Three-dimensional propagation modeling in shallow water

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Abstract: Much interest exists in problems of shallow water propagation, where three-dimensional spatially dependent waveguide effects are sometimes very large. In these cases the three-dimensional dependence of the acoustic field can be accounted for in a variety of ways other than solving the often intractable fully coupled problem. Yet, because these models are extensions of efficient two-dimensional models they have explicit and implicit limitations on their applicability. Some of the advantages and limitations of these pseudo three-dimensional models will be demonstrated through their application to data collected during the SWellEx-96 matched-field experiments. [Work sponsored by the Office of Naval Research.]

Introduction

To ensure that the tremendous efforts of the past two decades of acoustic propagation modeling should not have been spent in vain, it will finally become necessary to put the various models to work; actual calculations to analyze real-world experiments must be made. This is as opposed to the sterile benchmark calculation. Benchmark problems are a proper first step in model validation, but are almost always too simple and/or pathological to be of much practical importance to scientists wishing to use the model for experimental analysis. These problems are even more poignant given the rush to create three-dimensional fully coupled models to be used in shallow water environments where environmental variability is at a maximum. Once thought intractable and believed beyond the capability of yesteryear's super-computer, the three-dimensional fully-coupled acoustic propagation model is still the "Holy Grail." However, advancing technology and judicious approximations have made three-dimensional models attainable and pseudo three-dimensional models practical. Several of the most useful methods employ approximations reducing the fully three-dimensional problem to a series of two-dimensional problems that can be solved via powerfully optimized techniques.1-4

Experiment

These approximation techniques were recently employed to analyze data collected during a series of Matched-Field-Processing (MFP) exercises held off the California coast near San Diego, entitled SWellEx-96. The data collected during this experiment was taken on linear arrays in three different orientations. Here we will use data collected on the Naval Research Laboratory's Satellite-linked Vertical Line Array (SVLA): A thirty-two hydrophone array positioned at 32°36'57.6" North Latitude and 117°21'37.8" West Longitude.

As can be seen in Fig. 1 the bathymetric features of the test range provide an excellent opportunity to test the accuracy and usefulness of three-dimensional models. A source was towed at a nominal depth of fifty-five meters by the R/V Sproul along many different tracks to test the viability of performing MFP in shallow water environments. Many events were also stationary, allowing for long integration times and high signal-to-noise conditions. During SWellEx-96 (May 1996), the weather and ocean environment proved to be exceptionally stable in the sense that temperature-salinity profiles in the test range were almost spatially and temporally invariant, thus negating the need to incorporate three-dimensional sound-speed profiles into modeling efforts. Several sharply defined tones between 50 Hz and 400 Hz with source levels of approximately 155 dB were broadcast by the source, making this data can ideal in testing the ability of any three-dimensional model to account for bathymetric variability using any linear matched-field processor.

Models

As previously intoned, most three-dimensional models are, in fact, pseudo three-dimensional: An approximation is made to reduce a fully three dimensional problem into a series of approachable two-dimensional ones. This is no more evident than in what has become known as the N×2D model; where the acoustic field along a series of straight
two-dimensional slices is calculated. Any method may be used to calculate the field along such a trajectory, however it is most typical to use a parabolic-equation (PE) method, so that at least vertical coupling of the outgoing energy is included in the model solution. Where the PE model is the solution to the parabolic reduced wave equation where the pressure $p$ is rescaled by the transformation $p \rightarrow u/\sqrt{r}$, and a solution to the PE.

$$\frac{\partial u}{\partial r} = i k_0 \left[1 + \hat{X}\right]^\frac{1}{2} u$$

where the operator $\hat{X}$ is the depth operator of the full acoustic wave equation. Where $k_0$ is some reference wave number and $k = 2\pi v/c$. The $N \times 2D$ model's basic assumption is that no energy can propagate between the various radial trajectories, i.e. no azimuthal coupling. In certain regimes this model can be extended to a fully coupled three-dimensional model, if the environment is translationally invariant. We point out that this type of environment is similar to many shallow water areas where iso-bathymetric contours are roughly parallel. In this case $\hat{X}$ is modified to include the cross-range wavenumber $k_y$. By integrating the resultant field over the parameter $k_y$, a fully coupled three-dimensional field is recovered.

The Adiabatic-PE method which has recently been modified to handle both vertical and azimuthal coupling called the Coupled Mode-PE, uses a slightly different reduction of the wave equation. In these models the vertical part of the wave equation is separated and solved independently via a normal mode model, and a modified PE is used to propagate the modal coefficients out in range and azimuth. Typically this is done for a single source and receiver depth pair, thus to map out the entire three-dimensional space, requires different input parameters to be propagated. Thus all of these pseudo three-dimensional methods are about equally efficient despite their different approaches.

References


