# 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 PhilSea10 oceanographic data sets, and Monte Carlo testing of shallow water coupled mode transport theories which include effects from random internal waves and random sea surface roughness. This work is culminating in 2 publications for the Journal of the Acoustical Society of America (JASA) which are in preparation. In addition this year, Peter Worcester and I have obtained a contract with Cambridge University Press to publish a book entitled ``Ocean sound propagation through the stochastic internal wave field''. Peter and I have also served as guest editors for a special issue of JASA on deep water ocean acoustics. In that special issue I am author/co-author of 9 manuscripts. Lastly with Tim Stanton of the Woods Hole Oceanographic Institution we are publishing the results of Lt. Ben Jones Naval Postgraduate School PhD thesis.

## RESULTS

**A. Transport Theory: Shallow water**

Work on shallow water transport theory for mean intensity and intensity variance (e.g. mean TL and errorbar) has focused on extending the theory to handle kilohertz frequencies and to simultaneously account for random internal waves and random sea surface roughness. Working with my postdoc Dr. Kaus Raghukumar we have developed a hybrid transport theory that is accurate and can handle the large number of modes needed at high frequency. In the hydrid approach we solve for second and fourth order mode amplitude correlation matrices by assuming that cross mode correlations are dominated by adiabatic phase effects. Mode energy redistribution from coupling is handled by replacing the initial mode amplitude terms in the adiabatic expressions with range evolving ones based on Creamer's approximation. The method works exceptionally well for mean intensity and scintillation index at kilohertz frequencies for the SW06 environment with random sound speed perturbations from internal waves. We are presently writing up this work for JASA.

We have also developed codes to do Monte Carlo simulation and transport theory for random sea surface roughness and combined calculations with both internal waves and rough surfaces. This work is just starting to bear fruit and we should have new results early in FY14.

**B. Internal Tide Sound Speed Structure: Philippine Sea**

Previous analysis of Philippine Sea oceanographic data has revealed very energetic internal tides which are comparable or larger than the stochastic internal wave component. In addition, the internal tides are seen to have a rich modal structure thus giving ride to a diverse span of depth and horizontal scales that are important to both acoustic phase and amplitude fluctuations. Furthermore, because of the time dependent tidal generation processes at work in the Philippine Sea the internal tides show remarkable variability over month and seasonal timescales. Working with the University of Hawaii, the Scripps Institution of Oceanography, and the University of Washington we have developed a methodology to use the Philippine Sea acoustic and oceanographic data to map out the complex space and time evolving internal tide field at both the diurnal and semi-diurnal frequencies. In the next fiscal year we hope to apply these methodologies to the PhilSea10 data set and provide the NPAL group with internal tide maps for the duration of the experiment that can be used for acoustic analysis.

**C. Monograph: ``Ocean Sound Propagation Through the Stochastic Internal Wave Field''**

Since March of 2013 Peter Worcester and I have been working on a monograph that will be the sequel to the 1979 classic ``Sound Transmission through a Fluctuating Ocean'', By Flatte, Munk, Dashen, Zachariasen, and Watson. We submitted a book proposal to Cambridge University Press (CUP), in May and after external review the proposal was accepted by the editorial board in September. Three of the 11 chapters are now written and we expect to complete the book over FY14 during my sabbatical.

**D. Internal Waves Effects on Echo Clutter from Fish Schools**

My PhD student Lt. Ben Jones developed a two-way parabolic equation code to simulate clutter from fish schools in realistic ocean environments including the sound channel, bottom interactions, sloping bottom, and random sound speed fluctuations caused by internal waves. The code also simulates real sonar systems having realistic vertical and horizontal beam patterns. The key physical mechanism affecting the echo PDF's is the degree to which all of these factors (sonar system and environment) enhance or diminish multipath. Ben's research showed that the echo *amplitude* PDF is bound between two asymptotic forms, the Rayleigh and the exponential. Using this information Ben developed a highly efficient phasor summation method to estimate echo PDF's and the method was successfully tested tested with Monte Carlo simulations. The method was also tested using data obtained by Roger Gauss near Georges Bank.

## 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/ transport theory developed by our group could conceivably be used as a Navy model for predicting low and high frequency mean TL, errobar, and coherence. Work is underway to develop computationally tractable codes that also handle random sea surface effects.
2. The Philippine Sea 2010 oceanographic and acoustic data sets will allow construction a regional internal tide model incorporating many modes and both diurnal and semidiurnal fluctuations: the relative important of internal tides to acoustic variability, however, is yet to be determined.
3. The writing of a monograph covering the development of the subject of sound transmission through the stochastic internal wave field will establish where we have gone in this important area over the last 30 years and it will point to new directions in which the field can go in the future. The authors hope this book will be an indispensable part of students, researchers, and academics libraries on underwater acoustics.

## TRANSITIONS

None

## RELATED PROJECTS

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

## REFERENCES/ RECENT PUBLICATIONS


1. Colosi, J.A., ``On horizontal coherence estimates from path integral theory for sound propagation through random ocean sound-speed perturbations'', J. Acoust. Soc. Am., 134(4), pp??-??, 2013.
2. 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., 134(4), pp??-??, 2013.
3. 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., 134(4), pp??-??, 2013.
4. Stephen, R.A., S. Bolmer, I. Udovydchenkov, P. Worcester, M. Dzieciuch, R. Andrew, J. Mercer, J. Colosi, and B. Howe, ``Deep seafloor arrivals in long range ocean acoustic propagation'', J. Acoust. Soc. Am., 134(4), pp??-??, 2013.
5. Andrew, R., A. W. White, J.A. Mercer, P.F. Worcester, M.A. Dzieciuch, and J.A. Colosi, ``Wavefront intensity statistics for 284-Hz broadband transmissions to 107-km range in the Philippine Sea: observations and modeling'', J. Acoust. Soc. Am., 134(4), pp??-??, 2013.
6. 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., 134(4), pp??-??, 2013.
7. Colosi, J.A, L.J Van Uffelen, 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., 134(4), pp??-??, 2013.
8. 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 , ``Weakly dispersive modal pulse propagation in the North Pacific Ocean'', 134(4), pp??-??, 2013.
9. Colosi, J.A. and P.F. Worcester, ``Deep Water Ocean Acoustics: Forward'', J. Acoust. Soc. Am., 134(4), pp??-??, 2013.
10. Jones, B.A., J.A. Colosi, and T.K. Stanton, ``Echo statistics of individual and aggregations of scatterers in the water column of a random oceanic waveguide'', J. Acoust. Soc. Am., submitted, 2013.
11. Jones, B.A., J.A. Colosi, T.K. Stanton, R. C. Gauss, J.M. Fialkowski, and J. Michael Jech ``Classification and statistics of long range mid-frequency sonar measurements of aggregations of fish'', J. Acoust. Soc. Am., submitted, 2013.


## 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.
3. ONR Young Investigator Award, 1997.