Estimating sound pressure levels that acoustically detected beaked whales were exposed to during a US Naval training event in Hawaiian waters Feb 2011

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Abstract

Sound pressure levels (SPLs) are estimated for beaked whale groups exposed to mid-frequency active (MFA) sonar activity during a US Navy training event which occurred Feb 2011 at the Pacific Missile Range Facility, Kauai, Hawaii. Beaked whales (family *Ziphiidae*) and AN/SQS-53C MFA sonar activity were automatically detected post-exercise in recorded acoustic data. Manual validation of the detections was performed to ensure they fit known characteristics of beaked whale: foraging echolocation clicks, inter-click-intervals (ICIs), and dive vocal periods and that they coincide with MFA sonar activity. The whales are localized within a maximum 6 km detection radius from a hydrophone. Estimates of the SPLs the beaked whale groups received from MFA sonar activity are provided utilizing the US Navy's standard personal computer interactive multi-sensor analysis tool (PCIMAT).

Ten beaked whale dives were found to occur during MFA sonar activity at distances from potentially as close as 12.4 km to over 57 km with estimated exposure levels vary from 81 to 139 dB re 1 µPa (mean 115 dB, s.d. 9.5 dB) while the animals were at depth foraging. SPL estimates are also provided for these dives to represent the SPLs the animals would be exposed to when near the surface due to ducted propagation typically present in the area. The estimated SPLs for animals near the surface in the ducted propagation region are an average of 34.4 dB higher than those at depth and vary from 139 to 161 dB re 1 µPa (mean 150 dB, s.d. 5.7 dB). The species of beaked whales detected in the recordings are suspected to be Blainville's beaked whales.

I. INTRODUCTION

Beaked whales (family *Ziphiidae*) consist of at least 21 different species in six genera with relatively little known about many of the species. Both Blainville's (*Mesoplodon densirostris*) and Cuvier's (*Ziphius cavirostris*) species were among the species which stranded in association with a US Naval training event in the Bahamas in 2000 (D'Amico et. al. 2009). This resulted in an emphasis on research into beaked whales, especially on the two species involved in the 2000 stranding. Results of research have identified echolocation click characteristics for these two species from different areas of the world based upon data from instrumentation tags attached to the whales (Zimmer et al. 2005, and Johnson et al. 2006). Both of these species were found to utilize foraging echolocation clicks with frequency modulation characteristics and relatively consistent inter-click-intervals (ICIs). Acoustic characteristics have also been reported for the following species: Gervais' (*Mesoplodon europaeus*); Baird's (*Berardius bairdii*); and Longman's (*Indopacetus pacificus*) as reported in the literature (Gillespie et al. 2009, Dawson et al. 1998 and Rankin et al. 2011, respectively). A common characteristic of many of the reported beaked whale species foraging clicks are short duration signals (< 0.4ms) with frequency modulated sweeps from as low as 15 kHz to over 50 kHz. Longman's species in Hawaii have also been reported to use lower frequency clicks with no appreciable FM characteristics (Rankin et al. 2011).

Beaked whale-like acoustic signals have been detected in the Pacific at Palmyra atoll with suggestion towards a new species based both upon skulls that are not similar to existing species and differences of the acoustic characteristics of the signals (Baumann-Pickering et al. 2010). Acoustic signals recorded at Cross Seamount near Hawaii (McDonald et al. 2009) have also shown frequency modulation characteristics but with longer durations (~ 1ms), wider bandwidth (20 to 90+ kHz) and shorter ICIs than normally reported for beaked whales.

Beaked whale foraging dive behavior has been identified for Blainville's and Cuvier's species using various tag data and reported in the literature (Tyack et al. 2006, Johnson et al. 2006, Baird et al. 2006, and Baird et al. 2008). These two species are known to only produce foraging clicks while at depths greater than ~ 200 m during foraging dives for approximately 30 min per dive. The interval between foraging dives vocal periods is on the order of 2 h or more (Tyack et al. 2006, Tyack et al. 2011). The foraging dive vocalizations include two types of echolocation clicks: foraging clicks for finding prey and rapid buzz clicks for short range prey capture. Foraging echolocation clicks can be generally characterized as short waveforms (0.175 to 0.4 ms upswept pulses) with relatively flat spectrums between 30kHz and 50kHz, source levels over 200dB re 1 uPa and mean ICIs on the order of 0.3 to 0.5 s (Johnson et al. 2004, Moretti et al. 2010). Shallower dives are observed between the foraging dives with no click activity present. Much of the dive and click characteristics are for data from other regions of the world, however Baird (Baird et al. 2006 and Baird et al. 2008) reports on dive characteristics for both Blainville's and Cuvier's species off the island of Hawaii.

Given the available information that exists for the acoustic click characteristics of beaked whales, a variety of different beaked whale click detection methods currently exist which enable automated processing of passive acoustic data to detect these clicks (Yack et al. 2010). The use of automated detectors for beaked whale clicks allows processing large volumes of data available from many sources (e.g. survey vessel towed hydrophones, long term acoustic recording packages and US Navy training ranges' hydrophones cabled to shore). Extension of passive acoustic monitoring methods for beaked whales includes density estimation based upon click (cue) counting techniques (Marques et al. 2009) and acoustically determined beaked whale foraging dive counting based density estimation methods (Moretti et al. 2010).

The beaked whale acoustically determined dive count method of density estimation also shows reduced dive activity and abundance at the Atlantic Undersea Test Center (AUTEC) located in the Bahamas' (Moretti et al. 2010, McCarthy et al. 2011 and Tyack et al. 2011) during MFA sonar activity, during similar training events, compared to before and after the training events. These efforts show that Blainville's beaked whales appear to depart an area where mid-frequency sonar activity is occurring and gradually return after a two to three day period after sonar activities cease. The studies at AUTEC reported four samples of AN/SQS-53C MFA sonar activity ensonifying Blainville's beaked whales at distances from 14.7 to 19km with estimated sound pressure levels of 127 to 133 dB re 1 µPa. These reports also included 13 other sources of higher frequency sonar exposures (AN/SQS-56 equipped US Navy ships and foreign ship sonar's). When pooling all sources of sonar, the exposures on Blainville's beaked whales ranged from 101 to 157 dB re 1 µPa (mean 128 dB, s.d. 15 dB). The major differences between this study and the AUTEC study are that the recorded hydrophone spacing is farther apart, which does not allow detecting all beaked whale foraging dives occurring on the range, and that different techniques are employed to detect beaked whale foraging vocal periods.

This report describes the methods utilized to acoustically detect beaked whale group vocal activity coincident with MFA sonar activity and estimate the sound pressure levels the whales were exposed to. The SPLs the animals would be exposed to when they are near the surface are also estimated.

II. METHODS

A. Data Collection

PMRF hosts a variety of US Naval training events every year and has hundreds of hydrophones mounted off the seafloor and cabled to shore for supporting performance analysis for US Naval systems. PMRF has supported US Navy funded research on acoustics of marine mammals over the years when training events are not occurring. With appropriate approved requests, it is possible to obtain data during training events to support marine mammal monitoring efforts. Ship locations and recorded acoustic hydrophone data are provided post-exercise.

Recorded hydrophone data from thirty hydrophones and a precise analog time code signal were provided for the training event conducted Feb 14-19, 2011. This was the first training event that acoustic data was provided post-exercise for the time of the event for analysis for marine mammals. The hydrophone recordings are simultaneously sampled at a rate of 96 kHz using 16 bit analog to digital converters. The data are stored as sequential data files, each containing approximately 10 minutes of data. A 2 terabyte drive allows continuous recording of 30 hydrophones for approximately three and a half days. The recorded time code signal allows precise alignment of acoustic data with ship positions in post-exercise analysis.

Figure 1 shows the approximate locations of the hydrophones recorded during this training event (hydrophone L06 data was not available due to technical issues). Spacing between the recorded hydrophones varies from ~4 km in two areas (i.e. hydrophones 406, 407, 504, 505; and 101, 102, F13, F14, F16) to ~ 8+ km for the others. Water depths vary from ~ 650 m (near phone 110) to over 4700 m (at phones I10, K11 and L10). The depth decreases gradually as the latitude decreases from 22.8 N to ~ 22.3 N. The depth decreases more steeply below 22.3 N as the distance to the island decreases. Recorded hydrophones have three different frequency responses: all phones with labels beginning with I, J, K and L respond from ~ 20 Hz to 48 kHz; hydrophones labeled 101, 110, 301, 304, 501 and 505 respond from ~ 100 Hz to 48 kHz; and 102, F13, F14, F16, 406, 407 and 504 respond from approximately 10 kHz to 48 kH. Thus, all hydrophones provide suitable frequency response for beaked whale analysis. Hydrophone calibration information was not available.

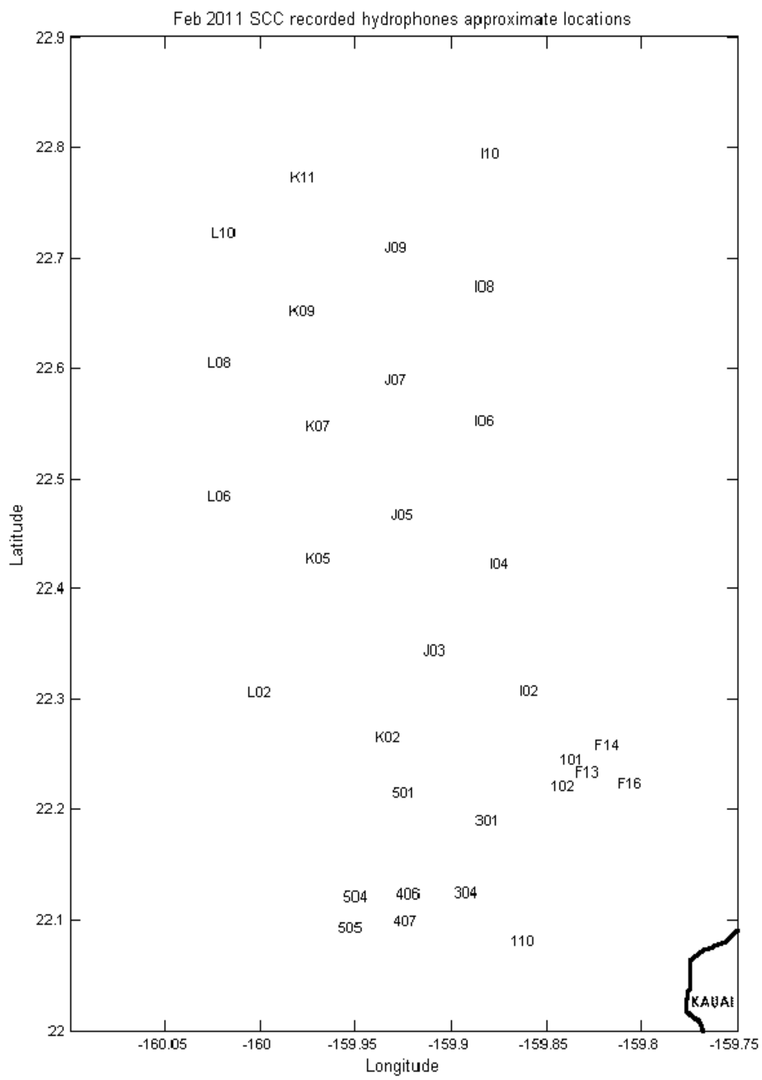

Figure 1: Approximate locations of the 30 recorded hydrophones. The western tip of the island of Kauai is shown lower right. Note: figure is not to scale; horizontal axis is exaggerated for clarity.

B. Acoustic detection, classification and verification

Mid-Frequency Active Sonar

An automated detector was utilized to detect presence of the nominal 3.3 kHz MFA sonar activity and binned into ten minute intervals. Various other sound sources were present during the exercise (e.g. higher frequency AN/SQS-56 sonar), but the focus of this analysis was on the MFA sonar activity from the AN/SQS-53C. A MATLAB® based tonal detector described in Mellinger et al. 2011 was tuned to detect the nominal 3.3 kHz MFA sonar signals. The detection threshold was set such that the majority of the nominal 3.3 kHz sonar activity were detected with very few false positives. The outputs of the MFA sonar signal detector are utilized to focus the analysis for beaked whale presence during MFA sonar activity. Manual inspection was performed to verify MFA sonar activity for all detailed analysis periods where beaked whale SPL exposures were estimated.

Beaked Whale Clicks

A MATLAB ® based frequency modulated click detector (FMCD) was utilized for detecting beaked whale clicks in hydrophone data. This detector has detected beaked whale clicks from Cuvier’s (from sources such as www.mobeysound.org), pygmy (Yack et al. 2010), undetermined species recorded at Cross seamount (McDonald et al. 2009) and Blainville’s (from the 2007 Boston Detection, Classification and Localization workshop data set). The FMCD utilizes three stages. The first stage, termed the ‘screener’, high pass filters the data at 20 kHz, dynamically estimates the standard deviation (s.d.) of the time series amplitudes in one second intervals, and declares a screener detection using a 0.5 ms decision interval for all intervals which exceed +/- seven standard deviations. This provides detection of all high pass filtered acoustic energy above 20 kHz and over the detection threshold. The second stage of the FMCD processes the screener detections for frequency modulation with upsweeps at a rate of approximately 100 kHz per ms and these detections are termed ‘FM detections’. The final stage processes the FM detections for inter-detection-intervals (IDIs). IDI is utilized (vice ICI) as the source of the automatic detections is unknown. If detections are validated to be from an individual animal they are ICIs. However, detections can also be from multiple beaked whales, other odontocetes, or other (non-biologic) sources of acoustic energy. The FM detectionshave appreciable false positives from other echolocating species of marine mammals such as short-finned pilot whales (*Globicephala macrorhynchus*), Risso’s dolphins (*Grampus griseus*) and melon-headed whales (*Peponocephala electra*) thus requiring manual validation of the outputs in order to have high confidence that detected clicks are from beaked whales.

Due to the FM detection processes high false positive rate and the large quantities of potential detections, not all FMCD outputs are manually-validated. The 0.5 ms decision interval utilizes allows 1.2 million opportunities for FM detections from each 10 minutes of data for each hydrophone, couple this with 30 hydrophones over one day and the opportunities for false positives soars to over 5 billion. To deal with the large number of potential FM detections, an approach using all three stages of the FMCD outputs is utilized to identify promising sections for typical beaked whale foraging dive vocal behavior.

If beaked whales perform a foraging dive within detection range of a hydrophone, and no other echolocating species are nearby, the screener and FM detection counts over time will have a temporal pattern. The pattern reflects the time period the whales are producing foraging clicks: nominally 30 min of foraging clicks during a dive with no detections before and after the dive vocal period. The screener and FM detection IDIs will also show peaks at the particular species mean ICIs (i.e. ~0.3 s for Blainville's and ~ 0.45 s for Cuvier's). When large groups of other echolocating marine mammals are present (e.g. dolphins, melon-headed whales, short-finned pilot whales, Risso's) the screener detections typically have much higher screener detection counts for longer periods of time compared to those for beaked whales. The IDI histograms will also typically have large peaks at intervals much shorter than ~0.3 s. While beaked whales do perform foraging dives when other species are in the area, the amount of manual-validation effort required to find the beaked whale clicks, if present, is considered excessive. This method will therefore miss detecting beaked whales when there are a lot of other echolocating species present. Promising times of beaked whale clicks are then manually-validated to ensure the detections are beaked whale clicks which fit the known acoustic characteristics for beaked whales.

To streamline manual validation of beaked whale clicks when using the FMCD a custom MATLAB® program was developed. The program, termed beaked whale click validation (BWCV) utilizes the FMCD output structure which contains the times of: screener detections; FM detections; ICI filtered detections; along with features utilized in the FM detection process. The BWCV program starts with the operator selecting a hydrophone and ten-minute time period (file) for validation. The BWCV program then displays a histogram of the IDIs for both the screener detections and FM click detections, if any exist. Even though a group of beaked whales may have several individuals present, the directional characteristics of the acoustic beam coupled with their tendency to scan nearly in all directions will typically result in a local, if not global, peak in the IDI's corresponding to the particular beaked whale species present. If the IDI histogram is not promising in terms of showing peaks at known ICIs and the quantity of both screener and FM detections is large, the file under consideration is typically rejected from further investigation.

If the IDI histogram is promising, or an operator wants to view the characteristics of the detected clicks, the BWCV program then presents five plots of each FM detection sequentially. Two high pass filtered time series plots (1.25 ms and 1 s duration) with the detected click centered on the horizontal time series axis allow investigation of both the detailed waveform and other click activity within +/- 0.5 s. The amplitude of the time series plots are in analog to digital converter counts, or +/-16,384 counts full scale. Two other plots show spectrogram type information, one for the high pass filtered click using 32 point FFTs with 97% overlap (one sample slip), with time increasing from top to bottom, while the other plot is a time-frequency representation of the full bandwidth (i.e.

not high pass filtered) data over a 2 ms window with time increasing from bottom to top. The last plot provides the spectrum of the detected click. The operator may also play a version of the click time series, time stretched to the human aural range by replaying data at a lower sample rate, for aural analysis. If the operator believes the click is from a beaked whale based upon the validation presentations, they check a “valid beaked whale” box and the results are saved in the MATLAB® detection structure in manually-validated fields. Additional boxes are provided for individual species of beaked whales (e.g. Blainville’s, Cuvier’s, Longman’s) for future use when an operator is more confident in identifying the signals to a species.

Beaked whale dives

Group sizes for Blainville’s and Cuvier’s beaked whales in Hawaiian waters are reported as 3.6 and 2.6 whales per group respectively (Baird et al. 2006). Group sizes > 1 provide more opportunities to detect beaked whale clicks. The number of clicks detected is related to the distance of the individual whales, the number of animals in the group, and their orientation with respect to the hydrophones. The distance of the animals from a hydrophone determines how much propagation loss is experienced (spreading losses and absorption of sound in the seawater). Ultrasonic signals, such as beaked whale foraging clicks, are not detected at distances much over 6km due to the transmission losses. Orientation of the animal relative to the hydrophone affects the apparent source levels of the clicks due to their directional nature and spectral content.

The relatively large separation between hydrophones utilized in the analysis may result in detecting only a portion of beaked whale group’s vocal periods so vocal period durations were not analyzed. A dive vocal period is typically ~ 30 min in duration, but can extend in time for up to approximately 50 min, so up to 6 ten-minute sequential files from the same hydrophone can be linked and considered a single dive of a group of beaked whales near that hydrophone. For cases where adjacent hydrophones detect beaked whale foraging dives at the same time they are considered the same dive (biases the number of dives low). The hydrophone with the most manually-validated beaked whale FM detections for a dive is considered the closest to the group of foraging beaked whales, and considered the ‘hot’ phone of the dive.

A review of raw hydrophone data with beaked whale foraging dives is also conducted for both the period of the dive and ten or twenty minutes before and after the dive for: additional confirmation of beaked whale foraging clicks, no clicks before or after the dive, and presence of MFA sonar activity during the dive. A custom C language program is utilized which allows review of multiplexed raw data with: pause, fast forward and rewind capabilities: and a broadband energy waterfall for the 30 hydrophones with respect to Zulu time. Additional displays are provided for a single operator selected hydrophone: an aural display, a compressed time series display and a spectrogram display for. More detailed analysis is performed on de-multiplexed single channels of data utilizing Adobe Audition ® to yet again re-affirm the foraging clicks are from beaked whales, that MFA sonar activity is truly present, and to also look for presence of buzz clicks.

C. Localization

Beaked whale group foraging dives are localized in post-event processing, to be somewhere within the maximum detection distance (6 km is utilized) from the ‘hot’ detection hydrophone. The 6 km maximum detection distance was selected based upon two published reports. A maximum detection distance of 4km is reported for hydrophones located close to the sea surface, such as towed hydrophones (Zimmer et al. 2008). A maximum detection distance of 6.5 km is reported for deep hydrophones at AUTEC (Ward et al. 2008). Due to the large spacing of recorded hydrophones, one is also spatially sampling for beaked whale presence, and thus cannot guarantee detection of all beaked whale deep foraging dives in the area. None the less, this process is felt to provide a high confidence in detecting a beaked whale foraging dive present near the ‘hot’ hydrophone. Plotting the beaked whale foraging dives by hydrophone with MFA sonar activity detections overlaid, allows determination of which dives are being performed during (nominal 3.3 kHz) MFA sonar activity. For each beaked whale dive found coincident with MFA sonar activity, the sound pressure level the group of whales was exposed to is estimated.

D. Estimating Sound Pressure Levels

In order to estimate the SPLs received by the beaked whales, the following items are required: ship position at the time of the beaked whale foraging dives, location of the ‘hot’ hydrophone with the most beaked whale clicks (post-event manually-validated FM detections), environmental information (e.g. wind speed, bottom type, sound velocity profile) and an acoustic propagation model. Hydrophone latitude and longitude positions are provided with PRMF data products. Ship positions are provided in PRMF standard data products as GPS ship locations updated every second during the training event. The ship position for the SPL estimates is chosen by finding the closest point of approach (CPA) of the ship while transmitting MFA sonar signals to the 'hot' hydrophone within the detected foraging dive time period. The ship and hydrophone locations are used with a propagation model to estimate the SPLs the whales received from the ships’ MFA sonar activity at this time.

Beaked whales foraging clicks are detected during post-event processing during times of group vocal periods which are produced when the animals are at depths > ~ 200m. However, one needs to keep in mind that the animals were at the surface before the dive and will return to the surface after the dive due to biological necessity. Historic sound velocity profiles show surface-ducted propagation typically present in this area. The ducted propagation region has lower transmission loss than normal propagation which will expose the group of whales to higher SPLs when they are near the sea surface and not clicking (and therefore not acoustically detectable). Therefore, two animal depths are utilized in the SPL estimation process; one at a nominal foraging depth of 1 km, and one near the sea surface at a nominal depth of 10 m to represent exposures they would have received if near the surface at the time. If the bathymetry for the area under consideration is less than 1 km, the depth in the area is utilized in the estimation process.

The Personal Computer Interactive Multi-sensor Analysis Tool (PCIMAT) is a standard US Navy tool which utilizes propagation modeling to estimate SPLs. The acoustic propagation model utilized within PCIMAT was the Comprehensive Acoustic System Simulation (CASS) model. The model includes historic sound velocity profiles (by month and day) for the area, detailed bathymetry of the area, and selectable bottom type, wind speed and sea state. Acoustic source inputs to PCIMAT include frequency (3.3 kHz), depth (11m) and source level (235 dB re 1 μPa rms utilized). The receiver (beaked whale) depths utilized were both 10 m (at/near surface) and 1 km (while foraging). The maximum and minimum SPLs received by the beaked whales were estimated by subtracting the transmission loss from the source (ship) at the CPA distance to the 'hot' hydrophone +/- the maximum detection range of 6 km. Thus, for each beaked whale dive vocal period detected simultaneously with MFA sonar activity there are four estimated SPLs for the animals: the max and min when the animals are at presumed foraging depth, and the max and min as if the animals were near the surface. Model validation is felt to be very important; however there were no acoustic sensor data available near the sea surface during the training event to enable validating sound fields in the surface duct and it-situ sound velocity profiles were not collected.

III. Results

A. Data Collection

Thirty hydrophones of passive acoustic data was collected continuously (with one 8.5 h exception) for approximately 257 h between 0820 Feb 11 and 1032 Feb 22, 2011 HST. Focus here was placed on the portions of this training event with nominal 3.3 kHz MFA sonar activity, which occurred in the ~ 68.8 h between 0645 Feb 16 and 0334 Feb 19, 2011 HST. This data was available from two separate hard disk drives with filenames as shown in table 1.

Table 1: Acoustic data recordings dates, times, filenames and number of hours of thirty hydrophones of data available.

HST start time & date	HST end time & date	File names	~ # hours
0645 Feb 16, 2011	1355 Feb 16, 2011	14Feb11_200233_269 to 312	7.2
1357 Feb 16, 2011	0334 Feb 19, 2011	16Feb11_235737_001 to 370	61.6

The training event consists of multiple sub-events with different objectives. PMRF standard data products provide ship positions for the periods of the sub-events; ship positions are typically not available for the periods of time between sub-events. However, MFA sonar activity typically only occurs during sub-events and the lack of continuous ship position typically not an issue.

B. Acoustic detection, classification and verification

The FMCD process was run on all hydrophone data shown in table 1. The BWCV program was run on promising sections of data showing temporal patterns consistent with beaked whale dive vocal activity. Figure 2 provides a sample of the five plots available during manual-validation for a high signal to noise ratio click selected as a valid beaked whale foraging click. This click is FM detected click number 118 of 139 detected in a ten-minute period from hydrophone 407 at approximately 0203 HST on Feb 17, 2011. Two plots show time series waveforms for 20 kHz high pass filtered data, one on a 1.2 ms time scale and one over a 1 s period.

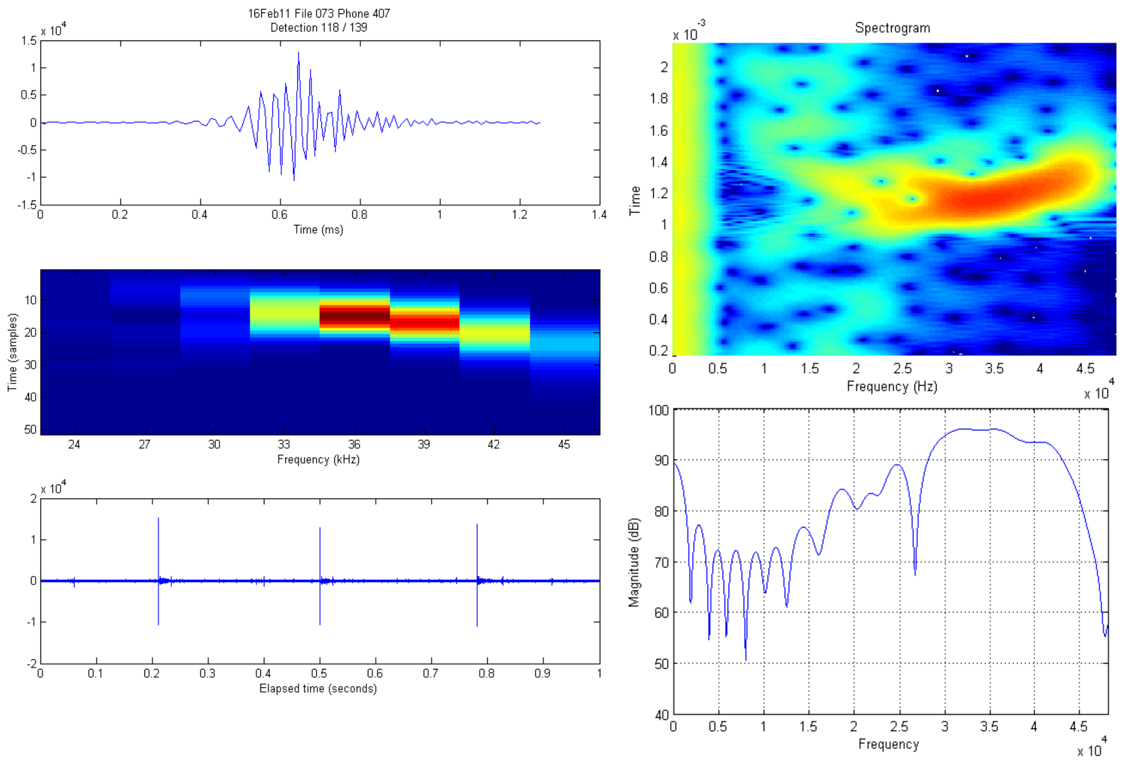

Figure 2: Manually-validated FM detection on hydrophone 407 at 0203 HST on Feb 17, 2011. Upper left: detailed waveform; middle left: click spectrogram 20-48 kHz; lower left: +/- 0.5 s around the click; upper right: time-frequency distribution of the click; and lower right: click spectrum.

The figure 2 plots shows typical features of valid beaked whale foraging clicks: i.e. (left upper) the time series with several cycles of amplitude modulated frequency upsweep character; the longer duration time series (left lower) shows an inter-click-interval for approximately 0.29 s and given the similar amplitudes are likely from the same individual; the spectrogram (left middle) and time-frequency transform (right upper) show definite frequency upsweep (~ 27 to 45 kHz) over the duration of the click (~0.3 ms), and the spectrum (right lower) illustrates the 27 - 45 kHz nature of the signal with a small peak at 25 kHz a few dB down in amplitude of the main click energy.

Sample histograms (figure 3) show the IDIs for FMCD screener detections (left side) and FMCD FM detections (right side) for hydrophone 406 for data from 0157 to 0207 HST on Feb 17, 2011. This is for a hydrophone located a few km from hydrophone 407 which was grouped into a single dive (dive # 4). Both of the histograms show peaks at approximately 0.3 s, typical of values reported for Blainville's beaked whales. The FM detections (right side) remove a large number of the screener detections for not having suitable features for the FM detection stage (probable false rejections).

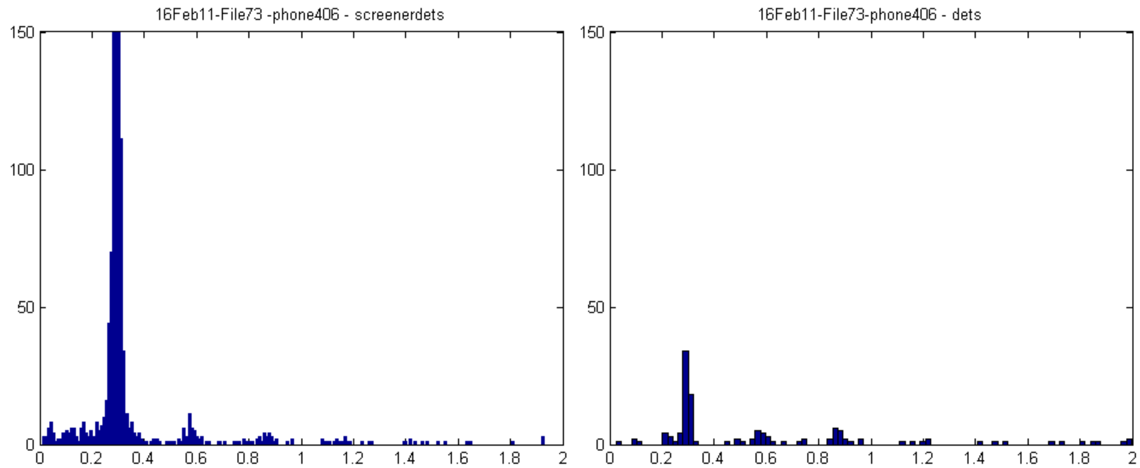

Figure 3: Histograms of inter-detection-intervals (IDIs) for: (left) automatic screener detections; and (right) automatic FM detections for hydrophone 406 for ten-minutes of data between 0157 and 0207 on Feb 17, 2011. Horizontal axis is time in seconds and vertical axis the # of automatic detections.

Dive Activity

Table 2 summarizes beaked whale foraging dives detected during MFA sonar activity showing: dive number, dates, times, detection phones, numbers of automatic FMCD screener detections, automatic FMCD FM detections and the times of peaks in histograms.

It is interesting to note that two beaked whale dives (Dive # 1 and 9) occurred at phones K11 and I10 which are far offshore in water depths of approximately 4.7 km. The other 8 dives occur in areas with depths between 800 m and 2.5 km depth with steep bathymetry. Six of the dives occurred between dawn and dusk hours while four dives occurred at between dusk and dawn (dawn and dusk occurred at approximately 0700 and 1830 HST).

Figure 4 provides a plot of the beaked whale foraging dives' number of manually-validated FM detections by hydrophone over time with MFA sonar activity presence indicated as green triangles overlaid on the plot at a constant vertical axis value of 80. The time period that MFA sonar activity occurred during this training event was between ~ 0645 Feb 16 and 0334 Feb 19, 2011 HST. The vertical axis is the number of manually-validated beaked whale foraging clicks in ten minute intervals. The manually-validated beaked whale foraging clicks are less than, or at most equal to, the number of automatic FM detections shown in table 2, depending upon the operators consideration of the validity of the automatic FM detections. The colored lines link ten-minute periods of sequential manually-validated beaked whale foraging clicks for a given hydrophone. The legend shows the hydrophone names corresponding to the symbols. Manual validations confirm presence of MFA sonar activity for periods of the beaked whale dives shown in table 2

Table 2: Periods defined as 'beaked whale foraging dives' based upon automatic FMCD outputs. Date, time (HST), dive number, phones detected on, phone with greatest FM detections ('hot'), auto screener detections, auto beaked whale FM detections, and the peak in the IDIs.

HST Day	HST time (HHMM)	Dive number	Detection phones	'Hot' Phone	Automatic Screener Detections	Automatic FM detections	IDI peak (sec)
16	0802	1	K11	K11	8554	26	.3 - .35
16	1312	2	504, 505	504	1158	57	.27 - .3
	1322		504,505	504	1236	51	
	1332		504	504	1694	45	
16	2247	3	406	406	614	131	.25 - .3
	2257		406, 407	406	1019	117	
	2307		406, 407	407	1269	92	
17	0157	4	406,407	406	1526	214	.27 - .3
	0207		406, 407, 505	407	8,227	439	
	0217		406,407	407	5458	434	
17	0557	5	406	406	1607	82	.28 - .3
	0607		406	406	3074	88	
17	0727	6	501	501	5614	194	.25 - .3
	0737		501	501	739	27	
17	2337	7	K02	K02	7092	54	.24 - .27
	2347		K02	K02	6700	49	
18	0747	8	501	501	4905	57	.27 - .3
	0757		501	501	6741	100	
18	1027	9	I10	I10	2724	23	.3 - .35
18	1357	10	406	406	2976	177	.28 - .3
	1407		406	406	4947	493	
	1417		406	406	821	88	

The beaked whale dives, as defined, are seen to continue throughout the entire period of time involving MFA sonar activity. For exposure analysis we only utilize dives that are occurring during MFA sonar activity (i.e. the ten dives shown in table 2) which are also annotated on figure 4.

The presence of buzz clicks during dive # 4 occurring during MFA sonar activity is noteworthy. This is indicative of attempts at eating prey, it is uncertain if the attempts were successful given the current knowledge and available data. A total of 9 buzz sequences were found on 'hot' hydrophone 407 between 0157 and 0217 on Feb 17th. The duration of the buzz sequences ranged from 0.19 s to 1.29 s (0.68 s mean, 0.36 s.d.). Buzz clicks were not found for the other nine dives analyzed. Due to the lower source levels for buzz clicks relative to foraging clicks (Johnson et al. 2004) this suggests the animals were relatively close to phone 407 at the time of dive 4. The lack of detected buzz sequences on the other dives could be due to longer distances and may not be indicative of unsuccessful foraging.

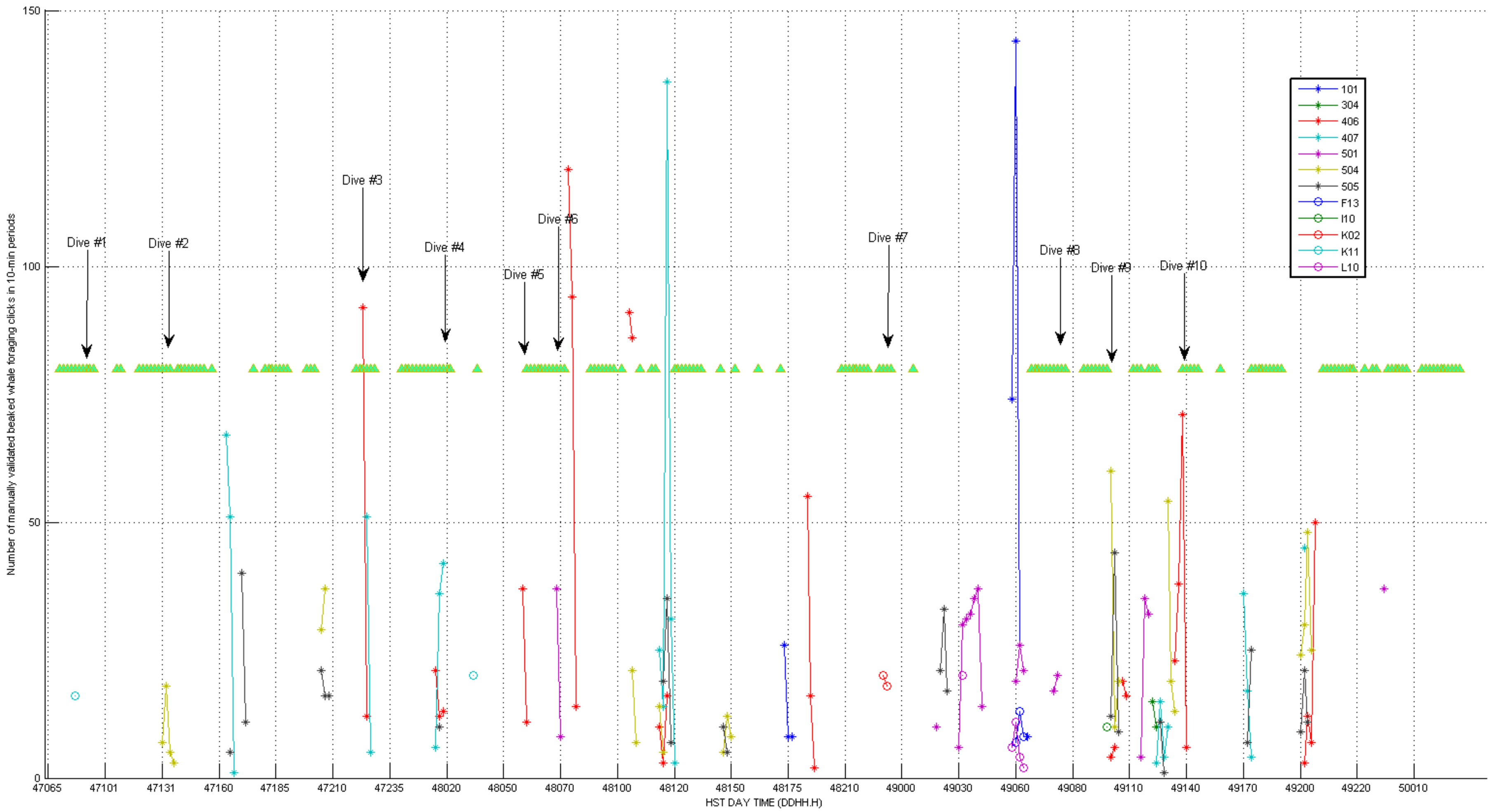

Figure 4: MFA sonar signal detections (green triangles) and beaked whale detected dive vocal periods plotted by hydrophone (colored lines) over the time period 0645 Feb 16, 2011 to 0334 Feb 19, 2011 HST. Legend indicates hydrophone designations. The colored lines link successive ten-minute periods from the same hydrophone with manually-validated beaked whale foraging clicks to indicate dives. Horizontal axis is DDHH.H (HST Day, hour and decimal hour). Vertical axis is the number of manually-validated beaked whale foraging clicks in ten-minute bins. The green triangles indicating MFA sonar activity are plotted at a vertical axis value of ~80 for clarity, not to imply a number of sonar pulses detected. Annotations show the 10 beaked whale foraging dive detected vocal periods.

C. Estimating SPLs

Table 3 provides the estimated SPLs for the ten dives shown in table 2. The HST day and start time of the detected dives is shown along with the ‘hot’ phone (the phone with the most validated beaked whale click detections) and time of CPA of the ship transmitting MFA sonar. The max and min CPA distances are shown for the group of whales located somewhere within a 6 km detection radius around the ‘hot’ phones. The estimated SPLs are shown for two presumed animal depths: one for at depth (1 km) while foraging; and a shallow depth (10 m) to represent levels they would receive when near the surface in a predicted ducted propagation region. It is not precisely known when the animals were near the surface, but it is a certainty they were there before and after the dive and that the SPLs are modeled as being higher due to ducted propagation expected by the historical sound velocity profile in the PCIMAT model. For each dive, and assumed animal depth, a minimum and maximum SPL is estimated to account for the location uncertainty of the group of animals due relative to the nearest hydrophone position.

Table 3: Estimated SPLs that beaked whales were exposed to for ten dives occurring during MFA sonar activity in Feb 2011. SPLs are estimated for animals at depth foraging and near the surface for a 6 km radius uncertainty from the ‘hot’ phone. Note 1: Depth limited to 800 m due to bathymetry.

Dive #	**Day in Feb**	**HST start time of Dive** (HHMM)	**‘Hot’ Phone**	**HST Time of CPA** (HHMM)	**CPA distance Max/Min MFA ship to beaked whales (km)**	**Min/Max estimated SPL @ 1km depth** (dB re 1 μPa)	**Min/Max estimated SPL @ 10m depth** (dB re 1 μPa)
1	16	0802	K11	0816	43.8 / 31.8	109 / 109	145 / 149
2	16	1312	504	1335	29.4 / 17.4	117 / 124	150 / 157
3	16	2247	406	2237	30.1 / 18.1	110 / 122	150 / 158
4	17	0157	407	0227	51.7 / 39.7	105 / 116 [1]	143 / 146
5	17	0557	406	0617	57.2 ./ 45.2	105 / 114	139 / 145
6	17	0717	501	0747	27.8 / 15.8	125 / 129	150 / 157
7	17	2337	K02	2356	29.6 /17.6	119 / 124	151 / 159
8	18	0747	501	0805	24.4 / 12.4	124 / 139	155 / 161
9	18	1027	I10	1030	48.6 / 36.7	105 / 115	144 / 148
10	18	1347	406	1427	53.6 / 41.6	81 / 118	141 / 146

Of the ten beaked whale dives analyzed, the estimated SPLs at 1 km depth span from 81 to 139 dB re 1 µPa with each dives averaged min/max for distance uncertainty, averaged across the ten dives is 115.4 dB re 1 µPa (9.5 dB s.d.). The estimated SPLs for the dives as if the animals were near the surface (10 m depth) similarly span from 139 to 161 dB re 1 µPa with an average across the ten dives of 149.8 dB re 1 µPa (5.7 dB s.d.) . The SPLs near the sea surface average 34.4 dB higher than those at the presumed foraging depth. Ducted propagation near the surface is a common condition in this area and is an important consideration when estimating SPLs beaked whales are exposed to.

V. DISCUSSION

The data presented here show that beaked whale dives continue to occur at PMRF while MFA sonar activity is occurring. The location of the whales is known to only a presumed 6 km detection radius from the hydrophone they were detected on. This results in two possible CPA distances (maximum and minimum) between the whales and the ship transmitting MFA sonar signals during a dive. Half of the dives occurred at CPA minimum distances of over 31 km extending out to a maximum distance of 57.2 km. The remaining dives CPA distances ranged from 12.4 km out to 30.1 km. The shortest distance observed was for dive # 8 where the MFA sonar ship CPA with the 'hot' phone (501) was 18.4 km, which results in the group of beaked whales' minimum and maximum possible distance from the ship of 12.4 to 24.4 km. The relative large uncertainty in distances between the ship and whales is reflected in mean differences of the max/min estimated SPLs of 11.1 dB (10 dB s.d.) for the whales at an assumed foraging depth of 1 km. The PCIMAT model's historical sound velocity profiles for the time of year and area show ducted propagation which result in mean SPLs being 34.4 dB higher near the surface compared to those estimated at 1 km depth. The lower transmission losses in the duct also result in smaller variations of the estimated SPLs (5.8 dB mean with s.d. of 1.7dB).

It can be concluded that beaked whale groups acoustically detected during MFA sonar activity were exposed to the higher PCIMAT predicted levels at the surface either before, or after, the dives. The group of whales in dives 4, 6, 8 and 9 were likely exposed to surface ducted MFA sonar signals prior to the start of the dives due to MFA sonar activity occurring for 2+ h before the dives. Similarly the group of whales in dive 5 may have been exposed to the higher MFA sonar signal levels after their dive as the transmissions continued for around 2.5 h after the dive was detected. Baird et al. 2006 reported that Blainville's and Cuvier's species spend a lot of time in the upper 50m of the water column based upon time depth tag data off the island of Hawaii. One could consider typical beaked whale dive profiles and include typical periods of time spent in the ducted region and potentially integrate some sort of dose exposure for a dive with contributions from both the ducted region and at depth regions SPLs.

The exposure levels for animals near the surface are on average 149.8 dB re 1 µPa based upon these ten dives and PCIMAT propagation modeling using historical sound velocity profiles for the area mid Feb. Tyack et al (2011) and McCarthy et al. (2011) reported that in similar training events in 2007 and 2008 at the AUTEC range, four instances of continued foraging with AN/SQS-53C MFA sonar exposures ranging from 14.7 to 19 km with SPLs of 127 to 133 dB re 1 µPa (rms). The AUTEC study also pooled 13 other sonar exposures (from AN/SQS-56and foreign sonars) and reported that the SPLs received by the beaked whales ranged between 101 and 157 dB re 1 µPa (mean 128 dB, s.d. 15dB). When considering ducted propagation at PMRF, the ten instances of AN/SQS-53C sonar exposures during foraging ranged from at PMRF ranged from 139 to 165 dB re 1 µPa (rms) with an average of 150 dB re 1 µPa (rms). This suggests that for beaked whales in the Hawaii area the disruption may occur at higher levels than observed at AUTEC.

Figure 4 indicates that approximately 32 beaked whale dives were detected over the 68.8 h in this analysis (the ten dives during MFA sonar activity and 22 other dives detected when MFA sonar activity was not occurring). It is not known if any of the dives are repeat dives by the same group of whales, although the intervals between several dives which occurred in the same area are consistent with beaked whale behavior. The majority (59%) of all dives occurred in the area of hydrophones 406, 407, 504 and 505 which agrees with water depths and steep bathymetry typically associated with beaked whale foraging dives (Tyack et al. 2006). Five of the dives (including 2 during MFA sonar activity) occurred in water depths of approximately 4.7 km with a relatively flat bottom which is nearly a km deeper than the maximum water depth that Cuvier's beaked whales were sighted off the island of Hawaii (Baird et al. 2006).

Attributing beaked whale clicks to a particular species was purposely conservative and not identified to a particular species of beaked whales. The observed acoustic characteristics do appear to fit best with reported information for Blainville's species. However, much is still unknown. Blainville's, Cuvier's and Longman's species are known to be present in Hawaiian waters, but it is possible that additional species could also be present (e.g. Ginko-toothed, Baird's, Hubb's and pygmy) (Macleod et al. 2006). Acoustic signals recorded at Cross Seamount in the area (McDonald et al. 2009) are quite different from known acoustic signal characteristics of species known to be in the area (clicks which last for ~ 1ms,sweep from 20 kHz to over 90 kHz and have ICIs < 0.3 s). These clicks could be from species known to be in the area using different signal types for different prey in a more reverberant environment, or from other species.

How well the acoustic propagation model matches actual conditions is always a consideration when using models. Here the US Navy standard PCIMAT model is utilized with high fidelity bathymetry, historical sound velocity profiles and bottom type models embedded. Surface ducted long range propagation is predicted by PCIMAT using historical sound velocity profiles. Data from hydrophones in the ducted region were not available to allow validation of the levels in the predicted ducted propagation region. In-situ sound velocity profiles will be available for future similar training events vice using historical data. Behavioral response studies utilize acoustic tags on animals to unambiguously measure the receive levels at the animal location. It would be worthwhile to see how well PCIMAT modeled exposures fit with BRS measured exposure levels as an attempt at model validation.

VI. CONCLUSION

This report provides estimated SPL exposures from MFA sonar activity for beaked whale groups during a US Naval training event in Hawaii. Results suggest beaked whales in Hawaiian waters may continue dives with higher SPL exposures (considering ducted propagation near the surface) than those reported for Blainville's whales at AUTEC

(Tyack et al. 2011, McCarthy et al. 2011 and Moretti et al. 2010). The AUTEC effort was for the same type of training event; however localization of beaked whale groups was more precise due to closer hydrophone spacing than those recorded at PMRF for this analysis. The ten estimated SPLs at PMRF for foraging beaked whales when the animals are at a presumed foraging depth of 1 km are in agreement with the levels reported for AUTEC. However estimated levels considering the predicted ducted propagation suggest animals at PMRF continue foraging at higher exposure SPLs (mean of 150 dB re 1 µPa s.d. 5.7 dB at PMRF vice a mean of 128 dB re 1 µPa, s.d. 15 dB at AUTEC).

This type of effort is recommended to continue to obtain additional data points of exposure levels on beaked whales. Improvements are also recommended (e.g. analyzing additional hydrophones to improve localization uncertainty and obtaining hydrophone data from sensors located in the upper 50 m of the water column to validate model outputs). In-situ sound velocity profiles have already been obtained from subsequent training events so the PCIMAT model can utilize actual, vice historical sound velocity profiles to provide more accurate SPL estimates. PCIMAT models runs from behavioral response studies tagged exposure data could also be performed to quantify how well the model matches in-situ recorded data from other areas of the world (AUTEC, Southern California Off-shore range, Mediterranean Sea).

This process of estimating SPLs that marine mammals are exposed to extends to other species with suitable detectors and classifiers. The process has already been applied to minke whale boing vocalizations from this same exercise (Martin informal report 2011) where an individual animal is localized (~ 200 m localization accuracy) from repeated vocalizations over 90 minutes of time during MFA sonar activity. Data from these types of efforts also have potential applicability to augment Behavioral Response Study (BRS) analysis efforts.

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