Shallow-Water Propagation

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LONG-TERM GOALS

Develop propagation models and related methods for complex shallow-water environments, test their capabilities and accuracy, and apply them to understand experimental data.

OBJECTIVES

(A) Treat propagation from both narrowband and broadband sources over range-dependent elastic and poro-elastic sediments, and estimate the geoacoustic parameters.

(B) Find field statistics efficiently from stochastic propagation models, quantify effects of random environmental and experimental variability, and analyze data using model simulations.

APPROACH

(A) We develop high accuracy PE techniques, incorporating energy conservation and dispersive corrections, for isotropic and anisotropic sediments. Simulated annealing techniques are adapted for parameter inversions.

(B) We construct stochastic ensembles for geoacoustic and ocean variability employing data and empirical orthogonal function representations. Field calculations are performed using PE, normal mode, and perturbation methods.

- Principal collaborators are: Rensselaer graduate students and recent graduates; Dr. Michael Collins (NRL), for model development; and Dr. Mohsen Badiey (Delaware), Dr. William Carey (BU), and Dr. James Lynch (WHOI), for modeling and analysis of experimental data.

WORK COMPLETED

(A) We finished formulating and implementing a PE model [1] for propagation over poro-elastic sediments with transversely isotropic (TI) properties. This model extends our recent work for isotropic poro-elastic sediments, to which inversion procedures are being applied for estimating material parameters [2]. Results from our PE and wave number integration models for TI elastic sediments [3] show the influence of anisotropy on transmission loss and spectra. The directional

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dependence of wave speeds in a TI elastic medium was resolved for synthetic data [4] by taking advantage of a coordinate rotation procedure. We are developing a new PE formulation for layered elastic media [5] in order to increase prediction accuracy while maintaining high efficiency. New examples illustrate three-dimensional propagation in waveguides near islands and coasts [6] for which substantial variations occur in the effective thickness. We determined several influences of causal dispersion, which arises from frequency-dependent attenuation, on broadband signals that propagate over elastic sediments [7].

(B) We modeled narrowband and broadband transmissions from the ACT III experiment [8] by accounting for the frequency dependence of attenuation in the upper sediment. Additional model validation was obtained by comparisons with independent measurements [9] of signal gain and pulse signal spread. We performed new normal mode calculations to confirm our PE predictions that certain observed intensity fluctuations from AGS92 data are due to strong sediment sound speed variability [10]. Wave number statistics arising from variations in sediment layer depths and sound speeds have been calculated [11], using our efficient modeling approach for random ensembles, for AGS95 experimental tracks. We completed determination of broadband intensity fluctuations [12] for comparisons with data from all AGS92 experimental tracks. Internal wave influences on time-frequency diagrams and time variations of received intensity for one track of SWARM95 data were modeled by PE calculations [13]. Broadband transmission loss and its relationship to internal wave parameters are being investigated [14] along the same track.

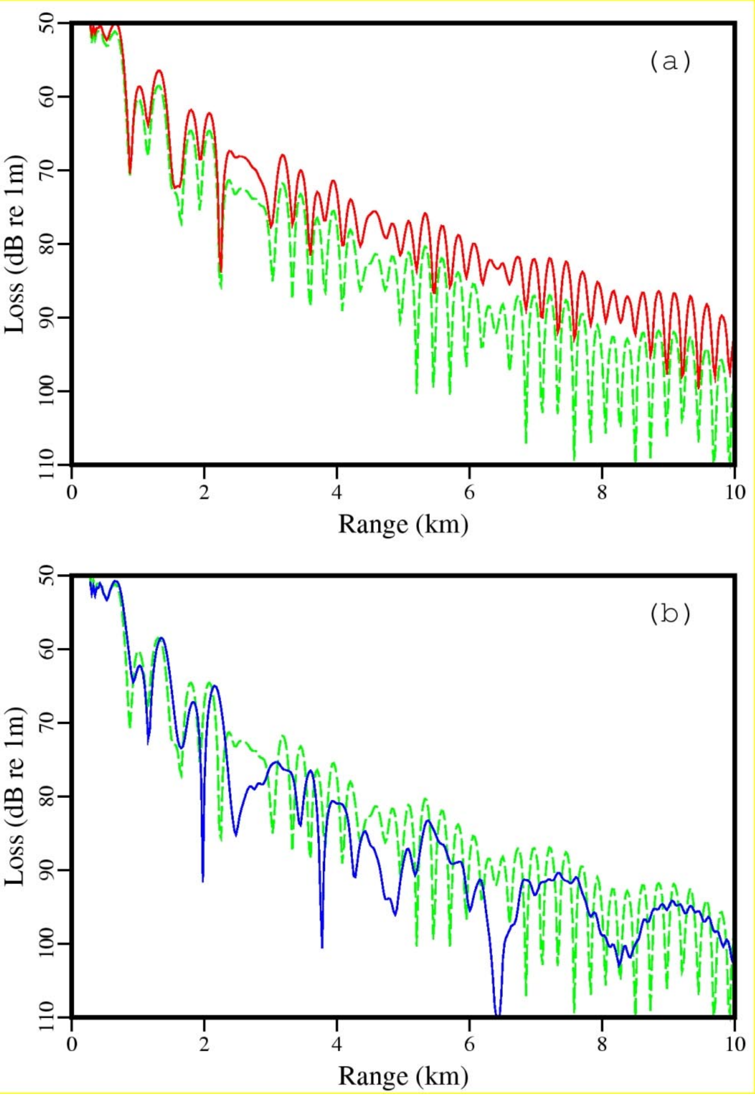
RESULTS(from three selected investigations)

- Since anisotropy is known to occur in many shallow ocean sediments, we constructed and tested a PE model for range-dependent propagation over transversely isotropic poro-elastic layers [1]. Such layers, which support three wave types, require specification of six speed values: three in the horizontal direction, $c_1(0)$, $c_2(0)$, and $c_3(0)$; two in the vertical direction, $c_1(\pi/2)$ and $c_2(\pi/2)$; and the extreme value $c_3(\theta_e)$. It is relevant for applications to know if any anisotropic environment has a corresponding "effective" isotropic one (requiring only three speeds $\hat{c}_1$, $\hat{c}_2$, and $\hat{c}_3$) that leads to essentially the same transmission loss patterns. From PE simulations and inversions, we conclude that an "effective" medium may not exist. Figure 1 shows loss curves from a TI environment and two isotropic candidates (one with wave speeds from the propagation direction, the other with speeds from direction averages) that are representative of the types of mismatches that occur.

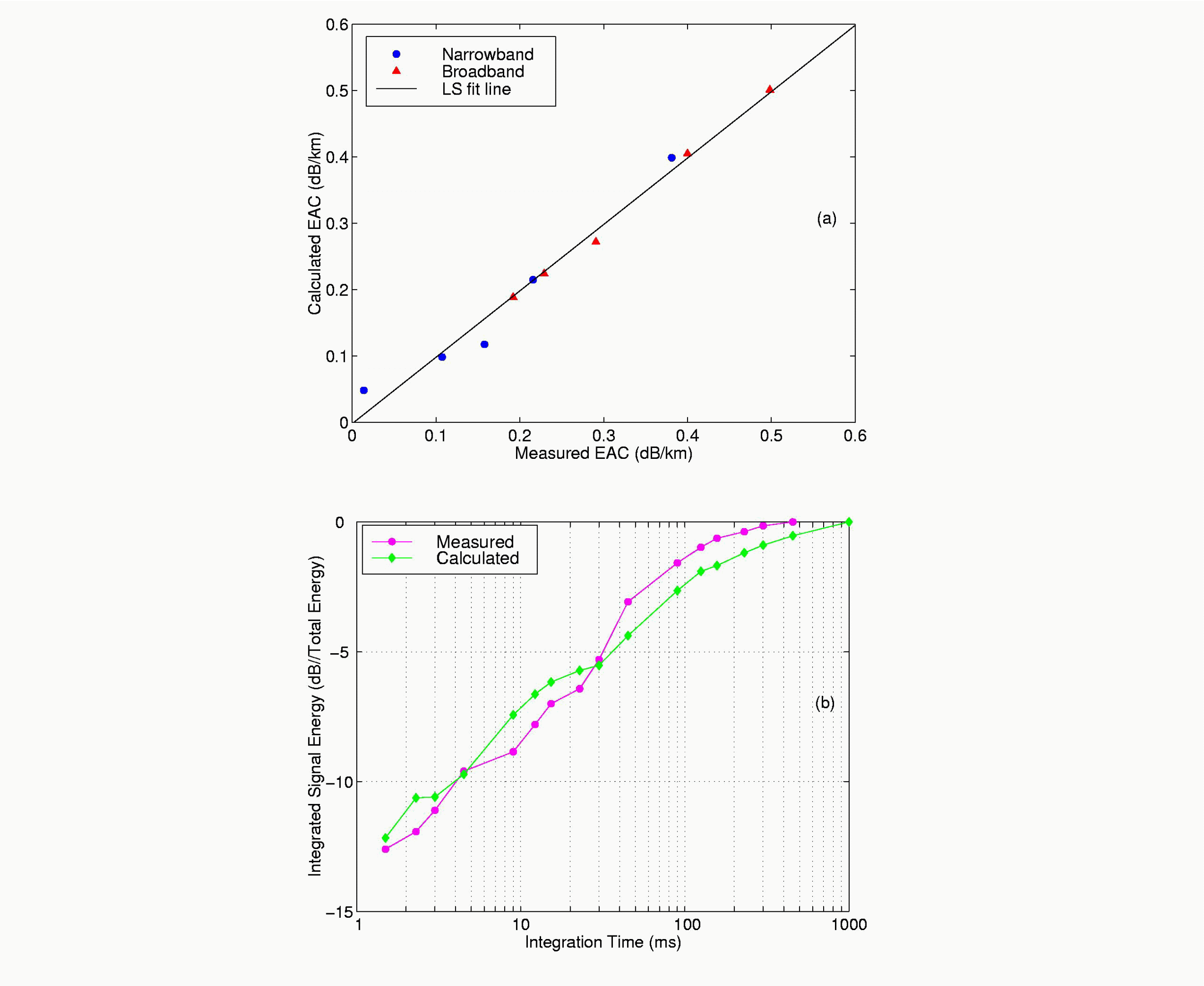
- Broadband sound can be significantly affected by the seabed in shallow regions such as the Strait of Korea. We modeled mean non-geometric transmission losses for five frequencies between 47 and 604 Hz in ACT III at that site. We employed a measurement based geoacoustic model, which was found to require nonlinear frequency dependence in the upper sediment layer attenuation [8]. The model was validated by comparing its predictions for a broadband source, over five intervals between 50 and 1000 Hz, with independent measurements. We demonstrated its effectiveness with additional comparisons using independent observations of signal time spread. Excellent agreement between simulations and data is shown in Figure 2. We conclude that our modeling procedures and evaluation criteria can produce a robust, site specific environmental model for analysis of other measurements including signal gain and coherence.

- Oceanographic variability is known to exert strong influences on shallow water propagation. Extensive internal wave activity at the SWARM95 site affects broadband transmissions from the

Delaware air gun source. We used PE simulations over two range-dependent tracks [13] that were populated by numerous internal solitary wave features, the locations of which were estimated from oceanographic observations. The model was applied first to comparisons with the geotime behavior of depth- and time-averaged intensity data along both tracks. More detailed comparisons between measured and simulated time-frequency diagrams revealed certain propagation patterns that are well accounted for by the model. We conclude from results such as those in Figure 3 that larger amplitude internal wave features produce acoustic variations in lower frequency bands that can be captured by propagation simulations.



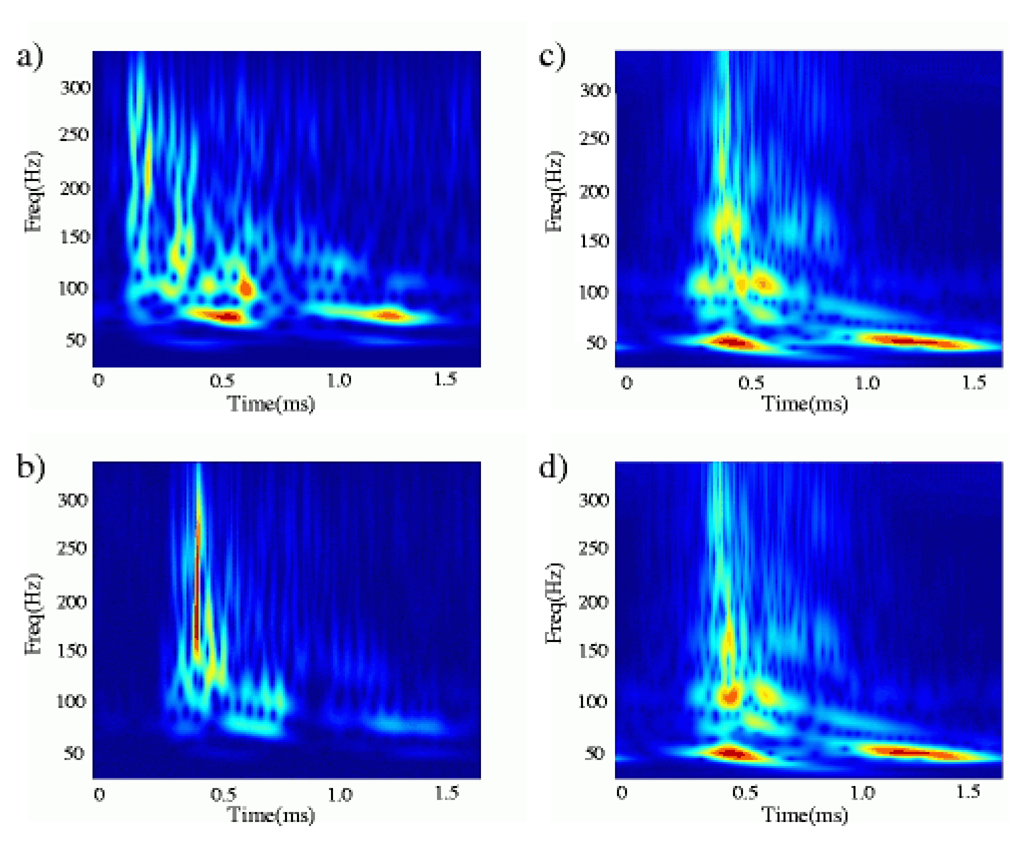
1. Environment A has water { c_w = 1500 m/s, d_w = 200 m } overlying a TI poro-elastic layer { [$c_1(0)$, $c_1(\pi/2)$] = [2050, 1950] m/s, [$c_2(0)$, $c_2(\pi/2)$] = [525, 475] m/s, [$c_3(0)$, $c_3(\theta_e)$] = [1000, 1050] m/s, [β_1, β_2, β_3] = [0.2, 0.8, 0.4] dB/λ, ρ = 1.5 gm/cm^3, τ = 0.25, porosity = 0.3 }, with f = 25 Hz, z_s = 195 m. (a) Transmission loss for A (dashed green) and an "effective" isotropic { $\hat{c}_1$ = 2050 m/s, $\hat{c}_2$ = 525 m/s, $\hat{c}_3$ = 1000 m/s } environment B (solid red) that produces nearly the same interference pattern but significant level differences. (b) Transmission loss for A and an "effective" isotropic { $\hat{c}_1$ = 2000 m/s, $\hat{c}_2$ = 500 m/s, $\hat{c}_3$ = 1020 m/s } environment C (solid blue) that produces lower level values than B but a different interference pattern from A. An "effective" isotropic poro-elastic medium that produces transmission loss results of an anisotropic medium need not exist.



2. Comparisons between measurements, at three different arrays from Run A-TL-1 of ACT III in the Strait of Korea, and PE simulations at range 20 km. Environmental input uses SSP and bathymetry data, along with a core based, four-layer geoacoustic model. The upper sediment layer attenuation has dependence on frequency to the power 1.8. (a) Scatter plot of Effective Attenuation Coefficients, which measure mean non-geometrical transmission loss, for five cw signals (blue) between 47 and 604 Hz and five broadband intervals (red) between 50 and 1000 Hz. The linear least squares fit has slope 1.001. (b) Integrated signal energy from received time series versus integration time, for data (magenta) and simulations (green). Excellent agreement is obtained between the environmental model with nonlinear sediment attenuation and three independent data sets.

IMPACT/APPLICATIONS

New or improved capabilities for handling sediment material properties, including porosity, anisotropy, and dispersion, will be available for propagation predictions. Efficient specification of field statistics arising from environmental fluctuations and experimental variability will be possible. Enhanced inversion procedures will allow improved estimates of parameters specifying properties such as coherence lengths and geoacoustic anisotropy. Data analyses and comparisons will assist in appraising the influences of physical mechanisms in experiments and applications.



3. Time-frequency diagrams of received intensity (increasing from dark blue to red), from the air gun source for the Hatteras-NRL/VLA SWARM95 track, and PE simulations at range 18 km. Environmental input uses measured SSPs and bathymetry, estimated geoacoustic profiles, and solitary wave features with locations estimated from oceanographic data. Measurements, (a) at a reference time and (b) 7 min later, first show signal spreading in time and then show compression. For example, the arrival near 100 Hz in (a) appears earlier than in (b). Simulations (c) and (d) at corresponding times contain similar spreading and compressing patterns. The arrival concentration near 100 Hz changes its temporal position as in the data. By using oceanographic observations, simulations can model certain principal features of the acoustic arrivals.

TRANSITIONS

Results have been used for modeling and data analyses of several series of experiments (HCE, AGS, ACT, SWARM) that are directed in part toward improving sonar systems and predictions in shallow water. Implementations of new propagation models and interpolation techniques have been distributed.

RELATED PROJECTS

- Additional research with Dr. Michael Collins includes derivation of a wave number spectral solution [15] that conserves energy at interfaces between range independent regions, incorporation of mean horizontal flows [16] into a PE model for internal gravity waves, and an unexpectedly complicated generalization of that model [17] for treating wide-angle propagation.

- Continuing research with Dr. William Carey involves applications to additional data [18] of recent results on propagation and coherence modeling in shallow water waveguides [8], [9].

- Ongoing research with Dr. Mohsen Badiey and Dr. James Lynch includes demonstrating that heterogeneous coastal sediments can cause azimuthally coupled propagation [19], and specifying the influences of nonlinear internal waves on broadband propagation [20] in conjunction with continuing modeling and analysis of experimental observations [13], [14].

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PUBLICATIONS

- Published: [3], [15], [16]
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