Range-dependent Inversion for Ocean and Sediment Properties from Modal Dispersion Curves

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LONG-TERM GOAL

To obtain range-dependent model for the sound speed in the water column and sediment properties from the dispersion relation of the propagating modes.

OBJECTIVES

The present study is limited to the estimation of range-dependent sediment properties from dispersion data.

APPROACH

The acoustic field in range independent shallow water can be represented as the sum of contributions from a set of normal modes and is given by the expression given below:

$$P(r, z_s, z_r, w) = ip \sum_{n=1}^{N} f_n(z_s) f_n(z_r) H_o^1(k_n r) \quad (1)$$

In the above expression, P is the acoustic pressure, ω is the frequency, H_0^1 is the Hankel function of zero order and first kind, N is the number of modes, f_n is the mode function of the nth mode, k_n is the eigenvalue of the nth mode, z_s and z_r are the source and receiver depths, and r is the range.

Using the asymptotic approximation for the Hankel function the above equation takes the form

$$P(r, z_s, z_r, w) = i\sqrt{\frac{2}{p}} e^{ip/4} \sum_{n=1}^{N} f_n(z_s) f_n(z_r) \frac{\exp(ik_n r)}{\sqrt{k_n r}} \quad (2)$$

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In a range-dependent case where the adiabatic approximation is valid, the pressure field is given by the expression

$$P(r,z_s,z_r,\omega) = i\sqrt{\frac{2}{\pi r}}e^{i\pi/4}\sum_{n=1}^{N} \phi_n(z_s,r=0)\phi_n(z_r,r)\frac{e^{\int_0^r ik_n(s)ds}}{\sqrt{k_n(r)}} \qquad (3)$$

The modal phase is therefore given by the expression

$$\theta_n = \int_0^r k_n(s)\,ds \qquad (4)$$

Taking the difference on both sides we have

$$\Delta\theta_n = \int_0^r \Delta k_n(s)\,ds \qquad (5)$$

Let us consider the situation where the only change in the environment is in its compressional wave speed. Then at any given range location s, the change in compressional wave speed is related to the change in the eigenvalue by the relation (Rajan, 1987)

$$\Delta k_n = \int_0^\infty \frac{1}{k_n}\frac{\omega^2\Delta c(s,z)}{c^3(s,z)\rho(s,z)}\,|\phi_n(s,z)|^2\,dz \qquad (6)$$

where $\Delta c(s,z)$ is the change in the compressional wave speed at range s and depth z, c(s,z) and $\rho(s,z)$ are the background compressional wave speed and density respectively, and ϕ_n (s,z) is the mode function at the location.

Inserting this expression for Δk_n in equation (5), we obtain the equation

$$\Delta\theta_n = \int_0^r\int_0^\infty \frac{1}{k_n}\frac{\omega^2\Delta c(s,z)}{c^3(s,z)\rho(s,z)}\left|\phi_n(s,z)\right|^2 dsdz \qquad (7)$$

The travel time for the nth mode is given by

$$t_n = \frac{\partial\Delta\theta_n}{\partial\nu} = \frac{\partial}{\partial\omega}\int_0^r\int_0^\infty \frac{1}{k_n(\omega)}\frac{\omega^2\Delta c(s,z)}{c^3(s,z)\rho(s,z)}\left|\phi_n(s,z,\omega)\right|^2 dsdz \qquad (8)$$

The double integral can be changed into a double sum given below:

$$t_n = \sum_p\sum_q A(s_p,z_q)\Delta c(s_p,z_q) \qquad (9)$$

where p and q represent the range and depth grids.

Similar expressions relating the arrival time to the changes in the compressional wave speed can be obtained for different frequencies. This set of equations can be reduced to a matrix equation and the equation solved to determine the quantity Δc (s,z).

The experimental set up for this approach is to use a broadband source for transmitting the signal. A receiver placed at some distance from the source acquires the signal. By performing a short time Fourier transform or wavelet analysis of the received signal, the dispersion relationship is obtained. This dispersion relation yields the arrival time of each mode at different frequencies. This forms the data vector. The elements of the quantity $A\ (s_p\ ,\ z_q\ )$ are computed for each mode at the different frequencies for the initial model for the environment. Having computed these quantities, the matrix equation is solved to find the corrections to the environmental parameter. As the problem is ill conditioned, regularization methods will need to be adopted to solve the inverse problem.

It is proposed to test this approach using data to be acquired in two field experiments scheduled to take place in the years 2000 and 2001. The first is an experiment sponsored jointly by ONR and Japan Defence Agency. The experiment will be conducted in the general area of the Hudson Canyon. As part of this experimental program, Woods Hole Oceanographic Institution will deploy a number of drifting sonobuoys in an experimental scenario similar to experiment that have been performed by WHOI to study the evolution of modes in the shallow water environment. Normally this experiment is conducted using a source, which puts out a number of pure tones. A broadband component has been added to this experiment. Two types of broadband signal will be transmitted; a signal that is a sum of CW pulses at different frequencies and a FM sweep. These will be transmitted when the sonobuoys are at range of 10 – 15 km from the source. The signal received by the sonobuoys will then be analyzed to determine the dispersion relation for the modes. We propose to work closely with Dr. G. V. Frisk (PI for the WHOI experimental effort) to design the broadband component of the experiment and analysis of the data. The second field experiment is the East China Sea experiment scheduled to take place in the year 2001. During this experiment, Dr. James Miller from the University of Rhode Island will obtain modal dispersion data from acoustic data acquired on a vertical array. Explosives will be used as the broadband source for this experiment. We propose to work with Dr. Miller and analyze the data to determine the range-dependent bottom properties.

WORK COMPLETED

Two types of broadband signals were designed for the US-Japan experiment. The first one is a sum of CW pulses and other is an FM sweep. The dispersion curves for the two types of signals are shown in Figures 1 and 2. Both these types of signals will be generated using J15 source. In the experimental configuration, the source will be stationary. The receiver carried by the sonobuoy and its drift during the time it receives the broadband signal will be very small and can be neglected.

In the proposed experiments the propagation will take place over fairly large distances. This will require the range dependent inversion to include inversion for the water column sound speed profile and the bottom depth. The linear inversion approach outlined above can be modified to take into account changes in the water column sound speed profile and bottom depth with range.

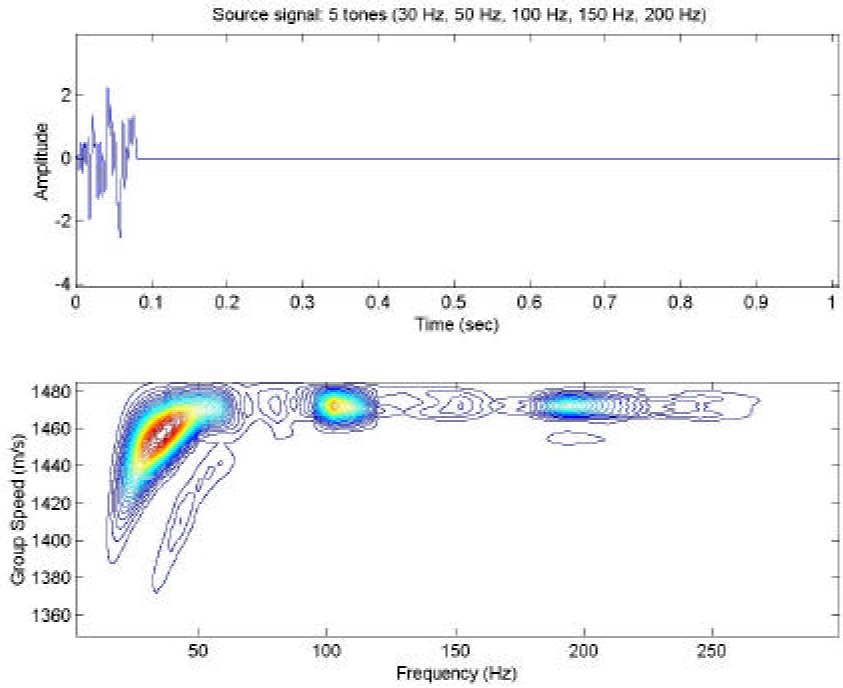

Figure 1. The transmitted signal consisting of 5 CW pulses and the dispersion curve.

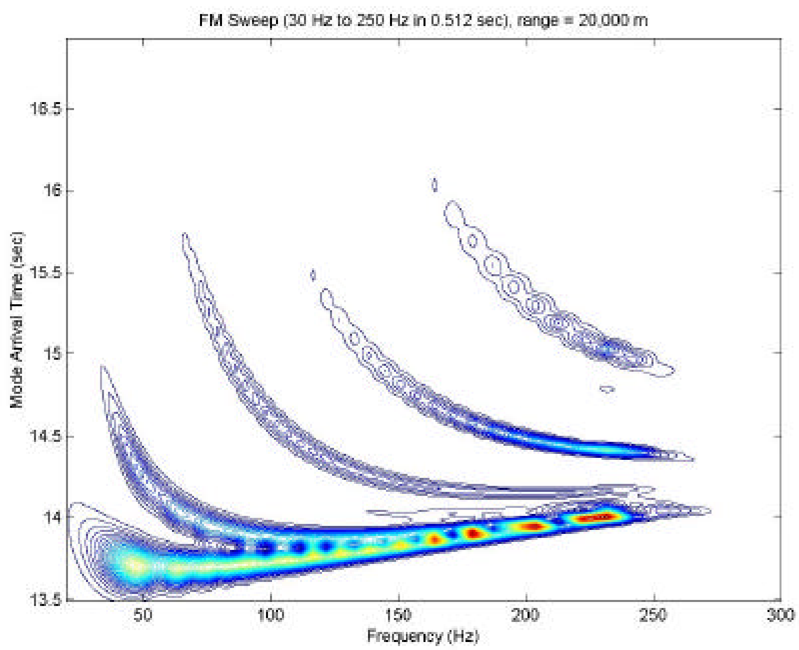

Figure 2: Dispersion curve for FM sweep.

However, simultaneous inversion of all these parameters poses a challenge. First we need to verify whether the problem is linear. Simulations conducted indicate that changes in modal group speed with changes in bottom depth is highly nonlinear where as the changes in the group speed with changes in bottom compressional wave speed is only weakly non-linear. The non-linearity of the change in group speed with changes in depth is weakest for the lowest mode. This analysis show that it is necessary to conduct preliminary bottom surveys to get good initial estimates of bottom depth. Further in order to obtain estimates of all the range dependent parameters a hybrid scheme that uses non-linear approach and a linear method may be required. Currently inversion with simulated data is in progress.

IMPACT/APPLICATIONS

The approach outlined above permits the estimation of range-dependent properties of the environment. This coupled with the use of drifting sonobuoys can be used determine environment parameters in real time and will prove an excellent asset for adaptive sonar design and for rapid environment assessment.

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