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Analysis and Modeling of Ocean Acoustic Fluctuations and Moored Observations of Philippine Sea Sound-Speed Structure

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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 not only because they are computationally efficient but also because they elucidate the relevant space-time scales of ocean variability affecting acoustical fields. 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 to this research is to rigorously test acoustic fluctuation models using Monte Carlo numerical simulation thereby isolating the important acoustical physics when the environment is perfectly known. Once the models have passed the Monte Carlo test, they can be subsequently used for the interpretation of observations where the environment has considerably more uncertainty. Experimental analysis involves the study of both acoustical and oceanographic observations.

WORK COMPLETED

Work completed in the previous year has focused on analysis of the Philsea 09 and SW06 oceanographic data sets, Monte Carlo testing of coupled mode transport theories, application of transport theory to the LOng range Acoustic Propagation EXperiment (LOAPEX), and refinement of

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Feynman path integral expressions for horizontal coherence. This work has culminated in 2 publications for the Journal of the Acoustical Society of America (JASA) special issue on the acoustics of continental shelfbreaks, and 3 accepted and 2 pending manuscripts for the JASA special issue on deep water ocean acoustics for which I am a co-guest-editor.

RESULTS

A. Transport Theory: Deep Water

Work on deep water transport theory has focused on extending the theory to predict temporal, horizontal and vertical coherence for single frequency signals. The results of this work are presented in reference 4. Second moments of mode-amplitudes at fixed frequency as a function of separations in mode number, time, and horizontal distance were investigated using mode-based transport equations and Monte Carlo simulation. These second moments were used to study full-field acoustic coherence, including depth separations. Calculations for low-order modes between 50 and 250 Hz were presented using a deep-water Philippine Sea environment. Comparisons between Monte Carlo simulations and transport theory for time and depth coherence at frequencies of 75 and 250 Hz and for ranges up to 500 km show good agreement. The theory is used to examine the accuracy of the adiabatic and quadratic lag approximations, and the range and frequency scaling of coherence. It is found that while temporal coherence has a dominant adiabatic component, horizontal and vertical coherence have more equal contributions from coupling and adiabatic effects. In addition, the quadratic lag approximation is shown to be most accurate at higher frequencies and longer ranges. Lastly the range and frequency scalings are found to be sensitive to the functional form of the exponential decay of coherence with lag, but temporal and horizontal coherence show scalings that fall quite close to the well-known inverse frequency and inverse square root range laws. Vertical coherence is shown to also scale as frequency to the minus one power, but the range scaling is much slower showing a range to the minus 0.2 power law.

B. Transport Theory: Shallow water

Work on shallow water transport theory has focused on the observables of mean intensity and intensity variance for single frequency signals. In addition the effects of nonlinear internal wave packets were studied when a random background internal-wave field was present. This work was reported on in reference 2. Second and fourth moment mode-amplitude statistics for low-frequency ocean sound propagation through random sound-speed perturbations in a shallow-water environment were investigated using Monte Carlo simulations and a transport theory for the cross mode coherence matrix. The acoustic observables of mean and mean square intensity were presented and the importance of adiabatic effects and cross-mode coherence decay were emphasized. Using frequencies of 200 and 400 Hz, transport theory was compared with Monte Carlo simulations in a canonical shallow-water environment representative of the summer Mid-Atlantic Bight. Except for ranges less than a horizontal coherence length of the sound structure, the intensity moments from the two calculations are in good agreement. Corrections for the short-range behavior were presented. For these frequencies the computed mode coupling rates are extremely small, and the propagation is strongly adiabatic with a rapid decay of cross-mode coherence. Coupling effects were predicted to be important at kilohertz frequencies. Decay of cross-mode coherence has important implications for acoustic interactions with nonlinear internal waves: For the case in which the acoustic path is not at glancing incidence with a nonlinear internal-wave front, adiabatic phase randomizing effects lead to a significantly reduced influence of the nonlinear waves on both mean and mean square intensity.

C. LOAPEX Observations and Transport Theory

Because of the success of the transport theory comparisons to Monte Carlo simulations described in reference 4, my postdoc Tarun Chandrayadula and I analyzed mode statistics from the LOAPEX experiment and compared them to predictions from transport theory. This work is presented in reference 5. Second order mode statistics as a function of range and source depth were presented from the Long Range Ocean Acoustic Propagation EXperiment (LOAPEX). During LOAPEX, low frequency broadband signals were transmitted from a ship-suspended source to a mode-resolving vertical line array. Over a one-month period, the ship occupied seven stations from 50-km to 3200-km distant from the receiver. At each station broadband transmissions were performed at a near-axial depth of 800-m and an off-axial depth of 350-m. Center frequencies at these two depths were 75-Hz and 68-Hz respectively. Estimates of observed mean mode energy, cross mode coherence, and temporal coherence were compared with predictions from modal transport theory, utilizing the Garrett-Munk internal wave spectrum. In estimating the acoustic observables there were challenges including low signal to noise ratio, corrections for source motion and small sample sizes. The experimental observations agree with theoretical predictions within experimental uncertainty.

D. Ocean Sound-Speed Structure: SW06

To better understand the statistics of the SW06 acoustic fields an analysis of the space/time scales of SW06 sound speed fluctuations was carried out. Results from this study were reported in reference 1. Environmental sensors moored on the New Jersey continental shelf tracked constant density surfaces (isopycnals) for 35 days in the summer of 2006. Sound-speed fluctuations from internal-wave vertical isopycnal displacements and from temperature/salinity variability along isopycnals (spiciness) were analyzed using frequency spectra and vertical covariance functions. Three varieties of internal waves were studied: Diffuse broadband internal waves (akin to waves fitting the deep water Garrett/Munk spectrum), internal tides, and to a lesser extent nonlinear internal waves. These internal-wave contributions are approximately distinct in the frequency domain. It is found that in the main thermocline spicy thermohaline structure dominates the rms sound-speed variability, with smaller contributions coming from (in order) nonlinear internal waves, diffuse internal waves, and internal tides. The frequency spectra of internal-wave displacements and of spiciness have similar form, likely due to the advection of variable-spiciness water masses by horizontal internal-wave currents, though there are technical limitations to the observations at high frequency. In the low-frequency, internal-wave band the internal-wave spectrum follows frequency to the -1.81 power, while the spice spectrum shows a -1.73 power. Mode spectra estimated via covariance methods show that the diffuse internal-wave spectrum has a smaller mode bandwidth than Garrett/Munk and that the internal tide has significant energy in modes one through three.

E. Ocean Sound Speed Structure: Philippine Sea

As an aid to understanding long-range acoustic propagation in the Philippine Sea, statistical and phenomenological descriptions of sound speed variations were developed. These results are reported in reference 8. Two moorings of oceanographic sensors located in the Western Philippine Sea in the spring of 2009 were used to track constant potential-density surfaces (isopycnals) and constant potential-temperature surfaces (isotherms) in the depth range of 120-m to 2000-m. The vertical displacements of these surfaces were used to estimate sound-speed fluctuations from internal waves and eddies, while temperature and salinity variability along isopycnals was used to estimate sound-speed fluctuations from intrusive structure often termed spice. Frequency spectra and vertical covariance functions were used to describe the space-time scales of the displacements and spiciness. Internal-wave contributions from diurnal and semi-diurnal internal tides and the diffuse broadband internal-wave field (akin to that described by the Garrett-Munk (GM) spectrum) were studied. It is found that diffuse internal waves and nonlinear internal tides dominate the sound-speed variability, and that the observed spice and eddy fluctuations were weaker than expected. The internal wave and spice frequency spectra have similar form in the upper ocean but are markedly different below 170-m depth. Diffuse internal-wave mode spectra show a form similar to the GM model, while internal tide mode spectra scale as mode number to the minus two power. Spice is seen to decorrelate very rapidly with depth, with a typical correlation scale of ten's of meters.

F. Path Integral Theory: Horizontal Coherence

Previously published results from path integral theory for the horizontal coherence length utilized an empirical relation for the phase structure function density that was quite different from path integral results obtained for depth and time coherence where the phase structure function density was expanded to second order in the lag. Our work presented results for horizontal coherence length which carries out the quadratic expansion and analytically solves the integral equations. Some simple calculations of horizontal coherence length demonstrate the differences between the present and old expressions. In contrast to the empirical result the present expression shows the expected one over square-root range and one over frequency scalings. The results also show more clearly how transverse coherence is sensitive to the space-time scales of internal waves and other environmental parameters. These results were presented in reference 3.

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. Work is underway to develop a computationally tractable and accurate transport theory for intensity variance (i.e. errorbar on the TL).
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.
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.
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

1. MURI – Integrated Ocean Dynamics and Acoustics (Tim Duda, WHOI MURI Leader)

REFERENCES/ RECENT PUBLICATIONS

1. Colosi, J.A., T.F. Duda, T.T. Lin, J. Lynch, A. Newhall, and B.C. Cornuelle, ``Observations of sound speed fluctuations on the New Jersey continental shelf in the summer of 2006'', J. Acoust. Soc. Am., 131(2), pp1733-1748, **2012**.
2. Colosi, J. A., T.F. Duda, and A.K. Morozov, ``Statistics of low frequency normal mode amplitudes in an ocean with random sound speed perturbations: First and second moments of intensity in shallow water environments'', J. Acoust. Soc. Am, 131(2), pp1749-1761, **2012**.
3. Colosi, J.A., ``On horizontal coherence estimates from path integral theory for sound propagation through random ocean sound-speed perturbations'', J. Acoust. Soc. Am., accepted **2012**.
4. Colosi, J. A., T. Chandrayadula, A. G. Voronovich, and V.E. Ostashev, ``Coupled mode transport theory for sound propagation through an ocean with random sound-speed perturbations: Coherence in deep-water environments'', J. Acoust. Soc. Am., accepted **2012**.
5. Chandrayadula, T., J. A. Colosi, M.A. Dzieciuch, P. Worcester, R.K. Andrew, J.A. Mercer, and B. Howe, ``Observations and transport theory analysis of low frequency, long range mode propagation in the Eastern North Pacific Ocean'', J. Acoust. Soc. Am., accepted **2012**.
6. Udovydchenkov, I.A., M.G. Brown, T. F. Duda, J.A. Mercer, R. K. Andrew, P. F. Worcester, M.A. Dzieciuch, B. M. Howe, and J. A. Colosi, ``A modal analysis of the range evolution of broadband wavefields in the Long-range Ocean Acoustic Propagation Experiment: Low mode numbers'', J. Acoust. Soc. Am., 131, pp4409-4427, **2012**.
7. Worcester, P.F., M.A. Dzieciuch, J.A. Mercer, R.K. Andrew, A.B. Baggeroer, K.D. Heaney, G.J. D'Spain, J.A. Colosi, R.A.Stephen, J.N.Kemp, B.M.Howe, and L.J. VanUffelen, ``The North Pacific Acoustic Laboratory (NPAL) deep-water acoustic propagation experiments in the Philippine Sea, J. Acoust. Soc. Am., submitted **2012**.
8. Colosi, J.A., L.VanUffelen, B.D. Cornuelle, M.A. Dzieciuch, P.F. Worcester, B.D. Dushaw, and S.R. Ramp, ``Observations of sound speed fluctuations in the Western Philippine Sea in the spring of 2009'', J. Acoust. Soc. Am., submitted **2012**.

PATENTS

None

HONORS/AWARDS/PRIZES

1. Medwin Prize in Acoustical Oceanography, 2012, for furthering the understanding of ocean sound-speed structure and its effects on acoustic propagation in both deep and shallow water. Acoustical Society of America.
2. A. B. Wood Medal, 2001, for "significant contributions to the understanding of acoustic scattering by internal waves in long-range propagation". Institute of Acoustics and Acoustical Society of America.