Seafloor Scattering in Three Dimensions by Time Domain Finite Differences

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LONG TERM GOALS

The long term objective here is to understand the dominant physical mechanisms responsible for propagation, attenuation and scattering in three dimensionally rough and heterogeneous environments such as found on continental margins and elsewhere in the ocean basins. Many Navy acoustic systems operate at high frequencies in shallow water over complex bottoms. In many environments the bottom has range dependent properties such as seafloor roughness or volume heterogeneities within the seafloor. To optimize the performance of these Navy systems it is necessary to fully understand the behavior of acoustic wave propagation in these complex environments. The time domain finite difference (TDFD) method has proven to be useful in studying acoustic wave propagation in complex media in two dimensions. When applied in three dimensions, however, it is computationally unwieldy. There are other, more efficient algorithms. For example, the Spectral Element Method (SEM) has the potential to handle much larger domains than TDFD and can address the larger scale problems that are necessary for Navy applications.

OBJECTIVES

Progress in three-dimensional numerical scattering studies must proceed in four directions pretty much simultaneously:

1) we need to identify, write or acquire software codes that have the potential to solve Navy problems,

2) we need to access the necessary high performance hardware on which to run the codes,

3) we need to verify the validity of the results by comparisons with analytical solutions and other numerical techniques and

4) we need to apply the code to field data and experiments of interest to the Navy.

The implementation and application of a three dimensional numerical scattering chamber is a large, multi-year task. If time and resources had permitted in the first two years we would have liked to address the following tasks:

1) A version of Spectral Element Method (SEM) code which runs on a Beowulf cluster is available to academic institutions from Cal Tech.   We would have liked to implement this code on a small cluster in order to gain some experience with it.

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14. ABSTRACT

The long term objective here is to understand the dominant physical mechanisms responsible for propagation, attenuation and scattering in three dimensionally rough and heterogeneous environments such as found on continental margins and elsewhere in the ocean basins. Many Navy acoustic systems operate at high frequencies in shallow water over complex bottoms. In many environments the bottom has range dependent properties such as seafloor roughness or volume heterogeneities within the seafloor. To optimize the performance of these Navy systems it is necessary to fully understand the behavior of acoustic wave propagation in these complex environments. The time domain finite difference (TDFD) method has proven to be useful in studying acoustic wave propagation in complex media in two dimensions. When applied in three dimensions, however, it is computationally unwieldy. There are other, more efficient algorithms. For example, the Spectral Element Method (SEM) has the potential to handle much larger domains than TDFD and can address the larger scale problems that are necessary for Navy applications.

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2) We pursued options for accessing larger and more up-to-date clusters for full-scale Navy relevant problems.

3) We would have liked to compare solutions from the SEM method for acoustic benchmark models with well known reference solutions [*Jensen and Ferla*, 1990, for example].

4) We continued to interface with the High Frequency Acoustics bottom interaction field programs to provide environmental information to define our models and to provide field data to ensure Navy relevance of the modeling effort [*Thorsos and Richardson*, 2002, for example].

APPROACH

Over the past twenty years we have developed finite difference methods for bottom interacting ocean acoustics in range dependent elastic, anelastic and porous media primarily in two-dimensions [*Dougherty and Stephen*, 1988; *Dougherty and Stephen*, 1991; *Greaves and Stephen*, 2000; *Greaves and Stephen*, 2003; *Stephen*, 1983; *Stephen*, 1984; *Stephen*, 1988a; *Stephen*, 1990; *Stephen*, 1991], but also in three dimensions [*Bradley and Stephen*, 1996; *Burns and Stephen*, 1990]. These methods are ideal for studying scattering from soft sediments in shallow water environments at moderate to high frequencies [*Stephen*, 2000; *Stephen and Swift*, 1994b]. Because of the shear properties of the bottom and the strong lateral heterogeneity of most shallow water sediments, a fully elastic/anelastic wave code, such as the finite difference method [*Stephen*, 1988b; *Stephen and Swift*, 1994a] is necessary to unravel the complex physical mechanisms involved in the propagation and scattering [*Swift and Stephen*, 1994]. We have already run some preliminary models to demonstrate the effectiveness of finite difference modeling to shallow water problems [*Stephen*, 1992]. NSC results can be applied to a broad range of frequencies because the spatial scales of heterogeneities are defined in terms of wavelengths [*Stephen*, 1996, for example].

Our three dimensional code is based on traditional time-domain finite differences (TDFD) and runs on a single workstation or serial supercomputer. It is restricted by memory and run time requirements to problems that are about 10 wavelengths (at 1KHz about 15m) on a side, which is much too small for many realistic problems. This corresponds to a physical volume of 10^3 cubic wavelengths, about 3×10^3 cubic meters at 1KHz and a 3-D mesh of about 10^7 points (assuming 20 points per wavelength). A typical 3-D continental margin problem at these frequencies may extend to at least 100m on a side, or a physical volume of 10^6 cubic meters, 3×10^5 cubic wavelengths and a 3-D mesh of over 3×10^9 points!

The Spectral Element Method, developed at Harvard and CalTech [*Komatitsch and Tromp*, 1999; *Komatitsch and Tromp*, 2002], has been used to compute earthquake propagation on a grid representing the whole earth at frequencies lower than about 0.10Hz. This corresponds to a physical volume of about 10^{21} cubic meters, 10^6 cubic wavelengths and a 3-D mesh of about 10^8 points (the radius of the earth is about 6375m with a typical velocity of 10km/sec and SEM needs about 5 points per wavelength for the same accuracy that the TDFD obtains with 20 points per wavelength). The SEM has at least the following advantages over TDFD:

1) Traditional TDFD suffers from grid dispersion so that larger models require more points per wavelength. SEM is a spectral method and does not suffer from grid dispersion.

2) SEM uses a more efficient interpolator (or template) than TDFD and requires only about 5 points per wavelength rather than 20 points per wavelength for TDFD.

3) The SEM algorithm lends itself to efficient computation on parallel computer architectures like Beowulf clusters and grids.

Some issues that will need to be addressed in transitioning the SEM code to high frequency bottom interacting ocean acoustics include:

1) defining the grid parameters adequately to handle fluid-solid boundaries in a Cartesian coordinate system while allowing for the large contrast between the shear velocity in the sediment (perhaps as low as 30m/s) and the compressional velocity in the water and sediments (greater than 1500m/s).

2) Testing the adequacy of the absorbing boundary formulation that will be necessary to study Cartesian grids. 3) Considering extensions of the elastic/anelastic/acoustic code to include the effects of poro-elasticity.

We expect that this new code will permit a quantitative study of the importance of three dimensional scattering from rough surfaces and volume heterogeneities in environments of interest to the Navy.

WORK COMPLETED

We have been unsuccessful at making any progress with the 3-D SEM research. As a complementary effort, however, we have packaged our 2-D TDFD Fortran code for distribution through the Ocean Acoustics Library (http://oalib.saic.com/). This includes relatively user friendly pre- and post-processors written in Matlab. Two User Manuals are in press [*Bolmer and Stephen*, in press; *Stephen and Bolmer*, in press].

In Spring 2005 Bob Odom and Ralph Stephen held a workshop at WHOI under joint ONR and NSF funding on "Seismoacoustic applications in marine geology and geophysics" (ONR grant N00014-03-1-0894). One result of the workshop was the recognition that long range acoustic propagation in the ocean is not completely trapped in the SOFAR (SOund Fixing And Ranging) channel even in very deep water. The evidence comes from two disciplines.

a) In long range controlled source acoustic propagation experiments at frequencies around 75Hz many aspects of observed acoustic fields are statistical in nature because of scattering due to ocean internal waves and density compensated fine structure. Energy which theoretically should be trapped in the water column (Acoustic Shadow Zone Arrivals at SOSUS Stations for example) is vertically scattered into the bottom where it can propagate on sediment and crustal paths and re-radiate into the water column down range.

b) In marine seismology the reciprocal problem occurs for abyssal T-phases at slightly lower frequencies (1-30Hz). Energy from earthquakes below the seafloor which should theoretically not couple into the sound channel is ubiquitously observed. In both disciplines the problems are the same:

1) we do not understand the interplay between oceanographic induced acoustic mode coupling (internal waves, etc), bathymetric mode coupling (abyssal hills, sea mounts, mid-ocean ridges, etc), and bottom attenuation, and

2) we don't have observations of the vertical structure of T-phases, or of the seabed response to controlled sources, to validate against forward models.

Under the funding for this TDFD grant we pursued three aspects of the long range acoustic propagation problem: a) observations of SOFAR channel propagation in shadow zones well outside the channel, b) securing OBS's for the LOAPEX experiment to enable controlled simultaneous observations of signals in the sound channel and on the deep seafloor, and c) TDFD modeling of long range acoustic propagation.

RESULTS

We prepared and presented a paper on SOFAR channel propagation observed deep within the seafloor under a deep ocean {Araki, 2005 #8124}.

Last summer we "piggy-backed" ocean bottom seismometer (OBS) instrumentation on the NPAL controlled source "Long range Ocean Acoustic Propagation EXperiment (LOAPEX) that began in September 2004 (Mercer and Howe 2004; Mercer, Andrew et al. 2005). Direct funding for the OBS's came from WHOI and NSF. ONR provided the additional ship time for the deployments and recoveries. (We are particularly grateful to the Chief Scientists, Jim Mercer and Peter Worcester, for helping to make this possible.) The data was retrieved in June 2005. The goal is to observe both controlled sources and earthquake T-phases on the four OBS's and on the NPAL "SPICE04" vertical line arrays (VLA). Our OBS's were also each equipped with a hydrophone, so we have an important acoustic data point at the water-seafloor interface.

We obtained TDFD results for 10Hz propagation out to 30km range for a full ocean velocity profile, a rough and laterally homogeneous bottom, including a thin sediment layer (Figure 1). These results were presented at a workshop on Seismic Waves in Laterally Inhomogeneous Media {Stephen, 2005 #8125}.

IMPACT/APPLICATIONS

We expect that our work on numerical acoustic codes will permit a quantitative study of propagation and scattering in shallow water environments at high frequencies. What are the best ways to define the necessary parameters for a heterogeneous, three-dimensional media? What are the dominant physical mechanisms for scattering, propagation, and attenuation in heterogeneous media? These issues go well beyond seafloor acoustics and will have significant impact on the fields of physical acoustics, aero-acoustics, geophysics and medical acoustics.

TRANSITIONS

This past year we continued to work with Dr. Lindwall in the Marine Geosciences Division (Code 7432) of the Naval Research Laboratory at the Stennis Space Center on applications of our 2-D TDFD code.

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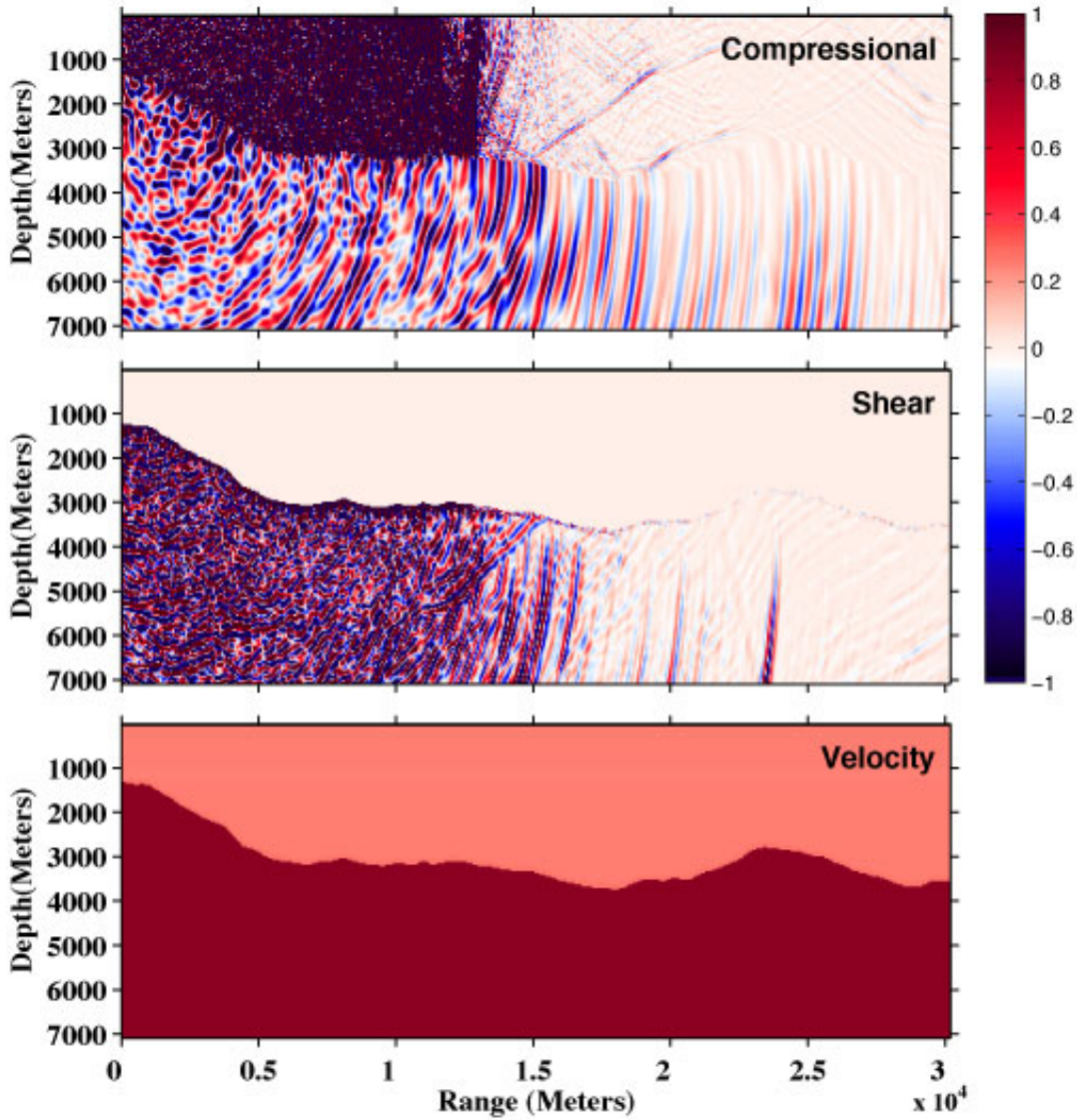
Figure 1: Snapshot of the wavefield from a point source at the sound channel axis for a typical ocean sound channel profile over a representative seafloor bathymetry with a thin sediment layer (Vp=1600m/s, Vs=250m/s, density= 1200kg/m^3) and gradients in the basaltic basement. Scattering from the roughness and heterogeneities as well as reverberation in the sediment layer removes distinct multi-paths and contributes to incoherent, "signal generated noise". We hypothesize that this signal generated noise is a ubiquitous feature of ocean sound channel propagation and explains shadow zone arrivals.