

Passive acoustic monitoring using a towed hydrophone array results in identification of a previously unknown beaked whale habitat

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Beaked whales are diverse and species rich taxa. They spend the vast majority of their time submerged, regularly diving to depths of hundreds to thousands of meters, typically occur in small groups, and behave inconspicuously at the surface. These factors make them extremely difficult to detect using standard visual survey methods. However, recent advancements in acoustic detection capabilities have made passive acoustic monitoring (PAM) a viable alternative. Beaked whales can be discriminated from other odontocetes by the unique characteristics of their echolocation clicks. In 2009 and 2010, PAM methods using towed hydrophone arrays were tested. These methods proved highly effective for real-time detection of beaked whales in the Southern California Bight (SCB) and were subsequently implemented in 2011 to successfully detect and track beaked whales during the ongoing Southern California Behavioral Response Study. The three year field effort has resulted in (1) the successful classification and tracking of Cuvier's (*Ziphius cavirostris*), Baird's (*Berardius bairdii*), and unidentified Mesoplodon beaked whale species and (2) the identification of areas of previously unknown beaked whale habitat use. Identification of habitat use areas will contribute to a better understanding of the complex relationship between beaked whale distribution, occurrence, and preferred habitat characteristics on a relatively small spatial scale. These findings will also provide information that can be used to promote more effective management and conservation of beaked whales in the SCB, a heavily used Naval operation and training region.

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I. INTRODUCTION

Beaked whales (family Ziphiidae) are a poorly understood but diverse and widely distributed group of cetaceans, known for their deep diving capabilities. They are important apex predators in deep water ecosystems (MacLeod and Zuur, 2005) that appear to be particularly sensitive to anthropogenic noise, as evidenced by a number of mass stranding events associated with military sonar exercises (Frantzis, 1998; Jepson *et al.*, 2003; Balcomb and Claridge, 2001; Johnson *et al.*, 2004; Fernández *et al.*, 2005; Cox *et al.*, 2006; D'Amico *et al.*, 2009). Given these concerns and the need for basic information on beaked whale occurrence and life history, the ability to detect beaked whales and identify

areas of relatively high density is critical for effective conservation and management of these species.

Standard visual survey methods are not well suited to detect and study beaked whales because these species spend the majority of their time at depth. In addition, they are relatively inconspicuous at the surface due to typically small group sizes, low profiles in the water, and a lack of surface displays and obvious blows. Visual surveys are further constrained by poor weather and light conditions, which is particularly problematic for beaked whales given the subtle surfacing behavior described above. These constraints have resulted in difficulty in gathering information about these animals in the field and have resulted in limited or even misleading conclusions regarding the abundance and distribution of various beaked whale species (Claridge, 2006). Such inconclusive results impede scientific efforts to accurately characterize and define a beaked whale habitat and provide inaccurate information to policy makers and resource managers about conservation, management, and mitigation measures for these species.

While conventional visual methods are limited, recent advances in acoustic sensing and signal processing capabilities

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offer new tools to support these efforts (Gillespie *et al.*, 2008, 2009). Beaked whales produce directional ultrasonic clicks to echolocate on their pelagic and benthopelagic prey (Johnson *et al.*, 2006). Recent research on Blainville's and Cuvier's beaked whales suggests that stereotyped frequency-modulated (FM) clicks are produced continuously when the animals are foraging at 400 to 1200 m depth (Madsen *et al.*, 2005; Tyack *et al.*, 2006; Johnson *et al.*, 2004, 2006; Zimmer *et al.*, 2005, 2008). Typically, clicking starts at approximately 400 m on the descent as they presumably begin foraging. Although it appears that several species of beaked whale produce similar click profiles, specific characteristics of the signals vary from species to species (Tyack *et al.*, 2006). Beaked whales can be discriminated to a species and/or genus level for many species as well as from other odontocetes by several unique characteristics of their echolocation clicks including, duration $>175 \mu\text{s}$, inter-click intervals typically between 0.2 and 0.4 s, and unique frequency upsweeps (Madsen *et al.*, 2005; Tyack *et al.*, 2006; Johnson *et al.*, 2004, 2006, 2008). Peak frequencies vary by species and range from approximately 16 to 66 kHz for known beaked whale signals (Baumann-Pickering *et al.*, 2011, 2013). The unique characteristics of beaked whale echolocation behavior combined with the limited efficacy of visual observation provide an opportunity for PAM to play an important role in research, mitigation, and conservation efforts for these species. The integration of PAM and visual observation into a focused beaked whale study offers the most effective approach to fill in our current knowledge gaps for these species.

The Southern California Bight (SCB) and specifically the Channel Islands region, is comprised of deep slope waters that are expected to provide a good foraging habitat for beaked whales (Mead, 1989; Santos *et al.*, 2001; MacLeod and Zuur, 2005). While a population of beaked whales has been consistently observed offshore of San Clemente Island (Falcone *et al.*, 2009; Wiggins *et al.*, 2012), there exist few sightings of beaked whales in the vicinity of the other Channel Islands (Hamilton *et al.*, 2009). In this study, towed hydrophone arrays were used to acoustically detect and track beaked whales in the SCB, outside of any known areas of concentration, to determine if these species were present in regions of the Channel Islands with habitat that is similar to areas off San Clemente Island where they are known to occur.

II. MATERIALS AND METHODS

Combined visual and acoustic monitoring methods were used to detect and track beaked whales in the SCB over three summer/fall field seasons. In 2009, a 50 ft sailing vessel was used to tow a linear array of three hydrophones from August 18–25. In 2010, as part of a scouting survey for the Southern California Behavioral Response Study (SOCAL-BRS), a motorized vessel was used to tow a linear array of two to three elements from August 6–17. And in 2011, there were four survey legs conducted on four different vessels, two were motorized and two were sailing vessels that were used to tow a five-element linear array or a four-element tetrahedral array. The survey periods for 2011 were as follows: June 8–9 (equipment test survey); July 15–27 (SOCAL-BRS scouting survey); August 1–6; and September 17–29

(collaborative effort as part of SOCAL-BRS). During all surveys due to the specific nature of the survey goals (scouting, tracking, and tagging) and prior knowledge of beaked whale habitat preferences from other studies, we elected to transect slope waters and deep basins in the SCB, rather than follow planned transect lines.

A. Visual effort

A team of three scientists rotated between visual observation and data recorder positions from the survey platform. This protocol was standardized on the motorized platform survey legs and was less rigidly followed on the sailing platform legs. Marine mammal observers typically used handheld 7×50 binoculars or the naked eye to scan the horizon from 0° to 90° of the ships' heading. During the 2011 field season, $25\times$ power "big-eye" binoculars were opportunistically used from the motor-vessel platform. Typically, two additional scientists surveyed for marine mammals from a rigid hull inflatable boat (~ 5.5 m) that operated in close proximity to the sailboat during daylight hours. All marine mammal sighting information was written onto paper forms or entered into computer-based spreadsheets. Photo identification and biopsy samples from beaked whales were collected opportunistically as conditions allowed.

B. Acoustic effort

A hydrophone array was towed approximately 100 to 120 m behind the vessel during all daylight hours (2009–2011) and two overnight transits (2009 only). Two different array configurations were used: (1) A linear oil filled array consisting of two to five hydrophone elements, or (2) a tetrahedral array with four hydrophone elements (2011 only; Fig. 1) (Table I). Analog acoustic signals were passed through a signal conditioning filter/amplifier (Magrec), which provided high-pass filtering and gain capabilities for each channel. Typically, the hydrophone signals were high-pass filtered at 1 kHz and digitized at either a 384 kHz sample rate (in 2009) or a 192 kHz sample rate (in 2010 and 2011) using a National Instruments 6251 USB data acquisition board (Ecologic HP/27ST Magrec Stereo Monitor Box). The digitized signal output was sent to a 12 V fanless computer for signal processing, recording, and display. This system was used to continuously record acoustic data to computer hard



FIG. 1. Tetrahedral array used during the 2011 survey. The vertices of the tetrahedron included two hydrophone elements in the top tube and one element in each of the bottom tubes.

TABLE I. Hydrophone array properties for the towed-arrays used during each survey year.

Year	Array type	Number of elements	Frequency response	Gain	Received HP sensitivity	Transmit HP sensitivity	HP distance (cm) relative to HP1
2009, 2010	Linear oil-filled	3	Flat 1.5 to 150 kHz	46 dB	-211 dB re 1 V/uPa	135 dB re 1 uPa/V	0, 30, 200, 230
2010	Linear Seiche potted	2	Flat 1.5 to 150 kHz	46 dB	NA	NA	NA
2011	Linear oil-filled mid frequency*	3	Flat 500 Hz to 30 kHz	46 dB	-155 dB re 1 V/uPa	NA	0, 100, 200,
2011	Linear oil-filled high frequency*	2	Flat 1 Hz to 180 kHz	46 dB	-203 dB re 1 V/uPa	145 dB re 1 uPa/V	50, 250
2011	Tetrahedral	4	Flat 1.5 to 100 kHz	46 dB	NA	NA	0, 30, -14.5/+25.5, +14.5/-25.5

*Asterisks indicate that hydrophones are part of the same array.

disks using Logger 2000 data-acquisition and recording software (International Fund for Animal Welfare, IFAW). In 2010 and 2011, two hydrophone channels were also output from the Magrec to a Fireface UFX audio digital interface that was connected to a Windows 7 64-bit laptop for automated click detection using PAMGuard software (Gillespie *et al.*, 2009). All acoustic hardware was powered by 12 V direct current batteries so that the power was completely independent of the ship power, to reduce electrical noise in the recording system.

Semi-automated methods were used to detect and classify beaked whale echolocation clicks in real-time. This was accomplished using either Rainbow Click (IFAW) (Gillespie and Leaper, 1996) (2009) or PAMGuard software (2010–2011) (Gillespie *et al.*, 2009). Click classifiers were configured for both a general beaked whale guild and Baird’s beaked whales. The classifiers were tested prior to each survey (see Yack *et al.*, 2010 and Jacobson *et al.*, 2013 for classifier details). In real-time, an experienced acoustician simultaneously monitored the click display and a scrolling spectrographic display. The acoustician then used information from the waveform (*duration*: ~ 0.3 to 0.5 ms), spectrum (*frequency peaks*: Baird’s = 16 to 22 kHz, Cuvier’s = 38 to 40 kHz, and Mesoplodon sp. 34 to 66 kHz) (Baumann-Pickering *et al.*, 2011, 2013), and associated Wigner-Ville transformation plot (FM *upsweep verification*) (2011 only) to assign mutually exclusive classification confidence categories to encounters. A Wigner plot is a quadratic time-frequency representation used to analyze the time-frequency structure of broadband cetacean clicks (Papandreou-Suppappola and Antonelli, 2001). The Wigner plot is an advantageous way to view beaked whale clicks because it enables the user to easily see and identify the frequency upsweep inherent in beaked whale clicks.

Beaked whale detections were categorized as follows: (1) *Possible detections*—based primarily on the automated classification of a click train containing three or more beaked whale classified clicks in a one minute time window (2009) or assigned based on real-time review of waveform, spectrum, and Wigner plot with a qualitative confidence assessment of 70% (\sim) (2009–2011); (2) *probable detections*—based on a combination of automated classification and an experienced bioacoustician’s review of the waveform, spectrum, inter-click-interval containing five or more confirmed beaked whale clicks in a 1 min window (2009–2011), and Wigner-Ville plot with three or more upsweep verifications

(2010–2011). Probable detections have a qualitatively assessed confidence score of 85% (\sim); and (3) *definite detections*—either associated with a sighting (2009–2011) or Wigner-Ville plot upsweep verification for five or more clicks resulting in an acoustic only definite encounter (2011). Definite detections have a qualitative confidence score of 95% (\sim). A frequency upsweep is a key feature unique to beaked whale echolocation clicks and as such, the confirmed presence of five or more upsweeps was determined to be robust enough to classify a detection as a definite beaked whale (*in 2011 when this methodology was available*). All acoustic encounter information and confidence category assignments were logged to a Microsoft Access database using Logger 2000 (IFAW) software.

The acoustic detection and tracking methods and protocols evolved over the three survey years. We began in 2009 with a limited and simple automated detection and classification system implemented in Rainbow click software and monitored in real time by an experienced acoustic technician. We had no bearing angle mapping or spectrographic display capabilities during this survey year but were nonetheless able to successfully acoustically detect areas of beaked whale presence with a strong degree of confidence (Yack *et al.*, 2011). During this survey year we towed the hydrophone array at a fairly shallow depth (<8 m) from a small (45 ft) sailing platform. Bearing angles were calculated using target motion analysis methods in Rainbow Click. Bearing angles for beaked whale clicks typically ranged from 60° to 120°. The lack of variation in bearing angles suggested that these were not true horizontal angles but rather slant angles comprised primarily of a depth component. Additionally, during the 2009 survey year, methodology for counting beaked whale detections differed from future years. Each click bout received within <10 min (period of continuous clicking) was counted as a unique detection. In future years, only acoustic “encounters” were counted. An encounter was defined as a period of semi-continuous click bouts received with <20 min in between confirmed click trains. This method was adopted because our beaked whale classification confidence increased after the 2009 survey due to our success confirming beaked whale detections (Yack *et al.*, 2011). As such, after 2009, we often went “on chase” when we had probable beaked whale detections and remained in acoustic contact with the target animals for long periods.

To address the localization issues encountered in 2009, in 2010 we towed the hydrophone array at a deeper depth

($\sim >12$ m) from a larger motorized vessel. We used PAMGuard software which provided the ability to view scrolling spectrographic displays at the same time as the automated click detection display, and had the ability to plot bearing angles from detected click trains to a map display. In spite of these additions, localization still proved difficult, so in 2011 we addressed this issue by developing a tetrahedral array with the capacity to localize in three dimensions. During the 2011 survey we alternately used either a five-element linear oil-filled array or a four-element tetrahedral array to monitor acoustic signals (Table I). We were able to easily switch between arrays through the use of underwater connectors attached to the tow cable. Figure 2 shows an example of the PAMGuard display features during a 2011 Cuvier's beaked whale encounter. In the time bearing display [Fig. 2(a)] in this example, we were able to track four different animals simultaneously.

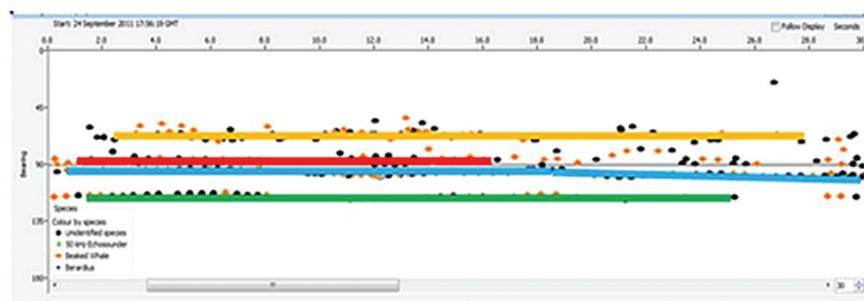
III. RESULTS

Between 2009 and 2011 there were 50 days of PAM survey effort over 4246 km of track-line. These efforts resulted in ten “joint” visual and acoustic beaked whale encounters. From these visually confirmed acoustic encounters we estimate our detection range to be within 4 km, and sightings and re-sights that occurred following acoustic detection were

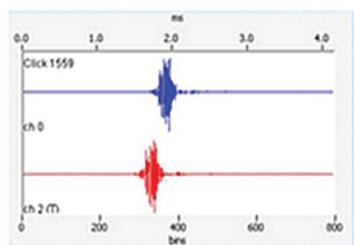
obtained within an average distance of 1.8 km (range: 0.2 to 4 km). Of these, seven encounters (70%) were first detected acoustically prior to a visual sighting and in the other three cases beaked whales were sighted within 6 km of a previous acoustic only encounter. The 2009 survey resulted in 40 acoustic only detections of click bouts. The 2010 and 2011 surveys resulted in a total of 51 unique acoustic encounters [Table II; Fig. 3(A)]. It should be noted that the acoustic encounters although considered “unique” for analysis purposes could be repeated interactions with the same individuals or groups.

Beaked whales were acoustically detected in the SCB in areas that had no previously reported sightings (Hamilton *et al.*, 2009). However, these surveys specifically targeted deep-water basins that were likely a preferential habitat for beaked whales within the SCB. The definite acoustic encounters that were coupled with corresponding visual sightings occurred in eight primary regions, with some possible species specific differences [Fig. 3(B)]. For the purpose of this paper a “region” is defined as an area where an acoustic and visual beaked whale encounter occurred greater than 15 km from another combined visual and acoustic beaked whale encounter.

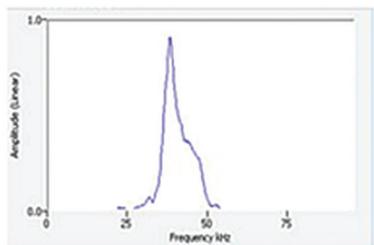
Baird's beaked whale acoustic detections and associated sightings occurred in three regions: (R1) the north-western Santa Cruz basin, (R2) the north-western Santa Monica basin,



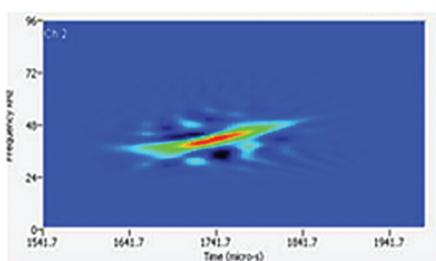
a. Bearing Time Display



b. Waveform



c. Spectrum



d. Wigner Plot

FIG. 2. PAMGUARD click detection display showing example Cuvier's beaked whale acoustic encounter (a) bearing time display with bearing angle on the x axis and time on the y axis, (b) waveform, (c) power spectrum, and (d) Wigner plot. Colored lines represent bearing angle trajectories for individual whales.

TABLE II. Survey effort in kilometers and days is provided for each year and vessel type (Motorized = M and Sailboat = S). A summary of acoustic only and combined acoustic and visual encounters for each acoustic category and species is also provided (2009–2011). The combined acoustic/visual encounters were associated with a visual sighting in the field and are mutually exclusive from the *acoustic only* definite encounters.

Year	Vessel	Effort (km)	Effort (days)	Acoustic only encounters			Combined acoustic/visual encounters			
				Possible	Probable	Definite	<i>Ziphius cavirostris</i>	<i>Berardius bairdii</i>	Unid. Mesoplodon	Unid. beaked whale
2009	S	950	8	8*	31*	1*	1	0	0	—
2010	M	967	12	12	5	—	1	2	—	—
2011 a	S	297	2	4	1	1	—	—	—	—
2011 b	M	1025	10	6	4	2	1	1	1	1
2011 b	S	1007	18	14	1	1	1	1	—	—
Total (2009–2011)	—	4246	50	44	42	5	4	4	1	1
Total (2010–2011)	—	3296	42	36	11	4	3	4	1	1

*In 2009, each click bout received within <10 min (period of continuous clicking) was counted as a unique detection. In future years, only acoustic encounters, defined as a period of semi-continuous click bouts received with <20 min in between confirmed click trains (>3 clicks/train).

and (R3) the north-western San Nicolas basin. In 2010, using improved monitoring methods that included PAMGuard software, we were able to successfully track a Baird's beaked whale group and obtain multiple re-sightings over a 10 h period in the north-western Santa Cruz Basin [Fig. 3(B); R1]. During the 2011 survey in the north-western Santa Monica basin [Fig. 3(B); R2], there was an acoustic only encounter on the evening of July 25, and the next morning there was a joint acoustic/visual encounter in the region. During the joint encounter two Baird's beaked whales were sighted. In the north-western San Nicolas basin [Fig. 3(B); R3] during the 2010

survey we were able to acoustically locate and subsequently obtain a visual sighting and re-sighting of a small Baird's beaked whale group during Beaufort 3 sea conditions over a period of approximately 4 h.

Cuvier's beaked whale acoustic detections with coincident sightings also occurred in three distinct regions: (R4) the north-western Catalina basin east of Santa Barbara Island, (R5) the south-eastern Santa Cruz basin between Santa Barbara and San Nicolas Islands, and (R6) the south-eastern Santa Monica basin [Fig. 3(B); R4–R6]. In 2009, the acoustics team had multiple detections on the north-western Catalina basin east of the Santa Barbara Island [Fig. 3(B); R4] survey area over 2 days with high sea conditions. The acoustic detections led us to survey the area again in calm sea conditions which subsequently resulted in a visual encounter with three Cuvier's beaked whales within 1 nmi of the prior acoustic detections. Probable beaked whale detections also occurred in this region during the 2011 survey. In the south-eastern Santa Cruz basin [Fig. 3(B); R6] acoustic only encounters occurred in 2010 and 2011. In 2011 the visual survey team aboard a separate vessel sighted a group of Cuvier's beaked whales within 6 km of an acoustic only encounter the previous day. The acoustic vessel joined the visual team and we were able to jointly track and stay with the group using visual and acoustic methods for over 10 h. In the south-eastern Santa Monica basin [Fig. 3(B); R6] joint visual and acoustic encounters occurred during two survey years (2010 and 2011), during both surveys a single animal was sighted.

Unidentified beaked whales were only encountered in one region during the survey period (R7). An unidentified beaked whale was sighted after acoustic detections were made in previous years and prior to the sighting on the same day in the Gulf of Santa Catalina, about 45 km east of Oceanside Harbor [Fig. 3(B); R7].

The last region with acoustic beaked whale detections coincident with a sighting was located in the eastern San Diego trough about 25 km offshore of San Diego [Fig. 3(B); R8]. The acoustics team had definite acoustic detections of a *Mesoplodon* species during 3 days of surveying this region (clicks with ~43 kHz peak frequency characteristics and distinct upsweeps). However, the sea conditions were too rough (Beaufort 3 or greater) for effective visual surveys of beaked

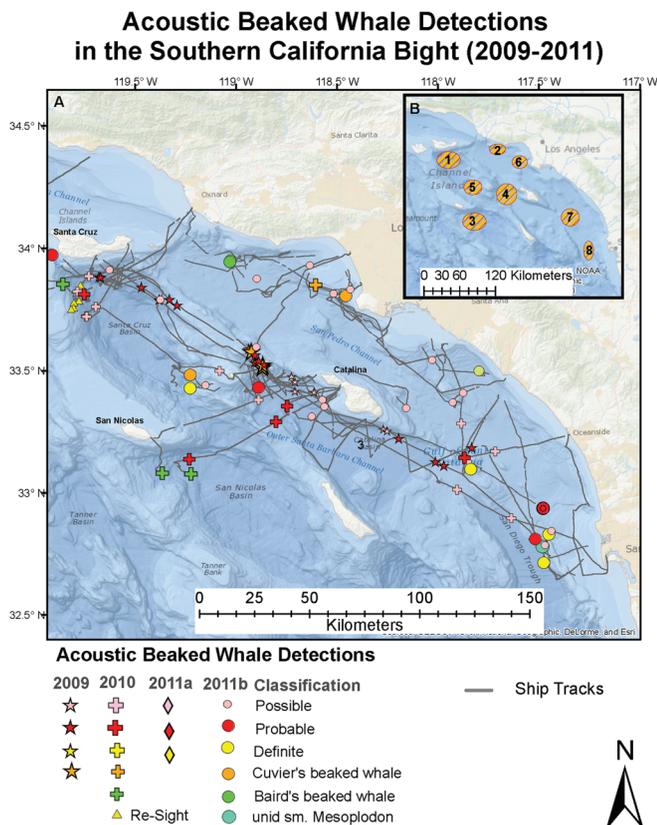


FIG. 3. (A) Survey track lines for each year and beaked whale acoustic and combined visual and acoustic encounters for PAM surveys 2009 (stars); 2010 (crosses); 2011 Trial (diamonds); and 2011 (circles). The insert (B) depicts the survey area with distinct encounter regions (1–8) shaded in orange.

whales during these days. On the fourth day of surveying this region, when sea conditions improved to less than a Beaufort 2, the acoustics team was able to position the ship within a kilometer of the animal and the visual team observed two surface events of an unidentified *Mesoplodon* species. The sea conditions quickly worsened and we were unable to obtain a positive species identification for this beaked whale encounter.

IV. DISCUSSION

This study demonstrated that combined visual and acoustic survey methods can be used to effectively identify regions of beaked whale habitat. Beaked whales of several species were detected in deep-water areas around the Channel Islands that have a similar habitat to that of San Clemente Island, an area where beaked whales are consistently detected visually using small boat surveys and acoustically from a large bottom mounted hydrophone array (Falcone *et al.*, 2009). As our results indicate, there were a far greater number of acoustic encounters compared to visual encounters (Table II). All visual encounters were also acoustically detected and 70% of all confirmed sightings were first detected using acoustic methods and the other three encounters detected first visually were within 6 km (~) of a previous acoustic only encounter. This indicates that PAM using a towed hydrophone array can greatly improve the success of beaked whale studies.

Beaked whale presence in the deep channel island basins appeared to be stable during survey periods as well as among years [Fig. 3(A)] during the months surveyed (Aug.–Oct.). This suggests that these areas represent an important habitat for multiple beaked whale species in the SCB. The ease of access to these relatively near-shore beaked whale habitat regions in the SCB offers a unique opportunity for continued long-term year-round studies using combined visual and acoustic survey techniques.

The results of this study demonstrate that real-time detection and tracking of beaked whales using a towed hydrophone array platform is an effective survey method. We were reliably able to detect and track beaked whale signals using a towed-array within a 4 km (~) detection range and successfully provide bearing and range estimates to signals within a 1.5 km (~) detection range. This research has resulted in several advancements in beaked whale research. First, we identified a previously unknown beaked whale habitat in the SCB. Second, we increased our understanding of beaked whale echolocation click characteristics. The examination of click characteristics of visually confirmed acoustic encounters will allow us to modify our classification algorithms and we expect this future work will ultimately result in more robust species classification for Baird's beaked whale, Cuvier's beaked whale, and *Mesoplodon* species. And last, we anticipate that the data collected during these surveys will allow us to develop fine scale acoustic based habitat models for beaked whales in the Southern California Bight. Efforts toward this end are currently underway and the resulting improvements to knowledge of the spatial distribution of these species of high interest given their apparent sensitivity to human sounds will have direct and timely contributions to management decisions.

The evolution of survey methods over three survey years provided ample opportunity for feasibility testing and software and hardware development. Software improvements included additional features for PAMGuard's click classification displays and tools. For example, in the latest release of PAMGuard, a Wigner plot is available in the click display options, an inter-click-interval display is available, and an alarm module is available (i.e., an alarm can be configured to sound whenever beaked whale clicks are classified). None of these modules were available when this study began in 2009. The resulting success of our methodological improvements is evidenced by the rudimentary assessment of beaked whale encounters we were able to provide in 2009 compared to subsequent years (Table II). The ability to view Wigner plots (which were used to positively differentiate beaked whale clicks from other odontocete species by visually confirming the presence of a frequency modulated upswEEP in the echolocation click) in real-time greatly improved our success in positive identification of beaked whales acoustically. The addition of this feature effectively reduced the rate of false positive detections relative to methods we used in previous survey years. Improvements have also been made in hardware design and development (i.e., design and testing of a tetrahedral array) which we believe will lead to better localization and tracking capabilities.

While this study demonstrated the efficacy of using towed array methods to study beaked whales, there is still room for improvements to hardware and especially software. For example, testing of the tetrahedral array in 2011 proved it to be extremely useful for dolphins. However, the hydrophone sensitivity was not equal on all hydrophones, limiting its utility for localizing beaked whales during the 2011 field season. Modification of the tetrahedral hydrophone array design likely will improve our capabilities for beaked whale tracking in future survey years. Software classification techniques are currently working well but localization techniques were limited during all three survey years. Modifications recently made to the bearing time display in the latest release of PAMGuard software (Pamguard_BETA_1_11_02b) now allow the user to define beaked whale click trains manually and selectively plot these bearing angles to the map display module. This new modification is expected to greatly improve localization and tracking in future survey years.

Methods developed and refined in this study were successfully implemented to support the multi-year effort (2010–2015) SOCAL-BRS. The results from this study will allow researchers and managers to better understand beaked whale occurrence, behavior, and reactions to sound. Additionally, our results provide the opportunity to further explore beaked whale habitat relationships on a relatively small scale. This will in turn fulfill critical knowledge gaps that are needed for effective management and conservation of this poorly understood living marine resource.

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- Balcomb, K. C., and Claridge, D. E. (2001). "Mass whale mortality: U.S. Navy exercises cause stranding." *Bahamas J. Sci.* **8**, 1–12.
- Baumann-Pickering, S., Simonis, A. E., McDonald, M. A., Oleson, E. M., Rankin, S., Wiggins, S. M., and Hildebrand, J. A. (2011). "Comparison of beaked whale echolocation signals." *3rd Symposium on Acoustic Communication by Animals*, Cornell University, Ithaca, NY.
- Baumann-Pickering, S., Simonis, A. E., Roch, M. A., McDonald, M. A., Solsona Berga, A., Oleson, E. M., Wiggins, S. M., Brownell, R. L., Jr., and Hildebrand, J. A. (2013). "Spatio-temporal patterns of beaked whale echolocation signals in the North Pacific." *Pacific Scientific Review Group Meeting*, San Diego, CA, PSRG-2013-B07, 24 pp.
- Claridge, D. E. (2006). "Fine-scale distribution and habitat selection of beaked whales." M.Sc. thesis, Department of Zoology, University of Aberdeen, Aberdeen, Scotland, UK.
- Cox, T. M., Ragen, T. J., Read, A. J., Vos, E., Baird, R. W., Balcomb, K., Barlow, J., Caldwell, J., Cranford, T., Crum, L., D'Amico, A., D'Spain, G., Fernandez, A., Finneran, J., Gentry, R., Gerth, W., Gulland, F., Hildebrand, J., Houser, D., Hullar, T., Jepson, P. D., Ketten, D., MacLeod, C. D., Miller, P., Moore, S., Mountain, D. C., Palka, D., Ponganis, P., Rommel, S., Rowles, T., Taylor, B., Tyack, P., Wartzok, D., Gisiner, R., Mead, J., and Benner, L. (2006). "Understanding the impacts of anthropogenic sound on beaked whales." *J. Cetacean Res. Manage.* **7**, 177–187.
- D'Amico, A., Gisiner, R. C., Ketten, D. R., Hammock, J. A., Johnson, C., Tyack, P. L., and Mead, J. (2009). "Beaked whale strandings and naval exercises." *Aquat. Mamm.* **35**, 452–472.
- Falcone, E. A., Schorr, G. S., Douglas, A. B., Calambokidis, J., Henderson, E., McKenna, M. F., Hildebrand, J., and Moretti, D. (2009). "Sighting characteristics and photo-identification of Cuvier's beaked whales (*Ziphius cavirostris*) near San Clemente Island, California: A key area for beaked whales and the military?." *Mar. Biol.* **156**, 2631–2640.
- Fernández, A., Edwards, J. F., Rodriguez, F., Espinosa de los Monteros, A., Herraiz, P., Castro, P., Jaber, J. R., Martin, V., and Arbelo, M. (2005). "Gas and fat embolic syndrome" involving a mass stranding of beaked whales (family Ziphiidae) exposed to anthropogenic sonar signals." *Vet. Pathol.* **42**, 446–457.
- Frantzis, A. (1998). "Does acoustic testing strand whales?." *Nature* **392**(6671), 29.
- Gillespie, D., Dunn, C., Gordon, J., Claridge, D., Embling, C., and Boyd, I. (2009). "Field recordings of Gervais' beaked whales *Mesoplodon europaeus* from the Bahamas." *J. Acoust. Soc. Am.* **125**, 3428–3433.
- Gillespie, D., and Leaper, R. (1996). "Detection of sperm whale *Physeter macrocephalus* clicks and discrimination of individual vocalizations." *Eur. Res. Cetaceans Abstracts*, **10**, 87–91.
- Gillespie, D. M., Gordon, J., McHugh, R., McLaren, D., Mellinger, D., Redmond, P., Thode, A., Trinder, P., and Deng, X. Y. (2008). "PAMGUARD: Semiautomated, open source software for real-time acoustic detection and localization of cetaceans." in *Proceedings of the Institute of Acoustics*, 30 Pt 5. United Kingdom.
- Hamilton, T. A., Redfern, J. V., Barlow, J., Ballance, L. T., Gerrodette, T., Holt, R. S., and Taylor, B. L. (2009). *Atlas of Cetacean Sightings for Southwest Fisheries Science Center Cetacean and Ecosystem Surveys: 1986–2005* (NOAA-TM-NMFS-SWFSC-440), National Oceanic and Atmospheric Administration, Washington, DC.
- Jacobson, E. K., Yack, T. M., and Barlow, J. (2013). "Evaluation of an automated acoustic beaked whale detection algorithm using multiple validation and assessment methods." U.S. Department of Commerce, NOAA Tech. Memo. NMFS-SWFSC-509, 26 pp.
- Jepson, P. D., Arbelo, M., Deaville, R. P., Patterson, I. A., Castro, P., Baker, J. R., Degollada, E., Ross, H. M., Herraiz, V., Pocknell, A. M., Rodriguez, F., Howiell, F. E., Espinosa, A., Reid, R. J., Jaber, F. R., Martin, V., Cunningham, A. A., and Fernández, A. (2003). "Gas-bubble lesions in stranded animals: Was sonar responsible for a spate of whale deaths after an Atlantic military exercise?." *Nature* **425**, 575–576.
- Johnson, M., Hickmott, L. S., Aguilar Soto, N., and Madsen, P. T. (2008). "Echolocation behavior adapted to prey in foraging Blainville's beaked whale (*Mesoplodon densirostris*)." *Proc. R. Soc. London, Ser. B* **275**, 133–139.
- Johnson, M., Madsen, P. T., Zimmer, W. M. X., Aguilar de Soto, N., and Tyack, P. L. (2004). "Beaked whales echolocate on prey." *Proc. R. Soc. London, Ser. B* **271**, S383–S386.
- Johnson, M., Madsen, P. T., Zimmer, W. M. X., Aguilar de Soto, N., and Tyack, P. L. (2006). "Foraging Blainville's beaked whales (*Mesoplodon densirostris*) produce distinct click types matched to different phases of echolocation." *J. Exp. Biol.* **209**, 5038–5050.
- MacLeod, C. D., and Zuur, A. (2005). "Habitat utilization by Blainville's beaked whales off Great Abaco, northern Bahamas, in relation to seabed topography." *Marine Biol.* **147**, 1–11.
- Madsen, P. T., Johnson, M., Aguilar de Soto, N., Zimmer, W. M. X., and Tyack, P. L. (2005). "Biosonar performance of foraging beaked whales (*Mesoplodon densirostris*)." *J. Exp. Biol.* **208**, 181–194.
- Mead, J. G. (1989). "Beaked whales of the genus *Mesoplodon*," in *Handbook of Marine Mammals*, edited by S. H. Ridgway and R. Harrison (Academic Press, London), pp. 349–430.
- Papandreou-Suppappola, A., and Antonelli, L. (2001). "Use of quadratic time-frequency representations to analyze cetacean mammal sounds." NUWC-NPT Technical Report (Newport, Rhode Island).
- Santos, M. B., Pierce, G. J., Herman, J., Lopez, A., Guerra, A., Mente, E., and Clarke, M. R. (2001). "Feeding ecology of Cuvier's beaked whale (*Ziphius cavirostris*): A review with new information on the diet of the species." *J. Mar. Biol. Assoc. U.K.* **81**, 687–694.
- Tyack, P. L., Johnson, M., Aguilar Soto, N., Sturlese, A., and Madsen, P. T. (2006). "Extreme diving of beaked whales." *J. Exp. Biol.* **209**, 4238–4253.
- Wiggins, S. M., McDonald, M. A., and Hildebrand, J. A. (2012). "Beaked whale and dolphin tracking using a multichannel autonomous acoustic recorder." *J. Acoust. Soc. Am.* **131**, 156–163.
- Yack, T. M., Barlow, J., Calambokidis, J., and Rankin, S. (2011). "Passive acoustic beaked whale monitoring survey of the Channel Islands, CA." NOAA-TM-NMFS-SWFSC-479.
- Yack, T. M., Barlow, J., Roch, M. A., Klinck, H., Martin, S., Mellinger, D. K., and Gillespie, D. (2010). "Comparison of beaked whale detection algorithms." *Appl. Acoust.* **71**, 1043–1049.
- Zimmer, W. M. X., Harwood, J., Tyack, P. L., Johnson, M. P., and Madsen, P. T. (2008). "Passive acoustic detection of deep-diving beaked whales." *J. Acoust. Soc. Am.* **24**, 2823–2832.
- Zimmer, W. M. X., Johnson, M. P., Madsen, P. T., and Tyack, P. L. (2005). "Echolocation clicks of free-ranging Cuvier's beaked whales (*Ziphius cavirostris*)." *J. Acoust. Soc. Am.* **117**, 3919–3927.