

Adaptive CFAR Performance Prediction in an Uncertain Environment

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LONG-TERM GOALS

The long-term goal of this task is to more accurately predict passive sonar detection performance when both the signal wavefront and noise field directionality are uncertain.

OBJECTIVES

The objective is to bound the behavior of actual sonars by using the performance of optimal constant false alarm rate (CFAR) detection statistics, such as the adaptive matched subspace detector (AMSD), in the presence of realistic ocean environmental uncertainty and limited noise-field training data.

APPROACH

The well-known sonar equation (SE) is the classical method of predicting passive sonar performance. The SE is derived assuming both the signal wavefront and noise field directionality are known exactly. As a consequence, the SE depends only on post-detection signal-to-noise ratio (SNR). Detection performance calculations in uncertain environments with known noise field directionality have been previously addressed using Gaussian signal wavefront models and are also being developed by Nolte using Bayesian priors on environmental variables. In our work, we evaluate detection performance when both the signal wavefront and noise field are unknown. This is the so-called adaptive detection problem where, in addition to SNR, detection performance is limited by both signal wavefront uncertainty and the amount of training data available to estimate the noise covariance matrix. We use the adaptive subspace detection framework developed in (Kraut, et.al. [1]) for an M sensor array with a p dimensional signal subspace which increases with environmental uncertainty. The value of p is found from the signal wavefront covariance matrix computed over an ensemble of environmental realizations. Adaptive detection, in this framework, assumes that a set of K “signal-free” training data vectors is available to estimate the noise covariance matrix. Strictly speaking, this is not true in the passive sonar problem where the signal may be in the training data. However, the performance of optimal adaptive detectors considered here can reasonably be expected to bound the performance of the more realistic, but thus far theoretically intractable, situation.

WORK COMPLETED

The evaluation of detection performance was performed using the generalized likelihood-ratio test (GLRT) for this problem, which is an extension of the Kelly GLRT to the problem of detecting multi-rank signals in noise with unknown covariance matrix. Although Monte Carlo methods can be used to

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predict detection performance by randomizing over ocean parameters and noise covariance uncertainty, this approach is computationally intensive and gives little insight into the cause of performance degradation. In our work, we have applied recent analytic results for the performance of adaptive constant-false-alarm-rate (CFAR) detectors of multi-rank signals in Gaussian noise with unknown covariance [ref. 1] to the passive sonar problem. In particular, analytic expressions for the PDF of the multi-rank extension of the Kelly generalized likelihood ratio test (GLRT) are compared with the statistics of this detector operating on real passive sonar data. Horizontal array data from the SWELLEX-96 data set collected off the San Diego coast was used to validate the analytic detection performance predictions in terms of probability of detection (PD) versus signal-to-noise ratio (SNR). The real data results are shown to be in good agreement with theory provided that sufficient wavefront uncertainty is assumed and that the signal does not contaminate the assumed signal-free noise training data. The effect of signal contamination of the training data was evident when the SNR was high and the training data was very limited. These results demonstrate that fast quasi-analytic performance prediction can be achieved when both the signal wavefront and noise covariance matrix are uncertain as is typically assumed by modern adaptive beamforming-based passive sonar detection systems.

RESULTS

The SWellEx-96 experiment dataset, courtesy of MPL/SIO, was used to validate the analytic distributions and detection performance predictions. The SWellEx-96 Experiment was conducted between May 10 and 18, 1996, off Point Loma in San Diego. The results below use data from the S5 Event of the experiment and the northern horizontal line array (HLA North) with $M=27$ elements. The bearing-time record for the 109 Hz source tonal is shown in Figure 1. The distribution of the GLRT detector using this dataset was compared to the analytical distribution predicted by the theory in [1] and is shown in Figure 2, under the noise-only hypothesis (using the 143 Hz frequency bin) and the signal-plus-noise hypothesis (using the 135 Hz frequency bin where the source was known to be present). In real data, the SNR varies from snapshot to snapshot so the PDF's are marginalized over SNR. Note from Figure 2, the theory accurately predicts the actual distribution under both hypotheses.

Direct comparison of detection performance with real data versus analytical results for the GLRT was also performed using the S5 event and HLA North array dataset. The following performance results consider effects of using various levels of signal wavefront uncertainty and noise covariance matrix training data. Figures 3 illustrates the probability of detection (PD) versus SNR achieved for a fixed probability of false alarm (PFA) by the adaptive CFAR GLRT detector for different levels of environmental uncertainty which maps to signal rank, p . In Figure 3, the large training data case ($K=300$) shows good agreement between theory and data for the uncertain wavefront ($p=4$) model (red curves). Note that the mismatch for $p=1$ in the theoretical prediction versus real data when plane-wave beamforming is assumed may represent the prediction errors encountered in current practice.

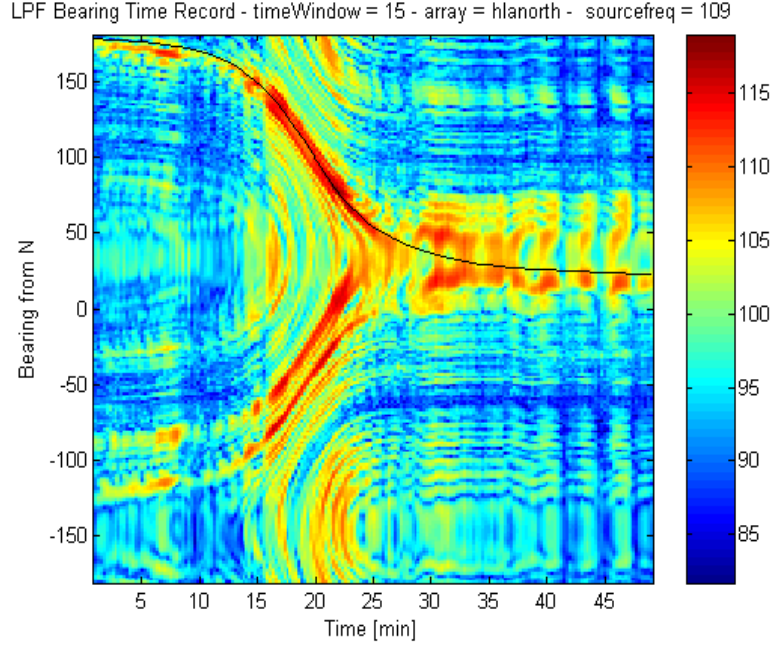


Figure 1: Bearing-Time Record for S5 Event using HLA and 109 Hz Tonal
[Graph: BTR indicating track of source in S5 SWELLEX-96 Data]

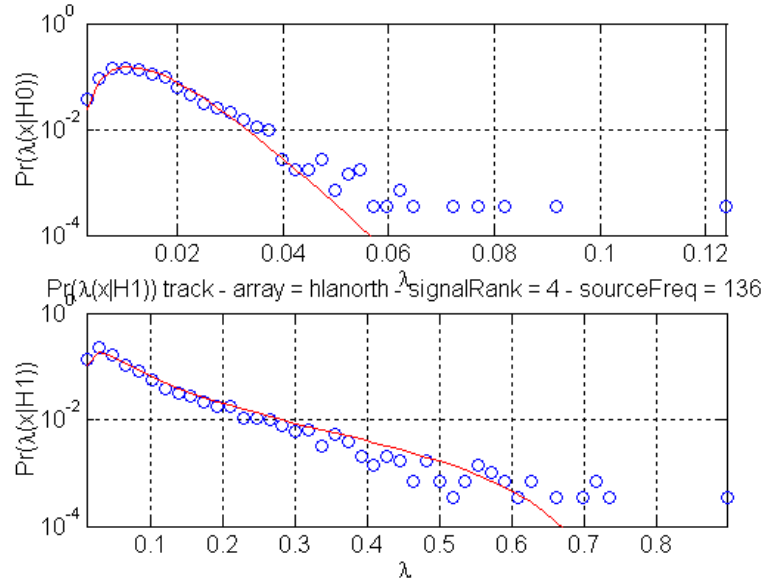


Figure 2: Comparison of Analytic PDF vs. SWELLEX-96 data under H_0 (noise only, top) and H_1 (signal+noise, bottom)

[Graphs: Histograms of GLRT statistic vs. analytical PDF's showing good agreement between theory and SWELLEX-96 data under H_0 and H_1]

Adaptive GLRT detection performance prediction for the S5 event as a function of the number of training data snapshots is shown in Figure 4 for the case of signal wavefront uncertainty corresponding to $p=4$. Note that there is good agreement between theory and data for the $K=300$ case corresponding to the long noise observation time case. For smaller noise training data support (e.g. $K=32$), the PD

with real data is below that predicted by theory. This can be explained by the assumption of signal-free noise training data which is violated at high SNR where noise from the tow ship (at the same bearing as the source) was very evident in the 143 Hz. frequency bin.

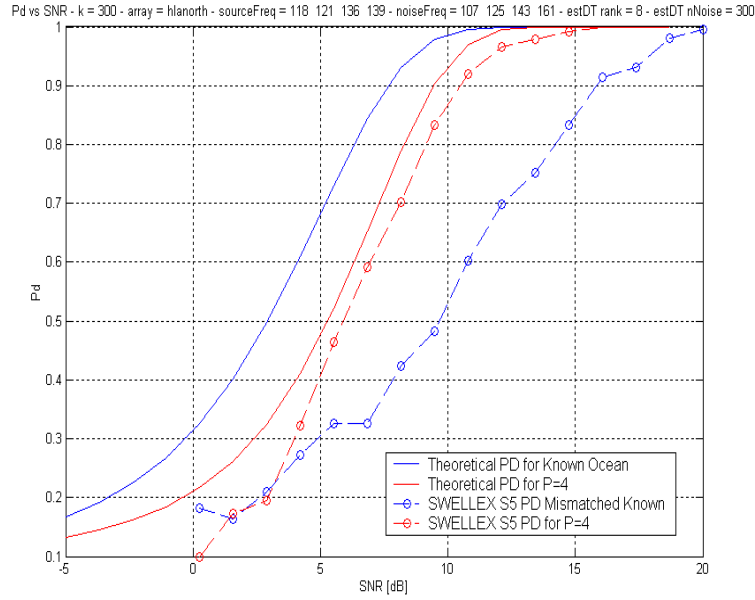


Figure 3: Prob. of Detection vs. SNR at PFA=0.1 for Adaptive GLRT for an Uncertain Environment
[Graphs: PD vs. SNR showing agreement with theory assuming uncertain signal wavefront model and large noise training data set.]

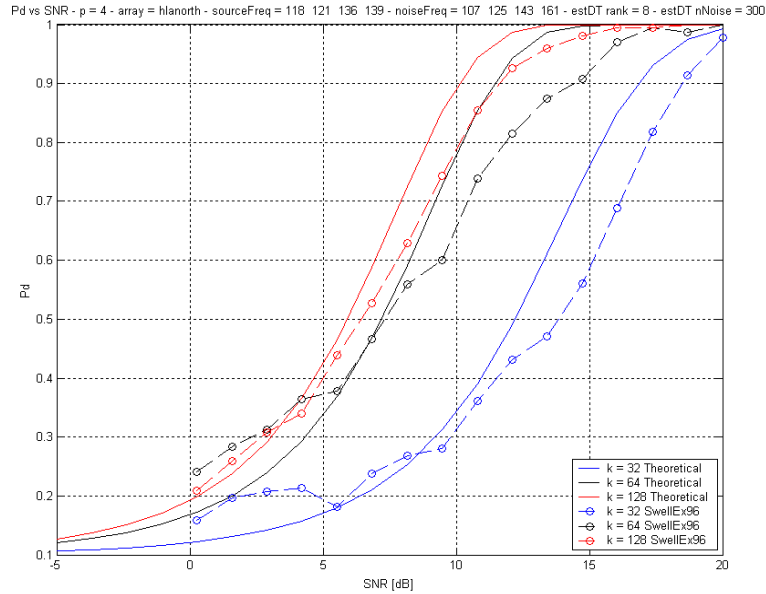


Figure 4: Prob. of Detection vs. SNR at PFA=0.1 for Adaptive GLRT with Limited Noise Training Data
[Graphs: PD vs. SNR showing agreement with theory for uncertain wavefront and low SNR. Mismatch at high SNR due to signal component in noise training data.]

In conclusion, we have evaluated the expected detection loss due to limited noise covariance training data, in the presence of signal wavefront uncertainty, for adaptive CFAR detectors. We have demonstrated good agreement between analytical detection performance predictions and the performance of optimal detectors, matched to the degree of environmental uncertainty, using SWELLEX-96 S5 event data. Future work will include the comparison of detection performance predictions in the presence of interference and environmental uncertainty using the SWELLEX-96 S59 event data.

Evaluation of comparative performance prediction accuracy using horizontal versus vertical array configurations in an uncertain environment are also planned.

IMPACT/APPLICATIONS

This work could impact the development of tactical decision aids for passive sonar which incorporate environmental uncertainty and limited training data in their detection performance predictions.

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2. Book, P, Krolik, J., and Kraut, S. "Analytic prediction of adaptive sonar detection performance in an uncertain ocean", *IEEE Workshop on Underwater Acoustic Signal Processing*, October, 2003.