UASP 2011

A Book of Abstracts for the

2011 Underwater Acoustic Signal Processing Workshop

October 12–14, 2011
Alton Jones Campus
University of Rhode Island
West Greenwich, RI, USA

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the Acoustical Society of America, and Raytheon

Welcome to the 2011 IEEE workshop on Underwater Acoustic Signal Processing. This year the special session, organized by Warren Fox and Jason Stack, focuses on signal and information processing for autonomous underwater sensing systems.

The organizing committee would like to thank and acknowledge the continued support of the Office of Naval Research, the IEEE Oceanic Engineering Society for their sponsorship of the Wednesday evening dinner. We also thank Michael Janik for his efforts in arranging for Raytheon Integrated Defense Systems to sponsor our Thursday evening dinner. We are pleased to announce our new promotional partner, the Acoustical Society of America, who is sponsoring the Thursday lunch.

Finally, the organizing committee is proud to announce that this year's recipient of the UASP Award is Dr. G. Clifford Carter of the Naval Undersea Warfare Center.

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The 2011 UASP Award is Presented to Dr. G. Clifford Carter

in recognition of over four decades of contributions to sonar signal processing, leadership and mentoring in Naval research and development.

Dr. Carter received the B.S. degree in engineering science from the U.S. Coast Guard Academy in 1967 and, after active-duty service time, joined the Navys Underwater Sound Laboratory (USL) in New London, CT in 1967 as a mathematician, commencing an extensive career in government civil service. He earned the M.S. degree in 1972 and the Ph.D. Degree in 1976, both in electrical engineering and from the University of Connecticut, gaining expertise and prominence in coherence and time-delay estimation. Throughout over four decades, Dr. Carter's career in Naval research and development included both research and line management positions in active and passive sonar signal processing at the USLs descendant organizations, now the Naval Undersea Warfare Center (NUWC) in Newport, RI. Dr. Carter's expertise garnered him two different technology management positions at the Office of Naval Research in Arlington, VA and culminated his career with NUWCs prestigious senior technologist position in acoustic signal processing. The IEEE recognized Dr. Carter's leadership in this field by designating him a Fellow in 1988.

The 2011 IEEE Workshop on Underwater Acoustic Signal Processing honors Dr. Carter for his contributions to sonar signal processing, leadership and mentoring in Naval research and development. Dr. Carter's contributions to sonar signal processing began with coherence and time-delay estimation and continued in detection and classification for both active and passive sonar. Despite the intrusion of several management tenures, Dr. Carter continually published throughout his lengthy research career, including conference papers, journal articles, book chapters, and a definitive book on coherence and time-delay estimation. Dr. Carter's leadership in science and technology was matched by his mentoring as evidenced by his efforts in extra-curricular teaching of graduate courses in electrical engineering, accruing an extensive number of younger co-authors in his publications, and taking a genuine interest in the next generation.

Schedule at a glance

Wednesday October 12, 2011		Thursday October 13, 2011		Friday October 14, 2011	
		8:15–9:55	Session B Autonom. I Laurel	8:15–9:30	Session H Autonom. III Laurel
		9:55–10:20	Break Laurel	9:30–9:55	Break Laurel
		10:20–12:00	Session C UW ACOMMS Laurel	9:55–12:00	Session I Active Laurel
		12:00–1:00	ASA Lunch Whisp. Pines	12:00–1:00	Lunch Whisp. Pines
		1:00–1:50	Session D Env. Sens. Laurel	1:00–1:50	Session J Modeling Laurel
		1:50–3:05	Session E Autonom. II Laurel	1:50–3:05	Session K Passive Laurel
		3:05–3:30	Break Laurel		
		3:30–5:10	Session F Array Proc. Laurel		
5:00–6:00	Welcome Reception Whisp. Pines	5:10–5:35	Session G MFP Laurel		
6:00–8:00	OES Dinner Whisp. Pines	6:00–8:00	Raytheon Dinner Whisp. Pines		
8:00–9:00	Session A Plenary Laurel	8:00–?	SOB Session Laurel		

Sessions: Titles and presenters

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

Special Session Plenary Talk

A–1 *Adaptive Acoustic Sensing and Communication in Autonomous Undersea Surveillance Systems*
Henrik Schmidt, Massachusetts Institute of Technology

Session B: Thursday Morning, 8:15am–9:55am

Special Session I: Autonomous Underwater Sensing Systems

B–1 *Underwater Data Collection using a Robotic Sensor Network*
Geoffrey Hollinger, University of Southern California

B–2 *Kriging for Undersea Collaboration*
Douglas Horner, Naval Postgraduate School

B–3 *Robust Cooperative Exploration with a Switching Strategy*
Wencen Wu, Georgia Institute of Technology

B–4 *Advances in Concurrent Mapping and Localization*
Ashwin Sarma, Naval Undersea Warfare Center

Session C: Thursday Morning, 10:20am–12:00pm

Underwater Acoustic Communications

C–1 *Iterative Coherent Broad-Band Sparse Acoustic Response Estimation with Application to the Reception of M-ary Orthogonal Signaling with Large Spreading Gain*
Paul Gendron, SSC-Pacific

C–2 *Tracking the Non-stationary Rapid Fluctuations of the Shallow Water Acoustic Channel using Sparse Optimization Techniques*
Ananya Sen Gupta, Woods Hole Oceanographic Institution

C–3 *An Exploration of Rate-Compatible Punctured Convolutional Codes for Underwater Acoustic Communication*
Erica Daly, University of Illinois

C–4 *Partial FFT Demodulation: A Detection Method for Doppler Distorted OFDM Systems*
Srinivas Yerramalli, University of Southern California

Session D: Thursday Afternoon, 1:00pm–1:50pm

Environmental Sensing

D–1 *Sediment Layer Tracking with Particle Filtering*
Zoi-Heleni Michalopoulou, Department of Mathematical Sciences, New Jersey Institute of Technology

D–2 *Ocean Acoustic Tomography and Matched Field Tomography Performance Versus the Spreads in the Group and Phase Speed Spreads*
Arthur Baggeroer, Massachusetts Institute of Technology

Session E: Thursday Afternoon, 1:50pm–3:05pm

Special Session II: Autonomous Underwater Sensing Systems

E–1 *Automatic Target Recognition as an Enabler for Multi-Vehicle Autonomy: Current Capabilities and Future Requirements*
Scott Reed, SeeByte Ltd

E–2 *Automatic Target Recognition Algorithm Approaches for Multi-Frequency, Multi-Aspect Acoustic Sensors and Magnetic Sensors*
Ted Clem, NSWC Panama City

E–3 *Automated Performance Assessment in Synthetic Aperture Sonar*
Roy Edgar Hansen, Norwegian Defence Research Establishment

Session F: Thursday Afternoon, 3:30pm–5:10pm

Array Processing

F–1 *Modeling the Dominant Mode Rejection Beamformer Notch Depth with Random Matrix Theory*
John Buck, UMass Dartmouth

F–2 *Comparing Experimental Data with Model Predictions for the Dominant Mode Rejection Beamformer Notch Depth*
Kathleen Wage, George Mason University

F–3 *Estimating Covariance from Spatial Spectra and its Application to SwellEx-96*
Joseph Schwarzwalder, Argon ST

F–4 *Passive Ranging with Distributed Arrays in Underwater Acoustic Environments: Spatial Coherence Loss & Multi-rank Solution*
Hongya Ge, New Jersey Institute of Technology

Session G: Thursday Afternoon, 5:10pm–5:35pm

Matched Field Processing

G–1 *Why did Matched Field Processing Fail?*
Arthur Baggeroer, Massachusetts Institute of Technology

Session H: Friday Morning, 8:15am–9:30am

Special Session III: Autonomous Underwater Sensing Systems

H–1 *Cooperative Anti-Submarine Warfare at NURC "Moving towards Networked Sensing with Distributed Intelligence"*
Robert Been, NATO Undersea Research Centre

H–2 *Broadband Passive Spatial Spectrum Estimation in a Dynamic Environment*
Jonathan Odom, Duke University

H–3 *Automated Bearings-Only Target Localization with a UUV*
Donald Eickstedt, iRobot Corporation

Session I: Friday Morning, 9:55am–12:00pm

Active Sonar Processing

I–1 *A Gammatone Filterbank Compressive Sensing Model for Active Sonar Receivers*
David Hague, University of Massachusetts Dartmouth

I–2 *Physics-Based Depth Discrimination of Multi-Static Active Sonar Target Echoes*
Geoffrey Edelson, BAE Systems

I–3 *MaxMin Sonar Signal Design for Optimal Detection of Elastic Targets in Signal-Dependent Noise*
Patrick Loughlin, Dept. of Electrical & Computer Engineering

I–4 *Waveguide Invariant Features for Enhanced Data Association and Tracking*
Christian G. Hempel, Naval Undersea Warfare Center

I–5 *Low-Frequency Cues for Assessing Object Size*
Luca Cazzanti, University of Washington, Applied Physics Laboratory

Session J: Friday Afternoon, 1:00pm–1:50pm

Noise Models

J–1 *Some Exact Results for a Time and Space Dependent Noise Model*
Leon Cohen, City University of NY

J–2 *Generation of Correlated Non-Rayleigh Distributed Clutter Samples*
Bruce Newhall, Johns Hopkins U. Applied Physics Lab.

Session K: Friday Afternoon, 1:50pm–3:05pm

Passive Sonar Processing

K–1 *Examination of Algorithms for Bearing Estimation Using Time Delay for a HF Acoustic Intercept Processing System*
Chunsheng Liu, Defence R&D Canada - Atlantic

K–2 *Complex Demodulation of Propeller Noise*
Ivars Kirsteins, Naval Undersea Warfare Center

K–3 *Passive Acoustic Tracking of Baleen Whales with Advanced Array Processing*
Arthur Newhall, Woods Hole Oceanographic Institution

Abstract Listings

Adaptive Acoustic Sensing and Communication in Autonomous Undersea Surveillance Systems

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The use of autonomous underwater vehicles as platform for passive and active acoustic sensing provides the possibility of adaptively changing the heading, speed and depth for optimal sensing performance. Depending on the environmental conditions, the adaptation can be either sensor-based or model-based. For example, by measuring the local ambient noise directivity, the autonomy can choose a heading which minimizes the interference with the source of interest, or the vehicle can use its measured sound speed profile to model the environmental acoustics and then choose an optimal depth for sensing or communication with other assets. The latter type of environmental adaptation requires that robust features of the acoustic environment are identified and modeled. In shallow water this is possible to a very limited degree, e.g. selecting a depth which is on the same side of the thermocline, whereas other features focusing the acoustic energy are in general unreliable due to fluctuations in the acoustic environment. In deep water, on the other hand, the deep pressure gradient of the sound speed is extremely stable and may be robustly exploited. Thus, a platform operating near the bottom in the deep ocean will have a direct acoustic path to and from a shallow receiver or source within the so-called RAP cone (Reliable Acoustic Path), extending to ranges of approximately 30 km. However, by moving up in the water column, the upward refractive sound speed profile will extend the direct path up to 60 km range. This convergence zone path is extremely stable and predictable, and combined with available information on the spatial diversity of the ambient noise the platform can then determine an optimal depth for acoustically connecting with a shallow source or receiver. An efficient ocean acoustic modeling and prediction capability has been embedded into the open-source MOOS-IvP autonomy software infrastructure, allowing autonomous acoustic sensing platforms to forecast the environmental acoustics based on available environmental data and the platform's operational constraints, and then autonomously request speed, heading and depth which optimizes the sonar or communication performance. The performance of both sensor- and model-based environmentally adaptive sensing concepts will be illustrated using results from recent field deployments for multistatic MCM and ASW in shallow water, and using a high-fidelity simulation environment, the performance of future deep ocean deployments exploiting the convergence zone path and the spatial noise diversity in the deep ocean will be demonstrated.

[Work supported by ONR, DARPA, and the NATO Undersea Research Centre.]

Underwater Data Collection using a Robotic Sensor Network

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We examine the problem of planning paths for an autonomous underwater vehicle (AUV) to collect data from an underwater sensor network. The sensors in the network are equipped with acoustic modems that provide noisy, range-limited communication. The AUV must plan a path that maximizes the information collected while minimizing travel time or fuel expenditure. This problem is closely related to the classical Traveling Salesperson Problem (TSP), but differs in that data from a particular sensor has a probability of being collected depending on the quality of communication. We propose methods for solving this problem by extending approximation algorithms for variants of TSP, and we compare our proposed algorithms to baseline strategies through simulated experiments with varying levels of communication quality.

While executing a path, the AUV can improve performance by communicating with multiple nodes in the network at once. Such multi-node communication requires a scheduling protocol that is robust to channel variations and interference. To solve this problem, we develop and test a multiple access control protocol for the underwater data collection scenario. We perform simulated experiments that utilize a realistic model of acoustic communication taken from experimental test data. The results demonstrate that planning the tour for the entire network while exploiting the appropriate scheduling protocol and communication model during planning improves performance.

This paper demonstrates the benefit of utilizing scheduling protocols to design path planning algorithms for autonomous underwater data collection. We show that simulated analysis with varying parameters can be used to build up a frontier of solutions that tradeoff between mission time and information gain. Without such analysis, it would not be possible to generate this frontier of solutions, and the path planning algorithm would need to execute blindly. Thus, improved scheduling protocols and analysis of communication provide a powerful tool for optimizing path planning algorithms in data collection scenarios.

[The authors gratefully acknowledge Jonathan Binney, Arvind Pereira, Hordur Heidarsson, and Srinivas Yerramalli at the University of Southern California for their insightful comments. Thanks also to Chris Goldfinger of Oregon State University, the captain and crew of the R/V Pacific Storm, and Elizabeth Clarke of the NOAA Northwest Fisheries Science Center for their support of this work. This research has been funded in part by the following grants: ONR N00014-09-1-0700, ONR N00014-07-1-00738, NSF 0831728, NSF CCR-0120778 and NSF CNS-1035866. Thanks to program managers Jason Stack and Marc Steinberg at ONR.]

Kriging for Undersea Collaboration

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For a variety of applications, it is necessary to conduct detailed surveys of restricted waterway areas such as harbors, canals, estuaries and rivers. Technologies available today such as a single surface, aerial or underwater vehicle are inadequate; they either take too long or create an inaccurate survey. A fleet of Autonomous Underwater Vehicles (AUV) is a potentially better solution. They can accomplish this task in a quicker, more efficient and robust way. Moreover, the AUV can move around the harbor with relative impunity since it avoids surface traffic and, with the proper sensors, can build a better three-dimensional map of the environment.

In order for a fleet of AUVs to accomplish this, there are several hurdles to overcome. First, the vehicles must be coordinated in conducting the survey. Restricted waterway areas are frequently dynamic environments and it would be difficult to determine, in advance, how long it would take to survey sub-regions. This means that while there is a prior plan, with regard to partitioning the survey space, it must be flexible. The ability to dynamically re-plan also creates a more robust system, in that, if one or more vehicles fail, the system can adapt and continue the survey. Second, underwater acoustic communications in shallow water is bandwidth and range limited and error prone. For a group of AUVs to coordinate behaviors, they must account for the communications network for collaborative navigation strategies to work effectively.

Estimating the ability to transfer information throughout a region of interest through an acoustic underwater network can be defined as a communication map of the robot's configuration space. Complete knowledge of this map can be used to guide collaborative Autonomous Underwater Vehicle (AUV) navigation to ensure overall system stability. For a variety of reasons, complete prior knowledge of the map is difficult to obtain.

The geophysical community developed a technique known as Kriging for estimating spatial field densities. This technique is also useful for communications channel estimation. This presentation will discuss the in-stride building of an underwater acoustic communications map through the use of Kriging and its part in the overall framework for collaborative AUV navigation in cluttered, dynamic, shallow-water undersea environments.

[Work supported by Tom Swean, ONR.]

Robust Cooperative Exploration with a Switching Strategy

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Biological inspirations lead us to develop a switching strategy for a group of robotic sensing agents to search for a local minimum of an unknown noisy scalar field. Starting with individual exploration, the agents switch to cooperative exploration only when they are not able to converge to a local minimum at a satisfying rate. We derive a cooperative H infinity filter to provide estimates of the field value and the field gradient during cooperative exploration, and give sufficient conditions for the convergence and feasibility of the filter. The switched behavior from individual exploration to cooperative exploration results in faster convergence, rigorously justified by the Razumikhin theorem, to a local minimum. We propose that the switching condition from cooperative exploration to individual exploration is triggered by a significantly improved signal-to-noise ratio (SNR) during cooperative exploration. In addition to theoretical and simulation studies, we develop a multi-agent test-bed and implement the switching strategy in a lab environment. We have observed consistency between theoretical predictions and experimental results that are robust to unknown noises and communication delays.

[The research work is supported by ONR grants N00014- 08-1-1007, N00014-09-1-1074, and N00014-10-10712 (YIP), and NSF grants ECCS-0841195 (CAREER), CNS- 0931576, and ECCS-1056253.]

Advances in Concurrent Mapping and Localization

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Concurrent Mapping and Localization (CML) or Simultaneous Localization and Mapping (SLAM) is a tracking technique used by the robotic and unmanned vehicle communities. The goals of the technique are to use optical/acoustic sensors on the platform to:

(a) Construct coarse maps of the locations of strong point scatterers in the sensors field-of-view
(b) Register these scatterer locations with respect to an absolute World Reference Frame (WRF)
(c) Continually improve these maps as more sensor data arrives
(d) Simultaneously achieve improved platform self-localization

As sensor data is relative to the platform, registration of scatterer locations in the WRF requires connection to platform location estimates in the WRF. This coupling is studied in this work. We describe an adjustment of the conventional CML method that provides maximum use of the sensor measurements.

Virtually all tracking techniques utilize a statistical data association method for the collection of "measurements," or tracker inputs. Such methods can (and do) reduce the performance of the CML/SLAM method. We describe a deterministic data association method for persistent scatterer determination. The method is based on platform location estimates provided by an Inertial Navigation System (INS) and eliminates the statistical data association problem.

Finally, we study the question of "optimal use of optical/acoustic sensor data when scatterer maps are not of direct interest." Analysis of the observability conditions of the historic CML method can lead to simplifications. These simplifications provide improved self-localization estimates as well as decreased complexity to allow for real-time implementation.

[This work was sponsored by ONR 333W.]

Iterative Coherent Broad-Band Sparse Acoustic Response Estimation with Application to the Reception of M-ary Orthogonal Signaling with Large Spreading Gain

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Shallow water acoustic response functions at high frequencies and large bandwidths are generally sparse and vary significantly with volume and boundary conditions as well as source-receiver motion. Considered here is a mixture-Gaussian assignment over angle, Doppler, and propagation delay employed to describe the behavior of acoustic response functions over received signal duration, aperture and bandwidth [1]. Accurate modeling of the dependence between the mixture components can be handled by considering dependence among neighboring indicator variables of the mixture assignment allowing for a more adaptable description and improved estimator performance. Accurate estimation of the response allows for compensation of the bulk time-varying dilation among all acoustic paths over the entire duration of the transmission based on all of the data. This adaptive structure is applied to underwater M-ary spread spectrum acoustic communication transmissions in Buzzard's Bay and off the coast of Martha's Vineyard at 32 kHz and 10 kHz respectively. The posterior conditional expectation of the acoustic response function is used iteratively to jointly estimate bulk time-varying path dilation and to improve symbol decisions. These coherent channel estimates demonstrate a greater than 2 dB improvement over standard rank based / maximal path combining methods. Accuracy is measured in terms of the empirical bit error rate (BER) as a function of received SNR. A BER = 10^{-6} at SNR = -16 dB for 3 element combining is demonstrated for 8-ary with 27 dB of processing gain in a drifting source receiver scenario.

[1] Gendron, IEEE Trans. SP, Vol. 53, No. 5, 2005.

[This work is supported by the Office of Naval Research and by NISE-BAR. Thanks to Lee Frietag and Jim Priesig of WHOI for the execution of these acoustic experiments.]

Tracking the Non-stationary Rapid Fluctuations of the Shallow Water Acoustic Channel using Sparse Optimization Techniques

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Tracking the rapidly fluctuating delay spread and time-varying delay-Doppler spread in shallow water acoustic communications is a well-known challenge. Recent efforts in applying popular sparse optimization techniques to adaptively detect the sparsely distributed channel coefficients have been met with limited success. This is primarily due to the ill-conditioned non-stationary nature of the channel estimation problem as well as the need to track the rapidly fluctuating channel coefficients directly over the complex field without the knowledge of any prior model. We investigate the performance of current sparse reconstruction approaches in shallow water acoustic communications and present recent work on non-convex fast optimization developed for this paradigm. Specifically, we focus on the issue of tracking the sparsity of the channel over field data in real time and discuss equalization techniques that exploit the sparse time-varying channel structure for potential BER improvements.

An Exploration of Rate-Compatible Punctured Convolutional Codes for Underwater Acoustic Communication

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Underwater acoustic communication is impeded by a non-stationary channel compounded by a slow propagation speed. Thus, any channel state information (CSI) fed back to the transmitter from the receiver is stale. This paper explores using feedback to support a rateless code, which is a good option for energy-efficient, high-throughput communication without the benefit of reliable CSI at the transmitter. Specifically, a punctured convolutional coded is used. Initially, the information is protected with a rate 9/10 error correcting code (ECC), which is generated by puncturing a rate 1/4 convolutional code. If the receiver is unable to receive the message at this rate, it requests additional parity bits. The transmitter then transmits a second packet containing some of the bits that were punctured from the convolutional coded to generate the first packet. The receiver appends the second packet to the first and again attempts to recover the information bits. If it cannot receive the information, it again requests additional parity. This continues until the information is received or every bit of parity is transmitted.

This rateless coding scheme was tested in shallow water off the coast of Kauai at the Pacific Missile Range Facility June 24th through July 4th 2011. The signals were transmitted acoustically from the ship to a buoy. The buoy received the signals using a linear turbo equalizer. The buoy then transmitted ACK/NAK feedback to the transmitter via an RF link. These tests demonstrate that a rate-compatible, punctured convolutional code scheme is a viable option for energy-efficient, high-throughput underwater acoustic communications with feedback.

[This work was supported in part by the department of the Navy, Office of Naval Research, under grants ONR MURI N00014-07-1-0738 and ONR N00014-07-1-0311 and by the NSF, under grant CNS-0708498.]

Partial FFT Demodulation: A Detection Method for Doppler Distorted OFDM Systems

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Orthogonal Frequency Division Multiplexing (OFDM) is now the primary signaling scheme for several wireless communication systems such as Long Term Evolution (LTE), WiMAX, Digital Video Broadcasting (DVB) and is also under consideration for underwater acoustic (UWA) communications. Recently, there has been an increased interest in OFDM signaling over highly time-varying channels, *i.e.*, in high mobility with significant Doppler effects. Employing Orthogonal Frequency Division Multiplexing (OFDM) signaling over time-varying channels results in inter-carrier interference (ICI) and degraded detection error probability due to the loss of orthogonality among the subcarriers. This problem is particularly exacerbated for systems operating in highly mobile scenarios such as underwater acoustic (UWA) communications.

To address the problem of data detection in such scenarios, we propose a novel demodulation strategy using several partial interval Fast Fourier Transforms (FFTs) instead of the conventional, single full interval FFT. The received OFDM symbol is first partitioned into several intervals using non-overlapping rectangular windows and an FFT is performed on each windowed segment of the received signal. The segments are then weighted and combined. If no weighting is applied, *i.e.,* if the partial FFT outputs for each segment are directly added, the result is equivalent to performing conventional, full FFT demodulation, which results in significant ICI due to uncompensated Doppler distortion. In contrast, by judicious weighted combining of the partial FFT outputs, we show that the ICI can be significantly reduced, improving the detection performance at a complexity that is comparable to that of typical ICI equalization. Algorithms for computing the weights used to combine the outputs of the partial FFT are presented for three scenarios: full, partial and zero knowledge of the time varying channel. Numerical simulations and an approximate theoretical analysis show that significant performance gains can be obtained over traditional equalizers at a very moderate complexity.

Sediment Layer Tracking with Particle Filtering

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A passive fathometer problem is addressed for the estimation of layers in oceanic sediments. It has been shown that, by processing noise data at a specific array location, a reflector sequence can be extracted, consisting of a summation of sinc pulses. The center of each pulse identifies the depth of a reflector in the ocean environment at that location. Extracting the peak locations of these pulses in the reflector sequence provides insight in the sediment structure of the medium. With the number of layers being unknown as well, an order selection model needs to be implemented. The approach is similar to spatial time delay tracking with Bayesian filters that sample from posterior density functions. Data are collected at multiple ranges and are related to the unknown depths via an observation equation. Using a relationship between unknown parameters at neighboring steps for prediction and the observation equation for updates, we implement a particle filter that tracks reflectors. The number of pulses varies with range, following changes in sediment layering. We present results after using two different beamforming techniques. We calculate probability density functions of the number of layers and their depths and demonstrate the successful tracking of changes in the structure of the ocean environment and the uncertainty therein.

[This work has been funded by the Office of Naval Research.]

Ocean Acoustic Tomography and Matched Field Tomography Performance Versus the Spreads in the Group and Phase Speed Spreads

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We demonstrate that the performance in estimating environmental parameters in ocean acoustic tomography (OAT) with a mode resolving array is scaled by the variance of the distribution of the group speeds of the excited modes weighted by their signal to noise ratios. Similarly, the performance for estimating the same parameters with matched field tomography is scaled by the variance of the distribution of the phase speeds of these modes similarly weighted.

Automatic Target Recognition as an Enabler for Multi-Vehicle Autonomy: Current Capabilities and Future Requirements

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Unmanned Underwater Vehicles (UUVs) are now used routinely in military and commercial offshore operations. However, the current level of autonomy on-board these systems is limited. Autonomy relies on the vehicle being able to robustly perceive and localize itself within its environment which may be cluttered, changing and unknown. This puts enormous expectations on the required processing to convert the vehicles raw sensor data into meaningful information upon which autonomous decisions can be made. This process is often called Automatic Target Recognition (ATR).

Within a military context, ATR has initially focused on the ability to detect mine-like objects. Historically, research has focused on developing monolithic classifiers which are slow to train and require huge amounts of example data. These models are generally static, performing well in simple scenarios but unable to adapt to changing environments or object appearance. The first section of this presentation will detail SeeBytes current ATR capabilities for AUV-mountable sensors. SeeBytes emphasis has shifted away from having a single classifier capable of detecting all possible mine-threats to developing specific ATR models for each object of interest. Novel aspects of the classifier such as the use of simulated data to train the system as well as the real-time processing capability as an autonomy enabler are discussed.

Long term adoption of ATR technology requires that these models can adapt to their environment. When running onboard an inspection vehicle, the ATR model may be required to track an object over extended periods of time during which the object appearance may change considerably. This requires that the ATR can adapt in-situ, re-learning in real-time using the available onboard processing capabilities. The second part of this presentation discusses SeeBytes development in this area looking at Detection through Tracking techniques coupled with fast-trained classifier techniques to allow in-line re-training.

Within the context of Autonomy, the scope of ATR must be seen in the much broader context of environment perception rather than simply identifying mine-like targets. Here, the ATR is used as feedback to on-board control, navigation and decision-making modules and may be required to provide the position of a diverse range of features dependent on the application. One commonality is that the ATR is required to run embedded on the vehicle and provide feedback in real-time, assuring vehicle stability and responsiveness. The third part of this presentation presents SeeByte involvement in using ATR as an autonomy enabler, highlighting results and challenges.

When moving to using multiple heterogeneous assets, collaboration can be difficult if the vehicles are equipped with different sensors. These sensors can provide a very different representation of the vehicles environment, making feature association between the different vehicles difficult. ATR models are typically sensor specific; there is no guarantee that a feature detected by one asset will be recognized by another. The final part of the presentation will look at novel work SeeByte is carrying out to develop sensor independent ATR capabilities enabling autonomy operations across different hardware assets.

[This work is supported in part by the Dr Tom Swean and the Office of Naval Research]

Automatic Target Recognition Algorithm Approaches for Multi-Frequency, Multi-Aspect Acoustic Sensors and Magnetic Sensors

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Automatic target recognition (ATR) algorithms are a key enabling technology in autonomous vehicle operations. The ability to accurately detect, classify, and localize (DCL) a target in a cluttered undersea environment is a crucial first step in any follow-on . In this paper we present two research efforts that support and demonstrate advanced underwater autonomous DCL. First we present several new algorithmic approaches to model seabed environments and detect and classify seafloor targets using multi-frequency, multi-aspect acoustic sensors. Next, we present recent results in which embedded signal processing has been demonstrated to realize sophisticated autonomous operations for autonomous underwater vehicles (AUVs) using integrated acoustic, magnetic, and optical sensors.

Currently ATR algorithms embedded on unmanned underwater vehicles are optimized for single-frequency side-look strip map images, i.e. single-pass, and extract pixel-based features from a limited set of training images. Here we present several ATR research thrusts enabled by next generation acoustic sensors that aim to improve classification performance in by 1) automatically adapting operating parameters to clutter environments by modeling the seabed texture, 2) coherently combining dual- and multi-frequency sensor information to reduce effects of high-frequency clutter, and 3) adding fidelity to target features by recognizing statistical shape patterns with multi-aspect sensing.

Next a concept is described in which embedded ATR is used to direct an AUV to perform multiple autonomous objectives in one seamless operation including: (a) initiate a reacquire and identify (RI) mission, (a) terminate the RI mission once the target is localized and identified with high confidence, (b) re-direct the system to drop a marker, and (c) survey the relative position of the marker with respect to the target (information used to expedite subsequent target neutralization with low cost assets). Recent results to realize this concept using an AUV integrated with acoustic, magnetic and optical sensors will be presented. In the current realization, DCL results from a magnetic sensor have been used to direct the autonomous behaviors although acoustic ATR or the fusion of ATR results from multiple sensors can be applied in the future. The signal processing for the magnetic sensor will be described to include the approaches developed for noise cancellation for magnetic sensing onboard a magnetically noisy AUV. In addition, embedded processing to fuse the acoustic, magnetic and optical data already demonstrated and its extension toward a capability for embedded identification is presented.

Automated Performance Assessment in Synthetic Aperture Sonar

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A substantial technological advance in the underwater domain over the last two decades is the emergence of autonomous underwater vehicles (AUV). The advantages include increased safety (keeping manned platforms out of high risk areas) and the possibility of performing covert operations with relatively large stand-off ranges to the host vessel. In addition the AUV brings the sensors closer to the actual scene of interest, and thereby provide better data quality. The trend goes towards little or no human interaction during AUV operations. This implies that the vehicle must be able to adapt to the environment and the task in hand, and intelligently operate the sensors such that the best possible data are gathered. A critical component of this, is to be able to estimate the performance of the sensors given the data collected, and to predict the performance given the ocean environment and the vehicle behaviour.

Synthetic aperture sonar (SAS) is a signal processing technique which increases the along-track resolution in the sonar image by coherent combination of the collected pings. SAS systems has the potential to image the seafloor with very high resolution and large area coverage rate. This makes SAS a well suited technology for detection and classification of small objects on the seafloor. Successful SAS image formation is, however, dependent on accurate knowledge of the ocean environment, the bathymetry and the vehicle track.

We suggest a model for automated prediction and assessment of SAS performance. This model consists of modules for generalized signal to noise, geometrical resolution, radiometric resolution (value accuracy) and image sharpness. We describe the functional content of the modules, and list some of the governing rules that affect SAS performance. We describe methods to assess key performance parameters using the signal coherence. We show example results from the HISAS 1030 interferometric SAS onboard a HUGIN autonomous underwater vehicle.

Modeling the Dominant Mode Rejection Beamformer Notch Depth with Random Matrix Theory

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The Dominant Mode Rejection (DMR) adaptive beamformer (ABF) [1] results from modifying the sample covariance matrix (SCM) used by the Minimum Power Distortionless Response (MPDR) ABF. Specifically, the DMR ABF replaces all of the weak eigenvalues in the SCM by their average, while the strong eigenvalues and all of the eigenvectors are left unchanged. Substituting this constrained SCM into the MPDR expression yields the DMR array weights. The resulting ABF beampattern steers nulls in the direction of strong interferers. In practical scenarios, moving interferers and nonstationary acoustic environments limit the number of snapshots that can be combined coherently to form the SCM estimate. The notches steered by the DMR ABF using a limited number of snapshots are often dramatically shallower than the notches predicted for DMR using the ensemble covariance matrix (ECM). Numerical experiments confirm that errors in the estimated eigenvectors are primarily responsible for this degradation in the ABF performance.

This talk presents a model explaining this gap between the ensemble performance and the performance obtained from a finite set of snapshots. The model exploits results on eigenvector fidelity from Random Matrix Theory (RMT) [2-5]. The model takes the functional form of straight-line asymptotes on a log-log plot of DMR notch depth versus number of snapshots. The locations of the breakpoints on the log snapshot axes and the slopes of the linear asymptotes are determined by the the array size, the interferer power, and interferer direction relative to the look direction. The model smoothly transitions from the conventional beamformer (CBF) at the low snapshot asymptote to the ECM performance at the high snapshot asymptote. Additionally, the model predicts the minimum number of snapshots needed to improve performance over the CBF and the number of snapshots required to achieve the ECM performance. This latter number is generally unrealistically large for any practical ABF scenario. For strong interferers, the DMR notch depth improves by 10 dB per additional factor of 10 in snapshots observed over most of the range between the high and low snapshot asymptotes. For weaker interferers, the improvement is only 5 dB of notch depth per factor of ten in snapshots. The model clearly predicts the threshold in interferer power for the transition from the 10 dB/decade to 5 dB/decade performance. The model also demonstrates close agreement with simulation results over a wide range of interferer power and array size.

[1] D. A. Abraham and N. L. Owsley, "Beamforming with Dominant Mode Rejection," *Proc. IEEE Oceans*, pp. 470-475, 1990.

[2] F. Benaych-Georges and R. R. Nadakuditi, "The Singluar Values and Vectors of Low Rank Perturbations of Large Rectangular Random Matrices," *Adv. Math.*, vol. 227, no. 1, pp. 494-521, 2011.

[3] I. M. Johnstone and A. Y. Lu, "On consistency and sparsity for principal components analysis in high dimensions," *J. Am. Stat. Assoc.*, vol. 104, no. 486, pp. 682-693, 2009.

[4] B. Nadler, "Finite sample approximation results for principal component analysis: a matrix perturbation approach," *Annals Stat.*, vol. 36, no. 6, pp. 2791-2817, 2008.

[5] D. Paul, "Asymptotics of sample eigenstructure for a large dimensional spiked covariance model," *Stat. Sinica*, vol. 17, pp. 1617-1642, 2007.

[Work funded by ONR Code 321US.]

Comparing Experimental Data with Model Predictions for the Dominant Mode Rejection Beamformer Notch Depth

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The Dominant Mode Rejection (DMR) adaptive beamformer attenuates loud interferers by steering notches in the beampattern towards signals contained in the subspace spanned by the dominant eigenvectors [1]. The dominant eigenvectors are associated with the largest eigenvalues of the covariance matrix. Assuming the ensemble covariance is available, the depth of a notch is determined by the interferer location, interference-to-noise ratio (INR), and array size. When the covariance matrix must be estimated from data, the notch depth also depends on the number of snapshots used to form the sample covariance matrix. In a companion paper Buck and Wage [2] present an analytical model that predicts the mean DMR notch depth as a function of interferer location, INR, array size, and the number of snapshots. The model is based on recent random matrix theory (RMT) results that predict the accuracy of the sample eigenvectors [3-6].

The 2010-2011 Philippine Sea (PhilSea) experiment provided an opportunity to compare measured DMR notch depths with the new RMT model. The notch depth analysis uses receptions recorded by an equally-spaced 31-element vertical line array (VLA). For frequencies less than 60 Hz, the PhilSea VLA data are dominated by cable strum interference. Since the strum lies within a subspace spanned by the first two eigenvectors of the covariance matrix, the DMR beamformer provides a useful way to remove this interference. This analysis quantifies the notch depths that can be achieved using different numbers of snapshots, ranging from 3 to 310. While the spatial characteristics of the strum are consistent throughout the year-long deployment, the power varies from reception to reception. This facilitates the analysis of DMR notch depth as a function of INR. Notch depth statistics obtained using a large set of receptions show good agreement between the RMT model and the PhilSea measurements.

[1] D. A. Abraham and N. L. Owsley, ”Beamforming with Dominant Mode Rejection,” *Proc. IEEE Oceans*, pp. 470-475, 1990.

[2] J. R. Buck and K. E. Wage, ”Modeling the Dominant Mode Rejection Beamformer Notch Depth with Random Matrix Theory,” submitted to IEEE Underwater Acoustic Signal Processing Workshop, 2011.

[3] F. Benaych-Georges and R. R. Nadakuditi, ”The Singluar Values and Vectors of Low Rank Perturbations of Large Rectangular Random Matrices,” *Adv. Math.*, vol. 227, no. 1, pp. 494-521, 2011.

[4] I. M. Johnstone and A. Y. Lu, ”On consistency and sparsity for principal components analysis in high dimensions,” *J. Am. Stat. Assoc.*, vol. 104, no. 486, pp. 682-693, 2009.

[5] B. Nadler, ”Finite sample approximation results for principal component analysis: a matrix perturbation approach,” *Annals Stat.*, vol. 36, no. 6, pp. 2791-2817, 2008.

[6] D. Paul, ”Asymptotics of sample eigenstructure for a large dimensional spiked covariance model,” *Stat. Sinica*, vol. 17, pp. 1617-1642, 2007.

[Work supported by ONR 321US and 322OA.]

Estimating Covariance from Spatial Spectra and its Application to SwellEx-96

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In practice, non-stationarity in the environment limits the ability to accurately estimate the covariance matrix as a component of adaptive beamforming for an acoustic array processing system. Additionally, correlated multipath may degrade adaptive beamformer performance due to the signal cancellation effect. Covariance from spatial spectra (CSS) is a structured covariance estimation algorithm that uses estimates of the frequency-wavenumber or power versus angle-of-arrival spatial spectra as a basis for estimating the covariance [1]. This approach operates well with very low snapshot support and constrains the resulting covariance to the uncorrelated plane waves in noise model, regardless of multipath correlation present within the data.

This presentation reviews the CSS technique using both classical power spectral estimation and Thomson's multi-taper spectral estimation (MTSE). The importance of dealing with impulsive components in the spectrum, e.g., incident plane waves, and the impact on performance is discussed. With these classical techniques as the spatial spectra 'engine', CSS is straightforward and most efficient for uniform linear arrays using FFT techniques. The technique can also be applied to non-uniform arrays, with some additional consideration given to the estimation of the inherent sensor noise component. Simulation results for uniform and non-uniform array designs will be presented.

The SwellEx-96 data set [2] contains controlled experiment data for both linear and non-linear arrays in a multipath littoral environment. This presentation concludes with results from application of CSS to various arrays and events in the SwellEx data set.

[1] J. J. Schwarzwalder and K. E. Wage, "ABF performance using covariance matrices derived from spatial spectra for large arrays," Conf. Record of the 43rd Asilomar Conf. Signals, Syst. Comput., pp. 1164-1168, Nov. 2009.

[2] "Welcome to the SWellEx-96 Experiment." Welcome to the Marine Physical Laboratory. Marine Physical Laboratory. Web. 07 July 2011. `http://www.mpl.ucsd.edu/swellex96/`.

[This work is supported by Argon ST IR&D, R0227 and R0337.]

Passive Ranging with Distributed Arrays in Underwater Acoustic Environments: Spatial Coherence Loss & Multi-rank Solution

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In this work, we introduce a more general formulation of spatial-temporal Gaussian data model, by considering into the factor of spatial coherence loss typically observed in data from distributed array systems. Based on such formulation, we then develop a maximum likelihood multi-rank processor for passive wavefront curvature ranging (WFC) systems using distributed arrays of hydrophones, operating in underwater acoustic environments subject to a spatial coherence loss. Under different levels of spatial coherence, the general multi-rank solution reduces to different special forms, hence leads to different implementation structures including fully coherent whole array processing, partially coherent sub-array processing and combining, and non-coherent triangulation. We establish an interesting connection of our proposed multi-rank processor to the conventional rank-1 processor, and to the non-coherence sub-array processor, under different operating conditions. A comparative stu dy is carried out in evaluating the performance of the proposed processors.

[This work was supported in part by ONR/NUWC.]

Why did Matched Field Processing Fail?

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The concepts for Matched Field Processing (MFP) stimulated many articles in the literature in the 1990's and early 2000's. MFP certainly received a lot of hype well beyond what anyone who understood it would believe. ONR invested significant amounts of funding. In the early days it focused around the so called "High Gain Initiative" in ONT where MFP was the answer for the ASW dB needed by the fleet. This application was premature and MFP clearly missed the mark then. As has been stated MFP is not a low SNR detection problem, but a high SNR estimation one. The many simulations could not be replicated when applied to field data. Nevertheless, there were a number of experiments which clearly demonstrated MFP could work. These included the NRL FRAM IV Experiment, the SAIC 1000 km deep Pacific Experiment, the Santa Barbara Channel Experiment, the SPAWAR SWELLEX, plus many, many others. The challenge then was/is to make MFP work robustly at low SNR's.

Many reasons for failure have been given besides the one cited above. These include:

(i) The environment could not be well measured even with tomographic adjuncts;

(ii) The acoustic element location (AEL) systems were not accurate;

(iii) Conventional processing led to sidelobe patterns with many ambiguities in the range/depth plane without enough bandwidth to average them out such as with microphone arrays;

(iv) There were never enough "snapshots" because of large arrays and moving (nonstationary) environments for ABF to mitigate sidelobes;

(v) The horizontal coherence was not separated as being distinct from multipath effects;

(vi) The vertical coherence modelling was hard to incorporate;

(vii) The tradeoff of HLA's for azimuthal rejection of clutter and VLA's for range/depth resolution was not well understood;

(viii) The tradeoff for smaller, but more robust, subarray processing was not developed;

(ix) There was too much emphasis on element space versus beam and subspace processing;

(x) Some applications required a computational capability beyond the the SOA;

(xi) Some applications were simply not appropriate;

(xii) Some investigators simply did not understand the signal processing especially the assumptions regarding phases when using real data.

Perhaps the answer is all of the above plus other reasons not stated.

Today, MFP certainly conjures negative connotations. Nevertheless, there has been virtually no serious detective work on "Why did Matched Field Processing Fail?" The purpose of this talk is not to reinvigorate MFP, but to derive some lessons learned given the very significant investment in funding, intellectual capital and false optimism of sponsors. We certainly should be able to extract some important principles applicable to current efforts in underwater signal processing. We hope for a lively discussion - perhaps a perspective review article?

[The author acknowledges past support by ONR and DARPA for his MFP efforts.]

Cooperative Anti-Submarine Warfare at NURC "Moving towards Networked Sensing with Distributed Intelligence"

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The NATO Undersea Research Centre (NURC) conducts R&T on off-board Low Frequency Active (LFA) sensors for use in Cooperative distributed ASW (CASW). The objective is to research scalable and autonomous systems that remove vulnerable personnel from the vicinity of high risk, are cheaper than conventional ship-based sonar and potentially leverage the benefits of multi-static operations by creating an increased diversity of assets and spatial distribution. Such systems would also release personnel to perform tasks elsewhere. NURC intends to demonstrate an open-architecture concept with a high degree of interoperability in 2012.

Over the last two decades, ASW focus has shifted towards the littoral. This operations area is characterized by high noise levels, discrete clutter and diffuse reverberation. As a result, coalition forces may have to operate in very difficult underwater acoustic environments with high false alarm rates against small, quiet adversaries. In addition, the number of platforms with ASW capabilities has reduced considerably within NATO. Frigate cost and limited availability are driving the need for off-board ASW sensors that are persistent, scalable and affordable [1]. The NURC CASW concept is based on distributed heterogeneous sensing, its rationale is implemented in the following structure:

- Concepts for Littoral Undersea Surveillance;
- Communications and Networking in the Maritime Domain and
- Decision Support.

The 'Concepts for Littoral Undersea Surveillance' project is investigating sensing technologies, real-time processing on embedded systems and distributed intelligence with autonomy. Detailed simulation, incorporating hydrophone level time series and vehicle dynamics [2], has enabled tests of both the real-time signal processing and ASW-relevant autonomous behaviors prior to the at-sea experiments.

'Communications and Networking in the Maritime Domain' focuses on the development of open architectures that support adaptive, ad-hoc networking with a high degree of robustness and interoperability. Distribution of tracking results and C2 is achieved via in-air data links, gateways and underwater acoustic communications.

The 'Decision Support' project addresses (autonomous) decision making in the presence of intelligent targets, by looking into game theoretical approaches, where the target has knowledge (with a level of uncertainty) of the position(s) and mode(s) of the observing autonomous ASW system. The project uses the MSTPA [3] decision tool, both for Monte Carlo and human-in-the-loop scenario evaluation.

One of the options that NURC investigates in the system-of-systems approach is off-board multistatics. NURC's sonar is an example application of a collaborative system with challenged - low bandwidth - communications; it comprises two sound sources and two receive arrays towed by AUVs. The hard- and software, however, have been created with a high degree of portability in order to facilitate easy integration on other platforms such as bottomed sensors, USVs or buoys.

The processing is performed locally, on board each AUV, rather than at a central processing node both to improve robustness to single-point failure and in recognition of the severely limited bandwidth and link intermittency of underwater acoustic communications. This architecture requires the AUV to display a high degree of autonomous processing and intelligent adaptive behavior [4].

The real-time suite includes standard sonar processing up to the level of tracking. Current modes are HFM and CW, engineering tests have been done for HFM / BPSK mode [5]. At this moment, classification is done via Doppler and the contacts' properties. The on-board intelligence ranges from simple (keep a perceived target in broadside) to more sophisticated information theory based methods [6].

This talk will cover the sensing, autonomous decision making, data communications and networking aspects of the CASW program. Simulation and sea-trial results will be provided for the NURC multistatic active sonar demonstrator.

[1] "Networked concepts look to square the ASW circle," Jane's international defence review, January 2011.

[2] Reverberation and time series generation for real-time ASW simulation applications, K. Le Page, NURC Technical Report.

[3] "Optimisation in the MultiStatic Tactical Planning Aid," A. Wathelet, C. Strode , A. Vermeij and R. Been, NURC Technical Report;

[4] NURC uses MOOS and MOOS-IvP: `http://oceanai.mit.edu/moosivp/home.html`.

[5] "False alarm reduction for LFAS with BPSK pulses: experimental results," M.E.G.D. Colin and S.P. Beerens, *IEEE JOE*, January 2011.

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Broadband Passive Spatial Spectrum Estimation in a Dynamic Environment

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Estimation of the time-varying acoustic field is essential for situational awareness in passive sonar. Adaptive processing often assumes both the field is stationary and the array is fixed for multiple observation windows. Highly dynamic scenarios such as high bearing rate sources or underwater maneuvers severely limit the utilization of multiple snapshots. Several models are considered for time-varying fields, and an online broadband maximum-likelihood estimator is introduced that is solved with an EM algorithm using as few as one snapshot. The number of estimated parameters can be reduced for broadband data when information, such as shape, about the source temporal spectra is known. Cramér-Rao bound analysis is used to understand effects of temporal spectrum knowledge on broadband processing. An example is given for the flat spectrum case to compare with conventional processing. The new spatial spectrum estimate leverages information across the temporal spectrum to reduce the impact of spatial grating lobes. Another feature of dynamic environments is array motion. Since underwater arrays are often subject to motion, the estimate must consider arbitrary, dynamic array shapes. Platforms such as autonomous underwater vehicles provide mobility but constrain the number of sensors. Exploiting maneuverable linear arrays with the new estimate allows for left-right disambiguation, more uniform angular resolution, and suppression of spatial grating lobes. Multi-source simulations are used to demonstrate the ability of a short, maneuvering array to reduce array backlobes as well as operate in the spatial grating lobe region. Detection performance of a weak high-bearing rate source in an interference dominated environment is evaluated for a flat spectrum.

[This work was supported by the Office of Naval Research under Grant No. N000140810947.]

Automated Bearings-Only Target Localization with a UUV

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As unmanned underwater vehicles (UUVs) have become more persistent, they have become more useful for a number of applications that have traditionally been performed by manned vehicles. One of those applications is the localization of a moving underwater target using a bearings-only acoustic sensor mounted on a moving vehicle. However, since command and control (C2) bandwidth to submerged UUVs is very limited and C2 latency is high, UUVs must have a high degree of onboard autonomy in order to respond to events of interest in real time. Because of the C2 limitations and the target/UUV speed mismatch, there is simply not enough time for a UUV to receive maneuvering instructions form an operator after making a detection; the UUV must be able to maneuver to obtain a localization solution using its onboard autonomy.

Estimating the state of a moving target using a single bearing sensor on a moving platform is a very difficult problem due to the observability of the resulting state estimate. A well-known constraint in tracking a constant-velocity target from a moving sensor platform is that, if the sensor platform also moves with constant velocity, the target motion parameters are unobservable. Therefore, the sensor platform must undergo acceleration with respect to the target. A simple change of course can satisfy this condition. The degree to which the sensor motion improves the observability and, hence, the variance of the parameter estimates can be quantified by the condition number of the Fisher Information Matrix (FIM) for the estimate covariance matrix. If the condition number is too large, the FIM is ill-conditioned and the parameters are unobservable. Even if the FIM is invertible, the parameters may be marginally observable depending on the actual value of the condition number.

The goal for an automated target localization system with a UUV should be to maneuver the UUV so as to minimize the condition number of the FIM (and therefore minimize the target location estimate variance) with respect to the sampled target bearings. With a UUV this means that the UUV would maneuver to collect a number of bearings, compute a state estimate for the target and then use this state estimate for further maneuvering in an attempt to minimize the solution variance. An unavoidable problem with this method is that the solution variance will depend not only on the observer maneuvers but also on the actual target motion meaning that unfortunate maneuvers during the beginning of the sequence of maneuvers of the observer could lead to the solution becoming unobservable. On a manned platform, a set of heuristics and operator experience are used to determine the observer maneuvers. On an automated platform we would like to obtain the optimal solution. As it turns out, the two are very similar, leading to a bang-bang type of control problem.

This presentation will describe a solution for automated localization of a moving target for a UUV with a bearing sensor. A UUV with a bearing sensor (and associated detection capability) is assumed. The presentation will describe the UUV behaviors and the algorithms developed to make decisions regarding UUV maneuvering once a detection has been made. The decisions are made using a combination of heuristics and optimal control theory using dynamic programming with the goal of robustly arriving at a state estimate (position, course, speed) for the target. Statistical analyses of the automated solution with respect to a number of different parameters and scenarios will be presented. The integration of the UUV behavior code into the MOOS-IvP autonomy architecture will be described. Simulation results using the MOOS-IvP UUV simulation environment with an acoustic simulator will be presented.

A Gammatone Filterbank Compressive Sensing Model for Active Sonar Receivers

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Active sonars operating in complex underwater acoustic environments must detect targets and resolve closely spaced reflectors in the midst of background noise and clutter. While this is a challenging task for man made sonars to achieve, echolocating bats are able to routinely accomplish this task in real time. The Big Brown Bat (Eptesicus fuscus) uses FM echolocation calls to accurately estimate range and resolve glints spaced down to 2 μs in time delay (0.35 mm in range). In addition, the bat's auditory system processes these echoes using sampling periods of 300-400 μs. This detection and resolution performance far surpasses traditional signal processing techniques. The Matched Filter (MF) is the optimum detector for a known signal in white Gaussian noise but its resolution is limited by the mainlobe width of the auto-correlation function of the echolocation call and attains 10-12 μs resolution. The Inverse Filter (IF) achieves optimal resolution for a known signal at the cost of significantly degraded detection performance for decreasing SNR. Recent work by Fontaine and Peremans [J. Acoust. Soc. Am. (2009)] demonstrated that a sparse representation of bat echolocation calls coupled with a decimating Compressed Sensing (CS) method facilitates distinguishing closely spaced objects over realistic SNRs. Fontaine and Peremans make no claim in regard to the biological plausibility of the CS method itself. However, their work raises the intriguing question of whether a sensing methodology similar to the mammalian auditory system contains the necessary information to achieve the resolution and detection performance reported in observational studies. This research expands upon the work of Fontaine and Peremans and estimates sparse target responses using a gammatone filterbank decimation sensing method closer to the bat auditory system. The target response is estimated by applying ℓ_1 minimization to the decimated filterbank outputs. The decimated filter outputs model the reduced time precision in the bat auditory system as the signals travel up the auditory processing chain. The aim of this research is to demonstrate that the reduced time precision of the bat's auditory system still contains sufficient information to reconstruct high resolution sparse echo signatures similar to that observed in behavioral experiments with bats. Simulations demonstrate that this model attains higher resolution than the MF and significantly better detection performance than the IF for SNRs of 5-45 dB while downsampling the return signal by a factor of six. In addition, the gammatone filterbank sensing model also maintains or exceeds the detection/resolution of the CS method employed by Fontaine and Peremans

[Work supported by ONR and the SMART Scholarship Program.]

Physics-Based Depth Discrimination of Multi-Static Active Sonar Target Echoes

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An approach is presented for the discrimination of multi-static active sonar target echoes using the physics of the shallow-water waveguide. Physics-based depth discrimination (PBDD) exploits the phenomenon of mode-trapping due to the sound speed gradient in a downward refracting shallow-water channel to separate surfaced and submerged sources of acoustic energy. In such an environment, low order modes exhibit a depth-dependence that transitions from near sinusoidal at depth to evanescent near the surface. The implication is that low order modes can only be excited by a source or scatterer at depth. We show that with a nominal degree of vertical aperture and approximate knowledge of the sound speed environment, a test statistic capable of discriminating the depth class of a near-specular target echo is possible.

For the application to multi-static active sonar, it is essential to show that the target scattering physics, waveform processing, and the constraints of limited spatial aperture, do not disrupt the observability of the mode-trapping phenomenon. In particular, aperture limitations lead to linear dependence between modal steering vectors, and overlap between signal subspaces, thereby degrading discrimination performance. We will review the theory underlying the discrimination algorithm, known as the matched subspace discriminator, and show how we contend with the signal subspace overlap imposed by limited aperture.

We demonstrate the performance of the depth discrimination algorithm using the Sonar Simulation Toolset for the case of a near-specular target echo using a linear frequency-modulated (LFM) source waveform. The broadband simulation results illustrate that the coherent spatial structure of the near-specular echo exploited by the test statistic is preserved by target scattering and matched filter processing. We will also present preliminary depth discrimination performance on data from the NURC CLUTTER09 exercise. Both the simulated and collected data results will clearly show the potential for separation in test statistic response between a surfaced and submerged scatterer in a downward refracting shallow-water environment.

[This work is supported by ONR Code 321US.]

MaxMin Sonar Signal Design for Optimal Detection of Elastic Targets in Signal-Dependent Noise

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Detection of underwater or buried objects using active sonar has been shown to be improved by designing the transmit sonar pulse based on the known impulse response of the object. However, in practice precise knowledge about the object's impulse response may be unavailable. Furthermore, a transmit pulse optimized for one object state may yield significantly worse performance if the object is actually in a different state (e.g. orientation or burial depth). We propose an extension to a recent approach that derived a signal that maximizes the probability of detecting a single object with known impulse response in the presence of signal dependent noise (e.g. clutter or reverberation). In our extension, we derive a transmit signal that maximizes the worst-case probability of detection associated with an assumed set of objects. Simulations demonstrate improved performance of this approach compared to transmitting an LFM pulse or a signal optimized for an object state different from the actual state.

[Research supported by ONR Code 321US.]

Waveguide Invariant Features for Enhanced Data Association and Tracking

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Algorithm designers have expended considerable effort trying to improve the performance of active sonar tracking methods by incorporating features that provide inference about target type (e.g., SNR, highlight structure, range and bearing extent) in order to achieve statistical separation between true and false detections and thereby improve, data association, track hold time and false track rejection. Recently, a new type of feature has been devised that is based on the effects of modal propagation which causes constructive and destructive interference within the transmitted signal band of active sonar systems and produces peaks at various frequencies in the power spectrum of the observed measurements. The peaks in the power spectrum move over time in a predictable way to produce a distinct pattern of frequency lines which is different for each object in the water column. This phenomenon is useful because it can provide inference about the origin of an active sonar echo and thereby improve data association and track hold. Unlike target type features, the time evolution of the locations of peaks in the frequency space depend on position and velocity of the sensor and target and are described by an equation based on the principle of a waveguide invariant γ as

$$f(n+1) = f(n)\left[1 + \frac{\dot{r}(n)\gamma\Delta t}{r(n)}\right].$$

This talk will present a theoretical analysis along with candidate sufficient statistics and features that are designed to capture this phenomenon with the fewest dimensions in a way that is readily exploitable by modern tracking algorithms. Real world issues such as the effects of noise, interference and imperfect echo extraction will be discussed and illustrated by simulation based results.

Low-Frequency Cues for Assessing Object Size

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We will discuss a system, under development at the Applied Physics Laboratory, to estimate cylinder dimensions from far field, monostatic sonar data. While obtaining such estimates is straight forward with high frequency imaging sonars, we face a number of challenges in doing so with a low-frequency system. Nonetheless, we are able to leverage a number of cues to estimate the physical extent of proud objects.

One of these cues is the phenomenon of edge diffraction. By Huygens Principle, each corner of an insonified object acts as a source. By detecting the timing of the return from each corner, we can estimate the size of the object. We present two automated systems for this detection and estimation. One system is based upon cepstral processing of the returns while the other performs detection in the time domain.

Our most recent work involves a second phenomenon related to cylinders: helical waves. Helical wave theory indicates that as the wave spirals around the cylinder, energy leaks into the water and may be observed at the receiver. The period of these returns is another indicator of the size of the cylinder. We describe our efforts to detect this comparatively weak component of each return, and to utilize it to yield another independent indicator of length and radius.

We will present initial evaluations of these systems which were performed using finite element modeling data of cylinders in free field for a scenario in which a monostatic sonar moves along a linear path. Finally, we will present results applied to over 40 sequences of returns from a rail system mounted in a large pool. In each sequence, a single solid, proud cylinder is insonified, and our system reports an estimate of cylinder length and radius. While histograms of these estimates cluster roughly around the true values, multiple independent assessments of size can be fused to provide even more accurate estimates.

[Work supported by the Office of Naval Research]

Some Exact Results for a Time and Space Dependent Noise Model

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One of the fundamental models of noise is shot noise, where it is modeled as the sum of impulses arriving at random times. The generalization of the standard shot noise model is where the noise is the sum of elementary signals and where the elementary signals are given some statistical properties, the most important being random phases. In the derivation of standard results, such as the Rayleigh distribution, one generally assumes stationarity. However, in many situations the noise is not stationary, a prime example being reverberation noise induced by a sonar pulse, where the elementary signals are the returns from scatterers. We have developed a generalization of the standard model where the elementary signals are functions of space and time and where propagation effects are taken into account. This produces non-stationary noise.

We have calculated the probability distribution for intensity as a function of position and time as the pulses evolves. A number of cases are done analytically, and for some other cases we obtained the probability distribution by simulation. We show that the approach to Gaussian is very sensitive to the position and time of observations. Also, we have calculated the ordinary and central moments explicitly, and obtained expressions for the scintillation index. The cases where the elementary signals are real and complex are considered and the relationship between them derived.

[Work supported by the Office of Naval Research.]

Generation of Correlated Non-Rayleigh Distributed Clutter Samples

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In creating a realistic simulation of acoustic clutter from an active sonar system much attention has been given to the non-Rayleigh distributions of the amplitudes of the clutter samples. Most simulators use independent random draws from these distributions in clutter simulations. However, real clutter exhibits correlations in time and space. The temporal persistence of clutter causes false tracks across multiple pings and is important to include in simulations of tracker performance. Clutter objects (or multipath time spread) larger than a resolution cell produce clutter that is correlated in space. We have developed and investigated several techniques to incorporate correlations of clutter samples while retaining the appropriate non-Rayleigh distribution. One approximate method employs correlated Rayleigh samples generated either by a wavenumber method or by an auto-regressive model (ARM) and applies a non-linear rescaling to achieve a non-Rayleigh correlated outp ut. A second method uses moment matching to obtain correlated K-distributed values from an ARM. This method is also approximate, but the errors are much smaller than the first approach. Finally, for an ARM we derive an exact general method that applies to any distribution. This method deconvolves distributions using the ratio of the characteristic functions. Although it is theoretically exact, care must be taken in numeric implementation, as the deconvolution can involve division by near zero. Examples of simulation results will be given.

Examination of Algorithms for Bearing Estimation Using Time Delay for a HF Acoustic Intercept Processing System

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The passive detection of short acoustic transmissions from underwater targets is a significant last line of defence in ship self-protection. A high-frequency (HF) acoustic intercept processing system was built for determining the bearing and other characteristics of the received acoustic signal. A series of trials at DRDC Atlantic's Acoustic Calibration Barge was carried out to validate the system performance. These trials included installing a square 4-element array of hydrophones inside a ship's sonar dome to check angular estimation accuracy. The original system produced very large errors in bearing estimation due to internal reflections within the dome. In order to solve the problem, this work takes a broader look at bearing estimation using Time Delay Estimation (TDE) for CW signals. After investigating several methods, a new Start Point Detection algorithm was developed for this application. This algorithm finds the time of arrival based on the energy of signal exceeding a predefined threshold and then applies a least square solution (for more than two received elements) to obtain the bearing. The threshold is established based on background noise characteristics. Error-checking must be performed to remove contaminated arrivals. To test the algorithms, a set of HF transmissions (10, 20, 30, and 40 kHz) received at the 4-element array inside a ship's sonar dome was collected. The algorithm was applied to these data with good results, however the performance of this algorithm was found to be highly dependent on signal to noise ratio at the start of the signal.

Complex Demodulation of Propeller Noise

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Propeller cavitation is the dominant source of noise from ships and is audibly rhythmic, yet broadband. Physically, as the propeller blades rotate, they encounter non-uniformities in the wake in-flow and hydrostatic pressure that modulates the formation of cavitation bubbles at the shaft rate. This consequently produces a periodic-like modulation of the radiated noise from the cavity collapses. Conventional wisdom is that propeller noise can be modeled as a real-valued, positive modulator multiplying a broadband noise carrier signal. This model forms the basis of standard DEMON processing. However, cavitation phenomena is highly non-linear with complex dynamics suggesting that DEMON signals may possess other properties which the classical model does not capture.

We now ask whether some form of complex demodulation of propeller noise signals may be possible using its analytical signal. Recently there has been much interest in the impropriety of complex signals and their processing [1]. By definition an improper complex signal has preferred phase orientations, i.e. the real and imaginary are correlated and/or have a variance imbalance, whereas a proper or circular signal has a phase that is uniformly distributed between 0 and 2π at any instant in time. Schreier et al. showed that conventional Hermitian statistics by themselves are not sufficient when the signal is improper and requires the measurement of the complementary statistics also [2].

Motivated by these results, in this paper we first establish the necessary properties in a real-valued random process for impropriety to occur in its analytical signal, namely the presence of modulation components at double frequencies and rapid rates of change in its real-valued second-order statistics. Using Hermitian and complementary modulation spectrum analysis, we then show the presence of impropriety in actual ship propeller noise and discuss methods for exploiting impropriety in DEMON processing. This is new information about the modulation process not previously available from conventional real-valued or Hermitian processing.

[1] P.J. Schreier and L.L. Scharf, Statistical signal processing of complex-valued data, Cambridge University Press, 2010.

[2] P.J. Schreier et al., "Stochastic time-frequency analysis using the analytical signal: Why the complementary distribution matters," IEEE Trans. Sig. Proc., vol. 51, no. 12, December 2003.

[This work was supported by the Office of Naval Research.]

Passive Acoustic Tracking of Baleen Whales with Advanced Array Processing

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Passive acoustic techniques have been applied extensively to marine mammal monitoring, localization and tracking. A normal-mode, back-propagation technique was used to localize sei whales during the 2006 Shallow Water Experiment off New Jersey from a single mooring site using an L-shaped hydrophone array. To test the technique further and monitor North Atlantic right whales, field work using hydrophone arrays and free floating buoys was conducted in Cape Cod Bay in the spring of 2011. Three vertical hydrophone arrays, and one horizontal array mounted on the seafloor, were deployed for 25 days and recorded a large amount of humpback, fin, sei, and right whales. Real-time acoustic tracking buoys were also deployed on two one-day cruises for several hours to ground truth the long-range whale localizations derived from the array network. An introduction to our passive acoustic technique and results from the localizations will be presented.

Attendees

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Wednesday October 12, 2011		**Thursday October 13, 2011**		**Friday October 14, 2011**	
		8:15–9:55	Session B Autonom. I Laurel	8:15–9:30	Session H Autonom. III Laurel
		9:55–10:20	Break Laurel	9:30–9:55	Break Laurel
		10:20–12:00	Session C UW ACOMMS Laurel	9:55–12:00	Session I Active Laurel
		12:00–1:00	ASA Lunch Whisp. Pines	12:00–1:00	Lunch Whisp. Pines
		1:00–1:50	Session D Env. Sens. Laurel	1:00–1:50	Session J Modeling Laurel
		1:50–3:05	Session E Autonom. II Laurel	1:50–3:05	Session K Passive Laurel
		3:05–3:30	Break Laurel		
		3:30–5:10	Session F Array Proc. Laurel		
5:00–6:00	Welcome Reception Whisp. Pines	5:10–5:35	Session G MFP Laurel		
6:00–8:00	OES Dinner Whisp. Pines	6:00–8:00	Raytheon Dinner Whisp. Pines		
8:00–9:00	Session A Plenary Laurel	8:00–?	SOB Session Laurel		