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Practical aspects of prestack depth migration with finite differences

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Summary

Finite-difference, prestack, depth migrations offers significant improvements over Kirchhoff methods in imaging near or under salt structures. We have implemented a finite-difference prestack depth migration algorithm for use on massively parallel computers which is discussed. The image quality of the finite-difference scheme has been investigated and suggested improvements are discussed.

Introduction

One of the most widely used methods for depth migration today is Kirchhoff migration. Kirchhoff migration is known to have problems, particularly for complex geologies. Many have attempted modifications with Kirchhoff to overcome these problems, but most of these problems are avoided if one uses a finite-difference approach. The biggest disadvantage of a finite-difference approach is the higher computer resources required for the method which makes it cost prohibitive to use in many cases. The use of massively parallel computers makes it feasible to consider finite-difference migration for problems today that would have been impractical in the past. The use of faster processor nodes and the increased number of nodes envisioned for future parallel computers along with further algorithm improvements will likely allow finite-difference depth migration to become more commonly used in the future.

In this presentation, we discuss an implicit finite difference migration code, called Salvo, that has been developed through an ACTI (Advanced Computational Technology Initiative) joint project. This code is designed to be efficient on a variety of massively parallel computers. It takes advantage of both frequency and spatial parallelism as well as the use of nodes dedicated to data input/output (I/O). Besides giving an overview of the finite-difference algorithm and some of the parallelism techniques used, migration results using both Kirchhoff and finite-difference migration will be presented and compared. We will start out with a very simple cartoon model where one can intuitively see the multiple travel paths and some of the potential problems that will be encountered with Kirchhoff migration. More complex synthetic models as well as results from actual seismic data from the Gulf of Mexico will be shown.

Method

The equation solved in Salvo is the paraxial approximation to the acoustic wave equation (Claerbout 1985, Yilmaz 1987, Li 1991).

$$\frac{\partial P}{\partial z} = \frac{i\omega}{v}\sqrt{1+\frac{v^2}{\omega^2}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)}P,$$

where ω is the frequency of the propagating wave. The positive and negative signs correspond to upcoming and downgoing wave fields. The evaluation of the square-root operator is numerically difficult, hence it is approximated by a series that has its origin in a continued-fraction expansion (Claerbout 1985, p. 84; Yilmaz 1987, p. 513). The continued-fraction expansion can be represented by ratios of polynomials (Ma, 1981) and the polynomial coefficients can be optimized for propagation angle (Lee and Suh, 1985).

For numerical speed, the continued-fraction expansion is split to separate the operators in the x and y directions. This produces an equation with three terms, which can be solved individually using method of fractional steps. The first term is the thin-lens term and involves a solution of a complex exponential. The second and third terms are the diffraction terms for the x and y directions which require efficient tridiagonal solutions across the solution domain.

The approximation of the square-root operator, and the operator splitting step introduce errors into the migration. Two different filters have been provided in Salvo to correct for these approximations. The Graves and Clayton filter (Graves and Clayton, 1990) corrects for errors introduced by the operator splitting, and the Li filter (Li, 1991) attempts to correct for both approximations. Finally we apply absorbing boundary conditions similar to those described in Clayton and Engquist (Xu, 1996).

Thus, the overall procedure of solution is to read in a velocity plane, calculate the thin lens and diffraction terms, correct for errors using one of the above filters, use an imaging condition to produce an image, and write this image to disk. This is repeated for each depth step as we march down into the earth's interior.

Computational Requirements

The computational requirements of finite-difference, prestack, depth migration can be substantial, and this can be exacerbated by the fact that the grid is not arbitrary, but must be chosen based on the velocities that are present, the frequencies that must be propagated and the angle at which these frequencies must be propagated. The computational requirements make the efficient use of massively parallel computers a practical necessity for 3D imaging. We have developed a modular, portable implementation of Salvo for these machines (Ober, et. al., 1997). This code is written in high-level languages (a combination of C and Fortran and uses the industry-standard MPI communication library. It has been ported to a range of platforms including the Cray T3D and T3E, the IBM SP2, the SGI Power Challenge and Origin machines, the Intel Paragon and the DEC 8400.

There are two main sources of parallelism, frequency parallelism in which different frequencies are divided among processors, and spatial parallelism in which different portions of the spatial (x and y) domain are divided among processors. Frequency parallelism is the most efficient since communication is minimal; however, this type of parallelism requires a substantial amount of memory for repeated storage of the velocity model.

Spatial parallelism reduces the memory requirements, but is less efficient because it requires the parallel solution of tridiagonal systems of equations. Salvo achieves efficient spatial parallelism by taking advantage of the fact that there are many tridiagonal systems to solve at each depth step and setting up a pipeline for their solution. The major sources of inefficiency in the pipeline are the relative small messages required between the different stages of the pipeline and the processor idle time while the pipeline is being filled and emptied. The inefficiency can be minimized by grouping the tridiagonal systems to balance communication and idle time. An efficiency in excess of 75% is then routine.

Seismic datasets are often large, and this presents another problem for massively parallel computing. For Salvo, the seismic trace dataset is distributed across many disks to increase the total disk-to-memory bandwidth. A subset of the available nodes is assigned to handle the I/O, and each node in this subset, termed an I/O node, is assigned to handle I/O from one file system.

The remaining nodes, termed compute nodes, can complete computations and communications. During the initialization phase, these nodes work in the background and perform FFTs and data redistribution tasks while the I/O nodes are reading the trace data from the disk. During the migration phase, these nodes perform the computations while the I/O nodes work in the background to read the velocity model, perform post-processing and write the image. A model can be developed to determine the correct balance between I/O and compute nodes for various computing platforms (Ober, et. al., 1997). In this way, I/O bandwidths near the machine maximum are attained while the idle time of the computational processors is minimized.

Comparisons of Kirchhoff and Finite Difference

The increased computational requirements for finite-difference, depth migration are offset by improvements in image quality. For example, multiple arrivals can cause problems for Kirchhoff methods but are handled naturally in finite-difference methods. In this section, we compare Kirchhoff and finite-difference methods for a range of problems.

The problem with multiple arrivals is shown in Fig. 1. A series of Gaussian impulses (central frequency of 30 Hz) are shown propagating through a salt structure taken from a Gulf of Mexico model.

To the middle right is a salt structure while the remaining region contains layered media. The impulses indicate that the there is a zone in which two travel paths are possible. These can be easily seen by the crossing of impulse patterns in the center bottom. Any method that cannot correctly account for these arrivals should not be expected to produce an accurate image near the flanks of the salt structure. In more general terms, this is a region were the imaged impulse has turned back onto itself and become convex. Thus if smoothed velocity models are used, a convex impulse response may suggest multiple travel paths even though no impulse crossings are apparent. This figure also illustrates that below the salt structure relatively weak signals are imaged (bottom right corner of Fig. 1) which is a common difficulty in imaging below salt.

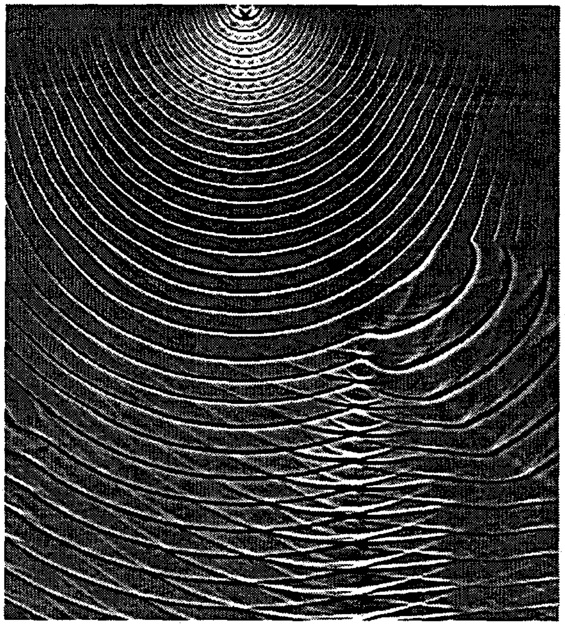

Figure 1. Impulses through Gulf model.

In Fig. 2, the velocity model is shown for a "Cartoon" model developed to illustrate the some of the advantages of finite-difference, prestack, depth migration in imaging around and under salt. Each layer in the model increases in velocity by 1 km/s, starting at 2 km/s for the top layer and ending with 5 km/s bottom layer. The simulated salt structure to the right has a velocity of 5 km/s. The domain is 201x301 grid points with $dx = 6.25$ m and $dz = 10$ m. A marine survey was simulated with the source leading the receivers and a 50m separation between source and first receiver. The receiver interval is 12.5m with the source advanced 6.25m between shots. A total of 260 synthetic shots, each with 60 receiver traces was collected. Trace data was collected with 4 msec sample rate for 1.4 seconds.

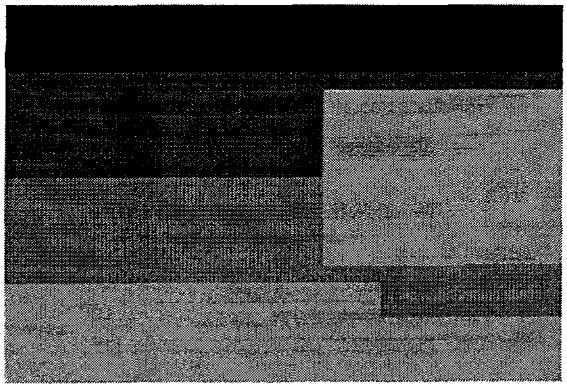

Figure 2. Velocity Model for "Cartoon" Model.

In Fig. 3, a Kirchhoff Migration of the Cartoon model data is shown. An interesting feature in this figure is that the middle layer between the 3 km/s and 4 km/s abuts the salt structure. In this region, multiple arrivals are possible through the layered earth and through the salt structure. As can be seen in Fig. 3, the Kirchhoff approach has inherit difficulties with which arrival to image. Additionally, this middle layer has a unimaged portion near the salt structure. The bottom layer between 4km/s and 5km/s is only imaged at the edges of the figure. The stimulated fault under the salt structure is not seen and the bottom layer could be confused with the bottom of the salt structure.

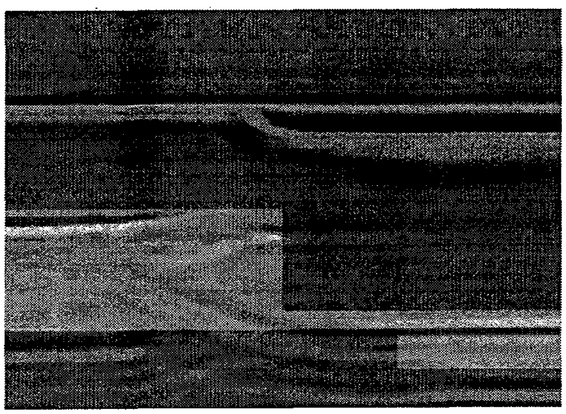

Figure 3. Kirchhoff Migration of "Cartoon" Model. The image overlaps the model.

In Fig. 4, the image of the Salvo migration is shown. The middle layer is continuous across the domain and closely estimates the correction location of the side of the salt. Although, close comparison shows that the imaged middle layer "bleeds" into the salt. Also, the bottom layer has been imaged more than in Fig. 3. However, no strong image was produced by the Salvo migration for the bottom layer between the left edge of salt and the fault.

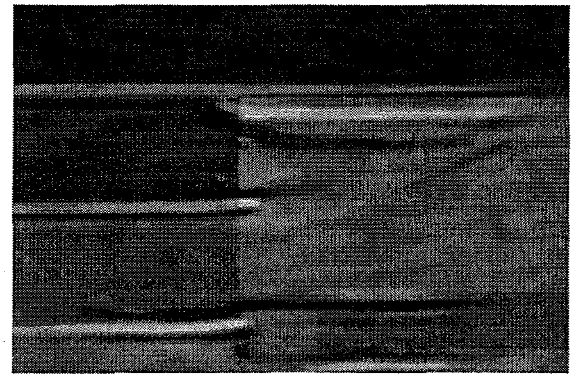

Figure 4. Salvo Migration of "Cartoon" Model.

In Fig. 5, a Salvo image of the Marmousi model is shown. In this prestack run only 24 shots were used. The computational domain had 369x751 grid points with a grid spacing of $dx = 25$m and $dz = 4$m. Additionally, an Ornsby source was used which had a frequency content of 0-30 Hz. Salvo migrated frequencies between 0-60 Hz. This was done to test the effects of source selection. The scalloping along the top indicates the location for each shot in the stacked image. The layers in this image are smooth and compact.

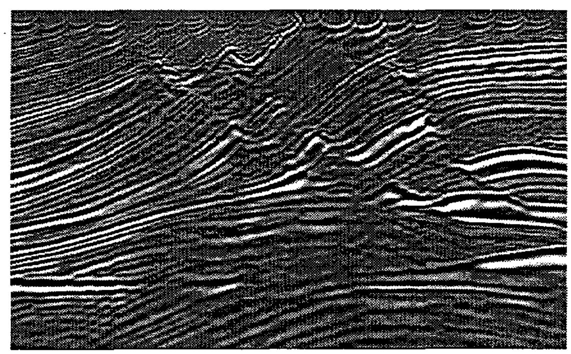

Figure 5. Salvo Migration using an Ornsby Source.

In Fig. 6, a Salvo image is shown of the Marmousi model using a source wavelet used in the generation of the original data. The frequency content of this wavelet is more broadband than the Ornsby wavelet. There were 240 shots used to image Fig. 6, and computational domain is the same as that used in Fig. 5. Frequencies between 0 and 60 Hz were migrated using Salvo which is the same as Fig. 5. Under some reflectors (middle right of Fig. 5 for example), there appears to a "rippling" of the layer, which suggests possible multiples or a broadening of the reflected image.

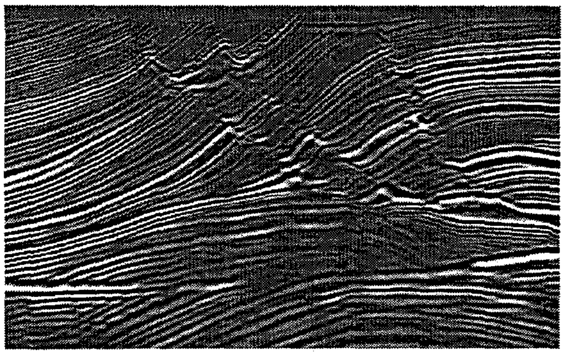

Figure 6. Salvo Migration using Actual Source.

Frequency Content of Images

It is often desirable to maintain the same frequency content in the time-domain image as in the original trace data. While this is natural for Kirchhoff methods, it is more difficult for finite-difference methods for several reasons. First, the imaging condition is often convolutional in nature. This has the effect of multiplying the frequency content of the source and receiver traces and significantly changes the shape of the image wavelet. Second, finite-difference migrations actually propagate the derivative of the recorded pressures due to the presence of the free surface. These effects can be mitigated somewhat by using an Ornsby source wavelet and by dividing out the derivative effects during in the imaging.

Conclusions

We have shown that through examples that finite-difference, prestack, depth migrations offers significant improvements over Kirchhoff methods in imaging near or under salt structures. We have also discussed the implementation of finite-difference migration on massively parallel computers, which will make this technique practical in the near future. We continue to improve the image quality of finite-difference methods and to reduce their computational requirements.

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