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14. ABSTRACT

Under ONR grant, work was performed in support of the Acoustic Observatory science plan. Specifically, the P.I. (Dr. James Lynch, WHOI) worked closely with Drs. Norman Owsley and Douglas Abraham in planning, hosting, and reporting on a two-day workshop held at Newport, R.I during June of 2002. This workshop formulated an overall science plan for the Acoustic Observatory, which will be used in guiding its funding and operation over the next five years. The formal report of this workshop is contained in a collection entitled "White papers submitted for consideration at the ONR Acoustic Observatory Science Plan Workshop, Newport, R.I. June 25-26, 2002".

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Low frequency attenuation inversions using spectral ratios

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Introduction

During the two previous acoustics field experiments (Shelf Break Primer and ASIAEX) acoustic data from broadband sources was used to invert for geoacoustics properties[1]. The two experiments were conducted in two distinctly different environments. Shelf Break Primer was conducted in the Middle Atlantic Bight on the east coast of United States whereas the ASIAEX experiment was conducted in the East China Sea. The two sites were in shallow waters (≅ 100 m) but the sediment properties were expected to be different. Explosive sources of weight 1.8 lbs were used in the Primer experiment and signals were collected at a range of 40 km. 0.36 kg and 1.0 kg explosives were used in East China Sea at various ranges.

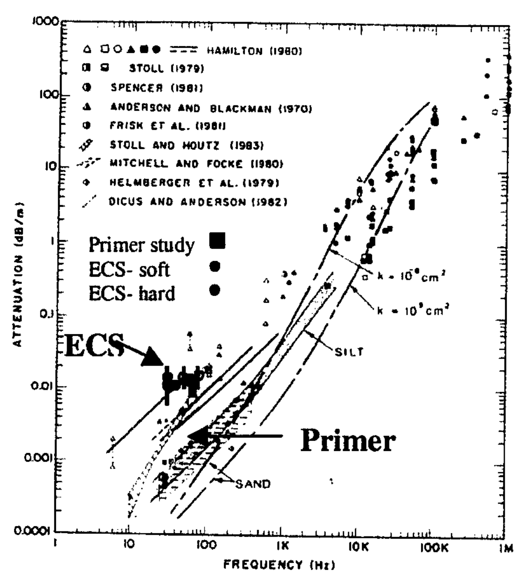

Figure 1: This figure shows the sediment attenuation inversions at the Primer and East China Sea experimental sites in comparison to some published results. The Primer attenuation values are low compared to the ECS values.

Figure 1 shows the attenuation inversions along with some published results. The inversions were carried out in the frequency range 10- 100 Hz. The attenuation values show considerable spread in the frequency range 10- 200 Hz. The Primer and ECS results

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tend to be in the middle and upper end respectively of this range. Both the inversions were based on spectral ratios and were identical. The factors contributing to the large difference in the values are being currently investigated.

Another issue of interest is the non-linear variation of attenuation and the velocity dispersion in the sediments. Many of the traditional models predict linear variation of attenuation with frequency over the entire frequency range of interest[2]. But significant amount of velocity dispersion has been observed experimentally and supported theoretically by the Biot theory. This theory also predicts non-linear relationship between intrinsic attenuation and frequency.

Objectives and Methodology

We propose to map the sediment acoustic parameters at the Acoustic Observatory site. Using broadband sources we plan to estimate the attenuation of the sediments in the frequency range 10- 200 Hz. These values will be compared with other published data in this frequency band.

Other objectives of this study will be to:

- Map the sediment acoustic properties in the study area in the frequency range 10- 200 Hz using our inversion techniques. Using available sediment data the inversions can be compared and verified. Based on prior results, spatial coverage of 30 km is reasonable; depth coverage to 30 m and accuracies of 10- 20 m/s for compressional wave speed is achievable.
- Using a broadband source estimate the attenuation as a function of frequency. This will enable us to observe the attenuation- frequency relationship. If a non-linear frequency dependence is observed predictions based on Biot theory can be used to compare this relationship.
- To use imploding sources comprising of evacuated spheres as broad- band sources. These sources produce higher source levels compared to light bulb sources[3]. They also have a significantly reduced bubble pulse presence. The design and timing of such imploding spheres is the subject matter of a related study.

We propose to use the broadband sources (imploding spheres/ other shapes) in the study area and use our inversion technique to map the sediment parameters over the area. This attenuation estimates obtained in a site where other environmental parameters can be accurately monitored will help us to understand the attenuation in sediments and its dependence on frequency.

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Time-Frequency-Space (TFS) Processing of Broadband Dispersive Signals in Littoral Waters Utilizing Environmental Feedback

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Introduction:

Recent experiments such as ShelfBreak Primer and ASIAEX collected long range propagation data in shallow water on vertical line arrays from Wide Band Source (WBS) explosives. Signals collected by the vertical arrays were processed using Morlet [1,2] wavelets to observe the unique arrival structure[3] due to group speed dispersion. Inversions for environmental properties using this data based on group speed dispersion are being carried out at University of Rhode Island. Based on analysis of the signals collected in the Middle Atlantic Bight and East China Sea, it has become evident that significant gains are possible using Time-Frequency-Space (TFS) processing. The goal of this study is to investigate higher resolution TFS analysis procedures to obtain better estimates of the inverted environmental parameters. In addition, there are possible payoffs using this technique in the detection, localization, and classification of transient signals in shallow water.

Objectives and Methodology

- Improve the time-frequency Matching Pursuit algorithms to use more compact support for greater time resolution and positively sloped signals (ground and head wave detection).
- Combine the above technique with spatial modeling to improve the match between the received and modeled time signals (TFS). An acoustic propagation model will be used to estimate the ocean propagation parameters (transfer function) and provide feedback to the matching pursuit algorithm to improve the data processing resolution.
- Quantify the signal processing gains made possible by TFS.

Dispersive acoustic signals contain significant amounts of information concerning the shallow water environmental structure. Ocean acoustic experiments are usually limited in the number of direct environmental observations. The proposed work has the potential to increase the resolution and decrease error bounds of inverted environmental parameters by providing greater time-frequency information of the received signals. Recent experiments such as ShelfBreak Primer and ASIAEX have shown that high time-frequency resolution is needed to better understanding the environmental effects on acoustic inversions.

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Acoustic signals are commonly used to estimate sound speeds, currents, and geoacoustic parameters. The broadband acoustic propagation in shallow water at long ranges is characterized by group speed dispersion. It is possible to unravel this modal propagation dispersion characteristic using a proper time-frequency analysis. Although the wavelet transform has better time-frequency resolution than the short-time Fourier transform to extract the arrival structure of the observed data, it is not sufficient to get good resolution for high frequencies. The matching pursuit algorithm is an alternative approach to provide excellent spectral localization for the dispersive acoustic signals (fig.1).

In the matching pursuit algorithm, a set of basis functions are generated by translating and modulating a single window function as:

$$\Psi_{(\tau,\theta)}(t) = \gamma(t-\tau)\cdot e^{j\theta(t)}$$

where τ is the translation and $\theta(t)$ is the frequency modulation. These basis functions are called "time-frequency" atoms. Based on wave propagation theory, we discover the Gabor atoms with the specific frequency modulation as:

$$\Psi_{(\tau,\theta)}(t) = \gamma(t-\tau)\cdot \exp(j\frac{2\pi f_m}{c}\sqrt{c^2t^2-R^2})$$

where f_m is the cut-off frequency of signal modal component, c is the average sound speed of water and R is the distance between the signal source and receiver. These atoms have covered all possible time and frequency locations in the time-frequency plane. Once these atoms are defined, the time-frequency information is calculated by projecting the atoms onto the signal as sown in the following equation:

$$TFR(\tau, f_m) = \int x(t)\gamma(t-\tau)\exp(j\frac{2\pi f_m}{c}\sqrt{c^2t^t-R^2})dt$$

The parameter for c (sound speed) will be replaced by the modal group velocity, $c_g(f)$, a function of frequency, and range R, determined from the inversion process using forward modal propagation modeling. This iterative process will be used to best fit the dispersion characteristics from the matching pursuit algorithm to the data. The goal of this study is to match the time-frequency and time domain signal characteristics in the ECS as well as Primer data by developing a signal processing technique incorporating environmental feedback.

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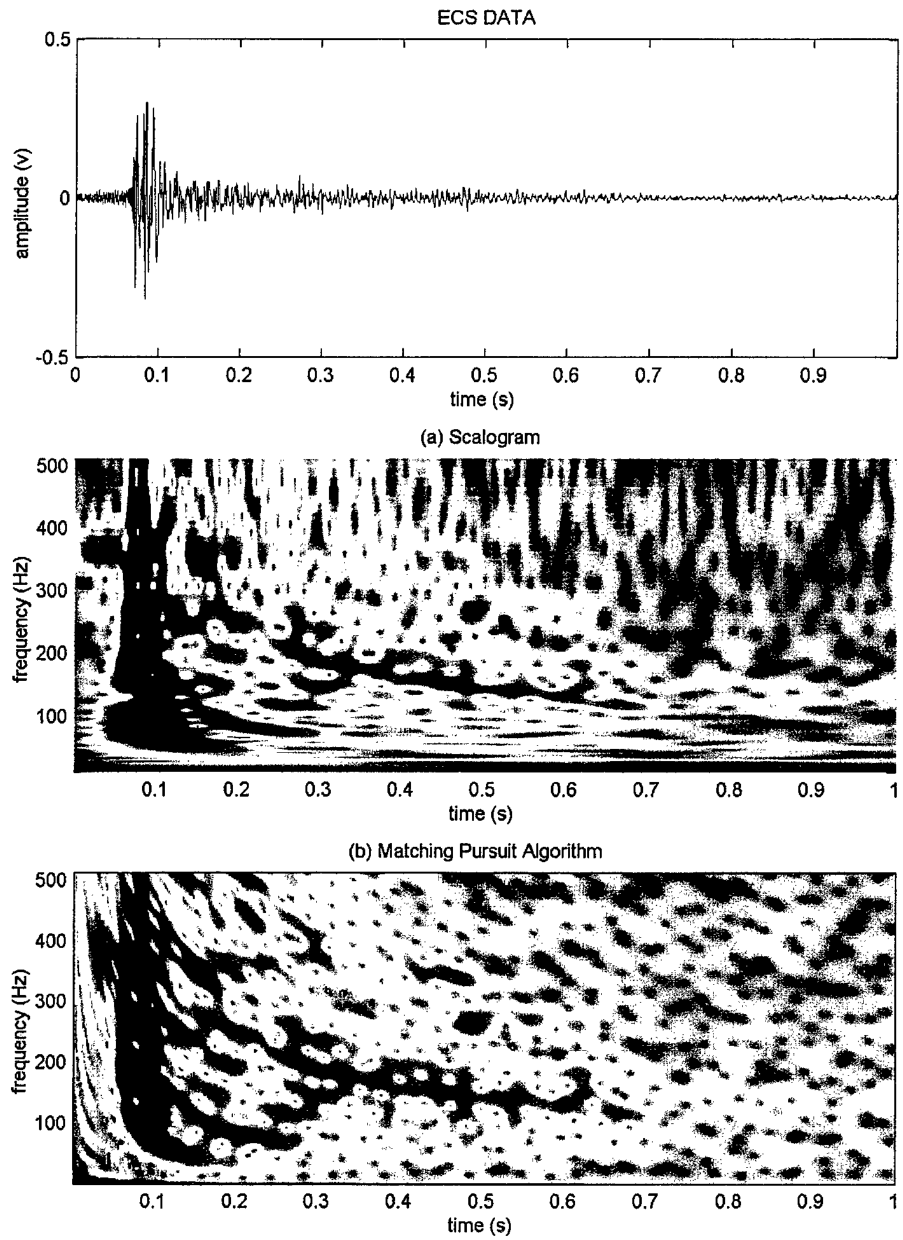

The wavelet transform and matching pursuit algorithm are implemented to analyze the ECS data as shown in Fig. 1, the modal dispersion structure, especially in high frequencies, can be disclosed using the matching pursuit algorithm.

Time and Depth Accurate Acoustic Implosion Source

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Introduction

Explosive sound sources present risks to both their users and the marine environment they are used in from chemical and pressure effects. One alternate broadband sound source under investigation is an implosive source.

Implosive sources offer several advantages over explosives:
1. An implosive source is intrinsically less hazardous
2. No special explosive ordinance training is required for the users
3. No toxic explosive byproducts are produced to remain in the environment

These sources consist of an air cavity crated by a collapsing cavity, such as a light bulb, glass globe (that is fractured at depth), and evacuated glass sphere, pipes with collapsing end plates or cavities with fast opening valves to create a broadband pulse [1,2,3].

Activation of many of these sources is passive, or by dropping, a messenger down the suspension line to activate the crushing mechanism. Exact timing of the source implosion is not achievable by these methods and an in-situ hydrophone is needed to monitor the signals to determine source timing. Lack of accurate timing increases experimental error and adds uncertainty to the solution of inverse acoustic problems.

Objectives and Methodology

We propose to design and fabricate an easy to use implosive source with accurate source timing. The timing uncertainty will be controlled by using a precision timed electrically activated solenoid. This system can either be controlled remotely by a computer-controlled switch, synchronized to GPS time or, to eliminate the surface connection, by using an autonomous local microprocessor outfitted with a programmable clock synchronized to GPS time. Ultimate timing accuracy is established by calibration of the solenoid mechanism. This will reduce the timing uncertainty to less than a millisecond from the timer command.

Additional objectives will be to provide user parameters for:
1. Source Level vs. depth for several source types
2. Source primary frequency
3. Bubble Pulse period for gas filled cavities

This source can be used for investigation of sediment properties (compressional wave speed and attenuation), sound speed structure, water column sound speed structure and other acoustic parameters.

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Appendix

The for an air filled sphere the primary resonance is given by Minnaert's Formula:

$$f(R, p0) := \frac{1}{2\cdot\pi\cdot Ro}\cdot\sqrt{\frac{3\cdot\gamma\cdot po}{\rho}}$$

po = hydrostatic pressure
γ = ratio of specific heats for gas in the bubble
ρ = density of the surrounding fluid
Ro = mean bubble radius at the hydrostatic pressure

For a given bulb or cavity size, frequency is related to depth[i] by

f $\propto$ (g(h+10)) ^(5/6)

where:
g = 9.8 m/s^2
h= source depth in meters

This relation shows that the primary frequency is controlled by the depth (ambient pressure) and the radius of the bubble, both under the control of the user.

Source level increases with depth and is related to the potential energy of the cavity at depth. Conversion efficiency from potential to acoustic energy is approximately 11.4% [3]. The empirical increase in source depth for 100-watt light bulbs from reference 3 is;

SL (db re 1uPa^2) = 160 + 26*log10(h)

For a 43 cm (17") diameter sphere at 50 meters, the peak source level is **~250dB//1uPa**.

Understanding Acoustic Propagation and Variability at the Site of the AO
The Florida Straits Propagation Experiments (FSPE)

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University of Miami

Propagation experiments (Nguyen, DeFerrari) recently completed off the coast of South Florida are similar to the planned AO measurements in several respects: 1) the site is the same and 2) hydrophone arrays at sea are connected to shore by fiber-optic cables. There are differences. Namely, the instrumentation suite is smaller (96 elements for the FSPE as compared to a planned 1500 elements for the AO) and the objectives differ (the FSPE study focuses on frequency, range and depth dependence of the sound field fluctuations statistics whereas, the AO focuses on ship noise cancellation to improve passive sonar performance).

On the other hand, the FSPE has been successfully completed and we have data in hand for channel broadband pulse responses at center frequencies from 100 to 3200 Hz in octave step, observed over a period of 28 days for two ranges, 10 and 20 km. Variability of the acoustic environment was observed during the acoustics measurements.

These precursor experiments offer a glimpse of the technical problems and scientific issues that the OA will encounter. The FSPE have revealed much about fundamental propagation and the variability of the acoustic environment, thus far, and the analysis continues. As our understanding improves, we may be able to predict some of the limitations on performance of the noise reduction algorithms, which are at the heart of the AO objectives.

Our objective for the workshop is to set down a base of scientific understanding about the acoustic propagation and variability at the site of the AO. Our results and conclusions are drawn from data and the extrapolation of data using full wave propagation models - namely normal mode (PROSIM and SNAP) and the parabolic equation (MMPE). From this vantagepoint of data and model studies we speculate about the scientific and operational issues facing the AO. Two papers will be available for distribution at the workshop: 1) Sound Speed Fields and Fluctuations and 2) Acoustic Propagation and Variability – Depth, Time, Frequency and Range Dependence. The basis for the speculation and discussion that follows is contained in these papers.

Issues Facing the AO

The issues separate in two groups: 1) technical topics that are problematic for the installation and operation of the AO systems and 2) scientific topics about the environment and the propagation that must be resolved. Here we sort out the more serious issues (our opinion) and make recommendations.

At the onset, let us clarify that we have chosen not to comment on the ocean engineering issues. These are legend and formidable. The plans are ambitious. Good Luck!

Technical Issues and recommendations:

1 Data Recovery for Basic Research. – How to sip from a fire hose.

The FSPE generated 700 g-bytes of raw samples - 16 bits fixed point for a 28-day measure from the multi –frequency UM Sound Machine. In its raw form the data are unusable for scientific analysis. So, a server and search engine were developed to handle processed averaged data in convenient form and format. The number of data points was reduced by a factor of 24 but the storage capacity only reduced to 200 g-bytes owing to floating point formats and other considerations. The final server is queried with integer values for frequency, transmission and hydrophone number and returns 1 hour worth of min pulse responses and 20 3 min interval sound speed profiles. The integer tag for each hour allows loops in FORTRAN or MATLAB languages so that one can conveniently draw down series in frequency, time or depth (h no.). Thus "bite size" and manageable chunks of data are easily downloaded. A single server can support dozens of scientific projects. We recommend that the AO develop a single server for scientific participants. The alternative is to pump out tera-bytes of raw data to many participants each of who will be required to repeat the same data pre-processing and storage

2 Travel Time errors for hydrophone positioning.
The hydrophone positioning system specification requires accuracy of a few centimeters. That translates into a few cycles of phase for the acoustic arrival time measurements. We doubt the ocean will support that precision if both the pinger and receiver are on the bottom. The water sediment boundary will act as a sound duct having a minimum sound velocity directly on the interface. Upward and downward refracting wave path result analogous to SOFAR propagation with source and receiver on the axis. Such propagation produces a complicated multi-path picture that may not allow precession of travel time observation. An alternative is to moor the pingers off the bottom to isolate a direct waterborne "Fermat" path that should be more precise. Preliminary experiments are recommenced to determine the limitations of travel time precision. To that end, we are collaborating with FAU to install acoustic sources on an AUV. The AUV can be pegged to the bottom at different ranges from the UM vertical array and then transmit for an extended period. In this way, measures of variability of travel time (i.e. pulse amplitude and phase) are obtained for the study of fluctuations. The AUV provides the flexibility to position the source anywhere in the water column. The approach will also allow us to evaluate the use of acoustic tomography or the direct observation with thermisters to compensate for variability of the mean sound speed field to improve element location precision.

Scientific Issues:

1. Observing the sound speed field. The oceanography of the area is complicated and very energetic. Sound speed profiles have strong negative gradients as are generally found inside western boundary currents. Further, meanders of the core of the Florida Current and wind driven up- and down-welling produce large slow fluctuations in the mean sound speed profile and also appear to generate internal waves.

The link between oceanographic fluctuations and the acoustics is the sound speed field. We have had good luck with arrays of SEAMON Mini self recording temperature sensors. Ten of these can be placed on a mooring for about 7 k and the cost of the mooring including acoustic releases is about 15 k. Thus for an equipment cost of around 150 k, ten moorings could be deployed. In this way it should be possible to get the big picture of the spatial coherence and speed of propagation or meanders, eddies, up welling and also the direction and speed of the internal wave field. Simple and inexpensive moorings can provide a wealth of information.

2. Moving sources. A great many experiments have been conducted with fixed (or moored) systems. Generally, signals are well behaved at shorter ranges (>15k) and have surprisingly good coherence and predictability so that matched field processing works well. At longer ranges signals are randomized by fluctuations in the propagation medium. However far less is known about acoustic fluctuations from moving sources. The problem is more complex and not well understood especially for the case of bottom interacting modes. Some analysis concludes that even small range fluctuation in bathymetry can randomize propagation.

At some point it will be logical to conduct a conventional fixed source transmission to the AO arrays –that is, an experiment like the FSPE. The source can be deployed deep to simulate a target and shallow to simulate a surface ship noise source. At that time an experiment with broadband towed source should be considered.

3. The Geo-Acoustic bottom and sub-bottom. Water borne propagation arrivals observed in experiments are predictable with PE and Normal Mode models with typical bottom properties at the FSPE site. However the lower frequency pulse responses 400 Hz and lower have arrivals that can only me modeled by assuming reflection or refraction from deep in the sub-bottom - as deep as 200 m. These arrivals and the modes/rays that produce them can only be understood by obtaining the knowledge of the geo-acoustic properties of the bottom with deep cores. Deep cores are necessary.

The Jodies Resolution deep drill ship will be passing through the Florida Straits late in 2002. I am preparing an ancillary proposal to Jodies to drill 6 cores and to fit two with re-entry cones so that it will be possible to place receiver arrays and sources in the wells to do bore hole Tomography.

AO White Paper Submittal
29 April 2002

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Title: Effect of Sub-bottom Propagation on the Time and Space Dependent Acoustic Channel Impulse Response

Background: The potential gains and robustness of conventional and adaptive beamformers and signal processors are dependent on the characteristics of signal and interfering noise. Given the time dependent amplitude and phase for a signal and all interference at some instant in time a unique system processor can optimize for that particular detection case. However the optimum solution is only valid for a relatively short period of time because of natural and man-made changes in the signal and noise field.

For deep water, long-range, fixed geometry cases where the surface and bottom interactions are minimal, a signal usually propagates by one or two paths and the acoustic channel impulse response can be stable for hours. Furthermore, the assumption of random interference is usually valid. In shallow water, as the environment and interference becomes more complex, the time frame during which the optimal solution is valid becomes shorter and shorter.

Issue:

In shallow water, acoustic propagation generally involves multiple interactions with the surface and bottom that depend on the sound speed profile. Because localized man-made noise often dominates the low frequency background noise, both signals of interest and interference arrive via multiple paths. Thus, for most shallow water environments the channel boundaries dominate the spatial and temporal stability of signals and localized interference.

The effect of the surface on propagation has received considerable attention over the past 50 years. While scattering near a randomly rough and dynamic sea surface is certainly not simple, nor well understood, there are at least some theoretical and empirical models to describe the time and space dependent signal modulation and attenuation processes that are independent of water depth. Thus, some rough estimates can be made of the variability in the channel impulse response, as induced by the sea surface and water column. For example, the extended works of H. DeFerrari have shown that pulse time spreads of 0.1 s for shallow water RBR conditions can be extended to nearly 1.0 s with the addition of energy transfer in and out of a surface duct (JASA 95 (6), p. 3129, June 1994).

In a similar vein, with the geoacoustic properties near the selected AO site and at the lower end of the frequencies of current interest, significant ocean-borne energy is likely to be transmitted into the bottom, propagated at relatively high speed and refracted back into the water column. Thus, the sub-bottom needs to be considered as a continuum of the water channel and the combined ocean and sub-bottom paths treated as the acoustic channel. Considering the impact of sound speed changes of tens of meters within the water column on acoustic propagation, the impact of a multi-layer sub-bottom, with much larger changes in sound speed, can result in significant changes in the complete channel impulse response. The occurrence, dynamics and impact on the impulse response are dependent on the water column sound speed, sub-bottom acoustic properties along the propagation path and the source-receiver geometry. For shallow water areas, significant changes in the water column can be expected as a function of time (hours, days, months, seasons) and significant changes in the sub-bottom layers can be expected as a function of range and bearing. Furthermore, the depth of sources of interest and sources of interference affect the degree to which the bottom is insonified.

Thus a key issue in assessing the performance limits and robustness of a system and optimal processing techniques over tactically significant periods of time is a fundamental understanding and quantification of the occurrence, dynamics and impact of sub-bottom propagation on the channel impulse response as a function of depth, range, bearing, frequency and time.

Concepts and Ideas for the Acoustic Observatory Program

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May 2002

The ONR Acoustic Observatory (AO) program provides a unique opportunity to quantify potential performance gains for the passive sonar ASW problem under carefully controlled conditions, greatly enhancing the development of future tactical towed-array systems for transition to the fleet. The AO program proposes that these performance gains should be achievable in three general areas: better arrays (larger, volumetric array apertures), better utilization of environmental information for beamforming, and better adaptive performance in dynamic environments. This paper outlines the concepts that the authors believe should be explored in order to maximize the above gains.

Baseline System Performance and Array Performance. The first step in understanding achievable performance gains is to quantify current baseline performance. Since the initial AO array is based on the TB-29 array, a reasonable baseline would be the Advanced Processing Build (APB) system for a single TB-29. Performance of the APB TB-29 system can be simulated for the south Florida underwater environment. The baseline system simulation will provide a means of quantifying how much of the gain achievable using the AO volumetric array (and variants) is due to the aperture.

Extending the APB system simulation to the AO volumetric array requires several processing choices, including a data processing strategy for the array (fully coherent, semicoherent, incoherent) and a dimension reduction strategy which may significantly differ from the beamspace processing in the baseline system. Once the processing choices are made, one can determine what benefit the AO volumetric array provides in terms of directional noise gain (especially wind noise gain), source discrimination (range and depth as well as bearing), and reduction of ambiguities (e.g., left-right). Insights from the simulation work (in this study and the ones below) will then contribute toward understanding the results of real data processing with the AO array.

Physics-based Signal Processing. Much attention in the underwater community has been applied to the idea of physics-based processing for both better detection performance through reduced signal gain degradation (SGD), and to achieve improved source localization in depth and range. Matched field processing (MFP) attempts to model the full acoustic field through propagation modeling and - with optimal performance - provides fine source resolution in both range and depth. However, MFP is sensitive to inaccuracies in environmental knowledge. One method that could be used to address this limitation is to use a strong source of opportunity (such as a surface ship) to dynamically estimate the environment. The extended deployment of the AO array offers a unique opportunity to collect long-term data on the ocean variability and quantify its effect on shallow-water acoustic propagation and signal processing algorithms.

Of perhaps greater practical interest than MFP are techniques that provide coarse range and depth discrimination while maintaining greater robustness to mismatch (via less dependence on environmental parameters). These techniques rely upon identifying aspects of the propagation structure that are sufficiently robust to be exploited for localization or classification improvement. For example, coarse depth discrimination may be achievable by exploitation of the modal vertical angle arrival structure as resolved by an array with significant vertical aperture. A basic study on the utility of environmental processing techniques such as this would involve the following: (a) determine which approaches produce significant performance improvements over conventional processing; (b) determine what array aperture (horizontal, vertical) is needed for a given environmental processing technique in order to achieve the above performance improvement; (c) determine what performance improvement is actually *achievable* for a given environmental processing technique with the AO array and determine how this performance improvement compares with that attained by full-field MFP, assuming reasonable mismatch levels; (d) corroborate simulation results with real data.

Adaptive Processing in Non-Stationary Environments. Surface ships, which are prevalent in shallow water environments, can severely limit the ability to passively detect quiet submerged targets. Application of adaptive signal processing algorithms can mitigate surface interference. However, adaptive interference suppression is degraded for sample-covariance-based adaptive processors when targets and discrete interferers move significantly during the time required to estimate the sample covariance matrix (SCM). The motion problem is exacerbated for large, high-resolution arrays (beams are transited more quickly) and for volumetric arrays (the array response changes more quickly). The AO array provides an important opportunity to evaluate motion-robust algorithms without the additional complication of towed array motion, and to quantify performance gains in an environment with high surface ship density.

Two general approaches to the problem of source motion are (1) to stabilize SCM computation for relatively few snapshots via reduced degrees-of-freedom (DOF) methods; (2) to incorporate source dynamics directly into the adaptive processing. Examples of reduced-DOF methods include subarray processing, beamspace processing, rank reduction (via eigenvectors or modes), and diagonal loading. Reduced-DOF methods help alleviate motion losses by both achieving faster convergence of the adaptive weights, and providing reduced sensitivity to source motion through coarser beams. However, DOF reduction invariably results in some loss of adaptive nulling capability and they require an intelligent method of determining the appropriate signal subspace. As an example, the choice of how to choose sub-arrays within a volumetric array needs to be addressed by considering array resolution, environmental effects (including signal coherence), and stationarity constraints.

An alternate approach to motion loss mitigation is the application of"dynamic adaptive processing" (DAP) methods, such as projection nulling, derivative-based updating, and both model-based and invariance-based target motion compensation. DAP methods make assumptions about the motion of sources (including source tracks, source velocity, and source range-frequency invariance) and build these assumptions into the adaptive processing. While they promise increased gains from exploitation of source dynamics, they can be sensitive to environmental inaccuracies and are more computationally intensive. A basic study on adaptive processing in dynamic environments, then, involves the following: (a) quantify (in terms of SGD, output SINR loss, and eigenvalue spectrum spreading) the effects of moving sources on adaptive output by direct comparison with the ideal (stationary-source) case; (b) for reduced-DOF methods, determine whether the tradeoff between reduced sensitivity to motion effects and reduced resolution is worthwhile; (c) for DAP methods, determine whether incorporating source dynamics into the adaptive processing produces enough gain to make the extra computation worthwhile, and determine whether the methods are robust to mismatch in the assumptions for source dynamics; (d) corroborate simulation results with data.

Applying the Results: Transitions. Practical application of results from the AO program requires threat-specific analysis. To this end, the results of the above studies must be reported within the context of specific source levels, source spectra, and feature characteristics of important threats of interest (i.e., diesel-electric and nuclear submarines). AO study results must also be extrapolated to include the additional challenges of detection with towed arrays (versus the stationary AO array), including array shape estimation and quickly-changing environments. The combination of systematic study and reasonable extrapolation to real-world scenarios, enhanced by the authors' previous extensive experience in passive sonar programs (SBCX, APB, RPS), promises strong, well-supported recommendations for the next-generation ASW passive sonar.

AO White Paper Submittal
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Title: Time Dependence of Spatial Coherence within Array Dimensions

Background: The potential gains and robustness of conventional and adaptive beamformers and signal processors are dependent on the coherence of signal and interfering noise at the sensor field. Low frequency (875-1375 Hz), shallow water experiments have been conducted using towed arrays and moving sources to gain an understanding and quantify changes in the coherence function between **moving** sources and receivers as a function of time and range to determine the existence and permanence of optimum ranges, depths, bandwidths and integration times. For example, Shepard (Ref.) has shown that in early summer, with a two-layer water column, the coherence between a shallow source and deep receiver exhibits more temporal change than when the source and receiver are both below the seasonal thermocline (fig. 1).

Constant Range: 13 kyd	Water Depth: ~70 m	Receiver Depth: ~30 m

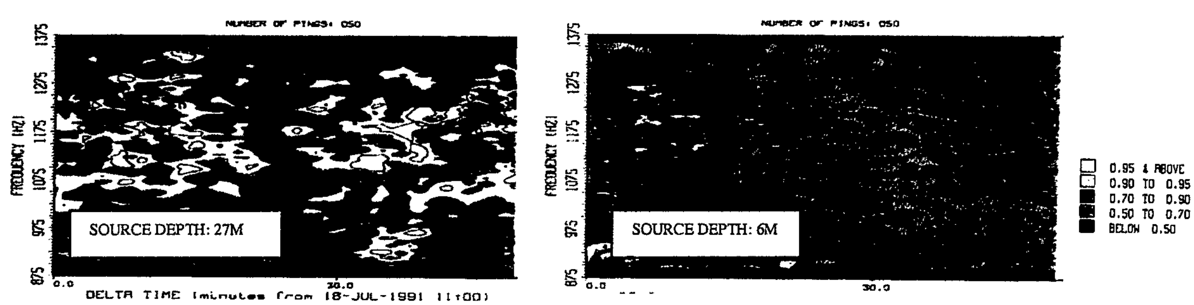

Figure 1: Coherence versus Frequency and Time with Zero Range Rate Moving Sensors

The figure also illustrates the impact of source depth on received signal coherence. Though not shown, he also quantified the difference in range dependence for deep and shallow sources. The data demonstrates the variability of coherence along a propagation path is dependent on time, space, and source depth. However, a key underlying issue for a spatial array is the magnitude and dynamics of coherence between array sensors for signals of interest and interference.

Issue:

There is a need to understand, quantify, and qualify the spatial and temporal limitations over which signals can be coherently exploited at low frequencies in shallow water.

Because localized man-made noise often dominates low frequency background noise, it is equally important to consider near-surface and deep sound sources.

For example, in designing adaptive processors to exploit the properties of desired and interfering signals, it is important to know the environmental parameters affecting update rates (hours, days, months, seasons) and integration times, and to determine if these intervals for near-surface and deep sources are significantly different. Assuming coherent rejection of interference and coherent signal enhancement is a processing option, it would also be invaluable to know the relationship between the inter-sensor coherence of near-surface and deep sources of energy as a function of range, bearing and depth

The spatial extent of the proposed AO system provides a unique tool with which to quantify the spatial and temporal extents over which coherent processing is optimal. Results could lead to improved processing algorithms that could adaptively select sub-apertures or differing integration times to better enhance signals of interest.

In shallow water, long-range acoustic propagation generally involves multiple interactions with the surface, bottom and, at very low frequencies, sub-bottom layers. The degree and complexity of the interactions, which directly affects coherence and ultimately system gain, depends on sound speed along the propagation paths and source/receiver geometry. Because these parameters exhibit significant variability in most shallow water environments, we can expect large changes in coherence within a relatively small volume over tactically significant times and changes in the range or bearing of signals of interest.

Thus a key issue in assessing the spatial limitations of an array system over tactically significant periods of time is a fundamental understanding and quantification of the occurrence, dynamics and impact of spatial coherence within the three dimensional space of an array as functions of range, bearing, depth, frequency, and time.

Ref: Shepard, et al; BBN Report No. 7937, "Acoustic Propagation Characteristics in Shallow Water", Nov. 1993

Improving the performance of matched field processing for robust passive localization

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Successful passive source localization in the ocean is often closely tied to accurate knowledge of the propagation environment. Matched field processing algorithms, matching the true received field to replica fields computed under certain assumptions for the underwater medium, have often given excellent results with real data for passive localization. There have been cases, however, where conventional (full-field) matched field processing fails to provide accurate location estimates. One of these cases is the Haro Strait data set where matched field efforts were hindered by a complex shallow water, range dependent environment [1, 2]. The sediment structure and geoacoustic properties are poorly known, resulting in mismatch between replicas and data because of inaccurate environmental modeling and leading to erroneous localization. In the Haro Strait case, the full-field modeling problem was circumvented with the selection of only parts of the field for localization. The received time series were thus "filtered". Arrivals that did not interact with the sediments were used in an arrival-time matching approach and the source was localized successfully and efficiently [3].

Application of the partial-field matching method was feasible for the Haro Strait data because the source was broadband and close to an impulse and the received data were near-range; the received signal was thus a superposition of narrow (in time) pulses and the "clean" arrivals could be easily identified. The approach is not so straightforward when factors such as the source-receiver range or the nature of the transmitted signals do not allow the resolution of different paths. The problem then arises of how to use matching techniques for passive localization that take advantage of the benefits of replica and true field matching without requiring detailed field modeling which could be too computationally demanding and also lead to erroneous estimates because of mismatch. Mode decomposition and selection of only those modes that are "deemed suitable" could be an approach to the problem for range independent problems; the approach has been often found beneficial for the reduction of environmental mismatch [4] or surface interference [5]. It is not clear, however, how field "filtering" could be *optimally* (in terms of *performance* and *efficiency*) extended to problems involving broadband sources of unknown signatures and, potentially, range dependence. The Acoustic Observatory resources are ideal for testing the robustness of matched field approaches, indicating how the field could be best used for passive source localization, and assessing how (whether) the existing degree of range dependence affects the localization process. The site is shallow with the sound interacting with the seafloor and the bathymetry has a slope; the sediment thickness and geoacoustic properties are not exactly known and could be range dependent [6]. Depending on the nature of the data, similar techniques to those applied to the Haro Strait data set (relying on filtering for arrival identification) will be applied and further tested. For data where path identification is not applicable, approximations relying on modal decompositions will be examined. Time-frequency techniques (in combination with simultaneous deconvolution, since the source waveform is unknown) will be tested on the identification of distinct components of the field [7] that can be subsequently employed for localization.

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A Basin-Scale Underwater Acoustic Communication Requirements Study using the Acoustic Observatory

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Undersea acoustic communication (acomms) at ranges of several hundred to several thousand kilometers will support new civilian and Navy applications of both manned and autonomous underwater systems. While the data rates of long range communications will be low due to bandwidth limitations at frequencies supporting basin-scale propagation, the capability to transmit or receive any information will enable control and monitoring of otherwise unreachable instruments or vehicles. Teleoperation of a vehicle in the middle of the North Pacific or monitoring of ocean-bottom seismometers hundreds of kilometers offshore may become practical. Navy submarines could use such a system for routine or emergency communications at very long ranges when unwilling or unable to surface. A very large scale underwater global positioning system will also require low rate telemetry to convey the subsea equivalent of satellite ephemeris information that is modulated on the GPS timing signal. Fundamental uncertainties exist, however, that must be resolved before a practical system could be fielded. The Acoustic Observatory is well suited as a test bed for the research needed prior to a basin-scale acomm system development.

The important question of whether or not basin-scale acomms is even possible has already been addressed by Freitag and Stojanovic when they treated the probe signals of the Acoustic Thermometry of Ocean Climate (ATOC) program as a binary phase shift keyed telemetry signal with a data rate as high as 37.5 bits per second [1]. Using the extensive ATOC vertical line array, the signal was successfully "demodulated" after traversing a 3250 km path. Even those preliminary results were quite suggestive of the direction continued research should take. The signal was dispersed in time by nearly 8 seconds or nearly 300 symbols. Freitag and Stojanovic found that at least 10 hydrophone channels of the 700 meter long vertical line array were necessary to increase the SINR of the equalized signal to 4.6 dB, adequate for reliable coherent signaling. Significant spatial apertures appear, at this point, to be a necessity for reliable basin-scale acomms.

A clear understanding of the role that spatial aperture plays in basin-scale acomms is a compelling research goal. The Acoustic Observatory notional architecture includes a variety of array apertures that are well suited to supporting this exploration. Two focus areas are proposed. First, the design space framed by spatial aperture and data rate must be investigated with a goal of defining requirements for either a submarine or mooring based (or hybrid) system. Presuming an articulation in the foreseeable future of a compelling U.S. Navy need for basin-scale acomms (a question outside of the scope of this white paper), the array requirements for such a system can be determined through research as is proposed here. Important questions include whether horizontal aperture alone is adequate and whether sparse arrays are as effective as conventional, dense arrays for communication signals. An experimental program would readily aid in answering these questions and form the basis for a reliable articulation of requirements for a subsequent development program.

The second focus area addresses the attainable data rates of such systems. As the successful work in basin-scale tomography has shown, a rich spatial structure is imposed on transmitted signals by the environment. The structure can possibly be exploited by using spatial modulation techniques that seek to create simultaneous, parallel communication channels out of the single, physical ocean medium. Recent experiments at much shorter ranges and higher frequencies [2] have shown that the techniques of spatial modulation can dramatically increase the bandwidth efficiency (bits per Hertz) of acomm signals even in the presence of dramatic channel spreading. Spatial modulation requires a transducer array as well as a hydrophone array to support resolution at both ends of the channel of mode and/or ray groupings. Orthogonal groupings of these modes/rays are then used to carry independent data streams. As the basis of a notional experiment, the Towed Line Array (a source array) developed at the Naval Undersea Warfare Center several years ago would easily support this research. The promise of successful research would be increases in attainable data rates of several-fold or more. Of course, uncertainties exist regarding suitable apertures for application of spatial modulation to low frequency communication. The spatial and temporal coherence of a low frequency basin-scale signal may well drive unique configurations. An intriguing, but secondary, question is the extent to which the use of source arrays can offer mediation to the issue of marine mammal protection through more efficient use of source energy.

An informal teaming arrangement exists with Geoff Edelson of BAE Systems (formerly known as Sanders) on data collection experiments that support 6.2 research topics in acoustic communications. Broadly stated, Dr. Edelson considers incoherent modulation while SAIC/WHOI investigates coherent signaling although the distinction may be blurred. Taken together, the research of the two groups offers the possibility for a comprehensive examination of the issues unique to basin-scale acomms.

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Use of High Frequency Radar at the ONR Acoustic Observatory

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Environmental measurements provided by thermistor chains and bottom mounted ADCPs have been suggested as part of the oceanographic instrumentation for the AO test site to provide the necessary environmental information to understand acoustic propagation. Although these instruments are clearly necessary, they will only provide information in the immediate area of the array test site. A key element for the science program of the AO, however, will be to understand the propagation over a wide area surrounding the test site. Such information will be necessary to understand any environmentally induced limitations to the performance of the various discrete contact suppression algorithms that may be developed, as well as to support algorithms that require detailed environmental information. This detailed information must be continuous in time and space to be of maximum utility.

In recent years high frequency (HF) radars have become more widely used for synoptic surface current mapping [1]. As stated in [1], "these radars allow one to map surface currents off-shore by means of land-based (HF) stations. The Doppler shift of the backscattered signal is used for measuring the radial current speed relative to the radar site." The underlying physics is that the returned signal is preferentially back scattered via Bragg scattering from ocean surface waves having half the radar wavelength. Since the velocity of these waves is known from deep-water surface gravity wave theory, the Doppler shift, either up or down, in the absence of surface currents is known. Any additional Doppler shift may be attributed to radially directed currents. To measure the total current at least two radar stations are needed; clearly, to achieve the best accuracy, the baseline between the stations should be selected to achieve close to a 90 degree crossing angle of the radar waves at the areas of interest. This implies that more than two stations, at spacings selected to cover the entire region of interest, may be needed.

Two basic forms of such HF radars have been developed. The first, and more obvious, is phased array radar, which uses beamforming to steer beams in the directions of interest. Such a system, referred to as the Ocean Surface Current Radar (OSCR), has in fact been used to measure surface currents near the SFOMC site proposed for the AO [2]. The second system, the Coastal Ocean Dynamics Applications Radar (CODAR) is much more compact than OSCR and more easily deployed. Each station consists of a three element crossed loop antenna system which uses direction finding techniques based on the MUSIC algorithm, rather than beamforming, to determine the arrival direction of the backscattered signal [3]. These units are commercially available. The primary advantages of CODAR over OSCR are cost, ease of installation, and perhaps most importantly, the ability to get permission to install the device for extended periods on highly coveted beachfront property. CODAR systems have been used with success in highly complex coastal environments [4].

The surface current measurements reported in [2] showed the existence of "complex surface circulation patterns, ...that included coherent, sub-mesoscale vortices with diameters of 2 to 3 km, inshore of the Florida Current ". These currents are clearly spin offs from the Florida current and it may be inferred that they sweep the area of acoustic interest to the AO with time varying water column properties that will affect the acoustic propagation. These surface current manifestations must therefore be related to the water column properties. The suggested study would first correlate the surface currents measured via HF radar with the currents measured using the ADCPs at the array site. Work along these lines is reported in [2] and [4]. Next, these current features should be related to temperature and salinity incursions, again at the array site, using thermistor chain measurements. The final stage would be to assimilate this data into an ocean current model and use this model along with the synoptic HF measurements to predict the internal structure of the water column over the entire acoustic area of interest [5]. CODAR systems are suggested as the HF system of choice because of the relative ease of getting permission for long-term installations. (One CODAR could, for example, be put on the roof of the condominium where the ship tracking radar is installed - assuming no interference effects.) Nonetheless, if the OSCR system described in [2] could be simultaneously deployed for a short period, this would afford the extremely valuable opportunity of comparing the performance of the two systems (a matter of some interest to the remote ocean sensing community).

Initial studies to determine the expected resolutions, and current measurement accuracies would be a sensible start for this work. Next, short-term pilot study CODAR installations should be set up (using, for example, systems available via the authors of [4] at nominal cost) to examine performance and compare current measurements with internal structure measurements from a short term thermistor chain deployment. In this way, at little cost, the utility of these measurements could be assessed.

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Environmental Impact on Array Gain, Signal Gain and Noise Gain in the Shallow Water Operating Environment

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Introduction: NRL Codes 7120 and 7180 have a long-term research program studying acoustic signal propagation in the shallow water environment. The effort has addressed the 100 - 1500 Hz frequency band.

During the past 8 years, the research has been focused on the continental shelf slope-break zone where the sound-speed field variability is controlled by a variety of fluid processes operating over a range of spatial and temporal scales. These include tidal forcing, internal waves, atmospheric forcing via fronts or storms, and boundary currents. The research has been in four distinct areas. The first three areas address the environmentally induced limits to array **signal gain** and the last addresses the environmental limit on our ability to reduce array **noise gain**. The four areas will be outlined.

The **first** is focused on quantitatively relating the sound-speed field variability to the temporal and spatial scales of both the fluid processes that perturb it, and the heterogeneity of the bottom and the subbottom. The **second** is measuring the spatial and temporal variability of the intensity and coherence of acoustic signals propagating through a variable sound speed field. We compare the measurements to 4-D numerical simulations of acoustic signals propagating through variable sound speed fields. The sound-speed field variability is predicted using either analytical/empirical representations of the internal tide and associated internal wave field, **or** nonhydrostatic model simulations of the tidal perturbation of the water column. The **third** is the measurement of the temporal variability of array beam wander and beam energy and comparison to numerical simulations. The **fourth** is the development of four dimensional noise models that incorporate random media propagation physics and newly developed representations of breaking wave and ship noise source functions. The noise models are being developed to improve the understanding of array noise gain variability for a variety of array processing approaches including conventional, adaptive and matched field.

The overall object of the research has been to quantitatively establish the environmental limits to signal gain and noise gain, and to develop a fully integrated capability to predict and model large aperture array performance in the littoral operating area. To date we have addressed large aperture line and planar array signal gain in a variable sound speed field as well as volumetric array noise gain response to shipping distributions. Conventional, adaptive and matched field processor output stability is being evaluated.

The ONR Acoustic Observatory offers us the opportunity to extend our measurements from a broad-shelf propagation environment dominated by the tide to a narrow shelf where propagation conditions may be dominated by a spring to neap tidal cycle, a strong offshore boundary current and seasonal variability related to atmospheric forcing.

Research Topics to Be Addressed: The AO research topics that we intend to address are extensions of the work outlined above and focus on quantitatively relating sound speed variability to the acoustic signal amplitude, phase and coherence variability. The signal variability will in turn be used to establish the limits of signal gain, noise gain and overall array gain. We require long-term continuous measurement of both the environmental variability along the acoustic propagation path and the acoustic field. We have been involved with 4 major shallow water experiments during the past 7 years and bring an extensive list of lessons learned to apply to the AO effort.

1. *Measurement of Sound Speed Field Variability*

We anticipate the permanently installed AO environmental sensors will provide spatially aliased sound speed measurements. We want to periodically measure, over several day intervals, the spatial variability of the sound speed field along the propagation path using tow-yo CTDs, high frequency flow visualization techniques, shipboard x-band radar and shipboard ADCP. We have used this measurement approach in the past to unravel the relationship between fluid-process induced sound-speed variability and the variability of acoustic signal intensity/coherence and array beam intensity/wander. The technique has been successfully used in the vicinity of both vertical and horizontal arrays. NRL has the necessary instrumentation to implement these measurements.

2. ***Range Dependent Acoustic Signal Intensity and Coherence Variability***

Shallow water acoustic signal intensity fluctuations and coherence are expected to be frequency and range dependent. This dependency will impact the array gain, signal gain and noise gain. No adequate simultaneous range dependent, long-term signal property measurements have been made to quantitatively establish both the range and time dependent properties of a volumetric acoustic field. The range dependent properties of the signals can impact the applicability of a number of signal processing approaches. We intend to use the AO array and the NRL SGAMS 128 channel vertical and horizontal array system placed at a fixed range from the acoustic observatory array to measure the properties of shallow water acoustic signals. NRL's array system will have to be complemented by other systems such as the WHOI Shark (James Lynch) and the Miami moored arrays (Harry DeFerrari) to measure simultaneously signal properties at other range points. NRL Code 7120 and 7180 presently have two autonomous acoustic sources that operate at 300 and 500 Hz center frequency. The sources and the NRL SGAMS array are operated with rubidium clocks. The systems have a 22-day endurance. We will combine the acoustic data set and the above sound-speed field variability data set both to relate acoustic signal variability to fluid processes and to test the efficacy of our combined fluid dynamic and acoustic propagation modeling efforts. We intend to develop an acoustic energy and coherence fluctuation budget and relate it to a variety of ocean processes. The combined data sets will also be used to validate a new theory of acoustic fluctuations currently under development. The theory explicitly relates fluctuations in acoustic pressure (magnitude and phase) to temporal changes in sound speed and bottom type.

3. ***Impact of Sound Speed Variability on the Robustness of Matched Field, Conventional and Adaptive Signal Processing with respect to Noise Gain Reduction***

NRL Code 7120 has demonstrated that sound speed variability related to tidal forcing can cause temporal variability in a matched field processor output. On the New Jersey Shelf a variety of matched field processors were found to be ineffective, due to sound speed variability, in localizing targets at ranges as short as 2 km. The sound speed variability at the proposed AO site may be more benign than either the New Jersey Shelf or the South China Sea experiment sites that we have worked at. In the case of the South China Sea, array beam power fluctuated by more than 10 dB and beam wander of up to 4 degrees was measured. We intend to place our 300 and 500 Hz sources at fixed ranges from the AO arrays with the objective of measuring the temporal variability of the volumetric acoustic field and apply conventional and matched field processor algorithms to localize the sources. The sound speed field measurements outlined in item 1 will be used to update the matched-field processing replica fields and quantitatively establish the ability of a matched field processor to localize a source while adapting to changing sound speed fields. We will quantify the range and frequency bounds on matched field processor performance as imposed by uncertainties in the sound speed field including those caused by tidal, internal wave, spring to neap and seasonal sound speed field variability. In addition, we will validate the aforementioned fluctuation theory ability to predict these bounds. The measurements will be used to quantify the effectiveness of a variety of sound speed measurement strategies to reduce processor degradation and address the potential for reducing processor degradation by using measurement-driven hydrodynamic models to generated real time realizations of the 4-D sound speed field. The MFP noise gain will be derived from the five dimensional (range, bearing, depth, frequency, time) MFP noise response using both conventional and adaptive processors. Range-frequency limits on the noise gain will be obtained through an interpretation of the results in terms of the space-time distributions of the noise sources and the range-frequency limits on the replica field predictability.

Guide Source Mitigation of Environmental Fluctuation

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BACKGROUND

The presence of a moored source and a vertical array in the ONR acoustic observatory near Port Everglades makes possible an experiment to test the performance of the guide source technique of Siderius et al [J. Acoust. Soc. Am. 102, 3439-3449, 1997]. The guide source idea has been adapted from an astronomic technique in which light from a bright star is used to correct atmospheric aberration of weaker objects that are nearby in the sky. According to Martin Siderius, the acoustic guide source technique has yet to be tested at sea. In underwater acoustic applications, the technique should have the capability to mitigate acoustic multipath and short term fluctuations due to variation in the acoustic environment (e.g., due to tides and wind driven currents). In the acoustic observatory, the guide source technique will be used to enhance signals from moving sources (vessels or marine mammals) whose acoustic path to the vertical array is similar to the path between the moored source and the vertical array.

PLANS

Equipment needed for this experiment are a moored acoustic guide source operating in roughly the 100 - 800Hz frequency range, a vertical array spanning most of the water column, and a moving acoustic source in the vicinity of the guide source. The default moving source will be the motor launch or vessel normally used to service the moored source and vertical array. Other moving sources of opportunity can be nearby shipping or marine mammals.

The moored guide source will emit a series of broadband pings, which are recorded on the vertical array at a distance up to a few km. Then time series from the moving source will be recorded on the vertical array. Signal processing of the vertical array data (as in Siderius et al) then allows the construction of a virtual receiving array at the guide source location on which signals from the moving source are subject to minimal environmental fluctuation and multipath. The goal of this experiment is to compare the data constructed on the virtual receiving array with the acoustic properties of the known moving source.

Title: Spatial and Temporal Robustness of Phase Conjugation

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BACKGROUND: It is well known that geometric dispersion can cause appreciable time spreading of impulsive signals, even in the relatively simple case of a range-independent environment. Understanding the role of the environment is essential to predicting dispersion and, hence, to the effective deployment and operation of sonar systems in shallow water (such as the choice of waveform or classifier).

When it comes to predicting propagation, there are both deterministic and stochastic sources of errors. The deterministic errors originate primarily from a lack of sufficient environmental data (such as *in situ* sound speeds and geoacoustic data). The stochastic sources of error are many. Some, like range variations in the sound-speed structure and/or geoacoustic range dependence are really deterministic. As acquiring such environmental information is impractical, it is much easier to ascribe some portion of the observed fluctuations to this lack of perfect knowledge. In addition, there are actual stochastic processes, generated by internal wave fields, sea surface wave motion, and source/receiver depth variations caused by surface wave motion. There are several approaches that have been developed for minimizing the effects of environmental mismatch. One promising area is the use of inverse methods for estimating some of the geophysical parameters from acoustic data. Another approach is aimed at developing *in situ* techniques that require minimal knowledge of the environment, such as phase-conjugation (acoustic time reversal).

APPROACH: In these planned experiments, the primary goal is to investigate the spatial (and temporal) robustness of phase-conjugation (acoustic time-reversal) techniques for mitigating environment-induced signal degradation and distortion. Secondary goals are to use the data collected to characterize time spreading and transmission loss.

The basic strategy is to exploit the multiple sensors of the Acoustic Observatory by having a fixed source periodically transmit a broadband signal, and one or more source/receiver combinations capture these signals and transmit ("echo repeat") various time-reversed versions of them to the field of Acoustic Observatory receivers (including one at the original source location). As each receiver in this field corresponds to a different source-repeater-receiver path, their signal correlations provide a measure of the spatial robustness of phase conjugation in the given environment. By not only transmitting and repeating a series of such signals (over hours, days, seasons), but stored time-reversed versions of the original captured signals, measures of the temporal robustness of phase conjugation can be achieved, both on short-term and long-term scales. Additionally, a standard (time-forward) echo repeat and a channel-characterization signal—the same as the original broadband signal—are broadcast from the echo-repeater source as well. (The former provides a measure of how well time reversal is working, while the latter provides a measure of 1-way propagation characteristics.) This procedure has been successfully demonstrated by the PI in a series of NRL/SACLANTCEN experiments in 2000-2002.

Title: Volumetric Array Evaluation and Beamforming

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Motivation: Currently, beamforming with linear towed arrays and stationary linear and volumetric arrays is based upon the assumption of free-field propagation with acoustic plane wave fronts impinging on the array. However in a shallow-water environment the incident sound is composed of modes or rays that interact with the ocean surface and bottom and essentially consist of up-going and down-going components. This complicated propagation causes sound from a small, distant source at any given azimuth to impinge on long linear array through the "sidelobes" of the free-field beam pattern, thus causing signal fading and also signal spreading into the adjacent beams. These effects are caused by the incident wave fronts being insufficiently plane (namely predicted by a plane wave) along the whole array. These deficiencies could be diminished by designing the array and beamformer with a better environmental model. Then signals from small distant sources would always be received by the array and be combined consistently throughout the array with less fading and spreading. The array design allows for the reliable reception of the signals and the beamformer design allows for the correct combination.

There are two general goals: development and testing of design criteria and beamforming algorithms that are based on a model of the acoustic coupling of distant sources to the array elements in the specific, local acoustic environment. This model has been shown [Gaumond, J. Acoust. Soc. Amer. 105, p 1310, 1999] to lead to quantitative assessment of the ability of an array to measure the complete acoustic field in the neighborhood. There are two criteria that roughly correspond to the resolution and sidelobe level of a line array. The model of the acoustic coupling also leads to a beamforming algorithm that roughly corresponds to matched field processing (MFP) that matches a measured incident field with a numerical model. These two algorithms will be developed for and exercised on the Acoustic Observatory array. Environmental measurements will be used to generate a quantitative assessment of the quality of the array. Acoustic data from radiating sources and ambient noise will be used to assess the ability of the beamforming algorithm to isolate individual sources.

Approach: The acoustic coupling from a distant source to an array will factored into three parts: the coupling of the distant source to the acoustic environment surrounding it, the coupling of the array to the acoustic environment surrounding it and the propagation of the acoustic field from the region of the source or scatterer to the region of the array. The problem of beamforming will be therefore reduced to deriving a transformation between the array elements and the azimuthal dependence of the acoustic field. A normal-mode model, such as KRAKEN, will be used with *in situ* environmental data to model the acoustic field from distant sources, which forms a straightforward algebraic relationship between the array elements and the expansion coefficients of the modal expansion of the field. The assessment of the invertibility of the coupling will determine the quantitative assessment of the array. The beamforming will be accomplished by using a constrained inversion technique, like the pseudoinverse, with suitable constraints. Passive acoustic data will be processed to assess the relevance of the design criteria and the quality of the beamformer with real signals in real noise.

Title: Geoacoustic Inversion Using Vertical and Horizontal Arrays

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Motivation:

Local environmental conditions have a significant impact on the propagation of sound in shallow water. State-of-the-art signal processing techniques such as matched-field processing rely on computer simulations requiring accurate modeling of full wave sound propagation for the detection and localization of sources. Such modeling requires good environmental information, especially geoacoustic parameters of the bottom and sound speed profiles. Very often such information must be extracted from the acoustic data even in situations where this is not the main purpose of the data collection effort. Well-tested and refined inversion methods for extracting geoacoustic information from acoustic data are thus vital to experimental/scientific activities at sea and to naval operations involving the collection and interpretation of acoustic data.

Approach:

The Acoustic Observatory provides an excellent opportunity for testing and further refining inversion methods developed by NRL's Code 7140 since there will be "ground truth" available to compare with the results of the inversion process. The availability of moored sources will also play an important role in such testing since the source position in this case is not an unknown or poorly determined quantity. The excellent radar coverage of the Acoustic Observatory region will provide accurate information on the ships in the area. This will allow us to test our inversion techniques using the engine noise of "ships-of-opportunity" as the sound source for the acoustic data. This approach to acoustic inversion has great potential application in operational situations where standard acoustic sources can not be deployed. We intend to apply our inversion techniques to data collected in both vertical and horizontal arrays. This will allow us to compare the effectiveness of inversion from data collected with each type of array. It will also allow us to further study the sensitivities of each type of array to different features of the geoacoustic environment. Of particular importance is the determination of what properties of the bottom can be reliably estimated with a given data set, and how to adapt the source/receiver geometry to improve the inversion results. We have developed a powerful tool to investigate such questions, namely the "parameter space coordinate rotation method" which is a main component of our approach to geoacoustic inversion. We must emphasize that our inversion techniques are fully developed. What we need is good data in geographic areas with available accurate "ground truth" to further test and refine those techniques. The Acoustic Observatory is an ideal venue for such work.

Title: Noise covariance, *a priori* information in signal processing, air/sea transmission, and acoustic data basing

PI: Michael D. Collins, NRL Code 7145, 202-404-4823, collins@noddy.nrl.navy.mil

Data from the Acoustic Observatory will be of great interest to us for several applications. Since data will be taken over a long period of time, it will be ideal for studying temporal variations in the noise covariance caused by variations in weather, shipping, biological activity, and the sound speed profile. This work will be of use for field-testing noise canceling MFP techniques that are based on measured, rather than modeled, noise covariances. Numerical tests of this approach have been very promising. However, it has not yet been tested experimentally. One of the keys to testing the effectiveness of this approach is to investigate temporal variations in the noise covariance.

Since ship positions will be tracked using radar, we are also interested in applying some of our signal processing techniques that exploit *a priori* information. We have a time-domain analysis tool, based on simulated annealing , that allows us to cancel interference without losing degrees of freedom. This technique has been tested at sea before, but the Observatory will allow us to demonstrate it in comparison to other techniques.

We have also been working on air/sea transmission problems recently and would like to propose the inclusion of receivers in the air in order to monitor atmospheric sources, such as aircraft, that transmit sound into the ocean. This would also permit studies of the transmission of sound from the ocean into the air.

Another problem that interests us is acoustic data basing, which was tested during the TESPEX experiments. This approach involves measuring and forming a database of acoustic fields as an alternative to measuring the environmental parameters in great deal and solving the acoustic wave equation. The Acoustic Observatory will be an ideal opportunity to further test this approach.

Title: Coherent Matched-Field Processing of Volumetric Arrays

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Motivation:
One of the most important outstanding issues in matched field processing concerns coherent multi-frequency methods and volumetric arrays. Because the fastest and most accurate full-field acoustic propagation models are frequency domain codes, traditionally the number of frequencies used in any matched-field processor is kept to a minimum. However, there are fundamental limitations on the time-bandwidth ($= N$) product that are placed on any approach. These limitations are exacerbated by the need to form a nearly independent set of data at each receiver. Thus the larger the array, the larger N must be: This is the so-called "snapshot" phenomenon. The traditional solution of this problem was to increase the "time" part of N, without increasing the bandwidth. This in and of itself, presents its own set of problems when one is attempting to detect a quiet moving source; as spatial coherence of the signal is sacrificed for the benefit of an increase in signal-to-noise at each receiver.

The standard method of increasing the time-bandwidth product via processing additional frequencies, is to incoherently sum several single frequency results [Baggeroer, Kuperman and Schmidt, "Matched-field processing: Source localization in correlated noise as an optimum parameter problem," J. Acoust. Soc. Am. **83**, 571-587]. This approach, while successful in many situations, quiet clearly discards 50% of the total information present in the signal (i.e., all phase information is lost to the "incoherent" summation process). This approach has been championed over coherent processors due to the fact that the later are hampered by a usual lack of reliability of the estimated phase information contained within a signal. While "absolute" phase information is usually unavailable, the "relative" phase information can under some circumstances be determined *in situ*, and consequently exploited, for man-made signals [Orris, Nicholas and Perkins, "The Matched-phase coherent multi-frequency matched-field processor," J. Acoust. Soc. Am. **107** (5), Pt. 1, 2563-2575].

Further complicating factors for large arrays is the coherence of the signal as the acoustic wave traverses the spatial extent of the array. Recent evidence has suggested that treating the full volume of the array coherently (spatial coherence), does not lead to the expected gain in performance [Nicholas, *et al.*, "Environmental inversion and matched-field tracking with a surface ship and an L-shaped receiver array," (submitted to J. Acoust. Soc. Am.)]. Also, it has been demonstrated with data from the Santa Barbara Channel Experiment and an experiment off the coast of Halifax, Nova Scotia, that the best results were obtained by treating each leg of a multi-legged array independently of the other legs [Perkins, et al., "Matched-field processing of two multi-dimensional arrays," J. Acoust. Soc. Am. **106**, (4) Pt. 2, 2127]. There is as of yet, no clear understanding as to why this semi-coherent approach out performed a fully-coherent one.

Approach:
Data collected from the Acoustic Observatory (AO) for a variety of scenarios using broadband and distributed sources would be used to investigate fully coherent multi-frequency matched-field processing. First, existing methods would be further developed to efficiently process data from a large number of receivers. These methods would include the development of more robust estimators of the inter-frequency phase relationships. Current acoustic propagation models as typically implemented within matched-field processors are yet point-to-point models. A reciprocal parabolic-equation model is to be used as the underlying engine [Orris and Perkins, "Three-dimensional propagation modeling in shallow water," J. Acoust. Soc. Am. **103**, (5) Pt. 2, 3029]. Modifications will need to be made to the code in order to properly account for the different computational grids used (i.e. a different grid is usually assumed for each receiver). A variety of known signals would be developed to be used to ensonify the test range, using Code 7145's new Source/Receiver Array. This vertical array can be computer controlled and steered to accurately simulate actual targets. Data collected would then be analyzed and used as a basis of comparison and to further implement enhancements into coherent processing. Finally, actual target data would be analyzed. Clearly, the AO would provide a unique means of testing and validating several new methods of coherent matched field processing on large volumetric arrays.

Horizontal-Beam, Vertical-Mode ASW Sonar Concepts

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With sufficiently large vertical and horizontal array apertures in an adequately measured downward-refracting environment, the ONR Acoustic Observatory can be used for the research of passive and active sonar methods that uniquely exploit the modal properties of the sound field in highly resolved bearings. Some of these modal sonar research problems are discussed next.

<u>Passive Detection</u> It is well recognized that the rejection of noise radiated by local surface ships is key to achieving a high detection probability at a low false-alarm rate in littoral regions. Therefore, a relevant and interesting research question to ask is: Can a vertical decomposition of the sound field into normal modes be used to reject the surface-ship interference? The idea is simple and is based on the assumption that, in a downward-refracting sound channel, surface ships do not excite the lower-order modes that turn below their shallow acoustic depths, whereas an interior submarine target does.

<u>Active Detection</u> One can also envision an analogous bi-static, active sonar problem involving a shallow projector and a target below the projector depth. Similarly, one can argue that the shallow projector excites only the higher-order modes but not the lower-order modes turning below it in a downward-refracting environment. Upon interaction with a deeper target, the higher-order modes scatter energy into the lower-order modes that can then be detected unambiguously in a modal decomposition separating the target echo from the direct arrival.

<u>Passive/Active Localization</u> In addition to the detection problem, the modal properties are exploitable in the localization and tracking problem. The distribution of the acoustic energy in the mode-number domain contains depth information about the target, whereas the interference between modes contains the range information in a known bearing. A good question is: Can robust localization be achieved by selecting the less contaminated lower-order modes in matched-mode processing?

<u>Environmental Acoustics</u> Environmental acoustics issues important to the sonar concepts discussed above include (1) mode coupling effects inherent to the environmental variability in the selected Observatory site, and (2) noise (ambient noise and reverberation) distribution in the mode domain. These are the potential system limiters and therefore need to be studied and characterized.

ONR Observatory White Paper

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Below are three proposed areas of investigation for the ONR Observatory that may be less obvious than applications in ocean acoustic tomography, geophysical inversion and ambient noise analysis.

(1) Forward Scatter and Extinction Measurements

The extinction theorem has recently been derived for an object in a waveguide [1]. This theorem relates the total power removed from an incident field, due to scattering and absorption by an object, to the object's forward scatter function, and consequently the object's physical properties such as its size. This theorem enables objects that pass between a source and planar receiving array, such as the observatory array, to be detected and classified by a measurement of the total power removed at the array by the object due to shadow remnants. The waveguide extinction theorem requires modal decompositions for robust object classification. The observatory could be used to test the waveguide extinction theorem on calibrated targets as well as naturally occurring anomalies in the waveguide such as internal waves. The former application is useful for low source level active detection and classification of submerged objects, the latter is useful to understand the physics of how environmental variations in the waveguide lead to transmission scintillation. The spatial and temporal coherence and statistics of acoustic transmissions [2] [3] [4] can also be studied with the extended aperture of the observatory and related to physical theories.

(2) Remote Active Imaging: General Waveguide Scattering and Reverberation Measurements

In shallow water scattering and boundary reverberation, scattering and propagation are convolved together due to waveguide effects [5]. Scattering and propagation effects can be separated with a vertical aperture by modal decomposition. Horizontal aperture enables specific bottom patches over finite azimuth to be studied. A 2-D array then enables scattering and propagation effects to be distinctly studied for specific seafloor patches or specific calibrated targets. This will enable the fundamental scattering properties of the seafloor to be studied as they pertain to long-range remote sensing systems.

(3) 3-D Passive and Active Localization of Moving Targets Including Instantaneous Velocity Estimation.

Targets moving in a waveguide lead to multiple Doppler shifts at a receiver due to multi-modal propagation. This theory has been developed for both passive [6] and active sonar [7], where Doppler distortion is greatly compounded in the latter case but the original source signal is always known, which is advantageous for target velocity estimation. The observatory array could be used to isolate targets in range azimuth and depth and also perform modal processing to determine the target's instantaneous velocity via application of waveguide Doppler theory.

It may be possible to passively image objects very close to the observatory array using naturally occurring ambient noise [8]. The observatory could also be used to make high resolution measurements of ambient noise directionality. (High noise directionality is necessary for imaging with ambient noise [8].)

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The Effects of Target Motion in Sonar Detection Systems

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Current sonar processing design almost universally accepts as an article of faith the notion of spatial processing arranged over fixed beam sets in a coordinate system that is attached to the center of the receive array. This viewpoint, which might be likened to a Ptolomeic view of sonar, was first adopted in the World War II era, when array processing was in its infancy, and has been the subject of little subsequent scrutiny. At the time, it was an absolutely necessary simplification in the reduction of sonar concepts to practical implementation because of the inability of technology of that era to efficiently manipulate information in other than the simplest of ways. The intervening half-century has seen an explosion of information processing technology, to the point where it would be fairly straightforward to implement alternative approaches should the inherent performance limitations of fixed relative beam sets so dictate.

In an era where the quieting trends of the last several decades have yielded submarines of unprecedented source levels, such conceptual limitations have brought passive sonar to the point where its viability as a system concept is now seriously in question. Fundamental performance improvement is necessary for such systems to have an effective role in future warfare systems. As a practical matter, there are only five places to search for such improvement:

1. Leeching out the imperfections of existing algorithms within the constraints of the existing conceptual architecture.
2. Mismatch reduction by more faithful prediction of the replicas being sought.
3. Expanded spatial integration through the employment of arrays with greater aperture and greater element count.
4. Expanded frequency integration.
5. Expanded temporal integration.

The first is the proper role of incremental improvement; the second is best represented by matched field processing, although other forms of mismatch may be equally important; the third is an obvious but expensive solution; the practical physics limits of the fourth have likely already been reached; and the fifth is by far the cheapest and simplest solution if it can be made to work, but has received little real attention over the last two decades.

A primary reason that expanded temporal integration time has received so little attention has been the unwillingness to question the concept of fixed beam sets. A good example is that of system integration time for passive towed arrays. For some years, the beam crossing rates of close-in, high-speed targets have been used to dictate the maximum acceptable integration time. This then leads to the appearance of a debilitating tradeoff between array length and integration time; longer arrays yield narrower beams, which in turn dictate shorter integration times. Attempts to alleviate this constraint have centered around the use of tracking technology to synthetically integrate over longer periods of time based on the fixed beam outputs. While such an approach can provide considerable additional improvement in performance, it too has a limitation: the front end must still produce "pre-detections" (these are actually just detections at a lower threshold, making them less reliable from a false alarm perspective) that are strong enough to be tracked in the first place.

It is important to note that these limitations are essentially self-imposed by our reliance on the construct of a fixed relative beam set. Optimal processing theory in its fundamental form shows no such constraints; instead, it dictates that the integration be carried out over the presumed target trajectory, which may be fully arbitrary in space-time. It is only an implementation choice to select as a search space one that covers only fixed relative coordinates.

A multi-dimensional search space over target position and velocity (most likely defined in fixed geographic coordinates, to also allow direct implementation of array shape compensation) can eliminate the perceived constraint on integration time for longer arrays. This would amount to beam sets that slew over time to stare at particular target trajectories. While this approach may seem ungainly, it has the distinct advantage that implementation considerations are dominated by the need for additional processing resources. Two other benefits are also likely to accrue:
1. Estimates of target velocity directly from the front-end processing become available. Such information is likely to be of major tactical utility.
2. In the investigation of such an approach, the community will likely identify a number of situations where the mismatch generated by the fixed beam set, even for current integration times, is larger than realized. This is especially likely in small signal limit cases, where every dB of mismatch in the front end equates to 2 dB of performance loss.

A number of derivative technical issues must be investigated in order to bring such a concept to fruition, including:

1. Smart sampling of the multi-dimensional position-velocity search space.
2. Computationally efficient processing architectures.
3. Effective display of the multi-dimensional search space.
4. Whitening and normalization schemes that actually yield extended integration time performance gains.
5. Sensitivity to propagation assumptions and to array position and shape.
6. The limits of practical temporal integration gains, including the limiting factors.
7. Tactical exploitability of the position and velocity estimates that become available.

The Acoustic Observatory is an obvious and near-ideal candidate data source for developing and maturing such a concept, which could not be done without continuing availability of large amounts of high-quality real-world data.

A Unified Approach to Sonar Processing for the Acoustic Observatory

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The focus of this letter is the use of the Acoustic Observatory (AO) in developing a unified approach to signal processing. The concept exploits a knowledge of the properties of the three-dimensional waveguide in order to optimize sonar processing in cluttered environments through the cancellation of discrete noise sources. The confluence of recent advances in the development of inversion methods using ships of opportunity, highly accurate acoustic propagation models in complex waveguides, and large array ABF concepts, place the sonar community in a position to translate an increased knowledge of the environment into significant processing gains. While various components of the concept have been previously advocated, our approach is unique in the degree that knowledge of the environment can be used to increase processing gain and the details of its implementation.

Figure 1 illustrates the essential elements of our unified sonar concept applied to data collected by the AO. A single well-verified acoustic propagation model used at all stages of the methodology acts to make the approach self-consistent. There are already a few propagation models, such as the high angle parabolic equation algorithm RAMGEO 1.5 [1], a two-way stair-step coupled mode approach [2], and a two-way integral equation coupled mode method [3] that have met the criteria of being able to reproduce a variety of acoustic benchmarks. Previous methodologies have not required the use of a high degree of modeling sophistication because of ignorance and uncertainty about environmental parameters. Surface ships of opportunity create a wealth of data for inversion of the three-dimensional seabed and those parts of the SSP not available through measurements. ARL:UT recently demonstrated that simultaneous environmental inversion and source localization on a system-like HLA employing a surface ship of opportunity allow for detailed information on the geoacoustic profile [4,5]. A unique aspect of the target of opportunity inversion approach is the employment of a cost function that is summed coherently over frequency, phone pairs, and time segments. The details of the source spectra are not required for the inversion method.[5] The inversions at the AO could make use of radar and satellite surveillance of the regional shipping to provide *apriori* information to the inversion methodology. Although *apriori* information is helpful in reducing the uncertainty of the estimated parameters, it is not an essential requirement. However, radar information can be used to validate inversion results. Due to the high variability typical in littoral areas, the inversions proceed over a time period to map the geoacoustic structure and its variability.

Once a certain level of knowledge on the environment has been reached, the same acoustic propagation model employed in the environmental inversion stage is used to determine the portion of the observed beam noise associated with the discrete interferes. Advanced ABF algorithms are then employed to reduce the influence of loud discrete interferers. A beam-based excision approach is currently under development, which coherently separates contributions attributed to identifiable discrete interferers from the received data. This allows for rapid adaptation for loud, nearby sources which may have short beam dwell times, by exploiting the propagation model and a good environmental representation. Coupled with the excision, an efficient reduced rank adaptive beamformer can exploit statistical information gained from the measured data to achieve gains. The adaptive processing effectively reduces the quiet beam level to the background associated with wind and distant shipping, allowing one to approach the theoretical limits of the detector. It is hypothesized that as the knowledge of the waveguide structure increases with time, so will the processing gain. The computed and observed environmental variability is employed in several parts of the analysis, including the optimization of ABF parameters.

In addition to providing key information to the ABF, the inversion supplies a highly accurate three-dimensional environment to perform matched-field processing (MFP) to localize and track detected targets of interest.

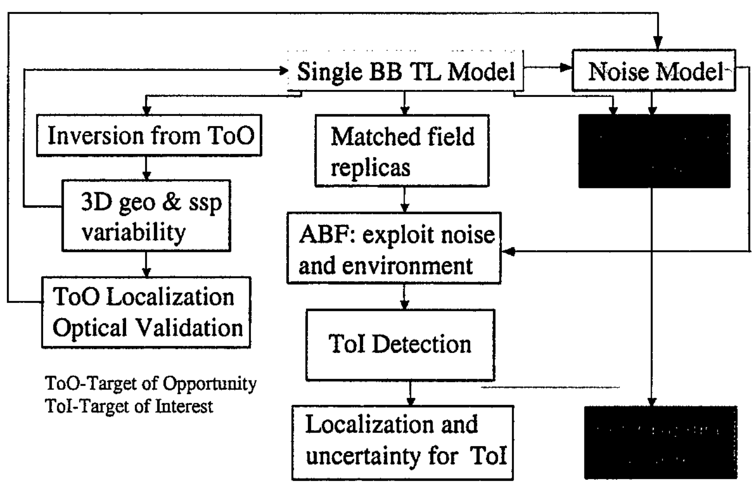

Figure 1: Unified sonar processing concept in the Acoustic Observatory

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White paper on AO issues of interest
Jim Lynch, WHOI

From my personal point of view, there are three main areas of interest in the Acoustic Observatory (AO) project. They are: 1) acoustic array element localization in the presence of internal waves, 2) the connection of the observed variation in important acoustic quantities to the variability in the ocean and seabed, and 3) the predictability of sonar system performance, given quantifiable environmental uncertainty. Each of these topics has many unanswered questions associated with it. Let me briefly look at each one.

The first topic, array element localization in the presence of internal waves and other oceanography, is a very practical one, as there are many people wanting to use coherent beam forming techniques with the Observatory array, who will not be able to do so unless the array elements are localized/navigated/positioned to within a reasonably small fraction of an acoustic wavelength. From the experiences of five major shallow water array deployments over the past decade (Barents Sea, SWARM, summer PRIMER, winter PRIMER, and ASIAEX), internal wave/oceanography effects on acoustic array element localization are very significant for mid-to-high frequency long baseline navigation systems (8-50 kHz), "light bulb" implosion positioning fixes, and distant LF source fixes. Moreover, from Harry DeFerrari's thermistor string measurements in the area, these effects are likely to be strong. I feel that some significant effort should be devoted to developing a scheme using combined acoustic and oceanographic (and perhaps optical camera) measurements to accurately place the receiver elements. This will be a particularly challenging problem if the receiver elements are held off the bottom.

The second topic, the connection of the variation of important acoustic quantities with the variability in the ocean and seabed, has been the focus of a significant amount of ONR sponsored shallow water research in the past decade. Understanding how the acoustic field is determined by the environment will eventually allow one to simplify the sonar system performance prediction problem to adequately measuring a reduced set of key ocean and seabed quantities. This is still work in progress, but I would contend that our progress has been substantial, and that the AO is ideally set up to allow us to make even more progress in that area. Specifically, the AO will allow us to make detailed acoustic measurements concurrently with high resolution oceanographic and geologic measurements. This will allow us to correlate ocean and seabed variability directly with acoustic variability. By further breaking the environmental variability into the space-time frequency/wavenumber domains of the characteristic processes (e.g. M2 tides, bottom roughness scales), we can then understand the acoustic scattering in terms of those processes. Since these natural processes are often general phenomena, i.e. not just local effects, we can then transport our understanding to shallow water sites in different parts of the world ocean. I hope to be able to give some examples of this in the course of the AO workshop.

The final topic, predictability, is one that we should endeavor to test by making some *a priori* estimates of array performance before we actually deploy the AO. This is a good chance to see just how good we currently are in the prediction game, as we will (one would hope!) have the ground truth measurements with which to compare. A good subtask of this is ascertaining which quantities most limit our predictive capabilities.

Sonar Techniques for Sensing and Exploiting the Shallow Water Environment

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Performance of ASW sonar systems varies depending on environmental factors such as sea-state, oceanographic conditions and seabed type. Among these, the seabed properties are usually the least well known but often have the biggest impact on Transmission Loss (TL). The impact of the environment on sonar system performance is closely tied to the processing methods used. On the most basic level, errors in calculating TL (for the sonar equation) lead to poor estimates for detection ranges. Environmentally adaptive processing can be used to improve target detection and localization but these methods require good characterization of the propagation channel. This paper first describes the research issues for determining seabed properties then describes how this information can be exploited for detection and localization.

Sensing the Environment

The U.S. Navy has developed sophisticated methods for obtaining and using environmental data. State-of-the-art, circulation models assimilate real-time oceanographic measurements to predict ocean conditions (e.g. ocean sound speed and currents). High-resolution bathymetry for many shallow water areas is measured and archived. Sea-state forecasts with wind speed and direction are available. All of this information can be accessed through environmental data servers. Existing databases containing seabed properties are far less developed. Data provinces can be large (ignoring important smaller scale seabed features) and often TL predictions using archived values for the seabed properties fail to agree with measurements.

Better estimates for the seabed properties can be made by taking acoustic measurements *in situ* and using these to estimate local seabed properties. That is, use available horizontal or vertical receiver arrays to invert measured acoustic data for geoacoustic properties of the seabed. Geoacoustic inversion has been successfully demonstrated with at-sea data using vertical arrays and recently this has been extended to horizontal arrays [M. Siderius, P. Nielsen and P.Gerstoft, "Range-dependent seabed characterization by inversion of acoustic data from a towed receiver array", *J. Acoust. Soc. Am (accepted for publication)* 2002].

The research issues described here focus on using horizontal arrays (towed or stationary) but can take advantage of vertical aperture. Much less is known about geoacoustic inversion with horizontal arrays compared to using vertical arrays. The experimental capabilities for the proposed Acoustic Observatory are ideal for testing and verifying basic research issues that need to be addressed to transition these inversion techniques to a fast, reliable and practical system. Some of these topics are:

- Effects from the environment
  - Oceanography (e.g. seasonal changes, random media)
  - Bottom type (e.g. bottom attenuation vs. scattering losses)
  - Surface scattering (effects from sea-state)
- Sound sources (e.g. self-noise, ships-of-opportunity, active sonar)
  - Source directionality

- Source transmit waveform
- Source location (sometimes unknown)

- Determine possible (and ideal) measurement geometries
  - Horizontal arrays (optimal range, depth)
  - Vertical arrays (short apertures, and requirements for up/down ambient noise processing)
- Inversion Errors
  - Variance of the estimates
  - Required accuracy
- Frequency bands (active and passive)
- Consistency, robustness and computational efficiency

The final bullet point above may be the most important. The techniques need to be robust, reliable and computationally efficient otherwise they are not practical. Important (and robust) features of the seabed can often be characterized with fairly simple procedures. To illustrate this point, consider the acoustic receptions shown in Fig. 1 where a measured (left panel), band limited (200-800 Hz) impulse response is shown together with two range-independent simulations (right two panels) for source-receiver separation of about 2 km (data is from the ASCOT-01 experiments taken off the New England coast in June 2001). The data shown in the figure is the envelope of the pressure field on a log scale. The seabed in the experimental area is relatively reflective as evident from the late arriving multipath. The data simulations used a seabed sound speed of 1750 m/s (middle panel) and 1550 m/s (right panel). These simulation results were generated in a few seconds with a ray trace code. An estimate for the seabed was found after just a few attempts using a correlation between measured and simulated pressure field envelopes. Although a vertical array was used here, the concept applies even to a single hydrophone.

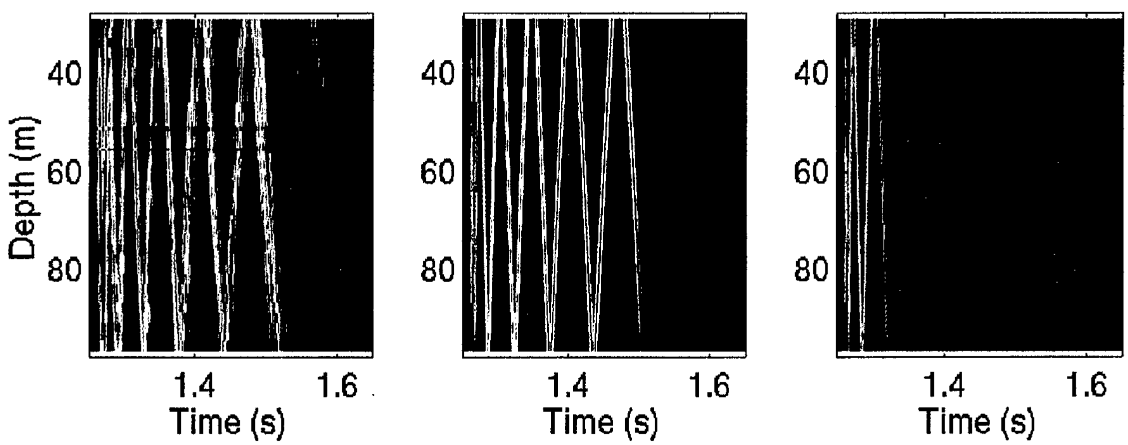

Figure 1 Left panel shows the measured impulse response on a vertical array. Middle and right panels are from range-independent modeling (2 km source-receiver separation). Middle panel uses a seabed speed of 1750 m/s and right panel 1550 m/s. (Relative amplitudes are shown with color scale spanning 30 dB)

Exploiting the Environment

The approach to estimating seabed properties using correlations between simulated and measured pressure field envelopes can be extended to localize sources. The seabed properties change the length and relative strength of the multipath structure. The arrival pattern also changes drastically with source position. High correlation between measured and modeled field envelopes occur at the true source location. Using the pressure field envelopes makes the method robust against environmental mismatch (in particular ocean sound speed and measurement geometry). This was particularly evident when processing data measured off the New England coast. In this case, the late arriving multipath caused by the fast seabed (see Fig. 1) coupled with highly variable water column sound speed causing problems for localization using phase-sensitive, (standard) Matched Field Processing (MFP). Using MFP, localization was failing at ranges beyond 1 km. The envelope processor appeared immune to the ocean variability and localization was successful out to 10 km for frequencies up to 1.5 kHz.

Processing goals for the Acoustic Observatory

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The acoustic observatory is unique in that the combination of VLA'S and HLA'S will provide a detailed sampling of the ocean acoustic field over a large volume (space and time). The resulting data set will be a benchmark for full 3D channel models. We are interested in 2 key ways of exploiting the Observatory.

Replica Vector Generation (Environmental Inversion and Channel Modeling)

We cannot begin to answer questions about achievable gain without first addressing the modeling limits. 'Coherence' lengths across an array implicitly assume a particular type of beamforming (usually planewave). Variations in the multipath structure across the aperture are seen as a loss of coherence. However, if an acoustic model can accurately predict variations in the multipath, those effects can be removed. In fact, the benefits of a volumetric aperture are not fully exploited if we do not compensate for those effects. In short the achievable array gain, especially on a large volumetric array is fundamentally determined by the ability of a channel model to undo or recompress the channel dispersion.

Thus a fundamental issue for the AO program is to do the best acoustic modeling we can to replicate the echo pattern seen by the observatory. This requires care to gather the environmental information including: 1) bottom structure varying over lat./long., 2) ocean thermal-structure (Gulf Stream for the S. Florida site), and 3) sea state (varying with storms). With that in hand, the model must be able to handle the physics properly, for instance, including horizontal refraction. Finally, it must be computationally efficient to provide full-field calculations on a huge number of sensors in a dynamic environment.

The first stage is to develop an environmental model and a channel model that best captures the physics of the acoustic field the observatory sees. Our strategy for achieving this is to use a Gaussian beam-tracing model (BELLHOP), which we have also been using extensively in other array processing efforts. A critical first step is to do the geoacoustic inversion for bottom properties; new approaches will be needed for rapidly mapping surficial sediment properties.

While some users will prefer to develop and use their own channel models, an effort to provide all users of the Observatory with a core set of tools as a baseline would be extremely useful. In other work we are extending BELLHOP for full 3D capability and porting the algorithm to MATLAB. In addition, a special option is being implemented for rapidly moving sources that eliminates artifacts due to the quasi-static approximation usually employed. Comparisons should be made with more sophisticated models treating horizontal refraction. A newly developed coupled 3D version of KRAKEN (written in MATLAB) is now also available and would also provide a useful benchmark.

Exploiting the reliable features

Within the limits of the best acoustic models there remains the question of optimal exploitation of the measurements. For instance, we can detect, classify, or localize a source by matching the spatial variation of the field considered tone-by-tone. Alternatively, we can match the time-changing power spectrum. In the time domain we can match time series, envelopes, or log-envelopes. We can also match arrival patterns considered in both time and angle. All of these options can be done on a sub-aperture basis.

These simple examples suggest a variety of non-linear transforms on independent variables (time, angle) or dependent variables (acoustic pressure). The effect of these transformations is to capture the reliable features of the channel and exploit those for improved system performance. That, of course, is one reason why they are frequently used as ways of presenting acoustic data. There is potentially a great pay-off in developing new objective functions for source detection, classification, and localization. Such alternative formulations need to be characterized in terms of the conditions (primarily environmental uncertainty but also SNR and array topology) that favor one objective function over another.

Interferer Kinematics vs Environmental Fluctuations in Snapshot Deficient Processing

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Issues and Objectives of Research

1) Theoretically and experimentally study the transition region between source motion and environmental effects on snapshot deficient passive array signal processing.
2) Develop robust signal processing algorithms to mitigate fluctuation effects in order to extend the range of passive processing.

Background

The ONR Acoustic Observatory (AO) panel (Zittel- ppt) identified interferer kinematics that lead to snapshot deficient processing as a central issue to passive array performance in shallow water. Among the causes of the snapshot limitations is the interferer transiting resolution cells faster than a processor can develop a stable CSDM. On the other hand, if the source is at longer ranges, the cell size vs kinematics issue is diminished and the effect of environmental fluctuation will become more pronounced. Therefore, there should be a transition region at which snapshot accumulation becomes limited by the environment. The highly nonlinear nature of this problem, which includes the major complication of signal-to-noise ratio dependence, requires in depth study of the set of associated signal processing and environmental snapshot requirements. If the signal processor does not deal with this transition region, then clearly we are at one of the limits to passive processing.

Measurements

For this research into the limits of Robust Passive Sonar, theory and algorithm development is required. However, the really central issue is measurement. In this case, with the AO, simultaneous, multidimensional, spatial and temporal measurements from stationary and moving radiators at an assortment of frequencies and ranges with associated environmental measurements must be performed to identify and confirm the transition region and to test the performance of proposed processors. In particular, there exists equipment in the community that could be used to augment the Acoustic Observatory to perform these measurements. At MPL, relevant equipment includes
1) Source buoys (2) each consisting of flotation for a large battery pack (a rack of 32, 12 volt, 65 AH gel-cell batteries), PC for remote signal waveform synthesis, power amplifiers, GPS time code for precise timing, and a 2.4 GHz wireless local area network (802.11b) for remote control.
2) Autonomous receiving arrays (2) each consisting of 16 elements equally-spaced over a 75 m aperture with 120 GB of internal recording capacity.
3) Environmental sensors including CTD's, 32 self-recording temperature loggers, and a 16-element thermistor string.
Towed Array We also would like to use the ONR towed array (originally constructed fro the geoclutter program). This unclassified towed array could provide the 6.1/6.2 community with the only possible unclassified towed array data in the vicinity of the AO.

Studies Using the Resources of the ONR Acoustic Observatory: Array Design/Beamforming, Acoustic Communications, Forward Scatter, Passive Synthetic Aperture, and the Spatially-Referenced Towed Array

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1. Beamforming/Array Design

The planned array layout for the ONR Acoustic Observatory (ONR-AO) provides a unique opportunity for the investigation of the performance of full and sparse array configurations in combination with beamforming and localization techniques over time as the environment changes due to weather, shipping patterns, etc. The array configurations that can be considered include linear, planar, and volumetric concepts. The localization techniques include conventional beamforming, adaptive beamforming, and matched field processing. This type of effort will forge an understanding of how and when configuration/technique combinations either excel or fail.

Our contribution in this area will focus on a method for computing sidelobe reducing weight matrices for non-uniform array geometries that is currently being investigated for underwater and air acoustic applications [1], [2]. In addition to reducing sidelobes, these non-adaptive weights are applied in beamspace, retain or improve beamwidth, and can be pre-computed and stored for use. This type of approach is useful if either the interference is highly non-stationary or the compute power is not available to support adaptive techniques.

2. Basin-Scale Underwater Acoustic Communications Optimization

The objectives of this research are to investigate the aperture requirements and appropriate modulation scheme to "optimize" the rate and reliability of basin-scale acoustic communications. Basin-scale acoustic communications has been shown to be feasible for binary phase shift keying (BPSK) data received on an extraordinarily large vertical array in the deep ocean [3]. These significant spatial apertures are not always available so the ONR-AO provides an excellent test receive configuration for investigating the horizontal and vertical array requirements as a function of data rate and received signal-to-noise ratio in shallow water.

Data rate and required aperture will undoubtedly also be dependent on the signaling selected. We propose to investigate frequency-hopped signaling as a complement to the PSK signaling proposed by the team of Dan Kilfoyle of SAIC and Lee Freitag of WHOI. An informal arrangement for at-sea testing exists between these two groups and, taken together, the research of the two groups offers the potential for comprehensive investigation of the issues related to basin-scale acoustic communications with the receive array in relatively shallow water.

3. Low-Frequency Forward-Scatter Measurements

Bistatic sonar has been employed for target regions outside an equal time-of-arrival ellipse that connects the source and receiver. Existing bistatic sonar systems do not attempt detection within this ellipse due to the very strong "direct blast" from the source. Using traditional processing techniques, this "direct blast" overwhelms any signature from a target located inside the ellipse, and the target is masked. To make detections within this ellipse the perturbations in the received signal due to the forward scattering from the target must be exploited. This is possible because there is large acoustic gain in the forward direction around the target [4].

In the case of a continuous tone, direct field variability due to environmental conditions requires further investigation. This variability needs to be identified in a physics-based sense as a function of time and space over a range of conditions. Other sources/signals have also been identified for potential use in a forward scatter system. The goal of this work is understand and quantify the natural variation in the forward scatter reverberation caused by the environment in the absence of a target. Forward scatter reverberation models can be validated against the data collected from the ONR-AO and algorithms / array design for target detection and localization can be developed. This work can culminate in an experiment with a target.

4. Passive Synthetic Aperture Sonar Performance Verification

Understanding the interplay between temporal and spatial coherence is especially critical for the synthesis of a synthetic aperture [5]. It has been argued by some that signals of interest do not have sufficient temporal coherence to allow a spatially coherent aperture to be synthesized. Others have argued that a spatially coherent aperture can still be created (even in the case of insufficient temporal coherence over the synthesis time) if compensation for the loss of coherence is applied to the received signal periodically within a time window less than the coherence time. By towing an array along the horizontal aperture of the ONR-AO, a nearly simultaneous data collection can be made on both systems allowing for a relatively fair comparison of results.

The utility of the ONR-AO to make signal coherence measurements across time and space is evident. The "ground-truth" ONR-AO coherence can then be used to define the theoretical limits of passive synthetic aperture formation as a function of frequency and to relate these limits to fixed-position (ONR-AO) array processor performance.

5. Spatially-Referenced Towed Array (SPARTA) Feasibility

Fixed-position arrays and towed arrays are of considerable interest because of their widespread use and, in the case of towed arrays, because of their potential to create a passive synthetic aperture (as noted in Paragraph 4). The spatially-referenced towed array (SPARTA), an alternative array design that has previously been shown to improve upon towed performance for plane and spherical wavefronts through Cramer-Rao bound analysis, consists of two subarrays that have different velocities [6]. For example, it has been shown that adding at least one hydrophone occupying a fixed position in space can considerably improve the bearing estimates and the resolution capabilities of a towed array.

Until now, feasibility of the SPARTA approach has been difficult to demonstrate. The ONR-AO provides a unique opportunity to create and research the performance of a SPARTA in shallow water. The passive synthetic aperture research and experiment outlined in Paragraph 4 can easily be extended to the SPARTA by moving the towed array beyond the physical aperture of the ONR-AO. This type of experiment and research would add a further dimension to the spatial and temporal coherence trade by addressing the coherence between spatially separated subarrays.

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Water Column Considerations for the Acoustic Observatory

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It has now been demonstrated in SWARM, the shelf break PRIMER, and ASIAEX that temperature and salinity variations in the water column have a profound impact on acoustic propagation in the littorals. Even salinity, which is often a non-factor in blue water, can be important near the outflows of the world's great rivers. The environmental impacts are sometimes counter-intuitive, e.g. a warm core ring between a source and receiver may actually enhance acoustic transmission onto the continental shelf. Strong non-linear internal waves (solitons) between source and receiver may diffuse sound over the entire water column on the continental shelf that was previously trapped near the bottom when no solitons were present. Thus, water mass variability over a wide range of space (100 m – 200 km) and time (minutes to months) scales has demonstrable impacts on acoustic propagation in shallow water.

Despite their obvious importance, there is little discussion of these factors in the web-based observatory guidance so far. Most of the "environmental factors" discussed in the site selection process concern the bottom. There is some discussion on currents, but little on fronts, water masses, or internal waves. The physical oceanography observations supporting the acoustic observatory need to be able to resolve the important scales, and have an impact on site selection. The presently favored sites off south Florida and the eastern Florida Keys are similar oceanographically, and not optimal from the physical oceanography or operational perspective. The Gulf Stream dominates the story here: The high currents are difficult to work in and will limit deployment of the HLAs to the alongshelf direction only. Within the narrow confines of the Florida Straits, there is little meandering or seasonal variability, and a less active internal wave field than at most of the other suggested locations.

Perhaps this simplicity is desirable when focusing on other factors influencing detection, localization, and identification, but it is unfortunately not representative of other sites world-wide where the Navy is likely to operate. One cannot think of anywhere else that is at all like the Florida Straits. The Gulf Stream in the South Atlantic Bight would be much more similar to the Kuroshio in the East China Sea, with a broader continental shelf, some meandering, eddy and "shingle" formation etc. Lessons learned there would be more readily transportable to other areas of operational interest.

Physical Oceanographic Issues at the OAO Site

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The oceanographic conditions at the OAO site are obviously very dynamic, given the presence of the Florida Current as it moves northward through the narrow Florida Strait to become the Gulf Stream.

Much of the work done in this area previously has focused on motions at subtidal time scales. The topics of interest have been related more to identifying long period meanders in the flow, correlating them with variations in transport through the Florida Straits region, and examining how they impact the Gulf Stream farther north.

Only in recent years have a few higher frequency (tidal and below) measurements been made. Many of these have focused on the western shelf of the Strait, looking at eddies shed emerging from the flow as it meanders onto the narrow shelf and examining interactions with Florida coastal waters. Two excellent examples of this work are papers by Shay et al. (*EOS*, **81**(19), 2000 and a Web-based preprint of an IEEE *Journal of Ocean Engineering* paper [http:\\storm.rsmas.miami.edu\~nick] posted in 2002).

Not much effort has been expended to look at the high frequency processes in the deeper waters of the Miami Terrace, where the OAO will be installed. The site survey conducted by NRL in late July-August of 2001 is one of the few sources of high frequency current data and (limited) temperature data. These measurements clearly show variability at tidal and higher frequencies, as well as the expected longer periods. The current (ADCP and meters) data set shows clear vertical variability in currents and shear at two sites and gives some idea of horizontal variability between the sites. The temperature data is sufficient to point to episodes of variability at two locations separated in depth and range, but shed little light on processes occurring. These could have implications for acoustic propagation at the site.

A clear need exists for measurement suites to examine time and spatial scales of motions at the site - upslope, downslope, and in the upstream and downstream directions. Correlations with local surface meteorological conditions will also be required.

Processes along the western Florida Straits: Long-term variations, mesoscale and high frequency.

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The dynamics of the western side of the Gulf Stream in the Florida Straits are described based on hydrographic and mooring data. The mean currents and interannual variations observed as part of the long term monitoring array between West Palm and West End, Bahamas are briefly described. The mean profile exhibits a sharp front along the shelf edge with mean currents exceeding 2 m/s. This current has a distinct seasonal cycle that has changed over the past twenty years. The front brings cold thermocline waters up to the shelf edge where mesoscale meanders can lift the thermocline up over the supporting topography. The result is a northward moving mesoscale feature called a spin-off eddy, after Lee (1975). Analysis of data and recent observations using surface HF radar suggest that these features are largely a readjustment of the pressure field at the shelf edge involving inertial motions and internal gravity waves. The passage of cyclonic offshore meanders leaves a decaying flow of cold thermocline water along the shelf edge. Three to four types of events along the shelf break can be identified in moored ADCP data. These include these cold core eddy passages associated with upwelling and diurnal internal tides for the Gulf Stream thermocline, cold stratified bottom layers with internal solutions, and warm events that carry Gulf Stream core surface waters on to the shelf. Event time scales are approximately a week in total. The mismatch of the local radii of deformation across the shelf break and the highly nonlinear nature of the dynamics make it difficult to fully describe the dynamics of each type of event. The cold passages involve a coherent small-scale vortex with a leading and following regime dominated by diurnal internal tides. These are typical of the thermocline in the central Strait and are carried into the shallow waters by the advective field associated with the meanders. Consideration of the properties of the shelf environment suggests that these features cannot propagate on the shelf, leading to the conclusion that they must break. Deep bottom mixed layers during cold events are tied to the resulting mixing.

Potential Areas Acoustic Propagation and Communications Research At the Acoustic Observatory

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In the configuration as currently proposed, the Acoustic Observatory is well suited for investigating acoustic propagation issues and adaptive signal processing issues relating to acoustic communications at low frequencies. At these frequencies, bandwidth is relatively limited but communications system propagation ranges can be considerably longer than at higher frequencies. Hence, research issues relating to maximizing data throughput with constrained bandwidth and long range propagation in coastal shallow water environments are important to consider. A number of these issues are outlined below.

Dimensionality of sampled channel impulse response fluctuations: Channel estimation and adaptive equalization algorithms face a fundamental trade-off between the number of degrees of freedom in the impulse response that can be tracked, the rate of channel impulse response fluctuations, and the SNR. Most adaptive channel equalization algorithms assume that number of degrees of freedom is equal the number of significant taps in the sampled channel impulse response. However, empirical evidence indicates that the dimension of the subspace spanned by the sampled channel impulse response over a significant time period is significantly less than the number of significant taps in the sampled impulse response. The fixed long term observational capability of the Acoustic Observatory can be used in combination with either fixed or towed acoustic sources transmitting channel probe signals to provide the data to develop techniques to estimate the dimensionality of channel fluctuations as a function of range and environmental conditions. The Acoustic Observatory can also be used to investigate the loss of multipath complexity due to attenuation and scattering loss as a function of range and environmental conditions. If reduced dimension fluctuations are common and predictable, then reduced dimension channel estimation or equalization algorithms can be developed to provide improved performance in these environments and can utilize data collected at the Acoustic Observatory as part of the development process.

Channel Impulse Response Stability and Large Dimension Adaptive Equalizers: In coastal environments, the complex propagation environment and potential for a large number of discrete interferers can pose a significant challenge to low frequency communications systems. The use of large arrays such as those in the Acoustic Observatory can be used to improve system performance by both reducing the ISI caused by the multipath structure and by canceling the signals from the interferers. The ability to accomplish such performance improvements depends on the ability of an adaptive algorithm to adaptively "steer beams" to isolate multipath components of the impulse response or "steer nulls" to cancel interfering signals. Unlike multi-user communications systems that rely on the ability to demodulate "interfering" signals in order to cancel their impact on a "desired" signal, the cancellation of discrete interference such as shipping noise must rely on other techniques. Such algorithms will need to be able to adapt a large number of filter "weights" at rates necessary to track channel fluctuations and adjust for motion of both the source of interest and the interfering sources. The Acoustic Observatory can be used for research programs investigating the dependence of channel fluctuation rates in the shallow water environments on range and environmental conditions as well as the rate and nature of source motion induced channel fluctuations. In addition, the data collected can be used to develop and test adaptive equalization algorithms capable of operating with large numbers of spatial/temporal filter weights.

Future Observatory Enhancements and Acoustic Communications Related Research: The use of both transducer (source) arrays and hydrophone arrays in low frequency communications systems can be enhanced by the presence of stable features of the MIMO (Multiple Input, Multiple Output) channel impulse response between sources and receivers. With the addition of fixed source arrays, the observatory can be used to investigate the presence and characteristics of stable features and their dependence on environmental conditions.

While the currently planned observatory is focused on acoustic propagation at frequencies up to 500 Hz, the addition of suitable large aperture arrays cut for frequencies up to several kHz and sampled appropriately would greatly increase the range of acoustic communications related research issues that could be addressed. While the interference from discrete sources such as surface shipping is smaller at these frequencies, issues such as the impact of surface scattering on both channel fluctuations and signal loss will increase in importance. The addition of fixed sources at different ranges from the observatory receive arrays with the ability to transmit user defined communications signals would also enhance the acoustic communications research at the observatory.

While not critical for program success, the addition of fixed sources that can be programmed with communications signals and controlled from shore would greatly enhance the above mentioned research programs. Sources that share a common sample clock with the hydrophones or that have highly accurate sample clocks are most useful for realizing the full benefit of fixed programmable sources.

Acoustic Observatory Research Objectives

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Array Processing with a Stochastic Ocean

The Naval Studies Board report which recommended an Acoustic Observatory was concerned with the coherence length large arrays because this length effectively determines when to partition an array into linear beanforming sections followed by quadratic combination. The follow on Jason study added the discrete noise hypothesis wherein adaptive beamforming would have high array gains against in a high clutter environment by nulling these discrete components. The Acoustic Observatory Working Group (AOWG) examined these issues and found that the array gain was limited by the snapshot problem because large arrays imply high resolution which in turn makes the scale of stationarity required by the adaptation shorter. The overall objective of the Acoustic Testbed is to understand the issues associated with the limits of sonar array performance. Our efforts concern the limits imposed by a stochastic, or uncertain, ocean.

Spatial coherence is a consequence of a stochastic ocean whereby inhomogeneities and/or scattering processes lead to signal gain degradation (SGD). This can be as simple as wavefront aberrations of a plane wave model, or more complicated multipath decorrelation as used in computing the replica for matched field processing. For target detection high SGD ultimately leads defocusing and splattering of the beam into sidelobes. Similarly, MFP is very sensitive to SGD since it almost always sidelobe limited. Currently, all beamformers including MFP use a single replica, or one dimensional model, for the spatial correlation. A stochastic ocean requires more than a single replica to capture all the signal energy. The most common implementation of this dividing a linear array into diversity sections governed by horizontal acoustic length. (Beamforming in excess of this length degrades performance as one essentially is adding uncorrelated random variables.) The diversity segments are combined incoherently. The number of diversity components represents the dimensionality of the signal space. When there is a vertical component, or a long horizontal array, identifying the replica space is much more difficult as one must account for vertical wavefront aberrations and multipath decorrelation. Simulations have indicated that reasonable variability levels in the ocean environment lead to the signal space having more than one dimension.

A stochastic ocean also impacts adaptive beamforming algorithms. If a discrete noise source spreads to more than one degree of freedom, then the ABF must allocate a corresponding degree of freedom to null it. If a parametric nuller is used, nullers with more than one degree of freedom is required, again requiring a higher dimensional space. The important issue is that a stochastic ocean impacts both the signal and noise aspects of the processing. Moreover, higher frequencies lead to more degrees of freedom as the scattering processes usually scale with wavelength.

Our focus is to use the data from the acoustic observatory to examine the multidimensional aspect of signal representation. This will be correlated with the environmental sensors such as the CTD's to understand physical causes. Performance predictions will made using detection theory performance bounds and parameter estimation bounds developed by the author.

Geophone Arrays Propagation in the littoral always involves bottom interaction. The properties of the bottom always dominate transmission loss, signal dispersion and multipath. Loss mechanisms such i) mode conversion (shear), ii) scattering due to both bottom and interface roughness and iii) effective critical angles due to bottom contrast and high gradients all contribute to bottom interaction. Three component geophones were included in the AOWG recommendations because one cannot understand bottom loss mechanisms without measuring the the acoustic signals on both sides of the seafloor interface. The geophones will permit measurement of the seismic P and S waves and the conversion efficiency at the interface and lead to a better understanding on bottom loss mechanisms. Our effort would focus on a better characterization of bottom effects with the geophone arrays.

Geophones are vector sensors and consequently have directional capability. Moreover, they also can null directional interference. Very effective adaptive beamforming have been developed for multicomponent sensors and they are very effective against directional interference. With an array of multicomponent geophones should lead to a very effective system against a cluttered environment with many directional components. One of the limits of such an array is the coherence of the seismic signals in the bottom. We plan to evaluate the capabilities of multicomponent geophone arrays.