Spatial Structure of Deep Water Acoustic Propagation

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LONG-TERM GOALS

The long-term goals of this research are to understand the spatial (and less so the temporal) structure of deep-water acoustic propagation, with particular emphasis on deep-water ambient noise. Background noise in the open ocean is driven by local wind generated surface noise; interference from nearby ships; and at low frequencies is dominated by energy received from ships at significant distances. The extent to which scattering from seamounts, downslope conversion and internal waves affects the spatial structure (mode composition) of this ambient noise is the primary focus of this work. In spite of the deep water focus of this research, it turns out that sediment properties (geo-acoustics) of downslope regions and seamounts plays a role in the amount and type of scattering from these bathymetric features.

Estimation of the geo-acoustic properties of deep-water sediments has long been of interest. Inversion approaches have included single bounce inversions more akin to seismic sediment profiling where the backscattered energy is computed as a function of angle and the reflection coefficient for the sediment is estimated. These results compare well with the sediment cores taken during the deep-sea drilling project. The process of formation of deep-sea sediments is well understood, primarily being formed by falling detritus, called marine snow. This falling detritus forms a surface sediment layer, sometimes kilometers thick of very soft, unconsolidated sediment (silt), which often has a compressional speed lower than the water above the sediment-water interface. Underneath this soft sediment, is the hard submarine seafloor, formed of Basalt created at the mid-ocean ridges. Primary question for determining the geo-acoustic properties of a region in deep water (away from sills, sloughs and escarpments) is the thickness of the sediment over the basement. The question of sediment thickness is brought to the forefront when examining the 3-dimensional scattering of acoustic energy from an open ocean seamount. The extent to which the soft sediment layer is stripped off by deep sea and open ocean currents is not known. The north pacific basin contains a significant number of seamounts many of which are high enough to ascend beyond the deep water sound channel axis, generally on the order of 1000m. The acoustic interaction of sound with seamounts is an open research question involving the development of an acoustic shadow, it's subsequent healing due to diffraction, mode coupling and back-scattering.

Another long-term goal is to develop a mechanism, both theoretically and experimentally, for performing towed array tomography (TAT). The combination of a moored tomography array and a moving towed array will provide near real time coverage of a large volume of ocean. In order to accomplish this, array element location must be within 1 m and acoustic timing of the data must be within 5 ms.

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14. ABSTRACT
The long-term goals of this research are to understand the spatial (and less so the temporal) structure of deep-water acoustic propagation, with particular emphasis on deep-water ambient noise. Background noise in the open ocean is driven by local wind generated surface noise; interference from nearby ships; and at low frequencies is dominated by energy received from ships at significant distances. The extent to which scattering from seamounts, downslope conversion and internal waves affects the spatial structure (mode composition) of this ambient noise is the primary focus of this work. In spite of the deep water focus of this research, it turns out that sediment properties (geo-acoustics) of downslope regions and seamounts plays a role in the amount and type of scattering from these bathymetric features.

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The final long-term goal is the development of a deep ocean noise model that includes the effects of local geo-acoustics (bottom roughness), surface wind noise as well as long range ambient noise driven by downslope conversion as well as internal wave and seamount scattering.

OBJECTIVES

The primary objective of this work is to process, analyze and understand the data taken during the Basin Acoustic Seamount Scattering Experiment (BASSEX04). During this test, two time periods are of interest. The first involved the scattering of 250 Hz sound off of the Kermit-Roosevelt seamounts. Receptions from two sources at ranges of 520 km and 600 km were received at various positions behind and over the seamount. The predicted acoustic shadow was observed. The study conducted this year by PI Dr. Kevin Heaney was into determination of the geo-acoustic parameters of the seamount from receptions taken directly above the seamount. The open question here is how much

Preparation for the Philippine Sea 2009/2010 experiment is underway. Our primary objectives for this test are to explore the resolution of towed array tomography (TAT), to measure spatial distribution of signals generated within 2-3 convergence zones including scattering of sound off of the bottom near the towed and vertical line arrays, and to explore the ability to perform long range matched field processing using various vertical line array apertures. The above studies should lead to significant insight into the affect of local bottom geo-acoustics (and roughness) on signal and ambient noise modeling.

APPROACH

In this inversion, we will compare the beam time series data form the towed array, received just above the seamount with numerical model simulations using different sediment thicknesses. The beam-time series for both receptions are shown in Fig. 2. We therefore require a model that provides a beam-time series equivalent to the matched filtered response of the towed array beam data. The computational approach will involve a combination of PE modeling, mode decomposition and beamforming. The first step is to compute the narrowband acoustic field over the seamount as a function of sediment thickness, as was done in Section V. Here, however we compute the field for the entire bandwidth, 200 to 300 Hz, with a frequency spacing of ¼ Hz, as we anticipate the Inverse-Fast Fourier Transform (IFFT). In order to transform into the field received on the array, and then beamform, we use the orthogonality of normal modes to decompose the field at the specified range. Mathematically, at a particular range *r*, the complex modal amplitudes $b_n(\omega,r)$ can be computed from the local normal mode $\varphi_n(\omega,z)$ functions by:

(1) $$b_n(\omega,r) = \int \frac{\varphi_n(\omega,r,z)}{\rho(z)} P(\omega,r,z)dz$$

where the mode orthogonality requires

(2) $$\int \frac{\varphi_{mn}(\omega,r,z)\varphi_n(\omega,r,z)}{\rho(z)}dz = \delta_{mn}$$

In matrix language, with U being the mode matrix (in mode number/depth), we have the simple inner product:

(3) $$\vec{b} = U\vec{P}$$

where we have suppressed the frequency and range indices.

In order to map the field to the horizontal array, we invoke the adiabatic mode approximation which states that over mildly range-independent environments, energy is not transferred between modes. This approximation, along with the assumption that the source is in the far-field of the array, permits us to map the field at each receiver as a translation from the center of the array to the position of the hydrophone. The relative bearing of the source to the array enters this computation through the range offset of each hydrophone. For a hydrophone at a depth *z* and a range-offset (from the array center) *Δr* is computed via:

(4)
$$P(\omega, \Delta r_i, z) = \sum_n b_n(\omega, r, z)\varphi_n(\omega, z)e^{ik_n \Delta r_i}$$
$$\vec{P} = \Phi\vec{b}$$
where the phase translation matrix Φ is defined by
$$\Phi = \vec{\varphi} \cdot I \cdot \exp(kn^*)$$

The range scaling (1/sqrt(r)) is neglected in this approach but at ranges of 600 km it is on the order of .03%. Equation 4 permits us to compute the complex narrowband signal as a function of phone position for a distant source at a given bearing θ. We now apply conventional narrowband beamforming to the array data vector. With windowed steering vectors defined by:

(5)
$$w_i(\theta) = H_i \exp\left\{ i\frac{\omega}{c}\Delta r_i \cos\theta \right\}$$
normalized such that
$$\vec{\mathrm{w}} \cdot \vec{\mathrm{w}} = \|\vec{\mathrm{w}}\| = 1$$

where *H* is the Hanning weighting, c is the reference sound speed (1480 m/s). The beam steering vectors can be written as a matrix *W*, with element number and search direction as the rows/columns. The narrowband beam response is therefore the product of the pressure field with the beam steering matrix:

(6) $$\vec{B} = W\vec{P}$$

But recall that we have computed the pressure field by extending the modes in range. If we insert Eq. 5 into this equation we obtain a straightforward matrix computation from mode amplitude to beam response:

(7) $$\vec{B} = W\Phi\vec{b}$$

By at the computation in this fashion we see that the beam response is an inner product of the mode functions and the beam patterns. Further analysis of these two matrices demonstrates that this is simply a Henkel function integral of the mode field. Computationally we can collapse the entire product into a single matrix multiplication by inserting the mode decomposition integral into Eq. 8.

$$B(\theta) = (W\Phi U)\bar{P}(z) = MP \quad (8)$$

The above approach provides the opportunity to perform a single geometric based transformation from vertical PE field output to horizontal array beamformed narrow band snapshots. The narrowband snapshots can then be inverse fourier transformed to generate modeled beam-time series, with significant computational efficiency. Note that the matrix transformation M is independent of the field and can be pre-computed and applied to each PE field.

WORK COMPLETED

As part of the Basin Acoustic Seamount Scattering EXperiment (BASSX), a portable receiver array was used to record transmissions from an acoustic source located near Kauai, Hawaii. The broadband source has a center frequency of 75 Hz and is mounted on the seafloor. Bottom interaction significantly affects the propagation of acoustic energy. Because the source is mounted on a downslope, bottom-interacting sound is detectable, even at basin-scale ranges. Since the bottom material in this vicinity is expected to be volcanic basalt, the conversion of acoustic energy into elastic shear waves can impact the losses incurred upon bottom reflection. Simulations using equivalent fluids to represent the reflection properties of the elastic solid are used in an inversion to estimate the elastic properties of the local seafloor. Based upon experimental data taken at a range of 3.59 km, the bottom material can be represented with a density of 1500 kg/m^3, a compressional speed of 2700 m/s and a shear speed of 1500 m/s. Simulations using these paraemters are also compared to data for receptions at ranges of 11.5 and 21 km.The results were written up in a paper and submitted to JASA[1] with authorship: Heaney, Vera and Baggeroer, title: "*Geoacoustic inversion for volcanic seafloor using an equivalent fluid*".

Dr. Heaney began modeling basin scale acoustic propagation in an attempt to reproduce the Heaney, Kuperman and McDonald[2] results of 1991 "Perth-Bermuda sound propagation (1960): An adiabatic mode interpretation". Recently Dushaw[3] presented a rebuttal of this argument stating that adiabatic mode theory was insufficient to explain the results. Modern computational power is such that the full ocean 3D model can be addressed using broadband, horizontal mode-PE computations based upon Collins[4].

Dr. Heaney attended the NPAL 08 workshop in Borrego Springs in March. Dr. Heaney has also been involved in talks with Peter Worcester (SIO), Arthur Baggeroer (MIT), and Gerald L. D'Spain (SIO) in preparation for the upcoming PhilSea09 sea test, scheduled for May 2009.

RESULTS

The resulting geo-acoustic inversion for the Kermit-Roosevelt seamount structure, using the method outlined above (beam-time series data, model-data comparison) is shown in Fig. 3 below. This indicates that there is at least 50m of sediment, more likely 100-200m. The resolution of the approach prohibits determining if the sediment is very thick.

The effective fluid (with a complex density) approach to modeling shear using a standard Parabolic Equation technique was applied to the downslope propagation measurements taken off of Kauai during the BASSEX04 test. Rather than go through the entire method in this summary, we present a comparison of measured vs. modeled impulse response at a range of 20 km. The measured vs. modeled time series is shown in Fig. 4. This data was not used in the inversion, but is presented as an independent check of our results.

IMPACT/APPLICATIONS

The success of passive anti-submarine warfare in deep water depends critically on an understanding of the signal (direct source-receiver propagation) and the spatial extent of the ambient noise field. To this end, an quantitative understanding of the spatial structure of the ambient noise field will help facilitate the development of array apertures that optimize weak signal detection. The work of the Towed Array Tomography will possibly lead to a synoptic in-situ oceanographic measurement tool, which can measure ocean variability, upgrade dynamic ocean forecast models and lead to more accurate acoustic propagation input to sonar performance modeling.

RELATED PROJECTS

OASIS Inc. is currently not working on any related projects.

REFERENCES

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3. Dushaw, B.D., *Another look at the 1960 Perth to Bermuda long-range acoustic propagation experiment.* Geophysical Research Letters, 2008. **35**(L08601).

4. Collins, M.D., *The adiabatic mode parabolic equation.* Journal of the Acoustical Society of America, 1993. **94**(3): p. 2269-2278.

FIGURES

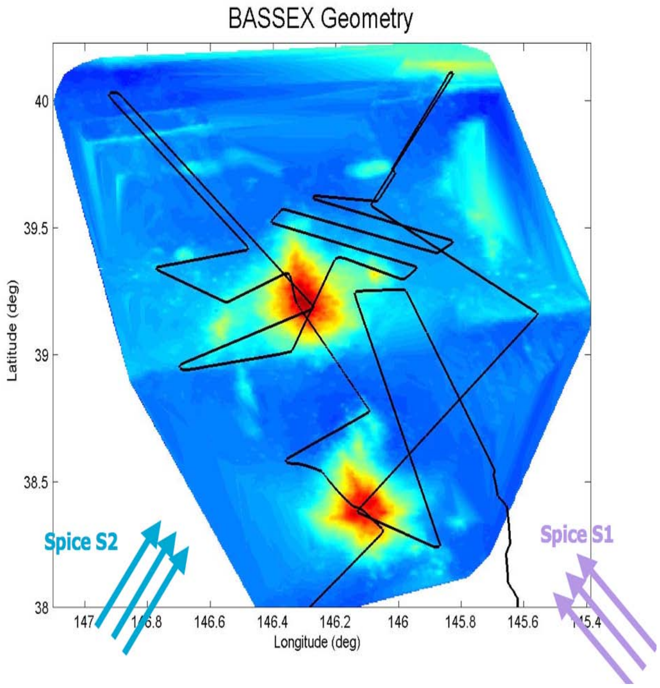

Figure 1. R/V Revelle GPS track during BASSEX04 experiment overlayed on the measured multi-beam bathymetry near the Kermit-Roosevelt seamounts. The relative positions of SPICE sources S1 and S2 are shown.

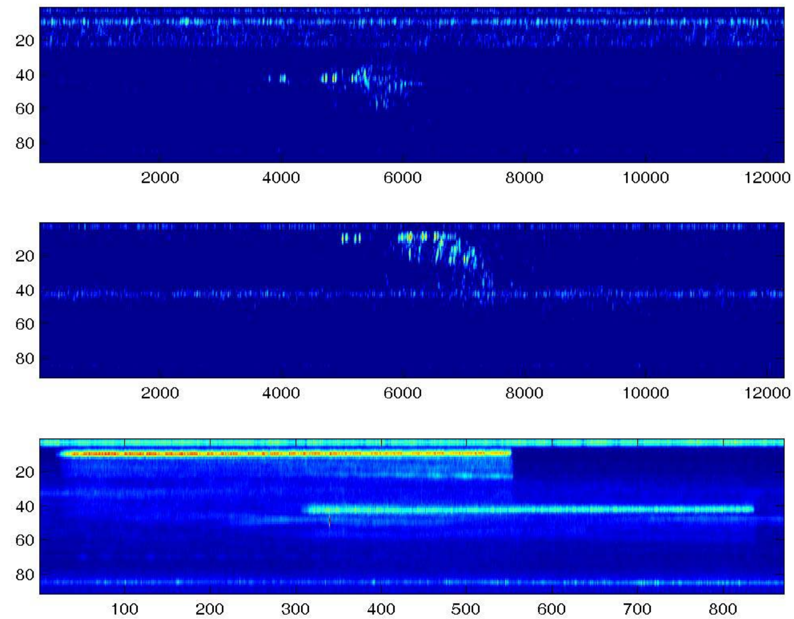

Figure 2. Processed results from reception jd264203233Spice, directly above the Kermit Seamount. The upper panel is the Bearing Time Record. Note thstrong arrival of S2 source, the later arrival of the S1 source at forward end-fire and the ownship noise. The central panel is the beam-time impulse response for the S2 source. Note the late arrival at 90 degrees, presumably sound coming directly up from the seamount below. The lower panel is the impulse response for the peak beam (52 degrees) for S2.

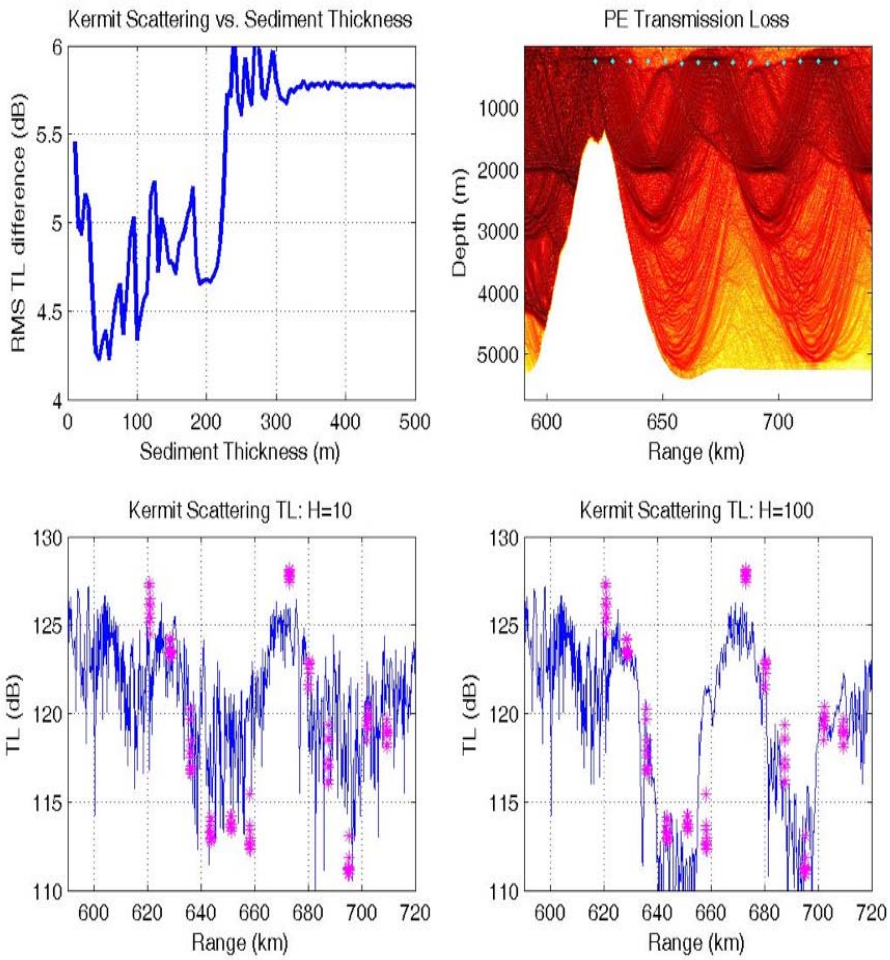

Figure 3. Inversion results for Day 264 transmission, moving towards S1 from behind Kermit-Roosevelt Seamount. In the upper right panel the RMS TL difference (cost-function) is shown. The upper right panel shows the modeled TL and the locations of receptions. The lower panels are data-model comparisons for 10m and 100m sediments. The 100m sediment matches the depth of both the primary and secondary shadows.

QuickTime™ and a
decompressor
are needed to see this picture.

Figure 4. Comparison of measured (green) and modeled (red) impulse response 20 km downslope from the Kauai NPAL source. The first two arrivals are both bottom interacting (first order and second order respectively). Later arrivals are not well modeled and have hit the bottom at least 3 times.