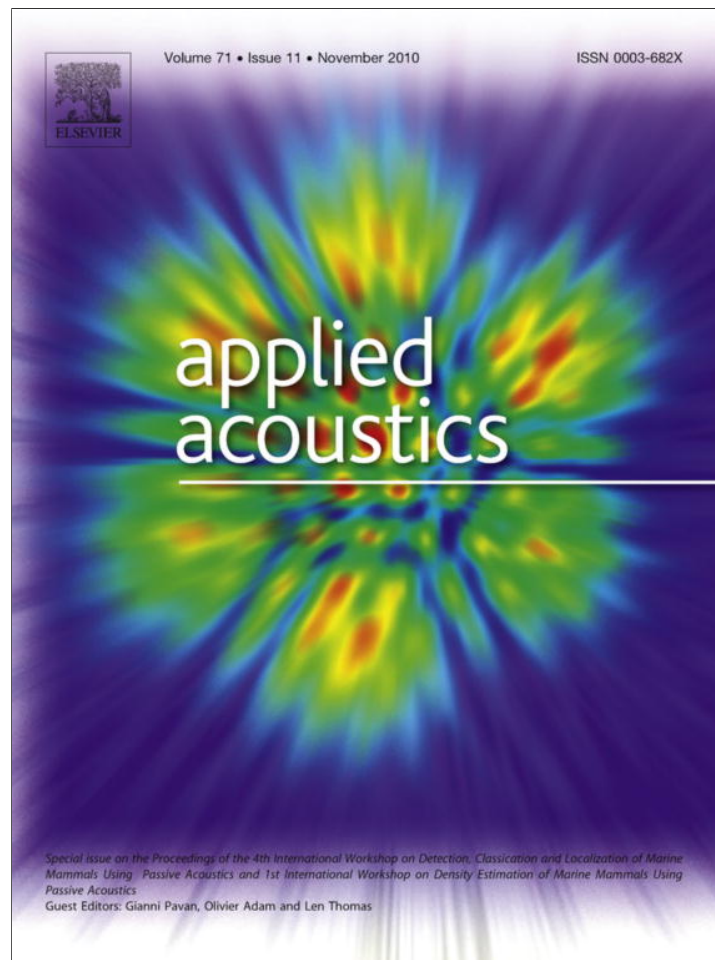


Provided for non-commercial research and education use.
Not for reproduction, distribution or commercial use.



This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

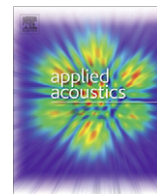
In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

<http://www.elsevier.com/copyright>



Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Comparison of beaked whale detection algorithms

Tina M. Yack^{a,b,c,*}, Jay Barlow^a, Marie A. Roch^d, Holger Klinck^e, Steve Martin^f, David K. Mellinger^e, Douglas Gillespie^g^a National Marine Fisheries Service, Southwest Fisheries Science Center, 3333 North Torrey Pines Court, La Jolla, CA 92037, United States^b Joint Doctoral Program in Ecology, San Diego State University & UC Davis, 5500 Campanile Dr., San Diego, California 92182, United States^c Bio-Waves Inc., 517 Cornish Dr., Encinitas, CA 92024, United States^d Department of Computer Science, San Diego State University, 5500 Campanile Dr., San Diego, CA 92182, United States^e Cooperative Inst. For Marine Resource Studies, NOAA Pacific Marine Environmental Lab, Oregon State University, 2030 SE Marine Sci. Dr., Newport, OR 97365, United States^f SPAWAR Systems Center San Pacific Code 71510, 53560 Hull Street, San Diego, CA 92152, United States^g Sea Mammal Research Unit, Scottish Oceans Institute, University of St. Andrew Fife, KY16 8LB Scotland, United Kingdom

ARTICLE INFO

Article history:

Available online 8 July 2010

Keywords:

Beaked whale
Detection
Classification
Towed-array
Passive acoustic monitoring
Echolocation

ABSTRACT

Due to recent advances in passive acoustic monitoring techniques, beaked whales are now more effectively detected acoustically than visually during vessel-based (e.g. line-transect) surveys. Beaked whales signals can be discriminated from those of other cetaceans by the unique characteristics of their echolocation clicks (e.g. duration >175 μ s, center frequencies between 30 and 40 kHz, inter-click intervals between 0.2 and 0.4 s and frequency upsweeps). Furthermore, these same characteristics make these signals ideal candidates for testing automated detection and classification algorithms. There are several different beaked whale automated detectors currently available for use. However, no comparative analysis of detectors exists. Therefore, comparison between studies and datasets is difficult. The purpose of this study was to test, validate, and compare algorithms for detection of beaked whales in acoustic line-transect survey data. Six different detection algorithms (XBAT, Ishmael, PAMGUARD, ERMA, GMM and FMCD) were evaluated and compared. Detection trials were run on three sample days of towed-hydrophone array recordings collected by NOAA Southwest Fisheries Science Center (SWFSC) during which were confirmed visual sightings of beaked whales (*Ziphius cavirostris* and *Mesoplodon peruvianus*). Detections also were compared to human verified acoustic detections for a subset of these data. In order to measure the probabilities of false detection, each detector was also run on three sample recordings containing clicks from another species: Risso's dolphin (*Grampus griseus*). Qualitative and quantitative comparisons and the detection performance of the different algorithms are discussed.

© 2010 Elsevier Ltd. All rights reserved.

1. Introduction

Beaked whales are notoriously elusive and difficult to study, especially using visual survey methods. Until recently, little was known about beaked whale vocalizations, however thanks to the pioneering work of Peter Tyack and Mark Johnson using Dtags, the echolocation signals of two beaked whale species (*Ziphius cavirostris* and *Mesoplodon densirostris*) are well characterized [1–4]. These species are highly vocal at depths between roughly 200 and 1300 m [2]. Acoustic methods can now be routinely used to detect diving beaked whales [5].

Echolocation clicks are the most promising method for detection and tracking of beaked whales due to their unique

characteristics, such as long duration (>175 μ s) clicks with center frequencies between 30 and 40 kHz and inter-click intervals between 0.2 and 0.4 s [1,2,4]. Additionally, beaked whale clicks typically show a frequency upsweep [1,2,4]. These unique characteristics of beaked whale echolocation clicks make these signals ideal candidates for testing automated classification algorithms.

There are several different beaked whale automated detectors currently available for use. However, no comparative analysis of detectors exists. Therefore, comparison between studies and datasets is difficult. The purpose of this study was to test, validate, and compare algorithms for detection of beaked whales in acoustic line-transect survey data.

2. Background

Southwest Fisheries Science Center Surveys (SWFSC), conducts visual surveys to estimate cetacean abundance. In 2000 passive

* Corresponding author at: National Marine Fisheries Service, Southwest Fisheries Science Center, 3333 North Torrey Pines Court, La Jolla, California 92037, United States. Tel.: +1 858 334 2867.

E-mail address: tina.yack@noaa.gov (T.M. Yack).

acoustic monitoring was integrated into SWFSC survey methods. This has resulted in an increase in both the rate and distance of marine mammal detection and enhanced our understanding of cetacean behavior [6]. These added benefits have made passive acoustic methods an integral and valuable part of SWFSC's marine mammal monitoring protocol.

On a typical survey, visual survey teams, consisting of three experienced observers rotate among two 'big-eye' 25 × 150 power binoculars and a data recording position. Observation takes place during daylight hours, typically in Beaufort sea states between 0 and 5. Meanwhile, down below decks, an acoustic technician monitors signals from two of the array hydrophones using stereo headphones and a real-time scrolling spectrographic display.

There are currently several acoustic beaked whale detection algorithms available. During this study six detection algorithms were evaluated and compared: (1) Ishmael, (2) XBAT, (3) PAMGUARD, (4) ERMA, (5) GMM detector, and (6) FMCD detector. The algorithms range from simple detectors to complex statistical classifiers. Detailed descriptions of each detector are provided in the following section.

3. Materials and methods

The six detection algorithms were tested on a dataset of eight SWFSC recordings. The dataset was compiled from a SWFSC dolphin survey conducted in the eastern tropical Pacific Ocean from 20 August to 28 November 2007. This survey was conducted in passing mode, meaning that the ship continued along a straight path and did not turn for visual sightings. Recordings were made from a custom-built, four-element hydrophone array (frequency response flat from 500 Hz to 48 kHz ± 5 dB; sensitivity –155 dB re 1 V/μPa) towed at a depth of 4–6 m approximately 300 m behind the NOAA ship *McArthur II* while traveling at a survey speed of 10 kt (18 km h⁻¹) during daylight hours and in sea states of Beaufort 6 or less. Data were recorded into 5-min, four channel, wav formatted files at a 16 bit, 96 kHz sample rate using Raven software (www.birds.cornell.edu/brp/raven/).

The test data included three days of data with beaked whale sightings and five confirmed Risso's dolphin (*Grampus griseus*) encounter periods from different days (Table 1 and Fig. 1). The beaked whale sighting days encompassed over 28 h of recordings and also contained other dolphin species. The Risso's dolphin encounter recordings encompassed approximately three hours of recordings and were included in the analysis to assess false detection probabilities. Risso's dolphin recordings were chosen because these signals are of the most difficult to distinguish from beaked whale signals found in the Pacific Ocean.

Three of the detectors are publically available; Ishmael, PAMGUARD and XBAT (Mellinger [7] and Gillespie [8]; www.xbat.org). Ishmael is a freeware, multi-purpose acoustic analysis tool. There are several detection methods available for use in Ishmael, but for this dataset an energy summation detection method was used

[7]. This method sums values in each vertical strip of the spectrogram. The ratio between the energy in two user-specified frequency bands is then used as the detection function [7]. PAMGUARD [8] (www.pamguard.org), is an initiative currently funded by the OGP E&P Sound and Marine Life project to provide standard software to address the needs of both developers and users of Passive Acoustic Monitoring (PAM) systems. The PAMGUARD click and whistle detectors are closely based upon the International Fund for Animal Welfare (IFAW) RainbowClick [9] and Whistle programs (available from www.ifaw.org/sotw). Several detectors are available for PAMGUARD, but here we used an energy band comparison method. Using the PAMGUARD click detector an energy band classifier was configured with user defined settings for beaked whale click detection. The classifier checks each click against the user-specified click types (i.e. beaked whale) sequentially. Clicks are then classified according to energy band comparison and peak frequency position. Energy band comparison compares the summed acoustic energy in two user defined frequency bands (test band and control band). The ratio of the energy in the test band must exceed that of the control band by a user defined number of decibels to count as a detection. XBAT (www.xbat.org) is an extensible sound analysis application and MATLAB platform for developing sound analysis tools. It is open-source, licensed under the GPL. XBAT also has many detectors available but for this study the data template method was used. This method uses a time cross-correlation sequence between an example event and the sound, and creates events corresponding to the significant peaks. Templates were created from Cuvier's (*Z. cavirostris*) and Blainville's (*M. densirostris*) recordings provided by MobySound (www.mobysound.org).

The other three algorithms are independent developments: The Gaussian Mixture Model (GMM) detector written by Marie Roch is a classifier that uses a Gaussian Mixture Model to represent each species. For this experiment, models were generated for Blainville's beaked whales, Risso's dolphins and Pilot whales. Likelihood ratios were generated by sample as beaked whale, bottlenose dolphin, Risso's dolphin or pilot whale. The frequency modulated echolocation click detector (FMCD detector), written by Steve Martin of SPAWAR detects beaked whale clicks in three primary stages. A screening stage determines the standard deviation (σ) of a 20 kHz high pass filtered signal in 1 s windows and further examines any .5 ms window where the signal exceeds $\pm 7\sigma$. The second stage looks for clicks with frequency upsweep modulation characteristics for each screener detection. A final test verifies that the inter-click interval is appropriate for beaked whale clicks (0.2–0.5 s apart). The inter-click interval test helps to reject dolphin clicks that typically have a shorter inter-click interval. ERMA (Energy-Ratio Mapping Algorithm), written by Holger Klinck, was developed primarily for use in gliders and, consequently, has low computational cost. It calculates the ratio between the energies in two frequency bands of interest, one above and one below the energy rise in the power spectrum (i.e. below 20 k and above 35 k for *Mesoplodon* sp.). For more detailed descriptions of these detectors the algorithm authors may be directly contacted.

The detectors were compared qualitatively and quantitatively. The qualitative comparison was based on nine factors; public availability, computational platform, real-time processing, localization methods, cost, detection quality measurement scores provided, inter-click interval testing, classification ability, and spectrographic display ability.

Next a quantitative evaluation was performed to examine beaked whale detection event peaks and evaluation of correct and false positive detections. Correct and false positive detection rates were calculated using a subset of 60 min of data from two of the trial days. For each 2-min time bin the presence of beaked whale clicks was confirmed by an experienced acoustic technician.

Table 1
Dataset recordings. Table lists the recordings used for the beaked whale algorithm comparison trials.

| Trial type | Recording date | Recording duration (min) |
|-----------------|----------------|--------------------------|
| Beaked whale | 9/7/2007 | 525 |
| Beaked whale | 9/11/2007 | 570 |
| Beaked whale | 11/17/2007 | 600 |
| Risso's dolphin | 9/27/2007 | 40 |
| Risso's dolphin | 11/9/2007 | 30 |
| Risso's dolphin | 11/13/2007 | 15 |
| Risso's dolphin | 11/17/2007 | 25 |
| Risso's dolphin | 11/17/2007 | 75 |

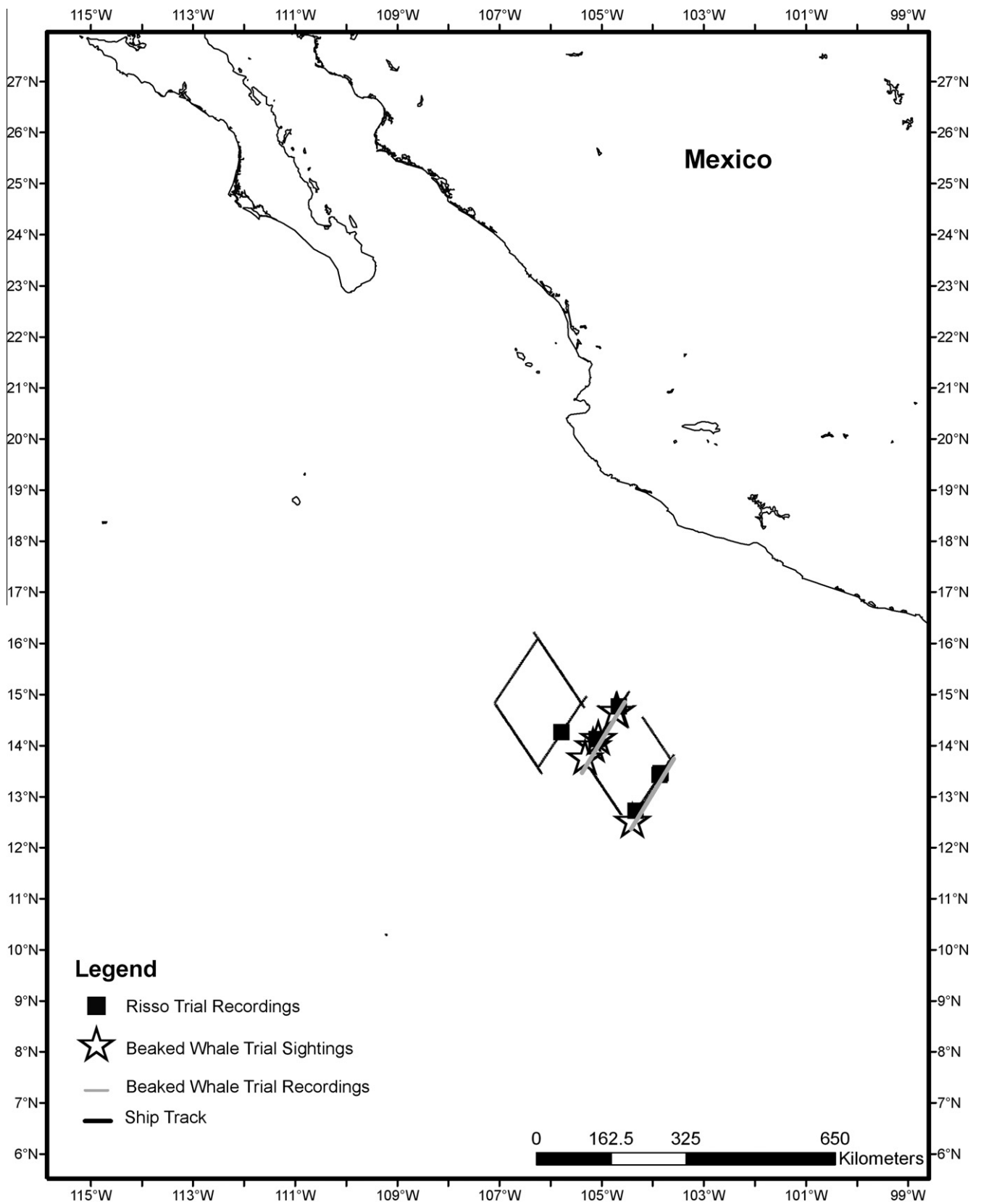


Fig. 1. Map showing where the data used in this study was obtained. The acoustic effort for the survey is shown as black lines. The map depicts the location of dataset recordings used for beaked whale trials (sightings indicated by white star and full recordings indicated by gray line) and Risso's dolphin trials (black square).

For each time bin where beaked whale clicks were confirmed, presence or absence of beaked whale click detections was determined and noted for each detector. The results of the data from the Ish-

mael and ERMA detections were post-processed to filter out detections with inter-click intervals less than 0.2 s and greater than 0.5 s (Ishmael-2 and ERMA-2).

Table 2
Qualitative evaluation table. Provides a qualitative assessment of the six detectors tested based on nine factors; public availability, computational platform, real-time processing, localization methods, cost, detection quality measurement scores provided, inter-click interval testing, classification ability, and spectrographic display ability.

| Factors | Ishmael | XBAT | PAMGUARD | ERMA | GMM detector | FMCD detector |
|-------------------------------|--------------|--------------|--------------|------------------------------|------------------------------|------------------------------|
| Current availability | Public | Public | Public | Not yet publically available | Not yet publically available | Not yet publically available |
| Platform | Stand-alone | Matlab | JAVA | Matlab and C | Matlab | Matlab |
| Real-time operation | Y | N | Y | Y | N | N |
| Localization | Y | N | Y | N | N | N |
| Cost | Free | Matlab | Free | Matlab | Matlab | Matlab |
| Detection quality measurement | N | Y | N | Y | Y | Y |
| ICI test | Post-process | Post-process | Post-process | Y | Post-process | Y |
| Classifier | N | N | Possible | Future | Y | N |
| Spectrogram display | Y | Y | Y | N | Y | Y |

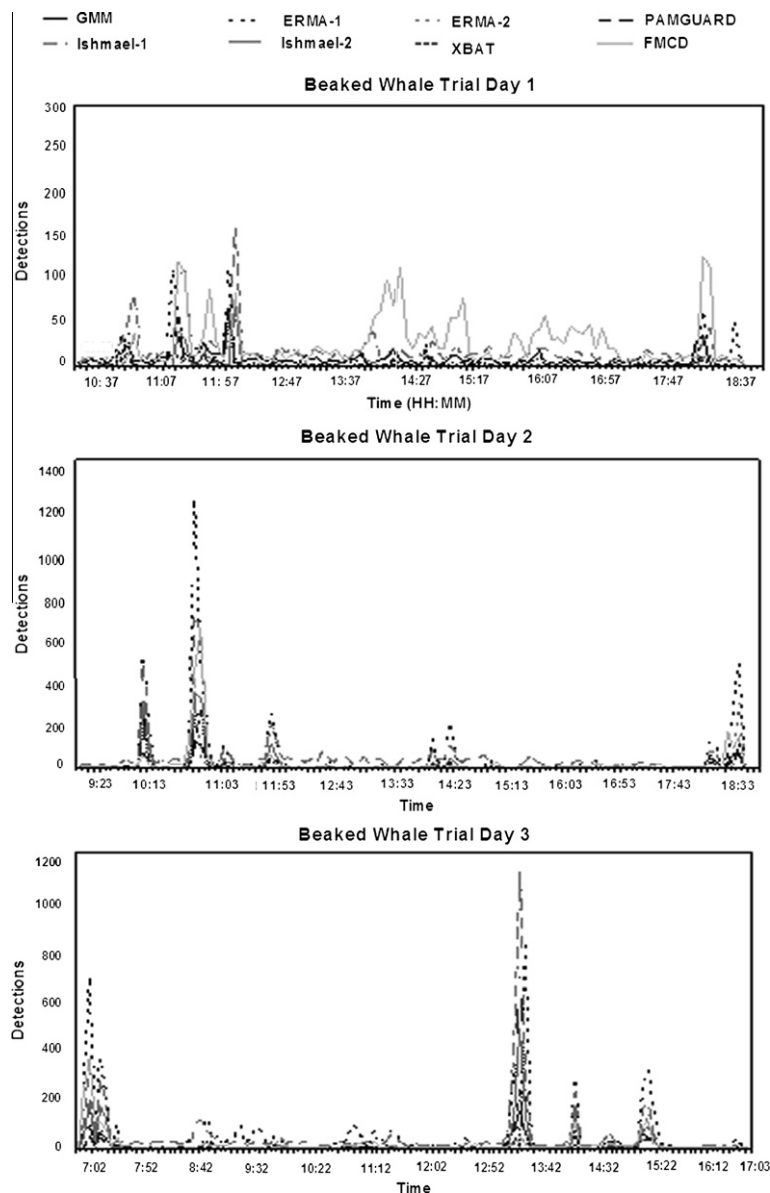


Fig. 2. Detections tallied into 5-min bins for each detection algorithm on all three beaked whale trial days to look at peak consistency: [GMM (black line); PAMGUARD (black dashed line); ERMA-1 (black dotted line); ERMA-2 (gray dotted line); Ishmael-1 (gray dashed line); Ishmael-2 (dark gray line); XBAT (black thatched line); FMCD (light gray line)]. Consistency in peak location indicates a generally low false alarm rate.

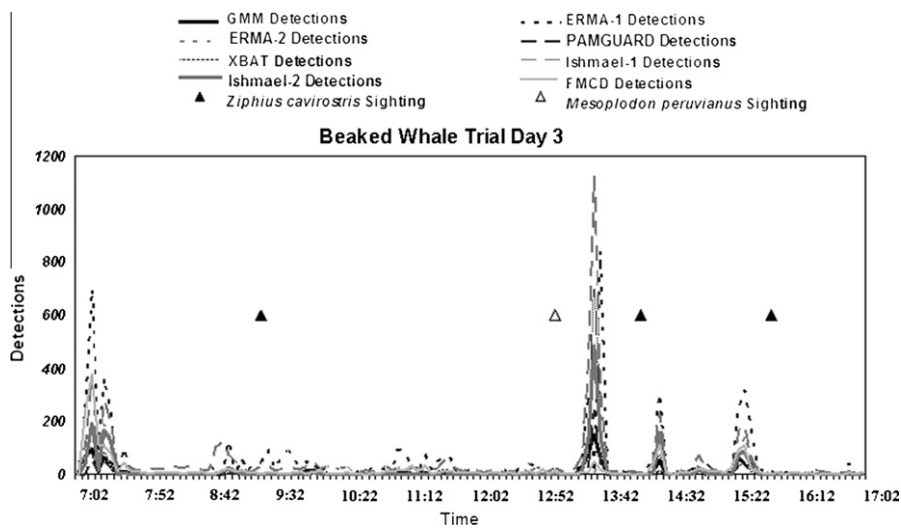


Fig. 3. Detection peaks for beaked whale trial day three with sightings. Detections are tallied into 5-min bins for each detection algorithm to look at peak consistency: [GMM (black line); PAMGUARD (black dashed line); ERMA-1 (black dotted line); ERMA-2 (gray dotted line); Ishmael-1 (gray dashed line); Ishmael-2 (dark gray line); XBAT (black thatched line); Martin (light gray line)]. Sightings for *Ziphius cavirostris* (black triangle) and *Mesoplodon peruvianus* (white triangle) are overlaid to show acoustic detection peaks that may be related to these events. Acoustic detections appear before and after sighting events as would be expected because clicks are only detected during the dive while animals are not visible at the surface.

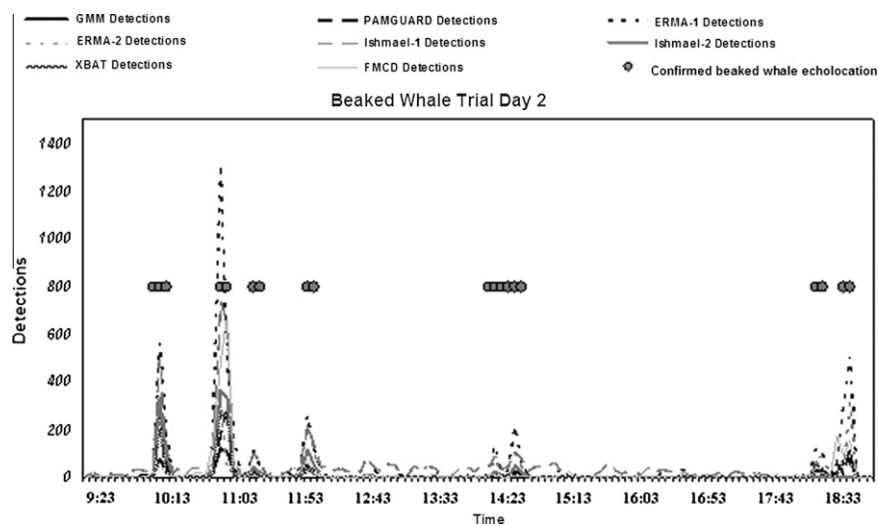


Fig. 4. Detection peaks for beaked whale trial day two with periods of confirmed beaked whale echolocation clicks present overlaid. Detections are tallied into 5-min bins for each detection algorithm [GMM (black line); PAMGUARD (black dashed line); ERMA-1 (black dotted line); ERMA-2 (gray dotted line); Ishmael-1 (gray dashed line); Ishmael-2 (dark gray line); XBAT (black thatched line); Martin (light gray line)]. Peak detection periods with confirmed beaked whale echolocation clicks present are indicated by gray circles.

Table 3

Quantitative comparison matrix. This table shows the correct and false detection rates for each detector. Correct and false detection rates were calculated using a subset of 60 min of data. For each 1 min bin, presences or absence of beaked whale clicks was determined and noted for each detector. The results of the data from the Ishmael and ERMA detections were post-processed to filter out detections with inter-click intervals less than 0.2 s and greater than 0.5 s (Ishmael-2 and ERMA-2).

| | Ishmael (%) | Ishmael-2 (%) | XBAT (%) | PAMGUARD (%) | ERMA (%) | ERMA-2 (%) | GMM (%) | FMCD (%) |
|------------------------|-------------|---------------|----------|--------------|----------|------------|---------|----------|
| Correct detection rate | 74 | 67 | 70 | 78 | 78 | 63 | 89 | 67 |
| False detection rate | 52 | 21 | 3 | 7 | 21 | 3 | 10 | 17 |

4. Results

4.1. Qualitative comparison

Table 2 shows the results of the qualitative comparison based on the nine factors previously discussed. The detector that one chooses will depend largely on the application it is being used for. For our purposes on line-transect surveys we were interested mainly in the nine factors discussed below. The goal for our pur-

poses was to indicate beaked whale presence in real-time and in post-processing modes. Ishmael, XBAT, and PAMGUARD are currently publicly available, while the other three may be publicly available in the future but are currently personal developments. The operational platform for XBAT, the GMM and the FMCD detector is Matlab, while Ishmael is a stand-alone application, ERMA is Matlab and C based and PAMGUARD is Java based. Real-time operation is currently only available in Ishmael, PAMGUARD and ERMA. Localization capabilities are currently only available in Ishmael and

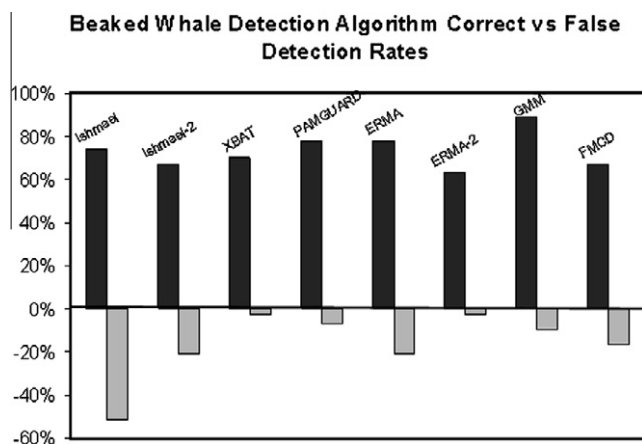


Fig. 5. Correct (black) and false positive (gray) detection rates for each detector. Correct and false detection rates were calculated using a subset of 60 min of data. For each 1 min bin, presences or absence of beaked whale clicks was determined and noted for each detector. The results of the data from the Ishmael and ERMA detections were post-processed to filter out detections with inter-click intervals less than 0.2 s and greater than 0.5 s (Ishmael-2 and ERMA-2).

PAMGUARD, which provide bearing angles to detections. PAMGUARD and Ishmael are free, while all other detectors require the purchase of Matlab software. Measurements indicating the quality of each beaked whale detection are provided by all of the detectors except Ishmael and PAMGUARD. Only the Roch detector is actually a multi-species classifier, although it is possible to add other energy band comparison detectors to PAMGUARD, essentially making it perform like a classifier, and future versions of ERMA will also classify. Finally, all detectors except ERMA currently have spectrographic display components.

4.2. Quantitative comparison

Five minute detection counts were tallied for each trial day and plotted (Fig. 2). A detection threshold of 150 detections/10 min period was applied to define detection peaks. The defined peaks for all six detectors were consistent, indicating that all have determined beaked whale presence within the same time periods.

Detection peaks were also compared with sighting information (Fig. 3). During one of the test days there were four beaked whale sightings. These sightings were all either preceded or followed by acoustic detection events. This would be expected since the animals are only clicking during the dive cycle when they are not visible at the surface. During all test days there were more acoustic beaked whale detections than visual sightings.

For one trial day, all detection peaks were verified manually. Clicks in each peak period were examined to identify the presence of a frequency upsweep in individual clicks and inter-click intervals were measured. Beaked whale signals were confirmed in each of the peak detection periods (Fig. 4). Three peak detection periods for a second trial day were also manually confirmed. A subset of these data, in which only beaked whale clicks were present, was used in the quantitative comparison.

For the verified peak detection periods and selected Risso's trial periods, a matrix was created based on the presence of detection events when only beaked whale clicks were present and when only Risso's dolphin clicks were present, to illustrate detection rates for Beaked whales and false positives for Risso's dolphin (Table 3 and Fig. 5). The GMM had the best correct detection rate (89%), followed by ERMA-1 (78%) and PAMGUARD (78%). The lowest false

detection rates were obtained by ERMA-2 (3%) and XBAT (3%), followed by PAMGUARD (7%) and the GMM detector (10%).

5. Discussion and conclusions

There are several caveats that must be considered to qualify the results of this data. First, the goals of each detector are different and therefore comparing detection rates may not provide a complete representation of the true 'quality' of a given detector. Also, detectors have used different training data, and none were trained on this dataset or towed array data in general. If the detectors had been trained on towed array data it is likely that the detection rates would improve for all detectors. The detectors presented here are constantly evolving and these results only provide a snapshot of detector quality. Additionally, detection thresholds for all detectors could be adjusted to improve the accuracy of detections for this dataset. Finally, this analysis included a subsample of data to quantify correct and false detections for each detector. The subsample included data from two test days and several detection peaks in order to provide a representative cross section of the data. Studies using other datasets with different species and recording qualities may have varied correct and false detection scores for the given detectors than those reported here.

Although all of the detectors used different methods of detection, they all had correct detection rates above 60%. Additionally, all detectors correctly determined beaked whale presence above the threshold level of detection applied to the test data. Running multiple detectors on a dataset may be useful way to automatically validate beaked whale presence based on peak consistency. Detector choice is ultimately dependent upon the application it will be used for, i.e. real-time, post-processing, determining beaked whale presence, or counting absolute numbers of beaked whale clicks. Each detector has been designed for a different application and it is important to evaluate detectors based on the application it will be used for, as we have done here. Before choosing an appropriate detector the authors would suggest that a similar qualitative and quantitative comparison be conducted, as results are like to vary between datasets.

There were more acoustic detections of beaked whales than visual sightings in each beaked whale trial day. The greater number of acoustic detections may ultimately be able to provide a greater precision in beaked whale abundance estimates than is currently available for visual based abundance estimates. Future studies should aim to compare acoustic and visual beaked whale detections in more detail.

Line transect data often include multiple species, which created a problem for all detectors. While the detectors did an excellent job of determining beaked whale presence they also were fooled by clicks from other species, including Risso's dolphin, on multiple occasions. Therefore, the detectors would not be appropriate for absolute counts of beaked whale clicks unless the false detection rates were determined for all species present in the data. Examination of this data highlights the need for continued classifier improvement, i.e. the ability to classify more species and/or classifiers that are robust to imposter species.

Acknowledgements

This work was funded by SWFSC and the US Navy (N45). We would like to thank the R/V McArthur II observers, acousticians, cruise leaders, survey coordinators, captain, officers and crew for assistance during shipboard surveys. We also thank Heriot-Watt University, Ecologic, SMRU and the OGP E&P Sound and Marine Life Joint Industry Program for development and funding of the PAMGUARD software.

References

- [1] Johnson MP, Madsen PT, Zimmer WMX, Aguilar de Soto N, Tyack PL. Beaked whales echolocate on prey. *Proc Royal Soc London B Biol Sci* 2004;271:5383–6.
- [2] Johnson M, Madsen PT, Zimmer WMX, Aguilar de Soto N, Tyack PL. Foraging Blainville's beaked whales (*Mesoplodon densirostris*) produce distinct click types matched to different phases of echolocation. *J Exp Biol* 2006;209:5038–50.
- [3] Madsen PT, Johnson M, Aguilar de Soto N, Zimmer WMX, Tyack PL. Biosonar performance of foraging beaked whales (*Mesoplodon densirostris*). *J Exp Biol* 2005;208:181–94.
- [4] Tyack PL, Johnson M, Aguilar Soto N, Sturlese A, Madsen PT. Extreme diving of beaked whales. *J Exp Biol* 2006;209:4238–53.
- [5] Pavan G, Fossati C, Priano M, Manghi M. Acoustic detection of Cuvier's beaked whales (*Ziphius cavirostris*). In: Dolman SJ, MacLeod CD, editors. Proceedings of the workshop: beaked whale research. ECS special publication series No. 51; 2009.
- [6] Rankin Shannon, Oswald J, Barlow J. Acoustic behavior of dolphins in the Pacific ocean: implications for using passive acoustic methods for population studies. *J Can Acoust* 2008;36:88–92.
- [7] Mellinger DK. ISHMAEL 1.0 user's guide. NOAA technical memorandum OAR PMEL-120. Available from NOAA/PMEL, 2600 Sand Point Way. NE, Seattle, WA 98115-6349; 2001.
- [8] Gillespie D, Gordon J, McHugh R, McLaren D, Mellinger D, Redmond P, et al. PAMGUARD: semiautomated, open source software for real-time acoustic detection and localisation of cetaceans. *Proc Inst Acoust* 2008;30(5).
- [9] Gillespie D, Leaper R. Detection of sperm whale (*Physeter macrocephalus*) clicks and discrimination of individual vocalisations. *Eur Res Cetaceans* 1996:87–91.