A Book of Abstracts for the

2003 Underwater Acoustic Signal Processing Workshop

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UASP 2003

Welcome to the 2003 IEEE workshop on Underwater Acoustic Signal Processing. This year we are pleased to have the participation of Dr. Ellen Livingston of the Office of Naval Research who has organized several special sessions on *Quantifying and Accounting for Uncertainty in Underwater Acoustic Signal Processing*. The special sessions are scattered throughout the workshop to encourage continued interaction between attendees.

The organizing committee would like to thank and acknowledge the sponsorship of Dr. John Tague at the Office of Naval Research and thanks Martin Cohen for his efforts in arranging for Raytheon Systems Company to sponsor our Wednesday evening dinner. We are also honored to present this year's UASP Award to two people that have a long history of contribution not only to the underwater acoustic signal processing community, but also to this very workshop, Prof. Donald Tufts and Dr. Henry Cox.

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2003 UASP Award Presented to Dr. Henry Cox

in recognition of the excellence of his work in the following three areas: (1) published results in underwater acoustics and signal processing, (2) important contributions to the design of sonar and ASW systems, and (3) a distinguished career as a naval officer, especially in influential R&D positions.

Dr. Henry Cox began publishing important and useful results and insights about adaptive beamforming in the 1960's and continues to do so in the 2000's. Earlier he had presented thought-provoking work on nonlinear Kalman filtering at the 1965 National Electronics Conference. Much of his published work has interdisciplinary aspects, often spanning underwater acoustics and signal processing. An example is his 1994 work on waveform design in which the "Cox combs" were proposed.

Some of us have seen portions of his unpublished work on the design of sonar and ASW systems. This work demonstrates Harry's unusual ability to combine principles of engineering, physics, and mathematics with knowledge of operational use and needs.

During his distinguished career as a naval officer, he held a number of important R&D positions, retiring as Captain USN in 1981. He was the Project Manager for the Undersea Surveillance Project, Division Director at DARPA, and Officer in Charge of the New London Laboratory of the Naval Underwater Systems Center. Currently he is Chief Technology Officer, Lockheed Martin Orincon Division.

In recognition of the excellence of his work in the following three areas: (1) published results in underwater acoustics and signal processing, (2) important contributions to the design of sonar and ASW systems, and (3) a distinguished career as a naval officer, especially in influential R&D positions, we the underwater acoustic signal processing community are honored to present the UASP Award to Dr. Henry Cox.

Contributed by Donald Tufts

2003 UASP Award Presented to Prof. Donald Tufts

for contributions to sonar, radar, speech, and communication, through his 40 years of research, service, and teaching in signal processing.

Prof. Donald Tufts has committed more than 40 years of his distinguished career to teaching and research in signal processing, where he has been one of its most imaginative innovators and vigorous advocates.

He has served the Signal Processing Society as a member of its Board of Governors, as a long-term President of the Providence Section of the IEEE, as Chairman of the SAM Technical Committee, and as Founder and Organizer of the biennial IEEE Workshop on Underwater Acoustic Signal Processing. He has been a life-long contributor to IEEE Transactions, Conferences, and Workshops. His course development at the University of Rhode Island, in signal processing and computer design, has been innovative, and it has bridged the gap between the mathematics of signal processing and the practical hardware implementation of algorithms. His role in the hiring of Leland Jackson, Steve Kay, Ramdas Kumaresan, Rick Vaccaro, Faye Boudreaux-Bartels, and Jim Cooley has made URI one of the world's premier institutions for teaching and research in signal processing.

In his PhD dissertation, Don Tufts cracked the Nyquist problem of jointly optimizing transmitters and receivers for transmitting PAM data over ISI channels. This paper has been reprinted as an IEEE reprint classic. For many years thereafter he worked on a variety of communication problems and served as PhD advisor for many luminaries in our field.

His earliest contributions to the digital signal processing literature were a series of collaborative papers on the design of digital filters, and the demodulation of phase- and frequency-modulated signals. But there is no doubt that his most revolutionary work came in 1982 with the publication of the classic Tufts and Kumaresan papers:

1. D.W. Tufts and R. Kumaresan, "Estimation of Frequencies of Multiple Sinusoids: Making Linear Prediction Perform like Maximum Likelihood," Proceedings of the IEEE, September 1982.
2. R. Kumaresan and D.W. Tufts, "Estimating the Parameters of Exponentially Damped Sinusoids and Pole-Zero Modelling in Noise," IEEE Transactions on Acoustics, Speech, and Signal Processing, December 1982.

These papers revolutionized the practice of linear prediction on noisy data and introduced the signal processing community to the power of matrix approximation by singular value decomposition. These papers, two of the most heavily referenced papers ever published in IEEE journals, produced a flurry of activity in improved spectrum analysis and direction-of arrival estimation. They stand as the original contributions to parametric spectrum analysis and direction finding for time series analysis and array processing. Moreover, they have influenced subsequent generations of students and researchers, who now think naturally about signal processing in low-dimensional signal subspaces. You have to read the SP Transactions before 1982 and after 1982 to appreciate how profoundly these papers have changed the modelling and processing of radar, sonar, and communication signals.

With this as preamble, we the friends and colleagues of Prof. Donald Tufts, proudly present him the UASP Award for contributions to sonar, radar, speech, and communication, through his 40 years of research, service, and teaching in signal processing.

Contributed by Louis Scharf and Henry Cox

Schedule at a glance

Wednesday October 8, 2003		Thursday October 9, 2003		Friday October 10, 2003	
		8:00-9:45	Session B Laurel	8:00-9:45	Session F Laurel
		9:45-10:15	Break Laurel	9:45-10:15	Break Laurel
		10:15-12:00	Session C Laurel	10:15-12:00	Session G Laurel
		12:00-1:00	Lunch Whisp. Pines	12:00-1:00	Lunch Whisp. Pines
		1:00-2:45	Session D Laurel	1:00-2:45	Session H Laurel
		2:45-3:15	Break Laurel		
		3:15-5:00	Session E Laurel		
5:00-6:00	Welcome Reception				
6:00-8:00	Raytheon Dinner Whisp. Pines	6:00-8:00	Dinner Whisp. Pines		
8:00-9:30	Session A Laurel	8:00-?	SOB Session Laurel		

Sessions: Titles and presenters

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

Special Session: Uncertainty and its effect on signal processing I

A–1 *Introduction to special sessions on* Quantifying and accounting for uncertainty in underwater acoustic signal processing,
Ellen Livingston, Office of Naval Research

A–2 *A Bayesian approach to quantifying uncertainty in geoacoustic inversion*,
Stan Dosso, University of Victoria

A–3 *Coherent acoustic communications through the imperfect ocean: adaptive least squares, time reversal, and connections to adaptive array processing*,
James Preisig, Woods Hole Oceanographic Institute

Session B: Thursday Morning, 8:00–9:45

Special Session: Uncertainty and its effect on signal processing II

B–1 *Bottomed acoustic array gain variability in the South China Sea*,
Marshall Orr, Naval Research Laboratory

B–2 *Sub-mesoscale oceanography: The effect of internal waves on beamforming*,
Steven Finette, Naval Research Laboratory

B–3 *Quantification of matched-field processor gain degradation in littoral oceans that have uncertain environmental variability*,
Peter C. Mignerey, Naval Research Laboratory

B–4 *Effect of environmental prediction uncertainty on target detection and tracking*,
Lawrence D. Stone, Metron Inc.

Session C: Thursday Morning, 10:15–12:00

Passive sonar signal processing

C–1 *High-frequency volumetric array designs and their passive detection performance in anisotropic noise*,
Pat Ferat, John Hopkins University, Applied Physics Laboratory

C–2 *Broadband noise source multi-path removal and localization using mutual information for multi-array networks*,
Josh G. Erling, Applied Research Laboratory, The Pennsylvania State University

C–3 *A surfaced/submerged discriminator based on mode filtering with sparse vertical apertures*,
Vincent E. Premus and John Pietrzyk, MIT Lincoln Laboratory

C–4 *Passive acoustic detection, data association, and hyperbolic tracking of marine mammals in the Tongue of the Ocean (TOTO)*,
David Moretti, Naval Undersea Warfare Center Division Newport

Session D: Thursday Afternoon, 1:00–2:45

Special Session: Effects of uncertainty on acoustics and the sonar equation

D–1 *Mesoscale eddies as a predictor of shallow water sonar performance*,
Harry A. DeFerrari, University of Miami

D–2 *Robust techniques for estimating environmental sensitivity in shallow water propagation*,
Kevin D. Heaney and Harry Cox, Orincon Corporation

D–3 *Evaluating the correlation of signal and noise amplitude fluctuations in littoral acoustic transmissions*,
Charles Gedney, OASIS Inc.

D–4 *Uncertainty, variability, and chaos in multistatic ASW performance prediction*,
Brian La Cour, The University of Texas at Austin

Session E: Thursday Afternoon, 3:15-5:00

General sonar session

E–1 *Using bispectral signatures for material discrimination*,
Paul A. Nyffenegger, The University of Texas at Austin

E–2 *Design of mode filters using WKB-like approximations*,
Kathleen E. Wage, George Mason University

E–3 *Performance comparisons between passive-phase conjugation and decision-feedback equalizer for underwater acoustic communications*,
T.C. Yang, Naval Research Laboratory

E–4 *Testing of DORT and GS algorithms using sea data*,
Charles F. Gaumond and David M. Fromm, Naval Research Laboratory

Session F: Friday Morning, 8:00–9:45

Special Session: Accounting for Uncertainty in Sonar Performance Modeling

F–1 *Predictive probability of detection under environmental uncertainty*,
Philip Abbot, OASIS, Inc.

F–2 *Analytic prediction of adaptive sonar detection performance in an uncertain ocean*,
Jeffrey Krolik, Duke University

F–3 *Incorporating environmental uncertainty into Bayesian sonar detection performance prediction*,
Loren W. Nolte, Duke University

F–4 *Signal processing in random/uncertain media*,
Leon H. Sibul, Applied Research Laboratory, Pennsylvania State University

Session G: Friday Morning, 10:15–12:00

Adaptive array processing

G–1 *Blind source separation, blind beamforming, ULV decomposition, subspace tracking, direction-of-arrival estimation*,
Christian M. Coviello, Applied Research Laboratory, Pennsylvania State University

G–2 *Adaptive interference cancellation using bearing associated subspace components*,
Brian F. Harrison, Naval Undersea Warfare Center Division Newport

G–3 *Methodologies for extracting the spatially incoherent components of the scattering response from buried symmetric targets*,
Ivars Kirsteins, Naval Undersea Warfare Center Division Newport

G–4 *Signal-dependent reduced-rank mulitbeam array processing*,
Michael D. Zoltowski, Purdue University

Session H: Friday Afternoon, 1:00-2:45

Active sonar signal processing

H–1 *Dynamical analysis of reverberation*,
Neil Skelland, Qinetiq

H–2 *Active sonar track detection algorithms*,
Christian G. Hempel, Naval Undersea Warfare Center Division Newport

H–3 *A probabilistic multi-hypothesis tracker for active sonar (PMHTAS)*,
Sheri L. Doran, Naval Undersea Warfare Center Division Newport

H–4 *Ping-to-ping echo-similarity studied via accurate estimates of multipath delays*,
Ashwin Sarma, Naval Undersea Warfare Center Division Newport

Abstract Listings

Introduction to special sessions on *Quantifying and accounting for uncertainty in underwater acoustic signal processing*

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The spatial and temporal variability of the ocean environment (ocean bottom and subbottom, water volume, surface, and interfaces) often cannot be sampled and modeled at scales adequate to represent accurately the underwater acoustic propagation environment. The resulting uncertainty in either the environmental or the acoustic fields must be accounted for in performance prediction models. Quantifying the effects of ocean uncertainty on signal processing algorithms allows for the design of more robust and specialized algorithms and permits the development of methods for estimating the impact of this uncertainty on acoustic applications. The papers in these special sessions address these issues with a focus on the classical problems of detection and tracking using new probabilistic formulations. The authors examine both single sensor and array processing approaches. There are innovative new insights into the role of environmental uncertainty in the use of the active and passive sonar equations and sonar performance prediction.

A Bayesian approach to quantifying uncertainty in geoacoustic inversion

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Estimating seabed geoacoustic parameters from ocean acoustic data provides a convenient alternative to direct measurements with a parameter sensitivity relevant to sonar applications. However, geoacoustic inversion can be strongly nonlinear and, hence, quantifying uncertainties for the recovered parameters is a crucial but challenging problem. This paper describes a Bayesian approach to geoacoustic inversion based on estimating the posterior probability density (PPD) which combines prior information about the seabed with the information from a measured data set. Markov-chain Monte Carlo methods are applied to extract PPD moments including optimal parameter estimates, marginal probability distributions, credibility intervals, and inter-parameter correlations. The Bayesian approach is general, and will be illustrated with a number of examples including matched-field inversion, inversion of reflection-loss data, inversion of reverberation data, and ambient noise inversion. The impact of geoacoustic uncertainties on source localization will also be discussed.

Coherent acoustic communications through the imperfect ocean: adaptive least squares, time reversal, and connections to adaptive array processing

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Adaptive coherent equalizers can be divided into two classes, the first being direct adaptation equalizers and the second being channel estimate based equalizers. Direct adaptation equalizers are those for which the filter weights of the equalizer are directly adjusted based upon observations of the received signal. Channel estimate based equalizers are those for which observations of the received signal are used to estimate the channel impulse response and possibly the ambient noise field and these estimates are used to calculate the equalizer filter weights. Channel estimate based decision feedback equalizers (CE-DFE), linear MMSE equalizers (L-MMSE), and Passive Time-Reversal equalizers (P-TR) are all examples of coherent channel estimate based equalizers. This work focuses on analytically characterizing the performance of these equalizers in realistic ocean environments.

The performance of coherent equalizers for demodulating received signals can be characterized in terms of the soft decision error (σ_{s}^2), that is, the mean squared error between the transmitted data and the demodulated data before quantization by a decision device. This error can be expressed as the sum of two components. The first is the mean squared error that would be achieved by the equalizer if it had perfect knowledge of the channel impulse response and the second order statistics of the received ambient noise. This error is referred to at the *minimal achievable error* and is denoted by σ_{o}^2. The second component is the additional error that is incurred due to errors in the equalizer's knowledge of either the channel impulse response or the statistics of the received ambient noise. This error is referred to as the *excess error* and is denoted by σ_{ϵ}^2. Thus:

$$\sigma_{\mathrm{s}}^2 = \sigma_{\mathrm{o}}^2 + \sigma_{\epsilon}^2.$$

For channel estimate based equalizers, the *minimal achievable error* is a function of the state of the channel impulse response, the ambient noise field, and the configuration of the equalizer. However, the *excess error* is a function of these factors as well as the dynamics of the channel fluctuations as well as the capabilities of the algorithm used to estimate the channel impulse response.

The expressions for characterizing equalizer performance are formulated in terms of the channel impulse response estimates, $\underline{\hat{f}}$ where the underline denotes a vector and the $\hat{}$ denotes an estimate. The true channel impulse is give by the sum of $\underline{\hat{f}}$ and an estimation error $\underline{\epsilon}$. The analytic predictions of equalizer performance are compared with observed performance using data from several field experiments.

For the three type of equalizers considered, (CE-DFE, L-MMSE, and P-TR) the expressions for σ_{o}^2 take the form of the results from classical estimation theory for estimation error achieved by MMSE and matched filter estimators. However, in this case these expressions can be interpreted to give insights into the characteristics of "good" and "bad" channels. Foremost among these insights is the performance degradation resulting from non-minimum phase channels.

The performance degradation resulting from channel uncertainty is quantified by σ_{ϵ}^2. For the special case that the channel estimate, $\underline{\hat{f}}$, is uncorrelated with the channel estimate error, $\underline{\epsilon}$, then the sensitivity of equalizer to channel estimate errors as quantified by σ_{ϵ}^2 is shown to be proportional to the 2-norm of the calculated feedforward filter weight vector of the equalizer. Note that this condition holds when the channel estimate is a minimum mean squared error estimate of the channel. This result is analogous to the standard result characterizing the sensitivity of adaptive array processors to mismatch. This result allows us to readily evaluate the relative sensitivity of all three types of equalizers to environmental uncertainties.

Bottomed acoustic array gain variability in the South China Sea

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The stratified sound speed field at the shelf break of the South China Sea is constantly perturbed by the tide and the passage of the internal tide, linear and nonlinear internal waves and associated fine structure. An 18-day acoustic propagation experiment was performed at the shelf break in May 2001 as part of the ONR supported AsiaEx experiment. A 32 element 465m bottomed horizontal array received 300 and 500 Hz center frequency FM acoustic signals from sources moored at a range of 18,9 km. The temporal and spatial variability of signal coherence, the array gain variability and residual signal gain variability has been extracted. Temporal and spatial variability of the signal coherence and array gain variability has a degree of correlation with temperature field variability measured near the source and receiver locations. These data as well as histograms of the residual array gain variability in time and space will be presented.

Sub-mesoscale oceanography: The effect of internal waves on beamforming

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Adaptive signal processors operating in dynamic ocean environments are designed to modify their behavior, responding to changes in the waveguide environment. A priori knowledge of oceanographic features that significantly alter acoustic propagation provides important information for adaptive acoustic signal processors. From the point of view of acoustic propagation, the relevant environmental information is contained in the waveguide sound speed distribution. In contrast to many deep ocean environments, this distribution is often a non-stationary function of space and time in littoral waters such as continental shelf-break regions. Through the results of computer simulation and modeling, we will discuss some physical effects that are associated with acoustic propagation through one of these features–internal gravity waves, and discuss their contribution to degradation in beamforming performance for frequencies less than 500 Hz. Solibores (a.k.a. undular bores or solitary wave packets) represent horizontally anisotropic variations in sound speed that can induce horizontal refraction of acoustic energy and acoustic coherence degradation, depending on the relative orientation of the horizontal array with respect to the wave packet direction of propagation. Conventional beamforming in such an environment can lead to significant beam wander, beam splitting and fading synchronized with the shape, position and speed of the solibore. These effects can be understood through an analysis of individual modal contributions comprising the acoustic field. The presence of space and time evolving internal gravity waves also induces time dependent signal gain degradation as well as changes in the waveguide invariant, indicating that matched field beamforming will be adversely affected by the presence of wave packets in the propagation path, unless they are taken into account by the processor.

[Work supported by ONR].

Quantification of matched-field processor gain degradation in littoral oceans that have uncertain environmental variability

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An acoustic field propagating through a littoral ocean is non-stationary because of variability induced by dynamic ocean properties that take place on the continental shelf. Non-stationary acoustic fields induce fluctuations in array gain and processor output regardless of the specific array configuration and signal-processing scheme adopted. The causes of ocean dynamics are several including forcing by the internal tide, the passage of internal solitons and mixing from processes such as shear instabilities.

The relative influence of various ocean processes on acoustic propagation and processor gain has been investigated in a continuing series of experiments carried out in littoral waters. The SWARM-95, SWAT-00 and ASIAEX-01 experiments approached these issues by simultaneously acquiring acoustic data with comprehensive oceanographic measurements taken along the acoustic propagation path. Findings from these data sets will be presented that illustrate both the overall dynamic nature of the environment and the relationship between specific oceanographic processes and array gain degradation quantitatively measured in a matched-field sense.

Results to be presented include the observation of a hydraulic jump flowing over a hill in the SWARM-95 environment and a simulation of array gain degradation induced by the jump. SWAT-00 results include a movie showing the chaotic evolution over three days of observed sound-speed fields with corresponding simulated acoustic fields at 1000 Hz. Further simulations show the uncertain acoustic fields inducing as much as 10-20 dB of degradation in the array gain of a matched-field processor operating on a vertical line array. In the ASIAEX-01 experiment, internal solitons entering an 18 km acoustic propagation path were found to be the direct cause of an order-of-magnitude drop (15 min to 2 min) in the observed matched-field auto-correlation time for a 300 Hz signal received by a vertical line array.

The overall conclusion from these observations is that in littoral waters, variability in the sound-speed field induces uncertainty in the acoustic field that can be the cause of significant fluctuations in the gain of linear matched-field processors.

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

Effect of environmental prediction uncertainty on target detection and tracking

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Chris Eggen and Andy Ganse
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As part of the Uncertainty Directed Research Initiative of the Office of Naval Research, the authors have been exploring the process of characterizing and quantifying the uncertainty in acoustic environmental predictions. In addition we are developing methods for reflecting and displaying the effects of that uncertainty on tactical systems that rely on environmental inputs. Examples of such systems are those that predict sensor performance, recommend search plans, or track and detect targets. In this paper, we discuss how we characterize uncertainty in the environmental predictions for the components of the sonar equation for multistatic active detection, and how this characterization is quantified and incorporated into a Bayesian track-before-detect system called, the Likelihood Ratio Tracker (LRT). We present an example showing the application of LRT to multistatic active detection and tracking that accounts for the uncertainty in the acoustic predictions. For this example, the explicit inclusion of environmental uncertainty in the LRT appears to make it more robust to errors in predicting signal excess and estimating detection probabilities. For multistatic active detection, the signal excess (in dB) is given by Urick [1] as

$$\overline{SE} = SL - TL_1 - TL_2 + TS - RL - DT \tag{1}$$

Where SL is source level, TL_1 and TL_2 are transmission loss to the target and from the target to the receiver, TS is target strength, RL is reverberation, and DT is detection threshold. We assume that we are in a reverberation limited case. $\overline{SE}$ is the mean signal excess predicted for a single sensor in the multistatic active system. Urick observes that about this mean there are short term fluctuations that that are approximately Gaussian in dB. Typically, the fluctuations have mean 0 and standard deviation of $\sigma = 8$ or 9 dB. Let ξ be a normal Gaussian random variable with mean 0 and standard deviation σ. In Urick's model, detection occurs when $SE + \xi > 0$. The variation represented by ξ is predictable only in a statistical sense and is already accounted for in many tactical decision aids used by the Navy. The uncertainty that we are primarily concerned with comes from the possibility that we have misestimated the mean of any of the components of signal excess equation (1). This produces an uncertainty in $\overline{SE}$, the mean signal excess. This mis-estimation can be caused by a using a poor estimate of the sound speed profile, bottom type, or any environmental input required for computing $\overline{SE}$. The resulting uncertainty in $\overline{SE}$ is represented by a probability distribution on $\overline{SE}$. To account for this uncertainty, we extend the state space of LRT to include signal excess prediction error as a component of tracker state. The initial distribution on prediction error is computed from the uncertainty distributions on each of the components in (1). This becomes the prior used by LRT. As sensor responses are obtained, LRT produces a joint estimate of target kinematic state and $\overline{SE}$ prediction error. In examples using simulated data, LRT produced good estimates of target kinematic state and signal excess prediction error in the presence of large numbers of false detections.

[1] R. J. Urick, *Principles of Underwater Sound*, 3^{ed} Ed., McGraw-Hill, 1983.

High-frequency volumetric array designs and their passive detection performance in anisotropic noise

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One of the benefits of operating passive sonars at high frequencies (> 5 kHz) is the absence of significant shipping clutter. However, at much higher frequencies (> 20 kHz) water absorption causes severe loss of received target energy that imposes a “range curtain” on the sonar performance. A study was conducted to determine a suitable frequency band and to design volumetric arrays that could exploit the noise notch to enhance passive detection of submerged targets. We initially compare the performance of the arrays in anisotropic noise and select an array that would also serve as the sensor of our measurement system. The main purpose of this talk is to evaluate the possible use of this array to infer the performance limits of high-frequency passive sonar systems. To understand its performance limits, it is important to understand the dominant mechanisms that may cause the noise notch to be filled. Under the most favorable environmental and measurement conditions the noise floor inside the noise notch is to be dominated by thermal energy. Bathymetric variability about the array is expected to spread some high-elevation energy into the notch at downslope directions. Volume scatterers in the water column may spread the forward-propagated energy from the sea surface into the notch. Internal waves and solitons are additional possible mechanisms that may fill-in the notch. A high-frequency model that accounts for noise anisotropy was developed to account for these notch-filling mechanisms with the purpose of investigating their relative effect in selected environmental conditions and to estimate their degrading effect on the array’s performance.

Broadband noise source multi-path removal and localization using mutual information for multi-array networks

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Passive detection, localization and classification of quiet, diesel-electric submarines in congested, noisy, and environmentally hostile (multi-path heavy) littoral regions will require new signal processing architectures. The establishment of high-capacity communications links between various sensor systems on or across navy platforms will allow multi-array networks that provide the backbone for these architectures. One specific problem is that broadband noise source signals propagate through multiple paths (horizontal and vertical) before arriving at the receive arrays. This presents a very difficult processing challenge for underwater systems attempting to conduct source direction of arrival (DOA) estimation. Second order techniques based on covariance estimation and eigenvalue decomposition (Principal Component Analysis, MUSIC, etc.) treat the signals arriving through horizontal multipath as separate, uncorrelated, sources. This results in a false picture of what is really going on in the environment. In order to produce a clear picture, the statistical redundancies in the data that are produced by the multipath must be removed. Independent component analysis (ICA) is a new multivariate statistical signal processing technique that handles multiple sources which are statistically independent, not just uncorrelated. Using the principles of ICA, a new multi-array approach to passive localization of broadband noise sources is presented. By utilizing a multi-array network DOA processor that is based on ICA, passive localization of statistically independent sources can be accomplished without the common problems of order estimation encountered in algorithms like MUSIC. The procedure can distinguish between independent noise sources and their associated multi-path interference. Multi-path signals that were generated from a single source can be modeled as replicas of the same source signal that has propagated through different channels. In this processing approach, multi-path removal is accomplished with a Blind Deconvolution algorithm that minimizes the amount of redundancy in the measured data. After the removal step, the data from multiple arrays are compared using a mutual information measure to localize the broadband noise sources. Results from several simulated underwater scenarios are presented to show the effectiveness of this processing procedure. In the simulations, the sensors are functioning in a passive mode and the arrays and the sources are stationary.

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A surfaced/submerged discriminator based on mode filtering with sparse vertical apertures

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Physics-based signal processing constitutes a passive sonar processing paradigm for acoustic source parameter estimation based on environmental response to source depth. In this work, a physics-based approach to surfaced/submerged discrimination is introduced which attempts to exploit qualitative differences in the temporal pattern of mode spectrum excitation. The method is based on two key premises: 1) Surfaced and submerged sources are well separated in mode space, and 2) Mode space representations are relatively robust to imperfect environmental and array calibration. The approach is designed to avoid fine-scale, uncertain received field structure that is difficult to predict and track. Instead, the goal is to develop a robust form of source localization that is limited to binary depth classification and constrained to rely only on predictable, coarse scale information embedded in the received acoustic field.

The practical limitations of mode filtering on vertical line arrays (VLA) that are sparsely populated and have limited vertical aperture necessitate the use of a simple test statistic. In this work, a test statistic is formed by taking the ratio of higher-order to lower-order mode correlation sums. Issues related to the implementation of a conventional mode filtering algorithm on a sparse, fractionally-spanning VLA will be discussed. It is well known that fully resolving each propagating mode is theoretically possible, but requires a densely populated vertical array that fully spans the water column and penetrates the sediment. It will be shown that mode subspace resolution sufficient to perform binary classification using the proposed discriminant is possible with far less vertical aperture. Mode space covariance animations for closing/opening sources of each class are used to motivate the proposed approach. The performance of the test statistic is simulated and its sensitivity to a number of sonar system parameters such as frequency, array length, and input signal-to-noise ratio (SNR) is examined. Simulation results will also be presented which suggest that the technique is robust to moderate levels of environmental (bottom compressional speed, thermocline slope) and array (unmodeled cant) calibration error. Lastly, experimental results will be shown demonstrating the concept using data from SwellEx-96.

[Sponsored by the U. S. Navy, under Air Force Contract F19628-00-C-0002. Opinions, interpretations, conclusions, and recommendations are those of the author and are not necessarily endorsed by the United States Air Force.]

Passive acoustic detection, data association, and hyperbolic tracking of marine mammals in the Tongue of the Ocean (TOTO)

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The Naval Undersea Warfare Center (NUWC) in Newport RI has developed marine mammal detection, data association, and tracking algorithms through the ONR (Dr. R. Gisiner) sponsored Marine Mammal Tracking on Navy Ranges (M3R) program. M3R has leveraged the infrastructure of the Atlantic Test and Evaluation Center (AUTEC). The AUTEC acoustic range consists of widely-spaced, bottom-mounted, broadband hydrophones. A database of marine mammal call data over a one year period has been established. Passive detection algorithms have been developed and implemented on the AUTEC signal processor. Data association algorithms necessary as a precursor to acoustic tracking algorithms have been developed. The associated marine mammal call detection reports are used in conjunction with NUWC hyperbolic tracking algorithms to produce 3 dimensional animal tracks. These tracks have been demonstrated on-site in real time. The algorithms and the results of these tests will be presented.

Mesoscale eddies as a predictor of shallow water sonar performance

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The influence of the mesoscale on the ocean acoustic environment at the site of propagation experiments in the Florida Straits offers a data based demonstration of how the mesoscale determines sonar performance days in advance. Acoustic propagation measurements in 150 m depth on the Florida escarpment observe the effects of the passage of a cyclonic eddy. As the stream core of the Florida Current meanders, the eddy is formed and propagates along the shelf edge. The sequence of events, over roughly a fortnight, is as follows: ahead of the eddy, warm surface water and cold bottom water are swept onto the terrace forming a steep thermocline and corresponding strong downward refracting $C(z)$. The gradient produce intense, focused RBR arrivals and the thermocline becomes a duct for internal waves to propagate shoreward. At first, the internal wave energy is minimal and propagation is stable and coherent. As the internal tides attempt to propagate on shelf, the sound speed field and the acoustic signals become increasingly variable. The variability reaches a crescendo as the 200 m long internal tide is blocked from propagating on to the narrower shelf and begins to break and overturn increasing small-scale variability. As the eddy passes, nearly iso-thermal conditions are restored along with quiescent internal wave fields and reduced signal variability. Here, the effects are quantized with data from fixed-system acoustic and oceanographic measurements demonstrating that mesoscale determines acoustic propagation conditions days in advance.

Robust techniques for estimating environmental sensitivity in shallow water propagation

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Environmental variability can be a dominant influence in the ability to predict acoustic propagation and therefore sonar performance in the shallow water environment. Capturing this uncertainty has been the focus of recent project sponsored by ONR. The fundamental factor in linking the estimated uncertainty (either variability or uncertainty) to the resultant acoustic field computation is the sensitivity of acoustic propagation to the particular environmental parameter. An approach, based upon the ideas of Weston, is presented to rapidly estimate the acoustic sensitivity to particular features of the environment. Using a combination of analytic ray acoustics, and computational normal mode amplitudes (and scattering matrices) the sensitivity of the acoustic field to particular environmental parameters is investigated. The technique is applied to various cases, including: a downward refracting, hard sand bottom case where the details of the sound speed structure are unimportant; a downward refracting, soft silt sediment case where the sound speed structure is important to propagation; and an upward refracting (northern latitudes) case where sediment properties are unimportant.

Evaluating the correlation of signal and noise amplitude fluctuations in littoral acoustic transmissions

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Acoustic signal transmissions in littoral regions can have as much as 25 dB of variability due to spatial and temporal effects in the local environment. Ambient noise levels in littoral regions can also have a high degree of variability that may also be directly related to the local environment. Since the amplitudes of both the signal and noise have a direct impact upon the performance of tactical sonar systems, we have studied these levels in an effort to develop methods of improving system performance. The goal of the work has been to relate the fluctuations in signal and noise amplitudes to the relevant oceanographic features such as internal solitary waves and/or tides, shelf-break fronts, internal surface ducting, etc. In particular, acoustic signal and noise levels processed through a vertical line array during the summer shelfbreak PRIMER experiment will be presented. The signal and noise amplitude fluctuations will be examined at the beamformer output to determine the degree of correlation for various beams and integration times (including geotime). If a portion of the signal amplitude fluctuations are correlated to the noise amplitude fluctuations and the relevant oceanographic features that produce this correlation can be identified, it may be possible to predict some of the signal variation from the noise variation.

Uncertainty, variability, and chaos in multistatic ASW performance prediction

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As part of the Capturing Uncertainty Departmental Research Initiative sponsored by the Office of Naval Research, our institution (ARL:UT) has been working to characterize the effects of environmental uncertainty at the signal processing level for purposes of active sonar performance prediction. Ours is part of a larger team, headed by Applied Physics Laboratories of the University of Washington (APL/UW), which includes members from the Naval Research Laboratories (NRL-SSC and NRL-DC), Metron Corp., and Oregon State University (OSU). ARL:UT's role in the project focuses on aspects of uncertainty in signal processing, as determined from environmental modeling performed by APL/UW, NRL-SSC, and OSU. Results of our work are, in turn, transferred to Metron and NRL-DC to study uncertainty in tracking and visualization, respectively.

We consider the various terms in the sonar equation for signal excess (SE) as the primary object of study. For the bistatic problem, $\mathrm{SE} = \mathrm{SL} - \mathrm{TL}_1 + \mathrm{TS} - \mathrm{TL}_2 - \mathrm{RL}$, where SL is the source level, TL_1 and TL_2 are the transmission losses from source to target and target to receiver, respectively, TS is the bistatic target strength, and RL is the reverberation level representing normalization. The source level is assumed to be fixed, and bistatic target strength is modeled deterministically by a composite of primitives; it is in the transmission loss and reverberation level that we find environmental uncertainty. The types of uncertainty can be described as either stochastic noise, spatio-temporal variability, or systematic bias. (Systematic bias is a predictive error resulting primarily from errors in environmental inputs to the acoustic model. As it is nonstochastic in nature, we do not consider it here.)

Stochastic noise, due primarily to reverberation from diffuse clutter, is generally modeled by either a Rayleigh or K distribution. We have developed an alternative model of reverberation-induced noise based on extreme value theory which may be better suited to characterizing the peculiar power-law behavior of high clutter extreme statistics. Our approach uses the asymptotic result that, for sufficiently large thresholds, the tail of the reverberation distribution will tend to follow a generalized Pareto distribution, which is used to model normalized matched filter intensity.

Underlying this stochastic component is the slowly varying spatio-temporal variability of the transmission loss and reverberation level which is observed, for example, in ping-to-ping and beam-to-beam variations. The reverberation level is usually estimated in situ through the matched filter normalization, so it is in the transmission loss that the effects of this variability are found to be most important. We discuss the effects of internal waves and local variations in sediment properties on the statistics of transmission loss and compare these with empirical measures of environmental variability from active sonar data.

Finally, we consider the presence of chaos in the ray dynamics of shallow water propagation and its effects on detection and localization using a Hamiltonian formulation of the problem. Floquet analysis is used to study the effects of range periodic structures in the sound speed profile (SSP) due to internal waves, while bifurcation analysis is applied to a study of parametric sensitivities in the littoral SSP.

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Using bispectral signatures for material discrimination

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We present a method for material characterization using bispectral signatures acquired from an object actively probed with acoustic pulses, and test the proposed technique with an ultrasonic apparatus. Within the last decade many researchers have applied higher order moments, cumulants, and cumulant spectra for system identification and signal detection. These methods have been accepted into the passive ranging framework, but have had more limited application in active ranging primarily because the physical mechanisms responsible for the active bispectral signatures are not well understood. In particular, little is known about the relative contributions to the bispectrum originating in the physical properties of the target material itself rather than from target structural acoustics and the propagation media. In a pilot experiment, we determine bispectral signatures using a submerged ultrasonic apparatus designed to isolate effects due to target properties from those attributable to propagation path, source, or receiver.

The bispectrum of the acoustic output of a ranging, profiling, or imaging system modeled as a discrete-time causal linear system is $B_x(f_1, f_2) = |H(f_1)H(f_2)H(f_1 + f_2)| \exp[i(\phi(f_1) + \phi(f_2) - \phi(f_1 + f_2))]$ where $H(f)$ is the system's complex transfer function and ϕ is the phase. The spectrum and the normalized bispectrum are computed using the frame-averaging estimation method. The spectrum-normalized estimate of the bispectrum is $\hat{b}_x(f_{k_1}, f_{k_2}) = \frac{(\sqrt{N}/L)\hat{B}_x(f_{k_1}, f_{k_2})}{\sqrt{S(f_{k_1})S(f_{k_2})S(f_{k_1}+f_{k_2})}}$ where L is the frame length, N is the length of the entire time series, and S and $\hat{B}_x$ are the frame averaged spectral and bispectral estimates respectively. The bispectral estimate manipulated into the form $2|\hat{b}_x(f_{k_1}, f_{k_2})|^2$ is asymptotically distributed as independent, two degree-of-freedom, non-central chi-squared variates. The bispectral signature is then the cumulative density function transformed into chi-squared probability values and displayed as an image.

The experiment incorporates a separate transmitter and receiver, and several consistency and sanity checks. We transmit a broad-frequency LFM waveform centered at 1.5 MHz. The transmitter, though not ideal for the selected waveform, adds several harmonics that act to fill out the bispectral principal domain. The targets are solid cylinders of similar dimensions composed of aluminum, polyethylene, and limestone, and time series at multiple transmitter-target offsets are acquired. For each experiment configuration we perform 200 trials, yielding 200 frames of the target echoes. The spectra of the target echoes differ by less than 10 dB at any particular frequency and discriminating between the targets based on their spectra would be difficult. In comparison, the bispectral signatures show remarkable variation consistent over the various transmitter-target offsets.

One rational explanation for the different bispectral signatures is the inherently different material damping characteristics found in the various targets. For example, polyethylenes have time or frequency dependent elastic moduli whereas aluminum alloys have elastic moduli or load deflection hysteresis loops that are independent of frequency. The aluminum damping model can be independent of frequency while the polyethylene damping model will include a complex frequency dependent terms. In the time domain, the aluminum target model would result in equations of motion having constant coefficients while the polyethylene target model would include time periodic coefficients for periodic target excitation. Therefore, although the equations of motion for both targets are linear, the target bispectral signatures should differ. The limestone target would possibly lie somewhere between the two other material extremes. The differences in damping characteristics and the observed dissimilarity in the bispectral signature for the three targets may lead to novel methods for discriminating between materials.

Design of mode filters using WKB-like approximations

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A number of matched field and tomographic applications rely on estimating the modal content of signals incident on a vertical line array (VLA). Spatial filtering for modes requires knowledge of the modeshapes, which requires knowledge of the environment. Unfortunately, environmental information is often incomplete. For example, during the North Pacific Acoustic Laboratory experiment the receiver environment was sampled by temperature sensors mounted on one of the VLA's. These sensors provided a year-long time series of temperature across the 1400 m span, but there is no record of the temperature above and below the array. Solving for the modeshapes requires a complete temperature profile. One way to facilitate the mode calculation is to use archival data for the missing parts of the profile. Another approach is to use an approximation for the modeshapes that does not require knowledge of the sound speed (thus the temperature) above and below the VLA. WKB theory provides such an approximation for modes spanned by the VLA. Using standard WKB theory to construct the mode filter is problematic because the approximate modeshapes it generates are singular at the turning points. Uniform WKB-like approximations, such as those described by Langer [1] and Miller and Good [2], are continuous at the turning points. This paper discusses the design of mode filters using uniform WKB-like approximations and analyzes their performance.

[1] Phys. Rev. 51, 669, 1937.
[2] Phys. Rev. 91, 174, 1953.

Performance comparisons between passive-phase conjugation and decision-feedback equalizer for underwater acoustic communications

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Passive-phase conjugation (PPC) uses (passive) time reversal to remove inter-symbol interferences (ISI) for acoustic communications in a multipath environment. It is based on the theory of signal propagation in a waveguide, which says that the Green function (or the impulse response function) convolved with its time-reversed conjugate, summed over a large aperture vertical array of receivers (the Q function) is a delta function in space and time. A decision feedback equalizer (DFE) uses a non-linear filter to remove ISI based on the minimum mean square errors between the estimated symbols and the true (or decision) symbols. These two approaches are motivated by different principles. In this paper, we analyze both using a common framework. We point out the commonality and differences, pro and con between the two methods, and compare their performance in realistic ocean environments. The performance measures are mean square error (MSE), output signal-to-noise ratio (SNR) and bit error rate (BER) as a function of the number of receivers. For a small number of receivers, DFE outperforms PPC in all measures. As the number of receivers increases the BER for both processors approaches zero, but at a different rate. The results are supported by both simulated and real data.

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Testing of DORT and GS algorithms using sea data

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Two techniques based on phase-conjugation/time-reversal concepts to improve detection of targets in shallow water are tested using sea data. The two techniques are multiple guide source (MGS) and broadband decomposition of the time reversal operator (BBDORT). The experimental data was collected during Geoclutter II which was conducted on the continental shelf in an area south of the Hudson Canyon off the New Jersey coast during May 2003. Data was collected using a time-reversing vertical source/receiver array and an echo repeater that functioned as a mid-water column target or guide source located at various ranges.

The MGS algorithm is presented as an algorithm that utilizes several one-way, broadband transmissions from the detection volume to the receiver in monostatic sonar. The eigenfunctions of the covariance of these transmissions are used as either a single or multiple matched filters to improve the detection target reflections in the detection volume. The number of required guide sources is related to the amount of information present in the acoustic field. The concept of information content in the acoustic field was presented [John R. Buck, Information theory for source localization, UASP 2001]. The improvement of detection by using information in a set of one-way transmissions from a variety of positions is shown using sea data. The data were taken using 3-7 contiguous elements of the VLA at mid-water depth. The target and guide source was an echo repeater positioned at various ranges and at mid depth. The transmitted signals were 3.0 to 3.5 kHz LFMs. The data are analyzed to show the amount of information present in the collection, a baseline probability of detection (PD) not using the collection of GS signals, and the improvement in PD from the use of various sets of GS signals. The dependence of the improvement as a function of range is also shown.

BBDORT is presented as a coherent, broadband extension of the work of Prada [C. Prada, S. Manneville, D. Spoliansky and M. Fink, J. Acoust. Soc. Am. 99, 2067-2076 (1996)]. This technique has the potential of isolating acoustically resolvable scatterers at various ranges and depths. The isolated targets are then more easily detected. Results are shown from the application of BBDORT to sea data taken using the vertical source/receiver array with 56 hydrophones spanning the water column and operating between 3.0 and 3.5 kHz. The elements were divided into four groups, with each group acting as a coherent, broadside source. Two methods were used for exciting the separate channels. One method was the use of subsequent LFMs and the other was the use of simultaneous transmission of four pseudorandom-noise signals. The target was a mid water column echo-repeater. Results based on back propagation techniques and singular vector analysis are compared with modeling based on in situ environmental measurements made during the experiment.

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Predictive probability of detection under environmental uncertainty

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Under the ONR Capturing Uncertainty DRI, we have developed a probabilistic method for sonar performance prediction. This method utilizes specific probability density functions (PDFs) that quantify the spatial and temporal variability in the environment (transmission loss, ambient noise, reverberation) as well as variability in the sonar system itself (source level, recognition differential), for a given geographic operating area and time period. These PDFs describe the distribution of the predictive capability of acoustic and systems models with respect to measurements of actual performance, and represent the uncertainty in one's ability to model the actual performance of the system. The PDFs account for the inherent variability of the environment and system that is not contained in the model inputs. In essence, variability has the effect of spreading detection acuity in the range domain, providing decreased acuity closer to the target and increased acuity further away. In these analyses, one must state the statistical dependence among the terms in the sonar equation. We provide a detailed example of passive broadband detection in the East China Sea, and outline the approach to passive and active narrow band detection.

Analytic prediction of adaptive sonar detection performance in an uncertain ocean

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This paper considers the prediction of sonar detection performance when both the multipath ocean environment and the noise field directionality are uncertain. When both the signal wavefront and noise covariance matrix are known a priori, the classical sonar equation bounds detection performance based on analytic non-central Chi-square probability density function (PDF). However when both the ocean environment and noise covariance are uncertain, the detection statistics used to predict performance in a known environment are not appropriate. Monte Carlo methods can be used to predict detection performance by randomizing over ocean parameters and noise covariance uncertainty but this is computationally intensive and gives little insight into the cause of performance degradation. In this paper, recent analytic results for the performance of adaptive constant-false-alarm-rate (CFAR) detectors of multi-rank signals in Gaussian noise with unknown covariance are applied to the passive sonar problem. In particular, analytic expressions for the PDF of the multi-rank extension of the Kelly generalized likelihood ratio test (GLRT) are compared with the statistics of this detector operating on real passive sonar data. Horizontal array data from the SWELLEX-96 data set collected off the San Diego coast is used to validate the analytic detection performance predictions in terms of probability of detection (PD) versus signal-to-noise ratio (SNR). The real data results are shown to be in good agreement with theory provided that sufficient wavefront uncertainty is assumed and that the signal does not contaminate the assumed signal-free noise training data. The effects of signal contamination of the training data was evident when the SNR was high and the training data was very limited. These results are expected to be useful in bounding the performance of modern adaptive beamforming-based passive sonar detection systems.

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Incorporating environmental uncertainty into Bayesian sonar detection performance prediction

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Physics-based Bayesian optimal detection theory is used as a framework to directly include ocean acoustic environmental uncertainties, as well as uncertainties in the acoustic source, for a given array configuration. Environmental uncertainties are quantified using probability density functions along with an ocean acoustic propagation model, and optimal sonar detection performance is quantified using the ROC (receiver operating characteristic). Because the number of uncertain environmental parameters can be large, determining the statistics of the likelihood ratio under each hypothesis, which are needed to obtain the ROC of the optimum detector, can become computationally intensive using Monte Carlo methods. In this research, analytical expressions are presented for the optimal ROC for a general class of ocean acoustic models in the presence of diffuse noise. These analytical expressions for the ROC, derived from the uncertainty of the physics of the problem, reveal the role and tradeoffs in sonar performance prediction of environmental uncertainty, which is represented and quantified by the rank of the propagated signal matrix, and the SNR at the received array, which incorporates the effects of propagation loss, the diffuse noise level and the source level. Importantly, these analytical expressions are a simple computation, compared to the computational intensity that can arise with Monte Carlo methods. Good agreement between analytical detection performance predictions and the performance of optimal detectors, matched to the degree of environmental uncertainty, using SWELLEX-96 S5 event data is also presented.

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Signal processing in random/uncertain media

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Realistic sonar performance prediction requires that the essential randomness and unavoidable uncertainties in the signal propagation and scattering are incorporated into sonar system performance prediction models. To this end statistics (mean, variance, and error bounds) of a random receiver operating characteristic for a narrowband, high frequency, passive source in a random/uncertain medium is plotted. It is assumed that the source strength is uncertain and that both source and receiver are in motion through an inhomogeneous medium that has random/rough boundaries. A ray acoustic model is used for derivation of expressions for decrease of signal coherence time, spectral spreading and increase of entropy (uncertainty). In this problem the probability of detection (PD) is a function of a multidimensional random parameter . The uncertainty and/or randomness is characterized by the probability density function (pdf). Expressions for Pd are determined by the maximum entropy method (MEM). Maximum entropy pdf agrees with known data and known statistical moments, but is maximally for missing data or unknown statistical moments. MEM incorporates all that is known but makes no assumptions that are not warranted by data or physics.

Blind source separation, blind beamforming, ULV decomposition, subspace tracking, direction-of-arrival estimation

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In blind direction-of-arrival (DOA) estimation and beamforming, the goal is to estimate the angles that mixed, multiple impinging source signals make on a sensor array in the presence of noise. Further, there exist scenarios where the targets are non-stationary, and as new data is taken by the sensors; the DOA estimation method must be able to track the moving sources both accurately and in real-time. Often to do this, one desires to track the singular values and left (or right) singular vectors corresponding to the signal subspace. Many algorithms for tracking these terms in this application setting have been presented, and many make use of updating the singular value decomposition (SVD) [1]

While the SVD is advantageous, it has some shortcomings including its high computational intensity (requiring roughly $\mathcal{O}(qN^2)$ operations to compute and the same to update or downdate where q is number of sensors and N is sample length) and the instability of updating and downdating a block processing algorithm. Our method, however, is to use the ULV decomposition (ULVD) [2] as an efficient approximation to the SVD since it requires only $\mathcal{O}(q^2)$ to update or downdate. While this has been proposed previously for subspace tracking [3], we make use of newer developments for ULVD methods.

Using the ULVD and a simple algebraic beamformer [4], we propose to show an an efficient, stable, and accurate, method for DOA tracking. Further, the results of this proposed method will be compared to other published methods for comparison.

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[2] G.W. Stewart, "Updating a rank-revealing ULV decomposition", SIAM Journal on Matrix Analysis and Applications, vol. 14, pp. 494-499, 1993.
[3] S. Hosur, A.H. Tewfik, and D. Boley, "ULV and generalized ULV subspace tracking adaptive algorithms", IEEE Transactions on Signal Processing, vol. 46, no. 5, pp. 1282–1296, May 1998.
[4] A. Van der Veen, "Algebraic methods for deterministic blind beamforming", Proceedings of the IEEE, vol. 86, no. 10, pp. 1987-2008, 1998.

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Adaptive interference cancellation using bearing associated subspace components

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The performance of localization algorithms for passive sonar can become severely degraded when the target of interest is in the presence of interferers. The technique of Eigen-Component Association (ECA) was developed to adaptively suppress interference from signals received on a horizontal array. ECA uses an eigen-decomposition to decompose the cross-spectral density matrix (CSDM) of the array data and then beamforms each of the eigen-components. The beamformed eigen-components are then associated with the estimated target bearing thereby revealing the relative contributions of target signal and interference contained in each component. At each CSDM update, ECA automatically identifies those eigen-components with low signal-to-interference power and removes them from the CSDM. In this manner, ECA is able to adapt to the hierarchical swapping of target and interference related eigen-components due to relative signal power fluctuations and target dynamics. Examples will be presented using a horizontal array that demonstrate the use of ECA enabling accurate localization estimates in the presence of interferers, which without the technique was not possible.

Methodologies for extracting the spatially incoherent components of the scattering response from buried symmetric targets

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Mines buried in a sandy seabed are generally considered to be undetectable and unclassifiable by conventional high frequency (> 50 kHz) minehunting sonars due to the lossy effect of the sediment. Since sediment attenuation decreases with frequency, lower frequency, broadband sonars (2–15 kHz) are applicable for the detection and classification of buried mines. In this regime, extensive modelling and experimental work has shown that mine-sized, man-made targets, even when partially or totally buried in the seabed, can support the excitation of structural waves that are consistent with their typical structural symmetries. Although deterministic, some of these waves (in particular, the A0 Lamb-type waves) have a noise-like incoherent space-time structure in contrast to the coherent spherical components from specular scattering. These waves represent potential classification clues, having scattering strengths comparable to that of the diffractive part of the response. The spatially incoherent elastic components specific of targets such as spherical shells is expected to provide a valuable classification clue vs.̊stones and rocks, the response of which is basically diffractive in nature and, hence, essentially coherent.

The question is whether classification features based on the spatial-temporal characteristics of the structural response can be reliably extracted from data. Their extraction and measurement is complicated by the presence of strong interference from coherent spherical waves arising from specular reflections. The objective of this work was to investigate signal-processing methodologies for isolating the incoherent waves from the coherent components. One approach we examined used the observation that spherical waves in space can be approximated as polynomial-phase signals in the frequency domain. Treating the polynomial-phase signal associated with the spherical wave as strong interference, we estimate the polynomial-phase parameters, demodulate the spherical wave interference to a plane wave, then apply the Principal Component Inverse (PCI) method to remove the spherical wave interference, and finally re-modulate the residual to estimate the weak incoherent waves. We also investigated the design of filters for isolating the incoherent components and the use of time-frequency distributions in the frequency domain for identifying their presence. The selected methodologies for separating incoherent from coherent components of scattering are first applied to simulated data of a spherical shell completely buried in a sandy bottom and insonified at low but supercritical grazing angle. Next, real measurements of buried spheres, recorded during the GOATS'98 trial are analysed. The separation of the wave echoes confirms the theoretically expected spatial incoherence and is shown to be reliable on both simulated and real data.

Signal-dependent reduced-rank mulitbeam array processing

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A key concept underscoring this paper is the difference between Signal-Independent Adaptive Beamforming and Signal-Dependent Adaptive Beamforming (ABF). The scenario assumes the formation of multiple adaptive beams, each pointed to a different "look" direction. For a linear array of N sensors, somewhere between $3N$ and $4N$ adaptive beams are formed encompassing end-fire to end-fire. In Signal-Dependent ABF, a Generalized Sidelobe Canceler (GSC) is formed for each "look" direction. Mathematically, the GSC serves to convert the constrained (quadratic) MVDR optimization problem to an unconstrained optimization problem. The GSC essentially forces adaptation to occur in a subspace orthogonal to the steering vector for the particular "look" direction. This serves to prevent "desired" signal cancellation, especially in cases of moderate to low sample support. Implementation of the GSC at each "look" direction requires the construction and application to the data of a blocking matrix for each "look" direction. The attendant computational complexity is substantial. Methods for reducing this complexity are the focus of this paper.

Further key to this paper is reduced-rank ABF to deal with issues related to inadequate sample support. Two forms of reduced rank adaptive processing are considered in this paper: Principal Components Inverse (PCI) and Conjugate Gradients-Multistage Wiener Filtering (CG-MWF). The Dominant Mode Rejection (DMR) algorithm is a Signal-Independent PCI algorithm based on eigenvectors of the sample correlation matrix. DMR does not effect a GSC for each "look" direction; thus, DMR has the advantage of using the same eigenvalues and eigenvectors to determine the ABF for each "look" direction. However, this computational expediency comes at a cost relative to performance, as evidenced in the simulation results presented in Figure 1 conducted by M. Wieppert at SAIC.

The simulation results in Figure 1 involved 14 azimuthal channels with 16 time-delay taps per channel for 224 total degrees of freedom. In addition to the desired source, there were four interfering sources at $-60°$, $-30°$, $45°$, and $60°$ with respective SNR's of 40 dB, 20 dB, 40 dB, and 40 dB. There were 224 data samples, equal to the dimension of the wideband ABF vector. Signal-Dependent CG-MWF yields its best performance at a "rank" of 64, where it is about 2 dB below the best SINR that could be achieved with infinite sample support. SD-PCI achieves the same best SINR as Signal-Dependent CG-MWF, but at a rank of approximately 90. Signal-Independent PCI (DMR) reaches its best performance at a rank of around 175 and is about 6 dB below the optimal SINR. This paper develops efficient Signal-Dependent CG-MWF for multibeam array processing using a low-cost blocking matrix in conjunction with diagonalization of the covariance matrix.

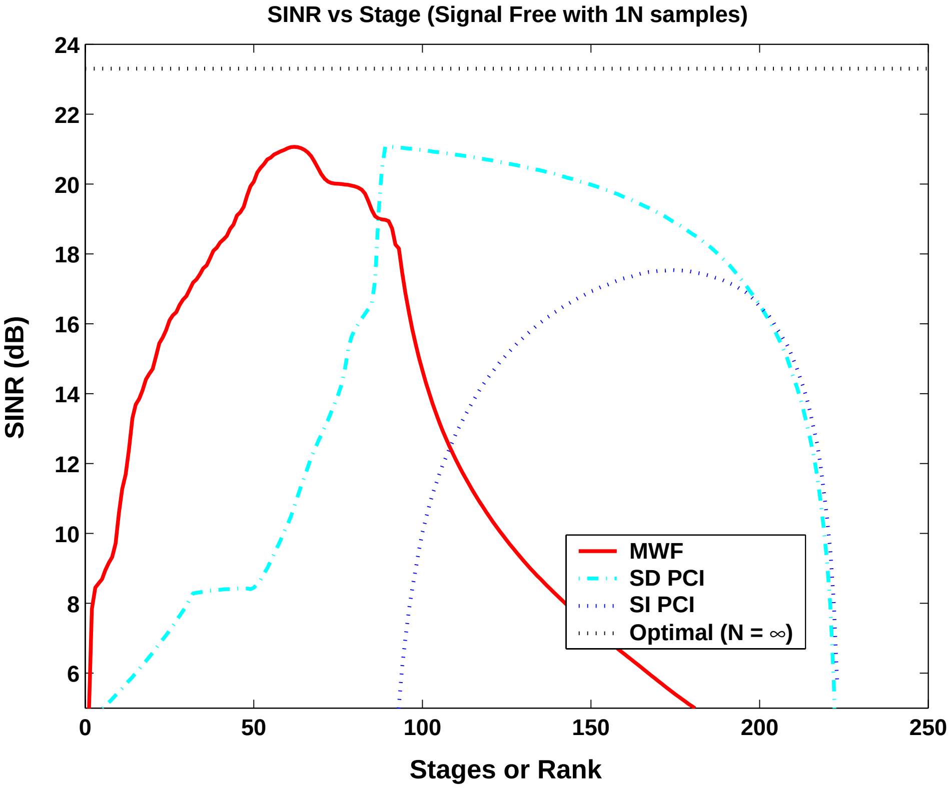

Fig. 1. Signal-Dependent Reduced-Rank Adaptive Beamforming yields higher SINR than their Signal Independent Reduced-Rank Adaptive Beamforming.

Dynamical analysis of reverberation

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When active sonars are operated in shallow littoral waters two environmental effects are immediately apparent: reverberation and multipath. Both Doppler processing and increasing bandwidth may be used to reduce the impact of reverberation. Even so, reverberation will often form the detection background. To achieve optimal performance an understanding of the character of background is required. Amplitude statistics are the classic requirement, which assumes a fixed amplitude distribution, so that a detection threshold can be set. However, the reverberation amplitude distribution is not stationary, which undermines the classic approach.

Multipath is more difficult to deal with, because the exact path structure is not known a priori, and would have to be determined during operations, if possible. For narrowband systems multipath leads to high levels of variability; for high bandwidth systems, the variability decreases, but as the multipath structure becomes resolved, the peak signal will decrease. Often the best that can be done is to integrate incoherently the reflected energy using a time constant estimated from experience or based upon current conditions.

In point to point communication systems, the 'channel' can be estimated: the multipath structure affecting the one-way transmission can be determined and exploited. For a search sonar, the two-way channel, is less easy to determine, unless there is a co-operative remote transmitter or reflector. Even then the channel is likely to vary with look directions.

Although the reverberation may be a problematic noise background, it is in fact, the response of the environment to the active sonar transmission. Thus the 'channel' information is embedded, or imposed upon it. Dix [1] reported a correlation between a reverberation statistic and the performance of the active sonar in multipath. This is a surprising result. However, it is evident from experience that a better understanding of the reverberation background as seen through the sensor is required; and it would be a bonus if it that led to channel characterisation.

This presentation will report the most recent findings of a study of reverberation characteristics using dynamical systems techniques. If there is a measurable dynamical, non-linear characteristic to reverberation, then it may be possible to optimise the signal processing using techniques developed for dynamical or non-linear systems.

Dix used the ensemble autocorrelation of the reverberation: requiring averaging over hundreds of pings. This approach is not realistic for use in an adaptive sonar system. We have attempted to use the ensemble method for data from a single ping, by averaging over well-separated samples; this should reveal non-stationarity. We have also related the ensemble autocorrelation method to the embedding theorem, and produced phase maps of the data. This latter method dispenses with the 'static' statistics of the reverberation, and we have used it to assess evidence for dynamical behaviour. In parallel with this, an estimate of non-linearity has been made using Taken's estimator [2].

It is expected that the reverberation will be 'high-dimensional', and it may be difficult to resolve dynamical, non-linear behaviour. Therefore, techniques for reducing the dimensionality of the data have been investigated. The well-known techniques of Fourier and wavelet transforms, suffer from projecting (and thus spreading) any possible dynamical behaviour onto fixed (and ad hoc) basis functions. Principal component analysis is an alternative, but represents average behaviour, thus assuming stationarity. The empirical mode decomposition proposed by Huang [3] appears to offer a locally adaptive method to decompose the signal to a few 'intrinsic modes'. Results from applying this decomposition to reverberation data will be shown, including an assessment of evidence for non-linear or dynamical behaviour.

[1] J Dix and D Hassal, "Wideband Active signal processor performance in the presence of multipath", Proceedings of the Institute of Acoustics, vol. 20, Pt 7, 1998

[2] H Kantz and T Screiber, "Nonlinear time series analysis", Cambridge University Press, 2002, ISBN 0 521 65387 8

[3] N Huang et al, “The empirical mode decomposition and the Hilbert transform for non-linear and non-stationary time series analysis”, Proceedings of the Royal Society of London, A (1998) vol. 454.

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Active sonar track detection algorithms

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The purpose of this talk is to present some new algorithms for active sonar track detection. A brief overview of the active sonar track detection problem and current automated tracking and detection methods will also be provided.

Many active sonar systems are capable transmitting several different waveforms (e.g., frequency modulated, continuous wave) in each ping. Current automated signal processing systems typically processes echoes from each waveform separately to produce several tables of tracks. Individual tracks are detected (i.e, declared to the operator) when their detection test statistics are above the detect thresholds. Combining multiple tracks from the same contact is then done either by the operator viewing several displays at once or by "post-track" fusion algorithms. In either case tracks which do not exceed the detection or display thresholds are never combined with other tracks and the echoes associated to those tracks are essentially lost.

A new technique called Multi-Waveform Tracking (MWT) can substantially improve the track detection performance of active sonar systems by sequentially updating one acoustic track table with echoes from both waveforms. The key innovation is a scheme to adapt the detection test statistics to varying levels of background interference and contact Doppler. A description of the MWT architecture and adaptive detection test statistics will be presented along with theoretical and simulated data performance analysis.

Two of the authors (Dr. Hempel and Ms. Doran) are currently investigating the applicability of the Probabilistic Multi-Hypothesis Tracking (PMHT) algorithm, invented by Dr. Roy Streit and Dr. Tod Luginbuhl, to active sonar. PMHT is based on the Expectation-Maximization (EM) algorithm and estimates sequences of target track states by maximizing a special objective function called the Q-function. A new detection test statistic based on the Q-function will be presented. Optimality properties of the Q-function based test statistic and how it can be applied to the multi-target track detection problem will be discussed.

A probabilistic multi-hypothesis tracker for active sonar (PMHTAS)

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We adapt Streit's and Luginbuhl's Probabilistic Multi-Hypothesis Tracker (PMHT) for use in active sonar applications. PMHT uses the Expectation-Maximization (EM) algorithm, which is known for its ease of implementation as well as for its convergence properties, to obtain MAP estimates of the target state. Thus, PMHT extends rather nicely to incorporate, for instance, amplitude information and maneuver models. One aspect of this work is to determine an appropriate method for initializing tracks, as PMHT requires that the number of targets is known a priori. We take a backward-looking approach which is loosely based on the Hough transform. The Hough transform is often used in image processing to find features in data, and has been proposed as a method for track initialization in PMHT [1]. Assuming that the tracks are approximately constant velocity over a short batch of scans, we subdivide the data space into bins whose centers represent space-time lines. The bin centers are input to PMHTAS as an initial estimate of the sequence of states, and an appropriate track detection statistic is applied to the resulting (converged) state estimates to identify valid tracks. We will mention key points of the PMHTAS algorithm design and discuss initialization. Some initialization results on simulated data will be presented.

[1] T. Luginbuhl, Y. Sun, P. Willett. "A Track Management System for the PMHT Algorithm". Proceedings of the 4th International Conference on Information Fusion. August 2001.

Ping-to-ping echo-similarity studied via accurate estimates of multipath delays

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When dealing with active returns associated with a track as in post-track classification, it is of interest to determine if the returns are somehow similar. For two-way returns we also wish to know if they are the result of interactions with the same physical object. This study compares the echo structure of neighboring pings by concentrating only on the relationships between the multipath delays. The hypothesis that multipath time delays are relatively more stable than the corresponding amplitudes and phases is studied using both received one-way and two-way returns. This hypothesis is considered the cause for neighboring one-way returns to appear visually different. High-resolution delay estimates from a variety of techniques [1,2,3] are utilized and a quantifiable measure of echo similarity is introduced. In addition to potentially improving classification performance, the methods explored here may reduce sensitivity of matched field localization and depth estimation to environmental uncertainties.

[1] I.P. Kirsteins, “High Resolution Time-Delay Estimation,” ICASSP 87.
[2] D.W. Tufts and R. Kumaresan, “Estimation of Frequencies of Multiple Sinusoids: Making Linear Prediction Perform Like Maximum Likelihood,” Proc. Of the IEEE, Vol. 70, No. 9, September 1982.
[3] S. Kay and S. Saha, “Mean Likelihood Frequency Estimation,” IEEE Trans. On SP, Vol. 48, No. 7, July 2000.

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Wednesday October 8, 2003		Thursday October 9, 2003		Friday October 10, 2003	
		8:00-9:45	Session B Laurel	8:00-9:45	Session F Laurel
		9:45-10:15	Break Laurel	9:45-10:15	Break Laurel
		10:15-12:00	Session C Laurel	10:15-12:00	Session G Laurel
		12:00-1:00	Lunch Whisp. Pines	12:00-1:00	Lunch Whisp. Pines
		1:00-2:45	Session D Laurel	1:00-2:45	Session H Laurel
		2:45-3:15	Break Laurel		
		3:15-5:00	Session E Laurel		
5:00-6:00	Welcome Reception				
6:00-8:00	Raytheon Dinner Whisp. Pines	6:00-8:00	Dinner Whisp. Pines		
8:00-9:30	Session A Laurel	8:00-?	SOB Session Laurel		