A Book of Abstracts for the

2007 Underwater Acoustic Signal Processing Workshop

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UASP 2007

Welcome to the 2007 IEEE workshop on Underwater Acoustic Signal Processing. This year the special sessions, organized by Dr. Keith Davidson, will be on *Signal Processing for Distributed Systems.*

The organizing committee would like to thank and acknowledge our promotional partners the Office of Naval Research Code 321 (Grant N00014-07-11093), the IEEE Oceanic Engineering Society for sponsoring the Wednesday evening dinner (through the efforts of Jim Barbera) and the Raytheon Systems Company for sponsoring the Thursday evening dinner (through the efforts of Marty Cohen and Jerry Bradshaw). We are also honored to present this year's UASP Award to Dr. John P. Ianniello.

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2007 UASP Award Presented to Dr. John P. Ianniello

in recognition of his outstanding contributions to the important area of incorporating more realistic physical models into signal processing algorithms.

Dr. Ianniello received the B. Eng. in Electrical Engineering from Yale University in 1965, the M.S. degree in Electrical Engineering from the University of Connecticut in 1968, and the Ph. D. Degree in Physical Oceanography from the University of Connecticut in 1977. His professional career began at the U.S. Navy Underwater Sound Laboratory in New London, CT, carried on to its descendant organization, the Naval Undersea Warfare Center in Newport, RI, involved a tenure at the SACLANT Undersea Research Centre in La Spezia, Italy and continues today with SAIC in Mystic, CT. He has been actively involved in the IEEE through service on the Underwater Acoustics Signal Processing and Sensor Array and Multichannel Processing Technical Committees of the IEEE Signal Processing Society, serving as Local-Arrangements Chairman of ICASSP 88, as well as being part of the organizing committee of many UASP Workshops. He has received several awards including the IEEE Signal Processing Society Senior Paper Award in 1988, the American Society of Naval Engineers Solberg Award for Individual Research in 1998, and the Department of the Navy Meritorious Civilian Service Award in 2000. His recent research has involved real-time signal processing and algorithm development for arrays towed by AUVs.

He is honored at the 2007 Workshop on Underwater Acoustics Signal Processing for his outstanding contributions to the important area of incorporating more realistic physical models into signal processing algorithms. Three of many possible examples are (1) an array shape estimation algorithm that used a Kalman filter and a three-dimensional hydrodynamic cable model as a plant model and incorporated compass and depth sensor measurements to get accurate towed array shapes, (2) his successful matched field work with a towed set of horizontal line arrays having vertical aperture, and (3) his development of a Kraken/Matlab propagation model and Matlab raytracing program which he shared with other researchers. His theoretical expertise in physics and signal processing is complimented by his hands-on experimental capability: he has been involved in several significant sea tests, including measuring the bearing accuracy of a spherical array, the first DIMUS submarine sea trial, and the first towed array wavefront-curvature ranging trial.

Schedule at a glance

Wednesday October 17, 2007		Thursday October 18, 2007		Friday October 19, 2007	
		8:15-9:30	Session B Laurel	8:30-9:45	Session G Laurel
		9:30-10:00	Break Laurel	9:45-10:15	Break Laurel
		10:00-12:05	Session C Laurel	10:15-11:55	Session H Laurel
		12:05-1:05	Lunch Whisp. Pines	12:00-1:00	Lunch Whisp. Pines
		1:10-2:50	Session D Laurel		
		2:50-3:20	Break Laurel		
		3:20-5:00	Sessions E & F Laurel		
5:00-6:00	Welcome Reception				
6:00-8:00	OES Dinner Whisp. Pines	6:00-8:00	Raytheon Dinner Whisp. Pines		
8:00-9:30	Session A Laurel	8:00-?	SOB Session Laurel		

Sessions: Titles and presenters

Session A: Wednesday Evening, 8:00pm–9:30pm

Special Session I: Signal and Information Processing for Distributed Systems

A–1 *Concurrent Multistatic Tracking and Field Stabilization in GPS-Denied Scenarios*,
Roy Streit, Metron, Inc.

A–2 *A Joint Likelihood Approach to Distributed Detection and Estimation*,
Michael Roan, Virginia Tech.

A–3 *Dynamic Ping Scheduling for Multistatic Sonar Buoy Networks under Energy Constraint*,
I-Jeng Wang, Johns Hopkins University Applied Physics Lab.

Session B: Thursday Morning, 8:15am–9:30am

Signal Processing for Underwater Communications

B–1 *Sparse Multichannel Estimation for Cooperative Underwater Acoustic Communications*,
Nicholas Richard, University of Southern California

B–2 *Communications in Sparse and Dynamic Underwater Acoustic Channels*,
Weichang Li, Woods Hole Oceanographic Institution

B–3 *On the Scalability of Multicarrier Underwater Acoustic Communication*,
Shengli Zhou, University of Connecticut

Session C: Thursday Morning, 10:00am–12:05pm

Special Session II: Node- and Field-level Processing for Distributed Systems

C–1 *Using Field-level Observations to Augment Node-level Signal Processing in Undersea Distributed Sensor Networks*,
Joseph DiBiase, Naval Undersea Warfare Center

C–2 *In-Network Fusion for Underwater Surveillance in Distributed Sonar Systems*,
Anshu Saksena, Johns Hopkins University Applied Physics Lab.

C–3 *Using Direct-blast Arrivals to Improve Synchronization Between Multiple Sonars*,
Pascal de Theije, TNO Defence, Security and Safety

C–4 *Submarine Localization Using an Ad-hoc Network of Rapidly Deployed Simple Sensors*,
Christian Berger, University of Connecticut

C–5 *Distributed Detection in Spatially-correlated Clutter*,
Douglas Abraham, CausaSci LLC

Session D: Thursday Afternoon, 1:10pm–2:50pm

Sonar Tracking

D–1 *Track Initialization for Multi-Static Active Sonar Systems*,
Christian Hempel, Naval Undersea Warfare Center, Division Newport

D–2 *Gaussian Mixture Cardinalized PHD Filter Performance on Multistatic Active Sonar Data*,
Peter Willett, University of Connecticut

D–3 *N-Step Ahead Prediction for Hybrid Stochastic Systems*,
William P. Malcolm, National ICT Australia

D–4 *Detection and Tracking of Underwater Targets Using Directional Sensors*,
Dragana Carevic, Defence Science and Technology Organsation, Australia

Session E: Thursday Afternoon, 3:20pm–4:10pm

Array Processing

E–1 *A Generalized Function Approach to Implementing Directional Acoustic Sensors*,
Dean Schmidlin, University of Massachusetts Dartmouth

E–2 *Robust Adaptive Beamforming of Volumetric Arrays*,
Ivars Kirsteins, Naval Undersea Warfare Center

Session F: Thursday Afternoon, 4:10pm–5:00pm

Signal Processing for Active Sonar

F–1 *A Continuous Multi-static Active Doppler Sonar Using m-Sequences*,
Harry Deferrari, University of Miami

F–2 *Classification of Clutter Types in Active Sonar Using Spatial Image Processing Techniques*,
James Gelb, Applied Research Laboratories, Univ. Texas at Austin

Session G: Friday Morning, 8:30am–9:45am

Propagation-Based Signal Processing

G–1 *Estimating Acoustic Mode Functions of a Deep Water Waveguide Using Ambient Noise Measurements*,
Khalid AlMuhanna, George Mason University

G–2 *Wave Propagation in a Random Medium: A Phase-Space Approach*,
Leon Cohen, City University of New York

G–3 *Propagation-invariant Classification*,
Patrick Loughlin, University of Pittsburgh

Session H: Friday Morning, 10:15am–11:55am

Detection and Classification

H–1 *Likelihood Ratios, Maximum Entropy, and an Estimator-Correlator Structure*,
Richard Lee Culver, Applied Research Laboratory and Graduate Program in Acoustics

H–2 *Source Classification Based on Amplitude Distribution Estimates*,
Colin Jemmott, Applied Research Laboratory and Graduate Program in Acoustics

H–3 *Human-mimetic Classification of Impulsive-source Active-sonar Echoes*,
Jason Summers, Naval Research Laboratory

H–4 *Acoustic Modeling and Simulation Tool for Marine Mammal Movement and Vocalizations*,
Alex Yakubovskiy, FarSounder Inc

Abstract Listings

Concurrent Multistatic Tracking and Field Stabilization in GPS-Denied Scenarios

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An alternating directions method is presented for joint maximum a posteriori estimation of target track and sensor field using bistatic range data. The algorithm cycles over two sub-algorithms: one improves the target state estimate conditioned on sensor field state, and the other improves the sensor field state estimate conditioned on target state. Nonlinearities in the sub-algorithms are mitigated by decomposing their likelihood functions using integral representations. The kernels of these integrals are linear-Gaussian densities in the states to be estimated, a fact that enables the derivation of estimation algorithms via missing data methods. The resulting sub-algorithms are equivalent to linear-Gaussian Kalman smoothers. The alternating directions algorithm is guaranteed to converge to (at least) a local maximum of the joint target-field likelihood function. Trajectory observed information matrices are given for both target and sensor field estimates. Recursions are derived for efficiently computing the filtered observed information matrices for target and sensor field. The recursively computed, filtered, observed information matrices are in situ proxies for Fisher information matrices.

A Joint Likelihood Approach to Distributed Detection and Estimation

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Abstract: A framework for the distributed detection of multiple acoustic sources and estimation of the source parameters (e.g. position, Doppler etc.) using multiple sensors will be the primary focus of this presentation. Through the use of a Bayesian framework for distributed detection and estimation (DDE), an ideal observer is created to make optimal decisions and inferences based on measurements made at multiple sensors that observe the same scene. The derivation starts with the establishment of a joint likelihood detection framework where hypothesis testing is done based on the observations at all of the sensors distributed in the field. The joint likelihood approach, although optimal, is shown through simulations to be very sensitive to sensor position errors. A sub-optimal approach based on an iterative approach that passes posterior probability density estimates as knowledge (incorporating uncertainty) between sensors is introduced to improve robustness to sensor position uncertainties. Simulations illustrate the relative performances of the optimal and sub-optimal algorithms. Lastly, source localization performances of the two algorithms are compared via simulation. The main conclusion given in the current work is under certain conditions, a large number of low resolution sensors can give better performance than high resolution sensors when sensor orientation error is considered.

Dynamic Ping Scheduling for Multistatic Sonar Buoy Networks under Energy Constraint

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In this paper we study the problem of dynamic optimization of ping schedule in an active sonar buoy network deployed to provide persistent surveillance of a littoral area through multistatic detection. The goal of ping scheduling is to dynamically determine when to ping, which ping source to engage, and what waveform to select in order to achieve the desirable detection performance. For applications where persistent surveillance is needed for an extended period of time, it is expected that the energy available at each ping source is limited relative to the required system lifetime. Hence efficient management of power consumption for pinging is important to support the required lifetime of the network while maintaining acceptable detection performance. Our approach to ping optimization is based on the extension of approximate Partially Observable Markov Decision Processes (POMDP) techniques such as the rollout algorithms and Q-learning. The POMDP formalism provides a sequential decision making framework that enables us to optimize the trade-offs between near-term detection performance and long-term energy management taking into accounts both the prior knowledge on environmental conditions and real-time detection results. Using high fidelity sonar simulations, we compare the proposed POMDP-based approach with the round-robin and greedy techniques in terms of detection performance and average system lifetime.

[This research is supported by the ONR Active Sonar Signal Processing D&I Program.]

Sparse Multichannel Estimation for Cooperative Underwater Acoustic Communications

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In a wide array of applications, it is highly desirable to utilize an underwater acoustic sensor network. In many of these systems, the objective is for data to be communicated from a single transmitting node to a distant destination node. It was shown in [1] that multihop communications, *i.e.* relaying data through physically close nodes, increases the overall bandwidth of the link, thus enabling a larger data rate to be achieved between the initial source to the final destination. Additionally, [2] illustrates that in a multihopping system, cooperative communications, *i.e.* several nodes jointly communicating the same data to a single receiver, provides spatial diversity and therefore improved bit error rates (BER) without increasing deployment costs. However, effects from intersymbol inteference (ISI) degrade the gains in BER to a prohibitive degree. Equalization schemes need to be utilized to mitigate the effects of ISI. It is well known that a decision feedback equalizer (DFE) can be utilized to reduce ISI. However, the complexity of a DFE increases as the channel length increases, which is extremely long in the case of cooperative underwater acoustic communications. In this presentation, a novel method of channel estimation for cooperative underwater acoustic systems is shown which can be used to develop intelligent equalization schemes. This strategy exploits the similarity in channel profiles of cooperating links as well as the sparse nature of individual channel profiles. Having an estimate of the overall channel profile, a structured least-squares channel estimate is then constructed. Simulation results are also shown, characterizing gains in the mean square error of the channel estimate over unstructured estimates as well as comparisons to their respective Cramer-Rao bounds. A comparison to an overall (single) channel estimation algorithm will also be made. Here it will be shown that at high signal-to-noise ratios, the two algorithms perform very similarly. However, at low to moderate signal-to-noise ratios the multichannel estimation algorithm provides significant gains over the single channel estimator.

[1] M. Stojanovic, "On the Relationship Between Capacity and Distance in an Underwater Acoustic Communication Channel," *Proc. of ACM WUWNet*, CA, Sept 2006.

[2] C. Carbonelli and U. Mitra, "Cooperative Multihop Communication for Underwater Acoustic Networks," *Proc. of ACM WUWNet*, CA, Sept 2006.

[This work has been supported in part by NSF GRFP, NSF ITR CCF-0313392, NSF OCE-0520324.]

Communications in Sparse and Dynamic Underwater Acoustic Channels

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In the presence of significant surface bounced multipath arrivals, shallow-water acoustic communication channels under wideband transmission can often be both highly dynamic and sparsely structured. Channel fluctuations are characterized by large Doppler spread which not only varies across delay taps but also evolves over time rapidly. In addition, with wideband transmission, the multipath arrivals can be well resolved in delay and form a sparse channel structure. The time delays of these multipath arrivals migrate in response to the propagation length fluctuation caused by the surface waves. This combination of dynamics and sparseness, in addition to the typically extended delay spread, poses significant new challenges to acoustic communications, both in terms of robust demodulation and performance prediction. This work focuses on developing new channel estimation and equalization algorithms for this type of channels.

Accurate estimation and tracking of channel impulse response is critical to phase coherent systems. In the case of extremely dynamic channels, state-space model based tracking algorithms have been developed which jointly estimate the channel impulse response as well as the dynamic parameters. However, for dynamic systems possessing a time-varying sparse state structure, parameter estimation becomes an ill-posed problem which may yield slow convergence or even divergence, and in turn degrade the channel impulse response estimate. Analytical results will be presented that establish the connections between parameter convergence, the Fisher Information Matrix and the system model properties including observability and controllability. Following that, modified channel estimation algorithms based on EKF and EM algorithms will be presented that adaptively carry out dynamic tracking and structure sparsing. Results of channel estimation and subsequent equalization will be demonstrated, based on both simulation and experimental data.

On the Scalability of Multicarrier Underwater Acoustic Communication

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Motivated by the success of multicarrier modulation in broadband wireless radio systems, many researchers are currently investigating its use for high-rate communications over underwater acoustic (UWA) channels.

We have recently developed a transceiver based on zero papped orthogonal frequency division modulation (OFDM), where null subcarriers are used to facilitate high-resolution Doppler compensation and pilot subcarriers are used for channel estimation. The receiver is based on block-by-block processing, and does not rely on channel dependence across OFDM blocks; thus, it is suitable for fast-varying UWA channels. At an uncoded data rate above 10 kbps with a bandwidth of 12 kHz, the data from two shallow water experiments near Woods Hole, MA, demonstrated excellent results even when the transmitter and the receiver are moving at a relative speed of up to 10 knots, at which the Doppler drifts are greater than the OFDM subcarrier spacing; see published results in the proceedings of OCEANS conference, Boston, 2006, and Aberdeen, 2007.

In this talk, we emphasize a nice property of OFDM that it is very scalable on the data rate in response to the changes on the available bandwidth. With the experimental data from AUV Fest at Panama City, Florida, June 4-16, 2007, we show how the transceiver accommodates different bandwidths of 3kHz, 6kHz, 12kHz, and 16kHz, with just a single parameter change on the number of subcarriers at the receiver side. This is in sharp contrast with single carrier transmissions, where changes of bandwidth lead to different numbers of channel taps in the discrete-time baseband model, which implies different channel equalizer lengths, adaptation parameters, and convergence behaviours.

Using Field-level Observations to Augment Node-level Signal Processing in Undersea Distributed Sensor Networks

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The role of deployable fields of distributed networked sensors is becoming increasingly important in antisubmarine warfare (ASW). Traditionally, ASW has required expensive submarine, surface or air platforms equipped with multiple high-gain sensor arrays and an operator-intensive analysis of received sonar data using interactive, graphical workstations. In contrast, undersea distributed networked systems (UDNS) rely, in part, on various types of relatively inexpensive sensor nodes to provide input to an automated detection and tracking process. Typically, this process is based on the fusion of independently generated node-level detections, and the associated field-level performance is driven primarily by the detection and false-alarm rates of the individual sensor nodes. With the desire to employ large numbers of simple and perhaps expendable sensors, the detection range of an individual node is necessarily limited compared to a manned ASW platform. The limited performance of simple autonomous nodes often leads to infeasible field densities or unacceptably poor field-level surveillance coverage and reliability. This work addresses these issues through the investigation of node-level signal processing techniques that yield improved performance when augmented with information observed by other nodes comprising the sensor network. This methodology enables collaborative processing among nodes and allows for adaptation based on network-wide observations of the underwater environment and the acoustically radiating sources that pass through that environment. With a prior knowledge that characterizes acoustic contacts and interferers, individual sensor nodes can perform both temporal and spatial filtering that simply cannot be applied to the binary output generated by independent node-level detectors. This type of filtering can theoretically provide the performance gains necessary to help achieve the required field-level surveillance coverage while controlling field densities and overall system costs. Example scenarios and node-level systems that demonstrate the advantages, and pitfalls, of exploiting network-to-node feedback within this context will be presented.

[This work is supported by Dr. John Tague of the Office of Naval Research (ONR321US).]

In-Network Fusion for Underwater Surveillance in Distributed Sonar Systems

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The problem of optimized distributed detection in a system of networked sensors involves a number of design aspects, including balancing probabilities of missed detection and false alarm as well as managing the communication resources through proper in-network information fusion. Moreover, a number of tradeoffs must be exercised, such as the one between the computational requirements for information fusion and sensor control and the communication requirements for information exchange. Therefore, overall system design decisions are best made by jointly considering the impact of design aspects and tradeoffs on the overall system performance. This paper addresses in-network fusion and associated networking algorithms that improve detection performance and energy efficiency for a multistatic sonar application. This is achieved by exchanging and fusing contacts among sonar buoys before transmission out of field. In-network fusion utilizes lower cost buoy-to-buoy communication for the majority of the data communication and enables a reduction in random uncorrelated false alarms by only reporting detections from multiple buoys that present sufficient correlation. The reduction of out-of-field contact transmissions allows a lower signal excess threshold for each buoy, corresponding to an increased probability of detection. We demonstrate the effectiveness of our distributed in-network fusion through both analysis and high fidelity sonar simulations.

[This research was supported in part by the JHU/APL IR&D Program.]

Using Direct-blast Arrivals to Improve Synchronization Between Multiple Sonars

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The success of multisensor tracking algorithms depends heavily on the quality of the input. If the different sensors (e.g. sonars) that cooperate in a multi-sensor operation are badly synchronized, either in position or in time, their contacts will be misaligned relative to each other. This may cause severe problems when trying to associate or fuse the contacts of the different sensors. Feeding a multi-sensor tracking algorithm with contacts that are badly positioned will cause true tracks to terminate or even not initiate.

In our work we have focussed on improving the synchronisation of multiple sonars by using the direct-blast arrivals of each source on each receiver. The direct-blast arrival of a source on its local receiver provides information on their mutual separation, the source direction with respect to the receiver axis, and the local sound speed (which is used for beamforming). The direct-blast arrival of a source on a stand-off receiver contains information of the global sound speed (used for ranging), the separation between the source and receiver, and on the receiver heading. Using simulated and experimental data, we will illustrate the improvements that can be obtained on a-priori estimates of source and receiver positions, sound speed, and receiver heading, using the available acoustic data. Good knowledge of these parameters is necessary to provide accurate (geographic) positions of the (sonar) contacts.

[This work has been sponsored by the Royal Netherlands Navy]

Submarine Localization Using an Ad-hoc Network of Rapidly Deployed Simple Sensors

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Based on our previous work ("Submarine Location Estimation via a Network of Detection-Only Sensors, IEEE Transactions on Signal Processing, June 2007"), which was targeted predominantly at shoreline protection via a rather static sensor setup, we develop a new scenario of locating low visible targets in the open ocean using a large number of rapidly deployed simple sensors. Using a sensor network is beneficial, since low visible targets like submarines are often only detectable using multi-static sonar, as the reflected signal strength can be highly aspect-dependent. Using such a multi-static setup the target is still only detectable by a receiver in a certain region, therefore the chance of detection increases considerably with the number of sensors, as we can "cover more ground". Accordingly we want to keep the sensors as simple, i.e., cheap as possible.

Our suggested protocol includes localizing the sensors first, and accounts for uncertainty in their position estimates in the following target localization – as we cannot assume a long setup phase to deliver highly precise sensor position information. We require sophisticated accoustic sensors only on the main platform, while the distributed sensors can be rather simple. The sensors are only equipped with a sonar detection mechanism activated by the direct blast and a clock or timer. The timer is necessary for their own localization, for which we use the round trip time when communicating the binary detection to the main platform, but can also be used to measure Time Difference of Arrival (TDoA) between the direct blast and possible detections. If the aspect dependancy of the target can be assumed known rather well, binary detection results deliver a good position estimate. On the other hand if we can't model this behavior accurately, we can achieve sufficient estimation precision by including the TDoA measurements, but incur increased communication overhead.

Finally we suggest an extension where we use several "artificial" targets to refine the sensor position estimates. This could be sonar buoys or another platform with accurately known position, e.g., via tracking their continuous signal or GPS.

Distributed Detection in Spatially-correlated Clutter

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Distributed sonar systems decide if a target is present through use of a rule that combines information from each individual sensor. The most basic of these are the 'and' and 'or' data fusion rules, which are both subsets of the more general 'm-of-n' rule. Analysis of these rules has typically been restricted to cases where the false alarms are assumed to arise from processes that are statistically independent from sensor to sensor and follow common statistical distributions (e.g., Gaussian processes). In active sonar systems operating in clutter-dominated areas, this assumption may be far from the truth. Active sonar clutter often has its origins in scattering from physical objects (e.g., shipwrecks, fish schools, rock outcroppings, or mud volcanoes). Particularly when the scatterers are small in terms of wavelengths, the false alarms can be highly correlated from sensor to sensor.

In this work, clutter scattering is modeled by the K distribution in its product form. At the complex envelope stage of the processing this results in the product between a zero-mean complex Gaussian random variable and the square-root of an independent gamma random variable. Keeping the gamma variate constant across all sensors introduces dependence in the clutter echoes. Allowing the complex Gaussian 'speckle' component to be independent from sensor to sensor retains some measure of randomness. The detection statistic of the 'm-of-n' fusion rule is simply the $(n-m+1)$st order statistic. The probability density function (PDF) of this detection statistic is seen to be a mixture of K PDFs when no signal is present, allowing analytical evaluation of the probability of false alarm. The probability of detection for a fluctuating target is obtained by approximation where the clutter is assumed to be Rayleigh-distributed and independent from sensor to sensor. Surprisingly, this approximation is quite accurate. Comparison between dependent-K-distributed clutter and independent K-distributed clutter with a fluctuating target model illustrated a significant overestimation of performance for the latter clutter model—spatial correlation in the clutter significantly reduces fusion performance when the clutter statistics are highly non-Rayleigh. The 'and' processor is seen to exhibit no fusion gain for a fluctuating target (i.e., the detection performance is constant with the number of sensors), as is the case of Rayleigh clutter. The optimal m in 'm-of-n' fusion was found to be approximately $0.2n$–$0.3n$, a result similar to that found in order-statistic normalization.

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Track Initialization for Multi-Static Active Sonar Systems

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A new method for detecting the arrival of a contact of interest in the search region of an active sensing system has been developed. Detection level data from current and prior scans are partitioned into Hough Transform type bins and the data in each Hough bin is tested for the appearance of a new contact of interest with Pages test. For discrete data (e.g., active sonar echoes), the Hough transform is a histogram version of the discrete Radon transform where the data are partitioned into sets of non-overlapping bins at various angles that represent different possible target track trajectories. Pages test is designed to detect changes in state by accumulating the values of an appropriate detector non-linearity. Theoretical performance predictions of the average target latency of the new method for centralized and distributed multi-static systems as a function of clutter level and registration error yielded predictable results. Indeed, when the data from multiple sensors can be accurately registered superior track initialization performance can be achieved by combining all of the measurements in a single track initialization algorithm instead of using a distributed architecture that initializes tracks on each sensor separately and combines the results. When the data cannot be accurately registered it becomes more difficult to ensure that measurements from the same contact but received on different sensors will be located in the same Hough bin; the registration error may cause the measurements from different sensors to appear in different Hough bins and thereby prevent them from contributing to the same Pages test statistic. The problem is further compounded when the clutter density is high because the size of the Hough bins must be reduced to maintain the probability of detecting a contact of interest. Smaller Hough bins increase the probability that registration error will cause significant misalignment of the data from multiple sensors. Under those conditions it is advantageous to initialize tracks on each sensor separately and combine the results with an appropriate track management method.

The purpose of the effort reported here is to validate the theoretical performance predictions with credible simulation studies. Researchers at The Netherlands Organization for Applied Scientific Research (TNO) have developed well characterized multi-static and multi-target data active sonar data sets for the purpose of algorithm evaluation. This study uses the TNO data set as a basis for a Monte Carlo analysis that quantifies the effects of clutter density and registration error on the average target latency of the new initialization method to determine the conditions that favor centralized or distributed track initialization schemes.

Gaussian Mixture Cardinalized PHD Filter Performance on Multistatic Active Sonar Data

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In this paper we analyze the performance of the Gaussian Mixture Cardinalized Probability Hypothesis Density (GM-CPHD) filter using a number of simulated scenarios and a recent sea-experiment sonar data collected by NATO Undersea Research center (NURC).

We propose a track management scheme for GM-CPHD exploiting the connectivity of the Gaussian modes of CPHD over time stamps. This scheme allows us to compare the performance of GM-CPHD with other conventional trackers.

Recently at NURC, a multi-hypothesis tracker (DMHT) developed for distributed multi-waveform active sonar systems. We compare the DMHT tracker with the GM-CPHD tracker and discuss the possibilities of the integration of GM-CPHD tracker into this distributed tracking system of NURC.

N-Step Ahead Prediction for Hybrid Stochastic Systems

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An enduring estimation and tracking problem in the underwater SONAR environment is the so-called passive-ranging problem for maneuvering targets. This problem is also referred to as bearings-only tracking. The military applications for this problem in the underwater environment are immediate.

In its basic formulation, (the passive-ranging problem), one supposes that a target/object is being measured via a passive sensor array, (for example a Torpedo being tracked by a Submarine). This generates a nonlinear observation model and henceforth a nonlinear estimation problem. It is also assumed, that the target/object can execute various classes of motion which cannot, (in total), be described by any one single mathematical model. This gives rise to the natural formulation of a hybrid system of candidate motion dynamics, where any specific model may be considered "active" by the state of a corresponding Markov chain. Here we generate a second complexity which shows itself in exact solutions suffering from exponential complexity on growth. The challenge, therefore, is to identify a suboptimal solution to this problem, whose memory requirements remain fixed in time and whose trade-off between complexity and performance is acceptable within the given context. In the history of this specific problem area one finds the literature dominated by the Interacting Multiple Model Algorithm (IMM) and more recently particle filter methods. Each of these algorithms have merit, however, the IMM is not based upon the exact solution to the problem and the particle filter methods can be computationally prohibitive.

We propose a solution to passive-ranging for maneuvering targets/objects based firstly upon the "exact" solution. It is surprisingly that this solution is not widely known and indeed relatively new, being published in 1996 by Elliott Sworder and Dufour, see [1]. While this important solution is exact, it cannot be implemented due to its complexity. In the SIAM article [2], a suboptimal solution was proposed based upon Gaussian mixtures techniques to approximate an unknown conditional probability density. The scheme presented in [2] has been shown to substantially outperform the IMM. In this work being reported here, the Authors further extend the results in [2] to N-step ahead prediction. This prediction task has been overlooked in passive-ranging, furthermore, the performance of the prediction step is critical to nonlinear estimation. We provide a closed form solution to the N-step ahead prediction problem and subsequently show its performance in a passive-ranging tracking context. Again, our prediction scheme is derived from the "exact" solution to the problem in question, it is not ad hoc such as the IMM formulation.

[1] R. J. Elliott, F. Dufour and D. Sworder. Exact Hybrid Filters in Discrete Time, IEEE Transactions on Automatic Control, 41, 1996 pp 1807-1810.

[2] R. J. Elliott, F. Dufour and W P Malcolm, State and Mode Estimation for Discrete-Time Jump Markov Systems, SIAM Jnl of Optimization and Control, Vol 44 issue 3, 2005.

Detection and Tracking of Underwater Targets Using Directional Sensors

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The problem of detection and tracking multiple targets in cluttered-three dimensional (3-D) underwater environments is considered. The measurements are time delays of arrival (TDOA) of passive transient signals. The (underwater) observer platform is modelled as consisting of a number of 3-D ideal geometric bodies. The receiving sensors used to derive the measurements are directional and are fixed on the observer.

The proposed technique uses a partial likelihood modelling approach whereby the measured data is assumed to contain only one target, and the measurements related to all other targets (the presence and/or number of which is not known) are modelled as clutter. The procedure extracts targets from the TDOA measurements batch in a sequential manner as it maximizes a set of partially modelled likelihood functions. A detection algorithm is applied to verify whether each motion parameter vector estimated in this way corresponds to a true target in the measurements batch. If a true target is detected, the associated TDOAs are removed and the procedure continues to estimate subsequent target model. The procedure stops when the detection algorithm indicates a false target. The robustness of this approach is facilitated by the fact that the measurements are taken using directional sensors. Namely, in general, we can assume that the targets are well separated in 3-D space, so the subsets of sensors that receive measurements related to different targets are also separated. Consequently, the target-related TDOAs can be identified and extracted relatively easily.

Simulation results are presented for a two-target tracking scenario and for high clutter density and number of false measurements in the measurements batch. The simulated TDOAs are obtained using a configuration that consists of 18 pairs of receiving sensors.

A Generalized Function Approach to Implementing Directional Acoustic Sensors

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In classical linear arrays, directivity is typically achieved by placing pressure sensors uniformly along a line in space. The maximum directivity is $20 \log N$, where N is the number of sensors. Since, for example, a standard linear array has a length of $\lambda(N-1)/2$, the maximum directivity depends on the extent of the array and a longer array is needed for a greater directivity. In contrast to an array of pressure sensors, a directional acoustic sensor attempts to make measurements of pressure and its various spatial derivatives at a single point in space. The maximum directivity of such a sensor is $20 \log(1+\nu)$, where ν is defined as the order of the sensor. Numerically, the order of the sensor is equal to the order of the spatial partial derivative of highest order. For example, the pressure gradient or vector sensor is of order one, since it measures the pressure and the gradient of the pressure (three spatial first-order partial derivatives). A directional acoustic sensor of order ν requires the knowledge of $(1+\nu)(2+\nu)(3+\nu)/6$ derivatives. The attractiveness of such a sensor is the possibility of achieving a large directivity or array gain though occupying only a relatively small region of space. However, a daunting task in the practical implementation of a directional acoustic sensor is the determination of the values of the spatial partial derivatives (especially those of higher order) in the presence of noise. It appears unlikely at the present time that one could obtain accurate measurements of spatial partial derivatives beyond order one or two. An alternative approach is to use divided differences to estimate the derivatives from measurements of acoustic pressure. The negative consequence of this approach is that divided differences of noisy data tend to amplify the noise. The objective of this presentation is to discuss an approach that is based on the utilization of generalized functions, namely, the Dirac delta function and its derivatives. This approach leads to a set of linear functionals which provide estimates of the various derivatives of a given function at a particular point.

Robust Adaptive Beamforming of Volumetric Arrays

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This paper addresses the development of adaptive beamforming algorithms for a prototype volumetric array consisting of equi-spaced triplet sets of hydrophones. Volumetric arrays are desirable in passive sonar applications because of their ability to resolve left-right ambiguity. However, adaptively beamforming volumetric arrays poses several unique challenges compared to linear arrays. These include the high dimensionality and the resultant lack of sample support, the necessity to know accurately the x,y,z positions of all the elements, which may be difficult to determine in practice because of bending and torsional twisting, and the highly correlated structure of the ambient noise because of the close hydrophone spacings.

Theoretical arguments are developed showing that the rich structure of volumetric arrays can be used to impart robustness against steering vector mismatch by adapting in a beam space formed using beams steered from individual subarrays. Furthermore, the subarray geometries can be selected to optimize performance based on the expected characteristics of the array calibration errors. The tentative approach presented here exploits the special geometry of the prototype volumetric array by first adaptively forming beams with each of the three individual line subarrays using an expanding Krylov space obtained from a vector conjugate gradient algorithm [1] and then adaptively beamforming the reduced-dimension line subarray beam outputs with Capons method. The new approach is demonstrated on actual at-sea and computer simulated data and compared against conventional adaptive beamforming methods. The experimental results corroborate the theoretical arguments that the two-stage subarray beam space approach is inherently robust against steering vector mismatch as a result of forming beams using the individual subarray lines rather than the full array and thus obviates the need of implementing complicated constraints for tolerance against steering vector mismatch. In addition, it reduces the problem dimensionality to improve relative sample support.

[1] L. L. Scharf, L. T. McWhorter, E. K. P. Chong, J. S. Goldstein, and M. D. Zoltowski, "Algebraic Equivalence of Conjugate Direction and Multistage Wiener Filters," Proceedings of the Eleventh Annual Workshop on Adaptive Sensor Array Processing (ASAP), Lexington, Massachusetts, March 11-13, 2003.

A Continuous Multi-static Active Doppler Sonar Using m-Sequences

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Multi-static and/or continuous active sonar is usually an unworkable concept owing to Doppler-time leakage from direct arrivals that swamps target returns by tens of dB. Shallow water reverberation and clutter are additional complications. Here, continuous m-sequence signals are considered for bi/multi-static active sonar. They have unique properties that allow “Hyperspace Cancellation” (HC), whereby both time and Doppler leakage are completely eliminated for direct arrivals, cross-talk from multiple signals from different sources, and for clutter from bottom returns. The result is a high resolution multi-static Doppler sonar approach that is noise limited except for very narrow zero Doppler ridges - one per source. The basic elements of the signal processing are, sampling the received signals to form a complete-ortho-normal (CON) set, a linear temporal Doppler algorithm that computes all Doppler receptions from the zero Doppler waveform, and implementation of the ultra-fast Hadamard transform to go back and forth between CON representations of the waveform and pulse responses of the propagation channel. Unfortunately, a theorem stated that there are no orthogonal m-sequences. However, nearly-orthogonal signals exist and the remaining weak cross terms can be eliminated by HC, making possible multi-static fields of M sources and N receivers forming NXM independent and overlapping sonar ranges. Numerical experiments are presented for realistic shallow water environments. Data from real ocean shallow water propagation experiments in the Straits of Florida demonstrate the robustness of the processing.

[Most all of the basic concepts and implimentations of M-sequences compiled here have been developed over the past forty years by T. Birdsall, K. Metzger and their students at the University of Michigan.]

Classification of Clutter Types in Active Sonar Using Spatial Image Processing Techniques

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Clutter, e.g., biologics and bottom structures, can lead to excessive false alarm rates (identifying clutter as submarines) in antisubmarine warfare (ASW) active sonar systems. In this paper, physically motivated image processing features are developed and extracted from digitized clutter images. These extracted features are then used to classify the images using a multi-class classification algorithm. The clutter images are generated by averaging mid-frequency active sonar acoustic returns, which have been convolved with an appropriate measurement error kernel, from sea trial archives over several pings of history. Only match filtered and normalized mid-frequency data from the full two-dimensional tactical field are considered, which avoids analyzing the complicated time series data directly. Marginal distributions of features extracted from each of the classes and multi-class classification results using log-likelihood techniques that take into account inter-feature correlations are presented. We also present fits to the non-Rayleigh tails of the normalized match filter output for each clutter class. This work addresses the first phase of our research on classifying mid-frequency active clutter, namely spatial image processing. The next phase of our work, not presented here, addresses temporal features derived from tracks.

Estimating Acoustic Mode Functions of a Deep Water Waveguide Using Ambient Noise Measurements

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Assuming that the signals recorded by a vertical line array (VLA) consist of a sum of uncorrelated modes, the modeshapes can be determined from an eigenvector decomposition of the measured cross spectral density matrix. Several authors have applied this technique to estimate the modes of shallow water waveguides. Wolf *et al.* estimated the modes of an 18 m deep waveguide using data from an array spanning the entire water column [Proceedings of the 1993 IEEE Oceans Conference, vol. I, pp. 99-104]. Hursky *et al.* explored the problem of using data-derived modeshapes and wavenumbers for matched field processing in the SWellEx-96 experiment [J. Acoust. Soc. Am., 109(4), pp. 1355-1366]. Nielsen and Westwood estimated modeshapes for the Hudson Canyon environment using both CW towed sources and ambient noise [J. Acoust. Soc. Am., 111(2), pp. 748-756]. While the general approach pursued by these authors should work for deep water environments, very few experiments have deployed VLA's with long enough aperture to resolve the modes propagating in a deep water waveguide. In previous work D'Spain *et al.* computed numerical estimates of modes from earthquake T-phase arrivals on a 3000 m VLA [Pure appl. geophys., Vol. 158, pp. 475-512]. In this work we focus on estimating the modeshapes for a deep water environment in the North Pacific using ambient noise data measured during the SPICE04 experiment. The SPICE04 VLA had 40 hydrophones spanning 1400 m and centered around the sound channel axis. Although noise measurements were not the primary focus of SPICE04, the experiment provided a large data set for this noise analysis. In addition to acoustic measurements, the SPICE04 experiment also included extensive sampling of temperature and salinity. This talk summarizes the noise statistics measured during 2004-2005 and compares the empirical modes derived from the data with the true modes derived from the measured environmental data.

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Wave Propagation in a Random Medium: A Phase-Space Approach

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The propagation of a wave in a random medium occurs in many areas and is particularly important in wave propagation in the ocean. The ocean has many random properties that affect propagation. For example, shallow-water ambient noise is strongly coupled to local conditions, such as temperature, wind speed, rain, and shipping traffic. When the wave equation is formulated to handle random parameters or inputs, the result is what is generally known as a random differential equation. These types of equations are particularly difficult to handle and that is especially so when nonstationary noise is involved.

We have developed a phase space approach to random wave propagation. The basis of the method is to transform the wave equation governing the propagation into a phase space differential equation: the phase space of position-wavenumber or time-frequency. A simple explicit method to accomplish this transformation is given. We show that an immense simplification occurs both conceptually and practically. Using this method, we have addressed a number of problems. We present results as to how a pulse behaves in a random medium and how one can define and calculate reduced quantities such as the mean and variance of the pulse as it propagates.

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Propagation-invariant Classification

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In active sonar, detection and classification of objects by their backscattered sonar signatures can be complicated by propagation effects. For example, sound waves propagating in sea water undergo frequency-dependent attenuation (or damping). The channel may also induce dispersion, which can be especially significant in shallow water, resulting in temporal and spatial spreading of the wave. In such environments, waves from the same source can differ because of these frequency-dependent propagation effects, which can adversely impact automatic classification.

In this talk, we consider the goal of propagation-invariant classification. We will present moment-like features extracted from the backscattered wave that are invariant to dispersion and damping, per mode, for any dispersion relation and exponential or power-law damping. Environmental knowledge is not needed, beyond knowing the general form of the damping, which is usually media-dependent and hence typically known. Simulations of classification of steel shells in channels with dispersion and damping, including random variations, will be presented to demonstrate the utility of these features. A dispersion-invariant matched filter receiver approach will also be presented.

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Likelihood Ratios, Maximum Entropy, and an Estimator-Correlator Structure

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We have implemented and expanded a Likelihood Ratio Test (LRT) developed by Schwartz (IEEE Trans. Inf. Theory, IT-23, 1977) and termed an Estimator-Correlator (EC) receiver. Our application is passive acoustic signal source discrimination in the ocean, and we have so far investigated our formulation for Gaussian signals and noise, and for sinusoids embedded in Gaussian noise. A useful aspect of the EC structure is that the noise need not be Gaussian, but need only belong to the exponential class, which is much less restrictive. Given noise samples, e.g. from a beam that does not contain signals, the Maximum Entropy (MaxEnt) method has been utilized to provide an exponential class probability density function (pdf) that fits the sample moments but does not make further, unwarranted assumptions. Also, the EC structure has been applied to generalize Gaussian-distributed noise, which has been shown to fit several kinds of ocean noise.

The EC-LRT processor uses signal parameter statistics to classify targets, and will be useful when one does not have vertical aperture and thus cannot use matched field processing (cf. Bucker, JASA 59, 1976) or the noise field is not well-fit by a Gaussian and one cannot apply the Optimum Uncertain Field Processor (Richardson and Nolte, JASA 89, 1991).

Our extension to Schwatzs EC is to allow the conditional pdf of the observation to become slightly more general, such that the term in the exponent involving the observation and the random signal parameter vector become arbitrary. (We allow $\theta g(x)$ to become $g(\theta, x)$). This causes no problems with the derivation and allows more flexibility in selection of the conditional pdf.

For Gaussian signal in Gaussian noise, we show that the EC detector is equivalent to LRT presented by Van Trees (Detection, Estimation and Modulation Theory, Vol. 1, 1968, Ch. 2, eqn. 327). We investigate sinusoids embedded in additive Gaussian noise and present an LRT receiver that distinguishes between signals from different sources and thus differently distributed signal parameters. An example is presented for Gaussian distributed signal amplitudes having the same mean but different variances, and we find that the detection statistic is the sample variance of the matched filter output, and the threshold is determined by the signal variances. Receiver operating characteristic (ROC) curves are constructed and the processor performance is seen to improve with signal-to-noise ratio (SNR) and signal-to-signal ratio (SSR). Robustness to errors in other signal parameters is investigated using simulation.

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Source Classification Based on Amplitude Distribution Estimates

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The overall goal of our research is to develop sonar classification algorithms that exploit knowledge of environmental parameters (depth, bottom type, sound speed profile, etc.), while being robust to environmental variability and uncertainty. Specifically, we have chosen to study a passive horizontal array in shallow water receiving a tonal (CW) signal, corrupted by noise. Previous work has concentrated on propagating deterministic and statistical knowledge about the ocean environment to signal parameter probability density functions.

This talk presents an analysis of event S5 during the SWellEX-96 measurement that took place in shallow water off the coast of California. The data consist of sinusoidal signals transmitted simultaneously from moving sources at two different depths and received at a bottomed horizontal array. Premus, Ward and Richmond (Asilomar, 2004) previously examined a mode filtering approach to vertical line array data from this same event. The motion of the sources maps spatial variability in transmission loss into temporal variability, resulting in as much as 30 dB changes in amplitude in tens of seconds. This is an interference phenomenon that is well known (e.g. Kuperman and DSpain, Ocean Acoustic Interference Phenomena and Signal Processing, AIP, 2001).

To understand the SWellEX data, received signal amplitudes are simulated using RAM for the two sources at different depths. A numerical maximum likelihood classifier is designed using kernel density estimates of simulated signal amplitudes. While exact deterministic modeling of the 4-D (space and time) ocean acoustic transmission channel is impossible, it seems the amplitude distribution is fairly insensitive to small changes (uncertainties) in environmental parameters.

All signals were processed to correct for spreading losses and equalize energy. The simulation was run using a highly simplified environment. Despite the similar signal amplitude distributions and model mismatch, the performance of the simulation-trained classifier processing the SWellEX data is quite good. Receiver operating characteristic curves and a simplified robustness study will be presented.

Human-mimetic Classification of Impulsive-source Active-sonar Echoes

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Motivated by recent psychoacoustical studies confirming evidence that listeners are able to discriminate target from clutter in cases for which automatic classifiers fail, the use of auditory perception as the basis for a human-mimetic classifier is investigated. To estimate the perceptual space in which listeners perform classification, a multidimensional scaling experiment with eleven naïve listeners was performed on a representative set of nineteen multistatic impulsive-source active-sonar echoes. In the resulting space of perceptual dimensions, stimuli form distinct clusters. Though listeners were unaware of the underlying target/clutter structure, target is discriminated from clutter along a single perceptual dimension. Listening to various sets of signals distributed along the perceptual dimensions indicates that, unlike those in similar studies of timbre, the dimensions in this space do not correspond to low-level perceptual features having simple algorithmic representations. Consequently, conventional methods to develop a mapping from signal space to feature space fail. Instead, dimensions reflect untrained categorical perception manifested through a mixture of top-down and bottom-up processes used by listeners: a high-level cognitive process for interclass dissimilarity ratings and a low-level signal-based process for intraclass comparisons. Listeners appear to behave as expert systems, rapidly assigning stimuli to definite categories based on prior experience, a listener-specific process analogous to the statistical description of classes in the class-specific method. In contrast, within-class comparisons reflect signal-derived features found to be most efficacious for differentiating between the signals, a process similar to generation of features by singular-value decomposition. Implications of these findings for design of a hybrid generative/discriminative human-mimetic classifier architecture are discussed.

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Acoustic Modeling and Simulation Tool for Marine Mammal Movement and Vocalizations

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Marine Mammal acoustic classification methods ([1,2] for example) are usually feature-based. The common idea is to detect and track target trajectory as well as detect and track vocalization features like curves in spectrograms. One effective way to evaluate the whole signal processing algorithm (detection + tracking + features extraction + classification) quality is to compare known trajectory and vocalization waveform features with estimates provided by algorithm. Since gathering known ground truth data (location track and vocalizations) is often difficult if not impossible, the authors propose the generation of simulated data as a possible substitution for or augmentation to ground truth data involving real marine mammals. The authors have developed a tool for modeling and simulating such data.

The model developed combines random walk 3D trajectory simulation [3] and vocalization simulation. Sound transmitting events are automatically linked to the 3D trajectory to ensure that simulated sounds are created while diving (i.e. animal is not at surface). Special types of sounds such as hunting clicks series are linked to specific diving events (i.e. foraging loops). The vocalization simulator algorithm works in top to bottom manner: First, fundamental time-frequency modulation and amplitude envelop curves are generated; Next, the waveform is generated using a DDS (Direct Digital Synthesis) method. Curves are defined by a few control points at creation stage and later on smoothed by Chaikin' algorithm [4]. Nonlinear transforms are applied to add harmonics and subharmonics. The whole model is based on a Marine Mammals Features Database, which accumulates reasonable limitations on movement and waveform parameters.

The authors will present scientific model as well as the tool used to implement the model. Examples of 3D trajectories and various types of simulated waveforms (harp seal's burst-pulse, dolphin's whistle, manatee call, etc.) will be discussed in comparison with recorded signals.

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[3] J.A. Byers, "Correlated random walk equations of animal dispersal resolved by simulation", Ecology, Volume 82, Issue 6, pp.1680-1690, 2001.

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Wednesday October 17, 2007		Thursday October 18, 2007		Friday October 19, 2007	
		8:15-9:30	Session B Laurel	8:30-9:45	Session G Laurel
		9:30-10:00	Break Laurel	9:45-10:15	Break Laurel
		10:00-12:05	Session C Laurel	10:15-11:55	Session H Laurel
		12:05-1:05	Lunch Whisp. Pines	12:00-1:00	Lunch Whisp. Pines
		1:10-2:50	Session D Laurel		
		2:50-3:20	Break Laurel		
		3:20-5:00	Sessions E & F Laurel		
5:00-6:00	Welcome Reception				
6:00-8:00	OES Dinner Whisp. Pines	6:00-8:00	Raytheon Dinner Whisp. Pines		
8:00-9:30	Session A Laurel	8:00-?	SOB Session Laurel		