ONR Graduate Traineeship Award

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LONG-TERM GOALS

The long term goals of this project are to investigate statistical models for signals propagating in long-range underwater channels and to design signal processing techniques to mitigate signal fluctuations due to random disturbances such as internal waves.

OBJECTIVES

At megameter ranges, broadband receptions consist of early ray-like arrivals and a finale that is best described in terms of the low order modes. The energetic low mode signals are more strongly affected by internal wave scattering than the ray arrivals. By focusing on the low order modes, this project seeks to develop a better understanding of internal wave effects. The first objective of this project is to derive range-dependent mode statistics from experimental data obtained during the 2004-2005 North Pacific Acoustic Laboratory (NPAL) experiment. Using these statistics, the second objective is to develop a statistical model to describe the low mode signals as a function of range. The third objective of this project is to develop new robust signal processing techniques based on the derived random channel model.

APPROACH

To characterize internal wave effects on the modes, this project will use the extensive data sets of low-frequency receptions recorded as a part of the North Pacific Acoustic Laboratory (NPAL) project. Two specific experiments are particularly relevant for the current work. First, the Long Range Ocean Acoustic Propagation EXperiment (LOAPEX) conducted in 2004 provided a unique opportunity to measure low mode receptions at a series of ranges from 50 km to 3200 km. In addition to LOAPEX, the 2004-2005 NPAL experiment included transmissions from a bottom-mounted source at Kauai to a receiving array at a range of 2400 km. This project will analyze the LOAPEX and Kauai receptions and compare the results to parabolic equation simulations. The results of this analysis will be used to develop random channel models for the low order modes and subsequently to develop new signal processing techniques for these modes.

The principal investigator for this project is Mr. Tarun K. Chandrayadula, a Ph.D. student in the Electrical and Computer Engineering Department at George Mason University. Mr. Chandrayadula's thesis advisor is Professor Kathleen E. Wage.

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WORK COMPLETED

Since the start of this project in January 2006, work has focused on analysis of the LOAPEX and Kauai receptions from the 2004-2005 NPAL experiment.

LOAPEX analysis: The maximal length sequence (M-sequence) receptions have been complex demodulated and match-filtered. Mooring data was missing for many parts of the LOAPEX experiment. To estimate the missing data an Empirical Orthogonal Function based estimation scheme was implemented and the mooring estimates were used to correct for array motion. A least squares mode beamformer was implemented for these signals and used to estimate modes 1 to 10. An initial set of statistics was derived for mode 1.

Kauai analysis: The signals received during the 2004 NPAL experiment from the source deployed to the north of Kauai were processed and analyzed. Various statistics of the low order modes such as mean, variance, mean power, kurtosis and skewness were estimated. The results of this analysis were presented at the NPAL Workshop held in April 2006 in Borrego Springs, CA.

RESULTS

This section describes the initial set of mode statistics derived from the LOAPEX and Kauai receptions on the Shallow Vertical Line Array (SVLA) deployed during the 2004-2005 NPAL experiment. The SVLA is a 40-element array spanning 350 m to 1750 m that was designed to sample the axial modes. This section focuses exclusively on the M-sequence transmissions from the suspended LOAPEX source and the bottom-mounted Kauai source.

LOAPEX receptions: As part of the LOAPEX experiment an HX-554 acoustic source transmitted M-sequences at ranges of 50 km, 250 km, 500 km, 1000 km, 1600 km, 2300 km and 3200 km from the SVLA. Figure 1 shows the average sound speed derived from the World Ocean Atlas using profiles for 20 points equally-spaced on the geodesic between SVLA and the station at 3200 km range. The LOAPEX source was suspended from the ship at depths of 800 m, 500 m, and 350 m. A carrier frequency of 75 Hz was used at 800 m and a carrier frequency of 68.2 Hz was used at 500 m and 350 m. The 800 m and 500 m source depths were intended to excite the low order modes directly, whereas the 350 m source depth was intended to excite the higher order modes so that scattering into the finale could be studied. The plot of the modeshapes in Figure 1 confirms that the 350 m source depth is outside the span of most of the low order modes.

Mode processing requires accurate estimates of the position of the array elements. Uncompensated array motion can cause time and phase shifts in the received signal and these errors affect the reliability of the mode estimates. The SVLA and the deep VLA (DVLA) deployed nearby were monitored by a baseline acoustic navigation system that tracked the top and bottom half of each array separately. Unfortunately, some navigation data was lost during the LOAPEX experiment due to the increased number of transmissions and the higher sampling frequency during this period. (The AVATOC hardware was busy writing signal data to disk, and consequently some navigation data was lost.) Although there are large gaps in the navigation data for a single AVATOC, there is good navigation data recorded for at least one AVATOC at all times. While the SVLA and DVLA span different depths, they are subjected to similar forces in the ocean, so their motions must be correlated. This suggests that the

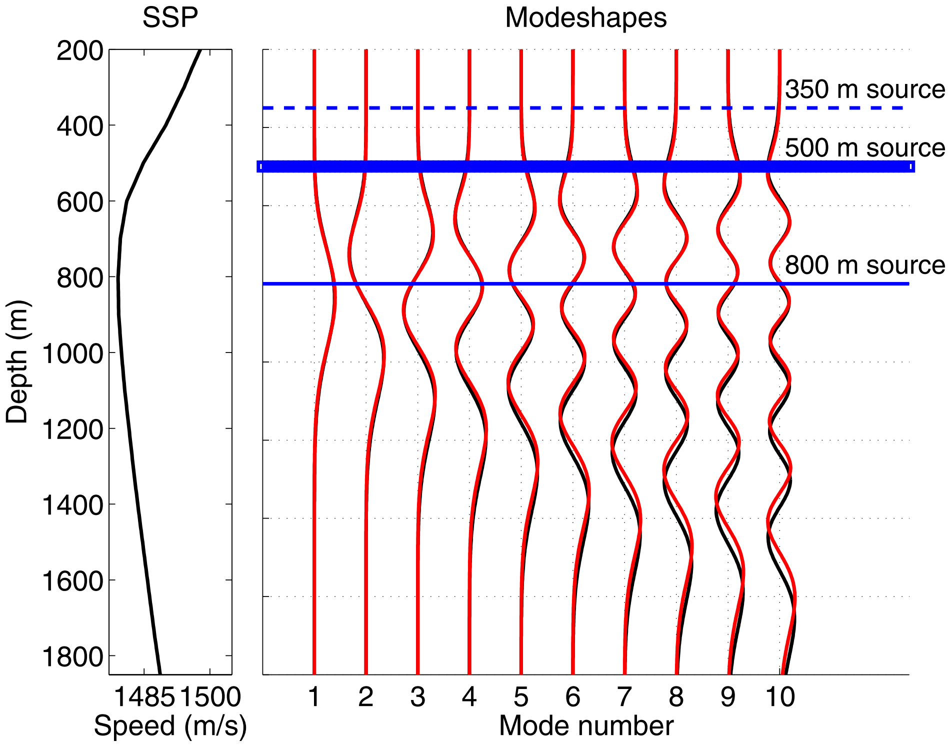

Figure 1: Sound speed profile and the derived modeshapes for the LOAPEX path. The left subplot shows the average sound speed profile for the LOAPEX path. The right subplot shows the modeshapes of modes 1 to 10 calculated from the average sound speed profile. The plot shows the modeshapes at 75 Hz depicted by the black line and the 68 Hz modeshapes plot depicted by the red line. The three horizontal lines on the plot indicate the respective source depths.

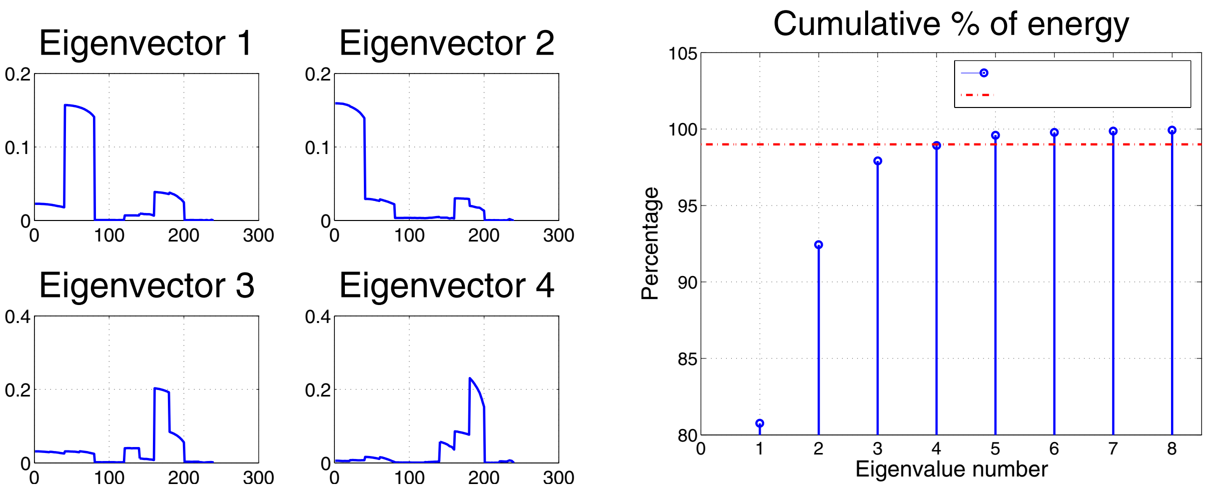

Figure 2: EOF analysis of mooring data. The left subplot shows the first 4 eigenvectors of the navigation matrix. The right subplot shows the cumulative percentage of energy of the first 8 eigenvalues. The first 4 eigenvalues make up 99% of the energy in the navigation data.

data for other instruments can be used to reconstruct the missing navigation data using Empirical Orthogonal Functions (EOF's). To implement the EOF approach, the SVLA and DVLA mooring data are concatenated into a single vector at each time step. A covariance matrix for the mooring data is estimated using a segment of time (yeardays 160 to 195) where all instruments recorded good data. The EOF's are extracted from the singular value decomposition of this covariance matrix. Figure 2 shows the 8 most significant eigenvalues of the covariance matrix and also the first four eigenvectors that span almost 99% ofthe energy in the navigation data. To obtain accurate estimates of the SVLA sensor locations during the gaps, the sparse mooring data was projected on the first four EOF's shown in Figure 2.

Using the mooring motion estimates provided by the EOF method, a least squares broadband mode beamformer [1, 2] was implemented for modes 1-10. Figure 3 shows the mean envelope of mode 1 for the 68.2 Hz source and the 75 Hz source at stations T50, T250, T500 and T1000. The number of receptions available for averaging varied for each LOAPEX station. The envelope of the 68.2 Hz mode 1 signal was averaged over 24, 21, 36 and 82 receptions at stations T50, T250, T500 and T1000 respectively. Similarly for the 75 Hz source, the mode 1 signal envelope was averaged over 30, 24, 42 and 5 receptions at stations T50, T250, T500 and T1000 respectively. Figure 3 clearly illustrates the increasing spread of the mode signal with range due to internal wave scattering. The figure also indicates that the receptions for the 350 m source depth are of a lower amplitude as is expected since the low modes are not directly excited. Note that additional work is necessary to further interpret these results. The mode filtering problem is a complicated one, particularly at short ranges where all modes arrive within a short time window. In this case higher order modes may corrupt low order mode estimates through cross-talk in the spatial mode filter. At long ranges, the cross-talk can be removed based on time of arrival, whereas that is not possible at short ranges. More analysis is required to determine the impact of cross talk for LOAPEX receptions. See references [1] and [2] for more detailed discussion on mode filtering.

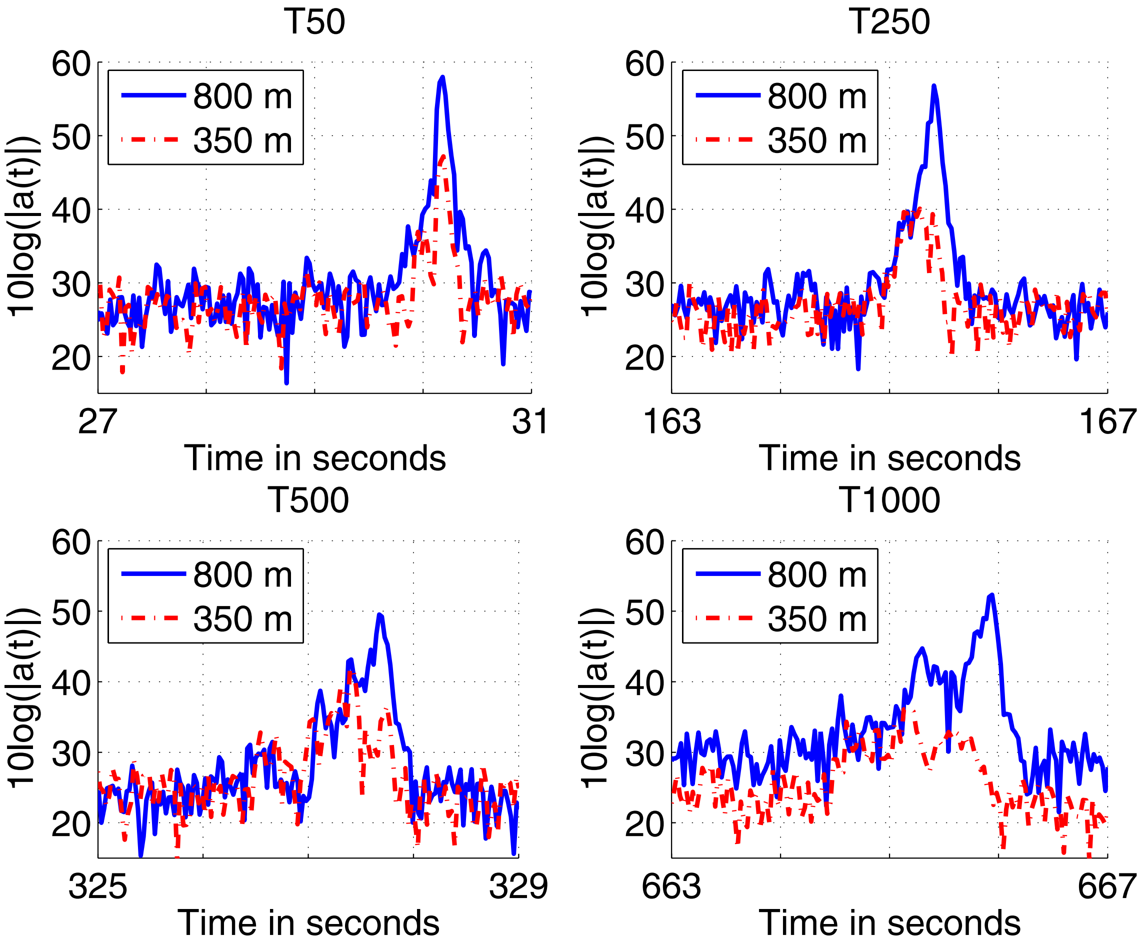

Figure 3: Log of the mean envelope of mode 1 at various LOAPEX stations for source depths of 350 m and 800 m. Going clockwise from the top plot on the left, the subplots show the mean at stations T50, T250, T1000 and T500. The plots show an increase in time spread with range. The mean envelope for the shallow source is much lower than that of the 800 m source.

Kauai receptions: As part of the 2004-2005 NPAL experiment, M-sequence transmissions were made from an HX-554 source North of Kauai to the SVLA. The signals received between yeardays 203 to 255 were processed and the statistics of the mode 1 signal estimated. Figure 4 shows the average power of mode 1 signal received from Kauai. While mode 1 exhibits a fairly sharp cutoff, there is a small group arrivals ≈ 0.5 seconds wide following the main arrival. These secondary arrivals are on the order of 10 dB lower than the main arrivals. This "afterglow" can be attributed to the bottom interaction at the Kauai source. Note that a similar afterglow effect was also observed in the mode 1 multipath intensity profile calculated for the signals received during the Acoustic Thermometry of Ocean Climate experiment conducted in 1995-1996 [6].

Figure 5 shows the mean and the variance of the mode 1 signal received from the Kauai source. The plot shows that mode 1 is a zero mean process with a non-stationary variance. Figure 6 shows the kurtosis and the skewness for the mode 1 signal. The kurtosis is ≈ 3 and the skew varies around a mean of 0, which are values typical of a Gaussian signal. Dozier and Tappert predict that internal wave scattering over long ranges results in Gaussian statistics for the modes [7, 8]. These results appear to confirm those predictions. Figure 7 shows the covariance coefficient matrix of the mode 1 Kauai signals. Mode 1 appears to be a white process except for the finale. The colored nature of mode 1 signal towards the finale may be useful as a finale detector.

IMPACT/APPLICATIONS

This research has both scientific and operational applications. First, statistical models for the underwater channel provide valuable information to guide the design of naval surveillance and communications systems. Second the development of signal processing techniques that can mitigate ocean fluctuations will improve the reliability of such systems.

RELATED PROJECTS

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

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, no. 2, pp. 801–817, February 2003.

[2] K. E. Wage, "Broadband Modal Coherence and Beamforming at Megameter Ranges," Ph.D. dissertation, MIT/WHOI, 2000.

[3] S. Levitus, R. Burgett, and T. Boyer, *World Ocean Atlas 1994 Volume 3: Salinity*, 1994, NOAA Atlas NESDIS 3.

[4] S. Levitus and T. Boyer, *World Ocean Atlas 1994 Volume 4: Temperature*, 1994, NOAA Atlas NESDIS 4.

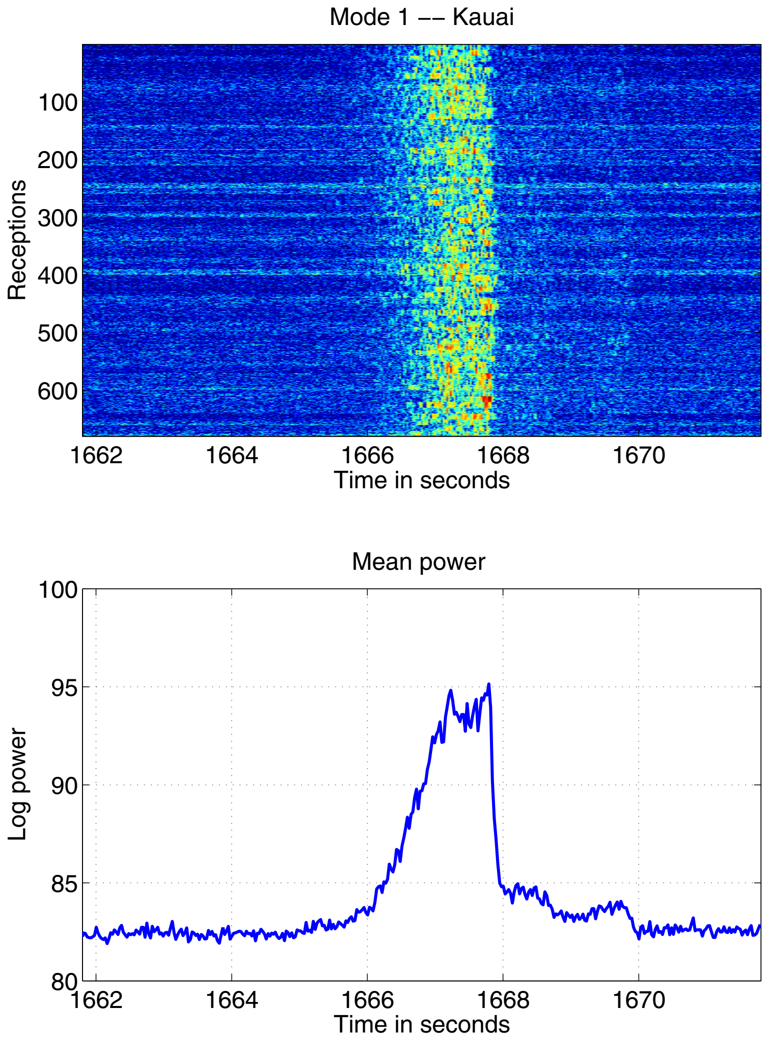

Figure 4: Mode 1 signal received from the Kauai source during the 2004-2005 NPAL experiment. The top subplot contains the envelope of the mode 1 signal plotted for all the available receptions between yeardays 203 to 255. The bottom subplot shows the log of the mean power of the mode 1 signal obtained by averaging across all the receptions shown in the top subplot. Mode 1 has a time width of $\approx$ 1.5 seconds and a sharp cutoff. There is a small group of arrivals $\approx$ 0.5 seconds wide following the main arrival that is 10 dB lower level than the main arrivals.

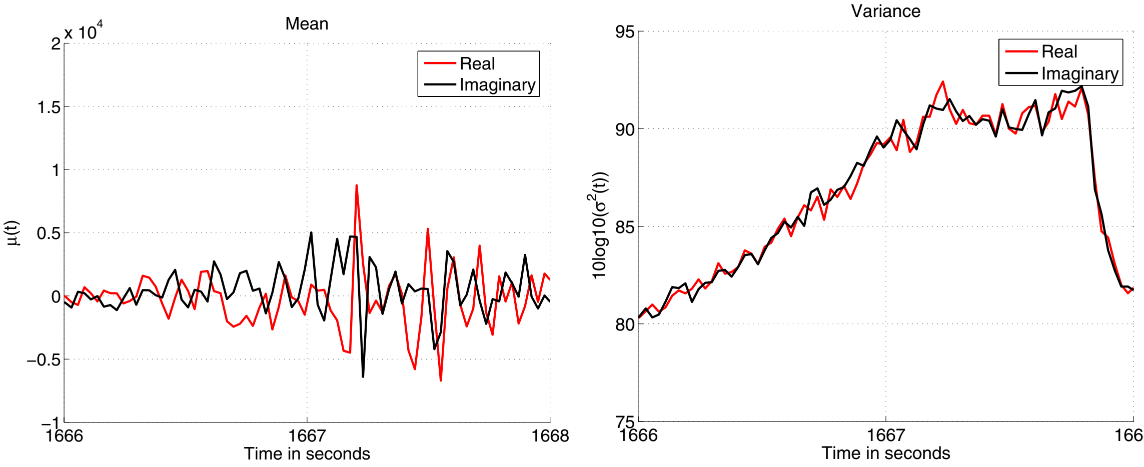

Figure 5: The mean and variance of mode 1 for the Kauai source. The left subplot shows the mean of mode 1 and the right subplot shows the log of the variance of mode 1. The red curve indicates the statistics of the real part of the mode signal and the black curve for the imaginary part. The mean is ≈ 0.

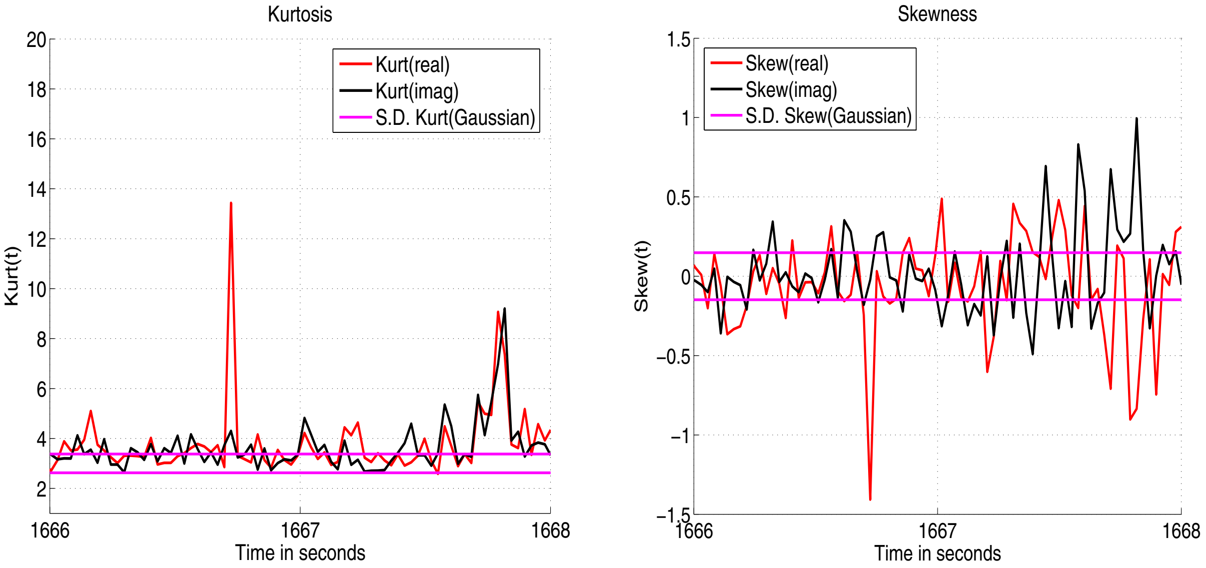

Figure 6: Kurtosis and skew of mode 1 for the Kauai source. The left subplot shows the kurtosis of mode 1 and the right subplot shows the skew of mode 1. The red curve indicates the statistics of the real part of the mode signal and the black curve indicates the imaginary part. The magenta lines on the subplot indicate the standard deviation of the kurtosis and skew assuming Gaussian statistics [9].

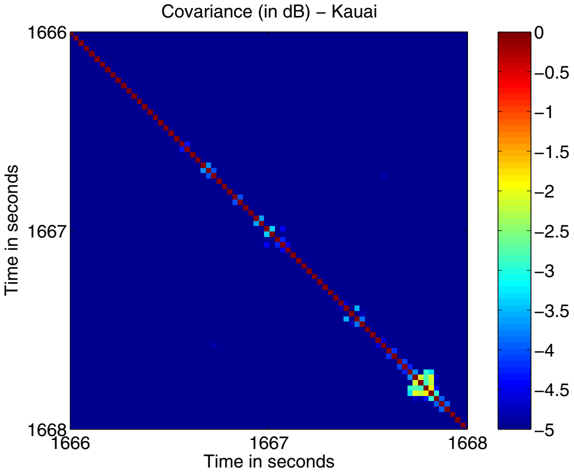

Figure 7: The covariance coefficient matrix of mode 1 signal for the Kauai source. The covariance coefficient matrix is a diagonal matrix except for the finale of mode 1.

[5] J. Mercer, R. Andrew, B. Howe, and J. Colosi, "Cruise Report: Long-range Ocean Acoustic Propagation EXperiment (LOAPEX)," Applied Physics Laboratory, Tech. Rep., April 2005.

[6] 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, no. 3, pp. 1565–1581, March 2005.

[7] L. Dozier and F. Tappert, "Statistics of normal mode amplitudes in a random ocean. 1. Theory," *J. Acoust. Soc. Am*, vol. 63, no. 2, pp. 353–365, February 1978.

[8] ——, "Statistics of normal mode amplitudes in a random ocean. 2. Computations," *J. Acoust. Soc. Am*, vol. 64, no. 2, pp. 533–547, August 1978.

[9] William H. Press, Brian P. Flannery, Saul A. Teukolsky and William T. Vetterling, *Numerical Recipes in C: The Art of Scientific Computing*, 1st ed. Cambridge University Press, 1992.