SIGNAL AND IMAGE PROCESSING TECHNIQUES AS APPLIED TO ANIMAL BIOACOUSTICS PROBLEMS

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Adopting the philosophy that diverse problems have similar solutions, signal and image processing techniques have been successfully used to solve problems in animal bioacoustics. Three examples are offered where standard time-series analysis techniques have been applied to data with biological origins:

– "Three-dimensional passive acoustic localization technique for marine mammals" uses spectrograms of acoustic time series followed by a model-based processor;
– "Applying diffraction theory to measure acoustically the in-situ orientation of marine animals" uses autocorrelations followed by Radon transforms;
– "Identifying individual clicking whales acoustically" uses spectrograms.

"This work explores the implementation of an algorithm to compute animal orientation from wide-band backscatter data collected in the lab from live fish."

Three-dimensional passive acoustic localization techniques for marine mammals

Passive underwater acoustic methods for monitoring the activity of marine mammals have been used for many years in censuring or behavioral studies because they are unobtrusive and can function when animals are out of sight. Methods for tracking the movement of animals underwater through analysis of their recorded vocalizations have now advanced

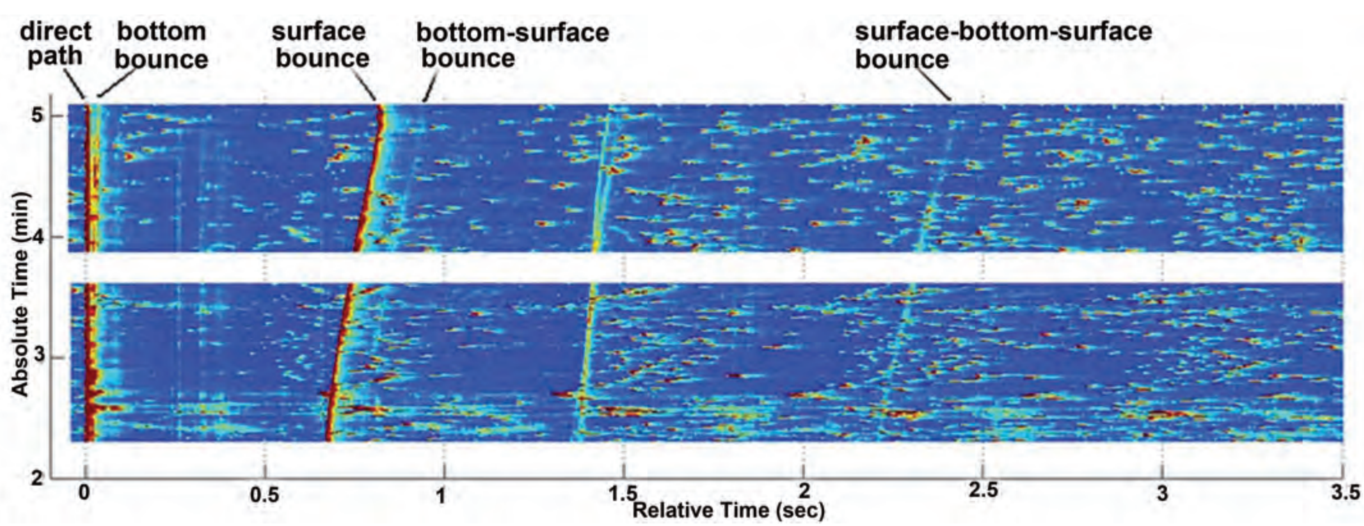

Fig. 1. Time aligned spectral sum excerpts, each starting with a direct-path arrival at relative time 0 sec, presented as a 2D surface. Persistent arrivals with identified acoustic path geometries are labeled. With permission of Canadian Acoustics.

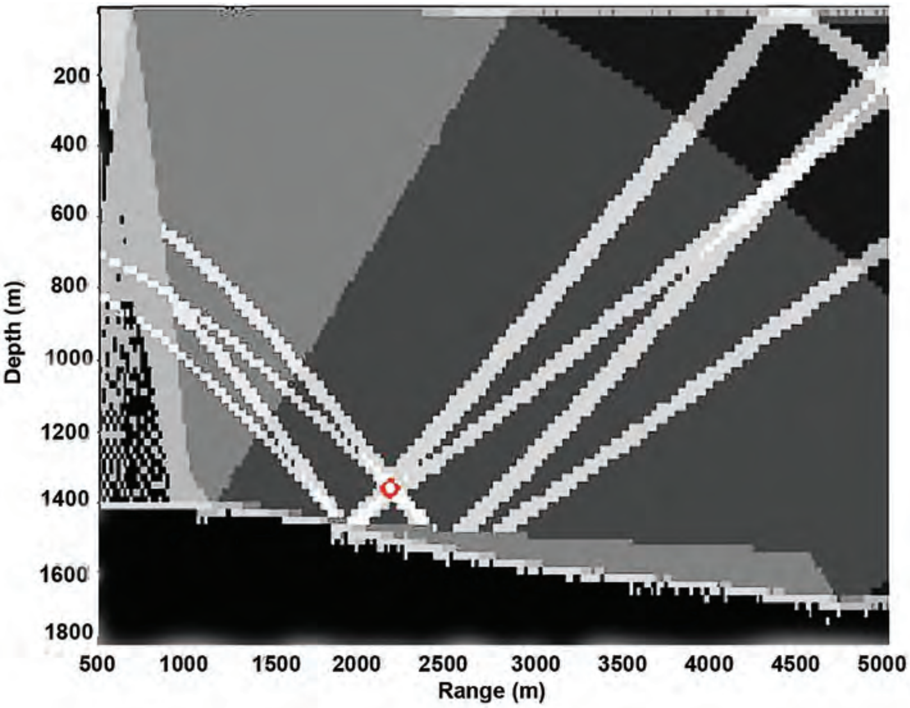

Fig. 2. An ambiguity surface representing agreement between measured and modeled arrival patterns for hypothesized source locations on a vertical range/depth slice along bearing 200º from the Bahamas receiver. The marked peak indicates the best estimate of source location. With permission of Canadian Acoustics.

far enough to use acoustic propagation models and multipath arrival information (echoes) for more accurate localization estimates, but these usually require use of an array of underwater sensors. However, Christopher Tiemann at University of Texas at Austin has demonstrated that a full three-dimensional estimate (range, depth, and bearing from a sensor) of a whale's location can be made using acoustic data from just a single sensor.

In two separate experiments in Alaska and the Bahamas, the echolocation clicks of endangered sperm whales were recorded on mid-water and bottom-mounted hydrophones. A single broadband click is often heard multiple times at a receiver due to different acoustic paths that echo off the sea surface or sea floor, attenuating with each bounce. It is these echoes that enable single-sensor localization, but the late arriving echoes can be very difficult to detect. Spectrograms are computed from the full measured time series. Integrating spectral power in the expected click frequency band over small time windows of acoustic data creates a time series where peaks mark the arrival of broadband clicks. When excerpts from this series are time-aligned with the first arrival of consecutive click events, persistent peaks from echoes can be recognized; even extremely faint ones from paths reflecting several times through the ocean waveguide (Fig. 1). The spacing of these arrivals serves as a unique fingerprint of whale location which can be compared to predicted arrival patterns from modeled sources at all ranges, depths, and bearings. A score representing their agreement can be viewed as an ambiguity surface (Fig. 2) where the location of the modeled source with the best score becomes the estimate of whale location. Repeating this process every time a whale clicks allows tracking of its motion over time. (Fig. 3)

Applying diffraction theory to measure acoustically the in-situ orientation of marine animals

A significant goal in the use of "active" acoustics for observing marine animals is to infer their size and type from the measurement of the reflected acoustic "pings." Using the relative amount of reflected energy has yielded important information; however there are substantial complications because the reflected energy is not only a function of size, but also orientation and composition. In order to explore the use of methods that could improve on the more traditional narrow band echo sounders, Jules S. Jaffe, Paul L. D. Roberts, and their group at the Marine Physical Laboratory, Scripps Institution of Oceanography, have been measuring the angular dependent wide-band backscatter from live fish in a laboratory environment. Using various techniques to process these data have yielded interesting insights into the utility of this additional information while also highlighting the significant challenges that occur for using advanced methods. This work explores the implementation of an algorithm to compute animal orientation from wide-band backscatter data (Jaffe and Roberts, 2011) collected in the lab from live fish. Orientation estimation is an important parameter in interpreting echosounder surveys as the amount of reflected energy can vary by several orders of magnitude as a function of orientation and hence, yield incorrect estimates of animal size.

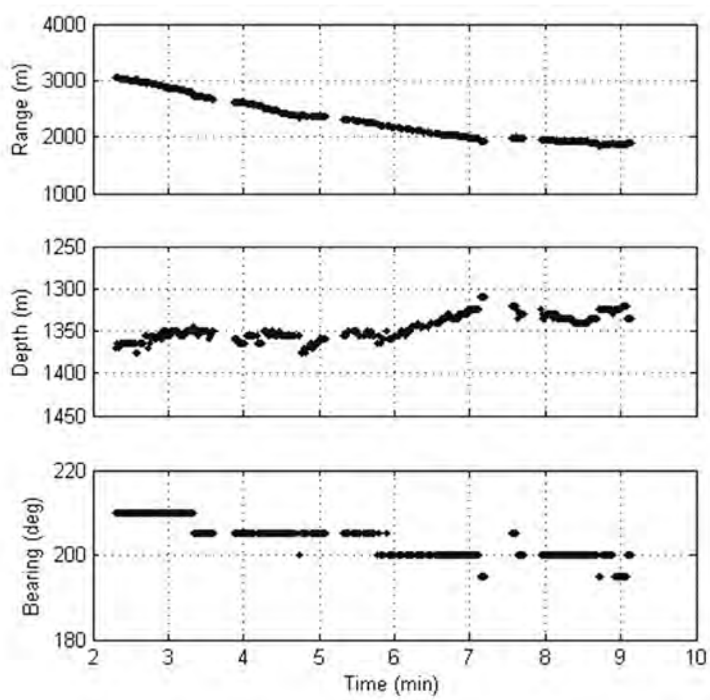

Fig. 3. Range, depth, and bearing estimates relative to a single receiver for a clicking sperm whale. Estimates were made using acoustic data from just the one sensor. With permission of Canadian Acoustics.

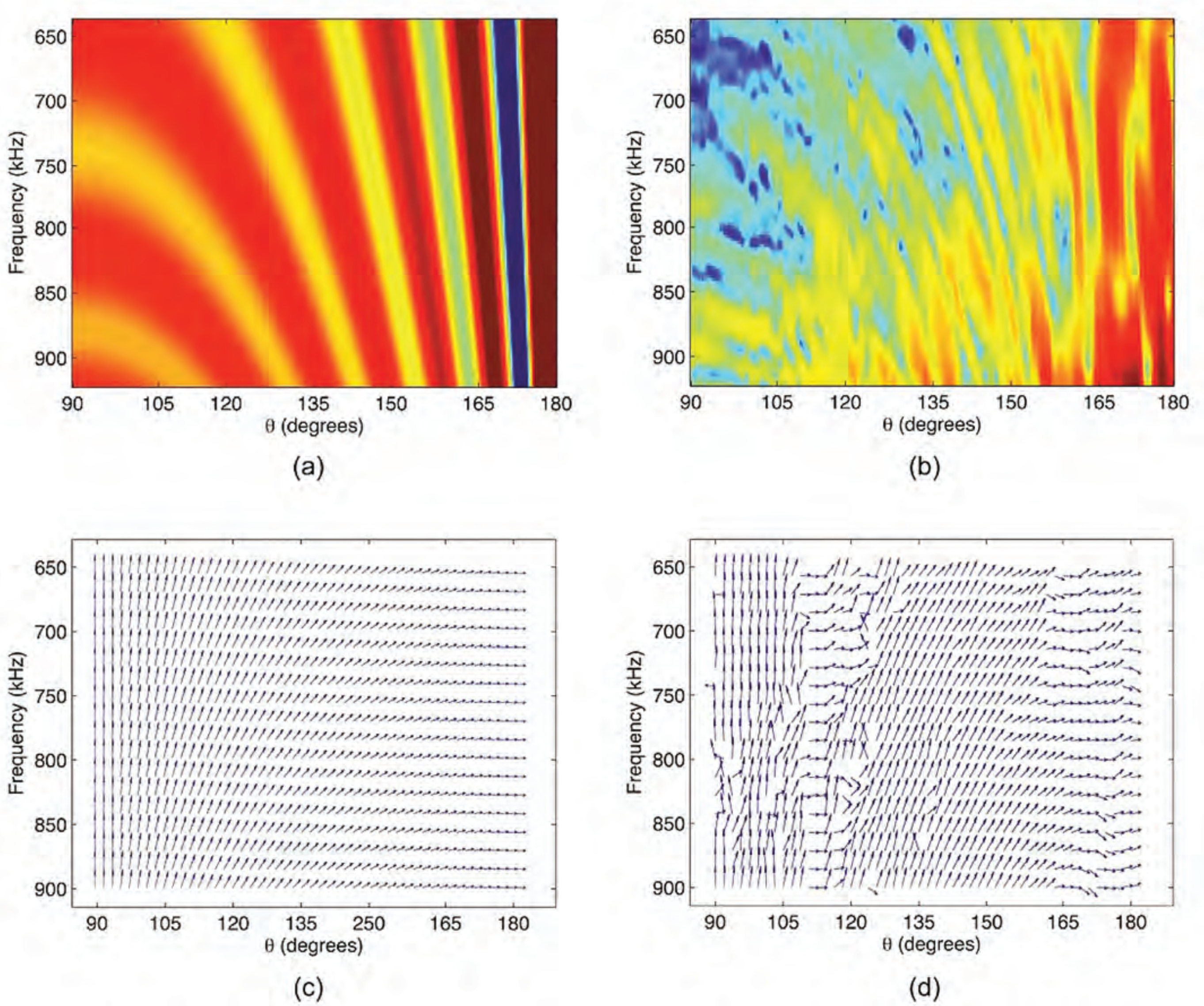

Fig. 4. (a) The wide band backscatter spectrum predicted from a simple bar target model (arbitrary log intensity units). (b) The wide band backscatter measurement from a single fish measured in a test tank facility. (c) The inferred orientation of the bar target, derived from the data in (a). (d) The inferred orientation of the fish, derived from the data in (b).

Figure 4 shows pictures of the logarithm of the intensity of the fraction of backscattered sound, related to target strength, as a function of frequency and orientation for both a simple bar target model (a) and a live animal (b). Based on the insight that the data consist of radially spreading spokes, going from the bottom right to the top left, locally perpendicular to the animal's orientation, an algorithm was formulated to compute the direction perpendicular to those spokes to estimate orientation. This fortuitously turned out to be a gradient operator; however, the application of the gradient to a noisy set of data like (b) is a challenge. The results whose details are describe in (Jaffe and Roberts, 2011), where the local estimate of orientation, as depicted by the direction of the arrow as a function of frequency and true orientation are shown for the simple bar target model (c) derived from (a) and the more complicated data (d) derived from (b). The results indicate that mostly, a reasonable estimate of orientation can be derived. However, there are clearly some problem areas as well. Nevertheless, because most animals are orientated at nearly 180 degrees in the field, it is hoped the pragmatic application of this method to a next generation of field deployable systems, when coupled with better models and more advanced signal processing, will yield ever-more accurate estimates of animal orientation and hence, permit the measurement of the size spectrum of marine animal populations.

Identifying individual clicking whales acoustically

In the last decade many new signal processing algorithms have been developed to understand social organization, population dynamics, and behavior patterns of large marine mammals, such as sperm and beaked whales. Because acoustics is their primary exploration and communication tool, it has been suggested that click acoustic characteristics and time patterns carry attributes of individuals among a group. Success in identifying individual marine mammals

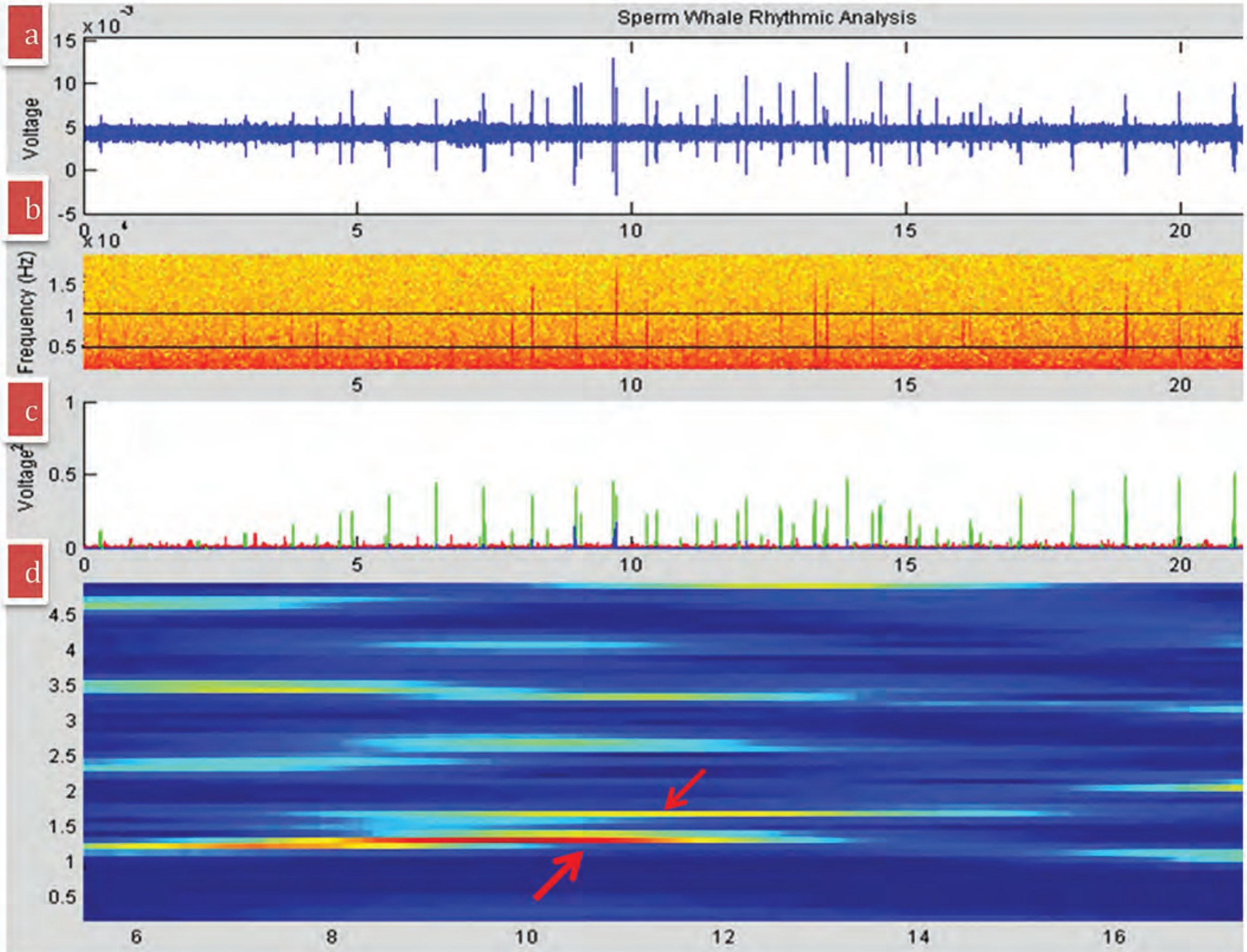

Fig. 5. Cadence frequency analysis of overlapping sperm whale click trains. (a) The 25 second acoustic data inset, recorded on a LADC Environmental Acoustic Recording System (EARS) buoy at a sampling frequency of 192 kHz, shows bioacoustic activity. (b) Applying a short-time spectrogram analysis indicates that the main energy of the clicks in the 5-10 kHz band, which is representative of the sperm whale phonation band. (c) The green curve is the band-limited energy as a function of time, obtained by summing squared amplitudes of the spectral components of the time signal (panel (a)) in the 5-10 kHz band. The Fourier analysis window is equal to a mean duration of sperm whale clicks (~10 ms). (d) The main result of the cadence analysis algorithm shows cadence frequencies and their harmonics (bright red-yellow horizontal lines) as functions of time, obtained by applying a long-time Fourier transform to the band-limited energy function (panel (c) green curve). One can easily identify two animals phonating simultaneously with slightly different intra-click interval (inverse of cadence frequency) between the 8 s and 15 s marks.

acoustically will bring a new era in bioacoustics research when the same animal can be observed and studied acoustically through its life in the wild. It can also assist scientists in understanding a more complete picture of the functioning of the mammal auditory system. Scientists from the Littoral Acoustic Demonstration Center (LADC), a consortium of scientists from universities and the Navy, have been collecting multi-year passive acoustic recordings of sperm and beaked whales in the Northern Gulf of Mexico and developing a multi-tiered approach including localization, signal attribute similarity (cluster) analysis, click train identification, cadence analysis, and click change detection to identify vocalizing individuals in a group (Ioup *et al.*, 2009; Sidorovskaia *et al*, 2011; Tiemann *et al.*, 2006). A team comprising Christopher Tiemann of the Applied Research Laboratories at the University of Texas at Austin, Natalia Sidorovskaia of the Physics Department of the University of Louisiana at Lafayette, George Ioup and Juliette Ioup of the Department of Physics at the University of New Orleans, all members of LADC, is trying to identify individual sperm and beaked whales from the acoustic properties of their clicks, taken both singly and collectively.

The cadence analysis technique was developed to test the hypothesis that sperm whales in a group, for example, can use slightly different rhythmic patterns while clicking so as not to clutter each other's acoustic information gathering and possibly use it collectively. Figure 5 shows the steps in a dynamic cadence analysis algorithm to identify the temporal evolution of individual rhythmic patterns in overlapping sperm whale click trains. Panel (a) is a 25 second temporal segment of passive acoustic data, recorded in the Northern Gulf of Mexico, rich in bioacoustic signals. Panel (b) gives a spectrogram of the same data segment, revealing that the main energy of clicks is in the 5-10 kHz band. This band is representative of sperm whale phonations. In the third processing step the energy in the band is calculated and displayed in green in panel (c). To reveal different rhythmic patterns, the band-limited energy function is analysed by a long-time (~11 s) Fourier transform with 99% overlap. The bright red-yellow horizontal lines of the last panel (d) of Fig. 5 represent the cadence frequencies and their harmonics as a function of time. One can clearly see two simultaneous cadence frequencies (identified by red arrows) encoding two fine-turned click rates associated with two animals. Thus clicks belonging to an individual can be associated by relating cadence frequencies to temporal signals (panel (a)). The cadence analysis algorithm is part of an integrated tool proposed by LADC for identification of individual animals in a group. In parallel, multi-attribute similarity (cluster) analysis and source localization are applied to the same volume of data. The results are integrated and compared to provide reliable identification and verification of the separate methods.

The initial motivation for working with individual clicks came when the Ioups noticed that all the clicks in a sperm whale coda were similar both in the time and frequency domains, but they could differ from coda to coda. Coda clicks are used for communication, and they occur in groups of 6 to 15 clicks with an interclick interval of approximately 40 msec and a click duration of 3 to 6 msec. It had earlier been shown that the time difference between peaks within a sperm whale echolocation click are related to the size of the whale (Norris and Harvey, 1972; Gordon, 1991), and the observation that coda clicks from a given whale are similar to each other but differ from the clicks of other whales is consistent with the connection of click properties to the size of the whale. Figure 6 shows the time domain signals and the spectrograms of two segments of four seconds of sperm whale clicks; each contains a coda. The top figure in each group of three is proportional to the pressure plotted versus time. The middle figure shows the spectrogram with frequency to 6000 Hz on the vertical axis and time on the horizontal axis. The color indicates the magnitude of the transform. The bottom figure shows the frequency to 1000 Hz. Figure 7 shows an overplot of the magnitude spectra of all the clicks in a coda for five different codas. Figure 8 shows an amplitude versus time overplot of the clicks within a coda, with similarity among the clicks evident. One method of grouping the clicks from a single whale is cluster analysis. Self-organizing maps has been the approach that has given the best results for cluster analysis. It has

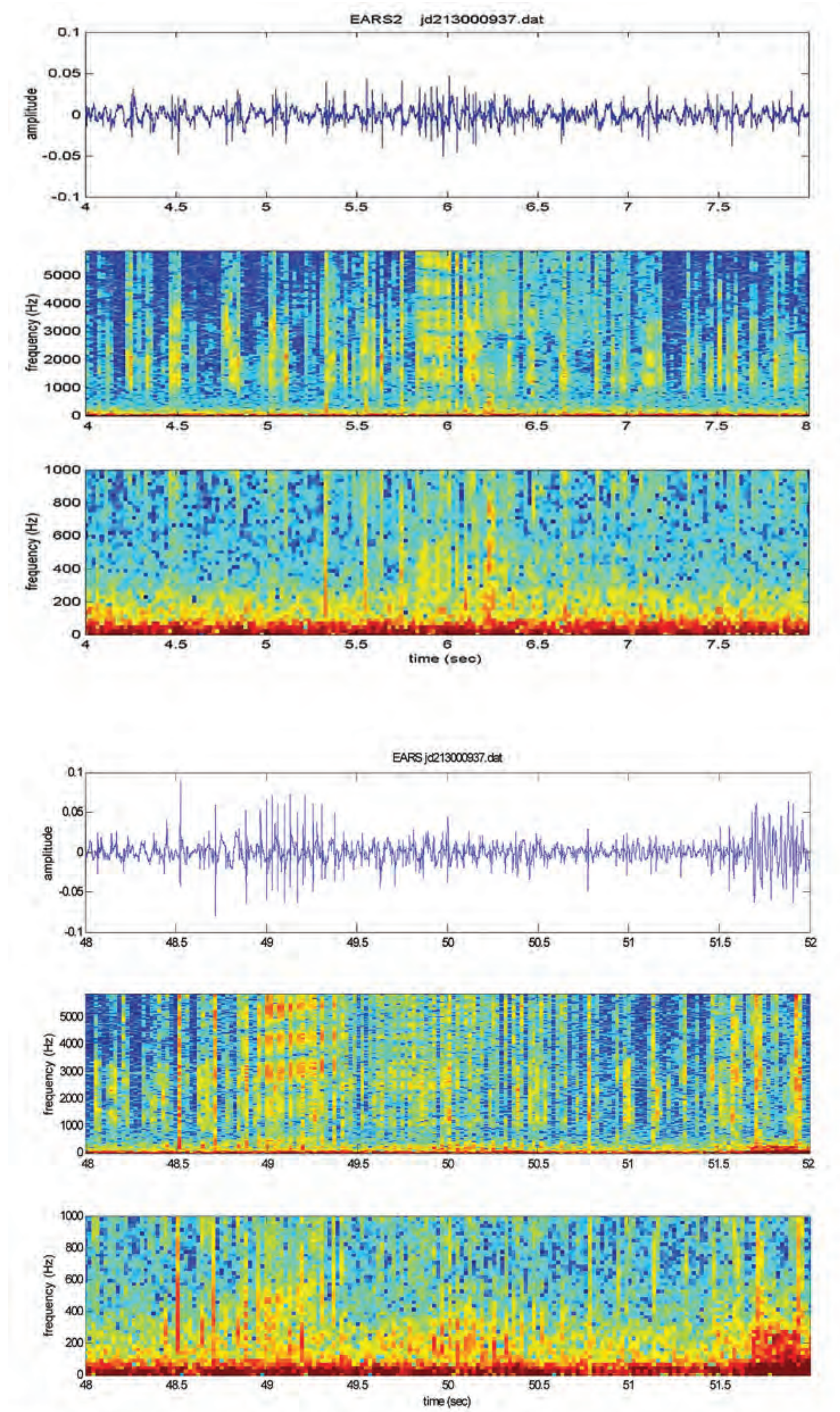

Fig. 6. Two 4-s segments of acoustic recordings from the Gulf of Mexico, containing sperm whale codas.

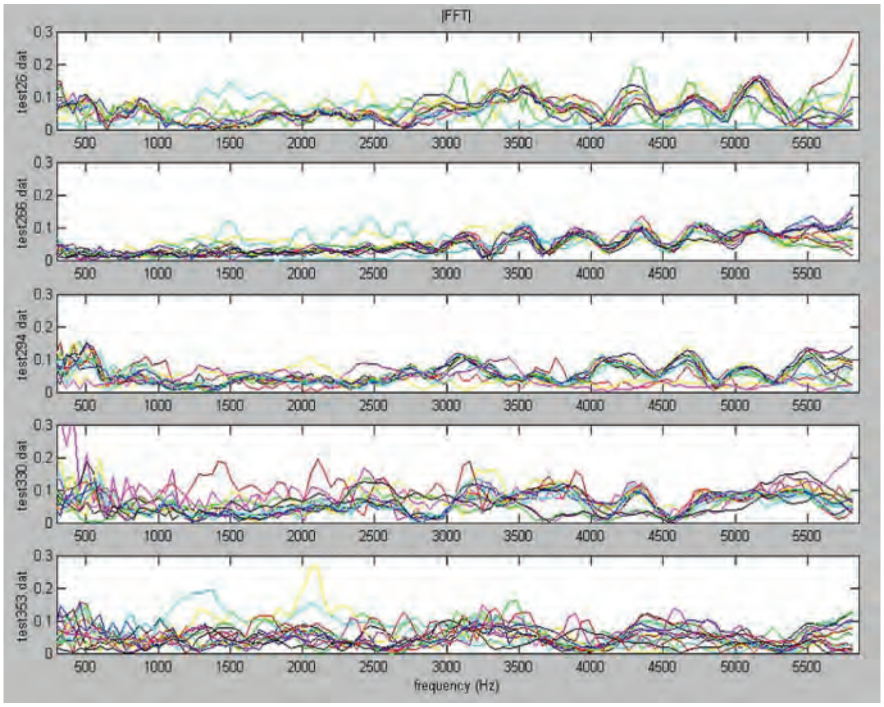

Fig. 7. Overplot of the magnitude Fourier spectra versus frequency for all the clicks in five sperm whale codas. Each panel is one coda, with individual clicks in each coda in a different color. Note that the shapes for the clicks in one coda are quite similar to each other, but distinctly different from those in other codas.

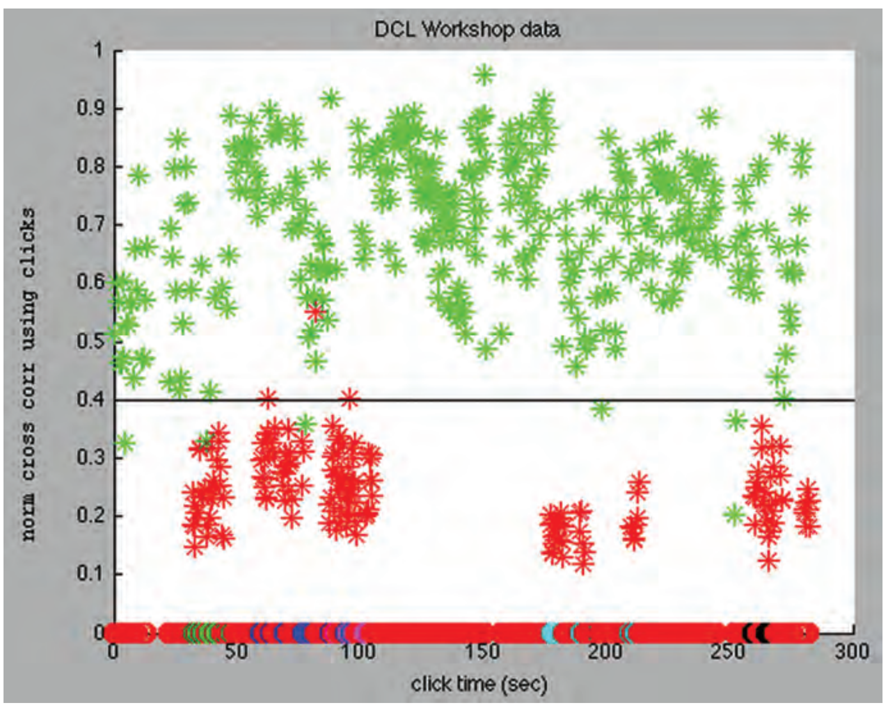

Fig. 8. Amplitude versus time for all the clicks in one coda from Fig. 3 plotted. Amplitude in each click is offset for clarity.

been applied to both sperm whale coda and echolocation clicks and beaked whale echolocation clicks. LADC scientists have been using cluster analysis for the last eight years (G. E. Ioup *et al.*, 2005; G. E. Ioup *et al.*, 2009; J. W. Ioup *et al.*, 2010).

Separately Christopher Tiemann has analyzed clicks collectively by doing manual click train identification. This involves following the click sequence of an echolocating whale including the identification of multiple reflections, and distinguishing it from the click sequences of other whales. He has developed several tools to facilitate the difficult work. Meanwhile the UNO scientists have developed click change detection (CCD) to deal with the problem of turning sperm whales which change their aspect with respect to the detector and therefore the properties of their received clicks (G. E. Ioup *et al.*, 2010, 2011; Starkhammar *et al.*, 2011). In comparing the results of CCD in determining if the same or a different whale is speaking to the manual click train identification of Christopher Tiemann, they achieve an agreement of over 98.5%. See Fig. 9.

All four LADC investigators have been working together to integrate cluster analysis, manual click train identification, localization, cadence analysis, and click change detection to identify individual clicking whales (Sidorovskaia *et al.*, 2010; G. E. Ioup *et al.*, 2011). The separate approaches also serve to validate each other.**AT**

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Christopher O. Tiemann received a B.S. degree in electrical engineering from Texas A&M University in 1994 and Ph.D. in Oceanography from Scripps Institution of Oceanography in 2000. He worked for Science Applications International Corporation in San Diego through 2004, and he is currently a researcher at Applied Research Laboratories, University of Texas at Austin. As a member of the Littoral Acoustic Demonstration Center (LADC), he pursues his interests in the passive acoustic study of marine mammals.

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Natalia Sidorovskaia is an associate professor and chairperson in the Physics department of the University of Louisiana at Lafayette. Her primary research interests include signal processing techniques for bio- and geo-acoustics, sound propagation modeling in oceanic waveguides, and high performance computing. She has co-authored over 30 research articles, two book chapters, and one book on acoustics. Dr. Sidorovskaia is an active member of the Acoustical Society of America and its technical committee on signal processing.

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