An Analysis of Long-Range Acoustic Propagation Fluctuations and Upper Ocean Sound Speed Variability

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LONG-TERM GOALS

The long-term goals of this research are to understand the predictability limits of long-range acoustic transmissions, and to delineate the important environmental factors contributing to predictability.

OBJECTIVES

The objectives of this work are both observational and theoretical. Several low-frequency and broadband long-range transmission data sets in which data was obtained on long vertical receiving arrays (VLA's) have been analyzed to quantify acoustic phase and intensity variability, as well as temporal and vertical coherence. One short range experiment (87 km) is being used to examine scattering over the first 2 upper turning points. In addition, analysis of oceanographic measurements of upper ocean processes will quantify acoustic scattering structures. Coupled mode, Geometric (ray-based) and parabolic equation models are used to examine the underlying acoustic scattering physics.

APPROACH

From an observational standpoint the approach here has been to study the acoustic fluctuation properties of the SOFAR finale since this is the most energetic part of the arrival structure; this is particularly important when issues of temporal variability are addressed. The finale is characterized by a complex multi-path interference pattern (much like typical shallow water arrivals) while the early "wavefront" arrivals show weaker multi-pathing. In the analysis, a novel 2-D (time and depth) phase unwrapping procedure is used to provide both phase and intensity information over a series of acoustic transmissions. This analysis allows quantification of phase and intensity PDFs and in the analysis of coherence, allows a description of the theoretical form of the coherence function. Analysis of one short range experiment (87 km) is allowing an examination of the fluctuations after the first two upper turning points.

Oceanographic observations I helped obtain during the North Pacific Acoustic Laboratory (NPAL) 98-99 field-year are being used to quantify upper ocean sound scattering structures. Moored thermistor, CTD, and ADCP data along with calibrated XBT and CTD transects are being used to quantify the space/time scales of sound speed variability in both mesoscale and internal wave frequency bands. A novel upper ocean acoustic scattering mechanism caused by near-inertial shear layers beneath the mixed layer is being examined.

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14. ABSTRACT

The long-term goals of this research are to understand the predictability limits of long-range acoustic transmissions, and to delineate the important environmental factors contributing to predictability

15. SUBJECT TERMS

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From a theoretical and modeling standpoint the initial approach was to examine ray propagation through Garrett-Munk internal wave fields to try and understand the breakdown of the path-integral formulation of acoustic scattering. Here I have worked closely with M. Brown (U. Miami), M. Wolfson (U. Washington), S. Tomsovic (Washington State), and G. Zaslavsky (New York University). Ray results have lead to new questions being addressed by parabolic equation numerical simulations, coupled mode theory, and a kinematic model of broadband multipath interference.

WORK COMPLETED

Work completed in previous years focused on the analysis of long range propagation data sets, and ray theory. This year the focus has been on a short range data set, the 87 km AET data, and stochastic acoustic normal mode theory similar to the Dozier Tappert work. Also some work was done to examine acoustic scattering by upper ocean shear currents, using moving media ray theory and observations of upper ocean (300-m) currents from the NPAL98-99 field years.

RESULTS

Regarding the short range observational work my student Jinshan Xu and I have obtained results from 6 days of 75 Hz broadband transmissions to a 20 element, 700-m long vertical array at 87 km range. The observed arrival pattern consists of two time resolved, and identifiable wavefronts; one with an initial downward ray angle and two lower turning points (LTP) and one upper turning point (UTP) (to be referred to as ID -3), and one with an initial upward ray angle and two LTP's and two UTP's (to be refered to as ID 4). Since acoustic scattering is most pronounced at the UTP (Flatte et al, 1979), these arrivals provide a view into the fundamental scattering at an UTP. Furthermore, since the average UTP depth for ID's -3 and +4 are 150-m and 250-m they nearly sample the same upper layers of the ocean. The acoustic transmission data were obtained over 20 and 40 minute observation times followed by multi hour transmission gaps. This sampling allows analysis of acoustic variability of the two arrivals over 20 minute, 40 minute, and multi-day (6 day) timescales. A novel 2-D phase unwrapping technique (Colosi et al 2005) allows examination of phase variability over the 20 and 40 minute times, but phase cannot be tracked across the multi-hour periods between the transmissions. Scintillation index (SI) and variance of log-intensity ($\sigma^2_{\ln I}$) are used to quantify intensity variability. Over the 6 day experimental period ID -3 had SI ~ 0.04 and $\sigma_{\ln I}$ ~ 0.8 dB, while ID 4 had SI ~ 0.4 and $\sigma_{\ln I}$ ~ 3 dB. This result indicates a significant and rapid growth of intensity variability with UTP number. In addition the relatively small fluctuation values suggest that weak fluctuation theory may be appropriate for these arrivals. The short time scale (20 and 40 minute observation times) behavior of the two arrivals in both phase and intensity is remarkably similar. The rms phase variability for the two arrivals (ID -3/+4) are 0.43/0.43 and 0.63/0.68 rad for the 20 and 40 minute observation times respectively, while the $\sigma_{\ln I}$ values for the two arrivals (ID -3/+4) are 0.25/0.26 and 0.41/0.43 dB again for the 20 and 40 minute observation times. Because the ID 4 arrival increases its $\sigma_{\ln I}$ value from 0.43 to 3.0 dB from the 40 minute to 6 day observation time while the ID -3 only increases its value from 0.41 to 0.80 we find that ID 4 has much more low frequency variability than ID -3. Since the two ID's have one of their upper turning points in the same location (40-50 km range) the low frequency variability must be coming from the first UTP of ID 4 (range 5-10 km). This result implies strong range dependence in the acoustical environment such that the two upper turning points separated by ~40km have very different scattering properties: This is unexpected. Vertical wave-number and frequency spectra of phase and log-amplitude over the 20 and 40 minute observation times show the space-time scales of acoustic variability.

In terms of theoretical results, Andrey Morozov and I have worked to develop a coupled mode theory to better understand acoustic intensity statistics. The approach is largely based on the work of Dozier and Tappert, and of Van Kampen, and the novel addition to the theory is the calculation of cross mode coherences. The primary scattering mechanism in the theory is a Bragg-like resonance between the difference modal wave-number and the internal wave wave-number. This work closely parallels efforts by Alex Veronovich and Frank Henyey. Initial comparisons between the new theory and parabolic equation simulations through Garrett-Munk internal waves at 250 Hz show the theory predicts the range evolution of the mean intensity to within a few dB (See figures below). The theoretical calculation (Fig 1) takes only a few minutes to compute while the Monte Carlo calculation (Fig 2) takes days. Comparisons should be even better at lower frequencies. Future challenges involve computing modal cross frequency coherences.

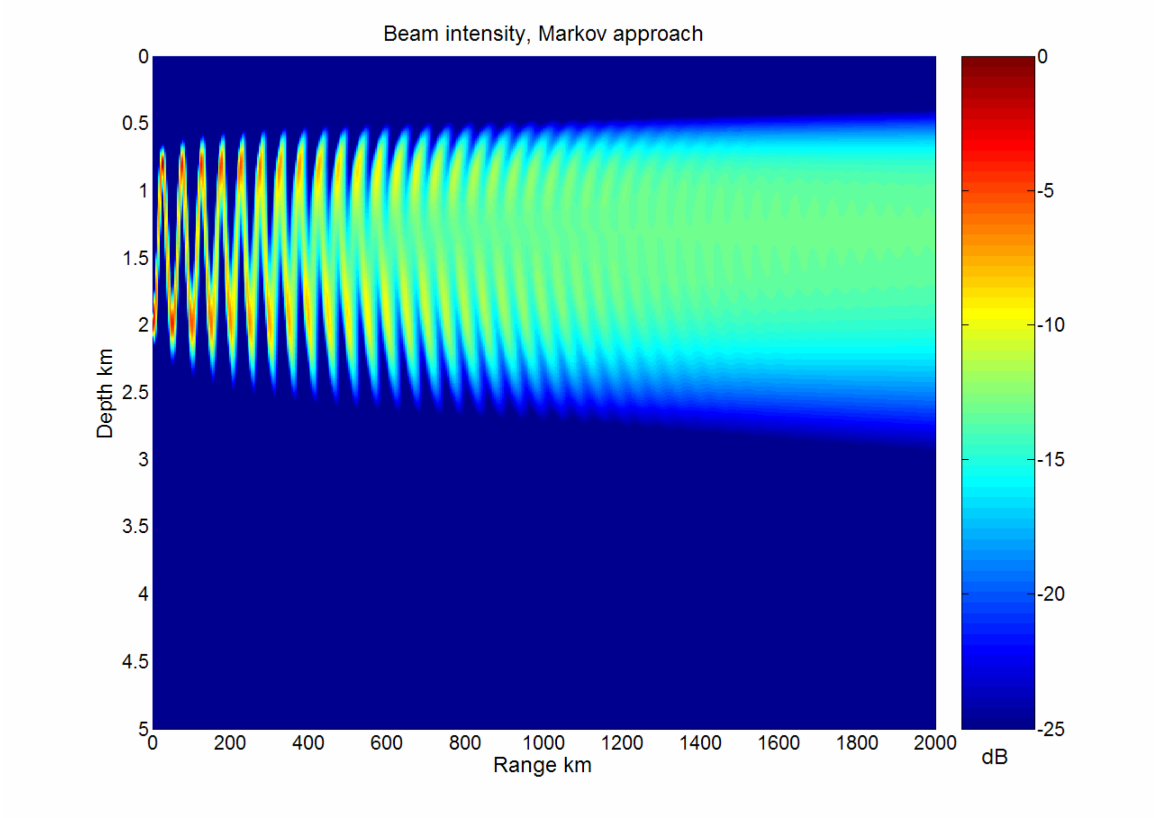

Figure 1: Mean intensity for a 250 Hz acoustical beam computed by our coupled mode theory. Random sound speed fluctuations are modeled using the Garrett-munk model.

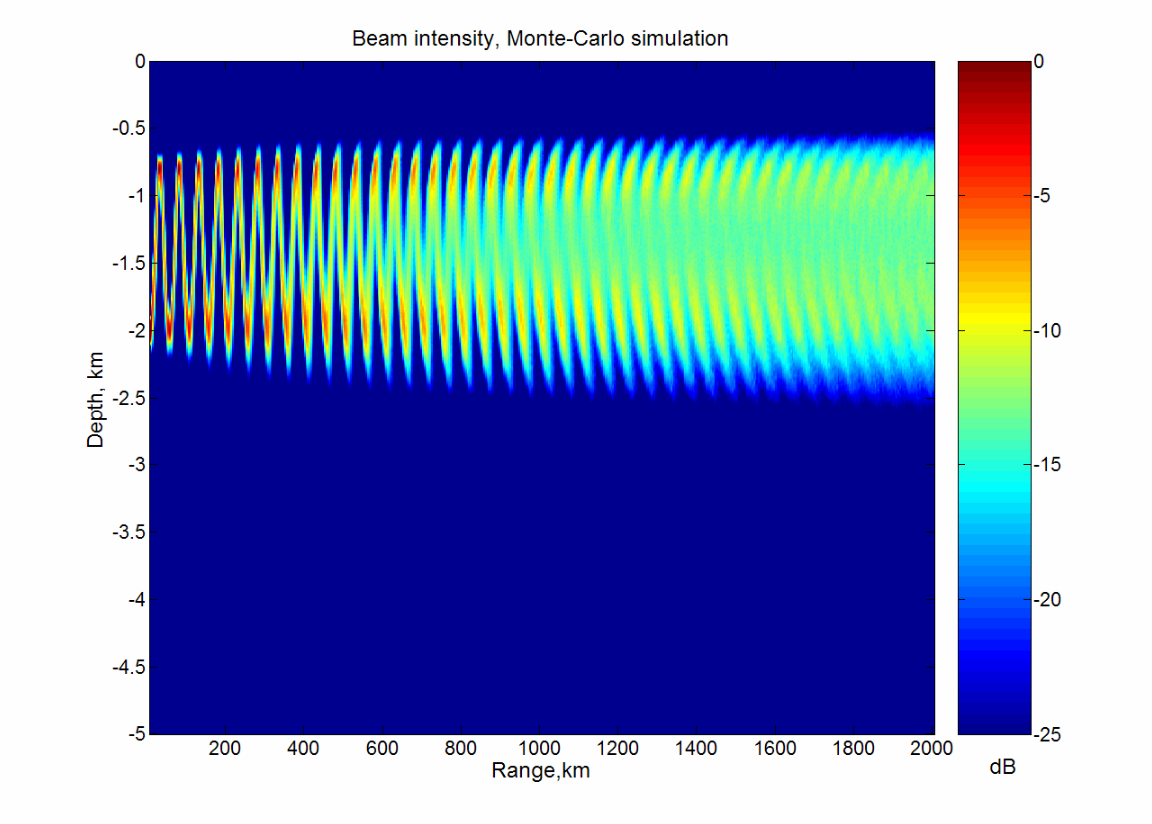

Figure 2: Mean intensity for a 250 Hz acoustical beam computed using Monte Carlo PE simulation.

Lastly, using ray theory for a moving medium it can be shown that sound speed gradient and shear enter the equations in the same way. So, using ADCP and thermistor data from the 1998-1999 NPAL field years I was able to compare fluctuating upper ocean vertical sound speed gradients and horizontal velocity shear. The observations show that the sound speed gradient and shear terms of the ray equation can be comparable, and thus future work will be needed to examine the integrated effect of the currents for upper ocean acoustic propagation.

IMPACT/APPLICATIONS

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

1) Analysis of the short range AET data shows the rapid increase in scintillation from one turning point to the next. Modeling work to complement the data analysis will be needed to understand the important scattering mechanism at work at the upper turning points.

2) Progress on a coupled mode theory for low frequency long range propagation may be able to fill the gap in understanding left when the path integral theory of acoustic fluctuations was shown to be seriously flawed. The coupled mode theory may also find application in shallow water environments. A comparison between Figs 1 and 2 is very encouraging.

3) Acoustic scattering effects from upper ocean shear need to be investigated further. This scattering mechanism may be related to the unexplained depth --penetration of deep ocean wavefronts (shadow zone arrivals).

TRANSITIONS

none

RELATED PROJECTS

Effects of Sound on the Marine Environment (ESME; ONR N00014-00-1-0931), and ONR uncertainty initiative.

REFERENCES

See Publications below.

RECENT PUBLICATIONS

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into the ESME sound exposure model," IEEE J. Oceanic Eng., Special Issue on the Effects of Sound on the Marine Environment (ESME), accepted, 2005.

9) J. A. Colosi, ``Geometric sound propagation through an inhomogeneous and moving ocean: Scattering by small scale internal wave currents'', J. Acoust. Soc. Am., conditionally accepted, 2005.

In Preparation:

1) J.A. Colosi, J. Xu, and The NPAL Group, "Observations of upper ocean sound speed variability in the North Pacific Ocean", J. Acoust. Soc. Am.

2) J. Xu, and J. Colosi, ``Observations and modeling of single and double turning point acoustic scattering for 75 Hz sound transmission in the North Pacific Ocean'', J. Acoust. Soc. Am.

Conference Proceedings:

1) A. Morozov and J. Colosi, "Entropy of acoustical beams in a random ocean", IEEE Oceans Symposium, September 2003.

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".