

Numerical Modeling of Acoustic Propagation In a Variable Shallow Water Waveguide

Daniel Rouseff
Applied Physics Laboratory
College of Ocean and Fishery Sciences
University of Washington
1013 NE 40th St.
Seattle, WA 98105

phone: (206) 685-3078 fax: (206) 543-6785 email: rouseff@apl.washington.edu

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<http://www.apl.washington.edu>

LONG-TERM GOALS

Random variability in shallow water will induce variability in a propagating acoustic field. The long-term goal of this research is to quantify how random variability in the ocean environment translates into random variability in the acoustic field and the associated signal processing algorithms. In the present funding cycle, the emphasis is on underwater acoustic communication.

OBJECTIVES

The specific objective for the current funding cycle is to develop a predictive capability for how variability affects the acoustic communication performance.

APPROACH

Coherent underwater acoustic communication depends on an equalizer that either implicitly or explicitly compensates for the time-varying multipath propagation prevalent in the ocean. Our approach is to determine empirically which equalizer parameters gives optimal communications performance. Having found the values for these parameters, we then relate them to the underlying physics. The relevant propagation physics changes with range with consequent effect on communications performance. By examining multiple data sets at multiple ranges, we can begin to develop a predictive capability.

Our current emphasis is on a communications algorithm based on a version time-reversal signal processing called passive phase conjugation [Rouseff *et al.* 2001]. In this approach, one uses a receiving array and matched filters based on estimating channel's time-varying impulse response. The specific version of phase conjugate processing has two crucial communications design parameters: the length of the matched filters, and the interval at which these estimates are updated [Flynn *et al.* 2004]. We examine how the optimal values for these two parameters vary with the source-to-receiver range and with local environmental conditions.

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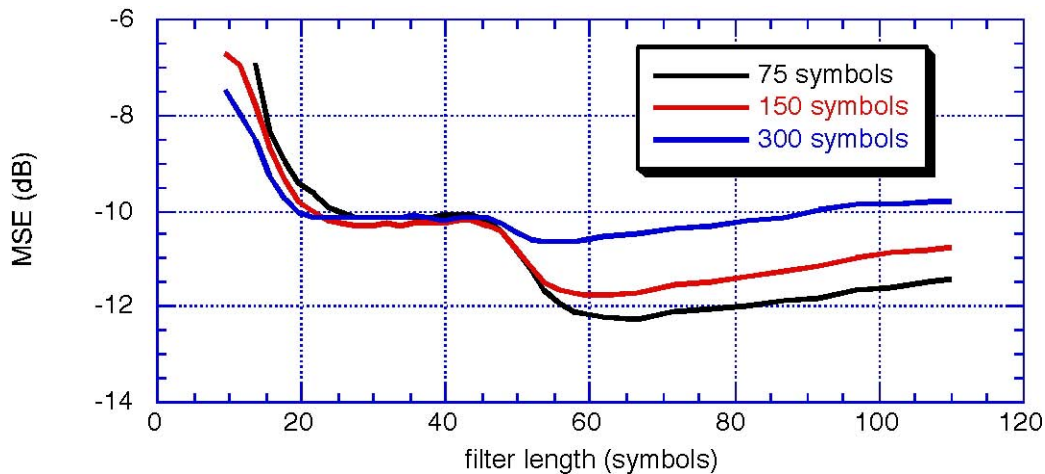


Figure 1: Mean Squared Error (MSE) in demodulation output. MSE plotted versus length of matched filter expressed in units of symbols. Range from transmitter is 1 km. Results shown for various update intervals M , also expressed in units of symbols.

WORK COMPLETED

In collaboration with investigators at the University of Delaware, data from the 2003 Kauai Experiment (KauaiEx) were analyzed [Porter *et al.* 2004.] The present analysis concentrated on acoustic data collected in the 8-16 kHz band on the 8-element APL-UW array. Chirp signals were used to study the propagation characteristics and interpret BPSK communications performance. Two data sets were studied: an 18-hour data set with the range between the transmitter and the array being 1 km, and a 16-hour data set at range 2 km.

Communications-specific results were documented in one conference paper [Rouseff *et al.* 2007]. Additional KauaiEx results were documented in two other conference papers [Badiy *et al.*, Song *et al.*, 2007].

RESULTS

Figure 1 shows how the design parameters in the communications algorithm affect performance. The mean-squared error (MSE) in the communication algorithm's soft demodulation output is plotted versus the length L of the matched filter expressed in units of symbols. Results are presented for various numbers M of symbols extracted before updating the matched filters. Consider first the results for $M=75$ symbols. Performance improves as L is increased up to 20 symbols. From ray tracing and the measured results for the transmitted chirps, $L=20$ symbols is sufficiently long to capture the first four acoustic paths: the direct path (D), the bottom-bounce path (B), the sea-surface bounce path (S), and the BS path. Increasing the matched filter length from $L=20$ to $L=46$ symbols offers no improvement in communications performance as this corresponds to a lull in arriving paths. Increasing L from 46 to 60 symbols allows two more acoustic ray paths (SB,BSB) to be included in the processing and the MSE decreases by about 2 dB. Further increasing the match filter length, however, actually increases the MSE. This corresponds to including late arriving, rapidly fluctuating ray paths that have been reflected multiple times off of the sea surface.

Figure 1 also shows results for various values of the filter update interval. If only four paths are included in the processing, the paths are stable and it is unnecessary to update the filter often. If the optimal six paths are included, more frequent updating is required with the corresponding increase in the computational burden in the processing. The results show a design trade-off between performance and computational burden.

The wind speed was 10 m/s or greater for the entire 18-hour period when data were collected at range 1 km. The significant wave height was between 1.4 and 1.0 m. Figure 2 shows communications results over the 18-hours. Results with both four and six paths are displayed. Retaining six paths, the MSE varies by less than 3 dB. The four-path result tracks the six-path result with the two extra paths yielding on average a 1.8 dB improvement in performance. The experimental result is consistent with the model developed in Rouseff [2005]; the model predicts $10\log[(6 \text{ paths})/(4 \text{ paths})] = 1.8 \text{ dB}$ improvement.

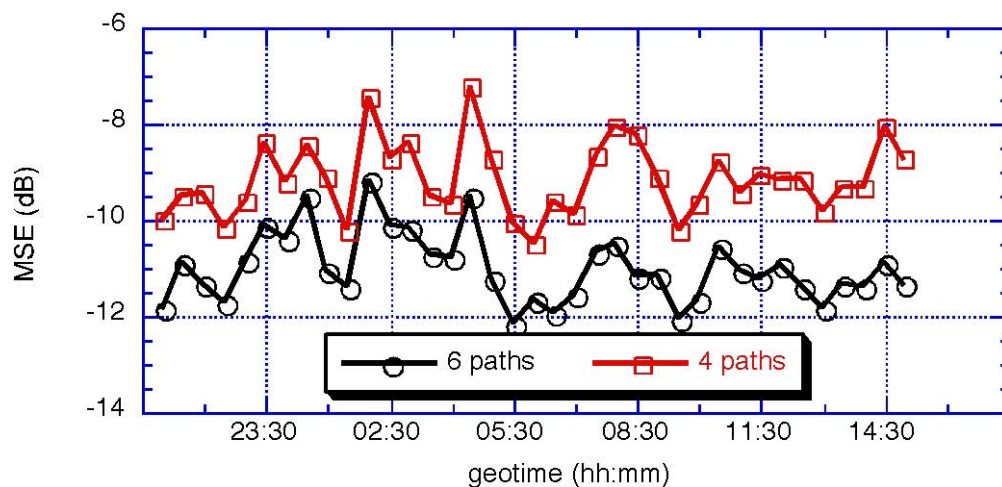


Figure 2: Mean Squared Error (MSE) in soft demodulation output. MSE plotted versus geotime for same 18-hour period shown in Fig. 2. Range from transmitter is 1 km. Results use filter length $L=60$ and update interval $M=75$.

The results suggest that the performance at 1 km for the conditions of the experiment is limited by sea surface interaction. The matched filter should be long enough only to include paths that have had no more than one bounce off the sea surface. Late arriving paths that have multiple bounces off the sea surface should be treated as noise rather than usable signal.

Data were also collected for 16 hours at range 2 km. Thermistor string data showed there to be a strong surface mixed layer. Ray tracing showed that this acoustically fast surface layer causes appreciable refraction of the acoustic rays at range 2 km. Figure 3 shows sample communications results. The MSE in the soft demodulation output is plotted as a function of the matched filter length for various update intervals M . At the more distant range, the acoustic arrival pattern is more compact with less separation between the different paths. As at 1 km, a local minimum in MSE occurs with a matched filter about 60 symbols in duration. This corresponds to retaining a total of eight ray paths; in addition to the six paths retained at 1 km, the SBS and BSBS paths are also retained. A filter of length 90 symbols admits the SBSB and BSBSB paths that may offer further slight improvement in performance. Unlike at 1 km, at 2 km it becomes desirable to retain at least some paths that have had

multiple interactions with the sea surface. The result can be understood by the fact that at the more distant range the acoustic paths are bouncing off the sea surface at a shallower grazing angle.

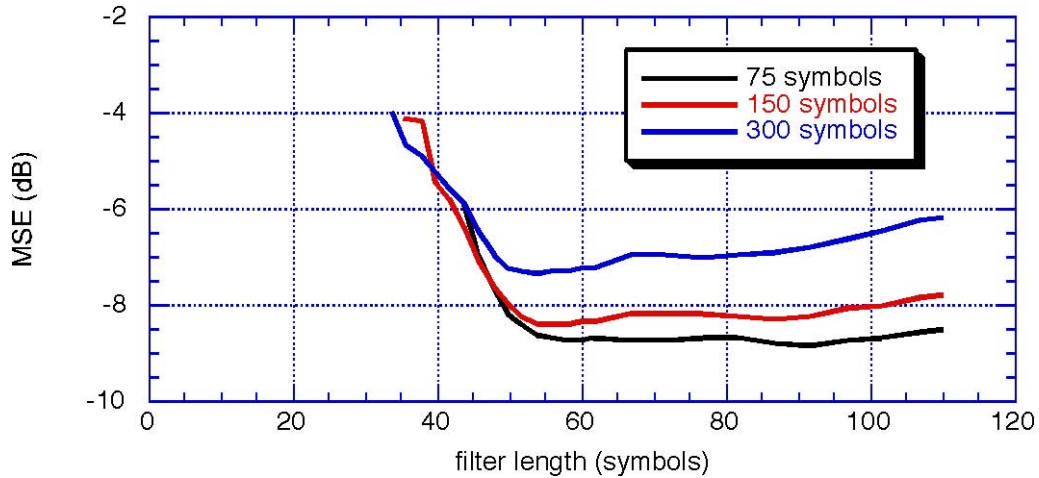


Figure 3: Mean Squared Error (MSE) in demodulation output. MSE plotted versus length of matched filter expressed in units of symbols. Range from transmitter is 2 km. Results shown for various update intervals M , also expressed in units of symbols.

IMPACT/APPLICATIONS

High data rate acoustic communication is important for numerous applications. By determining which environmental factors limit performance in controlled experiments, one can hope to eventually develop a predictive capability. A predictive capability would allow one fix the adjustable design parameters in such a way as to maximize the achievable communications performance for a given scenario.

TRANSITIONS

Not applicable at this stage in the on-going research.

RELATED PROJECTS

In conducting this research, we have worked closely with M. Badiy, University of Delaware, funded under separate support. During the current funding cycle, additional funding was obtained under the MURI “Impact of Oceanographic Variability on Acoustic Communications” lead by W. Hodgkiss, Scripps Institute of Oceanography.

REFERENCES

J. A. Flynn, J. A. Ritcey, D. Rouseff and W. L. J. Fox, “Multichannel equalization by decision-directed passive phase conjugation: experimental results,” *IEEE J. Oceanic Eng.* 29, 824-836 (2004).

M. Porter, P. Hursky, M. Siderius, M. Badiy, J. Caruthers, W. Hodgkiss, K. Raghukumar, D. Rouseff, W. Fox, C. de Moustier, B. Calder, B. Kraft, V. McDonald, P. Stein, J. Lewis, and S. Rajan, "The Kauai Experiment," in *High Frequency Ocean Acoustics*, edited by M. B. Porter, M. Siderius, and W. A. Kuperman (AIP, New York, 2004).

D. Rouseff, D. R. Jackson, W. L. J. Fox, C. D. Jones, J. A. Ritcey and D. R. Dowling, "Underwater acoustic communication by Passive Phase Conjugation: Theory and experimental results," *IEEE J. Oceanic Eng.* 26, 821-831 (2001).

D. Rouseff, "Intersymbol interference in underwater acoustic communications using time-reversal signal processing," *J. Acoust. Soc. Am.* 117, 780-788 (2005).

PUBLICATIONS

D. Rouseff, M. Badiy, and A. Song, "Effect of reflected and refracted signals on coherent underwater acoustic communication: Results from KauaiEx 2003." *IEEE J. Oceanic Eng.* [submitted].

J. E. Quijano, L. M. Zurk, and D. Rouseff, "Demonstration of the invariance principle for monostatic active sonar," *IEEE J. Oceanic Eng.* [submitted].

D. Rouseff, M. Badiy and A. Song, "Propagation physics effects on coherent underwater acoustic communications: Results from KauaiEx 2003" in *Proc. of IEEE/OES Oceans 07 Conference*, Aberdeen, Scotland, June 18-21, 2007.

M. Badiy, A. Song, D. Rouseff, H. Song, W. S. Hodgkiss, and M. B. Porter, "Ocean variability effects on high-frequency acoustic propagation in KauaiEx" in *Proc. of IEEE/OES Oceans 07 Conference*, Aberdeen, Scotland, June 18-21, 2007.

A. Song, M. Badiy, D. Rouseff, H. Song, and W. S. Hodgkiss, "Range and depth dependency of the coherent underwater acoustic communications in KauaiEx," in *Proc. of IEEE/OES Oceans 07 Conference*, Aberdeen, Scotland, June 18-21, 2007.

L. Matveyev, R. C. Spindel, and D. Rouseff, "Forward scattering observation with partially coherent spatial processing of vertical array signals in shallow water," *IEEE J. Oceanic Eng.* [accepted, refereed].

D. Rouseff and D. Tang, "Internal wave effects on the ambient noise notch in the East China Sea: model/data comparison," *J. Acoust. Soc. Am.* **120**, 1284-1294 (2006). [published, refereed]