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

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LONG TERM GOALS

The 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, including noise of unknown origin, identified signals, and intentional signals.

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-water environments. This may be somewhat analogous to the lambda-phi diagrams of the deep-water acoustic fluctuation theories developed over the last few decades.

The effort is aimed at summer conditions in the temperate ocean. This is a stratified regime that is downward refracting acoustically, and which supports internal waves. Observations show that packets of nonlinear mode-one internal waves often dominate. The effect of the bottom on signal spatial and temporal coherence is strong if the bottom is highly variable near the source, because sound penetrated into the bottom. However, after sound travels a few km the bottom interacting portion of the signal is weaker, and the sound interacts only weakly with the bottom, meaning that water-column sound-speed perturbations such as from internal waves play a larger role in sound fluctuation and coherence.

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The focus of modeling has thus far been sound propagation across fronts and across packets of straight 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 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 extend progress in this area, we plan the following work:

1. Extend propagation modeling through straight nonlinear wave packets to the band 50 to 1500 Hz. Most of our work cited above was for 400 Hz. The band 100-900 Hz has been examined.

2. Model the situation of only small linear internal waves, and small waves plus packets.

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.

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 ocean fluctuations that we model, and let us look at the full acoustic fields. We switched from Collins' FEPE model to RAM four years ago.

We are comparing our theoretically based ideas and model-derived results with ground-truth field observations. For instance, the ONR 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 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 acoustic fluctuations are complex and we strive to understand them.

Regarding the classification work, 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. At this time, a data clustering or cluster analysis approach is under examination.

WORK COMPLETED

A manuscript describing temporal sound-field coherence, and coherence in planes transverse to the direction of acoustic propagation, caused by moving internal waves in the region between the source and receiver, has been published. Expressions governing temporal and lateral coherence scales of the fluctuations are derived and tested numerically with N-by-2D RAM PE simulations. The expressions are for temporal and spatial coherence as functions of S, packet position, and the angle between sound and internal wave directions. 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 S that causes decorrelation of the field, which was the topic of previous research (Duda and Preisig, 1999).

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. Shelfbreak PRIMER VLA data were also examined (ONR sponsored experiment, 1996-1997). Signals from our moored sources and noise in bands not occupied by the sources were both beamformed. Results are given in the next section.

RESULTS

Better understanding of the spatial and temporal coherence behavior as a function of frequency, in a downward-refracting waveguide, as described in the journal article, 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 5 wavelengths when wave packets are near the receiver. There is additional information about spatial coherence from the work beyond the statistic of coherence scale, which by definition is an average of all conditions. Internal waves near the receiver can degrade the coherence in a much stronger way that waves near the source, resulting in deterministic changes to short-term average coherence scales.

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 acoustic fluctuations seem to be somewhat independent of internal wave strength, possibly a form of saturation.)

Figure 2 shows results for noise beamforming at 135 Hz. For each experiment, two panels are shown. The upper panel shows the mean (plus/minus standard deviation) of vertical beam power computed for the 50% of samples having noise level less than the median. The lower panel shows the same for the 50% of samples having noise level greater than the median. As expected, both situations show no noise notch for weak (distant) noise that has undergone mode stripping, while. However, the noise notch that is expected for louder nearby sources is evident only for the PRIMER summer experiment (lower left). It has been filled in for the ASIAEX experiment (lower right), presumably by mode coupling. Observations of fluctuations from fixed sources in ASIAEX are consistent with pervasive coupling. Note that the above-mean noises in ASIAEX are louder than those of PRIMER, so that a lack of nearby loud noise sources is an unlikely explanation for the missing ASIAEX notch.

IMPACT/APPLICATIONS

The application of the results may be in the signal processing domain, since algorithms may be developed that 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 a participant in the Littoral Environmental Acoustics Research (LEAR) portion of the ONR Shallow-Water 2006 experiment in the Mid-Atlantic Bight, and is currently processing and examining the data from the order-50 moorings that collected water-column variability in the area of the acoustic experiments.

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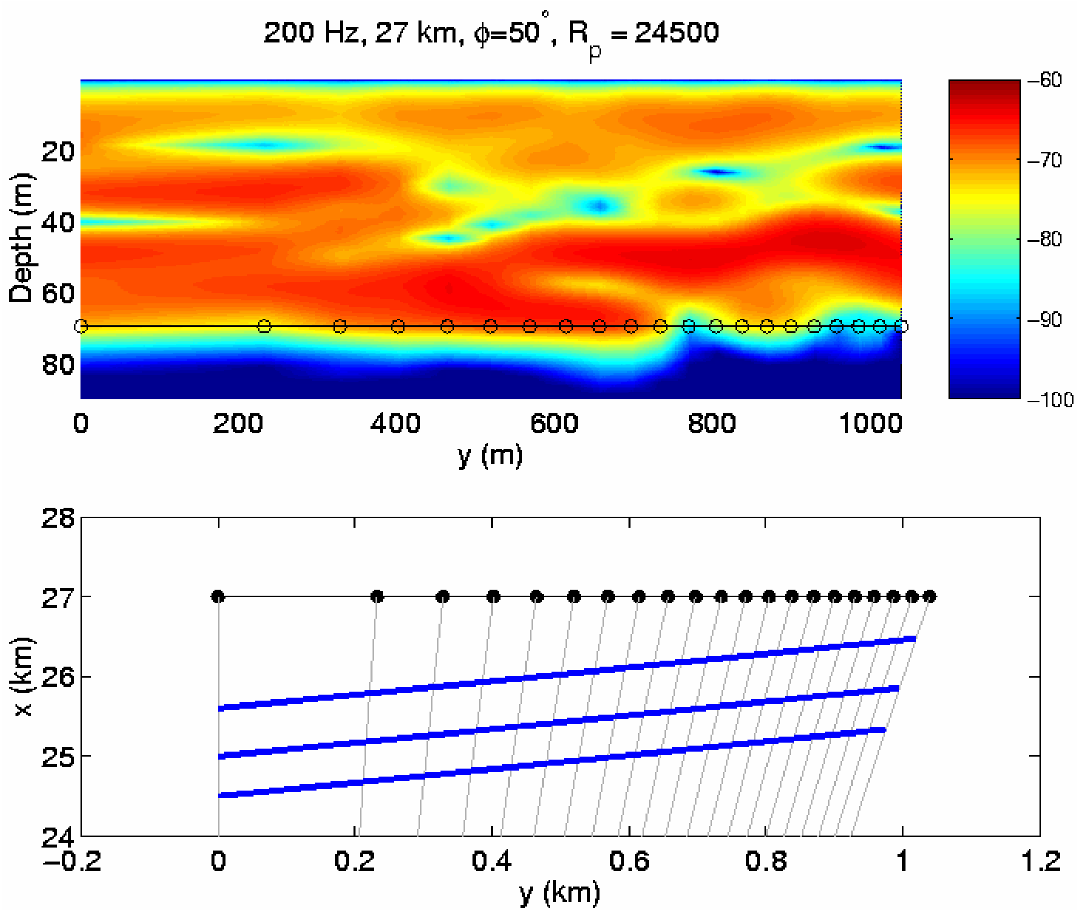

Figure 1: From the published manuscript (Duda, 2006). Lower panel: The vicinity of a receiver array used in a simulated shallow-water 200-Hz acoustic experiment is shown in plan view. Note the different scaling of the two axes. Receivers are shown with black dots. Sound is emitted from a source at position (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 50 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 28 km, y = -0.2 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), and 1.3 to 2.5 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.]

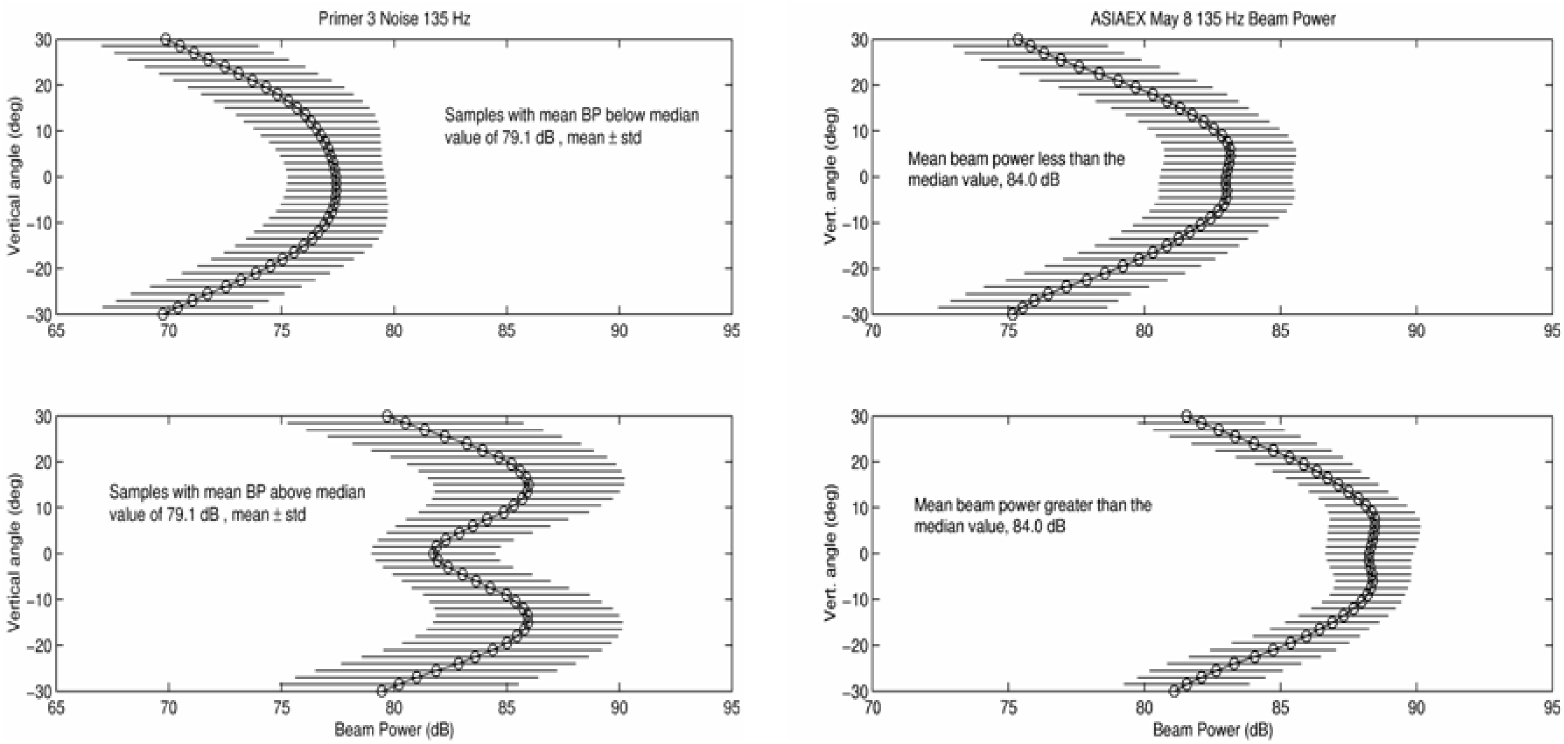

Figure 2: Vertical angular beamforming results for PRIMER (left) and ASIAEX (right) for noise in a band surrounding 135 Hz. The upper panels show mean +/- standard deviation beam powers for the 50% of the samples with sub-median noise level, and the lower panels show the same for samples with above-median noise level. There is a never a noise notch for low noise level. There is a notch for the high-noise PRIMER scenario, but no notch for the high noise ASIAEX scenario.

[Left upper panel: Beam power increases from 70 to 77 dB and back to 70 dB for angles from 30 to zero and then to -30 degrees, respectively. Right upper: the same graph for ASIAEX, with a similar form, except the levels go from 75 to 83 and back to 75 dB. Left lower: For the angles 30, 15, 0, -15 and -30 deg., beam power has two humps, going from 80 to 85 to 81 to 85 and finally to 79 dB. Right lower: For angles 30, 10, -10 and -30 deg., the beam power moves from 82 to 88 dB, maintains at 88 dB, and then drops to 81 dB.]