Advanced Methods for Passive Acoustic Detection, Classification, and Localization of Marine Mammals

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LONG-TERM GOALS

For effective long-term passive acoustic monitoring of today's large data sets, automated algorithms must provide the ability to detect and classify marine mammal vocalizations and ultimately, in some cases, provide data for estimating the population density of the species present. In recent years, researchers have developed a number of algorithms for detecting calls and classifying them to species or species group (such as beaked whales). Algorithms must be robust in real ocean environments where non-Gaussian and non-stationary noise sources, especially vocalizations from similar species, pose significant challenges. In this project, we are developing improved methods for detection, classification, and localization of many types of marine mammal sounds.

OBJECTIVES

We are developing advanced real-time passive acoustic marine mammal detection, classification, and localization methods using a two-pronged approach: developing improved DCL algorithms, and developing standardized interfaces and software.

First, we are developing, testing, and characterizing advanced DCL algorithms:

1. Echolocation click classification. Algorithms are being developed and tested for several species of beaked whales and small odontocetes.
2. Tonal signal detection and classification. Algorithms are being tested for several species of mysticetes and for small odontocetes.
3. Multi-sensor localization. Algorithms will be developed and tested on datasets containing sounds of both odontocetes and mysticetes.

Second, improved DCL software will be developed and both existing and new methods will be made available to users. The key contribution will be the development of four well-specified interfaces, for detection, feature extraction, classification, and localization.

APPROACH

Odontocete click detection and classification. A multi-class support vector machine (SVM) classifier was previously developed (Jarvis et al. 2008). This classifier both detects and classifies echolocation clicks from five species of odontocetes, including Blainville's and Cuvier's beaked whales, Risso's dolphins, short-finned pilot whales, and sperm whales. Here Moretti's group, particularly S. Jarvis, is improving the SVM classifier by resolving confusion between species whose clicks overlap in frequency.

The current real-time system of Roch et al. for odontocete click classification is based on Gaussian mixture models (GMMs) using cepstral feature vectors. Cepstral feature vectors provide a compact representation of the spectrum (Rabiner and Juang 1993) that let the system represent echolocation spectra using a reduced number of coefficients, providing a lower-dimensional feature space than using a standard representation of the spectrum. Issues were found in odontocete species identification with equipment and site differences through features derived from echolocation clicks. Methods were developed to mitigate these differences and applied to the 2015 Detection, Classification, Localization, and Density Estimation workshop (DCLDE) high-frequency development and evaluation data.

Tonal signal detection and classification. "Tonal signal" is a generic term for frequency-modulated calls such as mysticete moans or odontocete whistles. Methods for detecting and classifying such sounds are being developed and applied to both odontocete whistles and baleen whale vocalizations, including minke (*Balaenoptera acutorostrata*), blue (*B. musculus*), and humpback (*Megaptera novaeangliae*) whales.

Baleen whale vocalizations. Methods developed here for baleen whale detection and classification are based on automated detection and classification of minke whale 'boing' vocalizations using tonal signal methods which have been previously applied to US Navy hydrophone data at PMRF (Mellinger et al. 2011; Martin et al. 2013). The dominant spectral component (DSC, described in Martin et al. 2013) is used for detection of the call, as this component is typically the last component detected at long ranges (> 30 km). Minke boing call detection is used here has a first-stage detection step similar to the tonal detection processing described by Mellinger et al. (2011). A second stage is also used which processes a frequency band from 1320 to 1450 Hz to detect the onset frequency-modulation (FM) upsweep component of the call to obtain a more accurate estimate of the start time of the call for later localization processing. Then a third stage calculates the frequency with high spectral resolution (0.72 Hz per bin) of the DSC for each detected boing to help associate calls from individuals and in some cases to help track individuals over multiple hours.

Advanced localization algorithms. The first requirement for passive acoustic localization of marine mammals is the need to associate the detection of an individual signal as it is received across the array of widely spaced hydrophones. Moretti is leading the effort to develop a nearest-neighbor approach to detection association. This approach still uses TDOA/hyperbolic methods, but will not discard TDOA from pairs of detections when the normally requisite 3 detections are not achieved. Rather, detections from a given hydrophone will be associated with detections from all of its nearest neighbors and pair-wise TDOAs will be calculated.

Software and interfaces. An Application Programming Interface (API) is a specification of a set of procedure calls (for objects, methods), data types (scalars, structures, classes, etc.), and protocols for use of the procedures and data types, making it relatively simple for a developer to add new algorithms to an existing system. Ishmael's (Mellinger 2001) interfaces for detection and localization comprise a relatively complex set of object class methods (procedure calls) and data types; although it is standardized, it is hardly straightforward or well-documented. The M3R system (Morrissey et al. 2006) has a format for standardized data serving and detection message passing. We are developing and testing a plug-in architecture, with corresponding APIs, for these systems.

WORK COMPLETED

Meetings, data sharing site, and funding:

(1) We have had telephone meetings approximately monthly to discuss both technical details and project logistics, with a face-to-face meeting on 14-Jul-2015 at the DCLDE workshop.

(2) We established a private Internet-accessible site for sharing data sets, meeting minutes, and code. The site is private since some of the data, while not classified, is considered sensitive.

(3) We established a SourceForge site for sharing code and data from the project, with some code uploaded now (http://sourceforge.net/projects/marinemammalacousticdcl/).

(4) Funding for this year of the project reached Navy and OSU, though the FY15 funding only just reached OSU (on 9/29/15) and subcontract funds have not been transferred to SDSU yet.

RESULTS

Detection/classification algorithms: tonal sounds. A whistle clustering manuscript was revised with a new classification section showing that shape-related whistle features carry species-specific information useful for species identification. The revised paper is currently in review.

Improvements were made to the *Silbido* whistle detector that improved the precision rate from 76.0% to 89.7% with a corresponding penalty in recall of only 0.1%, representing a 57% decrease in false positives generated by the detector with trivial impact on correct detections. A manuscript detailing these results is underway. Also, as part of the *Silbido* effort to reduce false positives, we constructed a visualization and debugging utility that lets one examine how the algorithm is working and provided a level of abstraction to better understand where the algorithm was making mistakes and let us examine how proposed changes would affect performance. Having this type of abstraction was a critical component to recognizing that there were problems due to noise regime changes and that the whistle graphs associated with false positive detections had certain characteristics that we could exploit.

Detection/classification algorithms: odontocete clicks. An article (Roch et al., 2015) was published describing our work on the impact of equipment and site differences on odontocete species identification through features derived from echolocation clicks. The article demonstrates that there are significant performance impacts on species classification when training data are recorded with instruments of a specific type or at a specific location and tested under non-matching conditions. This has significant impact on any Naval monitoring scheme that uses features from broadband echolocation clicks. We were also able to demonstrate that simple noise estimates can be used to reduce this penalty significantly. Further research in this area has the potential to further mitigate for train/test mismatch.

One of the most important things learned over the last year is that when one moves to working with very large datasets that have not been hand-curated to extract sections with data from relevant target species, performance degrades quickly. Our analysis of the 2015 DCLDE development data led us to recognize that sporadic false positives from echolocation click detectors can wreak havoc on performance and we subsequently developed filtering rules that remove low frequency sporadic clicks as well as methods of identifying and removing instrument self-noise. Our work with Kullback-Leibler distances between encounters (new start N00014-15-1-2299) enabled us to inspect characteristics of specific encounters to better determine what problems exist, and we are continuing work on this productive path.

A class-specific support vector machine (CS-SVM) classifier (Jarvis 2012) was developed to classify the foraging clicks produced by several species of odontocete. The current CS-SVM classifier includes classes for the foraging clicks produced by Blainville's beaked whale, *Mesoplodon densirostris* (Md), Cuvier's beaked whale, *Ziphius cavirostris* (Zc), and sperm whale, *Physeter macrocephalus* (Pm), as well as a generic dolphin class. This classifier has been incorporated into the Marine Mammal Monitoring on Navy Ranges (M3R) system which is present at all three on the Navy's major undersea range facilities: the Atlantic Undersea Test and Evaluation Center (AUTEC), the Southern California Off-shore Range (SCORE), and the Pacific Missile Range Facility (PMRF) (Jarvis et al. 2014).

Beaked whales are also known to produce homing pulses, termed buzzes (Johnson et al. 2004), just prior to a prey capture attempt. Therefore buzz production can be used as a proxy for feeding behavior. However, beaked whale buzzes are much more difficult to detect than foraging clicks. Buzz clicks are produced at a much faster inter-click interval, have a different click structure and a significantly lower source level than foraging clicks (Jarvis et al. 2008). A CS-SVM classifier was developed specifically for Md buzzes. Taking into account the much lower source level than foraging clicks, the detection threshold of the buzz classifier was set correspondingly lower. To avoid possible generation of an unacceptable number of false alarms by the lower threshold, the buzz classifier is launched only after a Md foraging click-train has been detected. Then the buzz classifier runs for only 30 minutes, the average vocal period of an Md dive.

Localization and tracking. Two model-based localization methods were been developed for baleen whale (minke, fin, sei, Bryde's, and humpback whales) localization. One uses detection start times to determine time difference of arrivals (Martin et al. 2015) fully developed on this project, while the second method (Helble et al. 2015) was developed specifically for sequences of humpback song units detected via Generalized Power Law processing cross-correlated between hydrophone pairs. Both model-based baleen whale localization algorithms have been transitioned to an Operations and Maintenance Navy (OMN) funded effort monitoring for marine mammals in the Hawaii Range Complex (see associated projects).

The model-based localization method (using auto-detector start times rather than cross correlations) used for minke whale boing calls has being used to estimate the density of calling minke whales in a before-during-after paradigm, with results showing highly statistically significantly lower densities of calling animals during MFAS training periods (Martin et al. 2015). The density of calling minke whales metric utilized was a minimum minke whale density as corrections for the proportion of time calling whales call and the ratio of calling whales to the rest of the population (both currently unknown parameters) would increase the density estimate. Figure 4 (from Martin et al. 2015) shows the number of minke whales acoustically localized in the 3,780 km^2 study area in 1 h periods for available recorded data for Feb. 2011, 2012 and 2013.

Low-frequency (<100 Hz) baleen whale localization has also shown sounds attributed to Bryde's whales for several data sets (Aug 2013, Aug 2014, Sept 2014, Oct 2014). Data is being processed to establish a baseline for Bryde's whale occurrence at PMRF. Humpback whale localizations are being processed in the fleet monitoring effort for available data sets using the Helble et al. 2015 algorithm. Efforts at processing recorded data between 2011 and 2014 indicate a total of 81 humpback whales localized on the offshore range hydrophones (Henderson et al. in review).

The Matlab kinematic tracking code developed on the ADCL effort was uploaded to the SourceForge site with a sample data set of minke whale localizations from PMRF. By automating the process of assigning calls to individuals in this manner, studies such as Martin et al. 2015 can be done with much less manual effort. In addition, tracking is revealing interesting behaviors such as spatio-temporally clustered calls and potential interactions between species.

Software: The architecture for writing detection, classification, and localization modules has been completed and communication between Ishmael and PAMGUARD and a test module has been established. The architecture provides a translation library for each DCL platform supported that marshals data into a format that can be shared with other processes. Modules run as separate programs that share a limited region of memory with the DCL platform. This allows modules written on platforms that require separate processes (e.g. Matlab, R) to be gracefully handled. Users designing classification modules will configure the DCL platform to send data to their module and make calls to a standard interface library. Results are sent back to the DCL platform in a similar manner. The plug-in architecture has been successfully demonstrated in Ishmael with a detector in MATLAB. The architecture now supports multiple languages, and we are continuing work to refine the interface to make it as easy to use as possible.

IMPACT/APPLICATIONS

For the Navy, passive acoustic monitoring (PAM) provides a means of long-term monitoring of many cetacean populations, especially over areas of high interest. Such areas are repeatedly subjected to Navy exercises involving intense sounds, especially multi-ship mid-frequency active (MFA) sonar. Currently, required environmental monitoring is dependent primarily on visual line transect surveys that are costly and, in the case of aerial surveys, significantly dangerous. In both the areas critical to the Navy and in other areas critical to marine mammals, PAM is dependent on automated DCL methods. The advanced DCL algorithms being developed here will make PAM more effective and efficient; the algorithm implementations across standardized interfaces that handle both real-time and pre-recorded data streams from diverse platforms will make them available to Navy fleet operators as well as the wider marine mammal research community.

TRANSITIONS

Both model-based localization algorithms for baleen whales have been transitioned to COMPACFLT Operations and Maintenance Navy (OMN)-funded effort monitoring for marine mammals in the Hawaii Range Complex (see related projects). This has enabled processing thousands of hours of multiple hydrophone data sets to localize baleen species and documenting a behavioral response, in terms of reductions in the densities of boing calling minke whales in a study area 3,780 km2, to the US Navy mid-frequency active sonar training activities at PMRF (Martin et al 2015).

The *Ishmael* software package is being improved as part of an effort funded by the Navy’s Living Marine Resources (LMR) program to make a large suite of detectors and classifiers written in MATLAB, many developed under this grant, accessible and easy to load over the Internet. Ishmael is also being connected with the M3R system for use at Navy ranges.

RELATED PROJECTS

“Acoustically-equipped Ocean Gliders for Environmental and Oceanographic Research” (N00014-13-1-0682) award to D. Mellinger and H. Klinck. This is a DURIP grant to purchase acoustically-equipped Seagliders that will use automated detection/classification methods developed here.

“Autonomous Passive Acoustic Monitoring of Marine Mammals in the Hawaii Range Complex (HRC), the Gulf of Alaska (GoA), and the Mariana Islands Range Complex (MIRC)” (N62470-

10-D-3011 (award to HDR, Inc., with subcontract to D. Mellinger/H. Klinck)). The methods developed here are being applied to sounds recorded on glider flights in the specified areas.

"Simple performance-characterized automatic detection of marine mammal sounds" (N39430-14-C-1434) award to D. Mellinger et al. This project is creating a means to download detectors/classifiers over the Internet and use them in Ishmael, and establishing a two-communications channel with MATLAB so that detection/classification reports made there can be imported back into Ishmael.

"Acoustic Metadata Management and Transparent Access to Networked Oceanographic Data Sets" (NOPP N00014-11-1-0697) award to PI Marie Roch, Co-PI Simone Baumann-Pickering, John A. Hildebrand, et al. A metadata management system is being developed, which allows access to locally stored acoustic detections and metadata and links in a standardized way to external sources, such as oceanographic or ephemeris data. We will design our DCL plugins to provide outputs that can easily be stored in the acoustic metadata database.

"PMRF acoustic data collection and analysis" (N000701WR4C673) Operations and Maintenance Navy (OMN)-funded effort supporting COMPACFLT's Hawaii Range Complex monitoring of marine mammals during training activities.

"Improving the Navy's automated methods for passive underwater acoustic monitoring of marine mammals" LMR project PI Tyler Helble. Collaboration with localizing humpback call sequences.

"Obtaining cue rate estimates for some Mysticete species using existing data" (N0001414WX20588) ONR effort PI: Tyler Helble. Collaboration on localization efforts for cue rate estimation.

REFERENCES

Bar-Shalom, Y., and T. E. Fortmann, 1988. *Tracking and Data Association* (Academic Press).

Baggenstoss, P. M. 2012. An algorithm for the localization of multiple interfering sperm whales using multi-sensor time difference of arrival, Journal of the Acoustical Society America (2012).

Baggenstoss, P. M. 2014 Processing advances for localization of beaked whales using time difference of arrival, Journal of the Acoustical Society of America.

Bastian, M., Heymann, S. and Jacomy, M. (2009). Gephi: An Open Source Software for Exploring and Manipulating Networks. In Intl AAAI Conf Weblogs and Social Media. San José, CA.

Benard-Caudal F. and H. Glotin, 2009. Highly defined whale group tracking by passive acoustic stochastic matched filter", in Technical report, Systems and Information Sciences Laboratory (LSIS) (UMR CNRS 6168, University of South-Toulon-Var, BP 20132 83957 La Garde Cedex France).

Challa, S., M. Morelande, D. Musicki, and R. Evans. 2011. Fundamentals of Object Tracking (Cambridge University Press).

Deecke, V. B. and Janik, V. M. (2006). Automated categorization of bioacoustic signals: avoiding perceptual pitfalls. J. Acous. Soc. Am. 199, 645-653.

Deecke, V.B., V.M. Janik (2006) Automated categorization of bioacoustic signals: avoiding perceptual pitfalls. J. Acoust. Soc. Am., 199:645-653.Freund, Y., S. Dasgupta, M. Kabra, N. Verma. (2007) Learning the structure of manifolds using random projections, Adv. in Neural Info. Proc. Systems (NIPS), Vancouver, B.C., Canada.

Elbert, T. E. 1984 Estimation and Control of Systems (Van Nostrand Reinhold)

Frasier, K. E., Henderson, E. E., Bassett, H. R., and Roch, M. A. (in prep). "Automated identification of common subunits within delphinid vocalizations," 9 pp.

Giraudet, P. and H. Glotin. 2006 Real-time 3d tracking of whales by echo-robust precise tdoa estimates with a widely spaced hydrophone array", Applied Acoustics 67, 1106 – 1117.

Helble, T. A., G. R. Ierley, G. L. D'Spain, M. A. Roch, and J. A. Hildebrand 2012. A generalized power-law detection algorithm for humpback whale vocalizations. J. Acoust. Soc. Am. 131(4), 2682-2699.

Helble, T.A., Ierley, G., D'Spain, G.,L. and Martin, S.W. (submitted). Automated acoustic localization and call association for humpback whales on the Navy's Pacific Missile Range Facility.

Hubel, D.H., and T.N. Wiesel. (1962) Receptive fields, binocular interaction, and functional architecture in the cat's visual cortex. J. Physiol. (London) 160:106-154.

Jarvis, S.M. (2012) *A Novel Method For Multi-Class Classification Using Support Vector Machines*. Ph.D. Dissertation. Univ. Massachusetts, Dartmouth.

Jarvis, S.M., N.A. DiMarzio, R.P. Morrissey, D.J. Moretti. (2008) A novel multi-class support vector machine classifier for automated classification of beaked whales and other small odontocetes. Canad. Acoust., 36(1): 34-40.

Jarvis, S.M., Morrissey, R.P., Moretti, D.J., et al. (2012) Marine Mammal Monitoring on Navy Ranges (M3R): A toolset for automated detection, localization, and monitoring of marine mammals in open ocean environments. Mar. Tech. Soc. J. 48(1): 5-20.

Johnson, M. Madsen, P.T., Zimmer, W.M.Z., Aguilar de Soto, N., Tyack, P.L. (2004) Beaked whales echolocate on prey. Proc. Royal Soc., 271(6): S383-S386.

Kaiser, J.F. (1990) On a simple algorithm to calculate the "energy" of a signal. Intl. Conf. Acoust., Speech, and Signal Process. IEEE, Albuquerque, NM: 381-384.

Kandia, V., Y. Stylianou. 2006. Detection of sperm whale clicks based on the Teager-Kaiser energy operator. Appl. Acoust., 67(11-12): 1144-1163.

Kershenbaum, A., and Roch, M. A. (2013). "An image processing based paradigm for the extraction of tonal sounds in cetacean communications," J. Acous. Soc. Am. 134(6), 4435-4445

Klinck, H., and D.K. Mellinger. 2011. The energy ratio mapping algorithm (ERMA): a tool to improve the energy-based detection of odontocete clicks. J. Acoust. Soc. Am. 129(4):1807-1812.

Landy, M.S., and J.A. Movshon, eds. 1991. Computational Models of Visual Processing. MIT Press, Cambridge.

Martin, A.Q., Marques, T.A., Thomas, L., Morrissey, R.P., Jarvis, S., DiMarzio, SN., and Moretti, D. 2013. Estimating minke whale (Balaenoptera acutorostrata) boing sound density using passive acoustic sensors. Marine Mammal Science 29(1): 142-158.

Martin, S.W., C. Martin, B. Matsuyama, and E.E. Henderson. (2014 in process) Minke whales respond to US Navy training in Hawaiian waters. Mellinger, D.K., Martin, S.W., Morrissey, R.P., Thomas, L. and Yosco, J. 2011. A method for detecting whistles, moans, and other frequency contour sounds. Jouranl of the Acoustical Society of America 129:4055-4061.

Martin, S.W., T.A. Marques, L. Thomas, R.P. Morrissey, S. Jarvis, N. DiMarzio, D. Moretti, and D.K. Mellinger. 2012. Estimating minke whale (Balaenoptera acutorostrata) boing sound density using passive acoustic sensors. Marine Mamm. Sci. doi:10.1111/j.1748-7692.2011.00561.x, online first 23-Apr-2012.

Mellinger, D.K. (2001) Ishmael 1.0 User's Guide. Natl. Oceanogr. Atmos. Admin. Tech. Memo. OAR–PMEL–120 (NOAA PMEL, Seattle). 30 pp.

Mellinger, D.K., R.P. Morrissey, S.W. Martin, L. Thomas, T.A. Marques, and J. Yosco. 2011. A method for detecting whistles, moans, and other frequency contours. J. Acoust. Soc. Am. 129:4055-4061.

Mendelson, J.R., and M.S. Cynader. (1985) Sensitivity of cat auditory primary cortex (AI) neurons to the direction and rate of frequency modulation. Brain Res. 327: 331-335.

Mitchell, S. and J. Bower, 1995. Localization of animal calls via hyperbolic methods, Journal of the Acoustical Society of merica 97, 3352–3353 (1995).

Morrissey, R. P., J. Ward, N. DiMarzio, S. Jarvis and D. Moretti. 2006. Passive acoustic detection and localization of sperm whales (Physter macrocephalus) in the Tongue of the Ocean. Applied Acoustics 67:1091–1105.

Morrissey, R.P., J. Ward, N. DiMarzio, S. Jarvis, and D.J. Moretti. (2006) Passive acoustic detection and localization of sperm whales (Physeter macrocephalus) in the Tongue of the Ocean. Appl. Acoust. 67: 1091-1105.

Norris R, Martin S, Thomas L, Yack T, Oswald JN, Nosal E-M, V Janik (2011) Acoustic Ecology and Behavior of Minke Whales in the Hawaiian and Marianas Islands: Localization, Abundance Estimation and Characterization of Minke Whale "Boings" in eds Popper, Hawkins: The effects of noise on aquatic life: Second international congress, Springer.

Nuttall, A. (1996). "Near-optimum detection performance of power-law processors for random signals of unknown locations, structure, extent, and arbitrary strengths," NUWC-NPT Technical Report, Newport, RI.

Oleson, E.M., Barlow, J., Gordon, J., Rankin, S., and Hildebrand, J.A. 2003. Low Frequency calls of Bryde's whales. Marine Mammal Science 19(2):407-419.

Rabiner, L.R., B.H. Juang. (1986) An introduction to hidden Markov models. IEEE ASSP Magazine: 4-16.

Rankin, S. and Barlow, J. 2005. Source of the North Pacific 'boing' sound attributed to minke whales. Journal of the Acoustical Society of America 118: 3346-3351.

Reid, D. B. 1979 An algorithm for tracking multiple targets", Transactions on automatic control 24, 843–854.

Roch, M. A., Klinck, H., Baumann-Pickering, S., Mellinger, D. K., Qui, S., Soldevilla, M. S. and Hildebrand, J. A. (2011b). Classification of echolocation clicks from odontocetes in the Southern California Bight. J. Acous. Soc. Am. 129, 467-475.

Roch, M. A., Stinner-Sloan, J., and Baumann-Pickering, S. (submitted). "The Effects of Site and Equipment Variation on Species Identification of Delphinids from Their Echolocation Clicks." Roch, M. A., Brandes, T. S., Patel, B., Barkley, Y., Baumann-Pickering, S. and Soldevilla, M. S.

(2011a). Automated extraction of odontocete whistle contours. J. Acous. Soc. Am. 130, 2212-2223.

Roch, M.A., B. Patel, S. Rankin, Y. Barkley, M.S. Soldevilla, J.A. Hildebrand. (2010) Identifying delphinid whistle contours using graph search (A). J. Acoust. Soc. Am., 127(3): 1936-1936.

Roch, M.A., H. Klinck, S. Baumann-Pickering, D.K. Mellinger, S. Qui, M.S. Soldevilla, J.A. Hildebrand. (2011) Classification of echolocation clicks from odontocetes in the Southern California Bight. J. Acoust. Soc. Am. 129:467-475. Ross, D. (1976) Mechanics of Underwater Noise. Pergamon: New York, xiv+375 pp.

Shaffer, J. W., D. Moretti, and S. Jarvis. (2013) Effective beam pattern of the Blainville's beaked whale (*Mesoplodon densirostris*) and implications for passive acoustic monitoring. J. Acoust. Soc. Am. 133: 1770-1784.

Soldevilla, M. S., Henderson, E. E., Campbell, G. S., Wiggins, S. M., Hildebrand, J. A. and Roch, M. A. (2008). Classification of Risso's and Pacific white-sided dolphins using spectral properties of echolocation clicks. J. Acous. Soc. Am. 124, 609-624.

Soldevilla, M.S. (2008) *Risso's and Pacific white-sided dolphins in the Southern California Bight: Using echolocation clicks to study dolphin ecology*. Ph.D. thesis, Univ. California, San Diego, La Jolla.

Thompson, P.O. and Friedl, W.A. 1982. A long term study of low frequency sounds from several species of whales off Oahu, Hawaii. Cetology 45:1-19.

Tyack, P.L., Johnson, M. 2006. Extreme diving behavior of beaked whales, J. Exper. Biol. 209: 4238-4253.

Ward, J., R. Morrissey, D. Moretti, N. DiMarzio, S. Jarvis, M. Johnson, P. Tyack, and C. White. 2008. Passive acoustic detection and localization of *Mesoplodon densirostris* (Blainville's beaked whale) vocalizations using distributed bottom-mounted hydrophones in conjunction with a digital tag (DTag) recording, Canadian Acoustics 36: 60–66.

White, P. , T. Leighton, D. Finfer, C. Powles, and O. Baumann. 2006. Localisation of sperm whales using bottom-mounted sensors, Applied Acoustics 67, 1074–1090 .

Wiggins, S. M. and Hildebrand, J. A. (2007). High-frequency Acoustic Recording Package (HARP) for broad-band, long-term marine mammal monitoring. Intl. Symp. Underwater Tech., pp. 551-557. Tokyo, Japan.

PUBLICATIONS

Baggenstoss, P.M. (2014) The Jonker-Volgenant algorithm applied to click-train separation. J. Acoust. Soc. Am. 135: 2485-2487.

Baggenstoss, P.M., and F. Kurth. (2014) Comparing shift-autocorrelation with cepstrum for detection of burst pulses in impulsive noise. J. Acoust. Soc. Am. 136: 1574-1582.

Baggenstoss, P.M. (2015) A multi-hypothesis tracker for clicking whales. J. Acoust. Soc. Am. 137: 2552-2562.

Baumann-Pickering, S., Roch, M. A., Brownell Jr, R. L., Simonis, A. E., McDonald, M. A., Solsona-Berga, A., Oleson, E. M., Wiggins, S. M., and Hildebrand, J. A. (2014). Spatio-temporal patterns of beaked whale echolocation signals in the North Pacific. PLOS ONE 9(1), pp. 17, doi:10.1371/journal.pone.0086072.g001.

Frasier, K. E., Henderson, E. E., Bassett, H. R., and Roch, M. A. (In revision.) "Automated identification of common subunits within delphinid vocalizations," 9 pp.

Helble, T.A., G.R Ierely, G.L. D'Spain, and S.W. Martin. (2015) Automated acoustic localization and call association for vocalizing humpback whales on the Navy's Pacific Missile Range Facility, J. Acoust. Soc. Am. 137:11-21.

Kershenbaum, A., Blumstein, D. T., Roch, M. A., Akçay, Ç., Backus, G., Bee, M., Bohn, K., Cao, Y., Carter, G., Cäsar, C., Coen, M., DeRuiter, S. L., Doyle, L., Edelman, S., Ferrer-i-Cancho, R., Freeberg, T. M., Garland, E. C., Gustison, M., Harley, H. E., Huetz, C., Hughes, M., Bruno, J. H., Ilany, A., Jin, D. Z., Johnson, M., Ju, C., Karnowski, J., Lohr, B., Manser, M. B., McCowan, B., Mercado III, E., Narins, P. M., Piel, A., Rice, M., Salmi, R., Sasahara, K., Sayigh, L., Shiu, Y., Taylor, C., Vallejo, E. E., Waller, S., and Zamora-Gutierrez, V. (In press) Acoustic sequences in non-human animals: A tutorial review and prospectus. To appear, Biological Reviews.

Kershenbaum, A., and Roch, M. A. (2013). "An image processing based paradigm for the extraction of tonal sounds in cetacean communications," J. Acoust. Soc. Am. 134(6):4435-4445.

Martin, S.W., C.R. Martin, B.M. Matsuyama and E.E. Henderson. (2015) Minke whales (*Balaenoptera acutorostrata*) respond to navy training, J. Acoust. Soc. Am. 137(5):2533-2541.

Mellinger, D.K., M.A. Roch, E.-M. Nosal, and H. Klinck. (In press) Signal processing. Chapter for *Listening in the Ocean*, M. Lammers and W. Au, eds. To appear.

Roch, M. A., Stinner-Sloan, J., Baumann-Pickering, S., and Wiggins, S. M. (2015) Compensating for the effects of site and equipment variation on delphinid species identification from their echolocation clicks. J. Acoust. Soc. Am. 137(1):22-29.

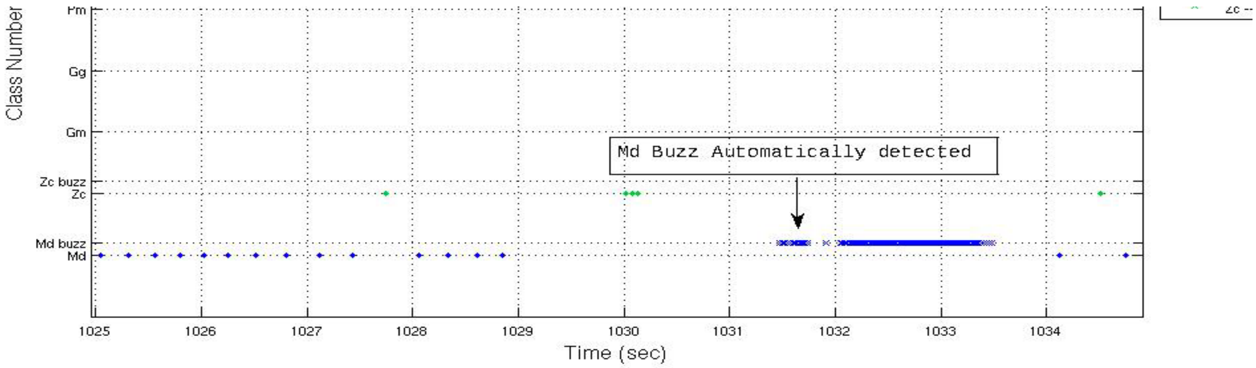

Figure 1: Md buzz detected within the context of a foraging dive. Blue dots represent clicks classified as Md foraging clicks and blue x's are clicks that were classified as buzz clicks. Green dots are clicks that were (erroneously) classified as Zc.

	A	B	C	D	E	F	G	H	I
1	Day	Dive #	Num. Buzzes	Start Hr (Z)	Hyds	Dive Strt (sec)	Dive Stop (sec)	Buzz Start (sec)	Buzz Stop (sec)
2	189			14:00	2,1,4,5,7,3,6	1721	4900		
3					2	3554	4855	4823.797	4824.024
4		1	11		4	1721	3268	1955.155	1955.476
5								2078.403	2078.638
6								2755.517	2755.866
7								2810.741	2812.472
8								2992.968	2993.069
9		2	9			3405	4900	4533.255	4535.187
10								4762.743	4764.843
11					5	1747	2812	2783.206	2783.484
12						3084	4874	4205.137	4207.414
13					7	1756	3572	2161.006	2161.093
14								2301.444	2301.626
15								2742.232	2743.258
16								3012.012	3012.818
17								3476.456	3476.696
18								3616.531	3616.942
19								3692.543	3692.572
20								4411.813	4413.643

Figure 2. Example of manually verified buzz detections from AUTEC. Over a 3-day period in July 2014, 69 dives with 1 or more buzzes were tallied, with an average of 3.696 buzzes per dive. These results were particularly encouraging because buzz detections were received on hydrophone across the entire range, an area encompassing 1000+ km^2. However, while several buzzes per dive were often detected, these represent a small fraction of the total number of buzzes produced per dive (avg.=29) (Tyack et al. 2006).

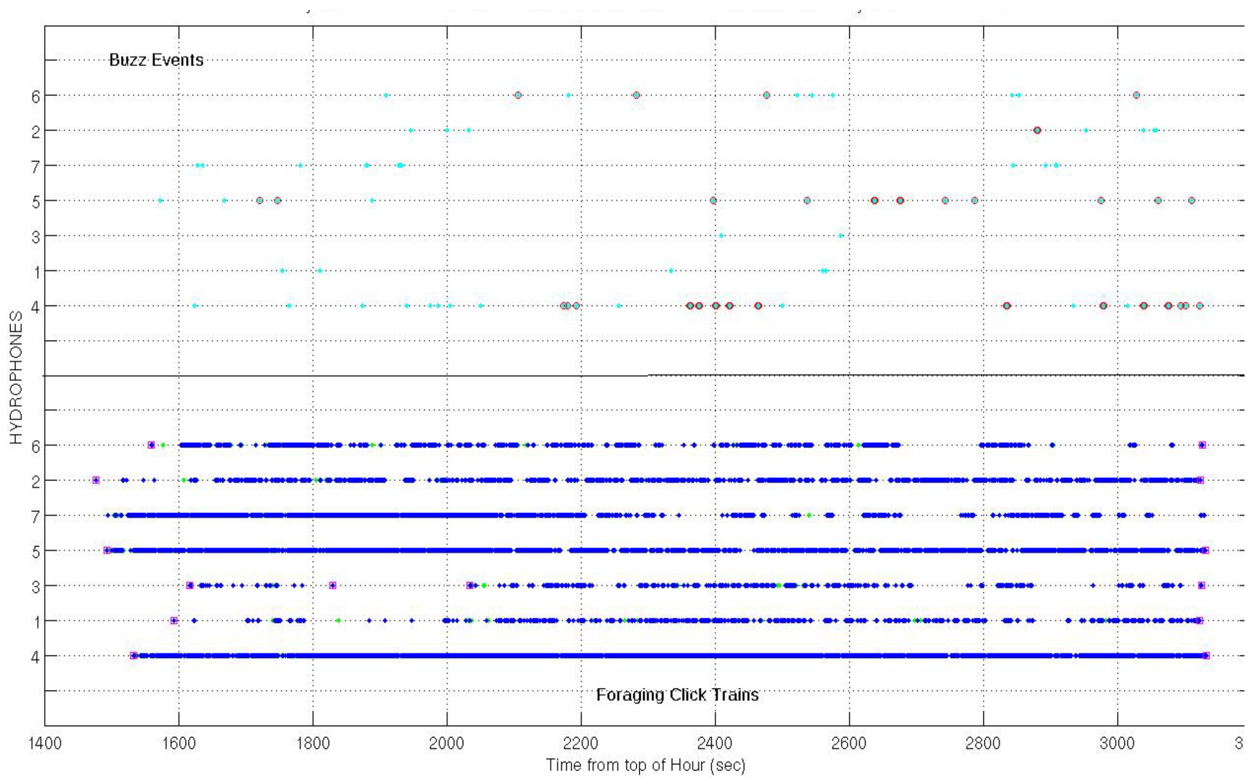

Figure 3. CS-SVM output from 7 hydrophones for an exceptional dive encounter involving a group of 3 vocal Md. Lower: Md foraging click classifications. Magenta squares indicate dive start and stop times automatically determined in post-processing. Upper: Md buzz click classifications versus time per hydrophone number. Red circles indicate buzz start and stop times automatically determined during post-processing. A total of 37 buzzes (95% of the 39 manually found) were automatically detected during this complex group dive event.

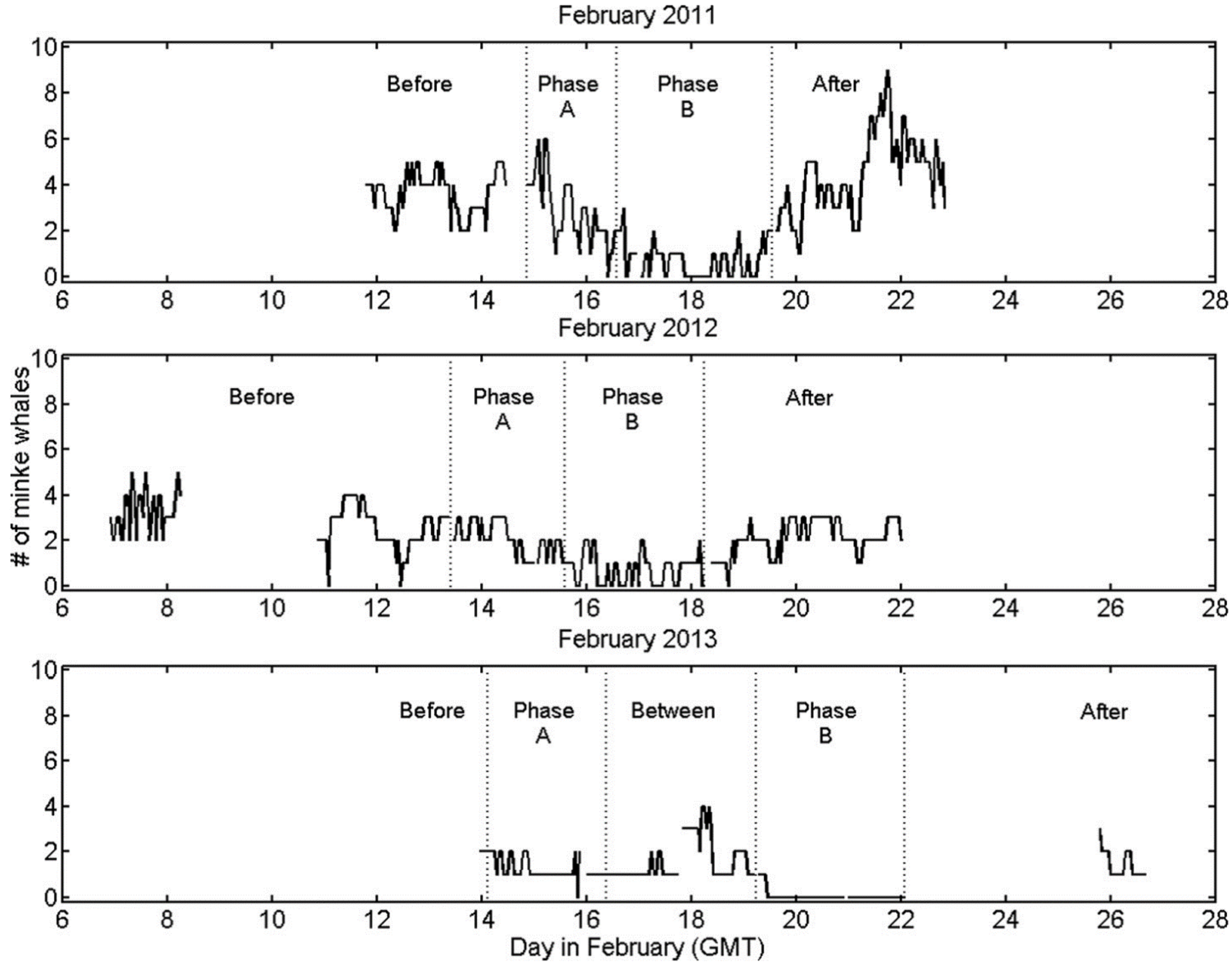

Figure 4. Number of minke whales acoustically localized in 1 h temporal bins for a study area of 3,780 km^2 (PMRF) offshore of Kauai, Hawaii (from Martin et al. 2015). The plots show the number of individual minke whales (y-axis) over time. "Before", "after" and Phase A and B refer to Navy training exercises, with only Phase B involving MFA sonar. Blank periods indicate when recorded data was not available. The reduced numbers in the phase B periods are clear.