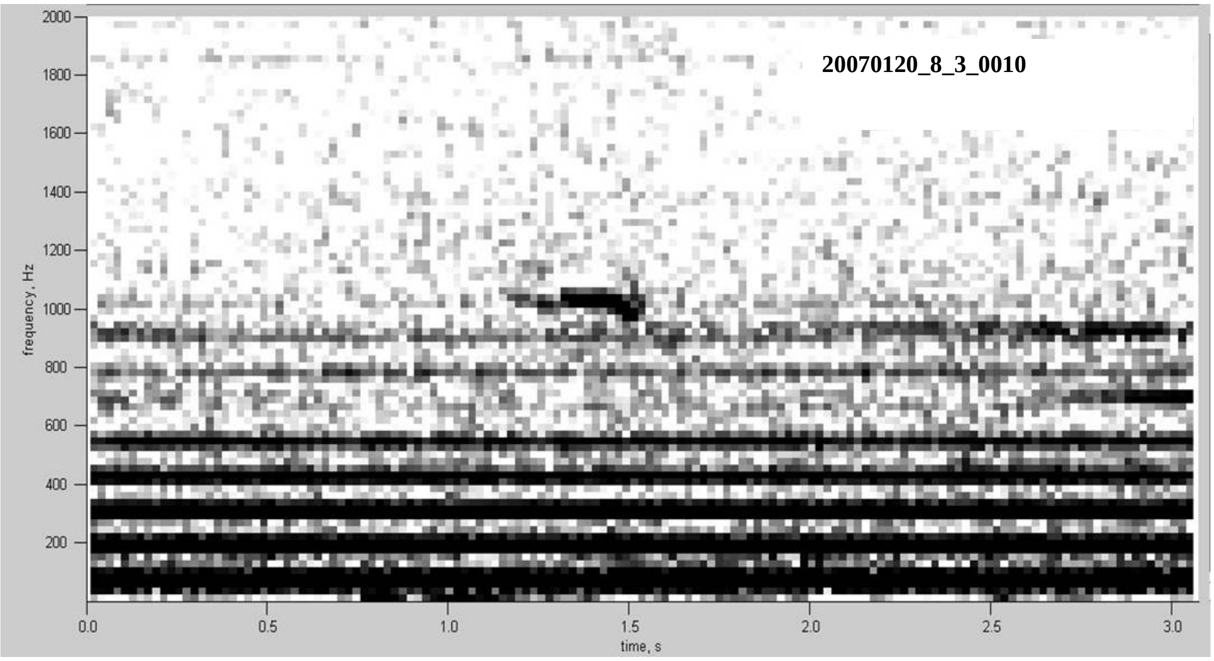


Figure 5-8. Example of Type 1B sei whale call spectrographic display showing frequency (Hz) along the y-axis and time (sec) along the x-axis with amplitude reflected as color intensity.

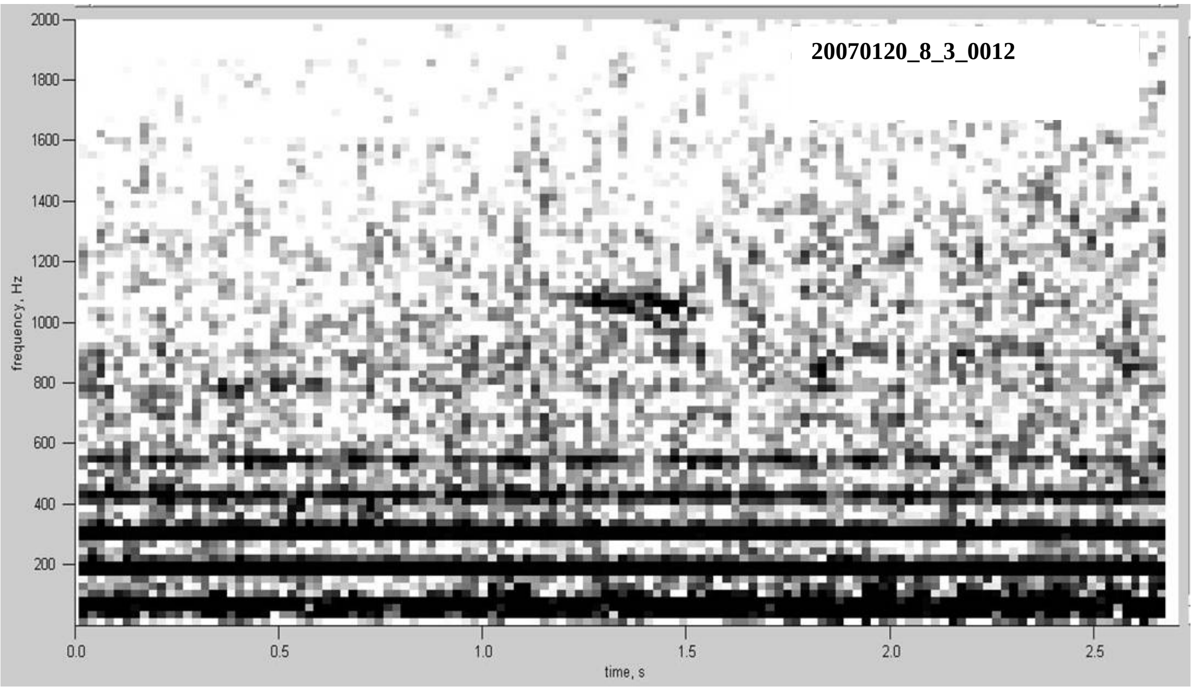


Figure 5-9. Example of Type 1B sei whale call spectrographic display showing frequency (Hz) along the y-axis and time (sec) along the x-axis with amplitude reflected as color intensity.

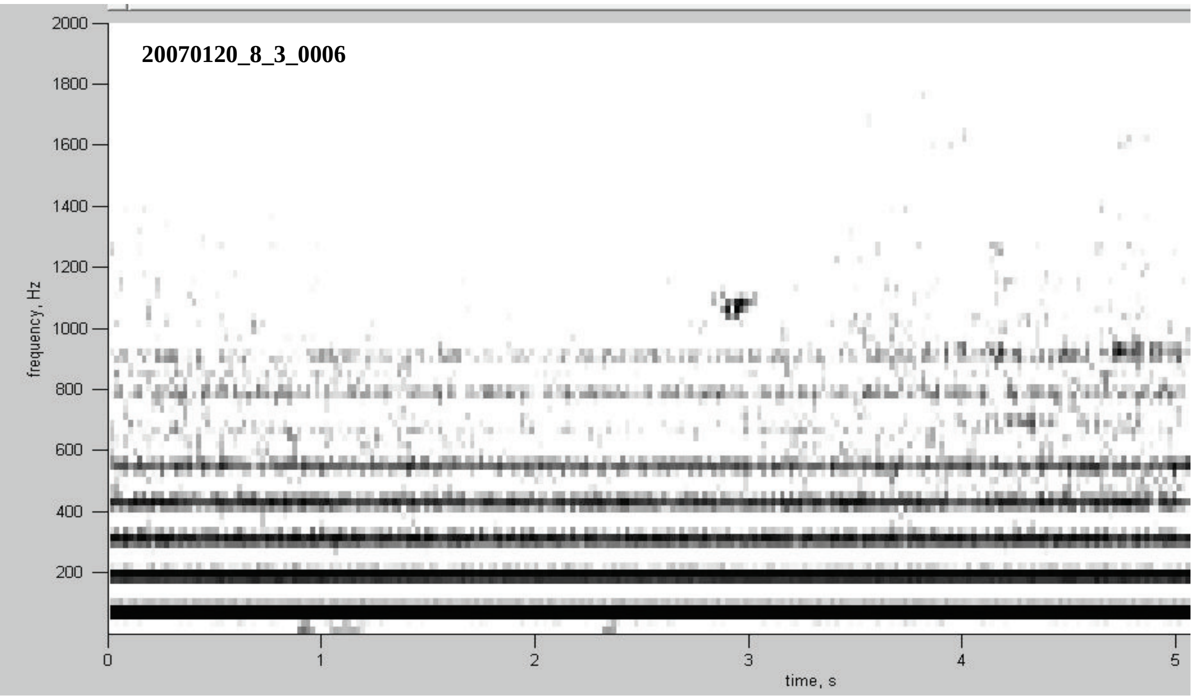


Figure 5-10. Example of Type 2 sei whale call spectrographic display showing frequency (Hz) along the y-axis and time (sec) along the x-axis with amplitude reflected as color intensity.

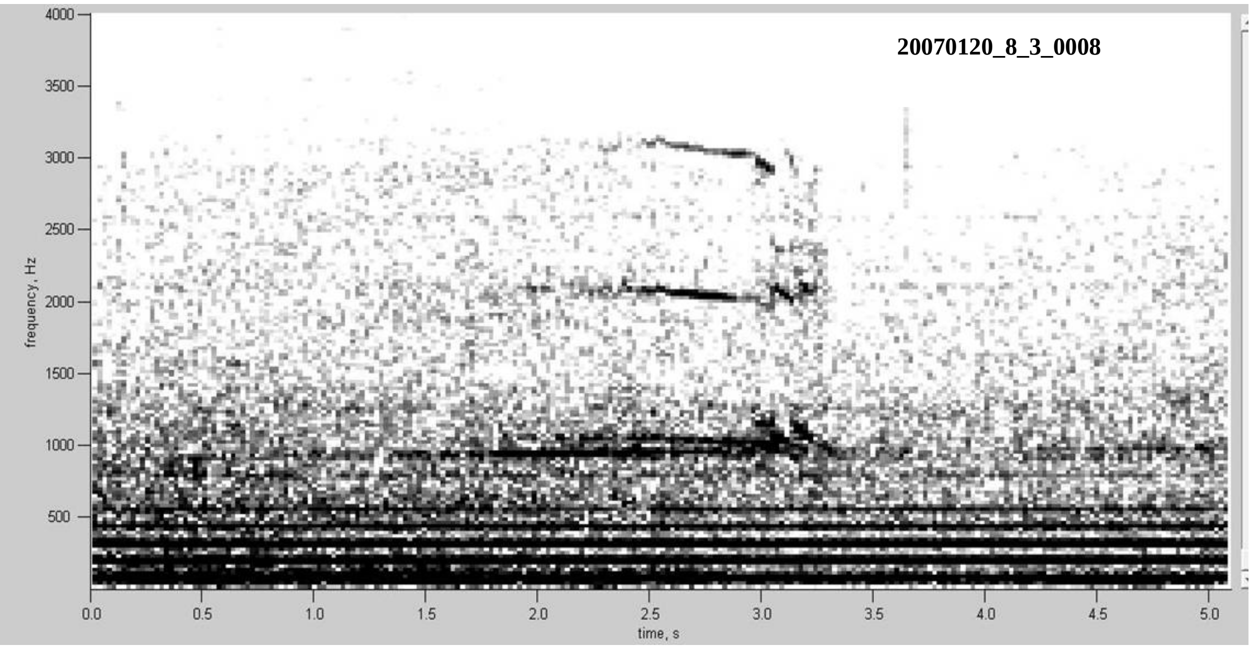


Figure 5-11. Example of Type 3 sei whale call spectrographic display showing frequency (Hz) along the y-axis and time (sec) along the x-axis with amplitude reflected as color intensity.

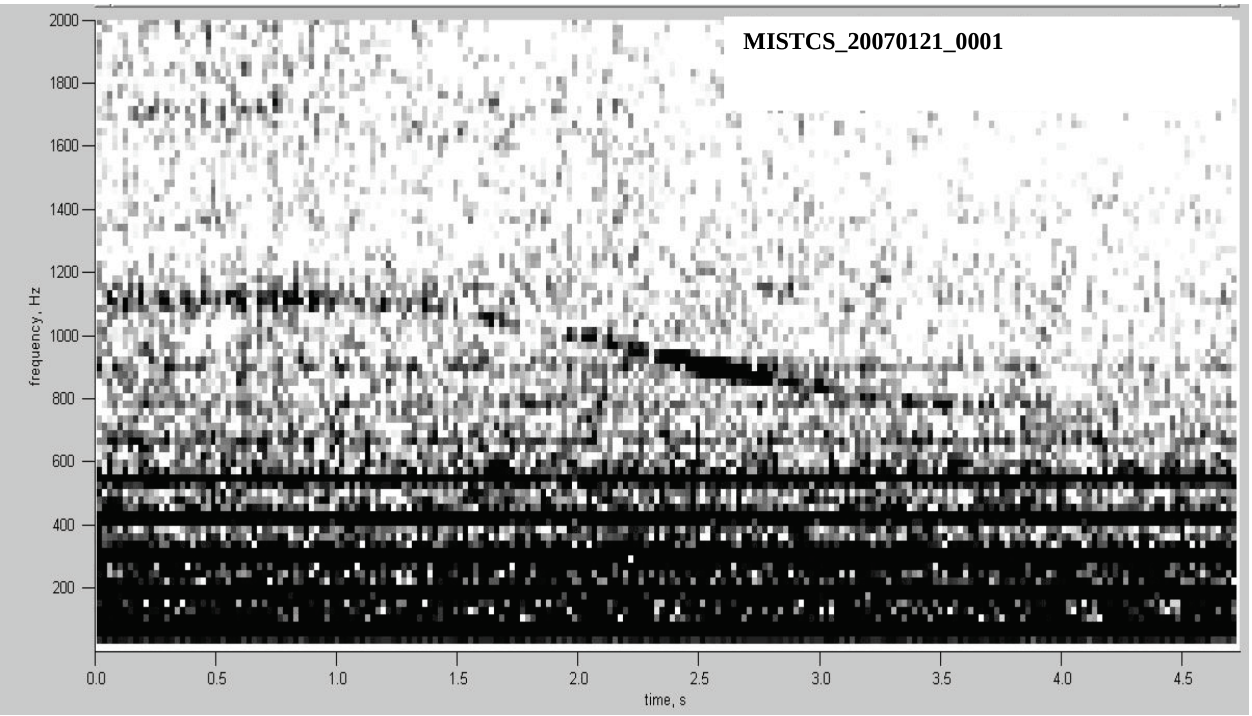


Figure 5-12. Example of Type 4 sei whale call spectrographic display showing frequency (Hz) along the y-axis and time (sec) along the x-axis with amplitude reflected as color intensity.

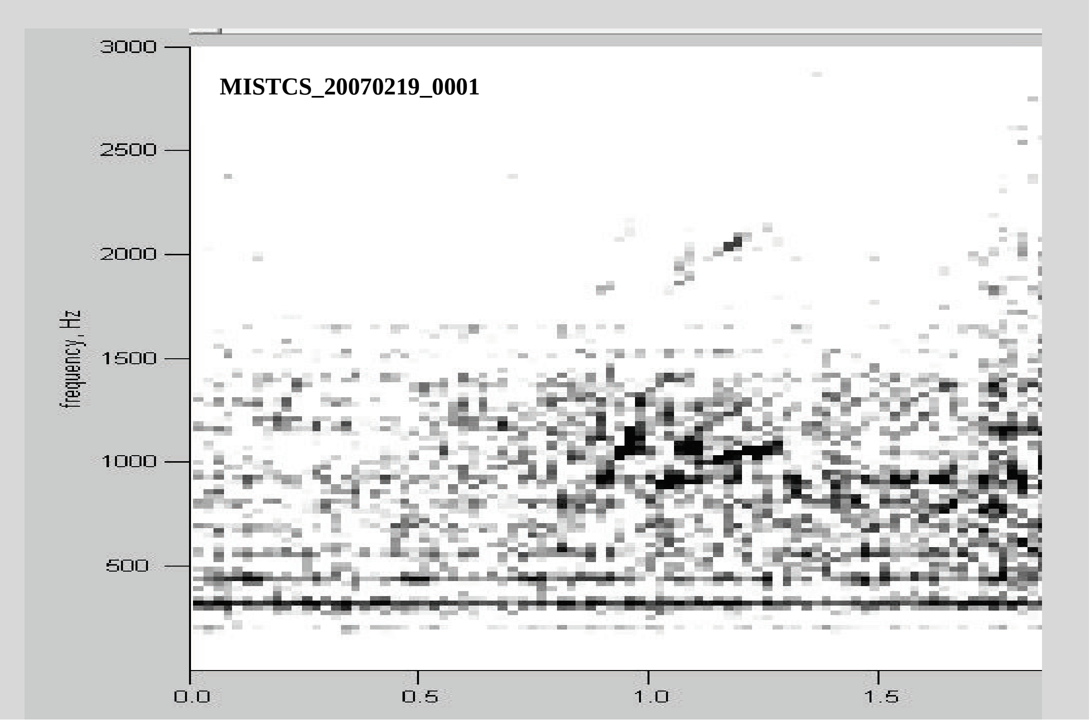


Figure 5-13. Example of Type 5A sei whale call spectrographic display showing frequency (Hz) along the y-axis and time (sec) along the x-axis with amplitude reflected as color intensity.

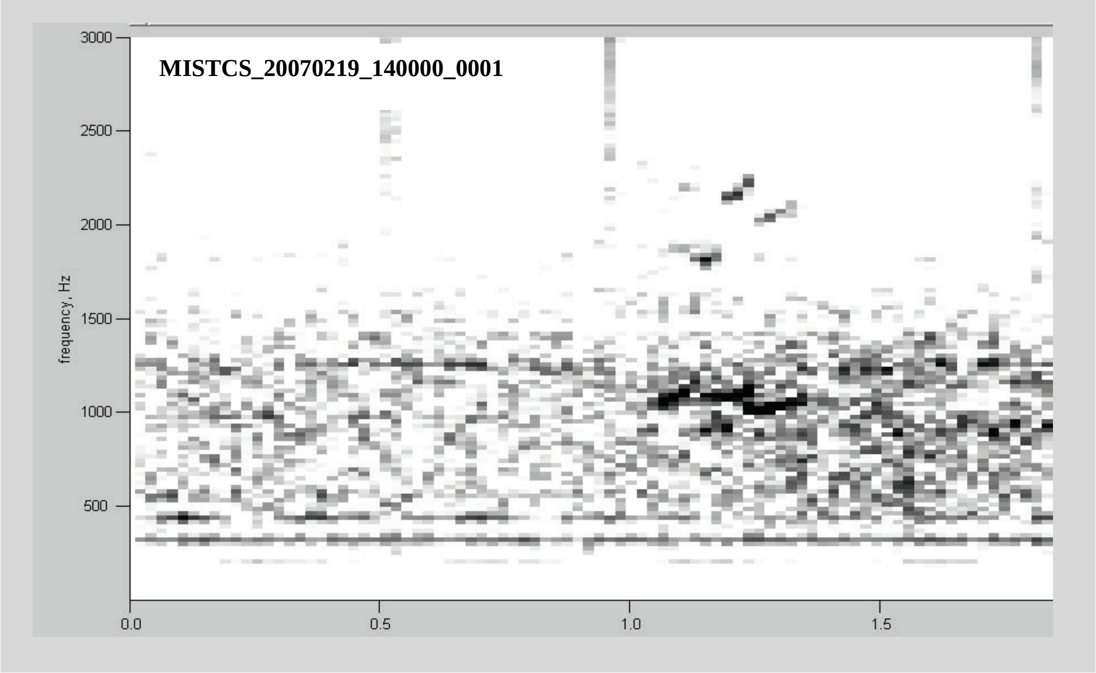


Figure 5-14. Example of Type 5A sei whale call spectrographic display showing frequency (Hz) along the y-axis and time (sec) along the x-axis with amplitude reflected as color intensity.

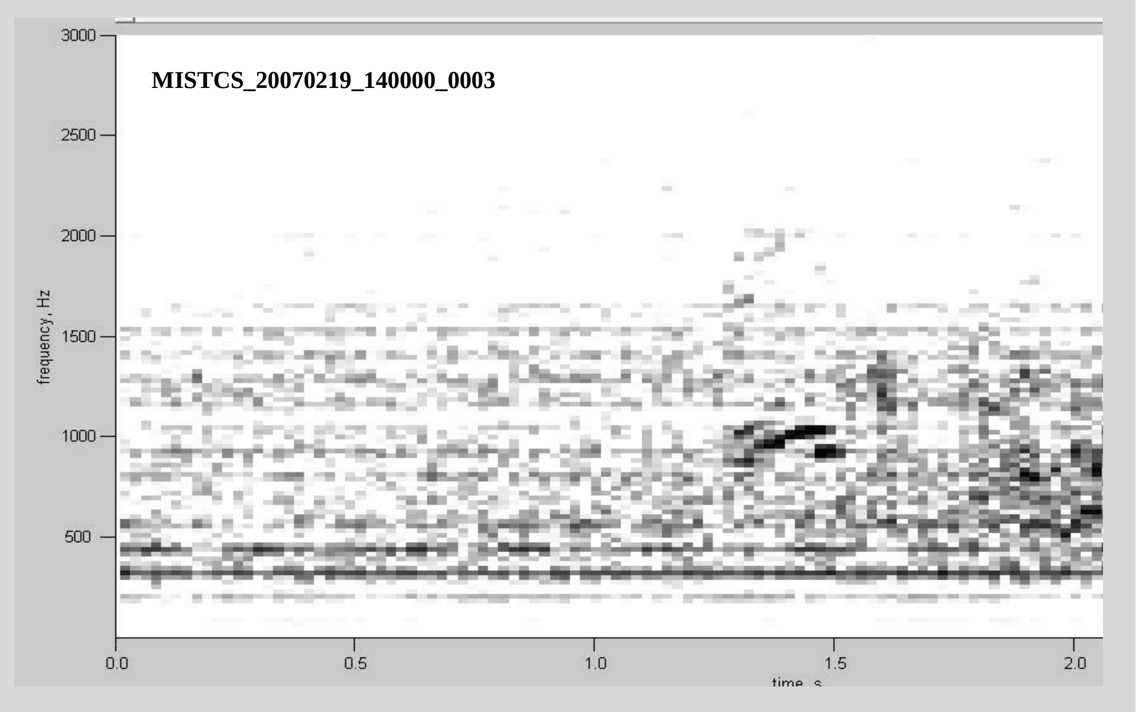


Figure 5-15. Example of Type 5A sei whale call spectrographic display showing frequency (Hz) along the y-axis and time (sec) along the x-axis with amplitude reflected as color intensity.

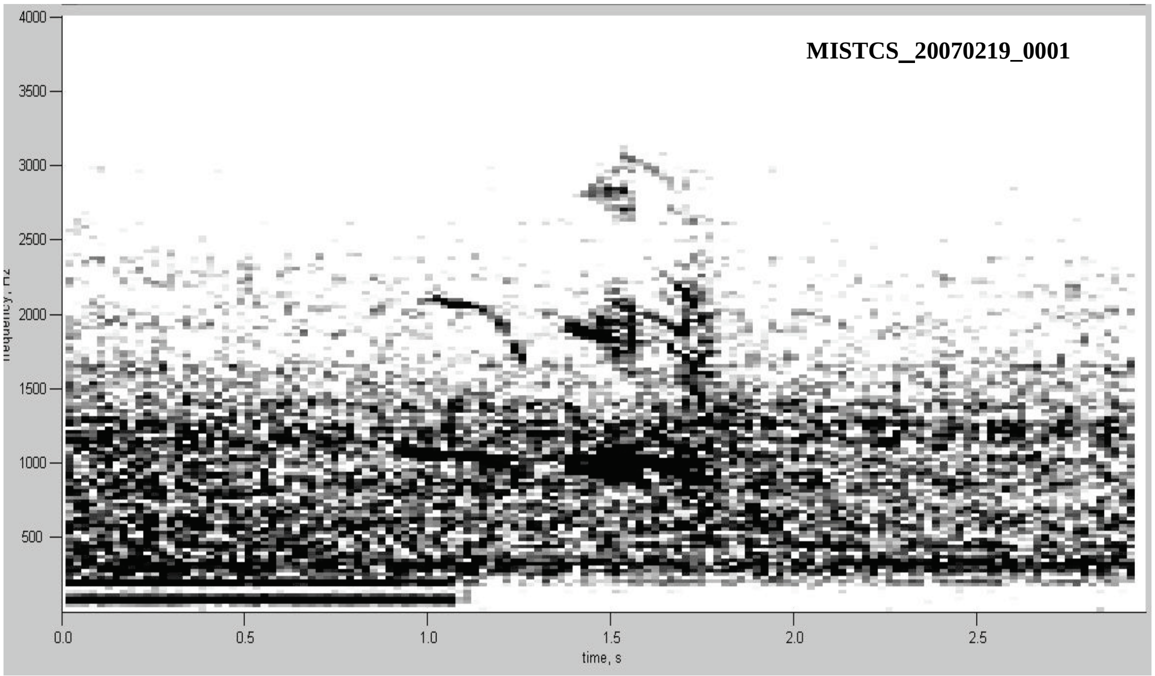


Figure 5-16. Example of Type 5B sei whale call spectrographic display showing frequency (Hz) along the y-axis and time (sec) along the x-axis with amplitude reflected as color intensity.

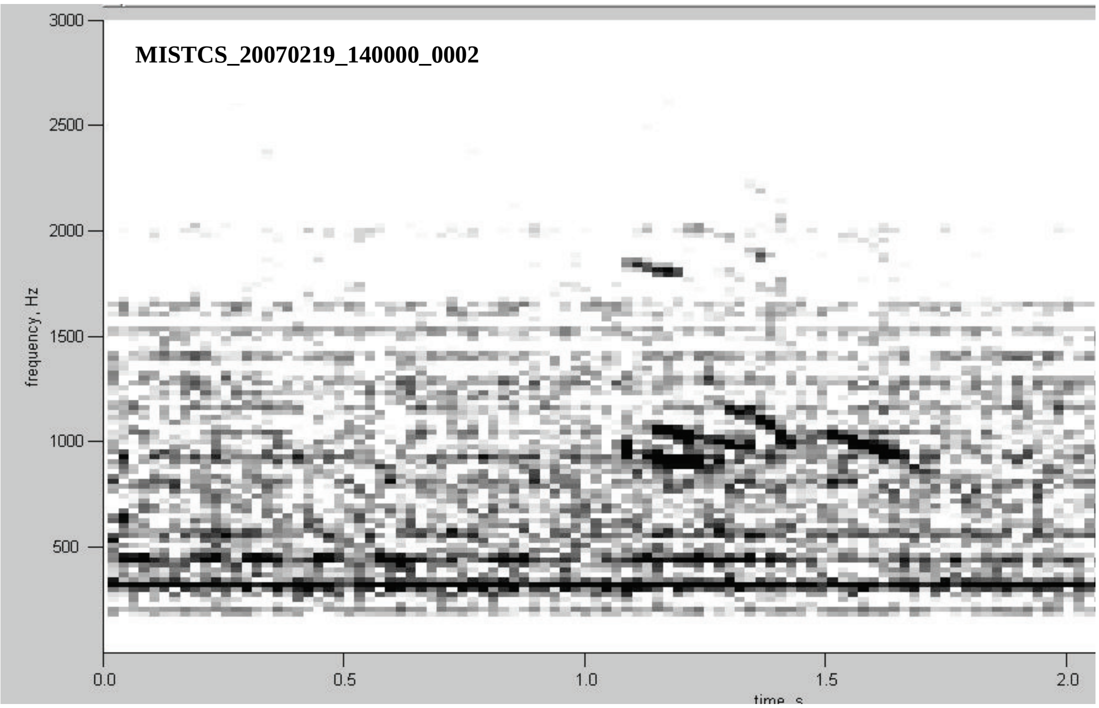


Figure 5-17. Example of Type 5B sei whale call spectrographic display showing frequency (Hz) along the y-axis and time (sec) along the x-axis with amplitude reflected as color intensity.

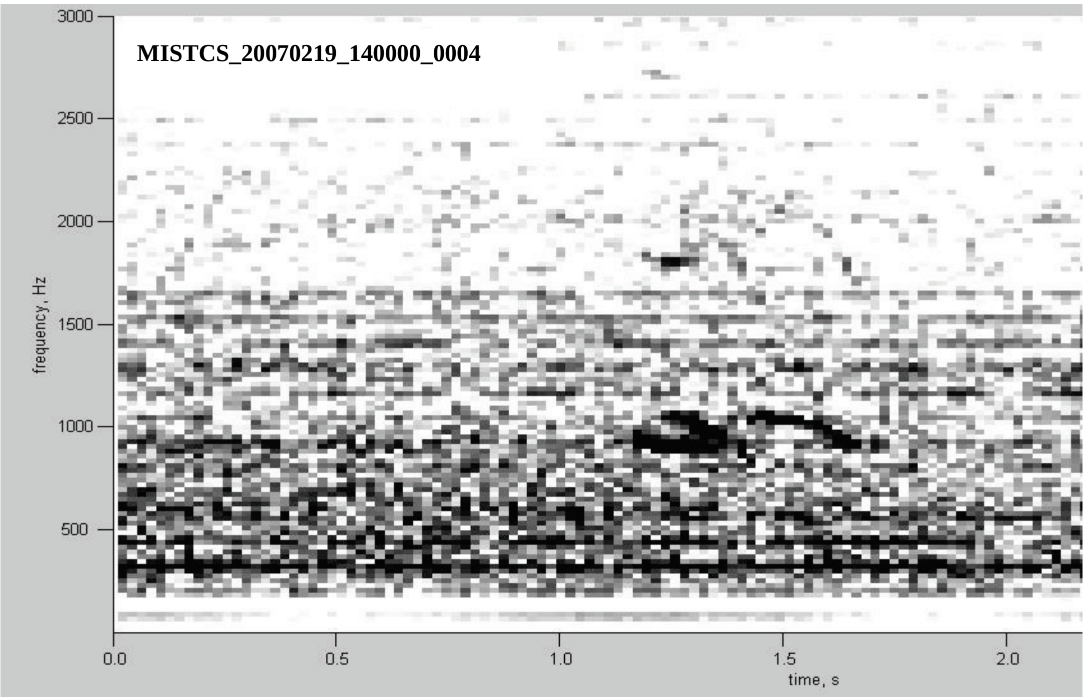


Figure 5-18. Example of Type 5B sei whale call spectrographic display showing frequency (Hz) along the y-axis and time (sec) along the x-axis with amplitude reflected as color intensity.

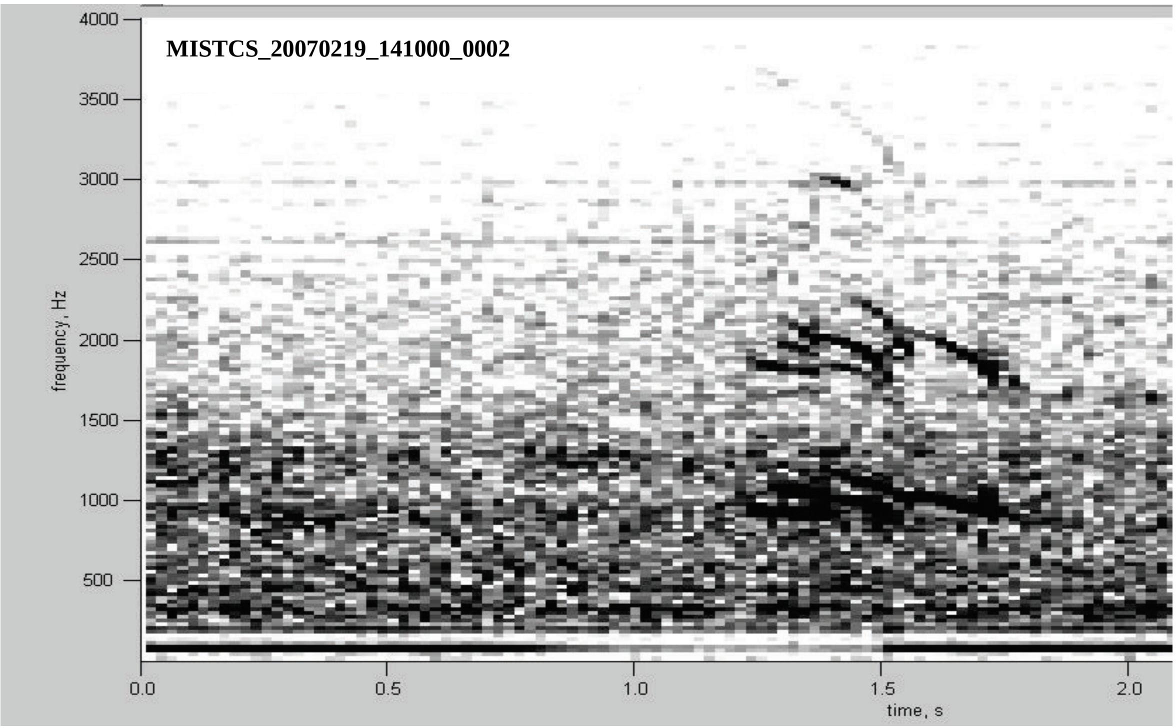


Figure 5-19. Example of Type 5B sei whale call spectrographic display showing frequency (Hz) along the y-axis and time (sec) along the x-axis with amplitude reflected as color intensity.

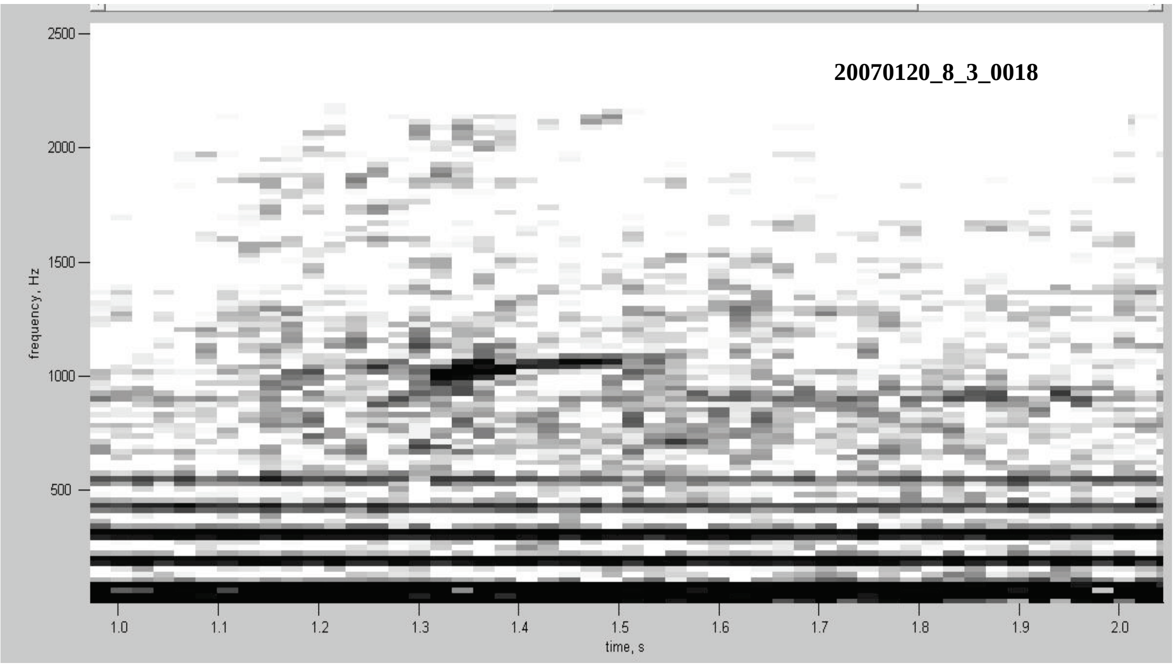


Figure 5-20. Example of Type 6 sei whale call spectrographic display showing frequency (Hz) along the y-axis and time (sec) along the x-axis with amplitude reflected as color intensity

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