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EFFICIENT PARALLEL HYBRID COMPUTATIONS FOR THREE-DIMENSIONAL WAVE EQUATION PRESTACK DEPTH IMAGING

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Abstract. Three-dimensional wave equation prestack depth imaging is an important tool in reconstructing images of complex subsurface structures, and it has become a technique gaining wide popularity in oil and gas industry. This is a large-scale scientific computing problem and can be considered a process of data continuation downward with the surface data or the boundary data, such as the shot-gather data. In this paper, we first discuss the decomposition of a two-way wave equation and investigate four different approaches to approximate the square-root operator. Using the known shot-gather data as input, an unconditional stable hybrid method for the wavefield extrapolation is presented. The most attractive feature of the proposed method is that it has a natural parallel characteristic and can be effectively implemented using a cluster of PCs, in which each processor performs its own shot-gather imaging independently. To demonstrate the computational efficiency and the power of the parallel hybrid algorithm, we present two case studies: one is the well-known SEG/EAEG subsalt model which has been commonly used for validation of the prestack depth imaging algorithms, and the other is the application to a 3D wavefield extrapolation problem with real data provided by the China National Petroleum Corporation. The results clearly show the capability of the proposed method, and it demonstrates that the algorithm can be effectively implemented as a practical engineering tool for 3D prestack depth imaging.

Key Words. prestack depth imaging, prestack migration, wavefield extrapolation, wave equation, hybrid method, parallel compuation, MPI

1. Introduction

The three-dimensional prestack depth migration or imaging is an important and effective engineering tool widely used in oil and gas industry, and it has become a standard technique for complex geological structures exploration. The 3D imaging process can be regarded as a data continuation downward with the surface data such as the shot-gather data. The downward continuation of the prestack data should be carried out in the 5D-space of a full 3D prestack geometry (recording time, source surface location, and receiver surface location). Due to the tremendous amount of the raw or field data, this requires a very expensive computational cost. For obvious reasons, it is important to develop efficient methods which can be economically applied in exploration.

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Generally speaking, there are two classes of methods: Kirchhoff and non Kirchhoff. The Kirchhoff approach proposed by Schneider (1978) is the most commonly used method for the prestack depth migration due to its high efficiency and great flexibility in dealing with 3D data geometry. It can be employed to efficiently migrate data sets with uneven spatial sampling and data sets that are subsets of the complete prestack data, such as common-offset cubes and common-azimuth cubes. These advantages have led the industry to adapt almost exclusively the Kirchhoff method for 3D prestack migration. It should be noted that the migration accuracy of the Kirchhoff approach relies on the high-frequency asymptotic ray approximation. In order to increase the imaging accuracy, more accurate ray-tracing scheme is required; however, the requirements of the multi-pathing and the correct amplitudes of each arrival are computationally expensive. For non-Kirchhoff methods, most of the computing resource is consumed in the calculation of the propagating wavefield components that are either equal to zero or they do not contribute to the final image. The performance of the non-Kirchhoff methods can be improved by developing fast algorithms such as the fast Fourier transform (FFT) and the use of parallel computations.

The inverse time migration (Baysal, et al., 1983) is one of the non-Kirchhoff migration methods. The technique is capable of obtaining wave solutions and is developed based on the full or a two-way wave equation. All reflections, including the multiples and arbitrary steep reflectors can be imaged, but the imaging precision is inferior to that of a one-way wave equation for complex velocity media and structures. In this paper, we focus on a one-way wave equation.

Unlike an asymptotic solution using a high-frequency assumption in the Kirchhoff migration, the methods based on a one-way wave extrapolation are derived from the full wave equation. Thus, it can handle large lateral velocity variations and steep dipping events. Various numerical algorithms have been implemented using this approach, for examples, the phase-shift method (Gazdag, 1978), the phase-shift plus interpolation method (Gazdag and Sguazzero, 1984), the split-step method (Stoffa, 1990) and the Fourier finite-difference method (Ristow and Rühl, 1995). These methods were originally developed for two spatial dimensional cases, but they are now extended to 3D applications for prestack depth migration.

By taking advantage of the fast Fourier transform Methods, Stolt (1978) implemented an efficient algorithm in the frequency-wavenumber domain, which is capable of dealing with the steep dips up to 90°; however, it can not handle the lateral velocity variations. To improve the Stolt's method, the phase-shift method which can adapt the media with velocity varying only in depth and the split-step Fourier (SSF) migration which can handle the lateral migration dip are proposed. A further enhancement can be achieved by applying the SSF method with taking account the multiple reference velocities and incorporating the Fourier finite-difference (FFD) method to attain the accuracy under the situation with a strong velocity contrast. The FFD method can be regarded as a cascade of the SSF method and the finite-difference method for downward continuation in applications to large lateral velocity variations and high steep reflectors.

Another type of approximating wave equation method is the plane wave imaging or the slant stack migration. Here, the data are first stacked with the raw shot-gather data. Ottolini and Claerbout (1984) presented a migration method for common midpoint slant stack seismic data in a constant velocity media. The common midpoint data are processed as a plane wave section and the migration is performed on the individual common midpoint plane wave sections. However,