Shallow Water Propagation

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LONG-TERM GOALS

Develop methods for propagation and coherence calculations in complex shallow water environments, determine their capabilities and accuracy, and apply them for modeling and understanding data.

OBJECTIVES

(A) Treat propagation from narrowband and broadband sources over elastic and poro-elastic sediments, and incorporate realistic bathymetric, topographic, and geoacoustic variations.

(B) Analyze and interpret acoustic data, quantify effects of random environmental and experimental variability, and compare predictions of field statistics for intensity and coherence.

APPROACH

(A) Develop efficient and accurate parabolic equation (PE) techniques for applications involving heterogeneous sediments. Treat range dependence and sediment layering by coordinate rotation and single scattering methods.   Benchmark results using data and calculations from other methods.

(B) Construct representations for ocean environmental and geoacoustic variability using data and parametric models. Perform acoustic field calculations with PE, normal mode, and perturbation methods.   Use computational results and data analysis to specify propagation mechanisms.

• Principal collaborators are: Rensselaer graduate students and recent graduates; Dr. Michael Collins (NRL) for model development; and Dr. William Carey (BU), Dr. Allan Pierce (BU), and Dr. James Lynch (WHOI) for data analysis and theoretical interpretations.

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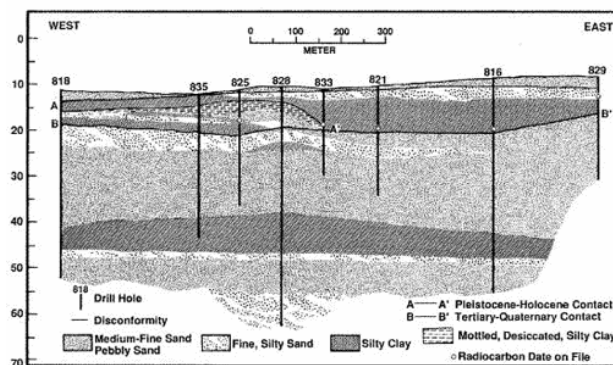Prescribed by ANSI Std Z39-18

WORK COMPLETED

(A) A major improvement in solving ocean seismo-acoustic propagation problems is achieved with the first method [1] capable of handing range dependent bathymetry and variable thickness sediment layers. One foundation [2] of the new method resolves the long standing problem of finding accurate and efficient solutions for ocean seismo-acoustic problems with range dependent bathymetry, by using a PE approach with coordinate rotations at locations of slope changes. Its other foundation is a treatment of range dependent sediment interfaces with large changes in slopes and elastic properties [3], for which the single scattering approximation produces accurate results efficiently for cases of purely seismo-acoustic propagation. An earlier technique, using a coordinate transformation to handle large variations in bathymetry and interface depths when the rate of slope changes is small [4], provides insight into the relative significance of environmental features. Moreover, the mapping technique is valuable in providing accuracy benchmarks [5] for problems to which both procedures are applicable. Important additional benchmarking for the new method is obtained from the excellent agreement in comparisons with high resolution laboratory data from propagation over a range dependent elastic slab [6]. An improved solution for the single scattering approximation, which is an essential component of the new method, is now known [7] to be free of the iteration requirements of earlier versions. Another technique allows increased efficiency for kHz frequencies [8] by combining two previous split-step algorithms for calculations in environments with relatively small parameter variations. The first propagation model that has range dependent capabilities for transversely isotropic poro-elastic sediments [9] demonstrates the effects of these environmental features. Vector intensity and acoustic particle velocity can be efficiently calculated with PE methods [10], which are useful to describe the parameter dependence of these fields.

(B) Evidence is summarized for nonlinear frequency dependence of the intrinsic upper sediment attenuation for compressional waves in shallow water waveguides with sandy bottoms [11], with emphasis on the critical role of depth dependence in acoustic and geoacoustic parameters. A re-examination of data from two earlier New Jersey shelf experiments near the SW06 site [12] shows that the frequency power-law exponent of the attenuation is about 1.85, rather than 1.5 as reported earlier using a different methodology. An extended analysis with additional data [13] confirms how the attenuation depth profile and power-law exponent, along with features of the bathymetry and water sound speed profiles, control the accuracy of propagation calculations at middle frequencies. The influence of range dependence on these conclusions is an important issue, and recent work [14] verifies that the results are robust with respect to the measured environmental variability. Incorporation of the nonlinear frequency dependence is also essential for close agreement [15] between data from a 1992 New Jersey AGS experiment and calculations of broadband intensity variations due to geoacoustic uncertainties. Modal attenuation coefficients that include nonlinear frequency dependence demonstrate significant sensitivity to downward refracting water profiles [16], and in particular are qualitatively different from those for the Pekeris waveguide. Corresponding differences arise using a parametric description of simple shallow ocean waveguides, developing analytical expressions for modal attenuation coefficients, and examining their frequency behavior [17]. Calculated modal attenuation coefficients compare well with data from the Gulf of Mexico, and a new connection is demonstrated [18] between modal and effective attenuation coefficients. Other modal calculations, of transverse coherence lengths using data from the ACT III experiment in the Strait of Korea [19], show strong horizontal variations when the environmental correlation functions have anisotropy or heterogeneity as a result of processes such as internal waves. Interference patterns arising from adiabatic modal interactions at small incident angles with wave fronts of internal solitons are modeled well [20] by treating the mechanism as a horizontal Lloyd mirror. In contrast, three-dimensional calculations show

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that horizontal mode coupling arises during propagation through two or more interacting soliton wave fronts [21], depending on the soliton strengths, orientations, and coherence lengths. A procedure for obtaining two-term perturbation approximations for mode shape functions and corresponding wave numbers for a class of downward refracting sound speed profiles [22] allows construction of parametric formulas for mode dependent quantities such as attenuation coefficients. An improved approach for the same types of waveguides [23] permits simpler mode approximation formulas with a larger parameter region of validity.

RESULTS (from two selected investigations)

(A) Ocean acoustic data analysis and applications require accurate and efficient calculation of propagation in shallow water waveguides including range dependent elastic sediments. Such problems are more challenging than modeling the sediment as a fluid because energy is distributed over a much broader wave number spectrum. Their solutions are also necessary to evaluate mechanisms of shear energy generation and propagation and to direct the development of methods for poro-elastic and other complex sediments. Our new procedure [1] has evolved from a series of advances: a PE formulation using non-traditional dependent variables; a technique using coordinate rotations at ranges where changes in bathymetry slope occur; single scattering corrections at stair-step approximations of sediment interfaces and elastic parameter variations; and an efficient iteration procedure for realistically large elastic parameter and slope changes. Successful tests of the method include excellent comparisons [6] with high fidelity data obtained from measurements of propagation over an elastic slab in an NRL water tank. The capabilities of the method for shallow water problems are illustrated in **Figure 1**. The upper panel illustrates complicated stratigraphy and sediment structure at the New Jersey coastal AGS site on one acoustic track, along which a University of Delaware experiment was conducted and detailed core profiling was available. The middle panel shows 50 Hz transmission loss contours for the sediment modeled by just two homogeneous layers, with the selection of elastic parameters detailed in [1]. The bottom panel contours are obtained for the sediment modeled by eight homogeneous layers and stratigraphy constructed to correspond closely to the upper panel. The acoustic energy patterns in the two contour figures are sharply different, not only in the sediments but also in the water. We conclude from these and other results that our new propagation approach provides the necessary capabilities for efficient and accurate propagation calculations in shallow water waveguides with range variations in elastic sediment structure and layering.
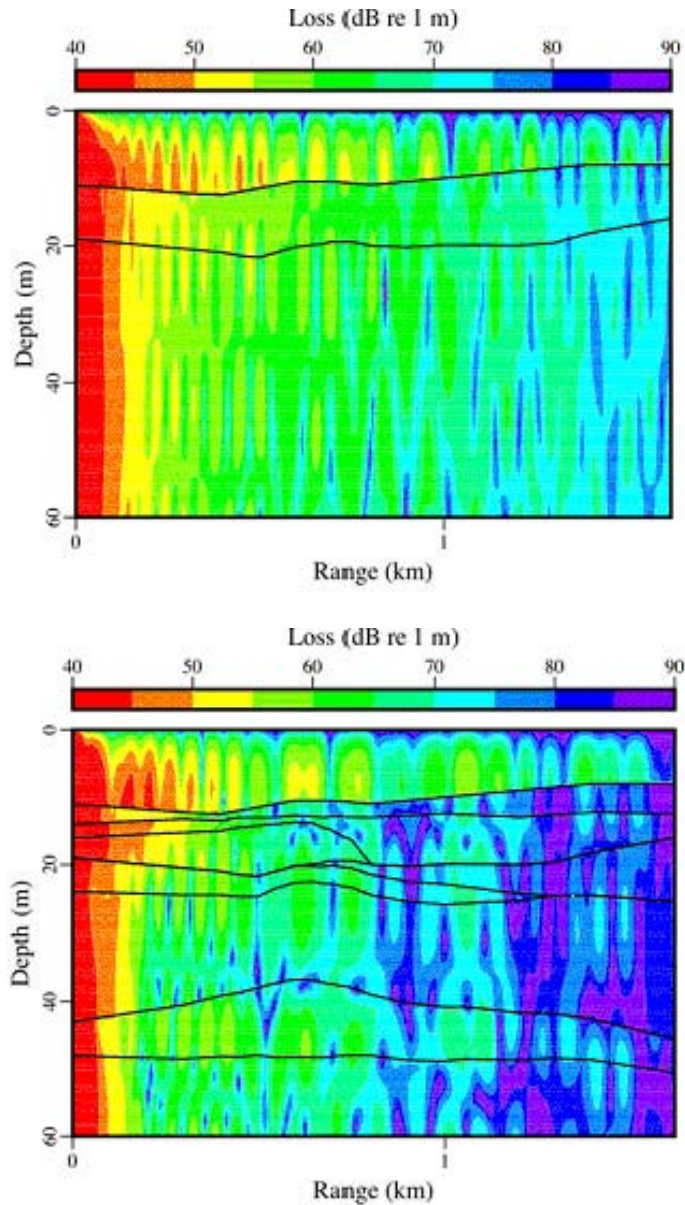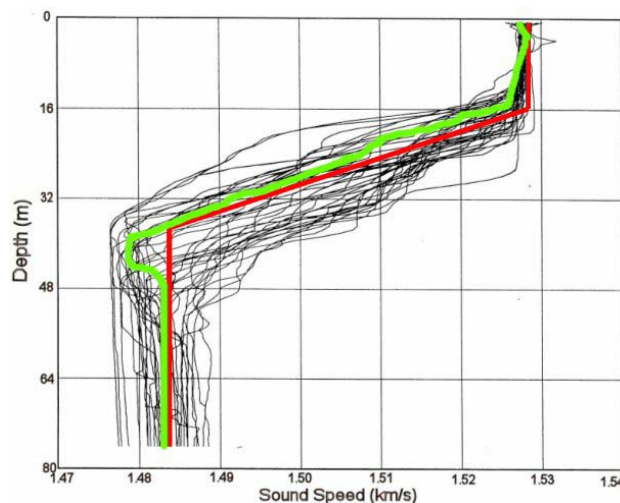
Figure 1. ***Propagation in waveguides over range dependent elastic sediment layers is handled accurately and efficiently by a new PE approach using coordinate rotations and single scattering corrections. Upper panel: Schematic shows multiple structurally distinct and range dependent layers in 50 m of sediment, below about 10 m of water at the New Jersey AGS site (courtesy Dr. M. Badiey). Vertical lines indicate borehole locations.   Middle panel: Color contours are transmission loss between 40 and 90 dB (re: 1 m) over 60 m depth and 1.6 km range for a 50 Hz source at 5 m. The sediment model has two homogeneous elastic layers with range dependent interface and bathymetry.   Considerable energy propagates in the water and the top sediment layer.   Lower panel: Corresponding contours when the bottom model has eight homogeneous elastic layers with range dependence based closely on the schematic. Considerably less energy propagates in the water and the sediment layer in this case. Realistic range dependent elastic sediment layer structure can significantly affect propagation in shallow water waveguides.***

(B) The intrinsic sediment attenuation in shallow water waveguides is a critical quantity for propagation predictability at low to medium frequencies. Our current interest is in ocean environments with sandy-silty sediments, moderately small bathymetry variations, and typical water volume range dependence. The frequency behavior of the intrinsic attenuation is anticipated from Biot theory to have a power-law behavior with exponent 2 for middle frequencies. Results from several procedures over many experimental sites [11] suggest that the power-law exponent is consistently about 5 to 15% lower than 2. An explanation of the mechanism for this striking behavior has recently been formulated by our BU colleagues. In a coordinated effort, a procedure is developed for estimating the power-law exponent and is used for extensive sensitivity investigations. The most useful metric for the procedure is an effective attenuation coefficient (EAC) for the reduced transmission loss, which is the slope of the linear least squares fit of suitable range and depth averages of measurements or PE calculations. For the 1988 New Jersey Shelf and 1993 ACT II experiments, estimates of exponents and surface attenuation values are in the ranges [1.8, 2.0] and [0.33, 0.35 (dB/m)] . Because these estimates rely on EAC values, it is essential to examine the sensitivity of the metric to variations in water sound speed profiles, bathymetry, and other parameters [14]. For example, **Figure 2** shows all measured water profiles for ACT II, along with a representative composite profile C (red) and the profile 64 (green) which is closest to the source location. As expected profile C provides very good comparisons between measured and calculated EACs, and profile 64 does nearly as well. A sample of six profiles from one run along one experimental track is shown in the middle panel. EACs calculated using either all six of these profiles or their average profile S (blue) compare poorly with measurements. We conclude from these and related calculations that the selection of a representative water profile is important for estimates of sediment attenuation parameters, while moderate range dependence in profiles and bathymetry is not.
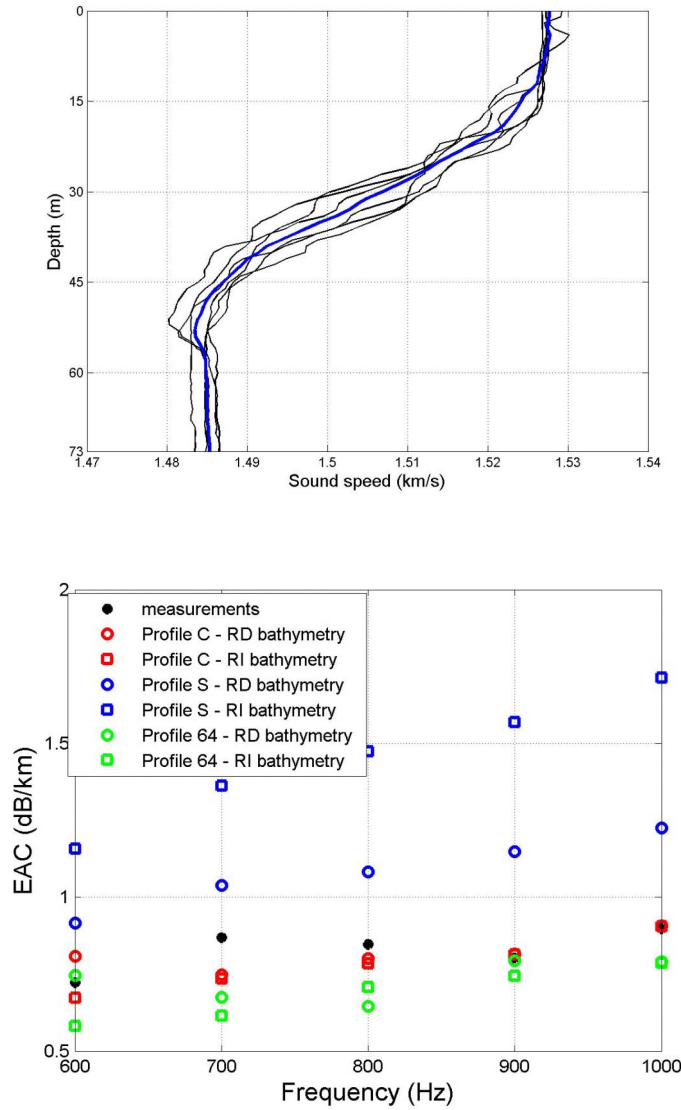
Figure 2*. An effective attenuation coefficient (EAC) metric for overall transmission-loss decrease is tested for sensitivity to water sound speed profiles and bathymetry, in regions of sandy-silty sediments and moderate range dependence. **Upper panel**: Measured profiles (black) over 73 m depth and 1475 to 1530 m/sec from the 1993 ACT II experimental site, a composite profile C (red) that represents the principal thermocline feature from 16 to 36 m, and the profile 64 (green) that is nearest the source location. **Middle panel**: Sample of six measured profiles (black) for one experimental run and their depth average profile S (blue). Among all measured profiles, the sample profiles have deep thermoclines. **Lower panel**: EACs in dB/km for five experimental frequencies from 600 to 1000 Hz. EACs from measurements (black) compare well with calculations using profiles C (red) or 64 (green) and either range dependent or range independent average bathymetry. EACs from measurements generally do not compare well with calculations (blue) using profile S or (not shown) the range dependent sample. At middle frequencies the EAC metric is sensitive to the average water profile and insensitive to moderate range dependence in water profiles and bathymetry.*

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IMPACT/APPLICATIONS

New capabilities for handling physical properties of shallow water sediments, including layering, elasticity, porosity, and anisotropy, are available for propagation predictions. Range dependent variability in bathymetry, topography, and sediment layer interfaces can be treated accurately in calculations. Intensity and coherence statistics that result from environmental fluctuations and experimental variability can be found efficiently. Data analyses and comparisons allow specifying for experimental and application purposes the relative significance of key physical mechanisms: linear versus nonlinear frequency dependence of sediment attenuation, water column versus bathymetric variability, sediment heterogeneity versus homogeneity, and vertical versus horizontal mode coupling due to internal solitons and bathymetry. Results from modeling and data analyses of experiments, including several New Jersey Shelf experiments and the ACT series, are directed partly toward improving shallow water sonar systems and predictions. New propagation model implementations, analysis tools, and data representation techniques are distributed to university, laboratory, and research and development groups.

RELATED PROJECTS

• Ongoing work with Dr. Michael Collins includes completion of a research monograph on parabolic wave equation models and applications [24], for which the critical research issues are resolved. Benchmark calculations [25] verify the accurate and efficient performance of propagation models for low frequency range dependent problems in elastic media. These results follow an earlier formulation [26] of challenging seismo-acoustic test problems.

• Other investigations with Dr. James Lynch, Dr. Mohsen Badiey, and their colleagues are concerned with influences of water column and sediment variability. For example, heterogeneous sediments with complex stratigraphy that occur in coastal regions produce cross-range acoustic effects [27].

• Additional research with Dr. William Carey and Dr. Allan Pierce examines predictability issues for narrowband propagation characteristics, including coherence scales and the frequency dependence of sediment attenuation. Analytical approximations that are useful for demonstrating parameter dependencies are developed for shallow water waveguide modes in thermocline conditions [28].

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PUBLICATIONS

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