

Analysis and modeling of ocean acoustic fluctuations and moored observations of Philippine Sea sound-speed structure.

John A. Colosi: PI

Department of Oceanography, Naval Postgraduate School, Monterey CA 93943

Ph: 831-656-3260, FAX: 831-656-2712, E-mail: jacolosi@nps.edu

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LONG-TERM GOALS

The long-term goals of this research are to understand the statistics of acoustic fields in both deep and shallow water ocean environments.

OBJECTIVES

The primary objective of this work is the development of accurate, and computationally efficient, reduced-physics acoustic propagation models for the prediction of the statistics of ocean acoustic signals in both shallow and deep-water environments. Examples of acoustic field statistics of interest are mean intensity, coherence, and intensity variance. The focus here is primarily on the Philippine Sea, and the SW06 site off the New Jersey coast, since these are the most recent and complete data sets. Reduced physics models are important to ocean acoustics not only because they are often computationally efficient but also because they elucidate what scales of the ocean can have the maximum impact on the acoustical field. This knowledge allows for more focused study on those oceanographic processes that will have large acoustical influences. Therefore centrally related to the primary objective of this research is an effort to characterize ocean sound speed variability, and develop ocean models that can be easily assimilated into acoustic fluctuation calculations. In the Philippine Sea, models of eddies, internal tides, internal waves, and fine structure (spice) are needed, while in the shallow water case a models of the random linear internal waves and spice are lacking.

APPROACH

The approach taken here is to first test our reduced physics models against Monte Carlo simulation, and then once the scattering physics is understood, apply the models to observations. This approach was successfully used in developing a model for mode coupling caused by shallow water nonlinear internal waves (Colosi, 2008). Two different theoretical approaches will be considered. The first is a coupled mode technique developed by our group (Colosi and Morozov, 2009), and the second approach is a hybrid path-integral/geometric ray approximation for coherence properties along a time resolved wavefront.

In our analysis of ocean sound-speed structure we are utilizing observations from the 2009 Philippine Sea field trial and from the SW06 experiment. In these experiments moored seabird temperature, conductivity, and pressure sensors, as well as ADCPs were placed on multiple moorings giving vertical, temporal, as well as geographic information concerning ocean fluctuations. These data are being used to characterize internal tides, mesoscale eddies, stochastic Garret-Munk type internal waves, and intrusive finestructure (spice).

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WORK COMPLETED

Work completed in the previous year has focused on analysis of the Philsea 09 and SW06 oceanographic data sets and Monte Carlo testing the coupled mode model for all second moments of the acoustics field.

RESULTS

A. Coupled Mode Theory: Coherence

Our group has developed a coupled mode transport theory that can very accurately predict cross mode coherence functions which can be used for important acoustical second moments like field coherence and mean intensity (Colosi and Morozov, 2009; Colosi, Duda and Morozov 2011). The theory assumes small angle multiple forward scattering and that the Markov approximation is valid. Regarding the environment both shallow and deep water cases can be treated, but the theory assumes that the ocean sound speed structure is dominated by a random superposition of internal waves, like those described by the Garrett-Munk (GM) internal wave spectrum. The range evolution of the cross mode coherence function $\langle a_{n1} a_{p2}^* \rangle(r)$ for separations between points (1) and (2) is given by

$$\frac{d}{dr} \langle a_{n1} a_{p2}^* \rangle = i(l_{n1} - l_{p2}^*) \langle a_{n1} a_{p2}^* \rangle - \sum_{m=1}^N \sum_{q=1}^N \langle a_{q1} a_{p2}^* \rangle I_{mn1, qm1} - \langle a_{m1} a_{q2}^* \rangle I_{mn1, qp2}^* - \langle a_{q1} a_{m2}^* \rangle I_{mp2, qm1} + \langle a_{n1} a_{q2}^* \rangle I_{mp2, qm2}^*$$

where $l_n = k_n + i\alpha_n$ is the complex mode wavenumber, and $I_{mn,pq}$ are scattering matrices which involved the spectrum of internal waves. The points (1) and (2) could involve separations in time, horizontal position, or frequency. In our work we have analytic forms for the scattering matrices for idealized internal wave spectra, as well as numerical methods for general internal wave spectra. For the case of time and frequency separations the scattering matrices are independent of range and the evolution equation is easily evaluated numerically. For horizontal separations the matrices depend on range but still can be evaluated numerically. Importantly, the cross mode coherence is central to predicting the coherence function given by

$$\langle p(r_1, \omega_1, t_1) p^*(r_2, \omega_2, t_2) \rangle = \sum_{n=1}^N \sum_{p=1}^N \frac{\langle a_{n1} a_{p2}^*(r) \rangle}{r} \frac{\phi_{n1}(z_1) \phi_{p2}(z_2)}{\sqrt{k_{n1} k_{p2}}}$$

where $\phi_n(z)$ are the depth eigenfunctions of the unperturbed problem.

Monte Carlo numerical simulations in a deep water environment with GM internal wave induced sound speed perturbations have been carried out and comparisons were made between the temporal coherence computed from the simulations and predictions from the theory: These comparisons are shown in Fig. 1. In this case 75 and 250 Hz point sources on the sound channel axis are simulated and the agreement between theory and Monte Carlo simulation is excellent (Colosi et al. 2011). While significant mode coupling is occurring in these cases, it has been found that the temporal coherence is strongly influenced by adiabatic effects (Colosi et al. 2011). Figure 2 shows the frequency (f) and range (R) scaling of characteristic time coherence defined as the point at which the coherence decays to $e^{-1/2}$. Here we find that the scaling is somewhat

steeper than the path integral theory expectations of f^1 and $R^{-1/2}$; this result is due to the fact that we don't make any approximations to the correlation function of the sound speed perturbations (Colosi et al. 2011). Comparisons of predictions from the transport theory, and observations from the LOAPEX are presented in an annual report for a different project. We anticipate these results to be equally good in shallow water environments. Codes exist to compute coherence for horizontal separations and across frequency

B. Analysis of the 2009 Philippine Sea Oceanographic data.

During the 2009 Philippine Sea field test, 30 Seabird microcats and microtemps, as well as ADCP's were deployed on each of the source and receiver moorings in order to quantify the space-time scales of sound-speed variability. Data were collected between April 5 and May 9, 2009 thus giving slightly over a one-month record. Because pumped microcats were used accurate estimates of salinity allow an analysis along isopycnals, where internal waves can be separated from spicy thermohaline structure. Using rms sound speed as a metric it is found that random internal waves (akin to those described by the Garrett-Munk internal wave spectrum) and internal tides are the dominant source of sound speed variability and they have roughly equal contributions. Spicy effects, on the other hand, are found to be quite small, except for near the mixed layer. Frequency spectra for the internal waves (See Figure 3) show a random internal wave field which closely matches the GM spectrum and a strongly nonlinear diurnal and semidiurnal internal tide (note large tidal harmonics). An analysis of vertical covariance functions and estimation of internal wave mode spectra is underway, but is incomplete at this point.

IMPACT/APPLICATIONS

There are several implications of this work to the understanding of acoustic predictability. A short list of the major issues/impacts are given below.

1. Many observations and numerical studies have shown that internal wave induced sound speed perturbations have a large effect on mean intensity (transmission loss) in both shallow and deep water environments. The coupled mode theory developed by our group could conceivably be used as a Navy model for predicting low frequency mean TL and coherence.
2. The SW06 sound speed fluctuation analysis shows that spicy sound speed structure dominates the fluctuation field. The shallow water community needs to explore the acoustic propagation implications of this result (Colosi et al. 2011).
3. Using computational methods we have shown that shallow water random internal waves can dramatically modify the acoustic interaction with nonlinear solitary-like waves; this is a compelling result, and warrants further exploration with observations (Colosi, Duda, and Morozov, 2011).
4. The high quality Philippine Sea 2009 oceanographic data set has allowed for a definitive separation of internal-wave induced sound-speed perturbations and those caused by finestructure or spice. With this information ocean models could be constructed that separately treat internal waves and finestructure.
5. The Philippine Sea 2009 oceanographic data set will also allow the construction of a regional internal tide model: the relative important of internal tides to acoustic variability, however, is yet to be determined.

TRANSITIONS

None

RELATED PROJECTS

None

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PATENTS

None

HONORS/AWARDS/PRIZES

A. B. Wood Medal for “significant contributions to the understanding of acoustic scattering by internal waves in long-range propagation”.

Figures:

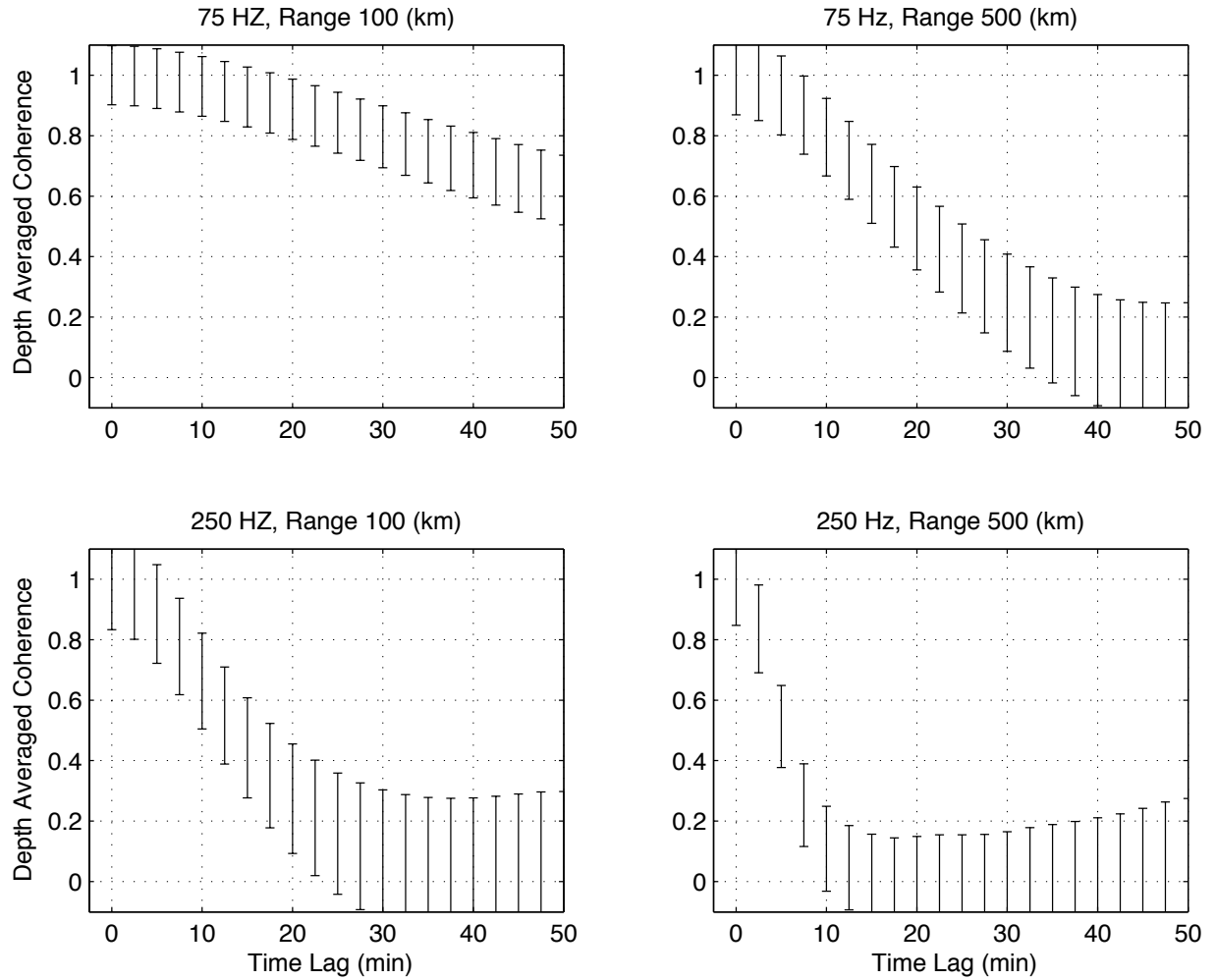


Figure 1: Comparisons of Monte Carlo simulation (solid with errorbars) and transport theory (dash) for depth average time coherence. The upper panels shows results for 75 Hz, while the lower panels are for 250 Hz. The left/right panels are for 100 and 500 km range respectively. Errorbars show 95 percent confidence intervals, assuming Gaussian statistics.

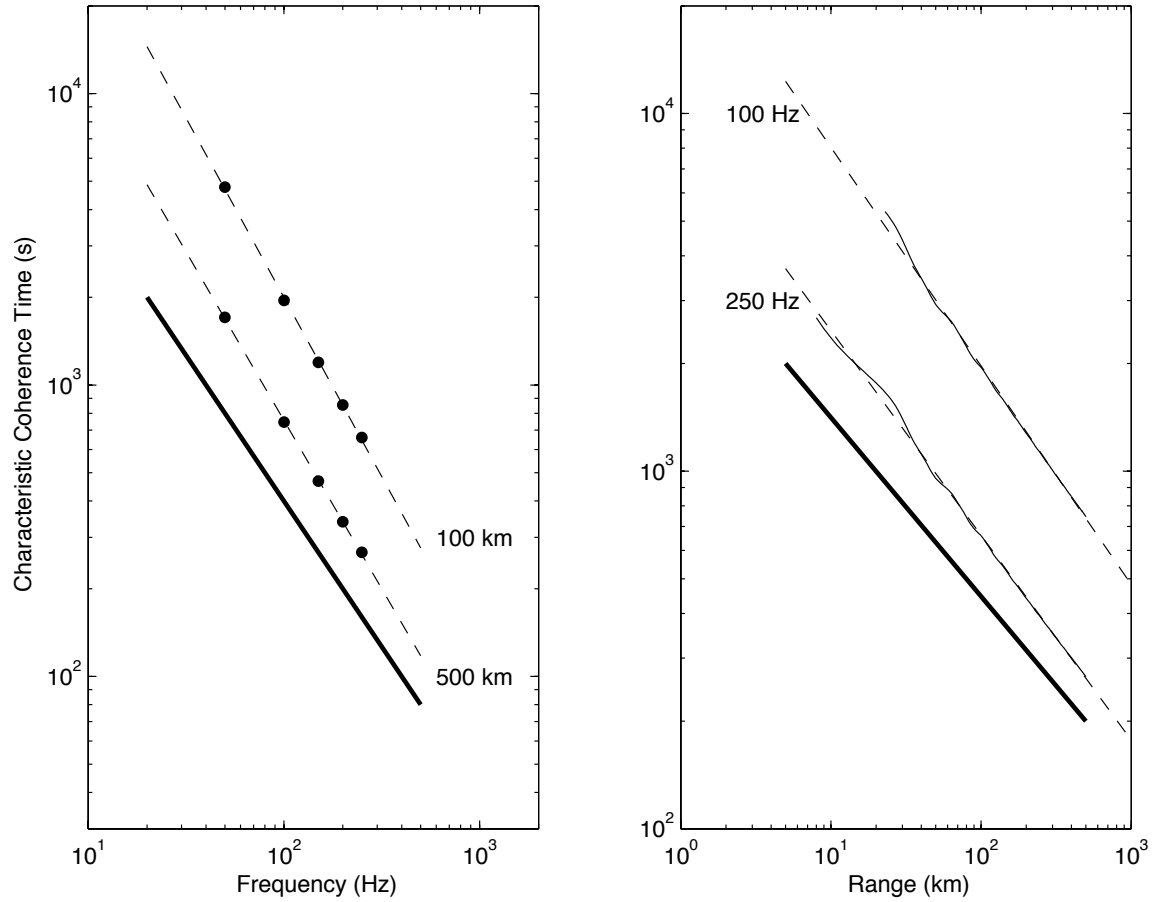


Figure 2: Frequency and range scaling of characteristic time coherence derived from the depth average coherence function. In the left panel the variation of time coherence as a function of frequency is shown for ranges of 100 and 500 km (points). Dash curves show power law fits to the values where the fitted exponents are -1.23 and -1.15 for the ranges of 100 and 500 km respectively. The thick curve shows a -1.0 power law. In the right panel variation of time coherence as a function of range is shown for frequencies of 100 and 250 Hz. Dash curves show power law fits to the values where the fitted exponents are -0.61 and -0.57 for the frequencies of 100 and 250 km respectively. The thick curve shows a -0.5 power law.

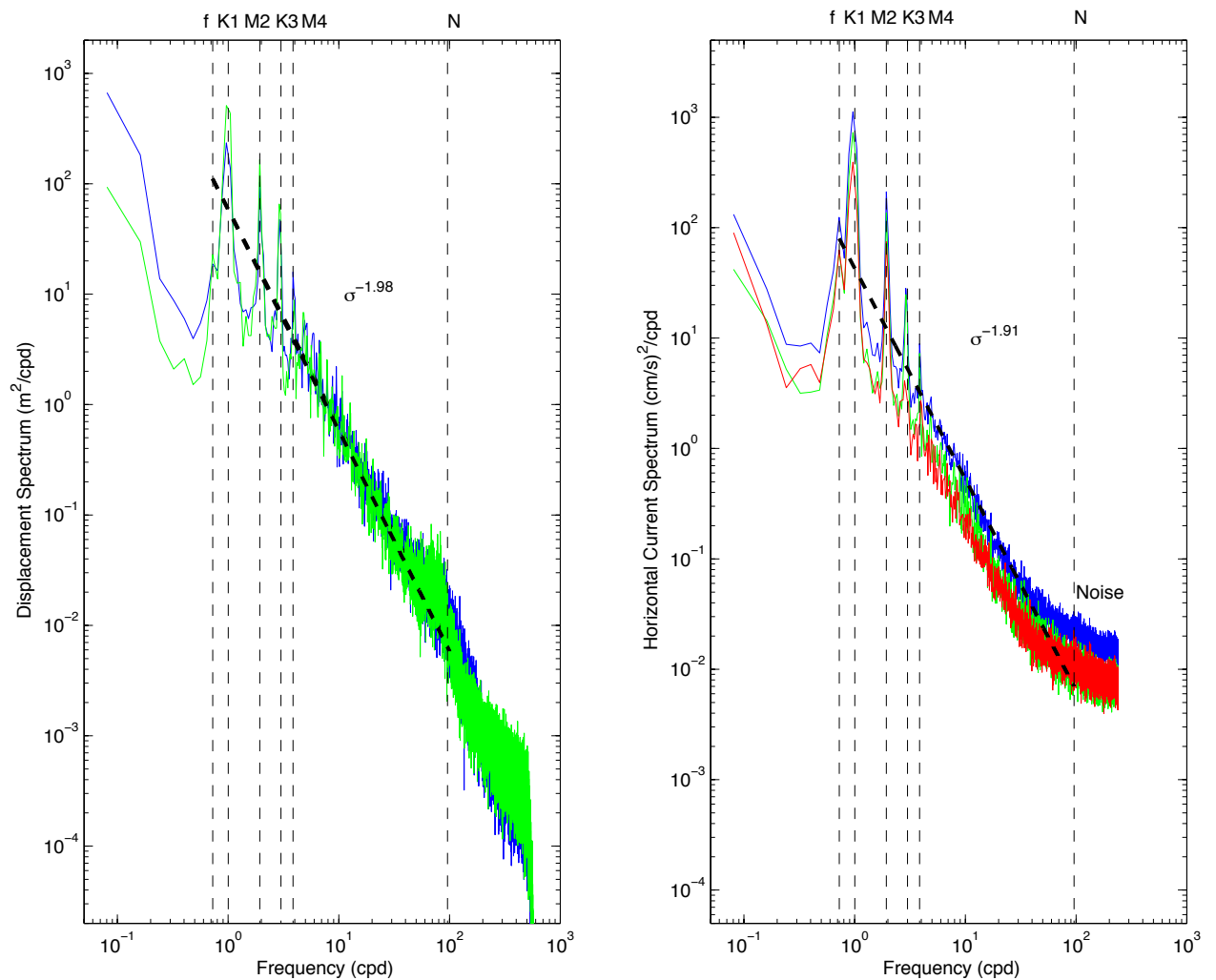


Figure 3: Spectra of isotherm displacement (left) and horizontal current (right). The displacement spectra are averaged over the depth regions 130-165 (Blue) and 170-454 (Green). Power law fits to the spectra in the frequency range 3.0 to 30 cpd are shown (dash). The horizontal current spectra shown are for the East-West component (Green), North-South component (Red), and the sum of these two (Blue). The current spectra are an average over observations taken in the depth range 130-170-m. A power law fit to the blue curve is shown (dash). Important frequencies are shown at the top of the graphs with associated vertical dash lines: *f* the Coriolus frequency, *N* a typical buoyancy frequency, *K1* a diurnal tide frequency, *M2* a semidiurnal frequency, *K3* the third harmonic of the *K1*, and *M4* a second harmonic of the *M2*.