Unified description of scattering and propagation
FY14 Annual Report

David Paul Knobles
Applied Research Laboratories
The University of Texas at Austin
PO Box 8029
Austin, TX 78713
phone: (512) 835-3687 fax: (512) 835-3259
email: knobles@arlut.utexas.edu

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LONG-TERM GOALS

The long-term goal of the research is to increase the physical understanding of acoustic propagation and scattering in continental shelf and slope environments in the 50-4000 Hz band. This includes both the physics of the seabed and the coupling to physical mechanisms in the water column in complex range- and azimuth-dependent littoral waveguides.

OBJECTIVES

For FY14, the first objective was to investigate the statistics of the mode intensity that result from scattering from a randomly rough seabed surface in a shallow water environment. The specific objective was to examine the feasibility of using a 2-way coupled mode methodology to analyze observed monostatic reverberation collected off Panama City, FL in 2013 in the 2-4 kHz band. The second objective was to extract information about the frequency dependence of seabed attenuation for a soft thick sediment. A third objective was to use ship radiated sound to extract marginal probability distributions for both α and γ, where $A(\mathrm{dB/m}) = \alpha\,(f/1000)^{\gamma}$, in a shallow water environment with a sandy seabed.

APPROACH

The methods used to achieve the scientific goals and objectives are based on theoretical advances made over the previous two years. A coupled mode integral equation method that separates forward and backward propagating modal amplitudes in a physically consistent manner is employed to compute the scattering from a randomly rough seabed. It is hypothesized that creating averages of the backscattered modal intensities from an ensemble of random realizations specified by a roughness power spectrum that characterizes the area around a receiver, can serve as a model for the averaging that occurs in monostatic reverberation for a non-cylindrically symmetric seabed surface. A maximum entropy (ME) method is applied to infer the statistical properties of parameter values that describe the

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seabed for two case studies. Of particular interest is the frequency dependence of the seabed attenuation. One case is for a bottom-limited deep-water environment with a thick mud sediment where the acoustic data result from multiple SUS deployments. A second case is for a shallow water environment with a sandy sediment where the acoustic data result from ship radiated noise. For the SUS data it is assumed that the source levels are known, however for the ship radiated noise the source levels have to be treated as random parameters. For both cases a conditional posterior probability distribution is formed for a parameter space that include the surface attenuation, the attenuation depth gradient, and the frequency exponent.

1. Reverberation with coupled modes for Panama City location

The effects of seabed roughness were previously studied with an approach utilizing an integral equation coupled mode method that *splits* the modal amplitudes into *forward* and *backward* components [1-2].

The 2-D coupled mode equations of dimension 2*N* for the forward and backward modal amplitudes ($R^+(r) = [R^+{}_1, R^+{}_2, \dots, R^+{}_{N-1}, R^+]$ and $R^-(r) = [R^-{}_1, R^-{}_2, \dots, R^-{}_{N-1}, R^-{}_N]$) in cylindrical coordinates are

$$\begin{aligned} R_n^+(r) &= \int_0^r G_n^+(r,r')S_n(r')r'dr' + \int_0^r G_n^+(r,r)\sum_{m=1}^{N} C_{nm}(r')R_m^+(r')r'dr' + \int_0^r G_n^+(r,r')\sum_{m=1}^{N} C_{nm}(r')R_m^-(r')r'dr' \\ R_n^-(r) &= \int_r^\infty G_n^-(r,r')S_n(r')r'dr' + \int_r^\infty G_n^-(r,r')\sum_{m=1}^{N} C_{nm}(r')R_m^+(r')r'dr' + \int_r^\infty G_n^-(r,r')\sum_{m=1}^{N} C_{nm}(r')R_m^-(r')r'dr' \end{aligned} \tag{1}$$

where S_n is the modal source function for the n*th* mode, C_{nm} is the mode coupling matrix operator, and *N* is the total number of modes. G_n^+ and G_n^- are the forward and backward propagating Green's functions that satisfy the appropriate asymptotic boundary conditions [3]. Random realizations of the seabed roughness are generated from a roughness power spectrum. For each realization Eq. (1) is solved for $R_n^+(r)$ and $R_n^-(r)$. For monostatic reverberation it is hypothesized that if a 1-D power spectrum of the seabed roughness adequately captures the scattering in a 2-D dimensional plane, then the distribution of modes of the scattered field will be related to an ensemble average of modeled modal intensities obtained from solving the 2-way integral equation equations for multiple realizations. The details of such a formulation and devising numerical tests for this hypothesis have yet to be completed.

The numerical difficulty is that backscattering is completely a consequence of mode coupling, which requires the coupled equations to be solved without approximation other than accuracy limitations imposed by numerical integration. Generally, the computation time required to solve Eq. (1) goes as $N^3 \ x \ N_r^2$ where *N* is the dimension of the coupled equations and N_r is the number of range mesh points. Often, 15 range points per wavelength are required for sufficient numerical accuracy.

2. Maximum entropy based approach to statistical inference

A statistical inference approach seeks to answer the question, "Given data D what information can be inferred about random model parameters forming the model hypothesis space M"? The central goal of a statistical inference method is to produce a mathematically consistent conditional posterior probability distribution (PPD). The maximum entropy (as does a Bayesian method) accomplishes this goal. In the ME method the PPD is a canonical distribution (from statistical physics) that becomes unique once certain constraints on the average error are specified. Reference 4 introduced a method where the constraint values can be estimated when a *sufficient* number of data samples exist to form an ensemble [4-5]. This idea of data ensembles is consistent with the concept of computing/measuring ensemble averages of acoustic fields in the ocean [2]. The ME approach can be employed to generate marginal probability distributions for seabed geoacoustic parameter values, including attenuation parameters.

WORK COMPLETED

The work completed in FY14 includes the application of the split integral equation coupled mode methodology to compute the backscattered field for an environment and frequency range inspired by recent measurements made during an ONR experiment off Panama City, Florida in 2013. Also, additional preliminary results have been obtained for the frequency dependence of the attenuation for a soft seabed sediment using data collected in the Gulf of Oman; specifically, mean values for both α, and its depth gradient, and γ have now been established. For the SW06 environment that has a sandy sediment, using the radiated noise of the R/V Knorr, marginal probability distributions have been derived for both α and γ.

RESULTS

1. Preliminary computations for the Panama City environment

The objective for FY14 was to test the ability of making 2-way coupled mode computations for an ocean environment off Panama City, Florida in the frequency band that the reverberation measurements were made. The background waveguide is 20 m deep with a stratified sound speed profile (SSP) over a half-space. The half-space sound speed and density are 1640 m/s and 1.8 g/cm^3, respectively (the estimate for the sediment sound speed was provided by Dr. J. Yang Applied Physics Laboratory, The University of Washington (APL:UW)). The halfspace attenuation was set to 0.15 dB/λ, a value that is consistent with the sediment sound speed. The frequency of the computations is 1900 Hz, which is the lower bound of the bandwidth of the reverberation measurements. The roughness wavenumber power spectrum employed to generate a 1-D rough seabed realization is

$$P(k) = \frac{K_L h^2}{\pi (K_L^2 + k^2)^{\gamma/2}}, \tag{2}$$

where h, K_L, γ, and k are the rms roughness height, the roll-off wavenumber given by the reciprocal of the roughness correlation length, the scattering exponent, and the spatial wavenumber, respectively. Values for these parameters were derived from information provided by Dr. T. Hefner at APL:UW Specifically γ, K_L, and h in Eq. (2) were 2.0, 3 m^{-1}, and 0.058 m, respectively. Random roughness realizations derived from Eq. (2) were then superimposed onto a 20 m flat bathymetry. It is important to note that these are only preliminary parameter values designed to grasp the essential physics of the scattering with the coupled mode model.

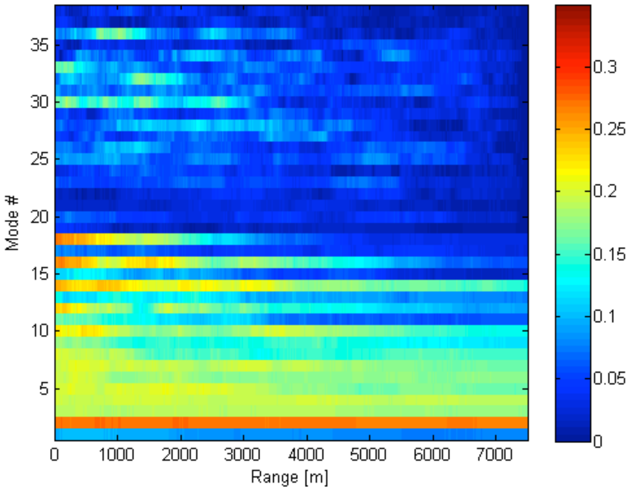

FIGURE 1: Averaged modal intensities forward components (1-19) backward component (20-38).

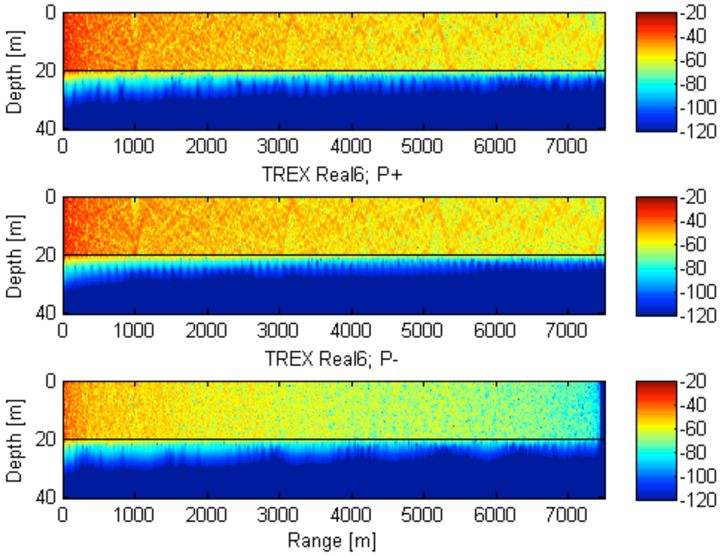

FIGURE 2: Transmission loss at 1900 Hz (a) total (b) forward (c) backward

Figure 1 shows the modal intensities in the trapped spectrum for both the forward- and backward-going modal components for a single roughness realization. There were nineteen trapped modes at 1900 Hz and thus the dimension of the coupled equations was 38. The maximum range of 7500 m was selected because it was reported by APL:UW that measured reverberation time series in the 1.9-4 kHz band had durations of about 10 seconds. The total number of range mesh points is about 1.5 x 10^5 and the total number of Lanczos vectors required for convergence was ten. Figure 2 shows the total transmission loss and the contribution from the plus and minus components of the field. The minus component is interpreted as the backscattered component. Note that on the spatial scale of the figure it is difficult to discern the roughness. Unlike the computations shown in Ref. 2 where there was large seabed roughness causing the number of Lanczos vectors needed for convergence to be greater than the dimensionality of the coupled equations, the smaller roughness scales observed by APL:UW make the coupled mode computation at about 2 kHz *marginally* feasible; about 60 hours per frequency for a single roughness realization on a 64-bit operating system with Intel(R) Xeon(R) CPU ES 1650 v2 @ 3.5 GHz and 64 GB RAM where the ratio of Lanczos vectors to the mode dimension is less than 1/3. The encouraging news is that it was possible to make such a size computation with the available computer resources and to demonstrate convergence as discussed in Refs. 1-2. Planned are computations for multiple realizations and frequencies with an increased level of computer resources.

2. Frequency dependence of seabed attenuation

A maximum entropy method was employed to obtain marginal probability distributions for values of the sound speed ratio and the sound speed gradient [5]. The specific types of data from which information about the sediment sound speed structure is inferred are those where most of the energy travels along sediment refracting paths. Using this information preliminary values for the attenuation parameters have been inferred via simple inversion, with

$A(f,z) = (0.005\ (\mathrm{dB/m}\ @\ 1\ \mathrm{kHz}) + 2.5\mathrm{x}10^{-4}\ (\mathrm{dB/m}^2\ @\ 1\ \mathrm{kHz})\ z)\ (f/1000)^{\gamma}$ with γ=1.0. The α value in db/m @ 1 kHz may be one of the lowest reported values inferred from forward propagation data. While there are physical models that explain why γ is approximately 1.8 for sandy sediments, future studies are needed to understand why γ appears to be on the order of unity for fined grained sediments. This work is incomplete as the final analysis awaits a ME computation for the marginal distributions for the attenuation parameters using as prior information the joint marginal distribution for the sound speed and gradient from Ref. 5.

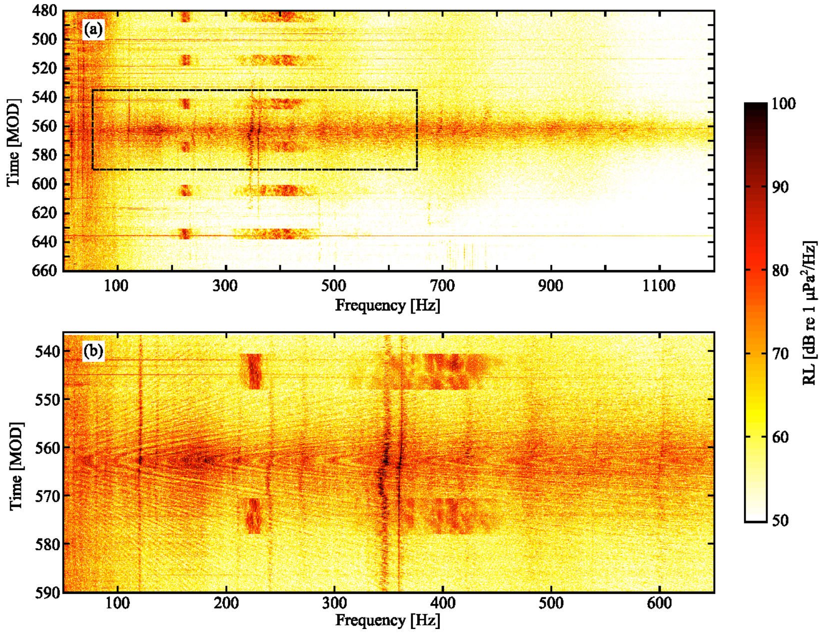

FIGURE 3: Spectrogram of RV Knorr travelling at 12 knots measured during SW06 (b) subset of data used in the analyses

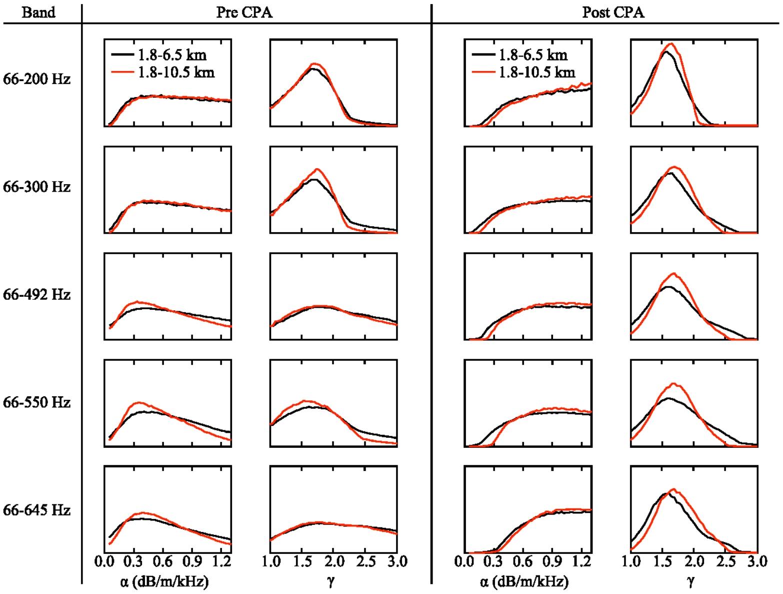

FIGURE 4: Marginal distributions for α and γ

Figure 3 shows a spectrogram of the R/V Knorr recorded during Shallow Water 2006 off the New Jersey coast. The ME method was used to compute the PPD for pre- and post-CPA range segments. A multistep method that employed short-range data was first used to obtain prior knowledge for the sound speed ratio and the average source levels as a function of aspect along with their uncertainties. Then, longer-ranged data were employed to compute the PPD for the source levels, α, and γ. Figure 4 shows the marginal distributions for α and γ for both pre- and post-CPA portions of the track in five frequency bands. The total number of frequencies in each band is eight, and thus the average spacing increased with an increasing bandwidth. While there is less resolution for α, the marginals for γ generally have a peak structure around 1.75, which is consistent with the effective sand model discussed by Zhou et al. [6]. Ongoing work is exploring the additional resolution that might be obtained for α by decreasing the frequency spacing and source level bounds.

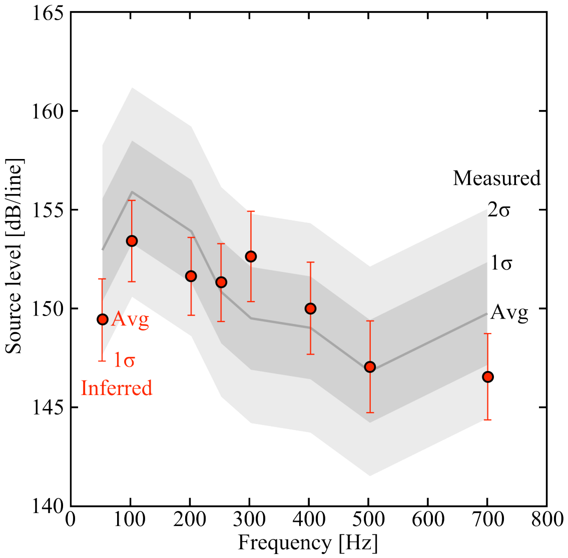

FIGURE 5:* *Validation of inferred attenuation parameters using measured source levels in separate data collection on post-CPA portion of track.

In addition to the ship radiated noise data, J-15 tow data with calibrated source levels were collected along the post-CPA portion of the ship track in the 50-700 Hz band. These data offered a means by which the results of using the ship radiated noise could be partially validated. The conditional PPD was constructed using the tow data with prior information provided by the marginals for the α and γ previously determined from the ship radiated noise data. From this new PPD the marginal distributions for the J-15 source levels were determined. Figure 5 shows the comparison between the average inferred levels and their standard deviations to the measured levels and their standard deviations. One observes *satisfactory* agreement, thus providing a partial means of validating the conditional PPD determined from the ship radiated noise.

IMPACT/APPLICATIONS

One potential impact of this research is that the inference of mud properties in a deep ocean sediment may prove useful in the upcoming Seabed Characterization Experiment (SCE) off the New England shelf in an area characterized by mud sediments. A desired outcome for the application of the coupled mode approach is to address the physics of scattering in shallow seas at the mid frequencies. If the ability to perform statistical inference in shallow water is generalized, it could compliment methods that use large amount of resources in establishing long-range transmission loss.

TRANSITIONS

The combined study of statistical inference and the effects of seabed scattering are expected to relate propagation statistics to physical mechanisms on continental shelf and slope environments. The knowledge of such statistics and their relationship to the physics of the propagation may be useful for sonar applications in continental shelf and slope environments.

RELATED PROJECTS

Related research projects include understanding the characterization of ship-radiated noise in deep water environments.

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PUBLICATIONS for FY14

First-Author

1. D. P. Knobles and J. D. Sagers, “Forward and backward modal statistics for rough surface scattering in shallow water,” J. Comp. Acous. **22**, 1440004 (2014).

Co-Author

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