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Principal Investigators: Arthur Baggeroer, Ford Professor of Engineering
Alan V. Oppenheim, Distinguished Professor of Engineering
Program Manager: Dr. Neil Geer, Division of Mathematical Sciences, ONR

This report summarizes the effort performed under the grant "Adaptive Array Processing in Uncertain Inhomogeneous Media" during the past year. The format of the report is a compilation of the theses, presentations and journal articles with copies of their abstracts which have been supported all or in part by the grant. The full texts have been sent to the program manager during the year as they were written.

Thesis Completed

[1] J.C. Preisig, *Adaptive Matched Field Processing in an Uncertain Sound Speed, Deep Ocean Environment*, PhD thesis, January 1992.

Presentations and Conference Proceedings

[1] J. Jachner and H. Lee, "Cramer-rao bounds on direction estimates of closely spaced emitters in multi-dimensional applications", presented at IEEE Conference on Acoustics, Speech and Signal Processing, San Francisco, CA, March 1992. Appears in *ICASSP 92 Proceedings*, Vol. II, pages 513–516.

[2] J.C. Preisig, "Optimal minmax estimation and the development of minmax estimation bounds", presented at IEEE Conference on Acoustics, Speech and Signal Processing, San Francisco, CA, March 1992. Appears in *ICASSP 92 Proceedings*, Vol. V, pages 285–288.

[3] A.B. Baggeroer and W.A. Kuperman, "Stochastic matched field processing", presented at The Acoustical Society of America, 1992 as an invited speaker. Also published in the *Journal of the Acoustical Society of America.*

[4] A.B. Baggeroer and W.A. Kuperman, "Matched field processing in ocean acoustics", presented at NATO ASI Meeting on Signal Processing and the Ocean Environment as an invited speaker. Proceedings to be published by Kluwer in January 1993.

Publications in Progress

[1] M. Feder, E. Weinstein and A.V. Oppenheim, "Multi-channel signal separation by decorrelation". Submitted to *IEEE Transactions on Singal Processing* and now in revision 1992.

[2] J. Buck and P. Tyack, "A quantitative measure of the similarity of tursiops truncatus signature whistles". Submitted to the *Journal of the Acoustical Society of America*, 1992.

[3] J.C. Preisig, "Adaptive matched field processing in an uncertain propagation environment, part I: Backward and processor formulation". Submitted to *IEEE Transactions on Signal Processing*, 1992.

[4] J.C. Preisig, "Adaptive matched field processing in an uncertain propagation environment, part II: Processor implementation and analysis". Submitted to *IEEE Transactions on Signal Processing*, 1992.

Adaptive Matched Field Processing in an Uncertain Propagation Environment

by

JAMES CALVIN PREISIG

Submitted in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
and the
WOODS HOLE OCEANOGRAPHIC INSTITUTION
January 1992

Abstract

Adaptive array processing algorithms have achieved widespread use because they are very effective at rejecting unwanted signals (i.e., controlling sidelobe levels) and in general have very good resolution (i.e., have narrow mainlobes). However, many adaptive high-resolution array processing algorithms suffer a significant degradation in performance in the presence of environmental mismatch. This sensitivity to environmental mismatch is of particular concern in problems such as long-range acoustic array processing in the ocean where the array processor's knowledge of the propagation characteristics of the ocean is imperfect. An Adaptive Minmax Matched Field Processor has been developed which combines adaptive matched field processing and minmax approximation techniques to achieve the effective interference rejection characteristic of adaptive processors while limiting the sensitivity of the processor to environmental mismatch.

The derivation of the algorithm is carried out within the framework of minmax signal processing. The optimal array weights are those which minimize the maximum conditional mean squared estimation error at the output of a linear weight-and-sum beamformer. The error is conditioned on the propagation characteristics of the environment and the maximum is evaluated over the range of environmental conditions in which the processor is expected to operate. The theorems developed using this framework characterize the solutions to the minmax array weight problem, and relate the optimal minmax array weights to the solution to a particular type of Wiener filtering problem. This relationship makes possible the development of an efficient algorithm for calculating the optimal minmax array weights and the associated estimate of the signal power emitted by a source at the array focal point. An important feature of this algorithm is that it is guarenteed to converge to an exact solution for the array weights and estimated signal power in a finite number of iterations.

The Adaptive Minmax Matched Field Processor can also be interpreted as a two-stage Minimum Variance Distortionless Response (MVDR) Matched Field Processor. The first stage of this processor generates an estimate of the replica vector of the signal emitted by a source at the array focal point, and the second stage is a traditional MVDR Matched Field Processor implemented using the estimate of the signal replica vector.

Computer simulations using several environmental models and types of environmental uncertainty have shown that the resolution and interference rejection capability of the Adaptive Minmax Matched Field Processor is close to that of a traditional MVDR Matched Field Processor which has perfect knowledge of the characteristics of the propagation environment and far exceeds that of the Bartlett Matched Field Processor. In addition, the simulations show that the Adaptive Minmax Matched Field Processor is able to maintain it's accuracy, resolution and interference rejection capability when it's knowledge of the environment is only approximate, and is therefore much less sensitive to environmental mismatch than is the traditional MVDR Matched Field Processor.

CRAMER RAO BOUNDS ON DIRECTION ESTIMATES FOR CLOSELY SPACED EMITTERS IN MULTI-DIMENSIONAL APPLICATIONS

Jack Jachner and Harry Lee

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ABSTRACT

The main results of this paper are characterizations of the Cramer-Rao (CR) bound on the variance of direction estimates for closely-spaced emitters in multiple parameter *(multi-D) scenarios. Specifically, simple analytic expressions* for the CR bound are presented for co-linear emitter configurations, which show the bound to be very sensitive to the maximum spacing between emitters ($\delta\omega$). Results also are cited for CR bound sensitivity to $\delta\omega$ for emitter configurations in which the emitters are not co-linear. The latter results exhibit greatly reduced sensitivity to the direction separation factor $\delta\omega$. Thus the results show that *degeneracies are present in multi-D parameter estimation scenarios that are not present in 1-D scenarios.* Specifically emitter resolution and direction estimation can be expected to be much more challenging for some emitter configuration than for others. The case of co-linear emitters appears to be a particularly stressful one.

OPTIMAL MINMAX ESTIMATION AND THE DEVELOPMENT OF MINMAX ESTIMATION ERROR BOUNDS

James C. Preisig

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ABSTRACT

It is often desired to create an optimal estimator of some parameter θ given the observation x. However, the relationship between θ and x may depend on another parameter ϕ which is unknown to the processor and not of direct interest. In this case, an estimator which performs well for one value of ϕ may perform poorly for another value of ϕ. One approach to dealing with this problem is to develop an estimator whose worst case performance evaluated over some range of ϕ is as good as possible. Such an optimal minmax estimator is derived. The derivation of this estimator also motivates an approach to developing lower bounds on the minmax estimation error achievable by any estimator.

6UW1. Stochastic matched-field processing. Arthur B. Baggeroer (MIT, Cambridge, MA 02139) and William A. Kuperman (Naval Res. Lab., Washington, DC 20235)

Matched-field processing (MFP) exploits the acoustic field to estimate either a source position or environmental parameters. Many have noted that the performance of MFP degrades rapidly with uncertainty about the field especially if adaptive methods are used to suppress sidelobes. It is clear that robust MFP methods are needed for working with experimental data. There are three categories of uncertainty that have been examined: (i) observational (array geometries and sensor responses are imprecisely known), (ii) statistical (ambient field covariances have errors), and (iii) environmental (the propagation is uncertain because of oceanographic characterization). The third category is examined in this presentation. The fundamental issue for robust MFP is to match the stochastic propagation with array processing that responds to an ensemble of replicas not just one from a deterministic model. At high SNRs one can search the ensemble for the appropriate sample vector using efficient searching algorithms such as simulated annealing. At modest SNRs the processing must incorporate errors from the noise. The approaches to MFP with environmental uncertainty are reviewed and some of the relevant signal processing literature for the "detection of random signals in noise" are noted. [Work supported by Mathematical Sciences, ONR.]

MATCHED FIELD PROCESSING IN OCEAN ACOUSTICS

Arthur B. Baggeroer
Massachusetts Institute of Technology

and

William A. Kuperman
Naval Research Laboratory

ABSTRACT. Matched field processing (MFP) is a generalized beamforming method which uses the spatial complexities of acoustic fields in an ocean waveguide to localize sources in *range, depth and azimuth* or to infer parameters of the waveguide itself. It has localized sources with accuracies exceeding the Rayleigh limit for depth and the Fresnel limit in range by two orders of magnitude. MFP exploits the coherence of the mode/multipath structure and it is especially effective at low frequencies were the ocean supports coherent propagation over very long ranges. This contrasts to planewave based models which are degraded by modal and multipath phenomena and are generally ineffective when waveguide phenomena are important. MFP is a spatial matched filter where the correlation signal, or replica, is determined by the Green's function of the waveguide. It can have either conventional or adaptive formulations and has been implemented with an assortment of both narrowband and wideband signal models. All involve some form of correlation between replicas derived from the wave equation for the impulse response and the data measured at an array of sensors. Since this impulse response generally has a complicated dependence upon the source location and environmental parameters, the wave equation must be solved over the parameter space. One can view MFP as an inverse problem where one attempts to invert for these dependencies over the parameter space of the source and the environment. There is currently a large literature discussing many theoretical aspects of MFP and supported by lots of simulations; a considerable number of experiments acquiring data for MFP now have been conducted in several ocean environments. Consequently, there is a modest understanding of both the theory and the experimental capabilities of MFP. This article provides an overview of both.

Multi-Channel Signal Separation by Decorrelation

Ehud Weinstein[1] Meir Feder[2] Alan V. Oppenheim[3]

August 13, 1992

In a variety of contexts observations are made of the outputs of an unknown multiple-input multiple-output linear system, from which it is of interest to identify the unknown system and to recover the input signals. This often arises, for example, with speech recorded in an acoustic environment in the presence of background noise or competing speakers, in passive sonar applications, and in data communications in the presence of cross-coupling effects between the transmission channels. In this paper we specifically consider the two-channel case in which we observe the outputs of a 2x2 linear time invariant system. Our approach consists of reconstructing the input signals by assuming that they are statistically uncorrelated, and imposing this constraint on the signal estimates. In order to restrict the set of solutions, additional information on the true signal generation and/or on the form of the coupling systems is incorporated. Specific algorithms are developed and demonstrated for the case in which the coupling systems are discrete-time causal finite impulse response (FIR) filters. As a special case, the proposed approach suggests a potentially interesting modification of Widrow's least squares method for noise cancellation, when the reference signal contains a component of the desired signal.

A Quantitative Measure of the Similarity of Tursiops Truncatus Signature Whistles

by

J. Buck and P. Tyack

Abstract

Bottlenose dolphins (*Tursiops truncatus*) are believed to produce individually distinctive narrowband "signature whistles." These whistles may be differentiated by the structure of their frequency contours. An algorithm is presented for extracting frequency contours from whistles and comparing two such contours. This algorithm performs non-uniform time-dilation to align contours and provides a quantitative distance measure between the contours. Results from two recognition experiments using the algorithm on recorded dolphin whistles are presented.

PACS Numbers: 40.80Jz, 43.80Lb, 43.80Nd

Adaptive Matched Field Processing in an Uncertain Propagation Environment Part I: Background and Processor Formulation

James C. Preisig*

July 6, 1992

I Introduction

The signals received by spatial arrays of sensors are often composed of the sum of signals emitted by both point and spatially spread sources at different locations. In order to estimate the signal, or the parameters of the signal, emitted by a source at a particular location, the array processor must often separate that signal from the other signals which are received. The separation of signals based upon the location of the source is referred to as spatial filtering.

Array processors achieve spatial discrimination through filtering by exploiting the fact that the spatial characteristics of a propagating signal as received at an array of sensors depend upon the location of the source of the signal. However, the spatial characteristics of a propagating signal also depend upon the characteristics of the medium through which the signal is

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*The author was with the Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA. The author is currently with the Department of Applied Ocean Physics and Engineering, Woods Hole Oceanographic Institution, Woods Hole, MA 02543. This work was supported in part by the Defense Advanced Research Projects Agency monotored by the Office of Naval Research under Grant N00014-89-J-1489 and in part by the Office of Naval Research under Grant N00014-91-J-1628.

propagating. Therefore, if a processor has inaccurate or incomplete information concerning the characteristics of the propagation environment, it may be unable to determine the spatial characteristics which should be exhibited by a signal emitted by a source at the location of interest. Thus, the environmental mismatch may result in a signal model mismatch. In these cases, the processor may have difficulty in accomplishing the spatial filtering necessary to estimate the parameters of the signal of interest.

While adaptive array processors have achieved widespread use because of their good sidelobe control and resolution, they have also been shown to be very sensitive to the signal model mismatch caused by environmental mismatch [1, 2, 3]. In ocean acoustic array processing problems where it is impractical for the processor to access detailed and precise environmental information, this sensitivity poses a serious problem. This paper proposes an approach to array processing which yields a processor capable of operating with only approximate environmental information while at the same time achieving levels of spatial resolution close to those achieved by adaptive processors having accurate and detailed environmental information.

The processor, which is referred to as the Adaptive Minmax Matched Field Processor, is developed within the framework of minmax signal processing. Given a range of environmental conditions over which the processor is expected to operate, the weights of the processor's linear weight-and-sum beamformer are adaptively adjusted to minimize the worst-case processor error criterion evaluated over this range of environmental conditions. Thus, rather than needing precise information as to the state of the propagation environment, the processor can operate effectively when it knows only that the environmental conditions fall within a reasonable range. The details of the minmax framework and error criterion and the structure of the array processor are covered in Section VI. Matched field processing techniques, which the processor merges with adaptive array processing techniques and the minmax signal processing framework, are reviewed in Section III.

This paper is the first in a series addressing the issue of adaptive processing in the presence of environmental uncertainty. The implementation and analysis of the processor proposed in this paper are presented in [4]. While the processor has its foundation in the framework of minmax signal processing, it can also be shown to be equivalent to both a particular type of Wiener filter and a combined signal model estimator and Minimum Variance Distortionless Response array processor (MVDR) [5, 6] (also referred to as the Maximum Likelihood array processor). These relationships are also developed in [4].

The signal model and the environmental and propagation models used throughout this paper and [4] are described in Sections II and IV, respectively. It should be noted that the array processing technique proposed here is not dependent on the particular signal, environmental, or propagation models used here and has applicability to other models and problems involving signal model mismatch. Finally, Section V contains a brief survey of proposed approaches to the problem of dealing with environmental uncertainty and signal model mismatch.

Adaptive Matched Field Processing in an Uncertain Propagation Environment Part II: Processor Implementation and Analysis

James C. Preisig*

July 6, 1992

I Introduction

An array processor, referred to as the Adaptive Minmax Matched Field Processor, which is capable of operating with only approximate environmental information while at the same time achieving levels of spatial resolution close to those achieved by adaptive processors having accurate and detailed environmental information is proposed in [1]. This capability is particularly useful in ocean acoustic array processing problems where it is impractical for array processors to access detailed environmental information. A review of matched field processing techniques and the minmax signal processing framework, and a formulation of the Adaptive Minmax *Matched Field Processor* are contained in [1].

In this paper, the relationship of the Adaptive Minmax Matched Field Processor to both a particular type of Wiener filter and a particular realization of the Minimum Variance Distortionless Response array processor (MVDR) [2, 3] (also referred to as the Maximum Likelihood array processor) is derived. The Wiener filter relationship is used in Section II to develop an efficient algorithm for implementing the matched field processor. The MVDR processor interpretation of the minmax processor is developed in Section III and leads to a slight modification of the algorithm. Finally, the performance of the processor is analyzed in Section IV.

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