Sound Speed and Attenuation in Multiphase Media

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LONG-TERM GOALS

One research goal developed from conducted shallow water (SW) acoustic transmission experiments in sandy-silty areas [1] revealed a nonlinear power law frequency-dependent attenuation at lower frequencies consistent with results reviewed in [2,3] and the observations by the ONR-HEP program. The Biot Theory [4] predicts that sandy sediment attenuation should have a quadratic dependence, however the nonlinear dependence observed was closer to a 1.8 power law most likely due to modal effects. Thus one long-range goal is to develop a simplified theory of sediment attenuation [5] verified by measurements that can be applied to ocean sediments.

A second long-range goal is to better understand that acoustical behavior of individual bubbles and bubbly assemblages in water and water-filled sediments. The focus is on attenuation, dispersion, and bubble response near and about the resonance frequency.

OBJECTIVE

The objective of the work was to determine the frequency dependent attenuation and phase speed characteristics of selected sandy and muddy sediments (both water saturated and partially saturated) at the lower frequencies to verify a simplified Biot theory [5] and to provide a theoretical / experimental basis for the water-sediment boundary condition necessary for the accurate prediction of wide band transmission loss in shallow waters.

APPROACH

This work was aimed at enhancing our understanding of saturated and partially saturated sandy sediment for frequencies ranging from 100 Hz to 10 kHz. The basic hypothesis is based on the simplified Biot sediment model [5] and the prediction that high permeability sands will have a quadratic frequency dependent attenuation, and that these measure-ments can be described by a Biot time constant. During the past year several major tasks have been performed. Holmes [3, 8] has compared this theory to experimental results for which the environmental conditions and the

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geophysical properties were known. While the theory predicts a power-law dependence with an exponent of 2, the experiments con-ducted in areas with similar sediments and environmental conditions yielded an exponent on average of approximately 1.8 with values of the attenuation constant consistent with Hamilton [6] at 1 kHz. To explain this difference modal propagation theory was used and calculations performed to determine the relevance of depth dependent geo-acoustic profiles on the attenuation observed in shallow water propagation. An experiment, the Nantucket Sound Experiment, was performed to quantify the acoustic properties of the bottom sediment between 220.5 and 1228 Hz and to determine the frequency dependent attenuation characteristic.

In this experiment characterization of the bottom properties used the synthetic-aperture Hankel transform described by Frisk et al. [7] an again by Holmes [8]. The details of the requisite signal processing to form a long array using an autonomous-vehicle towed array are given in reference [8, 9]. The basic method was to determine the horizontal wave-number spectrum that is an approximation to the Green's function;

$$g(k_r) = \int_o^\infty p(r) J_o(k_r r) r dr,$$

where *p(r)* is the pressure is a function of range, $J_o(k_r)$ is the zeroth order Bessel function, *r* is the horizontal range, and k_r is the horizontal wave number. The depth dependent Green's function, $g(k_r)$ satisfies

$$(\partial^2/\partial z^2 + k^2(z) - k_r^2) g(k_r; z, z_o) = -2\delta(z - z_o),$$

as well as the boundary conditions at the surface and the bottom and thus contains information about the bottom properties.

For long-range propagation when shear is not important, as is the case for sandy silty sediments, the modal representation of the pressure field is

$$p(r) \approx \sum_{n=1}^{M} a_n \phi_n(z) \phi_n(z_o) H_o^1[(k_n + i\beta_n) r],$$

where ϕ_n, k_n, and β_n are the eigenfunction, the eigenvalue (or modal wavenumber), and modal attenuation coefficient of the n^{th} propagating mode. A perturbation solution for the modal coefficients that was originally developed by Kornhauser and Raney [10] and revisited by Pierce yields the modal attenuation coefficient as

$$\beta_n(\omega) = v_{ph,n} \{ \int (\alpha(\omega)/\rho c) \phi_n^2 dz / \int (\phi_n^2/\rho) dz \}.$$

This expression shows that the modal attenuation is related to the intrinsic attenuation of the bottom by an integral over depth. Depth dependent profiles, therefore, are critical in correctly determining the frequency dependence of attenuation. A comparison of the measured pressure field using the autonomous-vehicle hydrophone-array system with the pressure field calculated using a normal mode propagation code, such as Kraken [11], with depth dependent profiles and an adjustable frequency dependence of attenuation can, therefore, reveal the attenuation characteristics of the bottom.

WORK COMPLETED

The Nantucket Sound Experiment used the autonomous-vehicle hydrophone-array system at a constant depth radially out from a source deployed from a small ship. Figure 1 shows a schematic of the configuration. The ship was kept in a 3-point mooring and was also used to deploy the vehicle. Motion of the source deployed from the A-frame on the ship was minimized by the use of an anchor and tension in the supporting cable. Sensors on board the ship included a global positioning system, acoustic Doppler current profiler, a precision depth sounder, and a conductivity temperature-depth profiler. Source depth was determined by a depth sensor attached to the source and the source level was monitored with a reference hydrophone 1m from the source. A signal generator with an external rubidium clock was used to generate signals composed of multiple narrow-band tones and the U.S. Navy calibrated source was driven with a Macintosh power amplifier.

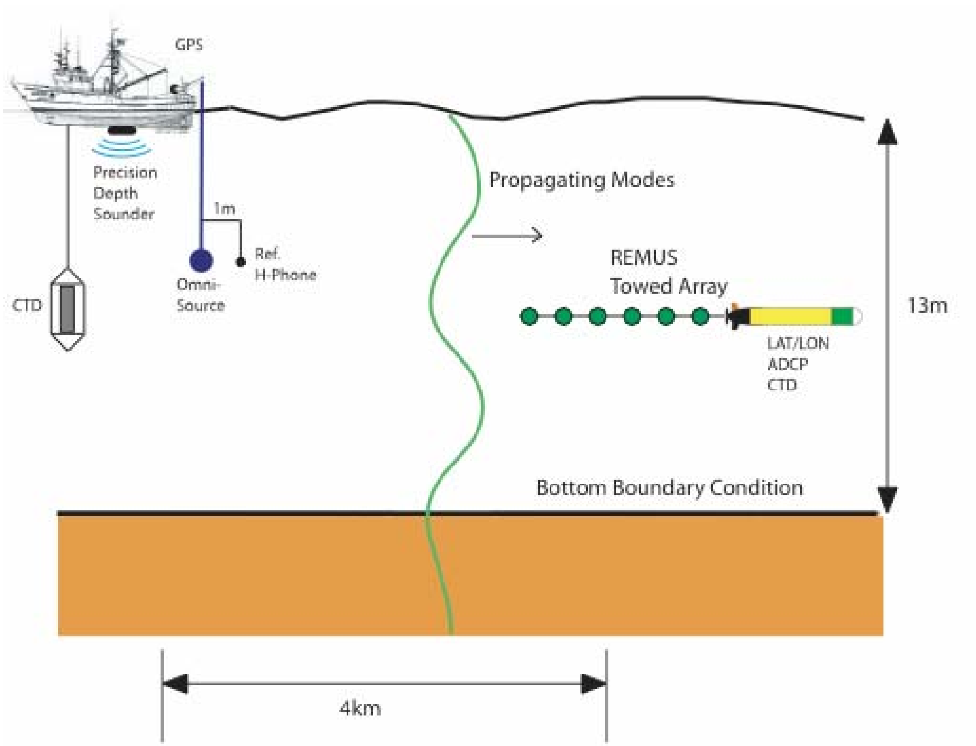

Figure 1: The Nantucket Sound Experiment

A pre-experiment site survey included precision depth sound measurements as well as grab samples. Cottom composition, layering, and bathymetry were characterized for the relatively constant-depth ($\approx 13m$) vehicle track over a silty-sand bottom (a mean grain size of 115 µm). This track was chosen because of its bottom type, constant bathymetry, proximity to the Frisk- Lynch-Rajan site [7], and the local protective geography.

Figures 2 and 3 shows the transmission results at 220.5 and 415 Hz. The top panels show the measured and calculated transmission loss as a function of range, the bottom left panels show the horizontal wavenumber computed from the measured complex pressure, and the bottom right panels show the horizontal wavenumber spectrum calculated using a depth dependent geo-acoustic profile. This depth dependent geo-acoustic profile was based on the pre-experiment site survey and used a sound speed profile varying from 1600 m/s at the interface to 1800 m/s at depth with a gradient decreasing with depth consistent with Hamilton's expectation for sandy bottoms [6]. The attenuation profile was assumed to be proportional to $c(z)^{-1}$ per the simplified version of Biot's theory [5].

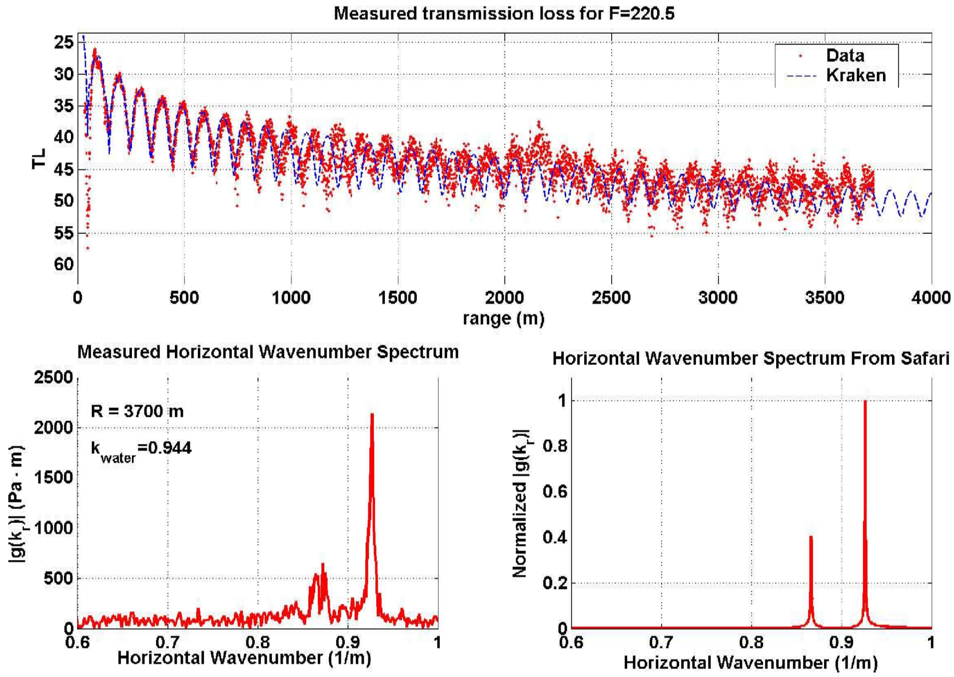

Figure 2: Sound transmission result for a frequency of 220.5 Hz

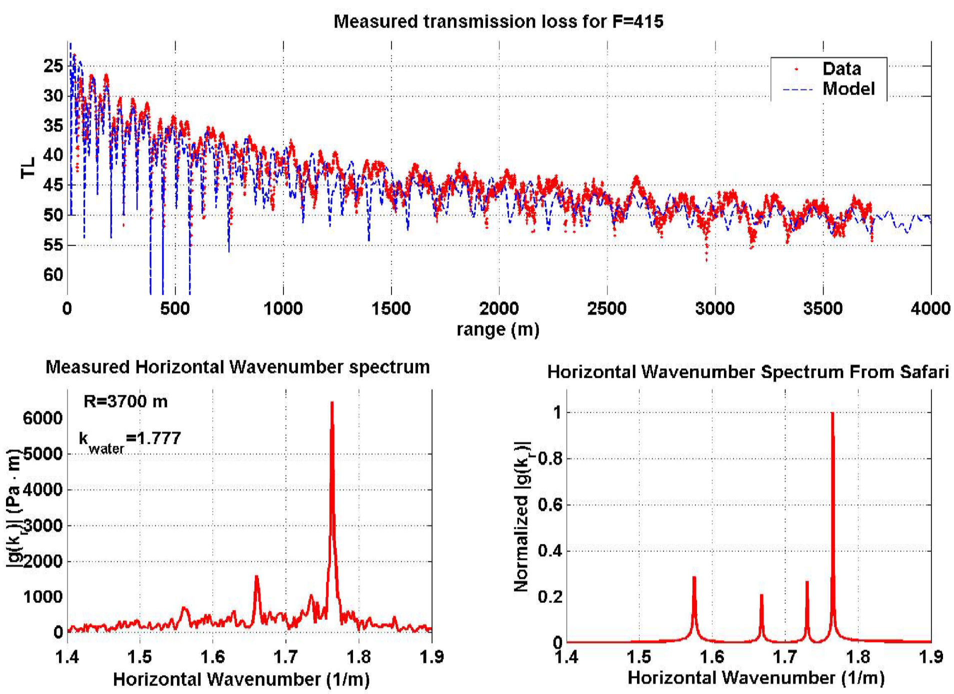

Figure 3: Sound transmission result for a frequency of 415 Hz

The attenuation at 1kHz was assumed to be consistent with Hamilton's value at that frequency and the density was assumed constant at the measured grab sample value of $1.7 g/cm^3$. Iterative comparison of the measured to calculated transmission loss while adjusting the frequency dependent attenuation revealed that the best fit of attenuation over all frequencies was

$$\alpha(f) = \alpha(f_o) \cdot (f / f_o)^n; \; with \;\; 0.261 \leq \alpha(1\, kHz) \leq 0.273 \; and \; n = 1.87^{+0.17}_{-0.21}.$$

This compares with a summary by Zhou [2] drawn from a larger and less restrictive group of experimental results yielded $\alpha(f_o) = 0.34; n = 1.84$ where the reference frequency is not specified.

RESULTS

A rapid, accurate and cost effective waveguide characterization tool, a prototype autonomous-vehicle towed-hydrophone-array system was used to perform a shallow water experiment. The attenuation result from this experiment was found to have frequency dependence consistent with Biot's theory for porous media when the depth dependence of the geophysical and geoacoustic parameters was used. Agreement between measured and calculated transmission loss showed that the propagation was well modeled by considering a non-linear frequency dependent attenuation with a magnitude consistent with Hamilton's results. Further, the agreement between measured and modeled horizontal wavenumber spectra showed that coherent processing was achieved and that the system can form a long synthetic aperture. The system was capable of characterizing a 4 km course in less than 1 hour while previous techniques required
up to 8 hours. Additionally, the experiment was performed from a single small ship with no moored assets. These accomplishments show that the autonomous vehicle towed array system is an accurate, cost-effective, and efficient ocean acoustics measurement tool.

IMPACT/APPLICATIONS

The measurement system described above was capable of characterizing a 4 km course in less than 1 hour while previous techniques required up to 8 hours. Additionally, the experiment was performed from a single small ship with no moored assets. The autonomous-vehicle towed-array system is an accurate, cost-effective, and efficient ocean acoustics measurement and surveillance tool and will have an impact on ocean acoustic experiments.

RELATED PROJECTS

The results of this research have the potential for dramatically improving the use of geo-acoustic models to accurately predict the propagation and dispersion of sound at the low frequencies (~100 Hz) to the high frequencies (~10 kHz). This effort is related to Awacs, (a project that consists of an interdisciplinary team from Oasis, Adept Systems, Boston University, WHOI, Naval Post Graduate School, Duke and Harvard), and to ONR-OA investigations at the Woods Hole Oceanographic Institution and the Rensselaer Polytechnic Institute and results in sharing resources and students.

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