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Efficient Parallel Implementation of Multi–Arrival 3D Prestack Seismic Depth Migration

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The goal of seismic migration is to reconstruct the image of Earth's depth inhomogeneities on the base of seismic data. Seismic data is obtained using shots in shallow wells that are located in a dense grid points. Those shots could be considered as special point sources. A reflected and scattered seismic waves from the depth inhomogeneities are received by geophones located also in a dense grid points on a surface. A seismic image of depth inhomogeneities can be constructed based on these waves. The implementation of 3-D seismic migration implies the solution of about $10^{4\div5}$ 3-D direct problems of wave propagation. Hence efficient asymptotic methods are of a great practical importance. The multi-arrival 3-D seismic migration program is implemented based on a new asymptotic method. It takes into account multi-pass wave propagation and caustics. The program uses parallel calculations in an MPI environment on hundreds and thousands of processor cores. The program was successfully tested on an international synthetic "SEG salt" data set and on real data. A seismic image cube for Timan-Pechora region is given as an example.

Keywords: seismic imaging, multi-arrival seismic migration, HPC, aiwlib.

Introduction

Among all the tools applied for oil and gas exploration at the moment seismic prospecting is the most accurate and widely used method to study the structure of the inhomogeneous Earth's medium. Seismic imaging implementation based on reflected and scattered seismic waves from the depth geological structures is known as a seismic migration. Special seismic surveys are performed in order to collect seismic data. Geophones on the surface register scattered and reflected waves from the depth inhomogeneities. These waves are produced by special shots in shallow wells as sources. For now the usual area of the survey is $10^{2\div3}$ km^2 and corresponding dataset size is around $10^{2\div3}$ GB. The seismic migration process demands to solve numerous problems of wave propagation in heterogeneous medium. Thus asymptotic ray methods in the context of the acoustic approximation overrule the field. It is common practice to use a single-beam assumption. It states that there is only one ray from the source to an arbitrary point in the medium, the one which passes through the point at the shortest time. In complex media, if caustic occurs, the assumption breaks down and the resulting image can degrade. Therefore, to improve the image, one should discard the single-beam assumption and take multipath propagation into account. The seismic migration based on this approach and its efficient implementation are the main topics of the authors' research.

1. Formulation of Seismic Migration

Two asymptotic methods to solve the direct scattering problem taking the multipath propagation and caustics into account are widely known. They are Maslov's method of the canonical operator [5] and the Gaussian beam summation method [4]. Applications of Maslov's method are constrained by the lack of suitable numerical scheme.

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Research described in [2, 3] allowed us to introduce an alternative convenient way to solve the problem. It was implemented as a program for multi-arrival 3D depth seismic migration of multi-fold seismic data. For the numerical implementation we used the integral asymptotic solution of the direct scattering problem in the source-receiver Cartesian coordinates:

$$f(\vec{r}) = \frac{1}{16\pi^2} \sum_{m,n} \int\limits_{S_m} \int\limits_{S_n} A_s^m A_g^n \widehat{H}^{I_m + I_n} \dot{u}(\vec{s}, \vec{g}, \tau_s^m(\vec{s}) + \tau_g^n(\vec{g}))\, d\vec{s}\, d\vec{g}, \qquad (1)$$

where $f(\vec{r})$ stands for image value at the point $\vec{r}$, S_m and S_n are surface areas touched by the wave front with KMAH indices I_m and I_n correspondingly coming from the source $\vec{s}$ and receiver $\vec{g}$ at the point $\vec{r}$. A is the integrable ray amplitude, $\widehat{H}$ means Hilbert transform, τ_s and τ_g signify the time that rays take to get to the source and the receiver from the point $\vec{r}$, $\dot{u}(\vec{s}, \vec{g}, \tau)$ is the data from the dataset differentiated with respect to time.

Typical seismic migration project requires about 10^{17} floating-point operations. Hence the computational cost of the procedure is exceptionally high. For the case of quasi-regular multi-fold seismic data acquisitions it is possible to reduce computational cost of ray tracings even farther to the amount of unique locations of sources and receivers. Therefore our procedure splits into two consecutive steps. On first step we obtain the ray Green's function (GF) by tracing beam fans, e.g. we calculate A, I and τ. And the second one is for calculation of integrals (1) with help of suitable quadratures and the previous step results. Since every GF contains up to a gigabyte of data, the overall intermediate information amount adds up to hundreds of terabytes. Efficient storage and transport of the intermediate data is the key problem arising in the program implementation of the multipath 3D depth migration.

2. Algorithm and Implementation Specific Features

Our algorithm uses distributed RAM on a cluster to store ray GFs. Usually the intermediate data amount is greater than the available RAM size on the computational system. Thus at the scheduling stage the whole task is decomposed into smaller ones which use seismic data subsets.

Little seismic datasets require smaller GFs set, therefore, the amount of memory demanded decreases. The optimal partitioning allows us to achieve program memory consumption inversely proportional to the number of subtasks for big subtasks and square root of the number for smaller ones. In the latter case GFs recalculations also take place. That increases the total computation time, but GFs computation still takes about $10 \div 20$ % of the runtime.

To keep additional costs less than a half of the integration time, we have to store at least several thousands GFs in the memory. Thus computational system is required to have several TB RAM to run the program fast enough. Each subtask updates the part of the seismic image (1). Since the size of the updated part is relatively small ($\sim$ 10 GB), an intermediate image may be safely stored in long-term memory, even if we take the redundancy margin into account. As a result we can ensure fault tolerance. After a fault it is necessary to restart only the failed subtasks.

The problem (1) provides plenty of opportunities to employ parallel computations. Our algorithm has three parallelization levels. It ensures the best locality of processed data and efficiency on parallel systems with distributed memory. The top parallelization level utilizes MPI protocol to make internode communications efficient. The middle level applies OpenMP interface to achieve optimal performance on multi-core systems with shared memory. The bottom level uses processor vector instructions (SSE2, AVX). On the first step of the algorithm the top level

(a) Edge flip (b) Edge split

Figure 1. Grid adaptation process

parallelise different beam fans tracings. The middle level thread processes its spatial GF tiles. The bottom level deals with the access to the medium. The second step parallelisation is done by GF tiles, seismic data subset and operations for interpolation of the medium model for levels from the top to the bottom correspondingly. The velocity model is given on a uniform Cartesian grid. VTI and TTI Tompsen anisotropy models are available in addition to the isotropic model.

The ray GF is reconstructed in heterogeneous half-space at nodes of the uniform Cartesian grid. If a caustic occurs, there may be several rays leading from the source to a node. The tracing of a ray implies solving the system of Hamilton's equations for bicharacteristics numerically with aid of Runge–Kutta 4-th order method. Hamilton's system is integrated over the travel time along the ray instead of the common parameter. The ray tracing is performed in two passes. From now on we will refer to them as α and β tracings. The purpose of α-tracing is to construct the dynamically adapting angular grid which approximates the wave front on every time step. The grid consists of triangular cells (the beam fragments corresponding to single time moment). Every grid node contains a ray. The grid of initial ray directions is a pentakis dodecahedron recursive subdivision [1]. In contrast to the spherical coordinates of the grid, this triangulation does not have a singularity on the poles, and for the same fineness it has half as many cells.

After updating all the rays positions to new time step, the grid adaptation is performed. All edges with the length above the specified threshold value are arranged in a queue. The queue is kept sorted so the longest edge is always the next to pop. The dynamic adaptation works as follows: it gets the edge from the queue, tries to flip it (Fig. 1a) and tries to split it (Fig. 1b) if the flip failed. All new edges longer than threshold value are added to the queue. If the algorithm cannot split the edge, it discards it. The adaptation stops when the queue is empty. The flip is accepted if directions of new adjacent cells normals are closer to directions normal to the wave front. It is worth mentioning that in addition to the ray position the tracing procedure provides us with time gradient which is orthogonal to the wave front.

The edge split is performed by tracing a new ray close to the middle of the line segment connecting centers of cells adjacent to the edge. Initial parameters of the new ray are deduced by means of the conjugate gradients method. The split is considered unsuccessful if the resulting ray is not close enough to the desired point.

In the presence of caustics and head waves in a complex heterogeneous medium the α-tracing is a costly procedure. Thus we can avoid repeating it by saving the adaptation history to the long-term memory. It is exactly why the α-tracing was detached from the β-tracing. During the β-tracing the same beam fans are formed again. The main point of the β-tracing is to provide the GF on a uniform grid. In view of this we have to find all the nodes each beam catches. The

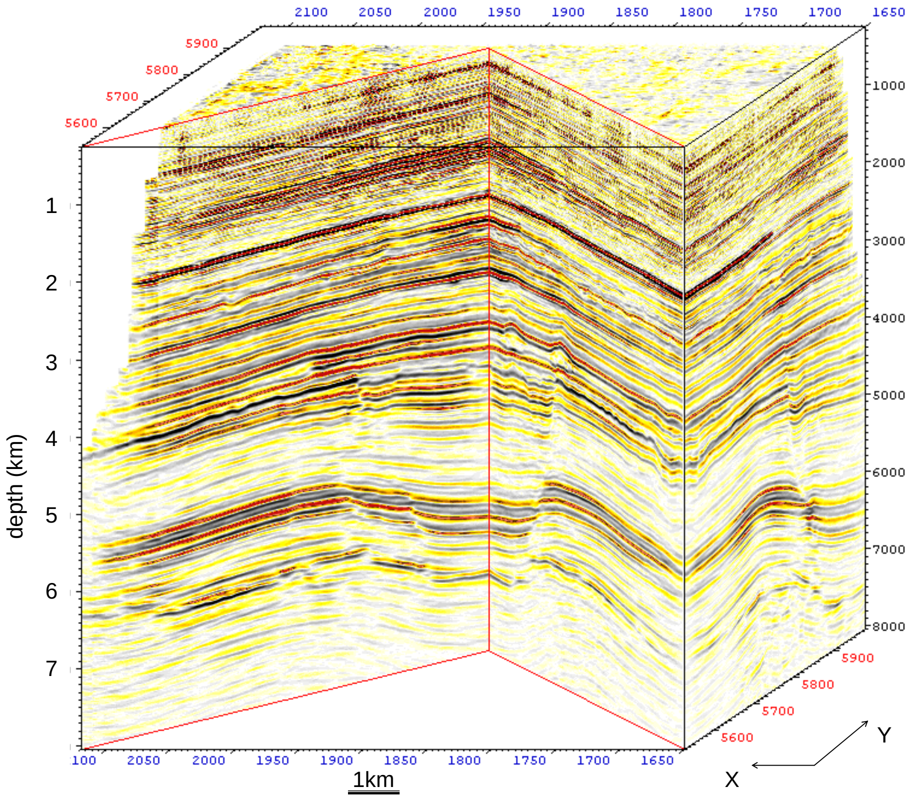

Figure 2. The seismic image by amplitude–preserving multiarrival 3D depth migration, Timan–Pechora region

beam segment between to consecutive time moments is considered to take the space between the corresponding triangular cells. For the linear ray segment approximation the problem of finding points inside the beam reduced to finding the solution of a cubic equation. That may be easily done by means of Newton method.

In order to calculate KMAH index for a beam, one should find the number of zeros Jacobian has had to the current moment. The same linear interpolation for the beam segment leads to Jacobian in the form of a cubic polynomial. Again Newton method saves us the trouble.

Unlike the integral in the ray parametric coordinates [3], the integral solution (1) contains singularities. Those integrable singularities arise from Jacobian vanishing on caustic surfaces. Special quadrature formulas explicitly localizing them are required in order to obtain the correct solution.

The described algorithm is implemented as a program in C++11. It works on OS Linux, requires aiwlib library [1] and uses MPI protocol. The code allows us to solve the multiarrival seismic migration problem for a complex heterogeneous medium cost effectively. The produced images were verified for SEG Salt synthetic dataset and a few real-world projects. Figure 2 displays the sample of seismic image for Timan-Pechora region produced by our code.

Conclusion

We have presented an original algorithm of multi-arrival 3-D seismic depth migration. It is based on a new asymptotic solution of Dirichlet problem for acoustic wave equation. A new asymptotic method is developed to correctly account for multipath ray propagation and caustics in a complicated inhomogeneous Earth's medium. A corresponding computer program has been implemented. It has been successively tested on international synthetic and real seismic data sets. The program uses parallel calculations on hundreds and thousands of processor cores in an MPI environment.

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References

1. Ivanov, A., Khilkov, S.: Aiwlib library as the instrument for creating numerical modeling applications. Scientific Visualization 10(1), 110–127 (2018), DOI: 10.26583/sv.10.1.09

2. Pleshkevich, A., Ivanov, A., Khilkov, S.: Asymptotic solution of wavefield continuation problem in the ray parametric coordinates. In: SEG Technical Program Expanded Abstracts 2017. pp. 5551–5555 (2017), DOI: 10.1190/segam2017-17633541.1

3. Pleshkevich, A., Ivanov, A., Levchenko, V., Khilkov, S.: Multiarrival amplitude–preserving prestack 3D depth migration. Russian Geophysics (S) pp. 76–84 (2017)

4. Semtchenok, N., Popov, P., Verdel, A.: Depth migration by the Gaussian beam summation method. Geophysics (75), 81–93 (2010), DOI: 10.1190/1.3361651

5. Vainberg, B.: Asymptotic methods in the equations of mathematical physics. Moscow: MSU (1982)