input data where the signal is usually taken to be reflection information and the remainder of the seismic wave field is generally classified as noise. While high-amplitude, randomly distributed (white) noise can make extraction of the reflection wave field difficult, the most harmful type of noise is the coherent part of the wave field known as ground roll. Removal of ground roll from seismic data has historically been a fundamental step but the completeness of its suppression without removing reflection information is partially linked to the acquisition method used in the field. Large receiver arrays reduce only part of the ground roll while attenuating certain parts of the reflection wave field. Long group intervals tend to alias the surface wave field making removal of residual coherent noise by methods such as velocity filtering difficult.

However, the effect of recording ground roll with truer fidelity using short arrays and small group intervals provides more efficient noise suppression than previously possible with conventional data. This effect is particularly noticeable in the deconvolution step where the higher S/N of the input data results in reduced phase distortion due to increased accuracy of the operator coefficients. This is because correlation is used to measure wavelet similarity in computing filter operators. Although ground roll has spectral components within the seismic band of interest, its wavelet shape is different from the reflection signal and interferes with the correlation process. Thus, the output signal from deconvolution performed on the high-density data after noise suppression has better vertical resolution because of a larger S/N and less phase distortion than the deconvolved conventional data. The increased performance of deconvolution also results in improved velocity and residual statics analysis particularly noticeable after array-forming the high-density data.

Seismic Finite Difference and Map Migration

Elastic 3-D Forward Modeling by the Fourier Method S15.1

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We present an elastic forward modeling algorithm based on the Fourier method. This modeling is capable of handling arbitrary velocity variation in both the horizontal and vertical direction. Although from a mathematical viewpoint 3-D modeling is not very different from 2-D modeling, from a computational viewpoint, however, 3-D modeling is an order of magnitude more difficult. For example, modeling of a region of size 5 km in all spatial dimensions with a frequency band reaching 40 Hz, requires a grid size of at least $250 \times 250 \times 250$. The total amount of computer storage required for such a problem is over 200 million words. Obviously problems of this magnitude pose a serious challenge to current computer technology.

The elastic modeling algorithm is first tested against simple problems for which the results can be readily understood. In a later stage more complicated problems will be introduced. The input for a typical problem includes the density and the P and S velocities at all grid points as well as a specification of the seismic source. The output can include a variety of displays such as displacement or stress time sections at selected receivers, or snapshots of these variables at fixed times.

Basic equations

Forward modeling is based on the integration in time of the equations of conservation of momentum, and the relations for an elastic medium undergoing infinitesimal deformation. Let X_j, $j=1,2,3$ denote a Cartesian coordinate system in which X_3 points in the vertical direction. The equations of momentum conservation then read:

$$\sum_{j=1}^{3} \frac{\partial \sigma_{ji}}{\partial X_j} + f_i = \rho \ddot{U}_i \qquad i=1,2,3 \tag{1}$$

σ_{ji} denotes stress components, f_i denotes body forces, ρ denotes density, and U_i denotes the displacement components. The convention where a dot above a variable denotes time differentiation was adopted. In order to make the system (1) determine additional equations, relating the stresses to the displacements is required. For an isotopic infinitesimal elastic region these relations read:

$$\sigma_{ij} = \lambda\theta\,\delta_{ij} + \mu\left[\frac{\partial U_i}{\partial X_j} + \frac{\partial U_j}{\partial X_i}\right], \tag{2}$$

with

$$\theta = \sum_{K=1}^{3} \frac{\partial U_K}{\partial X_K}, \tag{3}$$

λ and μ denote the Lame's constants.

The forward modeling consists of the solution of (1) and (2) in time. Time integration is carried out by time stepping by second-order differencing as in the 2-D case (Kosloff et al., 1984). Spatial derivatives at each time step are evaluated with use of the FFT (Kosloff and Baysal, 1982; Kosloff et al., 1984). Equations (1) and (2) contain a total of 18 derivative terms of this type. Thus for a cubic grid, each time step will involve the calculation of $18 \times 2 \times$ (number of points on an X_iX_j plane) FFTs. The input for the modeling includes the elastic constants λ and μ (or, alternatively, the seismic velocities) and the densities at all grid points. In addition the seismic source is introduced through a specification of the body forces f_i. These can include directional forces in which f_i points in a specified direction, or an isotropic pressure source as well as a variety of shear sources. Although not all these sources resemble exploration geophysics type sources, they can sometimes be useful in examining important effects like the generation of converted p-waves from an initial SH-wave.

As for the boundary conditions on the horizontal boundaries as well as the bottom boundary, we applied the absorbing boundary described in Cerjan et al. (1985). For the top boundary there is a possibility of introducing a free surface or allowing events to wrap around to the bottom of the grid and be eliminated by the absorbing region there. The free surface condition is effectively achieved through the introduction of a wide zone with zero seismic velocities above the upper surface of the model (or equivalently because of periodicity below the bottom of the model).

Numerical implementation

The 3-D elastic modeling algorithm was implemented on the Cray XMP4 computer. The Fourier method is highly vectorizable, and can also be designed to utilize simultaneously the four CPUs of the Cray computer. The calculations require a number

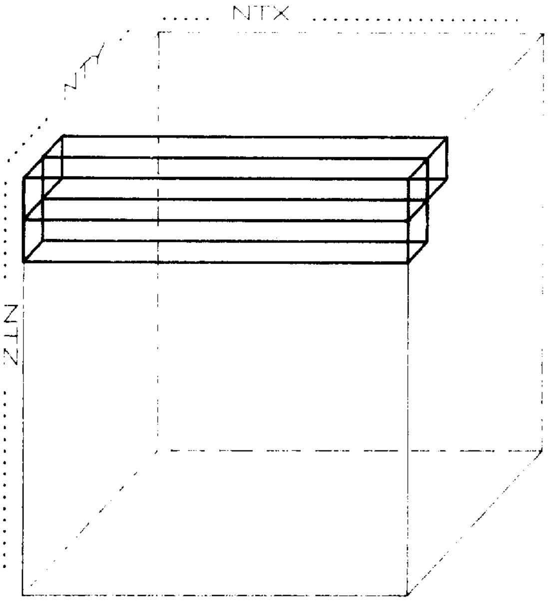

FIG. 1. Storage arrangement.

of global variables of size equal to the number of points in the numerical mesh. These include three displacements U_i, three velocities $\dot{U}_i$, material parameters ρ, λ, μ as well as 6 auxiliary variables which at certain stages contain either the 6 stresses σ_{ij} or the 3 accelerations of U_i. A typical 3-D problem of size $243 \times 243 \times 125$ will thus require over 110 million words of storage. This fits within the size of the 128 million words of the SSD memory of the Cray XMP4, but does not fit within the physical memory of 8 million words of the computer. A strategy of leafing through the storage at each time step is therefore required. The main goal is to minimize the amount of I/O and I/O requests between the host memory and the SSD.

The storage scheme which we finally adopted is based on a pencil structure (Figures 1 and 2). Denoting X_1, X_2, X_3 in equations (1) and (2) by x,y,z respectively, a time step of the algorithm consists of calculating new values alternatively in planes perpendicular to the Z-axis (*xy* planes) and planes perpendicular to the *y*-axis (*xz* planes). In each case a number of planes are first loaded into main memory by reading in a strip of pencils. The size of the strip must fit in main memory. Multitasking is achieved by allowing each of the four CPUs of the Cray XMP4 to operate on separate planes until values in all the planes in a strip of pencils have been updated. The pencil structure involves a special numbering of storage location (Figure 2), but the algorithm can be organized in a manner which keeps natural numbering in main data memory.

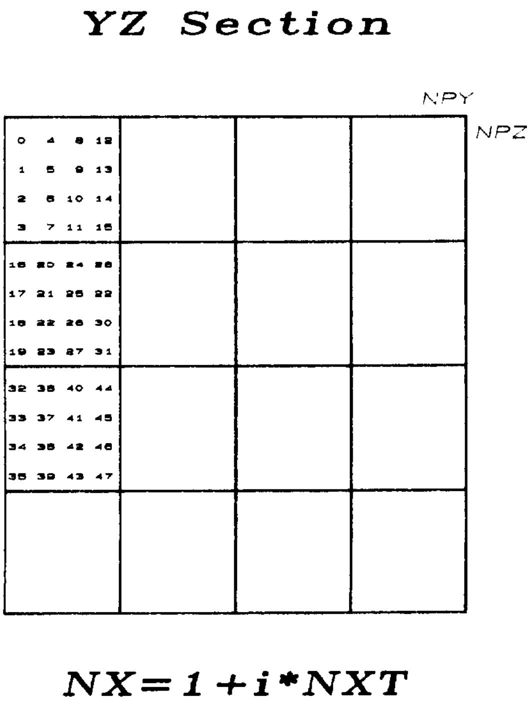

FIG. 2.

Numerical results and timings

The numerical algorithm will first be tested against problems with known analytic solutions and simple problems which give results which can easily be interpreted. Timings of typical runs will also be presented.

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Numerical Modeling in Seismic Prospecting S15.2

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The paper deals with the numerical modeling procedure of seismic wave propagation in heterogeneous media. For this purpose, the method suggested is based on a combination of finite integral transforms with respect to one of the spatial coordinates and finite difference technique with respect to the other. With the help of this approach one calculates complete synthetic seismograms in vertically inhomogeneous models of media (isotropic, anisotropic, liquid-filled porous, and linear nonelastic media). The approach described above was developed for complex 2-D and 3-D arbitrary subsurface geometries. Examples are given of calculating complete synthetic seismograms for different models of the media.

Numerical seismic modeling has recently become an invaluable tool for the study of the Earth's structure, and now it is an important part of seismic interpretation. Numerical modeling made it possible to calculate complete seismograms for complex subsurface geometries and compare them to observed records. In order to reach good agreement between synthetic and observed records, it is first necessary to select properly a physical model approximating a real medium. With the accumulation of experimental data our views on a physical model change.

In seismic prospecting one deals with 1-D and 2-D inhomogeneous models of anisotropic, attenuating, porous and some