Stochastic Models and Robust Estimation for Broadband Acoustic Mode Signals

Kathleen E. Wage
George Mason University
Electrical and Computer Engineering Department
4400 University Drive, MSN 1G5
Fairfax, VA 22003
phone: (703)993-1579 fax: (703)993-1601 email: kwage@gmu.edu

Award Number: N00014-02-1-0416
http://ece.gmu.edu/~kwage

LONG-TERM GOALS

The long term goals of this project are to develop stochastic models for broadband mode signals propagating in fluctuating ocean environments and to design robust signal processing techniques for these ocean environments.

OBJECTIVES

To develop a greater understanding of broadband mode signals in fluctuating ocean environments, this project focused on several closely-related research objectives. The first objective was to characterize mode fluctuations at megameter ranges using experimental measurements and simulations. Mode arrivals at long range are very complicated due to internal-wave-induced coupling. From a theoretical standpoint, the effects of internal waves on long-range sound propagation are not thoroughly understood, and much of the previous work in this area focused on the ray arrivals because they are amenable to analysis via the geometrical optics approximation. Characterizing the fluctuations is the first step towards the long-term goal of developing a sufficiently general model of mode propagation that explains recent experimental observations and clarifies the relationship between mode and ray representations of the field. The second objective of this project was to develop a framework for mode processing that mitigates the effects of environmental mismatch, sensor failures, and interference. Since mismatch is a problem that plagues many sonar applications, this work has implications beyond the current project.

APPROACH

To address the stated objectives, this project combined experimental data analysis with simulation and theory. Over the last 10 years, a series of ONR-sponsored experiments generated rich data sets for studying normal mode signals at megameter ranges. The Acoustic Thermometry of Ocean Climate (ATOC), Alternate Source Test (AST), and North Pacific Acoustic Laboratory (NPAL) experiments were the primary focus of this project. The ATOC, AST, and NPAL data sets include vertical array receptions at center frequencies of 28 Hz, 75 Hz, and 84 Hz at ranges of 3.5 Mm and 5.1 Mm. As a part of this project the PI and her students analyzed these data sets using signal processing techniques developed for processing the low order modes. The PI also contributed to the planning and

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**

4. TITLE AND SUBTITLE **Stochastic Models and Robust Estimation for Broadband Acoustic Mode Signals**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **George Mason University,Electrical and Computer Engineering Department,4400 University Drive, MSN 1G5,Fairfax,VA,22003**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**11**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

implementation of the 2004-2005 SPICE04/LOAPEX experiment that finished in June 2005.

Between 2002 and 2005, several George Mason University electrical engineering students worked on this project. Mr. Tarun Chandrayadula investigated the problem of designing adaptive equalizers for broadband mode signals. Mr. Aravinda Sringarapuram worked on mode estimation methods that can adapt to the changing interference characteristics of the channel. LT Eric St. Pierre attended GMU sponsored by the U.S. Coast Guard postgraduate training program. In 2004-2005, he developed a method for estimating the sound speed profile required for mode processing from sparse measurements of the temperature along a vertical array.

WORK COMPLETED

The duration of this project was 3.5 years, from April 2002 to December 2005. This report summarizes the work completed and the publications produced during the project.

ATOC/AST Mode Analysis: An extensive statistical analysis of the mode arrivals in the ATOC and AST experiments was completed in 2003-2004. Two articles by Wage *et al.* in the *Journal of the Acoustical Society of America* describe the mode statistics, such as coherence and time spread, computed from these experiments [1, 2]. Kathleen Wage summarized these results in an invited talk at the November 2004 meeting of the Acoustical Society of America [3]. She also presented interim reports on this work at three North Pacific Acoustic Laboratory Workshops between 2002 and 2004 [4, 5, 6].

Approximate Mode Filtering: Mode filters are typically designed using modeshapes derived from numerical solution of the Helmholtz equation for a measured sound speed profile (SSP). In experiments such as NPAL, the temperature (hence the sound speed) is only measured across the span of the array. To facilitate mode processing, it is helpful to have an approximate solution for the modes that only requires the environmental information along the array. Kathleen Wage presented a paper at the 2004 Asilomar Conference on Signals, Systems, and Computers that explored the use of a uniform WKB-like approximation to design mode filters [7]. She presented the initial results of this work at the Underwater Acoustic Signal Processing Workshop in 2003 [8].

Sound Speed Estimation from Sparse Environmental Measurements: Mode filtering requires accurate knowledge of the sound speed profile at the array. For long-duration experiments, the environment is typically measured using a relatively small set of temperature sensors located along the array. In the 2004-2005 a method was developed for extrapolating these sparse temperature measurements to obtain a sound speed profile for use in mode processing. The approach was applied to temperature measurements acquired during the NPAL experiment. Eric St. Pierre presented a paper describing these results at the September 2005 IEEE/MTS Oceans Conference [9].

Mode Equalization: At megameter ranges, the low mode arrivals are quite complicated. As a part of this project, the problem of equalizing these signals has been studied. Tarun Chandrayadula presented a paper on the design of mode equalizers at the September 2005 IEEE/MTS Oceans Conference [10]. He also presented a talk on the multi-mode decision feedback equalizer for underwater acoustic communications at the 2005 Underwater Acoustic Signal Processing Workshop [11].

SPICE04/LOAPEX Experiment: PI Kathleen Wage contributed to planning discussions for the 2004 experiment at several NPAL workshops. In particular she analyzed the mode-resolving capabilities of the proposed array geometries. These results were presented at NPAL workshops in 2002 [12] and 2003 [13], and summarized in a memo written in April 2004 [14]. Kathleen was also a member of the science team for the SPICE04 deployment and recovery cruises, which took place in June 2004 and June 2005, respectively. The chief scientist for these cruises was Peter Worcester (Scripps Institution of Oceanography). Two vertical line arrays (VLAs) and two source moorings were deployed for the SPICE04/LOAPEX experiment.

RESULTS

The following paragraphs summarize key results obtained from 2002 to 2005. Parts of this summary have appeared in previous annual reports.

ATOC/AST Mode Analysis: A key contribution of this project was the statistical analysis of the mode arrivals in the ATOC and AST data sets. This analysis is thoroughly described in two journal articles by Wage *et al.* [1, 2]. Figures 1 and 2 are representative of the mode statistics described in these two papers. Figure 1 shows the time spread measured at the Hawaii and Kiritimati VLA's, which were located at ranges of 3.5 Mm and 5.1 Mm, respectively. The figure illustrates increase in time spread as a function of mode number. The 28 Hz mode 1 measured at Hawaii show the least amount of spread. At 28 Hz the internal wave scattering is significantly reduced, and mode 1 is dominated by a single arrival. At higher frequencies and longer ranges, internal wave scattering produces a more complicated arrival pattern. Note that the average time spread for the first 10 modes is approximately 1.5 seconds, which corresponds to a coherence bandwidth of 0.67 Hz for the channel. Figure 2 compares the temporal coherence of mode 1 measured using receptions from the 75 Hz ATOC source and the 28 Hz AST source. The coherence time is significantly longer for the 28 Hz receptions than for the 75 Hz receptions. Both show reasonable agreement with simulations of propagation through internal waves. See the paper by Wage *et al.* for more discussion of temporal coherence and how to measure it [2].

Approximate Mode Filtering: Spatial filtering for modes requires knowledge of the modeshapes, which requires accurate knowledge of the environment. Unfortunately, environmental information is often incomplete. For example in both the 1998 North Pacific Acoustic Laboratory (NPAL) experiment and the SPICE04 experiment, the environment was sampled along the VLA span, but not above and below the array. To facilitate mode processing, an approximation to the modeshapes is needed that only requires the environmental information along the array. Ideally, the approximation should provide an analytical form for the modeshapes, rather than just a numerical solution. An analytical form is desirable because it provides more intuition about the filtering problem and may permit simpler design of robust mode filters. WKB theory provides the most common approximate solution to the mode problem. The main problem with using the standard WKB solution to design mode filters is that it is singular at the turning points. Miller and Good developed a uniform WKB-like solution to the Schrödinger equation that is continuous at the turning points [15]. The paper presented by Wage at the Asilomar Conference in 2004 describes the application of Miller and Good's method to the underwater acoustic mode problem [7]. The major finding of this paper is that the approximate mode filter may perform better (in terms of crosstalk) than the exact mode filter when the approximate filter can be designed using measured sound speed across the VLA and the exact mode filter can only be designed using an archival sound speed measurement.

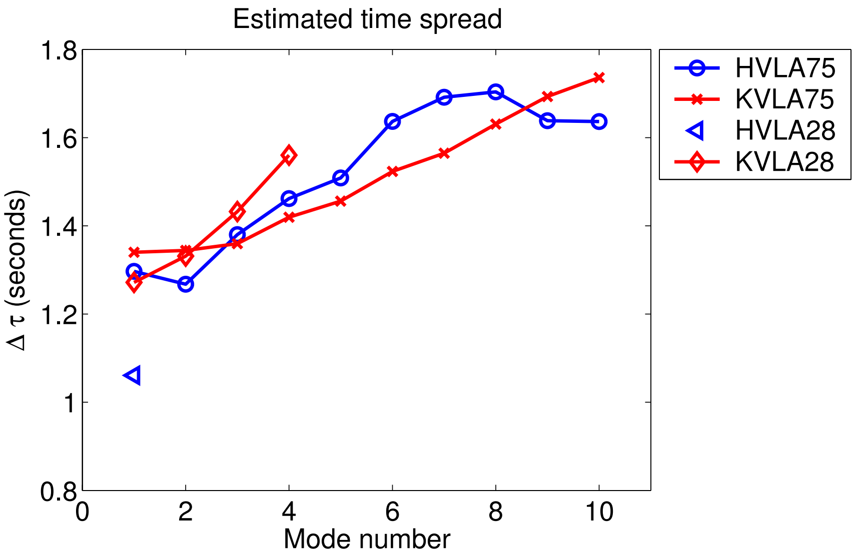


Figure 1: Time spread for the first 10 modes measured at the Hawaii and Kiritimati VLAs, denoted HVLA and KVLA, respectively. The 75 Hz results are for the bottom-mounted Pioneer Seamount source deployed for the ATOC experiment. The 28 Hz results are for the ship-suspended source deployed during the AST experiment. The average time spread is 1.5 seconds, and the spread increases with mode number. For a complete discussion of the mode time spread measured during the ATOC and AST experiments, see the paper by Wage et al. [2].

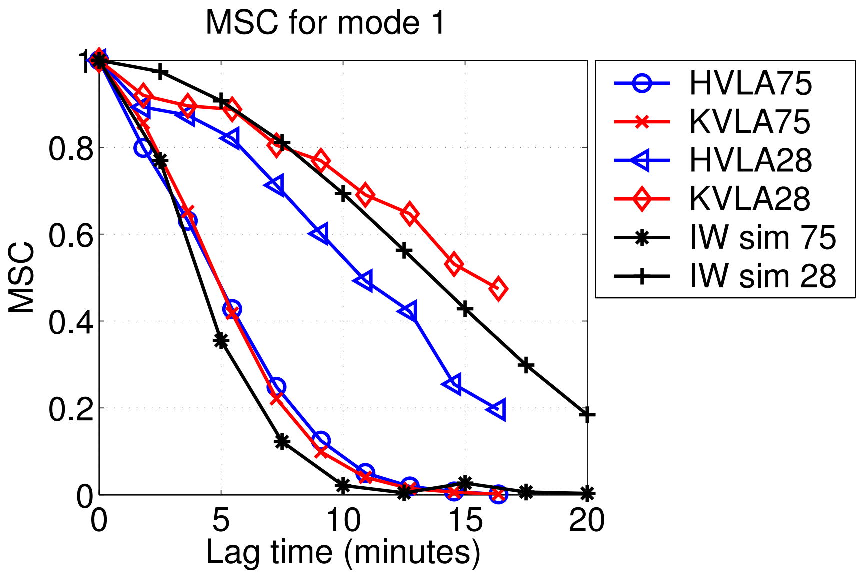


Figure 2: Comparison of magnitude-squared coherence for mode 1 at 75 Hz and 28 Hz measured during the ATOC and AST experiments with simulation results. The 28 Hz data show significantly longer coherence times than the 75 Hz data, and there is good agreement with simulation of propagation through internal waves. The paper by Wage et al. describes these results in more detail [2].

Sound Speed Estimation for Mode Processing: As noted above, mode filtering of underwater acoustic receptions depends on accurate knowledge of the mode shapes and wavenumbers. From an experimental standpoint, it is often impractical to measure the environmental parameters that determine the SSP on a dense grid in both time and depth. For example, in long-duration acoustic experiments such as NPAL, high resolution measurements of temperature and salinity are only possible during the deployment and recovery cruises. In the intervening months the environment is sampled by a relatively small number of sensors attached to the acoustic mooring. One approach to defining the SSP for mode filter design is to interpolate and extrapolate these environmental measurements. Other approaches would be to use archival environmental data or the output of an ocean model. The main problem with archival data and ocean model data is that it can be severely biased. In 2004-2005, we developed a method for interpolating and extrapolating the NPAL temperature measurements to obtain sound speed profiles. The technique, described in [9], assumes that the changes in the SSP associated with mesoscale and seasonal effects can be written in terms of the quasi-geostrophic dynamic modes. The dynamic modes are an orthonormal basis derived from historical oceanographic data for the VLA location. By fitting the observed temperature fluctuations to the dynamic modes, it is possible to obtain an estimate of the SSP required for mode processing. The Space-Time Kalman Filter (STKF) provides a convenient framework for solving the estimation problem. The paper by St. Pierre and Wage [9] describes the STKF implementation and examines its performance for the NPAL-98 data set. It analyzes the sound speed errors associated with the method and considers how those errors propagate through the mode computations.

Mode Equalization: Tomographic experiments use broadband low frequency signals such as maximal length sequences (M-sequences) to study the ocean. One problem in detecting the mode arrivals at megameter range is that multipath causes time spread in the transmitted M-sequence, leading to interference between adjacent symbols. This problem, called Inter Symbol Interference (ISI), is common in wireless channels. Equalizers are used in underwater acoustic communications to reduce ISI and provide SNR gain *e.g.*, see [16]. Working with data from the ATOC Engineering Test, Freitag and Stojanovic demonstrated that decision feedback equalizer (DFE) can be used for very long range underwater acoustic signals [17]. During the ATOC Engineering Test, M-sequence signals were recorded across a 20-element VLA. Freitag and Stojanovic's equalization scheme consisted of a multi-channel DFE that operated on the multiple channels of the VLA and successfully decoded the symbols with zero decoding error.

Motivated by this earlier work, we began exploring the design of equalizers for the low mode signals. In 2004-2005, we implemented a DFE-based equalizer for the low modes [10]. In tomography (as opposed to communications), the transmitted symbols are known. For the mode equalizer the transmitted symbols are fed back instead of the symbol decisions, hence the mode equalizer is equivalent to the DFE operating in training mode. The output SNR of the equalizer provides a useful metric for analyzing the mode arrivals. The mode equalizer works as follows. First, a spatial filter is used to estimate the desired mode time series that the equalizer will operate on. Then the equalizer is allowed to synchronize to a series of time instants and the output SNR is calculated for each. When the equalizer synchronizes to a time instant where it is unable to successfully combine multipaths, it will decode symbols with a high mean square error, thus the output SNR will be low. When the equalizer synchronizes to a time instant that enables it to combine all the multipaths in the signals, the decoded symbols will have a low mean square error, thus a high SNR. Chandrayadula presented a paper at the 2005 IEEE/MTS Oceans Conference [10] demonstrating that equalizers can be designed for the low mode signals in the NPAL receptions. Figure 3 shows examples of SNR vs. synchronization time curves for modes 1 and 10 in one of the NPAL-98 receptions (for the 40-element VLA located off California). The plots illustrate how the results vary when equalizers of different lengths are used. Ideally the equalizer length should be matched to the multipath spread of the modes. Since the SNR keeps increasing for equalizers up to 2 seconds long, it appears that the multipath spread of the modes in the NPAL-98 receptions is on the order of 2 seconds or greater.

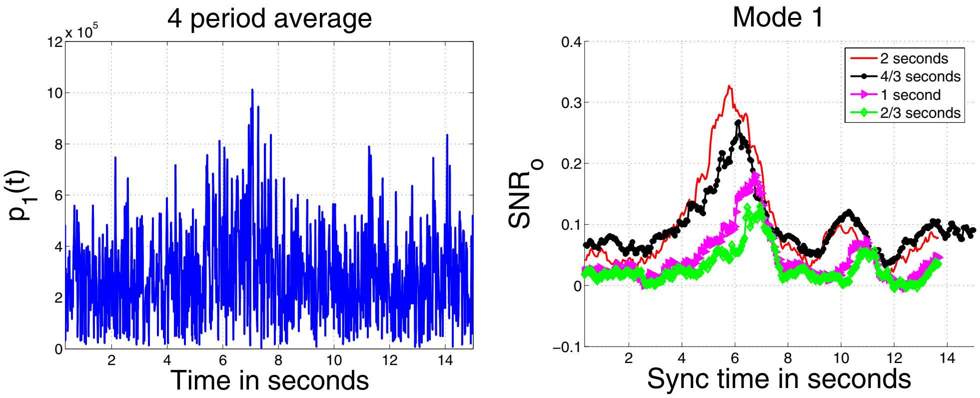
Long-Range Communications: In addition to investigating how equalizers can be used for tomography, this project also developed a multi-mode decision feedback equalizer (MMDFE) for communications applications and applied it to data from the NPAL-98 experiment. The MMDFE is based on the reduced complexity multi channel DFE by Stojanovic *et al.* [18]. Figure 4 shows the data processing path required for implementing the MMDFE on the NPAL-98 data. As shown, the VLA receptions are first corrected for clock drift and mooring motion. Then a least squares mode beamformer similar to the one designed by Wage [2] is applied to obtain the estimated time series for the first 10 modes. The mode filtering provides spatial array gain and reduces the computational complexity by a factor of two. The reduction in computational complexity is achieved in two ways. First, mode filtering reduces the number of channels the DFE operates on. Second, mode filtering also facilitates a reduction in the number of taps required for the DFE. To see this, note that the received pressure field is a linear combination of the mode signals. A multi-channel DFE operating on multiple channels of the VLA has to contend with more amount of multipath than a DFE operating on the mode signals. The multi-mode DFE can thus operate with a fewer number of taps for each channel. Figure 5 shows the scatter plots of the equalized symbols for various configurations of the MMDFE. The columns show the results for using 1 mode, 5 modes, and 10 modes in the equalizer. The rows show the results for using different amounts of signal averaging prior to implementing the MMDFE. As Figure 5 shows, the DFE operating on a single mode does not have enough spatial diversity to separate the symbols. Additional time averaging, which should improve the SNR, does not improve the performance of the single-mode DFE. In contrast, using 20-period averages appears to substantially improve the performance of the 5-mode and 10-mode DFEs. These scatter plots illustrate how the MMDFE is capable of exploiting the spatial diversity. Figure 6 further illustrates the effect of temporal averaging on the performance of the MMDFE. The plot shows the Bit Error Rate (BER) versus the number of M-sequence periods averaged. The BER curves show that the performance of the 10-mode DFE does not significantly differ from the 5-mode DFE. The fact that the DFE benefited from temporal averaging indicates that the multipath structure for the modes is coherent over multiple M-sequence periods.

IMPACT/APPLICATIONS

The objectives of this research have both scientific and operational applications. The statistical characterization of the acoustic channel provides crucial information to guide the design of long-range systems for tomography, communication, and surveillance. The signal processing techniques being developed are applicable in both short- and long-range propagation scenarios.

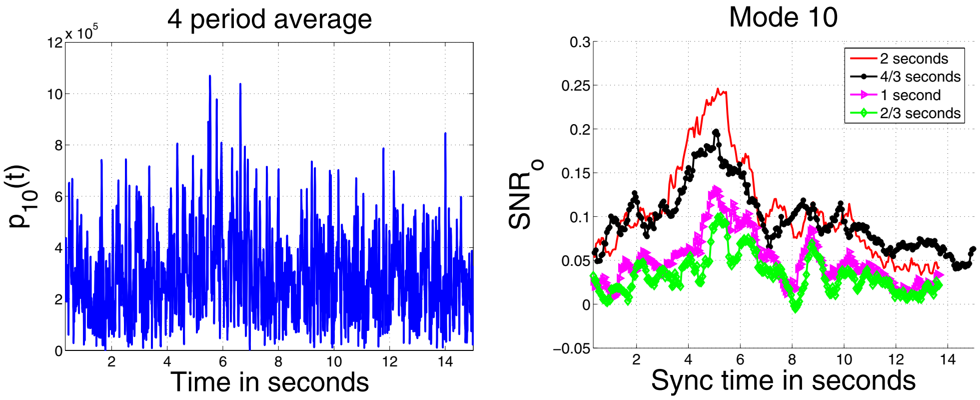
RELATED PROJECTS

This work is closely related to the North Pacific Acoustic Laboratory project, directed by principal investigators Peter Worcester (SIO) and James Mercer (APL-UW). A number of other ONR-sponsored researchers work on projects related to NPAL and participate in the NPAL Workshops.



(a) Mode 1 time series (4-period avg).

(b) Mode 1 equalizer output



(c) Mode 10 time series (4-period avg).

(d) Mode 10 equalizer output.

Figure 3: Example of mode time series measured in the NPAL-98 experiment and the corresponding mode equalizer outputs. The plots on the left show the mode 1 and 10 time series estimated from a 4-period average of the received signal. The plots on the right show the output SNR vs. synchronization time curves obtained from the mode equalizer. See the paper by Chandrayadula and Wage for more details about these results [10].

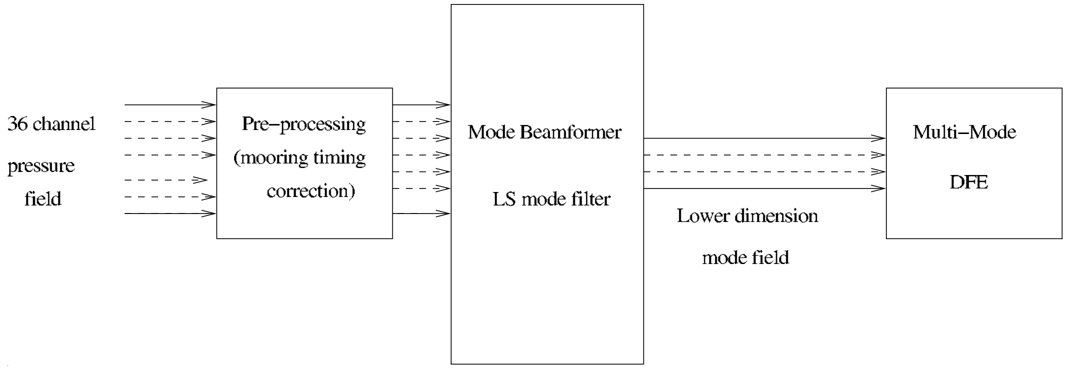


Figure 4: Block diagram of the multi-mode decision feedback equalizer (MMDFE) for the NPAL-98 experimental data. As shown, processing consists of mooring/timing corrections, followed by mode beamforming, and then decision feedback equalization. Mode beaforming provides spatial array gain and reduces the required dimension of the decision feedback equalizer.

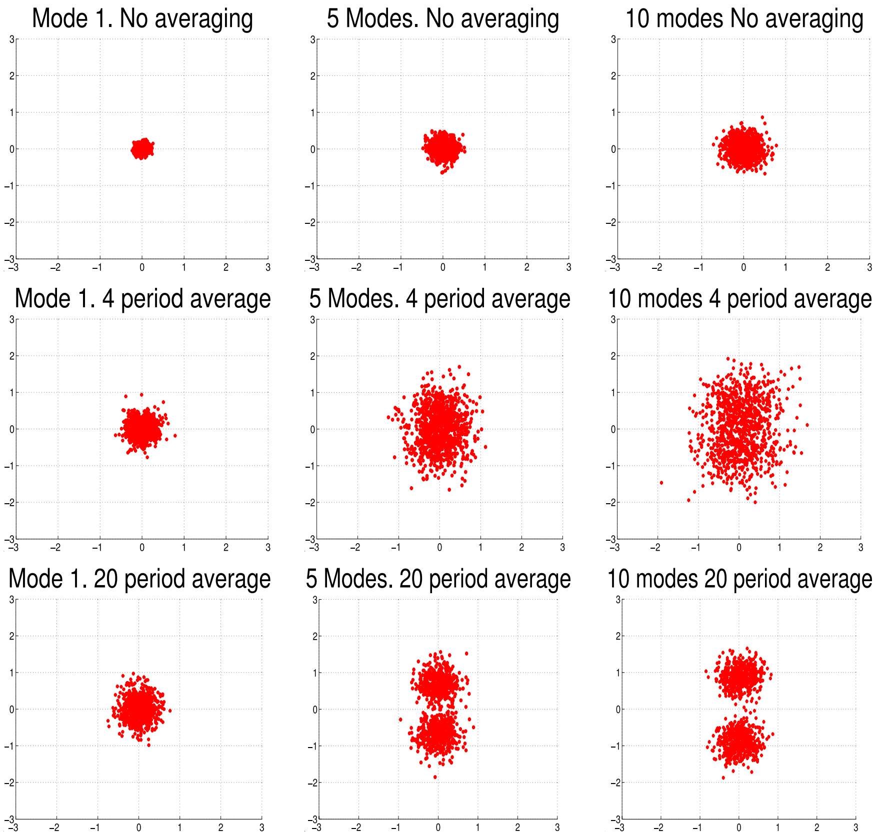


Figure 5: Scatter plots for various configurations of the MMDFE operating on NPAL-98 data. The rows show results for different amounts of signal averaging prior to processing. The columns show results for different numbers of modes included in the equalizer. This result was presented at the 2005 Underwater Acoustic Signal Processing Workshop [11].

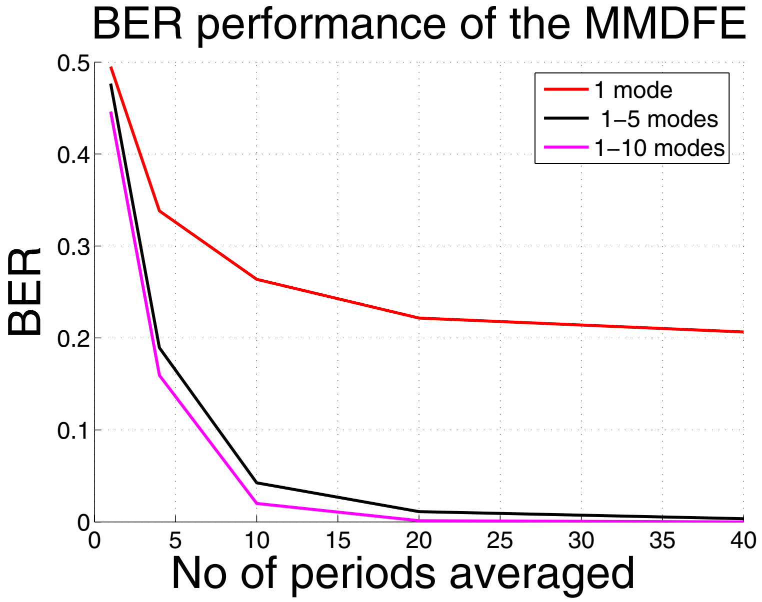


Figure 6: Bit error rate as a function of the number of M-sequence periods averaged prior to processing. This result was presented at the 2005 Underwater Acoustic Signal Processing Workshop [11].

REFERENCES

[1] K. E. Wage, A. B. Baggeroer, and J. C. Preisig, “Modal analysis of broadband acoustic receptions at 3515-km range in the North Pacific using short-time Fourier techniques,” *J. Acoust. Soc. Am.*, vol. 113, pp. 801–817, February 2003.

[2] K. E. Wage, M. A. Dzieciuch, P. F. Worcester, B. M. Howe, and J. A. Mercer, “Mode coherence at megameter ranges in the North Pacific Ocean,” *J. Acoust. Soc. Am.*, vol. 117, pp. 1565–1581, March 2005.

[3] K. E. Wage, “Experimental measurements of normal mode statistics at megameter ranges.” 148^{th} *Meeting of the Acoustical Society of America*, San Diego, CA, November 2004.

[4] K. E. Wage, “Low mode coherence as a function of range.” North Pacific Acoustic Laboratory Workshop, Borrego Springs, CA, March 2004.

[5] K. E. Wage, “Comparison of mode arrivals in atoc and ast.” North Pacific Acoustic Laboratory Workshop, Borrego Springs, CA, March 2003.

[6] K. E. Wage, “Recent mode processing results.” North Pacific Acoustic Laboratory Workshop, San Diego, CA, August 2002.

[7] K. E. Wage, “Approximate mode filtering,” in *Proceedings of the 38th Asilomar Conference on Signals, Systems, and Computers*, pp. 1436–1440, November 2004.

[8] K. E. Wage, “Design of mode filters using WKB-like approximations.” Underwater Acoustic Signal Processing Workshop, West Greenwich, RI, October 2003.

[9] E. R. St. Pierre and K. E. Wage, “Sound Speed Estimation from Sparse Environmental Measurements With Application to Mode Filtering,” in *Proceedings of the 2005 IEEE/MTS Oceans Conference*, vol. 2, pp. 1242–1248, September 2005.

[10] T. K. Chandrayadula and K. E. Wage, “Mode Equalization at Megameter Ranges,” in *Proceedings of the 2005 IEEE/MTS Oceans Conference*, vol. 2, pp. 1345–1351, September 2005.

[11] T. K. Chandrayadula and K. E. Wage, “Long-range underwater acoustic communications using a multi-mode decision feedback equalizer.” Underwater Acoustic Signal Processing Workshop, West Greenwich, RI, October 2005.

[12] K. E. Wage, “Mode-resolving characteristics of the proposed array geometry.” North Pacific Acoustic Laboratory Workshop, San Diego, CA, August 2002.

[13] K. E. Wage, “Performance analysis of the proposed array geometry (revised for the latest geometry).” North Pacific Acoustic Laboratory Workshop, Borrego Springs, CA, March 2003.

[14] K. E. Wage, “Memorandum on npal04 array design mode processing issues,” April 2004.

[15] S. C. Miller and J. R. H. Good, “A WKB-Type Approximation to the Schrödinger Equation,” *Phys. Rev.*, vol. 91, pp. 174–179, July 1953.

[16] M. Stojanovic, J. Catipovic, and J. G. Proakis, “Adaptive multichannel combining and equalization for underwater acoustic communications,” *J. Acoust. Soc. Am.*, vol. 94, pp. 1621–1631, September 1993.

[17] L. Freitag and M. Stojanovic, “Basin-Scale Acoustic Communication: A Feasibility Study Using Tomography M-Sequences,” in *Proceedings of the 2001 IEEE/MTS Oceans Conference*, vol. 4, pp. 2256–2261, November 2001.

[18] M. Stojanovic, J. Catipovic, and J. Proakis, “Reduced-complexity spatial and temporal processing of underwater acoustic communication signals,” *J. Acoust. Soc. Am.*, vol. 98, pp. 961–972, August 1995.

PUBLICATIONS

T. K. Chandrayadula and K. E. Wage, ”Mode Equalization at Megameter Ranges,” *Proceedings of the 2005 IEEE/MTS Oceans Conference*, vol. 2, pp. 1345-1351, September 2005. [published]

E. R. St. Pierre and K. E. Wage, ”Sound Speed Estimation from Sparse Environmental Measurements With Application to Mode Filtering,” *Proceedings of the 2005 IEEE/MTS Oceans Conference*, vol. 2, pp. 1242-1248, September 2005. [published]

K. E. Wage, M. A. Dzieciuch, P. F. Worcester, B. M. Howe, and J. A. Mercer “Mode coherence at megameter ranges in the North Pacific Ocean,” *J. Acoust. Soc. Am.*, vol. 117(3), Pt. 2, pp. 1565-1581, March 2005. [published, refereed]

K. E. Wage, “Approximate mode filtering,” *Proceedings of the 38th Asilomar Conference on Signals, Systems, and Computers,* pp. 1436-1440, November 2004. [published, refereed]

K.E. Wage, A.B. Baggeroer, T.G. Birdsall, M.A. Dzieciuch, B.M. Howe, J.A. Mercer, K. Metzger, W.H. Munk, R.C. Spindel, and P.F. Worcester, “A Comparative Study of Mode Arrivals at Megameter Ranges for 28 Hz, 75 Hz, and 84 Hz Sources,” *Proceedings of the IEEE/MTS Oceans Conference*, pp. 258-265, September 2003. [published]

K.E. Wage, A.B. Baggeroer, and J.C. Preisig, “Modal analysis of broadband acoustic receptions at 3515 km range in the North Pacific using short-time Fourier techniques,” *J. Acoust. Soc. Am.*, vol. 113, pp. 801-817, February 2003. [published, refereed]

AWARDS

Kathleen Wage received an ONR Young Investigator Award in 2005.

In 2006 Kathleen Wage received tenure and was promoted to Associate Professor of Electrical and Computer Engineering at George Mason University.