

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 and model experimental data.

OBJECTIVES

- (A) Treat propagation from narrowband and broadband sources over range-dependent elastic and poro-elastic sediments, and estimate relevant geoacoustic parameters.
- (B) Determine field statistics efficiently from stochastic propagation models, quantify effects of random environmental and experimental variability, and analyze data using model simulations.

APPROACH

- (A) Develop high accuracy, energy-conserving PE techniques for applications to shallow-water sediments with dispersion and anisotropy. Adapt simulated annealing techniques for sediment parameter inversions. Benchmark results using independent solution methods.
- (B) Construct stochastic ensembles for geoacoustic and ocean variability using data and empirical orthogonal function representations. Perform field calculations with PE, normal mode, and perturbation methods. Test model predictions using independent data sets.
- (C) Principal collaborators are: Rensselaer graduate students and recent graduates; Dr. Michael Collins (NRL) for model development; and Dr. William Carey (BU), Dr. Mohsen Badiy (Delaware), and Dr. James Lynch (WHOI) for modeling and analysis of experimental data.

WORK COMPLETED

- (A) For elastic sediments we derived a new PE formulation [1] that unlike any predecessor handles layered environments accurately and efficiently while remaining numerically stable. This formulation, based on different computational variables, can treat range dependent sediments and properly account for energy conservation [2]. We demonstrated additional properties and advantages of the new method [3], including results for seismic sources and for complex environmental variations. We showed significant propagation effects of causal dispersion that arises from frequency-dependent attenuation [4] for some broadband signals in elastic sediments.

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Our PE formulation has a close connection to one that we developed [5] for handling propagation over elastic sediments with transversely isotropic (TI) geoacoustic properties. We obtained additional results for resolving the directional dependence of wave speeds in layered TI elastic sediments from synthetic wave number data [6]. Computations were performed for a variety of examples of TI poro-elastic sediments [7] in order to illustrate influences of anisotropy on transmission loss and wave number spectra.

- (B) By modeling upper sediment layer attenuation with nonlinear frequency dependence, we were able to simulate key features of four independent sets of narrowband and broadband data from one leg of the ACT III experiment [8]. Further validation of our oceanic and geoacoustic models followed from comparisons [9] with independent measurements including signal gain along another leg. Additional normal mode calculations confirmed our PE predictions [10] that intensity fluctuations observed in some AGS92 data arise from substantial sediment sound speed variability. For AGS95 data we completed determination of wave number statistics arising from sediment layer depth and sound speed variability [11], by taking advantage of an efficient simulation approach for random ensembles. Accurate modeling of broadband intensity fluctuations for all AGS92 experimental tracks also requires a nonlinear frequency dependence of sediment attenuation [12]. Connections between variability in broadband transmission loss and internal wave parameters were illustrated [13] for two tracks of SWARM95 data using PE simulations. The sensitivity of our results to geoacoustic layer structure and source variability is being investigated [14], along with the correlations between thermal and intensity variations.

RESULTS (from two selected investigations)

- The efficient treatment of layered elastic sediments has been a critical unsolved problem for PE model development. These environments are clearly important in shallow water and must be accurately handled as the basis for extensions to more complicated bottoms that include range dependence, poro-elasticity, and other physical mechanisms. Our new formulation [1] resolved this problem by using different dependent variables and the same efficient and reliable numerical schemes as in fluid bottom models. The formulation accommodates all physical conditions at layer interfaces and is able to avoid stability difficulties that arise in other approaches. From our testing and benchmarking we conclude that it possesses the right characteristics for the needed extensions. **Figure 1** illustrates results from an initial implementation. Comparing the top two contour plots shows the changes produced by a waveguide in an elastic sediment, and the bottom plot demonstrates that this method, unlike other PEs, can treat seismic sources.
- A fundamental issue for broadband propagation is the type and amount of environmental data that is required for useful estimates of quantities such as averaged transmission loss, signal gain, and coherence. Particularly important in shallow water are the robustness of predictions and critical parameter sensitivities. For the Strait of Korea we developed a geophysically based, four layer geoacoustic model using one set of transmission loss data from one ACT III experimental leg. PE predictions using this model, which parameterizes nonlinear frequency dependence of the upper sediment layer attenuation, agree well with other data from the same leg. New simulations using it and available SSPs and bathymetry were compared with independent broadband and narrowband data from a distinct but nearby leg of the same experiment [9]. **Figure 2** shows the excellent agreement obtained. We conclude that robust, site-specific environmental models are feasible for average loss predictions if nonlinear frequency dependence of sediment attenuation is permitted.

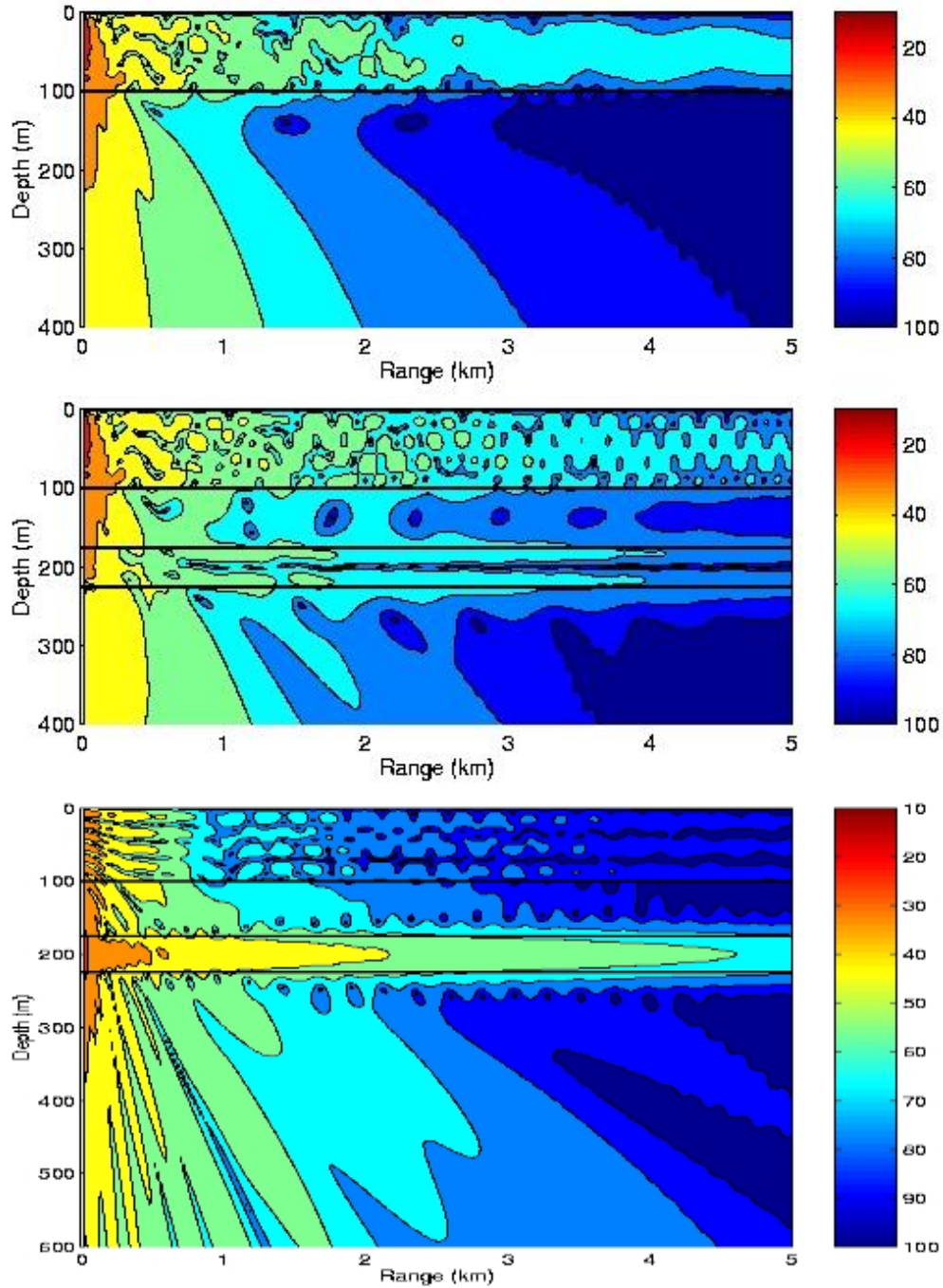


Figure 1. Ocean propagation can be affected by layered elastic sediments, which are treated accurately and efficiently by our new PE formulation. Transmission loss contours (to 5 km range and at least 400 m depth) for source frequency 25 Hz are shown for a shallow ocean ($c_w = 1500$ m/s, $d = 100$ m) overlying an elastic sediment. Top: Sediment is an elastic half space ($c_p = 1900$ m/s, $c_s = 900$ m/s, $\rho = 1.3$ gm/cm³), and source depth $z_s = 10$ m. After 2.5 km the water column energy is mainly in the lowest mode. Middle: A low speed layer ($c_p = 1600$ m/s, $c_s = 700$ m/s) is sandwiched in the elastic half space between 175 and 225 m. Substantially higher energy (up to 20 dB) propagates in the elastic waveguide. Multiple modes still propagate in the water at 5 km. Bottom: Same layered environment with $z_s = 200$ m. The new formulation applies for seismic sources, with energy strongly channeled into the elastic waveguide.

IMPACT/APPLICATIONS

New or improved capabilities for treating sediment physical properties, including elasticity, porosity, anisotropy, and dispersion, will be available for propagation predictions. Efficient specification of intensity and coherence statistics resulting from environmental fluctuations and experimental variability will be feasible. Enhanced inversion procedures will allow better estimates of parameters that influence oceanic and geoacoustic correlation lengths. Data analyses and comparisons will permit appraising effects of mechanisms such as sediment attenuation frequency dependence, both for understanding experimental results and for applications.

TRANSITIONS

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

RELATED PROJECTS

- Additional research with Dr. Michael Collins includes derivation and implementation of a PE model for internal gravity waves that includes mean horizontal flows [15] and major extensions of that model to handle both wide-angle propagation [16] and strong flows [17].
- Ongoing research with Dr. William Carey concerns signal gain and coherence modeling in the Strait of Korea waveguide [18] and additional investigations of predictability of range averaged broadband propagation properties [19].
- Continuing research with Dr. Mohsen Badiy and Dr. James Lynch includes new calculations that show how heterogeneous coastal sediments cause azimuthally coupled propagation [20] and that demonstrate correlations between field coherence and internal solitary waves [21].

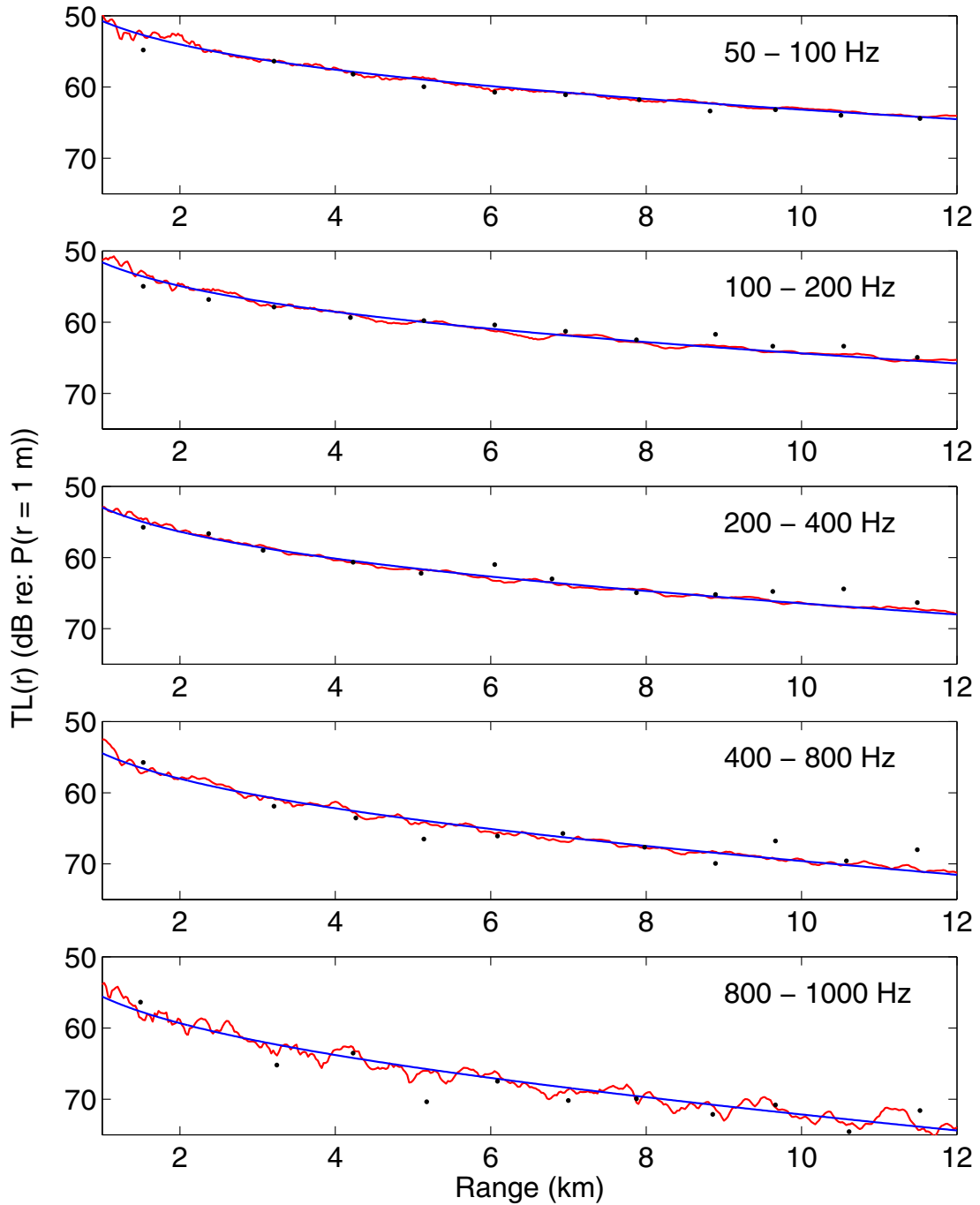


Figure 2. Shallow water propagation can be modeled across frequency bands when limited critical oceanic and geoacoustic information is available. Each of the five plots shows transmission loss versus range (to 12 km) for Leg 3 at Site 1 of ACT III in the Strait of Korea, averaged over a frequency band (50-100, 100-200, 200-400, 400-800, and 800-1000 Hz). Dots (roughly every km) represent experimental data. PE simulations (red curves) are obtained using available SSP and bathymetry data and a geoacoustic model developed previously for another experimental leg. The upper sediment layer attenuation depends on frequency to the 1.8 power. Fits to the simulations based on cylindrical spreading plus linear effective attenuation (blue curves) are included. For all five frequency bands, the agreement shown between experimental data and calculated results is excellent. Similar agreement is obtained between independent narrowband data for five frequencies and corresponding simulations, provided the nonlinear sediment attenuation is retained.

REFERENCES

- [1] W. Jerzak, W. L. Siegmann, M. D. Collins, and J. F. Lingeitch, "A new stable formulation of an elastic parabolic equation," (A) J. Acoust. Soc. Am. **108**, 2562 (2000).
- [2] W. Jerzak and W. L. Siegmann, "New parabolic equations for layered elastic media," Sixth SIAM Conf. on Math. and Comp. Issues in Geosciences, June 2001.
- [3] W. Jerzak, M. D. Collins, R. B. Evans, J. F. Lingeitch, and W. L. Siegmann, "Parabolic equation techniques for seismic waves," accepted for publication in J. Pure and Applied Geophysics.
- [4] W. Jerzak, W. L. Siegmann, R. S. Kulkarni, and M. D. Collins, "Attenuation and dispersion in pulse propagation over an elastic sediment," in preparation [see also (A) J. Acoust. Soc. Am. **106**, 2225].
- [5] A. J. Fredricks, W. L. Siegmann, and M. D. Collins, "A parabolic equation for anisotropic elastic media," Wave Motion **31**, 139-146 (2000).
- [6] A. J. Fredricks, W. L. Siegmann, M. D. Collins, and J. F. Lingeitch, "Estimation of anisotropic sediment parameters," in preparation [see also (A) J. Acoust. Soc. Am. **106**, 2132].
- [7] A. J. Fredricks, W. L. Siegmann, and M. D. Collins, "A parabolic equation for anisotropic poro-elastic media," submitted for publication.
- [8] I. Rozenfeld, W. M. Carey, P. G. Cable, and W. L. Siegmann, "Modeling and analysis of sound transmission in the Strait of Korea," J. Ocean Eng. **26**, xxx-xxx (2001).
- [9] I. Rozenfeld, W. M. Carey, P. Cable, and W. L. Siegmann, "Measurement based modeling for narrowband and broadband propagation," (A) J. Acoust. Soc. Am. **108**, 2577 (2000).
- [10] M. Jaye, M. Badiy, and W. L. Siegmann, "Geoacoustic profile estimation using empirical orthogonal functions," J. Ocean Eng. **26**, xxx-xxx (2001).
- [11] M. J. Longfritz, W. L. Siegmann, M. Badiy, and M. J. Jacobson, "Estimating horizontal wave number variations in stochastic shallow-water channels," submitted for publication.
- [12] M. Jaye, W. L. Siegmann, and M. Badiy, "Broadband propagation over randomly varying, range-dependent elastic sediments," submitted for publication.
- [13] S. Frank, W. L. Siegmann, M. Badiy, Y. Mu, and J. F. Lynch, "Frequency dependent transmission loss related to modal properties in layered nonlinear internal wave environments," (A) J. Acoust. Soc. Am. **108**, 2544 (2000).
- [14] S. Frank, W. L. Siegmann, and M. Badiy, "Influence of water column statistics and environmental parameters on time-domain simulations of SWARM95 experimental data," (A) J. Acoust. Soc. Am. **110**, xxxx, (2001).

- [15] M. D. Collins, B. E. McDonald, W. A. Kuperman, and W. L. Siegmann, "Parabolic equation modeling of azimuthally advected gravity waves," *Wave Motion* **31**, 131-138 (2000).
- [16] J. F. Lingeitch, M. D. Collins, D. K. Dacol, J. C. W. Rogers, and W. L. Siegmann, "A wide-angle parabolic equation for advected waves," (A) *J. Acoust. Soc. Am.* **108**, 2562 (2000).
- [17] J. F. Lingeitch, M. D. Collins, D. K. Dacol, D. P. Drob, J. C. W. Rogers, and W. L. Siegmann, "A wide angle and high Mach number parabolic equation," submitted for publication.
- [18] W. M. Carey and W. L. Siegmann, "Predictability of shallow water sound transmission in selected shallow water experiments," (A) *J. Acoust. Soc. Am.* **109**, 2420 (2001).
- [19] W. M. Carey and W. L. Siegmann, "Measurement of sound transmission and signal gain in the complex Strait of Korea," submitted to *Proc. MTS/IEEE Oceans Conf.*, September 2001.
- [20] X. Tang, M. Badiey, and W. L. Siegmann, "Azimuthal coupling of shallow water sound propagation due to anisotropic sediment layers," submitted for publication.
- [21] Y. Mu, M. Badiey, J. F. Lynch, S. N. Wolf, and W. L. Siegmann, "Broadband acoustic variability due to internal solitary waves," (A) *J. Acoust. Soc. Am.* **108**, 2577 (2000).

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