A Book of Abstracts for the

2015 Underwater Acoustic Signal Processing Workshop

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UASP 2015

Welcome to the 2015 IEEE workshop on Underwater Acoustic Signal Processing. This year's special session is on Sparse and Coprime Sensing.

The organizing committee thanks and acknowledges the continued support of our promotional partners, the Office of Naval Research, Raytheon Integrated Defense Systems, and the IEEE Oceanic Engineering Society. We also thank Michael Janik for his efforts in arranging for Raytheon Integrated Defense Systems to sponsor our Wednesday evening dinner. We thank the IEEE Oceanic Engineering Society for sponsoring the Thursday evening dinner. Finally, we are proud to announce that this year's recipient of the Donald W. Tufts UASP Award is Dr. Roy L. Streit.

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The 2015 Donald W. Tufts UASP Award is Presented to Dr. Roy L. Streit

For outstanding contributions to sonar automation, target tracking, and data fusion

Roy L. Streit graduated from East Texas State University in 1968 with a B. A. in Physics and Mathematics, from the University of Missouri in 1970 with an M. A. in Mathematics, and from the University of Rhode Island in 1978 with a Ph. D. in Mathematics. From 1970 to 2005 he was with the Naval Undersea Warfare Center (NUWC) and its predecessor the Naval Underwater Systems Center in New London, CT and then Newport, RI. In 2000, Dr. Streit advanced to be one of the few senior technologists (a senior executive service position) at NUWC, an acknowledgement of the breadth, depth, and impact of his contributions to Naval research. After retirement from NUWC in 2005, Dr. Streit joined Metron in Reston, VA as a senior scientist and has continued to contribute to the field through his research, publishing and professional service.

In this succinct recognition of Dr. Streit's accomplishments, it is not possible to describe all of the different research areas to which he has contributed. However, the underlying theme in Dr. Streit's career can be summarized as extracting tractable solutions to practical problems out of complex mathematical concepts. Some of Dr. Streit's most consequential contributions to the underwater acoustic signal processing (UASP) community include optimizing conventional beamformers for arbitrary array configuration, exploitation of hidden Markov models in detection and tracking, the probabilistic multi-hypothesis tracker, and joint tracking of kinematic and frequency feature spaces. His ability to view traditional sonar signal processing and automation problems from novel perspectives has often led to disruptive technology advancements. In addition to his significant research contributions, Dr. Streit has been a strong advocate and mentor for younger scientists and engineers. He has also dedicated time and effort to communicating his knowledge through tutorials, short courses, and books.

For all of his contributions to the field, we the UASP community are pleased to present the 2015 Donald W. Tufts UASP award to Dr. Roy L. Streit.

Schedule at a glance

Wednesday **October 14, 2015**		**Thursday** **October 15, 2015**		**Friday** **October 16, 2015**	
		8:15–9:05	Session B Sp/CoP II Laurel	8:15–9:05	Session I Sp/CoP IV Laurel
		9:05–10:20	Session C AUV Proc. Laurel	9:05–10:20	Session J Waveforms Laurel
		10:20–10:45	Break Laurel	10:20–10:45	Break Laurel
		10:45–12:00	Session D Param. Est. Laurel	10:45–12:00	Session K Class/Mod. Laurel
		12:00–1:00	Lunch Whisp. Pines	12:00–1:00	Lunch Whisp. Pines
		1:00–1:30	Session E Don Tufts Award Laurel	1:00–1:25	Session L Acoust. Mod. Laurel
		1:30–3:10	Session F Stat. Mod. Laurel	1:25–2:40	Session M Tracking Laurel
		3:10–3:35	Break Laurel		
		3:35–4:50	Session G Sp/CoP III Laurel		
5:00–6:00	Welcome Reception Whisp. Pines	4:50-5:15	Session H Turbulence Laurel		
6:00–8:00	Raytheon Dinner Whisp. Pines	6:00–8:00	OES Dinner Whisp. Pines		
8:00–9:30	Session A Sp/CoP I (Plenary) Laurel	8:00–?	SOB Session Laurel		

Sessions: Titles and presenters

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

Special Session I (Plenary): Sparse/Coprime Signal Processing

A–1 *Sparse and Coprime Sampling: Benefits, Challenges and Future Directions*
Piya Pal, University of Maryland, College Park

Session B: Thursday Morning, 8:15am–9:05am

Special Session II: Sparse/Coprime Signal Processing

B–1 *Linearized Perturbation Analysis for Coprime Co-arrays via Bi-affine Formulation*
Ali Koochakzadeh, University of Maryland, College Park

B–2 *Performance Breakdown in Parameter Estimation Using Co-prime Arrays*
Louis Scharf, Colorado State University

Session C: Thursday Morning, 9:05am-10:20am

AUV-centric Signal processing

C–1 *Quality Assessment of Acoustic Color Signatures*
Daniel Cook, Georgia Tech Research Institute

C–2 *Characterization of Underwater Target Geometry from Autonomous Underwater Vehicle Sampling of Bistatic Acoustic Scattered Fields*
Erin Fischell, MIT

C–3 *Passive Towed Array on HUGIN AUV*
Ole Lorentzen, Norwegian Defence Research Establishment (FFI)

Session D: Thursday Morning, 10:45pm–12:00pm

Parameter Estimation

D–1 *Lucky Ranging in Underwater Acoustic Environments Subject to Spatial Coherence Loss*
Ivars Kirsteins, Naval Undersea Warfare Center Division Newport

D–2 *Asymptotically Efficient Subspace Estimation for Sensor-Array Signal Processing*
Richard Vaccaro, University of Rhode Island

D–3 *Distribution of the Fisher Information Loss Due to Random Compression*
Ali Pezeshki, Colorado State University

Session E: Thursday Afternoon, 1:00pm–1:30pm

Don Tufts UASP Award Presentation

Session F: Thursday Afternoon, 1:30pm–3:10pm

Statistical Modeling of Signals and Noise

F–1 *Rayleigh, K, Log-normal, Weibull, and Other Reverberation Distributions: an Approximation for All*
Leon Cohen, City University of New York

F–2 *How Active-Sonar Pulse Duration Can Change Matched-Filter Envelope Statistics from Rayleigh to Rician*
Douglas Abraham, CausaSci LLC

F–3 *Applications of Featureless Classification in Non-Rayleigh Clutter*
Bruce Newhall, Johns Hopkins Applied Physics Laboratory

F–4 *On ROC Curve Performance Prediction for Clutter-Limited Environments: An Analytic Modeling Approach*
Christ Richmond, MIT Lincoln Laboratory

Session G: Thursday Afternoon, 3:35pm–4:50pm

Special Session III: Sparse/Coprime Signal Processing

G–1 *Design of Nested and Coprime Arrays for the North Elba Sea Trial*
Vaibhav Chavali, George Mason University

G–2 *Sparsity-Based Direction-of-Arrival Estimation of Coherent and Uncorrelated Signals Using Active Nonuniform Arrays*
Fauzia Ahmad, Villanova University

G–3 *Exploiting Array Motion for Broadband Synthetic Aperture Processing on Co-prime Sensor Arrays*
Juan Ramirez Jr, Duke University

Session H: Thursday Afternoon, 4:50pm–5:15pm

Turbulence

H–1 *Passive Sonar in the Human Body*
Norman Owsley, Phonoflow Medical, LLC

Session I: Friday Morning, 8:15am–9:05am

Special Session IV: Coprime/Sparse Spectral Estimation

I–1 *Multitaper for Co-prime Sensing Arrays*
Ian Rooney, University of Massachusetts at Dartmouth

I–2 *Gaussian Signal Detection and Spectral Estimation Using a Coprime Sensor Array With the Min Processor*
Yang Liu, University of Massachusetts Dartmouth

Session J: Friday Morning, 9:05am-10:20am

Waveform Design

J–1 *Co-prime Comb Signals for Active Sonar*
Jonathan Soli, Duke University

J–2 *The Generalized Sinusoidal Frequency Modulated Waveform for Continuous Active Sonar*
David Hague, University of Massachusetts Dartmouth

J–3 *Low Probability of Intercept Waveform Design Using The Chirplet Graph*
Bijan Mobasseri, Villanova University

<u>Session K</u>: Friday Morning, 10:45am–12:00pm

Classification and Modeling

K–1 *Application of Nonstationary Signal Processing Methods for Target versus Clutter Discrimination*
Patrick Loughlin, University of Pittsburgh

K–2 *A Hierarchical Mixture Model for Adaptive Filtering of Underwater Acoustic Signals*
Paul Gendron, University of Massachusetts Dartmouth

K–3 *Developing Target Detection and Classification Techniques Based on Dynamic Manifold Analysis*
Ivars Kirsteins, Naval Undersea Warfare Center Division Newport

<u>Session L</u>: Friday Afternoon, 1:00pm–1:25pm

Acoustic Modeling

L–1 *Analysis of Fields from a Time-Stepped Three-dimensional Acoustic Model With Oceanic Variability: Correlation Matrix Properties and Implications*
Timothy Duda, Woods Hole Oceanographic Institution

<u>Session M</u>: Friday Afternoon, 1:25pm–2:40pm

Tracking

M–1 *Using Relative Doppler to Improve Dolphin Tracking, Particularly by Enabling Better Association of Clicks to Individual Animals*
Paul Hursky, HLS Research Inc

M–2 *An Approach for Automated Detection and Localization of Passive Sonar Contacts*
Tom Northardt, MIKEL Inc.

M–3 *A New Architecture for Multi-Target Tracking*
Patrick Carroll, Naval Undersea Warfare Center Division Newport

Abstract Listings

Sparse and Coprime Sampling: Benefits, Challenges and Future Directions

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Coprime and nested sampling have been recently introduced as powerful sparse deterministic sampling techniques that can exploit statistical properties of signals to sample them at rates significantly lower than the Nyquist limit, without losing the desired information in many applications of practical interest. Coprime and nested samplers, in their original form, were designed for sub-sampling wide-sense stationary (WSS) signals, which commonly arise in a large number of applications such as spectrum estimation, source localization, wireless communication and so forth. Through judicious choice of sampling instants, these samplers can ensure that the autocorrelation of WSS signals get sampled at the Nyquist rate, although the WSS signal itself may be sampled at significantly lower rates. This can have profound impact depending on the application: for instance, in wideband spectrum sensing for cognitive radios, one can monitor a very wide frequency band to look for available spectral holes, without using a power hungry analog-to-digital (A/D) converter. Similarly for source localization in phased antenna arrays, one can identify $O(M^2)$ sources using only M sensors, thereby significantly saving hardware and real estate.

In this talk, I will first review the mathematical principles behind coprime sampling and a related concept of coprime filterbanks for sub-Nyquist sampling of WSS signals. The superior performance of coprime sampling over traditional samplers will be demonstrated with regards to two main applications: wideband spectrum sensing and direction-of-arrival (DOA) estimation. I will show further extensions of these sampling schemes to handle multidimensional signals, as well as those possessing higher order statistics (such as speech). I will also discuss challenges associated with practical implementation of coprime samplers, especially in presence of finite observation length, and under violation of WSS assumptions. These challenges give rise to the possibility of novel extensions, both with regards to sampling geometries, and reconstruction algorithms. I will conclude the talk by discussing some promising future research directions where nested and coprime sampling can be used as generic "data sketching" tools, to compress high dimensional data, and potentially augmenting compressed sensing based techniques, which largely use random sampling.

Linearized Perturbation Analysis for Coprime Co-arrays via Bi-affine Formulation

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New spatial/temporal sampling techniques namely coprime and nested sampling have been shown to be effectively capable of resolving $O(M^2)$ sources in a sub-Nyquist rate. However, little is known about the performance of these techniques in non-ideal settings. In the spatial sampling problem, the sensors can be perturbed from their nominal positions. Similar case in the temporal sampling problem happens when the samplers have unknown jitters (We ignore other non-ideal situations in this paper.) Assuming that the perturbations are small, we use a linear approximation to formulate this problem as a bi-affine problem, which is slightly different from the well-studied bilinear problems. We propose a novel approach to solve the bi-affine problem based on lifting and solving a rank minimization problem. Using an iterative approach we propose a method to get back the source powers, directions of arrival, and the unknown perturbations. We conduct numerical simulations to examine the performance of our algorithm.

Performance Breakdown in Parameter Estimation Using Co-prime Arrays

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We study performance breakdown of co-prime arrays for parameter estimation. The main source of performance breakdown in many parameter estimation methods is known to be the occurrence of a subspace swap, where some of the modes of the noise subspace better represent the measurements than some of the modes of the noise-free signal subspace. We consider two data models in which the parameters modulate the mean value function and the covariance of multivariate normal measurements, and derive lower bounds on the probability of the subspace swap for each data model. These bounds may be used to predict the threshold signal-to-noise ratios for parameter estimation using co-prime arrays.

Quality Assessment of Acoustic Color Signatures

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Mine countermeasures sonar traditionally involves sidescan surveys of the ocean floor using high frequencies, in the range of 100 kHz to 1 MHz. Improving performance has historically meant achieving better image resolution for a given area coverage rate, and target classification is based on features that are very much like those used for optical images. The main drawback to this approach is the potentially high false alarm rates in cluttered environments where both natural and man-made objects can resemble mines. Recent years have witnessed increasing interest and research into the use of wideband, widebeam, low frequency sonar, typically below 50 kHz, whose purpose is to excite and observe an objects structural response. This is usually represented as an aspect-dependent spectrum known as acoustic color. These signatures exhibit greater uniqueness allowing mines to be more clearly distinguished from clutter objects.

The acoustic color research to date has focused largely on modeling the target response and carefully observing it under ideal conditions such as test tanks and ponds or in the sea using sonars mounted to fixed rails. Real-world complexities have generally been limited to pose angle, burial state, and the type of surrounding sediment. This research explores a new aspect of the problem: consideration of imperfections in the data collection and processing. The primary example is the error caused by the non-ideal motion of the platform carrying the sonar. These errors are well understood for synthetic aperture sonar imaging, but have yet to be explored for acoustic color.

It has been hypothesized that motion errors will have a minimal impact on acoustic color, providing additional evidence of its robustness as a target classification tool. Nevertheless, since some amount of coherent beamforming is required to create acoustic color measurements in the ocean environment, the data products have the potential to be degraded by errors. It is therefore possible that the parts of the target signature carrying the most information for discrimination could become corrupted. In this work, we consider quality metrics, akin to traditional imaging resolution, that may be used to assess the level of degradation. We also examine the effect of several standard error types on an ideal acoustic color response.

[Work supported by ONR Grants N00014-15-1-2099 and N00014-15-1-2114.]

Characterization of Underwater Target Geometry from Autonomous Underwater Vehicle Sampling of Bistatic Acoustic Scattered Fields

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One of the long term goals of Autonomous Underwater Vehicle (AUV) minehunting is to have multiple inexpensive AUVs in a harbor autonomously classify hazards. Existing acoustic methods for target classification using AUV-based sensing, such as sidescan and synthetic aperture sonar, require an expensive payload on each outfitted vehicle and expert image interpretation. The operational paradigm used with these sensors is not well suited for fully autonomous target localization and classification: an AUV collects data on an area then an operator looks at the resulting images for target identification and classification. The goal for this work was to develop and demonstrate a payload and classification methodology explicitly designed for fully autonomous target classification on AUVs, with a low cost-per-vehicle sensor package. The approach to this problem was to apply a machine learning classification methodology to bistatic scattering amplitude data collected between a fixed acoustic source and seabed target using an AUV with a simple hydrophone nose array. Two experiments were conducted using the Bluefin 21 AUV Unicorn, outfitted with an acoustics and autonomy payload including a 16- element nose array and a precision timed acoustic data acquisition system. In both experiments, a time-synchronized acoustic source insonified the target using a 7-9kHz LFM chirp while the vehicle circled the target using broadside data acquisition behaviors. In the first experiment, bistatic data was collected around spherical and cylindrical targets insonified by a directional fixed acoustic source. This data was successfully used to demonstrate Support Vector Machine (SVM) classification of spheres versus cylinders based on bistatic-angle dependence of the scattered acoustic amplitude. In the second experiment, bistatic data was collected around a steel pipe target insonified from an omnidirectional ship-based source. The ship was moved to obtain bistatic data for different target aspects. Simulation data was used to train a SVM regression model. The model was then used to estimate the orientation of the steel target from the experimental data. The final models produced from real and simulated data sets were used for classification and orientation estimation of simulated targets in real time in the LAMSS MOOS-IvP simulation environment.

[This material is based on work supported by ONR Grant Numbers N00014-08-1-0011 and N00014-14-1-0214.]

Passive Towed Array on HUGIN AUV

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The Norwegian Defence Research Establishment (FFI) has been actively involved in autonomous underwater vehicle (AUV) development for two decades with the HUGIN AUV. Major results include the HUGIN system itself and the HISAS high resolution synthetic aperture sonar (SAS). FFIs own HUGIN AUV is currently equipped with a selection of high resolution, state-of-the-art sensors, including the HISAS sonar, the EM2040 multi beam echo sounder and an Edgetech sub-bottom profiler. Non-acoustic sensors include the TileCam full color optical imaging system, a methane sniffer, a magnetometer, and a turbidity sensor. For high quality navigation the NavP and NavLab systems are used, also developed at FFI. The navigation is aided by a Honeywell HG9900 inertial navigation unit, a doppler velocity logger and a forward looking sonar system. The navigation system is also aided by GPS in the surface, and from surface ship or transponders using the HIPAP acoustic positioning system when submerged. Alternatively, terrain navigation is also available both for the EM2040 and the HISAS system, and improving this technology is an ongoing research topic. The entire system, including all payloads and sensors, can operate down to 3000 meters water depth.

This year, in cooperation with the NATO STO Centre for Maritime Research & Experimentation (CMRE), we have obtained a towed array (TA) for scientific use with the HUGIN AUV. The full length of the towed array is about 70 meters, of which 52 meters contain hydrophone elements. The elements are spaced so that four different array configurations with equally spaced hydrophones can be used to sample different frequency ranges.

We intend to use our experience from SAS development and passive sonar systems to look into processing techniques for towed array processing. This includes adaptive beamforming, passive SAS (PSAS) and other processing techniques. We are also interested in how perturbations may affect the recorded signals, such as non-straight array shapes and noise from various sources. Using our towed array we can do research on these topics without some of the limitations that are imposed when working with operational sonar systems, while we still gain experience with towed arrays for both AUVs and manned submarines.

In this talk, we describe the vehicle with the towed array system. We also describe the signal processing flow and discuss alternative schemes, and show the progress that has been made so far.

Lucky Ranging in Underwater Acoustic Environments Subject to Spatial Coherence Loss

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In principle, a passive sonar system utilizing a long array can estimate range to a source by measuring its wave front curvature (WFC) based on the assumption of spherical spreading. However, range estimation in real underwater environments is often problematic because WFC ranging is highly sensitive to spatial coherence losses or equivalently, wave front distortions. Spatial coherence losses, a consequence of temporally-dependent wave front distortions caused by internal waves, fronts, etc., can result in large range estimation errors and biases and are usually of greater concern in WFC ranging systems than signal-to-noise ratio. One solution is to explicitly directly incorporate a model of the spatial coherence losses, either known or unknown, into the maximum likelihood estimator to improve performance [Paulraj&Kailath:JASA1988, Gershman:TSP1997]. However, empirical analysis and anecdotal evidence suggests that coherence loss processes have a complex non-stationary behavior that is difficult to model stochastically, making these approaches impractical. Such non-stationary degradation in spatial coherence bears similarity to atmospheric turbulence present in ground-based telescopes which causes image blurring by distorting the light wave fronts. Astronomers have developed a lucky imaging technique based on the following observation: a few percent of telescope images if captured at fast enough frame rates will have blurring that is momentarily small enough to yield high quality images. Our premise is that over very short time scales, even in environments with apparently poor coherence, array data is on occasion well-behaved, such that there is little or no distortion to the signal wave fronts aka lucky moments. Motivated by lucky imaging, we propose a new paradigm for WFC range estimation and array processing in environments with poor spatial coherence. We derive a lucky maximum likelihood range estimator based on a Gaussian mixture model where each collected data snapshot is either coherent or purely incoherent with some probability. This estimator in effect ranks the quality of the data snapshots according to an array gain-like quantity and requires no prior assumptions about the coherence loss processes.

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Asymptotically Efficient Subspace Estimation for Sensor-Array Signal Processing

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Algorithms for direction-of-arrival (DOA) estimation or adaptive beamforming rely on an estimate of an underlying covariance matrix. The estimate most commonly used is the sample covariance matrix (SCM). The span of the dominant eigenvectors of the SCM is an estimate of the underlying signal subspace; however, this subspace estimate can be improved. This talk introduces a recently developed lower bound on the error of an estimated subspace, as well as an algorithm that asymptotically achieves this bound. This new algorithm, called OSE (optimal subspace estimation), consists of a closed-form calculation of a correction term to the SCM signal subspace. The new subspace estimate may be used to estimate DOAs or it may be used to improve the covariance matrix estimate needed for adaptive beamforming. Simulation examples are given for DOA estimation using 1D and 2D uniform sensor arrays. The OSE-DOA estimates are unbiased and achieve the CR bound for both 1D and 2D arrays. An adaptive beamforming example shows that the OSE approach can achieve the same level of interference suppression as a standard adaptive beamformer (dominant mode rejection) using two orders of magnitude fewer snapshots.

Distribution of the Fisher Information Loss Due to Random Compression

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In this work, we study the impact of compression with random matrices on Fisher information for nonlinear parameter estimation in a complex multivariate normal measurement model. We consider the class of random compression matrices whose distribution is invariant to right-unitary transformations. For this class of random compression matrices, we show that the normalized Fisher information matrix after compression has a multivariate beta type one distribution, which is independent of the Fisher information matrix before compression and the values of the parameters. Our result can be used to quantify the amount of loss in Fisher information due to random compression.

Rayleigh, K, Log-normal, Weibull, and Other Reverberation Distributions: an Approximation for All

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The application of reverberation noise theory to the ocean started around 1965 with the classical works of Faure, Ol'shevskii and Middleton (FOM). FOM and others aimed to calculate the noise statistics and their dependence on a) dispersive propagation effects, b) the properties of the impinging pulse, c) the distribution of scatterers, and on d) the space and time dependence. While considerable progress was made, it is fair to say that after 50 years we do not have an effective theory. A common current attitude is that the Rayleigh distribution is fundamental and is observed in most cases, but that under some circumstances the observed data does not fit the Rayleigh distribution. Other distributions are then proposed in an ad hoc manner that seemingly fit the data better. These include the K, log-normal, and Weibull distributions, among others. By way of simulation and theory, we have obtained probability distributions for intensity as functions of space and time, and have shown that for certain space-time values, the intensity distribution does become Rayleigh but is often non-Rayleigh. However, these non-Rayleigh distributions are not the K, log-normal, or Weibull distributions, etc. A number of the early papers on reverberation noise attempted to obtain the correction to the Rayleigh by way of the so called Edgeworth and Gram-Charlier approximation methods. These methods are restrictive in a number of ways, and only partial success was achieved. We have developed a new method to approximate probability distributions, where the Edgeworth and Gram-Charlier are special cases. The value of having approximations is not only a question of possible numerical advantage for calculations, but often approximations give insight into the nature of the distribution. We describe a new method of fitting that does not rely on a particular distribution but is self adjustable. Our form encompasses the K, log-normal and other long-tailed distributions, and can be used as a general form for all cases where there are deviations from Rayleigh.

How Active-Sonar Pulse Duration Can Change Matched-Filter Envelope Statistics from Rayleigh to Rician

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Acoustic propagation through a shallow-water channel with random oceanography (e.g., internal waves or a rough surface or bottom) can result in a Rayleigh-fading channel when multipath phases are fully saturated. When there is a coherent component (e.g., from paths having minimal boundary interaction), a Rician-fading channel is obtained. Such analysis assumes propagation occurs through one realization of the random channel and for an active sonar system results in an echo with either a Rayleigh- or Rician-distributed matched-filter envelope. The focus of this presentation is on the case where the pulse duration exceeds the channel correlation time so different portions of the pulse encounter different realizations of the random channel. Suppose an active sonar system with a transmit pulse short enough for the channel to be considered static produces a Rician matched-filter-envelope distribution for a target echo where the coherent component is small enough for the distribution to be nearly Rayleigh. In terms of the echo's complex matched-filter response, the ratio d of the squared magnitude of the mean to the variance is small. The scintillation index (SI) for the Rician envelope is $SI = 1 - [d/(1+d)]^2$, illustrating how the Rician-distributed target echo can simplify to the Rayleigh distribution ($SI = 1$ when $d = 0$) on one extreme and be a deterministic signal on the other ($SI = 0$ as $d \to \infty$). If the transmit pulse is now lengthed to be longer than the correlation time of the channel, the effect on the complex matched filter response is for both the mean and variance to increase in a manner approximately proportional to the number of correlation lengths (n_c). Thus d becomes $n_c d$ so when d is small to begin with, a pulse duration shorter than the channel correlation time produces a nearly Rayleigh distributed echo while a much longer transmit pulse can produce a nearly deterministic signal, resulting in a Rician echo when accounting for additive Gaussian noise. The model describing the above scenario is introduced, relating the Rician distribution parameters to the auto-covariance function (ACF) of the complex multipath amplitudes. The effect of a deterministic frequency response induced by the channel or target scattering can be included in the analysis for frequency-modulated waveforms. Approximations for various ACF shapes are presented to illustrate the effect. Finally, data from the Office of Naval Research's 2013 TREX experiment [please see full TREX acknowledgement in presentation] are used to demonstrate the predicted effect.

[Sponsored by the Office of Naval Research.]

Applications of Featureless Classification in Non-Rayleigh Clutter

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Previously, the generalized likelihood ratio test (GLRT) was derived for the case of a signal subspace in acoustic clutter characterized by a spherically invariant random variable (SIRV) and applied to a simulation [1]. This extends that previous work to applications to active sonar data. First a set of simulated complex data signals are added to sonar clutter from the NATO BASE 04 data set. The clutter data are assumed to be modeled by a generalized Pareto distributed (GPD) SIRV. For these data the GPD based formula shows great improvement over traditional GLRT classification based on a Gaussian assumption. Next we consider applications where it is appropriate to ignore the phase of the signals for incoherent classification. Techniques and results are also shown in the incoherent case.

[1] B. Newhall and A. Slowikowski, Classification of signals in spherically invariant random clutter, J. Acoust. Soc. Am. 137 (4 pt.2), 2436-2437, Apr. 2015.

[Work supported by the Office of Naval Research.]

On ROC Curve Performance Prediction for Clutter-Limited Environments: An Analytic Modeling Approach

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A method is proposed for predicting receiver operating characteristics (ROC) curves under clutter-limited conditions, including performance versus probability of detection (PD), probability of false alarm (PFA), and signal-to-noise ratio (SNR). The proposed method builds on an approach proposed by Kelly and Lerner [1] and later leveraged by Van Trees [2] and Wong et al. [3] that models the returns of radar chaff (or clutter/reverberation) as those from a random collection of scatterers. The scatterer amplitudes are assumed distributed as a general Gaussian mixture that includes the K-distribution [4,5] and Weibull as special cases. The arrival times and the number of scatterers are modeled jointly as a nonstationary Poisson process with an arbitrary process rate. The process rate can be chosen to account for dominant features in the environment, e.g. a large stationary reflector. The goal of this effort is to calculate the PD and PFA obtained by thresholding the output power of a beamformer followed by a matched-filter, i.e. a single range-Doppler-azimuth resolution cell, when clutter is the dominant interference. The clutter is shown to yield a waveform dependent noise term as part of the detection statistic; indeed, a clutter term that depends on the actual characteristics of the waveform and not simply its total energy (as in the white noise limited case). Saddlepoint methods are used to approximate the distribution of the clutter waveform-dependent term, and standard statistical analysis yields the final desired ROC curves. Numerical examples based on radar/sonar systems will be presented that demonstrate the utility of the results.

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Design of Nested and Coprime Arrays for the North Elba Sea Trial

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Sparse array designs use fewer sensors to span an aperture, thus reducing hardware and maintenance costs. While sparse array design techniques exist, they have received less attention than comparable techniques for uniformly spaced arrays. Vaidyanathan and Pal describe two types of sparse arrays that use interleaved subarrays with uniform spacing, permitting the designer to apply well-known techniques to control sidelobe levels. Nested Arrays (NAs) consist of a relatively short subarray with half-wavelength spacing and a longer subarray with larger spacing [IEEE Trans. Signal Process., 2010]. Coprime Sensor Arrays (CSAs) use two subarrays that are undersampled by coprime factors [IEEE Trans. Signal Process., 2011]. Since both nested and coprime designs use undersampled subarrays, there is the potential for ambiguity due to aliasing. One way to eliminate this ambiguity is to multiply the scanned responses to obtain an unaliased output. There are two important issues affecting the performance of a multiplicative processor. First, the multiplicative beampattern tends to have higher sidelobes. Adhikari et al. show lower sidelobes can be achieved by extending the subarrays [EURASIP, 2014]. Second, multiplicative processing results in cross terms in the output that are not present in the output of a traditional linear beamformer. Vaidyanathan and Pal suggest that cross terms can be reduced by averaging over multiple snapshots, though they do not indicate how much averaging is required to reduce the cross terms to an acceptable level. This research considers the problem of designing nested and coprime processors to analyze the passive sonar data set recorded on a vertical line array near Elba Island [Gingras, SACLANT Tech. Report, 1994]. In previous work, we considered the design of a coprime array for the Elba data that provides the best tradeoff between number of sensors and performance [Asilomar Conf. Signals, Syst. Comput. , 2014]. This talk focuses on analyzing the effect of multiplicative cross terms and designing a nested array for the Elba data. We compare the results of nested and coprime processing using simulated and experimental data.

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Sparsity-Based Direction-of-Arrival Estimation of Coherent and Uncorrelated Signals Using Active Nonuniform Arrays

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Direction-of-arrival (DOA) estimation using sensor arrays is an area of continued research interest that finds broad applications in wireless communications and radar systems. Among the many DOA estimation methods that have been developed, subspace-based approaches, such as Multiple SIgnal Classification (MUSIC), are broadly used due to their low complexity and superior performance. However, these approaches often fail to provide reliable performance in case of coherent signal arrivals or a mixture of coherent and uncorrelated signals, which often arise in the presence of multipath propagation. This is due to the rank deficiency of the corresponding noise-free covariance matrix. Spatial smoothing technique can be used to decorrelate the coherent signals, thereby restoring the rank of the covariance matrix, but at the expense of reduced degrees-of-freedom (DOFs) for DOA estimation. Sparse reconstruction techniques have also been applied for DOA estimation of coherent sources. However, all of the aforementioned schemes employ passive or receive-only arrays for DOA estimation. In this paper, we perform DOA estimation of a mixture of coherent and uncorrelated signals using sparse reconstruction and active (transmit/receive) nonuniform arrays. The scene is illuminated by multiple narrowband transmissions from the different transmitters and the receivers capture the reflections from the targets. The transmitters can be used either sequentially or simultaneously; the latter requires use of orthogonal waveforms and a bank of matched filters to separate the various transmissions at the receivers. Further, the transmit and receive arrays are assumed to be co-located so that a target in the far-field appears to have the same direction at all transmitters and receivers. The target distribution is assumed to consist of both uncorrelated and coherent targets. Sparse reconstruction is employed to perform DOA estimation by considering the data measurements from multiple transmit and receive elements as observations from a virtual array, whose elements are given by the pairwise sums of the physical transmit and receive array element positions. In so doing, the number of DOFs is enhanced, leading to improved DOA estimation performance. Supporting simulation results are provided based on co-prime array configurations.

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Exploiting Array Motion for Broadband Synthetic Aperture Processing on Co-prime Sensor Arrays

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In this research, we apply synthetic aperture processing to enable wavelength specific broadband signal processing on a linear co-prime array. Synthetic aperture processing is used to create a virtual co-prime sensor array where the inter-element spacing is a function of the underlying received signal wavelength of interest. From this perspective, a different co-prime array is synthesized for each wavelength of interest with in the signal bandwidth. The use of synthetic aperture processing in this manner is designed to preserve array resolution across the bandwidth of the received signal. In this work we apply synthetic aperture processing in two stages, first a virtual co-prime array is synthesized and second the co-array of the virtual co-prime array is optimized for maximum degrees of freedom.

Passive Sonar in the Human Body

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In all likelihood, listening for sounds generated internal to the human body for the diagnosis of disease predates Hippocrates with credit given to the ancient Egyptians. In 1816, Frenchman Rene Laennec patented the stethoscope. Laennec pioneered the medical science of auscultation, the procedures for medical acoustic eavesdropping. We now have digital smart stethoscopes that claim superiority to listening with the human ear. Modern passive sonar has much to offer for the detection, location and classification of low-level noise mechanisms, primarily turbulent blood flow, that are below the human aural threshold. The premier turbulence detection problem occurs in the early, i.e., pre-symptomatic, detection of occlusive coronary artery disease. This presentation reviews the engineering essentials necessary to invoke modern sensor array processing and high gain post-processing for this application. Extending the performance of these modern techniques to turbulence induced vibrational waves in human tissue requires understanding dispersive elastic wave propagation, the non-stationary nature of coronary blood flow and the connection between arterial blockage morphology and the frequency spectrum of the turbulence induced vibration. This paper discusses these issues and gives some results from ongoing human pilot studies.

Multitaper for Co-prime Sensing Arrays

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Co-prime sensing is a sparse spatial sampling technique for estimating spatial power spectral densities (PSD) by combining interleaved under-sampled sub-arrays. Co-prime sensing arrays match the resolution of a fully populated and uniformly sampled array and save at least 33% of the sensors. However, co-prime PSD estimates have a larger variance than a fully-populated uniform line array with equal aperture. PSD estimates evaluated with Thomson's multitaper method have a smaller variance than those determined by periodogram. The variance reduction is accomplished by averaging statistically uncorrelated estimates from the same sample data. Orthogonal tapers (specifically, the Slepian sequences) form the uncorrelated estimates at the expense of resolution. Co-prime sensing and multitaper have a natural affinity, but no prior work exploits both techniques. This research introduces an algorithm that combines both the variance reduction of multitaper and the sensor savings of the co-prime sensing array to form a spatial PSD estimator with both advantages.

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Gaussian Signal Detection and Spectral Estimation Using a Coprime Sensor Array With the Min Processor

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A coprime sensor array (CSA) interleaves two undersampled uniform linear arrays (ULA) with coprime undersampling factors. A CSA requires fewer sensors to span the same aperture as a fully populated ULA while achieving the equivalent spatial resolution. Conventionally beamforming each subarray of a CSA produces two spatial spectra, or scanned responses, for the observed narrowband signals observed by the array. Each subarray scanned response contains grating lobes due to the spatial undersampling of the subarrays. Previous authors [Vaidyanathan and Pal, IEEE Trans. Signal Process., 2011] proposed multiplying one CSA scanned response with the complex conjugate of the other to resolve the spatial aliasing ambiguities. However, this product processor produces a spatial power spectral density (PSD) estimate with a peak sidelobe higher than the full ULA peak sidelobe. Moreover, the resulting spatial PSD estimate is not necessarily positive semi-definite and as a result, weak sources can be masked by the large negative side lobes of strong interferers.

This paper proposes a new CSA processor, named CSA min, which chooses the minimum of the two CSA subarray scanned responses at each bearing to resolve the spatial aliasing ambiguities. For an extended CSA repeating several periods of the spatial sampling pattern, the min processor reduces the peak sidelobe heights and total sidelobe areas over a product processor for the same CSA geometry and moreover, preserves the positive semi-definite characteristic. The probability density function (PDF) of the CSA min PSD estimate is derived as weighted sums of products of exponential functions and Marcum Q-functions. The closed form expectation and variance of the CSA min PSD estimate are also derived. Simulations show that the min processor achieves a lower variance over the product processor while keeping the same resolution for spatial PSD estimation. The min processor also improves the detection performance over the product processor for complex Gaussian signals in the presence of uncorrelated interferers and noise.

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Co-prime Comb Signals for Active Sonar

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This paper addresses co-prime frequency comb signals for underwater target localization. Co-prime comb signals consist of tones at non-uniformly spaced frequencies according to a 2-level nested co-prime array structure, where M and N are co-prime integers. It is shown that with a specialized non-match filter processing approach co-prime combs containing $2M + N - 1$ frequencies can achieve range-Doppler performance similar to a uniform comb containing $MN + 1$ frequencies. Co-prime comb processing involves transforming the ranging problem into a dual problem, analogous to bearing estimation with a spatial array. Next, a modified version of Pal and Vaidyanathan's rank-enhanced spatial smoothing technique is used to obtain a full-rank positive definite estimate of the spectral covariance matrix of the equivalent uniform comb which can then be steered to various hypothesized delays. One benefit of using a co-prime comb over the equivalent uniform comb is that because fewer tones are used, they occupy less bandwidth thus enabling spectrum sharing and interference avoidance capabilities. The cost is that the co- prime frequencies are distributed over a wider bandwidth extent. Assuming a fixed transmitter power, transmitting fewer tones results in more available transmit energy per-tone, thus increasing the signal-to-noise ratio (SNR). Transmitting fewer tones can also reduce the peak-to-average power ratio of the time series, thus increasing SNR in peak-power limited scenarios. Resolvability studies were also performed and is shown that with co-prime comb processing it is possible to resolve more targets than transmitted tones within one unambiguous range interval.

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The Generalized Sinusoidal Frequency Modulated Waveform for Continuous Active Sonar

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Continous Active Sonar (CAS) systems are bi-static sonar systems transmitting high duty cycle waveforms while constantly processing target echoes. This allows CAS systems to revisit the target scene more frequently than conventional Pulsed Active Sonar (PAS) systems. CAS systems typically transmit Linear FM waveforms with long duration (i.e. 20 seconds) and large bandwidth. The resulting echoes from these transmissions are processed by a bank of constant bandwidth filters followed by either Matched Filtering or Heterodyning to extract target information [1]. Processing the LFM sub- bands revisits the target more frequently at the cost of reduced Pulse Compression Gain (PCG) and Instantaneous Bandwidth (IB). A lower PCG results in degraded detection performance and a lower IB results in reduced range resolution and reverberation suppression. Work by Hickman and Krolik [2] first proposed utilizing pulse train waveforms for CAS to revisit the target scene more often while maintaining large PCG and IB. Sea trials [3] demonstrated these pulse trains capabilities and also highlighted the need for mitigating the strong interference from the transmitted acoustic signal, known as the Direct Blast (DBL). This research presents novel pulse train waveforms and processing methods for CAS systems. The pulse trains are composed of Generalized Sinusoidal Frequency Modulated (GSFM) waveforms [4]. The GSFM generates a family of waveforms by exploiting reflections in time and frequency as well as symmetry properties of the GSFM's Instantaneous Frequency function. The family of GSFM waveforms achieves low cross-correlation properties even when occupying the same band of frequencies. The processing technique trades off Coherent Processing Interval (CPI) and PCG against target acceleration tolerance while still revisiting the target scene every Pulse Repetition Interval (PRI). Simulations and data sets collected from the Atlantic Test and Evaluation Center (AUTEC) confirm the pulse train waveform designs and processing technique performance and additionally show that certain pulse train designs possess the ability to mitigate interference from the DBL.

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Low Probability of Intercept Waveform Design Using The Chirplet Graph

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Low probability of intercept (LPI) is one of the more desirable properties of underwater acoustic signals. The challenge is to design a waveform that is detectable by the intended receivers but invisible to the target [Willett]. The fundamental idea in this work is the distribution of the pulse energy over many shorter, lower energy waveforms that can only be detected in whole, not individually. The new LPI waveform design framework uses the formalism of chirplet graphs [Candes]. Chirplet graphs were originally proposed as a tool to detect unknown chirps in noise. A chirplet graph is a parametric family of signals $\{x_\theta, \theta \in \Theta\}$ where Θ is a multidimensional parameter vector that contains the offset and slope of the chirplets drawn from a codebook. This codebook is only available to the intended receivers. The key design feature here is that chirplets remain below ambient noise and are individually undetectable. The chirplet graph is detected in whole and only by visiting the graph nodes in the same order used at the source. In short, a long, high energy LFM is replaced by a series of short low energy chirplets. A bank of matched filters are each tuned to the offset/slope of the chirplet graph and outputs used in a sequential probability ratio test (SPRT).

The proposed LPI waveform is tested in simulation in SST. The channel is 4500m long, 200m deep, with ambient noise spectral density of 30 dB re 1μ Pa and source level of 185 dB re 1μPa. The LPI signal consists of 10 chirplets. At 4500m, the SNR available at the target is 7 dB. At this SNR, the ROC curves consist of chance lines showing the signal is unobservable by an energy detector. However, by accumulating the evidence collected along the carefully selected path in the chirplet graph using a bank of matched filters, the LPI waveform can be detected at the intended destination at rates of 80% or higher. Two way path loss can be mitigated as the energy detector fails even at SNR=17 dB, allowing for a 10 dB margin for the LPI waveform.

Application of Nonstationary Signal Processing Methods for Target versus Clutter Discrimination

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Classifying underwater targets from their sonar backscatter can be adversely impacted by target-like returns from non-target objects (i.e., clutter). Since clutter and target returns are in general nonstationary, joint phase space methods, such as time-frequency analysis, and time-varying filtering approaches have been explored for enhancing target versus clutter discrimination. We present two training-based approaches to enhance the discrimination of targets from clutter, one utilizing a minimum mean square time-frequency estimation method to design a bank of time-frequency filters, and a second that applies a minimum probability of error (MPE) classifier with LTV pre-filters. Simulation and experimental results will be presented.

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A Hierarchical Mixture Model for Adaptive Filtering of Underwater Acoustic Signals

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Underwater active acoustic sensor systems for location and communications in shallow water environments must invariably address the doubly spread nature of the sparse acoustic response. This is particularly the case for systems operated from mobile platforms and where coherent processing is essential. A hierarchical mixture Gaussian model is proposed and illuminated in order to advance coherent processing of broadband transmissions through delay and Doppler spread environments. The hierarchical model postulates that the acoustic response is composed of a relatively small set of ensonified dimensions in beam, frequency and Doppler. This small set resides along a low dimensional ridge that is characterized by a bulk dilation rate associated with the source receiver platform motion. In order to capture the sparsity of the acoustic response a beta-Bernoulli model is employed to specify the ensonification states of each observed channel dimension with the centroid of the field of beta probabilities constrained by the bulk dilation process. Credence is lent to the sparse model by considering canonical cases of fixed source and constant speed moving receiver with a fixed angle spread as well as that of a time varying piecewise constant receiver velocity process. Bayesian posterior inference of the broadband acoustic response provide a means for the estimation of the acoustic response given the hierarchical mixture model constraints that naturally shrinks non-coherent background clutter. The coherent estimation of the response permits the compensation for the shared time varying dilation process of the various coherent arrivals. An implementation of this approach is for coherent combining of multipath arrivals for an iterative communication receiver. The usefulness of the model is highlighted with the coherent reception of communication signals at extremely low SNR.

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Developing Target Detection and Classification Techniques Based on Dynamic Manifold Analysis

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We present recent innovations and related results in sonar target disambiguation against heavy environmental backscatter. Current state-of-the-art in undersea target detection offers a broad literature between the complementary approaches of statistical and physics-driven method. However, despite some success in resolving target features along low-noise subspaces and dominant elastic wave loci, low detection precision and high false alarm rates remain a bottleneck to target recognition in high-clutter environments. The joint challenge of tracking acoustic color deformation with changing experimental and background conditions, as well as interference from environmental backscatter provides the motivation behind this proposed work.

We propose to bridge the gap between statistical subspace-driven techniques and physics- based methods by formulating the sonar target recognition problem from a novel geometric perspective. Specifically we frame the target signature as geometric combinations of elastic waves that represent different wave loci undergoing homeomorphisms (smooth deformations) with evolving orientation and sediment characteristics. We provide model justification for identifying and tracking elastic waves that morph with changing aspect angle and sediment loadings. Topological connectivity across each deforming manifold preserves the corresponding wave geometry through the homeomorphisms. This provides the theoretical basis for robust disambiguation of target features against environmental backscatter.

Further disambiguation of environmental clutter and boundary effects is achieved by learning and tracking acoustic manifolds unique to the target using local dictionaries that evolve with the target response as a function of aspect angle and sediment impedance. We employ a range of supervised learning techniques to identify homeomorphisms across target-specific acoustic manifolds as they change over aspect angle and sediment impedance. The false alarm rate is naturally lowered as feature groups that represent unique geometric combinations within the targets scatter topography define equivalence classes that are ultimately separable against boundary effects and other environmental interference. By feature group, we refer to elastic wave features within the acoustic scatter signature of a target. Each wave group manifests as a deformable but topologically connected geometric structure, in contrast against disconnected topological characteristics of other scattering phenomena (such as boundary effects) in the received sonar signal. Recent results based on experimental field data are presented.

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Analysis of Fields from a Time-Stepped Three-dimensional Acoustic Model With Oceanic Variability: Correlation Matrix Properties and Implications

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A three-dimensional acoustic propagation model coupled to an ocean model that is driven with tidal forcing is used to simulate time-variable 300-Hz acoustic fields from a single source in areas of order 50 square km in size. Fields from an area with a canyon are examined here. Spatiotemporal correlation matrices are computed for synthetic horizontal arrays placed throughout the volume and then examined. Time samples are taken throughout two tidal periods. The properties of this matrix control the performance of algorithms ranging from simple beamformers to more advanced methods. Variation of the matrices as a function of location in the box will be examined. Amplitude and phase variation patterns that contribute to the correlation matrix structure will also be presented. Eigenanalysis of the matrices, i.e. calculation of the variance fractions described by the empirical orthogonal functions sorted in descending order, shows that a single eigenfunction does not describe the majority of the variation at some sites. The relationship between the signal correlation properties and environmental factors such as depth along the source-receiver track, proximity to a sloping seabed, and internal tidal excursion along the track will be explored.

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Using Relative Doppler to Improve Dolphin Tracking, Particularly by Enabling Better Association of Clicks to Individual Animals

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Acoustic tracking of dolphins, using their vocalizations, provides a valuable adjunct to visual observations, but poses a number of challenges. Dolphins make two kinds of sound, whistles and clicks, with whistles spanning tens of Kilohertz, and clicks spanning hundreds of Kilohertz in bandwidth. Although their speed through the water is modest, the high frequency of their vocalizations results in their having significant Doppler. Since we do not know the original waveform, we can only measure the relative Doppler among different observing sensors. Exploiting these Doppler differences overcomes several problems typically encountered in such tracking. For example, dolphins typically travel in groups. Whistles are more or less meandering tones, with reasonably distinct "melodies", so even with multiple overlapped whistles, we can be safe in assuming each distinct whistle belongs to one animal. However, clicks are more attractive for tracking, because of their greater bandwidth (providing better resolution for time-of-arrival estimation), but it is problematic to associate clicks to individual animals, because they are all so similar. However, the time scaling due to Doppler experienced at different observers allows overlapping sequences of clicks from individual animals to be differentiated. We will present results of processing clicks and whistles from separated hydrophones using correlators that include Doppler search. We will discuss how this impacts dolphin tracking and its various applications.

An Approach for Automated Detection and Localization of Passive Sonar Contacts

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This work seeks to advance the state-of-the-art of fully automated detection and localization of passive sonar contacts. The impetus of this work is the advancing state-of-the-art of large diameter unmanned underwater vehicles (LDUUV) and the need to automate their contact localization capabilities. A particle filtering track-before-detect approach is taken to develop three core algorithms to perform the above functionality. Each of the core algorithms are examined in pertinent respects using a real high-resolution sonar data set. The data set is highly cluttered, has varying noise levels, and consists of moving contacts that fade, cross, and merge in the bearing space. For comparison, a mainstay point-measurement-based particle filter approach using probabilistic data association is employed and shown to have greater difficulty addressing the scenario challenges than the developed approach herein.

A New Architecture for Multi-Target Tracking

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The Joint Probabilistic Data Association Filter (JPDAF) is a recursive algorithm designed to track multiple targets in close proximity and in the presence of false detections or clutter. The estimation performance of JPDAF is often quite good unless the clutter density is very high however the computational burden grows exponentially with the number of targets and clutter detections due to the number of assignment events that must be enumerated. This is especially true when JPDAF is implemented in an Interacting Multiple Model (IMM) architecture to handle target dynamics. There are several ad-hoc methods for dealing with cases where the computational burden of full IMMJPDA exceeds the capability of the computer. Pruning is one such method that eliminates all but the most likely data association events in the enumeration process. Global Nearest Neighbor simply selects the data association event that minimizes the total distance of measurements to tracks. So called Cheap JPDA uses an approximation to streamline the computation of the probability of association of track i with measurement j. The performance of each of these methods has been extensively studied in the literature. Some tracking problems involve target states other than conventional position coordinates where the primary components frequently exhibit independent dynamics; it is common to observe a rapid change in only one primary component. For example, the bearing from a cell tower to a particular phone and the carrier frequency are examples of attributes of a cell phone user that could be tracked together but may exhibit independent dynamics. Although it may be tempting to track these quantities separately, tracking them together may significantly improve track hold especially when tracking multiple phones in close proximity. This presentation will describe a new heuristic architecture that reduces the computational burden for such tracking problems by performing the data association jointly but updating the track components separately. The computational savings along with simulated data results will also be presented.

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Wednesday **October 14, 2015**		**Thursday** **October 15, 2015**		**Friday** **October 16, 2015**	
		8:15–9:05	Session B Sp/CoP II Laurel	8:15–9:05	Session I Sp/CoP IV Laurel
		9:05–10:20	Session C AUV Proc. Laurel	9:05–10:20	Session J Waveforms Laurel
		10:20–10:45	Break Laurel	10:20–10:45	Break Laurel
		10:45–12:00	Session D Param. Est. Laurel	10:45–12:00	Session K Class/Mod. Laurel
		12:00–1:00	Lunch Whisp. Pines	12:00–1:00	Lunch Whisp. Pines
		1:00–1:30	Session E Don Tufts Award Laurel	1:00–1:25	Session L Acoust. Mod. Laurel
		1:30–3:10	Session F Stat. Mod. Laurel	1:25–2:40	Session M Tracking Laurel
		3:10–3:35	Break Laurel		
		3:35–4:50	Session G Sp/CoP III Laurel		
5:00–6:00	Welcome Reception Whisp. Pines	4:50-5:15	Session H Turbulence Laurel		
6:00–8:00	Raytheon Dinner Whisp. Pines	6:00–8:00	OES Dinner Whisp. Pines		
8:00–9:30	Session A Sp/CoP I (Plenary) Laurel	8:00–?	SOB Session Laurel		