Tracking beaked whales with a passive acoustic profiler float

Haru Matsumoto[a)]
Cooperative Institute for Marine Resources Studies, Oregon State University, 2030 Marine Science Drive, Newport, Oregon 97365

Christopher Jones
Applied Physics Laboratory, University of Washington, Box 355640, 1013 Northeast 40th Street, Seattle, Washington 98105

Holger Klinck, David K. Mellinger, and Robert P. Dziak
Cooperative Institute for Marine Resources Studies, Oregon State University, 2030 Marine Science Drive, Newport, Oregon 97365

Christian Meinig
National Oceanic Atmospheric Administration (NOAA), Pacific Marine Environmental Laboratory, 7600 Sand Point Way Northeast, Seattle, Washington 98115

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Acoustic methods are frequently used to monitor endangered marine mammal species. Advantages of acoustic methods over visual ones include the ability to detect submerged animals, to work at night, and to work in any weather conditions. A relatively inexpensive and easy-to-use acoustic float, the QUEphone, was developed by converting a commercially available profiler float to a mobile platform, adding acoustic capability, and installing the *ERMA* cetacean click detection algorithm of Klinck and Mellinger [(**2011**). J. Acoust. Soc. Am. **129**(4), 1807–1812] running on a high-power DSP. The QUEphone was tested at detecting Blainville's beaked whales at the Atlantic Undersea Test and Evaluation Center (AUTEC), a Navy acoustic test range in the Bahamas, in June 2010. Beaked whale were present at AUTEC, and the performance of the QUEphone was compared with the Navy's Marine Mammal Monitoring on Navy Ranges (M3R) system. The field tests provided data useful to evaluate the QUEphone's operational capability as a tool to detect beaked whales and report their presence in near-real time. The range tests demonstrated that the QUEphone's beaked whale detections were comparable to that of M3R's, and that the float is effective at detecting beaked whales. © *2013 Acoustical Society of America.*
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I. INTRODUCTION

Beaked whales (family *Ziphiidae*) are found in all the oceans of the world except for high-latitude waters (MacLeod *et al.*, 2006), but little is known about these 20-plus species due to their cryptic appearance, long-duration dives (Tyack *et al.*, 2006), and deep-water habitat (e.g., Falcone *et al.*, 2009). As a result, no quantitative study has been conducted so far to estimate the worldwide population of these species, although populations and behavior of some species of beaked whales have been studied in several selected habitat locations (Balcomb and Claridge, 2001; Aguilar de Soto, 2006; Baird *et al.*, 2009; Falcone *et al*. 2009).

Though mass strandings of beaked whales have been rare, many cases have been documented in Europe and North America over the last half-century (Hildebrand, 2005) and some stranding cases were associated with the operation and use of powerful low to mid-frequency naval sonar (Hildebrand, 2005; Buck and Clavert, 2008; Tyack *et al.*, 2011). The association between strandings and military exercises was noted two decades ago in the Canary Islands by Simmonds and Lopez-Jurado (1991) and later by Frantzis (1998). Recent tagging studies of beaked whales during deep diving suggest a gas embolism as a result of abnormal behavior in response to high-intensity sonar or other threats (Tyack *et al.*, 2006; Johnson *et al.*, 2004). As a result of a public concern and the Marine Mammal Protection Act, the U.S. Navy has been compelled to minimize the impacts of its sonar operations on marine mammals and to mitigate any adverse impacts those operations may have (e.g., Schaffner, 2008). Mitigation has included posting trained lookouts prior to and during an exercise, and reducing sonar levels or ceasing use of sonar altogether if marine mammals are detected within certain distances of the vessel's sonar dome (Dolman *et al.*, 2009). However, visual search range is limited to 1–2 km under favorable weather conditions during daylight hours (Barlow and Gisiner, 2006). Furthermore, the short surfacing times of beaked whales, typically of 2 to 3 min, and the median dive time of 20–30 min (Barlow and Gisiner, 2006) severely limit visual detection probability.

Acoustic methods are now frequently used in part because of some distinct advantages, including the ability to detect animals underwater, to work at night and in poor

[a)]Author to whom correspondence should be addressed. Electronic mail: Haru.Matsumoto@oregonstate.edu

weather, and to record the relevant signals and post-process them if necessary. In the past, acoustic surveys have relied principally on two methods: long-term recordings made using either cabled hydrophone arrays or moored long-term acoustic recorders (Wiggins *et al.*, 2012; Širović *et al.*, 2007; Oswald *et al.*, 2011), and hydrophone arrays towed behind a ship to determine in real time whether marine mammals are present (Rankin *et al.*, 2008). Cuvier's (*Ziphius cavirostris*) and Blainville's (*Mesoplodon densirostris*) beaked whales emit echolocation click sounds of frequencies up to 100 kHz, with source levels at the center of beam of 200–220 dB re 1 μPa^2 at 1 m (Zimmer *et al.*, 2008; Johnson *et al.*, 2004; Madsen, 2005). Beam widths are approximately 15° and the estimated directivity index is in excess of 25 dB (Zimmer *et al.*, 2005), which limits the estimated detection range, and it is unlikely that beaked whale clicks are detected beyond 4 km except in conditions of exceptionally low ambient noise or unusual sound propagation (Zimmer *et al.*, 2008). The spectral and temporal characteristics of these clicks are unique to each species. For example, Blainville's beaked whales generate FM-chirped click trains of 24 to 51 kHz (−10 dB bandwidth) with an inter-click interval (ICI) of 0.2–0.5 s and each pulse lasting approximately 250 μs (Zimmer *et al.*, 2005; Johnson *et al.*, 2006; Küsel *et al.*, 2011). In contrast, Cuvier's beaked whale clicks have a −10 dB bandwidth of 30–40 kHz and a wider ICI range of 0.2–0.7 s (Frantzis *et al.*, 2002).

Utilizing these unique spectral and temporal signal characteristics typical to each species, methods for detecting beaked whale presence autonomously on mobile platforms are now being developed for low-power, high-speed processors. One such approach is to equip ocean gliders with hydrophones and a click-detection algorithm, and to transmit the detection results via satellite to observers onshore to monitor in near-real time (Klinck *et al.*, 2012). Gliders can survey a large area by autonomously navigating the defined area. However, such gliders are relatively expensive, at upwards of \$150 000 each (Rogers *et al.*, 2004; Klinck and Mellinger, 2011), and operating gliders requires a highly trained "pilot." Additionally, commercial gliders' depth ratings are typically 1000 m or less.

An alternative method is to use conventional profiler floats as acoustic platforms (Matsumoto *et al.*, 2006). The vertical profiler float has been a useful tool for the last 10 years for physical oceanography, measuring conductivity and temperature vs depth in the upper 2000 m (Roemmich *et al.*, 2004). The 2000-m rating of the profiler float is advantageous for acoustic monitoring since sound propagation loss is a function not only of range but also of depth of the source and receiver (Ward *et al.*, 2011; Küsel *et al.*, 2011). These floats have been relatively inexpensive (approximately \$14 000–18 000) and have an average lifetime of ~3.5 years using a 10-day cycle or ~130 profiles (Kobayashi *et al.*, 2009).

Combining the acoustic detection algorithm, a digital signal processor (DSP), and satellite communication technologies, a cost-effective method was developed to detect and report the presence of endangered marine mammals in near-real time. Here we describe the performance of a modified acoustic profiler float called the QUEphone (quasi-Eulerian hydrophone), which was configured to run the *ERMA* detection algorithm (Klinck and Mellinger, 2011) to allow detection of odontocetes in near-real time. Two QUEphone*s* were tested in the Navy's Atlantic Undersea Test and Evaluation Center (AUTEC) off the Bahamas, where beaked whales are known to occur. The QUEphone detection results are compared against results from the Navy's Marine Mammal Monitoring on Navy Ranges (M3R) system, which uses a cabled hydrophone array with element spacing of several kilometers. The relationship of signal-to-noise ratio (SNR), click detections, ICI, and estimates of ranges achieved by the QUEphone are discussed.

There are other QUEphone-like acoustic platforms that were built on different float platforms: one for detection of water-borne seismic signal detections (Simons *et al.*, 2009) and another that operates as an acoustic rain gauge (Riser *et al.*, 2006).

II. METHODS

A. System descriptions

The QUEphone is an acoustic platform built on the APEX float® from Teledyne Webb Research Corp., Falmouth, Massachusetts. The APEX's conductivity sensor was replaced by the hydrophone, and the resulting float has only two moving parts: an internal hydraulic motor to control the buoyancy and an airbag to gain an additional flotation at the surface. Buoyancy is controlled by transferring a small amount of oil between an internal reservoir and an external bladder (Roemmich *et al.*, 2004), and the resulting buoyancy change makes the instrument denser or less dense than seawater and causes the instrument to ascend, descend, or maintain constant depth (the "parking" phase) at low cost in energy.

The average ascent/descent speed of the floats is approximately 8.5 cm/s, making the one-way travel time approximately 3.5 h between surface and a typical parking depth of 1000 m. Advantages of operating the float near the sound channel compared to shallow depths include (1) ocean currents are slow there, allowing the acoustic float to stay in a small area for a relatively long period; (2) it is quieter there, as it is relatively far away from surface noise sources; and (3) at mid-latitudes, there is efficient horizontal sound propagation through the SOFAR channel, which occurs at this approximate depth (Urick, 1975, p. 146).

Near the ocean surface, the acoustic system's power is turned off to save power as well as to reduce false detections caused by noise from wind-driven waves, ships, and the float's frequent pump actions. As the QUEphone descends, the acoustic system is turned on below a threshold depth, and stays on while the float is in its descent, ascent, or park-drift phases, turning off as the QUEphone rises above the threshold depth. Occasionally the buoyancy pump is turned on for minor buoyancy adjustment; during this time, the *ERMA* detector is halted and no detection alerts are issued.

The QUEphone's passive acoustic system consists of an omni-directional hydrophone HTI92WB (High Tech Inc.), a pre-amplifier, and a Blackfin® BF537 DSP (Analog Devices). Figure 1 is a flow chart of the system, which digitizes the differential input signal at 125 kHz by a 24-bit sigma-delta

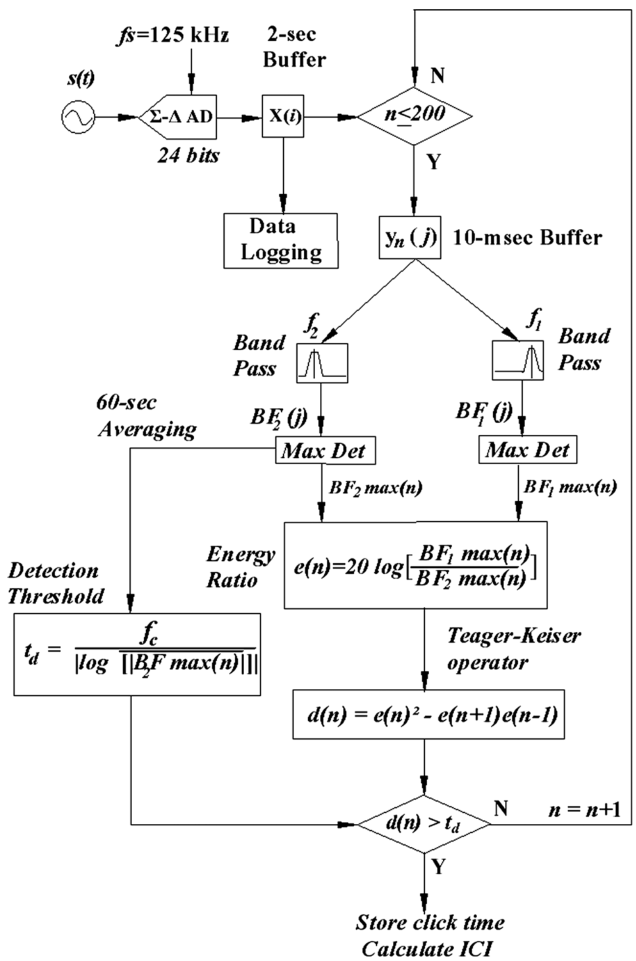

FIG. 1. Implementation of *ERMA* on a DSP-based click detector. The digitized signal is stored in a 2-s buffer and band-passed sequentially in 10-ms increment at two frequencies f_1 and f_2. The Teger–Keiser operator is applied to the energy ratio $e(n)$ between the two band-pass outputs to calculate the detection function $d(n)$, which is indexed and compared with the detection threshold t_d. Only the clicks rising above the mean detection threshold are evaluated and used to estimate the percentage of clicks within the specified ICI range and ML.

(Σ-Δ) analog-to-digital convertor, logs the raw data, and runs *ERMA* to detect odontocete clicks simultaneously. Due to the current DSP system's memory limitation (32 MB), the system processes the signal in 2-s increments instead of the 60-s increments of the MATLAB® implementation (Klinck and Mellinger, 2011). The rest of the processing algorithm remains the same: the 2-s buffer is divided into 10-ms sections and sequentially band-passed by second-order Butterworth filters. Each filter produces time series, $BF_1(j)$ and $BF_2(j)$, with center frequencies at $f_1 = 27$ kHz and $f_2 = 19.5$ kHz, each with 2.5-kHz bandwidth. The algorithm then calculates the energy ratios, $e(n)$, of the two band-passed time series and computes a detection function $d(n)$ using a Teager–Keiser energy operator for each 10-ms section. If any valid click detection occurs during a 60-s window, click time and click statistics are stored. Mean likelihood (ML) and percentage of the clicks falling in the specified ICI range (ICI%) are included for later data transmission. The drawback of this approach is that it does not detect click intervals longer than 2 s.

The number of false positive detections is further reduced by applying several checks to the detector output: Click bouts consisting of less than five clicks are discarded from further analysis. Click bouts consisting of more than five clicks have ICIs measured; if more than 33% of the ICIs within the click bout fall into the range 0.2–0.5 s, a "beaked whale likelihood value" is calculated for the bout. The likelihood value (range 0–1) is derived from the detection amplitude and ICI value of the detected clicks within the bout. An empirical analysis of test data sets indicated that 0.2 is a suitable threshold to detect beaked whale click trains reliably.

The APEX float controller's software (APF9-REV1.3©: propriety source code provided courtesy of the University of Washington) was modified to interface with the DSP and to communicate with a data buoy server on shore via Iridium® satellite when it is at the surface (Fig. 2). The controller periodically polls the DSP system for clicks within the specified ICI range and saves the results in its memory. The detection results along with float status are transmitted to the shore station via bi-directional Iridium modem when the instrument is at the surface.

The DSP board runs the μClinux® operating system at 500 MHz. It digitizes the differential input with 24-bit resolution and, due to the storage limitation, stores only the highest 16 bits of the data on a 128-GB memory card without file

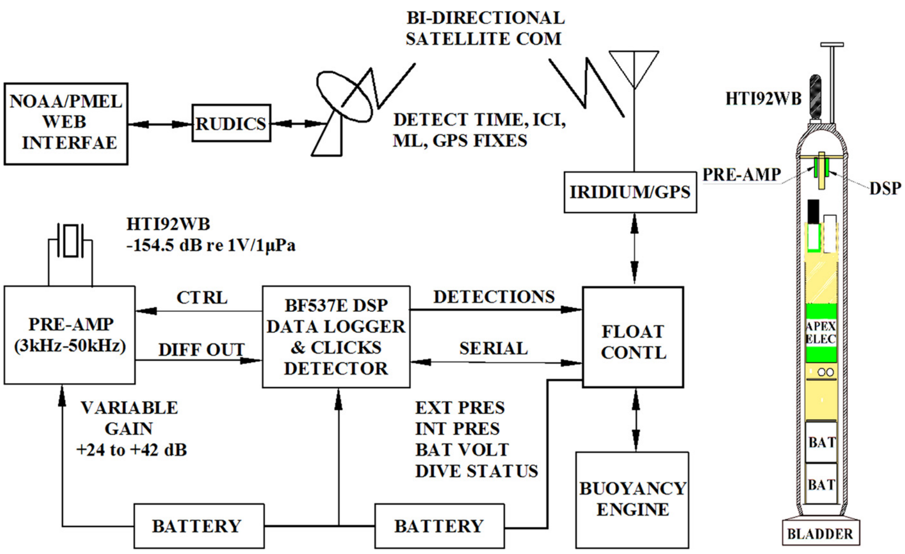

FIG. 2. (Color online) Block diagram of the QUEphone float system. Variable gain pre-amp's output is digitized by the DSP. The data are processed for click detections in real time and stored in a memory card. The float controller periodically checks the DSP for detection updates. The results are sent back to shore via Iridium® satellite and RUDICS server when it surfaces.

compression. Files are named according to the time of creation for convenience. A relatively short file duration (248 s) was chosen so that detection and signal statistics can be evaluated per file after instrument recovery. The pre-amp and DSP together draw ~80 mA at 15 V, and with alkaline batteries, the power budget calculation shows that the system should last approximately 14 days when operating the detector for 20 h per day and conducting one surfacing per day. With lithium batteries, system duration is estimated to be approximately one month; however, the 128 GB file system lasts only approximately seven days with no file compression. If the Free Lossless Audio Codec (FLAC; http://flac.sourceforge.net/, last viewed on 7/23/2012) is implemented, the file system potentially could last 20 days.

B. Field tests

The acoustic system was calibrated from a barge in Lake Washington, Seattle, Washington, in November 2009. The QUEphone was suspended by a tether vertically 2 m below the surface while a series of recorded Cuvier's beaked whale clicks was projected into water by a calibrated transducer (F37 NRL) at 6 -m distance. The system recorded the signal and ran the detector simultaneously. The signals were analyzed to measure the system sensitivity, resulting in an estimated sensitivity of -137 dB re 1 V/μPa at minimum pre-amp gain.

A first open-ocean engineering test was conducted in March 2010 off Kona, Hawaii, where Blainville's beaked whales are known to occur (Schorr *et al.*, 2009). Two QUEphones were deployed on 17 March 2010 and recovered three days later on 20 March after executing 1000-m dives once a day. While at the surface, the QUEphone transmitted detection counts and an engineering log, including depth-vs-temperature profiles, via satellite to NOAA's satellite data buoy web site. Although the 3-day combined click counts exceeded 5700, none had a sufficient ICI% ($\geq$30% for ICI = 0.2–0.5 range) nor the high ML ($\geq$0.2) for the beaked whales, and all were assumed to be dolphin clicks.

C. AUTEC test

Following the Kona test, two QUEphones (Q1 and Q3) were tested in the US Navy's acoustic range, AUTEC, in the Bahamas for a 4-day period in June 2010. The area is known as a habitat of Cuvier's and Blainville's beaked whales, and it is also where the M3R passive-acoustic surveillance system is operated by the Naval Undersea Warfare Center (NUWC). The AUTEC range hydrophone array consists of 93 seafloor hydrophones spaced approximately 4 km apart, covering an area of approximately 1500 km^2 within the basin (Fig. 3). M3R passively monitors ambient sound and locates marine mammals within the range. M3R's detection principle is based on 2048-pt FFT energy detectors (bin size ≈ 47 Hz at 96 kHz sampling rate) and noise-variable adaptive thresholds tuned for detecting appropriate odontocetes including start and end times and ICIs. It produces "binary spectrograms" or "click maps" (Jarvis and Moretti, 2002) first. It then determines if the clicks are of Blainville's beaked whale by (1) presence of maximum energy in the 24–48 kHz band, (2) less than 10% of the binary spectrogram bins in 0–24 kHz are "on," and (3) greater than 1% of the bins in 24–48 kHz bands are "on." Based on visual screening, 90% of extant Blainville's beaked whale groups were correctly identified, and 10% were believed to be false alarms associated with surface craft activities (Moretti *et al.*, 2006). If no click trains occur for more than 180 s, the train is considered ended (time-out-occurred rule, personal communication with S. Jarvis, Naval Undersea Warfare Center). For the purpose of validating the new instrument data, M3R monitored marine mammal vocal activity across the entire range, and detection results were made available to us.

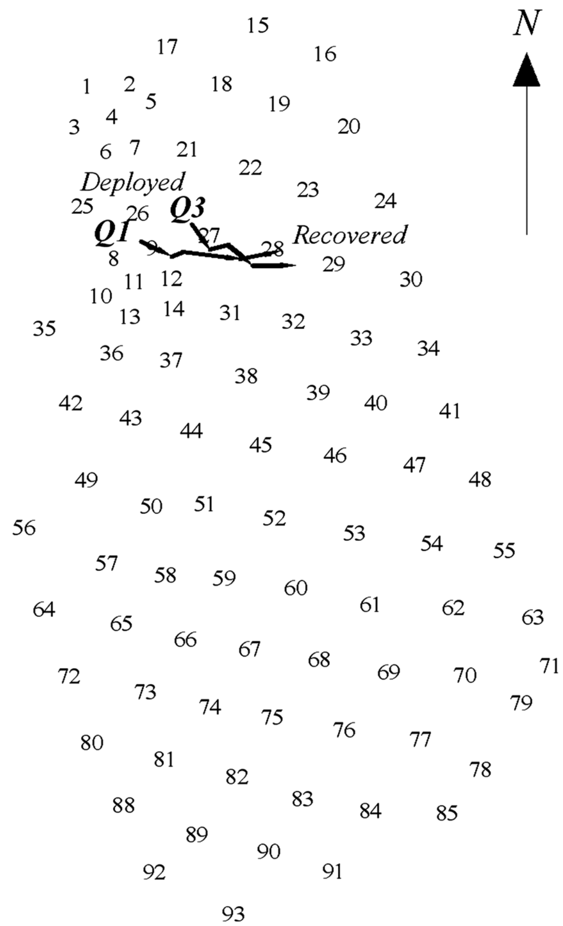

FIG. 3. The AUTEC seafloor hydrophone array and the QUEphones' surface positions on each day. Q1 and Q3 were deployed near hydrophone H9 and H27, respectively, on June 7, 2010. They drifted at a depth of ~1000 m towards H28 and were recovered near H28 on June 11, 2010 after moving approximately 6 and 3 km, respectively. Inset shows the estimated horizontal paths of the floats between known surface positions.

The sensitivity of Q1's and Q3's acoustic systems was set to -131 dB re V/μPa and -125 dB re V/μPa, respectively, from 3 to 50 kHz. The *ERMA* detector was configured to respond to ICI in the range of 0.2–0.5 s, with ICI% of at least 30%, and with ML $\geq$ 0.2 for Blainville's beaked whale, which was the predominant beaked whale species at AUTEC (Moretti *et al.*, 2006). To minimize possible time loss associated with recovery and redeployment operations if the floats drifted outside of the range, the two QUEphones were deployed in the center of the northern part of the range near hydrophones 9 and 27, where the bottom depth was approximately 1750 m. Deployment occurred on 7 June 2010 at 15:30 and 16:00 GMT, respectively, from the R/V *Ranger* (Fig. 3). Both instruments were configured to dive, turn on the *ERMA* detector when they passed 450 m depth, descend to 1000 m, and maintain constant depth there for ∼17 h/day. They were configured to surface once a day on a regular schedule and transmit data, although they can also be programmed to return to the surface when beaked whale click detection counts reach a certain threshold. The straight lines in the figure are the paths each instruments drifted estimated from the GPS positions at the beginning and end of dives. The wind was extremely calm and the Beaufort sea state was nearly 0 for the entire operation. The QUEphones' positions and detections were monitored from the Andros Island range facility in communication with the NOAA buoy data center. Q1 and Q3 drifted east-southeast at an average speed of approximately 2 cm/s, and after 4 days both were recovered by the R/V *Ranger* on 11 June 2010 near hydrophone 28 (hereon referred to as H28).

III. RESULTS

A. Ambient noise level

The AUTEC noise spectrum is shown (in red) in Fig. 4. It was observed by Q3 during the quiet periods of 10 June 2010 00:02 when free-drifting at 1005 m. No marine mammal calls were present in this record. Q3's noise spectrum in AUTEC was extremely low as a result of calm weather and unique bathymetric conditions there, i.e., a deep water basin surrounded by islands and shallow water that effectively blocks outside noise. At 30 kHz, the noise level was 17 dB re 1 μPa^2/Hz, which was equivalent to the sea-state-0 noise level (NL) of Urick (1975) (p. 188). This makes AUTEC one of the quietest ocean environments in the world. Although the system noise was relatively low, it was still affected by digital hardware noise at 32.768 kHz, as shown by a minor blip in Fig. 4. The extremely low noise conditions at AUTEC, as discussed by Ward *et al.* (2011), should help for detection of beak whale clicks at ranges longer than

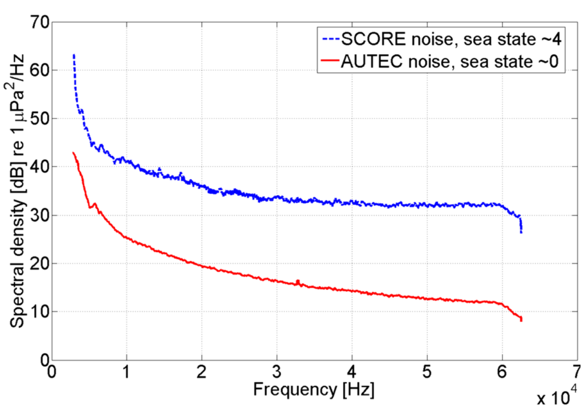

FIG. 4. (Color online) Top curve (blue dash), Q3's ambient noise spectral density re 1 μPa^2/Hz at AUTEC on June 9, 2010, 00:02 GMT (sea state ∼0) when it was drifting at 1005 m and bottom curve (red), SCORE's noise spectrum on January 5, 2011, 04:01 GMT (sea state 4) at ∼770 m when Q3 was still descending at ∼8 cm/s. 8-s long time series were analyzed by FFT with a 100-Hz moving average.

the 4-km limit discussed by Zimmer *et al.* (2008); their estimate was based on a noise level of 30 dB re 1 μPa^2/Hz at 40 kHz. In comparison, the noise spectrum at another U.S. Navy range, the Southern California Offshore Range (SCORE) on 5 January 2011 as measured by the same Q3 (in blue, Fig. 4) at 770 m while it was still descending at ∼8 cm/s was approximately 34 dB re 1 μPa^2/Hz at 30 kHz, and between 10 to 58 kHz, approximately 16–20 dB higher than that of the AUTEC level as a result of high wind (∼5.0 to 5.8 m/s at NOAA buoy 46086, equivalent to sea state 3–4).

B. Click detection counts

The two acoustic floats drifted eastward toward hydrophone H28 so that it is appropriate to compare the performance of the two QUEphones against M3R's record for H28. Table I shows Q1's and Q3's daily beaked whale click counts from the *ERMA* algorithm. The 4-day trends are similar among the three systems. In regard to the total number of click detections, Q3's click counts are similar to that of H28, whereas Q1 detected approximately half as many as Q3. The probability of detections primarily depends on SNR, which is affected not only by transmission loss and ambient noise, but also by the orientation of the whale. Blainville's beaked whales have a projected sound beam limited to a ∼15° cone (Zimmer *et al.*, 2005), with an approximately 25-dB difference between the center level and off-beam levels. Depth of the source and receiver also affects propagation loss by refraction.

Figures 5(a) and 6(a) compare the click counts by Q1, Q3, and M3R's H28. They also show the distances of Q1 and Q3 relative to H28 (in pink) and depth range (dotted gray). Q1 started profiling at a distance of 6.4 km from H28, whereas Q3 started at 3.7 km. To simplify the analysis, an assumption was made that if the time of detections by the two systems (QUEphone and M3R) coincide within two minutes, they were detecting the same click train from the same source. Following the same 180-s time-out-occurred rule of M3R, the QUEphone click counts are grouped together as the same detection if click train was continuous for more than 180 s. Figures 5(b) and 6(b) show the root-mean-squared (RMS) sound pressure levels (SPL_{RMS}) of Q1 and Q3 in dB re 1 μPa,^{2} respectively, between 25.75 kHz and 28.25 kHz as a function of time.

Both the click counts and the SPL_{RMS} of QUEphones whose clicks were interpreted as beaked whales by QUEphones and confirmed by M3R gradually increased as they

TABLE I. Daily beaked whale's click counts by Q1, Q3, and the AUTEC M3R's count for hydrophone H28 from June 7 through June 11, 2010.

Date	Q1	Q3	H28
7-Jun	72	107	389
8-Jun	680	6433	4844
9-Jun	661	214	882
10-Jun	2613	5478	5788
11-Jun	7911	7484	6036
Total	11 937	19 716	17 939

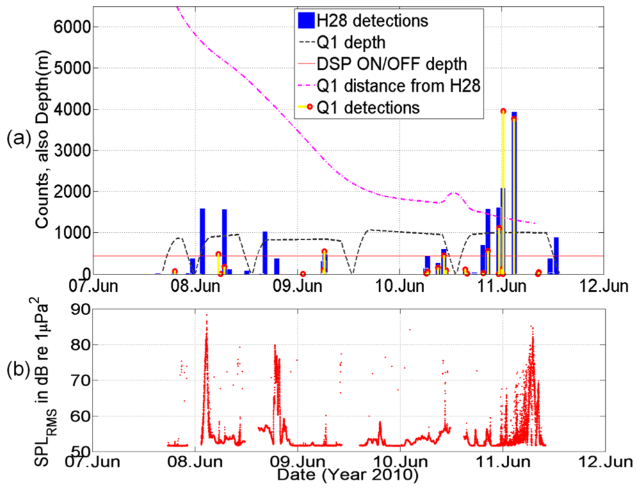

FIG. 5. (Color online) (a) SPL_{RMS} level of Q1 in the 25.75–28.25 kHz band in dB re 1 μPa^2. (b) Beaked whale click counts for Q1 (yellow bars with red circles) and AUTEC fixed hydrophone H28 (blue bars). Dotted line (gray) is the depth of Q1 in meters. Horizontal line (brown) is the depth (450 m) at which the acoustic system was turned on/off. Dashed curve (pink) shows the approximate distance in meters between Q1 and H28.

got closer to H28. These trends can be interpreted as beaked whales being active in the vicinity of H28. The DSP system was turned on deeper than 450 m [indicated by horizontal lines in Figs. 5(a) and 6(a)]. Compared to the M3R results from hydrophone H28, Q1 and Q3 missed a few bouts of calls because the acoustic system was powered off at depths shallower than 450 m, and also the QUEphones were somewhat distant from H28 and were not exposed to the same acoustic environment.

As the QUEphones drifted closer to H28, the match between the QUEphones and M3R improved significantly as they became exposed to the same acoustic environment. From 23:20 on 10 June to 03:00 on 11 June, the number of click counts and the temporal pattern of click bouts are nearly identical between the two systems. There were several

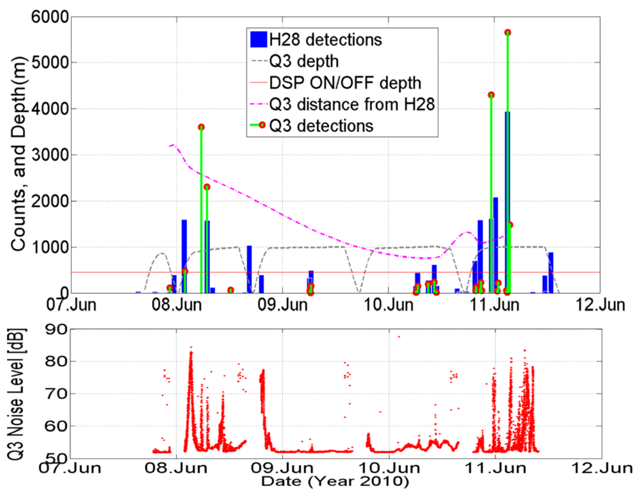

FIG. 6. (Color online) (a) SPL_{RMS} noise level of Q3 in the 25.75–28.25 kHz band in dB re 1 μPa^2. (b) Beaked whale click counts for Q3 (green bars with red circles) and AUTEC hydrophone H28 (blue bars). Dotted line (gray) is the depth of Q3 in meters. Horizontal line (brown) is the depth (450 m) at which the acoustic system was turned on/off. Dashed curve (pink) shows the approximate distance in meters between Q3 and H28.

occasions when the RMS NL exceeded 70 dB ($f_c = 27$ kHz with 2.5 kHz bandwidth). Calls were by species other than beaked whales, based on ICI% and ML values. Although noise levels from the other species were high on 10 June, between 4:00 a.m. and 11:00 a.m. no beaked whale clicks were reported by either system, suggesting that the detection capability of the QUEphone's DSP based *ERMA* system was comparable to that of M3R.

C. SNR vs click detection counts

To evaluate the performance of *ERMA* further, SNRs at times of continuous click trains are compared. SNR may be defined as

$$\frac{S}{N} = 10 \log\left(\frac{\text{signal}+\text{noise}}{\text{noise}}\right). \tag{1}$$

The "signal" is the maximum SPL_{RMS} at 27 kHz with 2.5-kHz bandwidth within ±3 min at the time of detections. The "noise" here is the SPL_{RMS} of background sound sources in the same frequency band as the signal. Instead of computing the instantaneous noise level within *ERMA*'s 10-ms time windows, a period too short to obtain an accurate noise estimate, noise levels were computed each 1 s throughout the recording, and the minimum within a 30-min time window was used as the noise level. This method allowed estimation of the noise floor level to not be affected by ephemeral marine mammal sounds or passing ships. The 30-min minimum was chosen because it is in the range of a typical beaked whale's dive time of 20–30 min (Barlow and Gisiner, 2006). The average of the minimum RMS ambient NLs was 51.7 dB re 1 μPa^2 for Q1 and 52.1 dB for Q3. Standard deviations were ±0.17 dB and −3.2 dB/+2.3 dB for Q1 and Q3, respectively. The standard deviations were small as a result of extremely calm and steady weather (sea state ∼0) throughout the 4-day experiment. Figure 7 shows the SNRs of the detections on Q1 and Q3, which were confirmed by the M3R detections on H28 by time association. There are four groups of clicks. The lowest SNRs with a valid *ERMA* detection occurred for Q1 with +1.5 dB at ∼01:19 on 9 June with 9 clicks in a 248-s file (ICI% = 62%, ML = 0.3), and for Q3 with +2.1 dB at ∼06:37 on 7 June with 101 clicks in

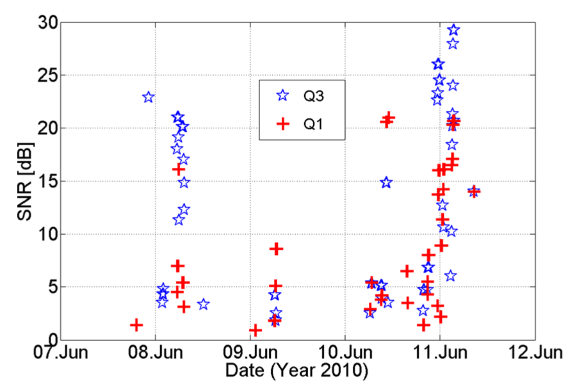

FIG. 7. (Color online) SNRs at 27 kHz with 2.5-kHz bandwidth of the click signals received by Q1 [red (crosses)] and Q3 [blue (stars)] during the AUTEC experiment.

a 248-s file (ICI% = 56%, ML = 0.3). The highest SNR was 21 dB for Q1, which occurred at 03:14 on 11 June with 805 clicks (ICI% = 53.7%, ML = 0.4), and 29 dB for Q3 at 03:22 on 11 June, with 1231 clicks (ICI% = 34%, ML = 0.2). For both QUEphones, despite the high clicks counts near H28, no SNR peaks were higher than 29 dB, suggesting a strongly stratified sound channel was affecting the propagation loss (Ward *et al.*, 2011; Küsel *et al.*, 2011).

To examine detection statistics in relation to SNR, *ERMA* click counts were evaluated per 248-s file and plotted as a function of SNR in Figs. 8 and 9. There were 81 segments whose detection criteria satisfied ML > 0.2 and ICI% > 30%. The highest number of clicks was 1231 with ML of 0.2, and 34% of clicks with ICI range of 0.2–0.5 with SNR = 29 dB. The total of 1231 clicks was close to the highest possible beaked whale click counts of 1240 (=248/0.2) for a duration of 248 s, assuming the minimum ICI = 0.2. The ICI median was 0.4, indicating that multiple beaked whales were making clicks at the same time. The upper bound of the data scatter (dashed line) closely follows the probabilistic limit of detection and resembles the asymptotic decay of probability of detection as the SNR drops as described by Ward *et al.* (2011).

Figure 9(a) shows SNR vs ICI% for the clicks with ICI in the range of 0.2–0.5 s. Figure 9(b) shows the SNR vs ML of detections, the latter computed with single-digit precision. No apparent relationships were found between SNR and ML, suggesting the ML parameter is independent of the SNR and *ERMA* performs relatively well in the presence of noise, at least in AUTEC's low-ambient-noise environment. For ICI%, on the other hand, there is a slight negative dependence on SNR, i.e., higher SNRs have lower ICI%. Again, this suggests the possibility of multiple beaked whales clicking simultaneously, making the apparent ICI shorter.

D. Detection range

Ward *et al.* (2011) developed a simple noise model by combining other noise process models including frequency-dependent surface noise NL_{surf} by Kurahashi and Gratta (2008), wind noise N_{ss} as a function of frequency (f) and sea state (ss) by Short (2005), hydrophone depth NL_{depth} by Lurton (2002), and random thermal noise ($NL_{thermal}$) by

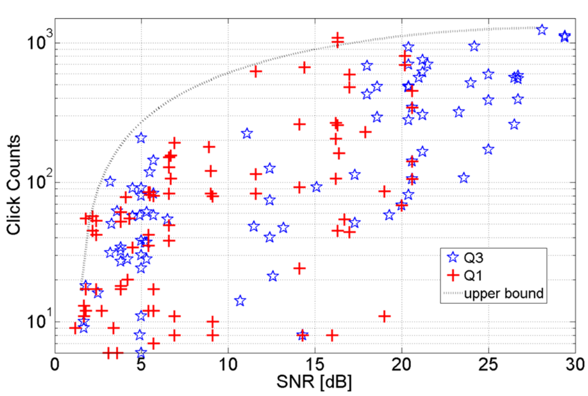

FIG. 8. (Color online) SNRs vs click counts of Q1 [red (crosses)] and Q3 [blue (stars)] in 248-s time bins. The highest SNR was 29 dB.

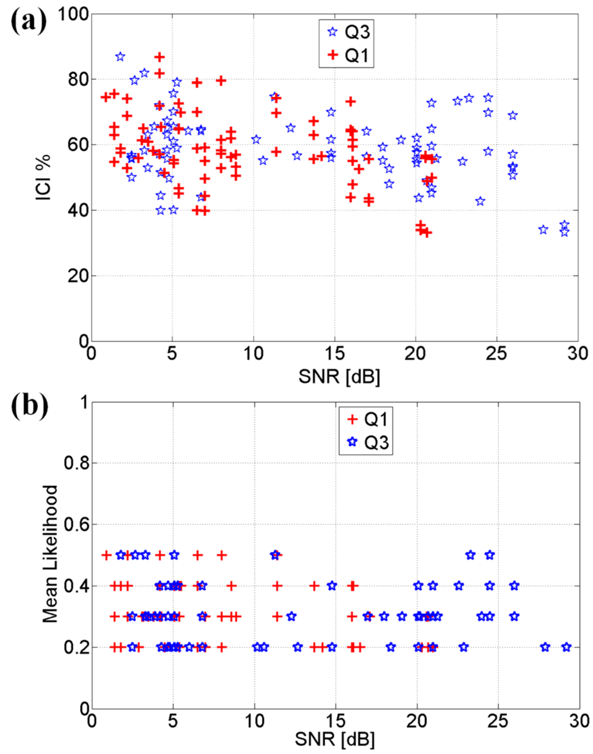

FIG. 9. (Color online) (a) SNR vs percentage of ICIs within 0.2–0.5. (b) SNR vs mean likelihood (ML). Only the clicks whose ICI% are ≥30% and ML ≥ 0.2.

Lurton (2002). Following the same procedure as Ward *et al.* (2011), assuming a beaked whale source level (SL) of 210 dB (Moretti *et al.*, 2006), directivity index (DI) of 25 dB (Zimmer *et al.*, 2008), source bandwidth (BW_s) of 35 kHz (Moretti *et al.*, 2006), detection threshold (DT) of 5 dB (Ward *et al.*, 2011), and the *ERMA* processor's bandwidth (BW_p) of 2.5 kHz, the maximum detection ranges R of the system were calculated using a spherical spreading model. The absorption coefficient α characterizing absorption per kilometer is a function of frequency, pH (ph), salinity (sal), temperature (T), and hydrophone depth (hd) (Ainslie, 1998). It is ~5.5 dB/km at $f = 27$ kHz, $hd = 1000$ m, pH = 8.0, salinity = 35‰, and temperature = 6 °C. The DT based on a simple sonar equation with spherical spreading transmission loss (TL) is

$$\begin{aligned} DT &= SL - \alpha(hd, f, T, ph, sal)R/1000 - 20\log_{10}R \\ &\quad - NL(f, ss, hd) - DI + 10\log(BW_p/BW_s), \end{aligned} \tag{2}$$

where R is range in meters. Setting DT = 5 dB and solving for R in sea states 0 to 7 yields the maximum range for a given sea state. Factors not included in this equation include anthropogenic noise, propagation effects of an inhomogeneous sound velocity profile between the source and receiver, and surface reflections. Anthropogenic noise could be significant depending on the distance to the shipping lanes, ocean depth, and the seafloor reflection coefficient. Figure 10 shows the detection ranges when only modeled noise sources are considered at the receiver-source depths of 1000 m ($T = 6$ °C) and 500 m ($T = 12.5$ °C), respectively. If the detection frequency is high, e.g., 40 kHz as used by Zimmer *et al.* (2008),

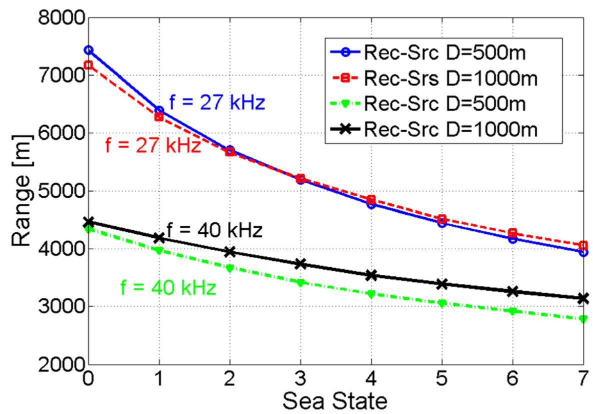

FIG. 10. (Color online) Maximum ranges of beaked whale detection at receiver-source depth of 500 and 1000 m by *ERMA* detector as a function of sea states. Top blue (solid) and red (broken) lines are based on detection frequency at 27 kHz and bottom black (solid) and green lines (broken) are at 40 kHz.

$\alpha \approx 10$ dB/km with the same conditions, which makes R significantly smaller. Additionally, a shallow receiver depth at 40 kHz makes the detector more susceptible to surface noise, making the detection range slightly shorter. No propagation effects due to the sound velocity profile are considered in these cases. Also, the receiver and source are assumed to be at the same depth.

IV. RESULTS AND DISCUSSION

Field tests were conducted to evaluate a new acoustic float, the QUEphone, for its performance using the onboard *ERMA* system to detect beaked whale clicks. The operation of the acoustic float, including mission programming, deployment, and recovery, are relatively simple and can be mastered in a short training session. During the AUTEC range test, two QUEphones, Q1 and Q3, were deployed. They repeated once-a-day cycles of descent-park-ascent between the surface and the sound channel for four days. A power budget calculation shows that ~14-day operation is possible with alkaline batteries and ~30-day operation with lithium batteries. Reviewing the detections of M3R on AUTEC's fixed hydrophone H28 and *ERMA* on the two QUEphones' hydrophones shows that detections were comparable, despite the fact that H28 was a fixed seafloor hydrophone and Q1 and Q3 were free-drifting platforms; the latter were released ~6 km (Q1) and ~3 km (Q3) from H28 and recovered ~1 km from H28. The lowest SNR with click detections validated by M3R was 1.5 dB, and the highest was 29 dB. No SNR was higher than 29 dB, even for periods with large numbers of clicks. Ward *et al.* (2011) described an eigenray propagation model when the source was at a depth of 800 m and receiver at 1630 m in the AUTEC environment and found that the highest SNR was ~27 dB. In the water with a stratified sound channel, a strong refraction effect of the sound channel may limit the detection range, and caution is needed in applying spherical spreading loss to estimate the range or SNR performance. High click counts in the high-SNR region of Fig. 9 suggest that not just one beaked whale was nearby, but rather the possibility that multiple beaked whales were clicking simultaneously, thus making apparent ICIs shorter. The ICI criterion used here is useful for a single animal but may lead to a false negative result if multiple whales are clicking within a short range.

The AUTEC validation test demonstrated the usefulness of the acoustic float as an inexpensive research platform as well as mitigation tool useful for the protection of odontocetes, including beaked whales. Comparing the AUTEC and SCORE ranges' ambient noise levels, there was 16–20 dB difference as a result of wind conditions and anthropogenic noise input.

One application of autonomous real-time acoustic platforms is to provide a warning when beaked whales are present. Such a warning system would require multiple platforms spaced so as to provide a high likelihood of detecting any whale present. The optimum spacing of multiple acoustic floats or similar instruments for such monitoring is largely dependent on detection distance, which in turn is dependent on sea state, detection frequency, anthropogenic noise, and propagation conditions. If multiple QUEphone-like instruments are deployed in a quiet area such as AUTEC, assuming steady current and using 50% overlap of between instrument coverage and an operating frequency of 27 kHz, optimum spacing would be approximately 7 km at sea state 0 and ~5 km at sea state 4. In contrast, in areas with high shipping noise, such as SCORE, spacing would need to be significantly closer.

QUEphone performance is constrained by both power and memory requirements. The current DSP, running at 500 MHz, offers more than enough computing power for *ERMA*-based detection, and could, in the future, include a species classifier. Power consumption now limits operation to ~14 days; further reduction of power use would lengthen this duration. One option is to reduce the clock speed. In addition, the system could be improved with a larger memory of 64 MB. This would help to improve the maximum measurable ICI, currently limited to 2 s, to allow detection of species with longer ICIs such as sperm whales. As lower-power processors (e.g., the BF592® "Blackfin" from Analog Devices is ~50 mW) are becoming available, and as the reliability of the *ERMA* detection algorithm becomes better known, an alternative to extend operation life would be to make the QUEphone a detection-only system with limited mass data storage. This would expand the range of applications for this autonomous acoustic float and allow a wide range of uses for cetacean research and conservation.

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