Ocean Acoustic Propagation: Fluctuations and Coherence in Dynamically Active Shallow-Water Regions

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LONG TERM GOALS

Our goals are to understand the nature and causes of acoustic signal fluctuations in the shallow water environment. This will allow prediction of acoustic system performance and exploitation of acoustic signal properties. Here, signal means any identifiable acoustic reception.

OBJECTIVES

An objective is to probe deeper into an acoustic transmission data set from past continental shelf-edge shallow water experiment to better define signal stability and fluctuation in terms of multiple parameters. Such parameters are, for example, intensity variance of randomly chosen multipath amplitudes, variance of peak intensity selected from multipath interference patterns, and decorrelation time scales of each of these. Both established and newer parameters related to signal variability will be employed. Another objective is to gain theoretical understanding of the fluctuation behavior.

APPROACH

In an effort to understand and predict the causes of shallow-water acoustic field fluctuations by first deducing the effects of various common oceanographic features, we (including collaborators) have been systematically doing the forward modeling and examining the effects of assorted features on acoustics. This is continuing under this grant. In addition, we are beginning a classification effort to find fundamentally different regimes of scattering that might be encountered in differing shallow-eater environments. This may be somewhat analogous to the lambda-phi diagrams of the deep-water acoustic fluctuation theories developed over the last few decades.

For the forward modeling, our major focus thus far has been on sound propagation across fronts and across packets of steep nonlinear internal waves. Coupled-mode propagation occurs in these situations. Other investigators have focused on propagation parallel to wave packets or fronts [Badiey et al., 2005], or within fields of weak homogeneous internal waves. Three of our publications describe in detail how and why these waves affect sound of a few hundred hertz. The waves create temporally variable horizontal gradients of sound speed, causing temporally variable coupled-mode propagation [Duda, 2004; Duda and Preisig, 1999; Preisig and Duda, 1997]. Temporally-variable intensity of sound from fixed sources recorded at fixed receivers has been shown to be consistent with predictions from those and similar studies [Chiu et al., 2004; Duda et al., 2004; Duda and Preisig, 1999]. Our

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14. ABSTRACT

Our goals are to understand the nature and causes of acoustic signal fluctuations in the shallow water environment. This will allow prediction of acoustic system performance and exploitation of acoustic signal properties. Here, signal means any identifiable acoustic reception

15. SUBJECT TERMS

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work in this area agrees well with results published by other groups using comparable methods [Finette and Oba, 2003; Oba and Finette, 2002; Rouseff et al., 2002; Tielburger, Finette and Wolf, 1997]. To further progress in this area, we plan the following work:

1. Extend modeling to a broad range of frequencies, 50 to 1500 Hz. (Most of our work cited above was for 400 Hz.)

2. Finish work in progress on temporal and cross-range coherence.

3. Start a modeling study of the sensitivity to seafloor geoacoustic properties.

4. Study the effects of more realistic fully three-dimensional internal waves rather than long-crested two-dimensional waves.

We plan to pursue ever-increasing opportunities to test our theoretical ideas and model-derived results with ground-truth field observations. For instance, the ASIAEX South China Sea study, which our group participated in, yielded four papers in the October 2004 IEEE Journal of Oceanic Engineering containing analysis of acoustic signals at 250-450 Hz from sources at ranges of 21 and 32 kilometers. Orr et al. [2004] found horizontal array gain degradation (29-wavelength array size) to range between -0.2 and -5.5 dB, typically being 1.5 dB. Mignerey and Orr [2004] found temporal correlation time of 300-Hz carrier unit-normalized vertical array field vectors to drop from 15 min during quiescent periods to 2 minutes when internal waves were present. A similar drop from 6 minutes to 1 minute was observed for 500 Hz. Both of these were for 21 km range. Chiu et al. [2004] found strong fluctuations of depth-averaged signal energy during an period of having numerous internal waves (rms fluctuations of 3-4 dB). A similar result was found by Duda et al. [2004] using a larger set of data. The complexity of the acoustic fluctuations is daunting, and we strive to identify and understand it.

Regarding the classification work, which was started in 2004, the goal is to identify unique relate shallow-water fluctuation regimes, measured in terms of fluctuation parameter state vectors received by an array, and relate them to their causes (large internal waves, small internal waves, focusing by alignment with internal wave crests, etc.). The ability to classify the propagation domain (i.e. identify the cause of dominating fluctuations) would enable modeling, prediction, and extrapolation. This would be a through-the-sensor classification or inversion technique. A specific objective is a multi-parameter definition of signal characteristics which allows description of the fluctuations in terms of physical conditions, which would serve to condense the complicated effects of moving internals wave (and/or fronts) into meaningful and potentially predictable measures of acoustic signal parameters.

The simulation portion of the forward-modeling work is done with the RAM 2-dimensional parabolic equation model. This was written by Mike Collins of NRL. We have modified the code by changing the input and output protocols. The modifications allow the code to run faster for the types of propagation media that we use, and let us look at the full acoustic fields. Three years ago we switched from Collins' FEPE model to RAM.

WORK COMPLETED

A manuscript describing sound-field fluctuations in planes transverse to the direction of acoustic propagation caused by moving internal waves in the region between the source and receiver has been completed and submitted for publication. Expressions governing temporal and lateral coherence scales of the fluctuations are derived and tested numerically with N-by-2D RAM PE simulations. Figure 1 shows a snapshot of an acoustic field from the study, with the waves at only one position. The transverse structure of the field arises because the distance at which the sound encounters the packet is a function of azimuth. Thus, the lateral decorrelation scale (or coherence scale) can be expressed as a function of the packet movement scale that causes decorrelation of the field, which was the topic of previous research (Duda and Preisig, 1999). Figure 2 effectively shows time series of acoustic intensity measured at a single point for three frequencies (upper panel). Intensity is plotted as a function of packet position, measured in kilometers from the source, but this can be converted to time using the component of the internal-wave speed in the direction of the sound. The lower panel shows unity-normalized autocovariance functions of the complex fields from which the intensities of the upper panel are derived. The scale of internal-wave packet displacement that causes decorrelation, when normalized by wavenumber, is a function of frequency. The intent of the manuscript is to more fully describe the behavior.

Signals recorded with the vertical line array portion of the WHOI HLA/VLA during the South China Sea portion of ASIAEX were beamformed under a previous grant and further analyzed this year. This was done in collaboration with OASIS, Inc, who designed software to do this for the Shelfbreak PRIMER data set (ONR sponsored, 1996-1997). Signals from our moored sources and noise in bands not occupied by the sources were both beamformed. The results are currently undergoing analysis.

RESULTS

Better understanding of the spatial and temporal coherence behavior as a function of frequency, in a downward-refracting waveguide, as described in the submitted manuscript, is one major result. Temporal correlation times are predicted to lie between 30 and 120 seconds, agreeing with data. Lateral horizontal scales are inversely proportional to the distance of the internal wave packet from the source, and vary widely. They can be as small as 15 wavelengths when wave packets are near the receiver.

Further results to date are the computation of time-series of the signal and noise VLA beamforming directional patterns. Vertical arrival angles of signals from the moored source to the moored array are seen to change significantly over 20-minute time intervals, or less, providing time scales of variability for this parameter. This time scale is intermediate between the intensity variation time scale (minutes) and the time scale of fluctuations in the intensity variance itself (hours to ½ day). The behavior of the moored-source signal vertical beam patterns in ASIAEX and PRIMER are decidedly different, which we ascribe to the virtually continual presence of internal waves at the ASIAEX site. (Note that the rms amplitude of ASIAEX internal waves is a function of time, but this doesn't seem to be the most important parameter.) Finally, the noise notch at low horizontal angle often observed in PRIMER data is rarely observed in ASIAEX data.

IMPACT/APPLICATIONS

The application of the results may be in the signal processing domain, since algorithms may be developed which are robust to or might exploit signal fluctuations. For example, processing might exploit fluctuations by utilizing intermittent but strong signal peaks, or predicting time limits for coherent analysis, or predicting wait intervals to reacquire signals after fade-outs.

RELATED PROJECTS

This project was undertaken as a continuation of work linked with the ONR ASIAEX Volume Interaction Experiment (acoustics), which involved field work during 2001 and involved multiple PIs and multiple projects. Many of the completed projects of the Capturing Uncertainty DRI are also related, in particular our own effort with the UNITES group. Other related past projects are the SWARM and PRIMER acoustics/shelfbreak front internal wave/acoustic experiments, and acoustic/internal wave interaction modeling studies. At this time, the PI is an active participant in the planning of the Littoral Environmental Acoustics Research (LEAR) portion of the upcoming ONR Shallow-Water 2006 experiment in the Mid-Atlantic Bight, with a commitment to making environmental physical oceanographic measurements.

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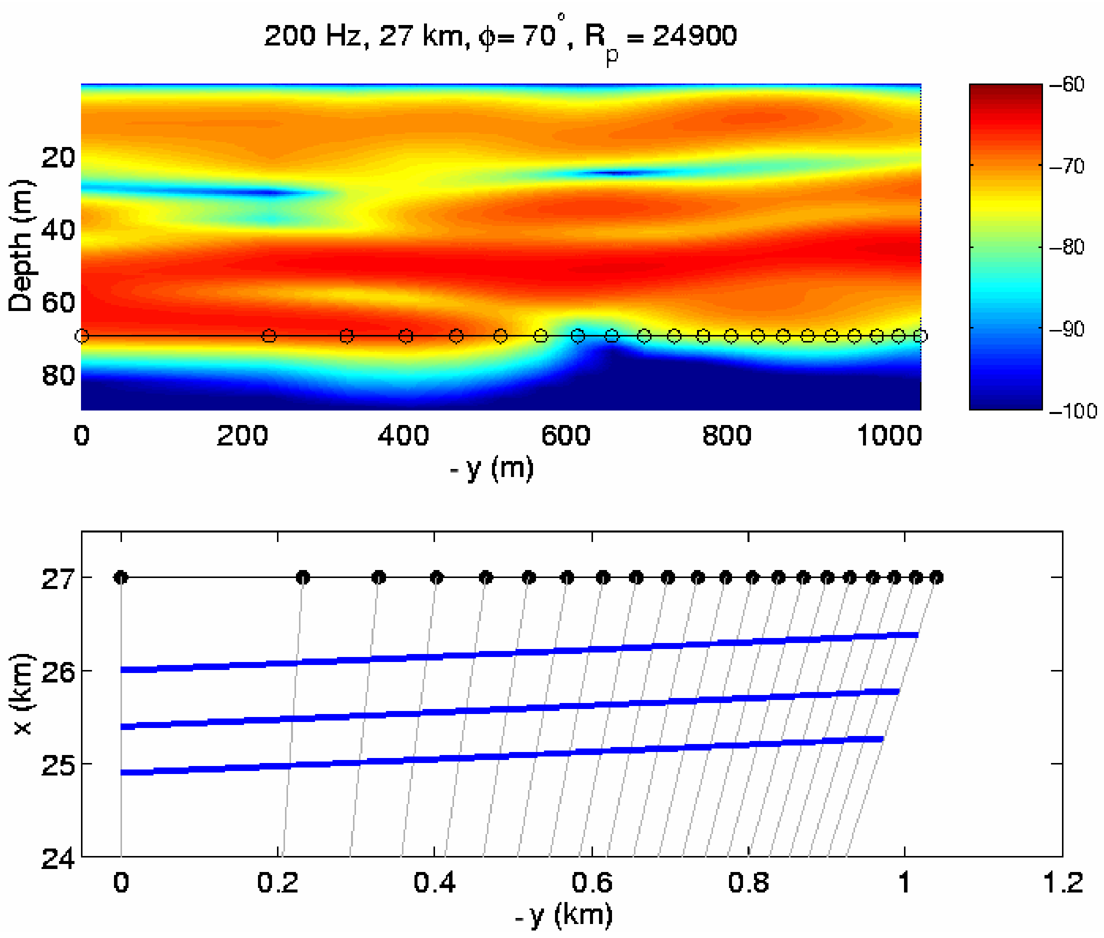

Figure 1: From the submitted manuscript. Lower panel: The vicinity of a receiver array used in a simulated shallow-water 200-Hz acoustic experiment is shown in plan view. Receivers are shown with black dots. Sound is emitted from a source at position (x, y)=(0, 0). The receivers are at x=27 km, with variable y from 0 to -1 km. The water depth is 70 m at the receiver, increasing to 130 m at the source. The source depth is 20 m. The water column is stratified so that internal gravity waves are realizable. Also shown are the positions of the troughs of three nonlinear internal waves of depression, aligned to be 70 degrees (nominally) from the acoustic paths. Upper panel: The acoustic intensity in the receiver plane is shown. In the absence of waves, the image would have horizontal stripes. The lateral structure of the acoustic field that is introduced by the waves is evident. The coherence scale is about 300 m.

[Lower panel: The area from x=24 to 27.5 km, y=-0.05 to 1.2 km is shown. The receiver plane at x-27 km is visible. The waves are approximately 0.5 to 1.8 km from the receiver at the right side (y=-1 km), 1 to 2.1 km from the receiver at the left side (y=0). Upper panel: The variable acoustic intensity in the 70-m deep, 1000-m wide receiver plane is shown ranging from 60 to 100 dB less than the source level.]

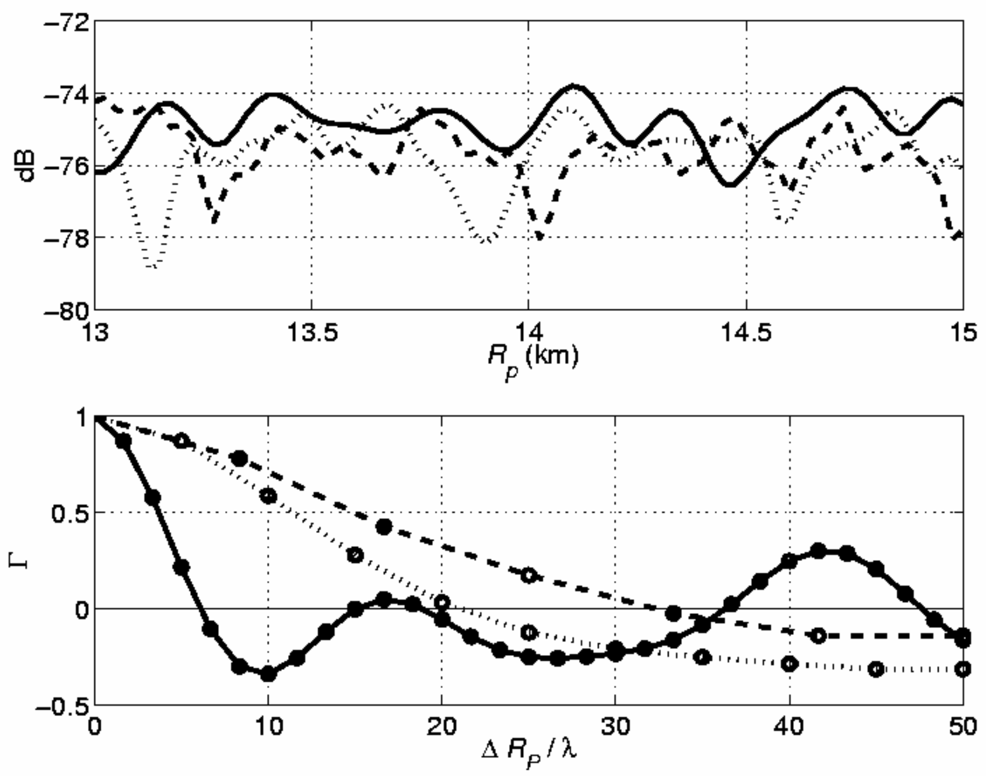

Figure 2: Upper panel: From simulations set up as in Figure 1, variable acoustic intensity measured at the sea floor at x=27 km, y=0, caused by movement of the internal wave packet is shown for three frequencies: 100 Hz (solid line), 300 Hz (dotted line) and 500 Hz (dashed line). Intensity is plotted as a function of packet position, which is the controlling parameter. The corresponding time interval of the plot is approximately 40 minutes. (The time interval depends on the wave packet alignment with respect to the acoustic path). Lower panel; The autocovariance functions of the complex fields that have their intensity shown in the upper panel are plotted. The coherence length scale, normalized by the acoustic wavelength, is seen to be a function of frequency, and ranges from 4 to 15 times the wavelength.

[Upper panel: Intensity fluctuations with an 8-dB dynamic range are shown for wave packets at locations from 13 to 15 km from the source, midway between source and receiver. Lower panel: The autocovariance functions descend from one at zero lag to zero at lag of 7 to 30 times the wavelength, passing 0.5 at lags of 4 to 15 times the wavelength. When normalizing in this manner, the most rapid decorrelation is for 100 Hz, the least rapid is for 500 Hz.]