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# Passive Autonomous Acoustic Monitoring of Marine Mammals with Seagliders

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## LONG-TERM GOALS

The U.S. Navy's use of tactical mid-frequency active sonar has been linked to marine mammal strandings and fatalities (NMFS 2001). These events have generated legal challenges to the Navy's peacetime use of mid-frequency sonar, and have limited the Navy's at-sea anti-submarine warfare training time. Beaked whales may be particularly sensitive to mid-frequency sonar. A mobile, persistent surveillance system that could detect, classify and localize beaked whales will help resolve the conflict between the Navy's need for realistic training of mid-frequency sonar operators and the Navy's desire to protect marine mammal populations worldwide. Underwater gliders equipped with appropriate acoustic sensors, processing, and detection systems – "passive acoustic monitoring (PAM) gliders" – may offer a partial solution to the problem. The acoustically-equipped Seaglider™ from the Applied Physics Laboratory of the University of Washington (APL-UW) is one such platform. A Seaglider can travel about 20 km/day through the water for a period of weeks to months, dive from the surface to 1000 m and back in a few hours, and use two-way satellite (Iridium) telemetry for data and command transfer. This makes it potentially highly useful for the long-term goal of this project, mitigating impacts of Navy operations on marine mammals.

## OBJECTIVE

The objective of this effort is to develop techniques for detection and classification of odontocetes echolocation clicks and especially beaked whale sounds for the PAM Seaglider. Because any methods developed must run in the operational environment of the Seaglider, they must have a low average computational cost because of the limited processing power and battery life of the Seaglider. The performance of the detection and classification system will be evaluated on several field trials.

## APPROACH

The detection/classification system for the PAM Seaglider is a two-stage system. Stage 1, click detection, is operated continuously, creating a constant load, and Stage 2, classification (verification) of detected clicks, is operated only a small fraction of the time and thus can be computationally more expensive.

*Stage 1: Detection using the ERMA detector*
Energy-based detection algorithms are commonly used to detect many types of sound signals, including odontocete clicks, in real time (e.g., Mellinger *et al.*, 2004). A major advantage of such algorithms is their relatively low computational cost, as they can operate in the time domain. However, for detecting a given species of odontocete, time-domain algorithms often result in a high number of false positive detections caused by clicks of other odontocete species. The energy ratio mapping algorithm (ERMA) was developed to reduce the number of false positive detections while keeping computational cost low, as is needed for long-term (weeks to months) real-time operation with the Seaglider. ERMA was tested in several bench trials (e.g., Yack *et al.*, 2010) and field trials (see below), and based on the results, modified and improved.

*Stage 2: Classification*
Work on the classifier is being conducted in collaboration with Marie A. Roch, San Diego State University and Scripps Institution of Oceanography.

*Field testing*
The detection/classification system requires testing, and to that end a number of field tests were conducted at sites in the Atlantic and Pacific.

## WORK COMPLETED

*Stage 1: Detection*
The most recent version of ERMA includes a likelihood measurement for detected clicks. Detection function amplitudes of detected clicks, number of clicks, and mean inter-click-intervals (ICI) of clicks within detected bouts are used to rank [a] data files of one minute duration containing detections and [b] individual clicks within those files. This ranking is important for time-critical applications, such as mitigation of potential impacts to beaked whales during naval exercises. Data files associated with highest likelihood values as determined by the ERMA detector are analyzed by the classifier first. Once detections have been verified by the classifier, the glider is programmed to return to the surface as quickly as possible to report the presence of beaked whales back to a shore or ship-based control center. In addition, raw acoustic data snippets containing individual high-likelihood clicks are transmitted for manual verification. A 'fixed point' version of the ERMA based detector is also available and was implemented on another autonomous platform: the QUEphone developed by Haru Matsumoto, OSU. A manuscript providing an in-depth description of ERMA has been published in the Journal of the Acoustical Society of America (Klinck and Mellinger, 2011).

To achieve an improved detection rate, a novel signal-to-noise ratio (SNR) improvement algorithm has been developed. To illustrate the need for improvements in detection rate, Fig. 1 shows the relationship between SNR and estimated detection rate for Blainville's beaked whales. This figure shows that the curve is very steep when SNR is from 2-10 dB. In the low SNR range where most clicks are received, a slight increase in SNR can greatly increase the probability of detection.

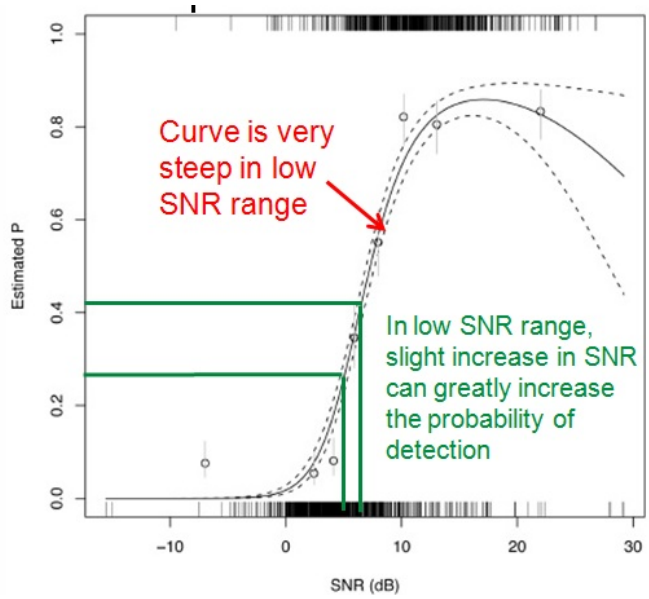


***Figure 1. Probability of click detection as a function of signal-to-noise ratio (SNR). The steepness of the curve in the 2-10 dB range indicates that a slight increase in SNR can lead to a large increase in detection performance. The clicks are from Blainville's beaked whales at AUTEC (Kusel et al. 2011).***

To improve the SNR, we first used least mean squares (LMS) filter which minimizes the mean squared of the error signal (Haykin, 2002). The LMS filter is chosen for its simple structure and low computational complexity. To further improve the SNR rate and overcome the slow convergence rate of the LMS filter, a subspace based algorithm (Hu et al. 2002) is used. This subspace method projects the noisy received-signal vector onto signal and noise subspaces. We also developed a detector based on the mean-squared error between the data before SNR improvement and after SNR improvement.

*Stage 2: Classification*

In collaboration with Dr. Roch, we developed a classification system for echolocation clicks of six species of odontocetes recorded in the Southern California Bight: bottlenose dolphins (*Tursiops truncatus*), short- and long-beaked common dolphins (*Delphinus delphis* and *D. capensis*), Pacific white-sided dolphins (*Lagenorhynchus obliquidens*), Risso's dolphins (*Grampus griseus*), and presumed Cuvier's beaked whales (*Ziphius cavirostris*). Echolocation clicks were represented by cepstral feature vectors (14 features) that are classified by Gaussian mixture models. A randomized cross-validation experiment (*n*-fold training/testing) was designed to provide conditions similar to those found in a field-deployed system. To prevent matched conditions from inappropriately lowering the error rate, echolocation clicks associated with a single sighting were never split across the training and test data. Sightings were randomly permuted before assignment to folds in the experiment. This allows different combinations of the training and test data to be used while keeping data from each sighting entirely in the training or test set. The system achieves a mean error rate of 22% across 100 randomized 3-fold cross validation experiments. Four of the six species had mean error rates lower than the overall mean, with the presumed Cuvier's beaked whale clicks showing the best performance (< 2% error rate). Long-beaked common and bottlenose dolphins proved the most difficult to classify, with mean error rates of 53% and 68% respectively. A manuscript providing an in-depth description of

the classifier has been published in the Journal of the Acoustical Society of America (Roch *et al.*, 2011).

A C-code version of the classifier is now available for use in the Seaglider. The code has been bench tests and results showed that the ARM-9 processor is powerful enough to operate the classifier on the Seaglider.

**RESULTS**

1. *Field tests.* Six field tests have been conducted with the PAM Seaglider (Table 1).

While the two tests off Kona, HI were primarily driven by engineering tests, the AUTEC trial was specifically designed to evaluate the detection performance and detection radius of the Seaglider. We deployed two Seagliders in the northwest corner of the AUTEC range and operated them continuously for 5 days. One glider was programmed to hold its position on top of the Whiskey 1 array ('stationary glider') while the second glider ('transecting glider') conducted East-West transects across the 'Tongue of the Ocean' basin. The experiment was highly successful: a total of 23 encounters with beaked whales were detected by the two Seagliders. The Whiskey 1 array features a closer hydrophone spacing which allowed us to locate vocalizing whales. These data were used to estimate the distance between the glider and the whales and to evaluate the detections performance and radius of our system.

In July 2012, the gliders were deployed off the coast of Washington and Oregon in a long-term test of acoustic cetacean monitoring. Unfortunately the glider hardware failed; one hydrophone cable developed a leak, causing levels of electrical noise loud enough to mask ocean sound, and the other one recorded for only 3 weeks. We are currently analyzing data from the latter deployment.

2. *Data analysis*
The ERMA detection algorithm has been improved, implemented on additional sensor platforms, and used to screen large passive-acoustic data sets for beaked whale echolocation clicks.

Improvements: Adaptive noise reduction algorithms have been developed to improve the overall detection performance of ERMA (Lu et al. submitted). These algorithms are currently being tested on the bench and are intended to be implemented on our autonomous instruments in near future.

Implementations: ERMA has been implemented on oceanographic gliders and floats (Matsumoto et al. in press, Klinck et al. 2012) and successfully detected the presence of beaked whales in various oceans (e.g., at AUTEC, SCORE, Kona Coast of Hawaii). A data set collected with an autonomous acoustic sailboat in the Baltic Sea in July 2012 was used to modify ERMA to detect harbor porpoise echolocation clicks. The modified version of the detector will be implemented on the sailboat and used to detect the presence of harbor porpoises in real-time during future field test. We are also planning on implementing the ERMA detection algorithm on the Passive Aquatic Listener (PAL) in collaboration with Jeff Nystuen, APL-UW. This modified PAL is supposed to be deployed at Ocean Station PAPA in the Gulf of Alaska to monitor high frequency cetaceans close to the U.S. Navy's Northern Edge Training area.

***Table 1. Overview of the 6 field trials of the PAM Seaglider conducted to date. The asterisk indicates partially corrupted data; we haven't yet determined how much of it is usable.***

| Location | Seaglider | Dates | Number of Dives (1 km) | Hours of Recording | GB of Recording |
|---|---|---|---|---|---|
| Haro Strait | SG022 | 4-SEP-2009 | 5 (0) | 2.8 | 3.7 |
| Kona I | SG022 | 27-OCT-2009 to 17-NOV-2009 | 116 (102) | 170.2 | 141.5 |
| Kona II | SG022 | 16-MAR-2010 to 26-MAR-2010 | 61 (42) | 101.8 | 84.6 |
| | SG023 | | 94 (36) | 107.1 | 89.0 |
| AUTEC | SG178 | 7-JUN-2010 to 11-JUN-2010 | 35 (12) | 58.5 | 48.6 |
| | SG179 | | 27 (12) | 71.7 | 59.6 |
| SCORE | SG178 | 4-JAN-2011 to 7-JAN-2011 | 30 (19) | 56.2 | 46.7 |
| | SG179 | | 30 (19) | 53.5 | 44.5 |
| WA /OR | SG178 | 11-JUN-2012 to 12-JUL-2012 | 149 (95) | * | * |
| | SG179 | | 155 (93) | * | * |
| Total | | 88 days | 702 (430) | 621.8 | 518.2 |

Analysis of large data sets: We provided ERMA to Whitlow Au, UH to analyze large acoustic data sets collected with the ALOHA cabled observatory. ERMA allowed our colleges to analyze the data set efficiently and reliably detected echolocation clicks of beaked whales in the recordings (Au et al. in review).

The Kona I data set (see Table 1) has been analyzed and a paper describing the results has been published (Klinck et al. 2012). Some highlights from the paper include the following:

a) Detection of beaked whales at numerous sites off the Kona coast (Fig. 2).

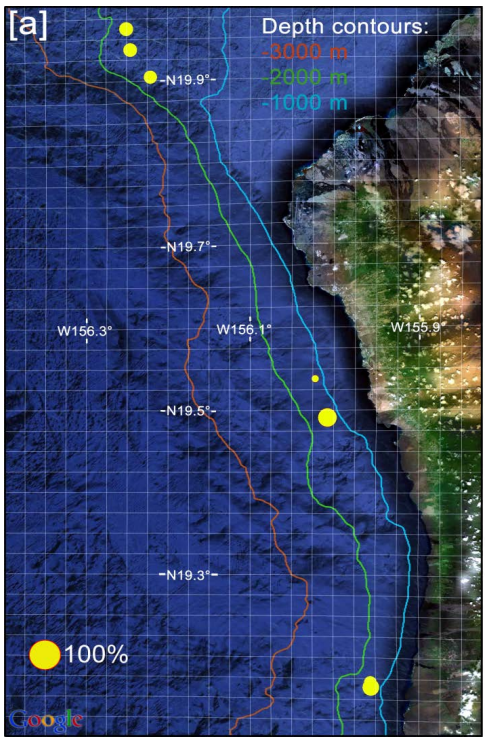


***Figure 2. Detections of beaked whales, most likely Cuvier's beaked whales, off the Kona coast. Numbers indicate the percentages of dives in which beaked whales were detected.***

b) Acoustic detection of a beaked whale close to the location of a tagged beaked whale (Fig. 3).

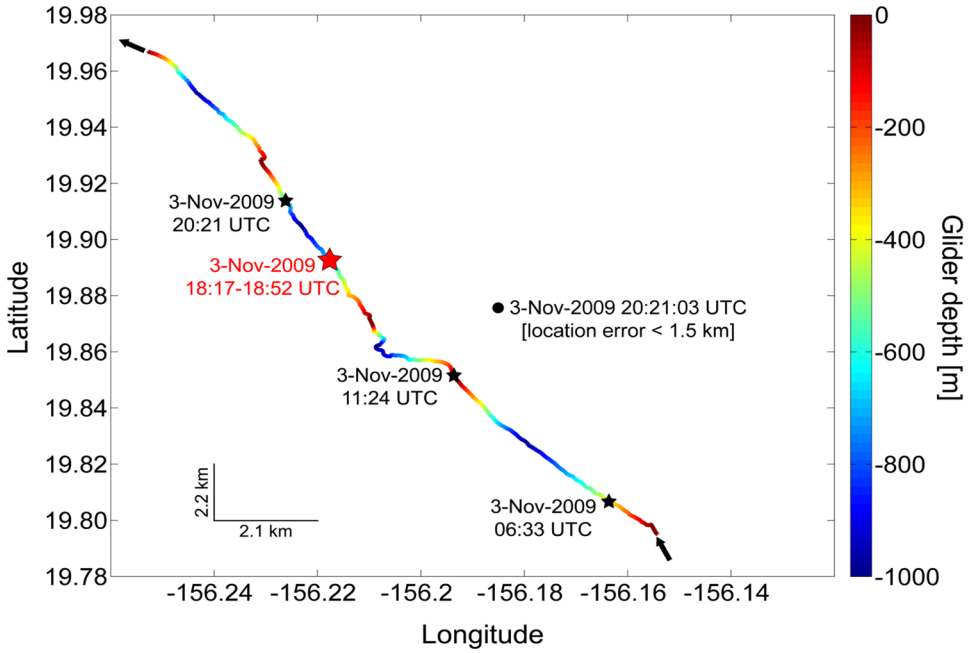


***Figure 3. Acoustic detection (red star) of a beaked whale, likely a Cuvier's beaked whale, close to the location of a tagged beaked whale (black dot).***

c) Dolphins and sperm whales diving activity has a significant diel pattern (Fig. 4). There is a hint that beaked whales may dive more during the day but it is not statistically significant.

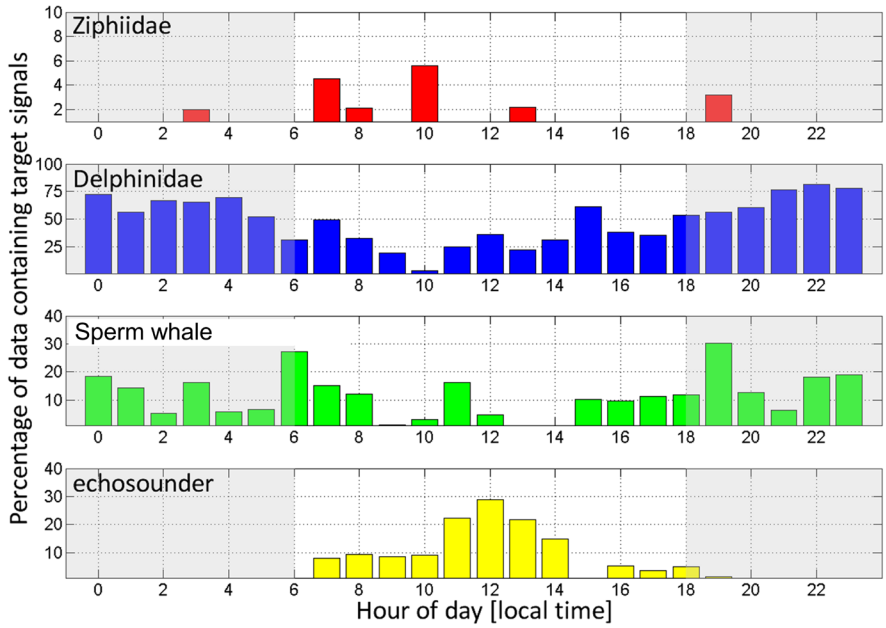


***Figure 4. Percentage of data containing each species (or echosounder clicks) as a function of hour of the day. Shaded areas indicate nighttime.***

The AUTEC 2010 data were also analyzed; some highlights from that data set include the following:

d) Click detections occurred principally below 250 m (Fig. 5).

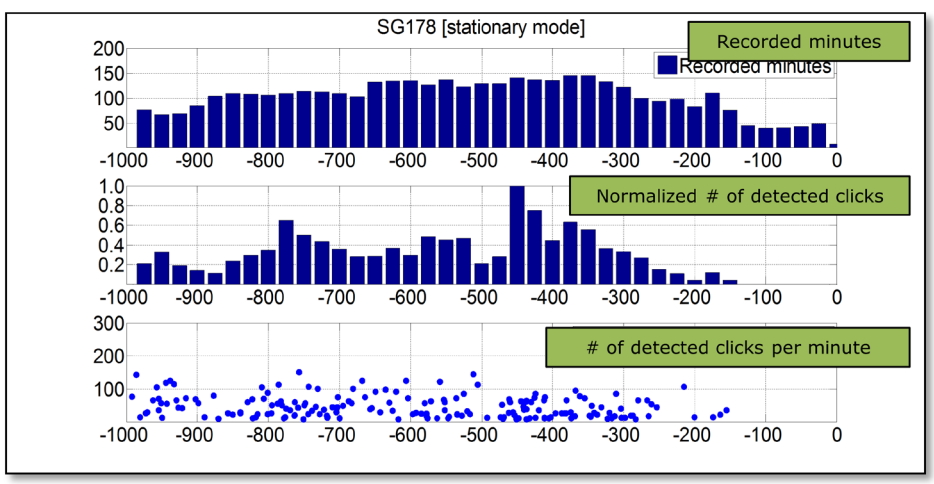


***Figure 5. Click detections at AUTEC. X-axis is depth in meters; "normalized" in the middle panel means that the number of clicks is scaled to fit into the range [0,1]. The middle and especially bottom panels show that Blainville's beaked whale acoustic detections occur principally below 250 m depth.***

e) The maximum detection radius of the Seaglider is in the range of approximately 4 km, a distance which agrees with results from theoretical models (Zimmer *et al.* 2008). The glider's detection radius was estimated by comparing distances at the time of detection between the glider and the closest AUTEC hydrophone which registered beaked whale activity.

f) The detector worked very well, with only a small handful of false detections (Figs. 6, Table 2).

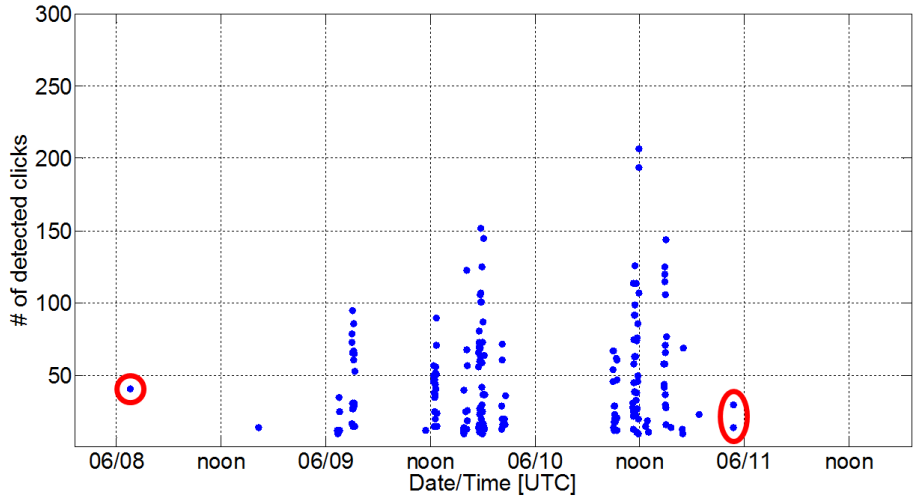


***Figure 6. Detections at AUTEC over the duration of the mission. Blue dots indicate detections by the glider; red circles indicate detections that were later found by manual inspection to be false positives – species other than beaked whales. Manual inspection of all recordings revealed that the detection system missed no whale encounters.***

***Table 2. Comparison of glider (ERMA) and M3R system detections. The close matches between the numbers indicate that the ERMA detector worked approximately as well as the benchmark M3R system. Exact agreement was not expected because the hydrophones for the two systems are in different locations – in the water column (glider) vs. on the seafloor (M3R).***

| Glider operation | BW encounters | ERMA detections | M3R detections | ERMA false detections | M3R false detections |
|---|---|---|---|---|---|
| **Stationary** | **11** | **11** | **10** | **2** | **0** |
| **Transiting** | **12** | **12** | **8** | **1** | **0** |
| **Total** | **23** | **23 (100%)** | **18 (78%)** | **3 (12%)** | **0 (0%)** |

In addition, the data sets recorded during the Kona I and II missions are currently also being analyzed for false killer whales as part of a different project by Erin Oleson, NOAA/NMFS/PIFSC.

3. *Visualization*. A tool was developed (Fig. 7) to visualize glider surveys to make it easier to identify spatiotemporal patterns. This tool animates gliders along their travel paths, and also shows the bathymetry of the area and any other instruments present such as hydrophones, QUEphones, etc. Hydrophones that register a glider detection are shown in a different color, allowing easy visualization of the match between glider detections and fixed-hydrophone detections of target species.

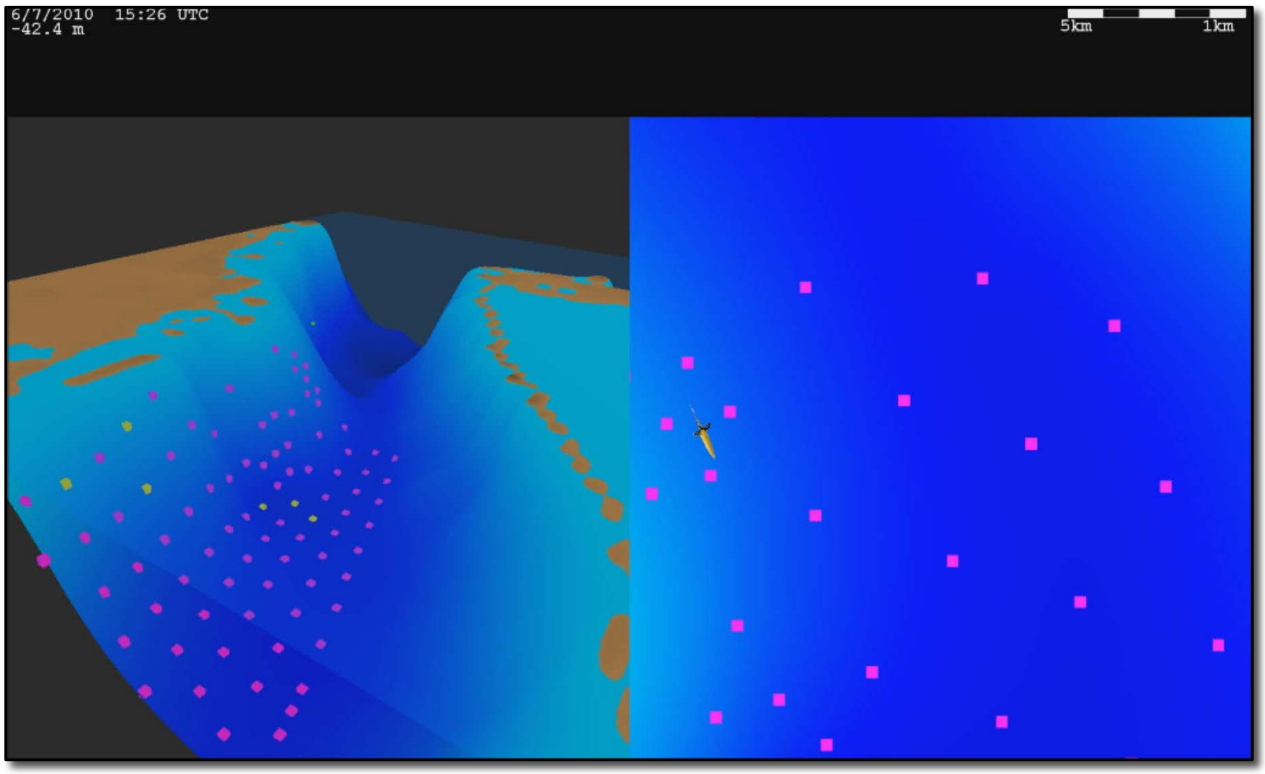


***Figure 7: Screenshot of a single frame of the glider visualization animation tool showing the AUTEC hydrophone array and glider positions in both perspective (left) and plan (right) views. Hydrophones colored yellow are registering beaked whale detections.***

4. *SNR improvement for better detection and classification*. Table 3 shows the SNR improvement for beaked whale clicks at AUTEC. In both datasets, over 60% of the clicks have SNR improvement, with an average SNR increase of 0.4 dB. The detection probability is not significantly improved after the noise reduction algorithm. One possible reason is the average SNR of the data tested is around 12 dB. Based on Fig. 1, there is not much improvement in detection probability for SNR larger than 10 dB. Also through simulations, the proposed detector is shown to be capable of detecting most of the desired clicks, but is not able to differentiate other co-existing species such as Risso's dolphins and pilot whales – that is, it efficiently detects *all* clicks. By combining the proposed detector with the Energy Ratio Mapping Algorithm (ERMA; Klinck et al. 2011), which measures energy differences between different species, higher detection accuracy for beaked whale clicks can be achieved. This is shown by the Detection Error Tradeoff (DET) curve in Fig. 8. A paper presenting these results has been submitted to the Journal of the Acoustical Society of America (Lu et al. in review).

***Table 3. Improvement in SNR with the subspace filtering algorithm. Improvement it not dramatic, but as Fig. 1 shows, not much change is needed to significantly improve detection. "SNR improvement rate" indicates the percentage of clicks whose SNR improves with filtering; the remainder have either the same or a lower SNR after filtering.***

| Species | Dataset | Dura-tion | No. of clicks | Avg. SNR | Avg. SNR improve-ment | SNR improvement rate |
|---|---|---|---|---|---|---|
| Blainville's beaked whale | Set4-A6-092705-H76-0155-0214-1030-1049loc_0300-0600min | 180 s | 1770 | 12.7 dB | 0.5 dB | 80.27% |
| Blainville's beaked whale | Set4-A7-092705-H84-0155-0214-1030-1049loc_0230-0430min | 120 s | 1012 | 12.4 dB | 0.26 dB | 63.76% |

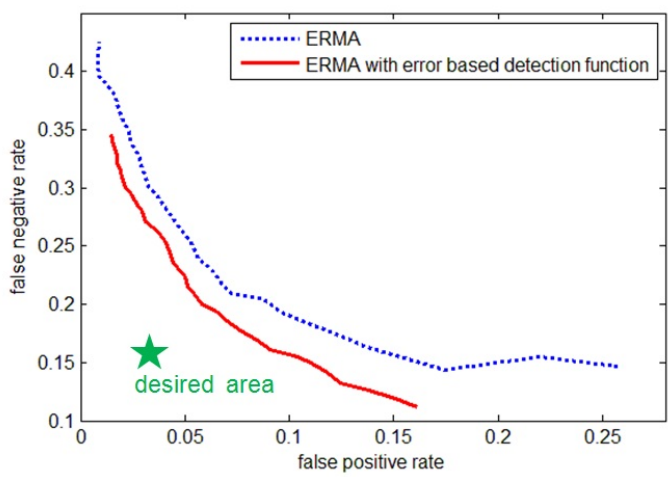


***Figure 8. The Detection Error Tradeoff curves for detection with and without use of information from the subspace filtering algorithm, showing that filtering significantly improves performance. Curves closest to the lower left corner indicate best performance.***

5. *Student mentoring*. We have mentored the following students:

- Michelle Fournier, Oregon State University, USA;
- Marci Shindel, Oregon State University, USA;
- Qi Lou, Oregon State University, USA;
- Nikoletta Diogou, University of Athens, Greece;
- Selene Fregosi, University of Santa Cruz, USA;
- Darin Padula (NOAA Hollings intern), University of Hawaii, USA;

- Alice McKinstry, Oregon Coast Community Colleague, Newport, OR, USA;
- Andrea Paula Capurro, University of Buenos Aires, Argentina.

## IMPACT/APPLICATIONS

It is hoped that a "marine mammal Seaglider" will be useful for the conservation of cetaceans by revealing their presence before, during, and after Navy operations, thus allowing for the use of mitigation measures to prevent harm to them. It is also hoped that Seagliders equipped with the detection technology developed here will be more broadly useful, perhaps for monitoring marine mammal population changes, studies of the seasonal distribution of marine species, marine mammal behavioral observation, and other applications that we have not yet anticipated. We are in contact with Navy personnel (Sean Hanser, Joel Bell, Julie Rivers) about deploying this acoustically-equipped Seaglider for marine mammal monitoring at sites of interest to the Navy, particularly Navy ranges. We have also applied for DURIP funding to purchase more Seagliders; if this is successful, it will greatly facilitate future marine mammal research.

## RELATED PROJECTS

We are closely collaborating with the projects "Acoustic Seaglider for Beaked Whale Detection" (award N00014-08-1-0309) and "Passive Autonomous Acoustic Monitoring of Marine Mammals: System Development using Seaglider" (award N00014-10-1-0515), with PIs Neil Bogue and Jim Luby of the Applied Physics Laboratory, University of Washington. The Bogue/Luby group is (1) developing and testing a new processor architecture for the Seaglider, (2) developing and testing an associated new multi-channel acoustic recording system for the Seaglider, (3) leading the fieldwork to test deployments of the "marine mammal Seaglider". We are primarily developing algorithms for detecting beaked whales and other odontocetes from the Seaglider and implementing these algorithms in the Seaglider's processing environment, while UW is developing hardware, building the acoustic processing environment, and operating the Seaglider.

The ONR-funded project "Acoustic Float for Marine Mammal Monitoring" (award N00014-08-1-1198, P.I. Dr. Haru Matsumoto, OSU) is also using the ERMA detector described above. It is implemented differently in the two projects, mainly because of different processor architectures used in the PAM boards of each instrument.

We have applied for a DURIP grant (proposal "Acoustically-equipped Ocean Gliders for Environmental and Oceanographic Research", submitted to ONR in Sept. 2012) to purchase Seagliders for use in marine mammal observation and research, ocean noise measurement, research in signal processing, ecosystem study, and ocean acoustic propagation.

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