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One-way wave equation migration of common-offset vector gathers: parallel multi CPU/GPU implementation

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Summary

We present an original algorithm for seismic imaging, based on the depth wavefield extrapolation by one-way wave equation. Parallel implementation of the algorithm is based on the several levels of parallelism. Parallelism of the input data parallelism allows processing full coverage for some area (up to one square km). Mathematical approach allows dealing with each frequency independently and treating solution layer-by-layer, thus a set of 2D instead of initial 3D common-offset vector gathers are processed simultaneously. Next, each common-offset vector image can be stacked and stored independently. As the result, we designed and implemented parallel algorithm which allows computing common-offset vector images using one-way wave equation-based amplitude preserving migration.

Introduction

One-way wave-equation (OWE) migration is usually considered as an intermediate step between the Kirchhoff-like ray-based or beams-based procedures and two-way wave-equation (TWE) migration. Advantage of the OWE migration is the possibility to deal with multiple ray paths, to treat caustics of wavefields, to account for the evanescent modes. All these complexities are hard to handle by the Kirchhoff-like methods. At the same time, if compared with the two-ways wave equation the OWE based migration is much faster and computationally efficient (Mulder and Plessix 2004).

From the computational point of view, OWE-based migration has several features, which make it suitable for processing of large common-offset datasets. First, Green's functions for different sources-receivers positions can be computed independently and then combined to construct image in (ω-x) domain. Second, Green's functions and thus images are extrapolated layer-by-layer. This means that at each step of the algorithm we deal with 2D cross-sections of the solution, thus we can deal with high number of solutions simultaneously. As the result for a fixed frequency at a fixed depth we can consider any combination of the Green's functions constructing any image; i.e. common shot, common receiver, common azimuth, etc.

In this paper, we present an original parallel algorithm for pre-stack OWE-based migration. Presented approach allows us to migrate common-offset vector gathers by OWE migration. The algorithm implies multi-level of parallelism with the OWE solved on GPU (one GPU for each subset of right-hand sides), images constructed on CPU and stored in RAM (one cluster node for each image). Thus the algorithm has the same functionality as modern Kirchhoff-based approaches but higher resolution and ability to deal with more complex models.

Mathematical background

We construct a seismic image by solving the one-way wave equation in $\omega - x$ domain:

$$\left(\frac{\partial}{\partial z} - \sqrt{\frac{\omega^2}{v^2(x,y,z)} - \frac{\partial^2}{\partial x^2} - \frac{\partial^2}{\partial y^2}} \right)[u] = 0, \quad u(\omega, x, y, 0) = u_0(\omega, x, y) .$$

using sixth-order accurate pseudospectral method (Pleshkevich et al. 2017). The solution at depth $z + \Delta z$ can be represented as follows

$$u(\omega, x, y, z+\Delta z) = \sum_{j=n}^{n+1} \alpha_j F^{-1}\left[\exp\left(i\omega\Delta z \sqrt{\frac{1}{v_j^2} - \frac{k_x^2}{\omega^2} - \frac{k_y^2}{\omega^2}} \right) F\left[u(\omega, x, y, z)\right] \right] + \alpha_0 u(\omega, x, y, z),$$

where F is the Fourier transform with respect to horizontal spatial directions and $v = v(x, y, z) \in [v_1, v_2]$ is the wave propagation velocity. Construction of the coefficients $\alpha_j(v, v_1, v_2)$ and discussion of the choice of discrete set of velocities v_n are discussed in (Pleshkevich et al. 2017). Important feature of the presented algorithm is the use of coarse mesh (25 or 50 m) in vertical direction and further interpolation of the solution to the fine enough mesh (5 m) by the rule:

$$u(\omega, x, y, \tilde{z}) = \frac{z+\Delta z-\tilde{z}}{\Delta z} u(\omega, x, y, z) \exp\left(-i\frac{\omega}{v}(\tilde{z} - z) \right) + \frac{\tilde{z}-z}{\Delta z} u(\omega, x, y, z+\Delta z) \exp\left(-i\frac{\omega}{v}(\tilde{z} - z - \Delta z) \right)$$

where $z \le \tilde{z} \le z + \Delta z$ and velocity is independent on vertical direction within the considered interval. Having a set of solutions for a number of right-hand sides; i.e. Green's functions for a number of sources/receivers positions one may apply imaging condition to construct series of common-offset vector images.

Parallel realization

To describe the idea of the algorithm and the way to compute the common-offset vectors images by OWE-based migration we need to go into details of the parallel implementation. We consider four principal features of the algorithm: parallel data treatment; computation of the sets of Green's functions and images by GPUs; data transfer, interpolation and summation of images; the output data organization.

We divide the input data into subsets so that each subset is processed by a single MPI process. We consider the area containing all the common image points and divide this area into rectangular subdomains. After that, we make a list of all source-receiver pairs corresponding to a single subdomain. Later we will call the set of sources and receivers corresponding to the subdomain. Examples of the stencils for the SegSalt narrow azimuth data and for onshore data are presented in Figure 1 (a) and (b) respectively. For the SegSalt data we provide only 103 of 2500 stencils, to keep the common image points distinct. For the real data, one may note the irregularity of the stencils following the river channel, to preserve efficiency of the MPI processes balancing.

Using GPU and qFFT procedure we solve the one-way wave equation for multiple right-hand sides. This process in performed for a single frequency. Solution is computed using coarse steps (50 m) in vertical direction. So that we simultaneously compute 2D Green's functions for all positions of the sources and receivers within the stencil for given frequency at particular depth. After that, we construct a set of 2D common azimuth vectors images (fixed frequency, fixed depth). It is clear that having all Green's functions available we can construct images of any type, including, common offset, common azimuth, common shot, common receiver etc. After that, the constructed 2D images are exported to the RAM.

Processing of the images by the CPU includes the data sorting and MPI data passing, so that single common-offset 2D image is sent to the particular node, so images for prescribed offset and azimuth for all stencils are accumulated at the particular computational node. On this node, we are using CPU to interpolate the image inside a thick slab, and then sum it up to the 3D images, where we accumulate all frequencies, depths, and stencils. Note, that while CPU process data inside a stab $[z_{j-1}, z_z]$ GPU computes the solution at the depth $z = z_{j+1}$. The block-scheme of the parallel algorithm is provided in Figure 2.

Each MPI process produces one common-offset vector image for all considered stencils. Note, that the same nodes are used to compute solution using GPU, and then acquire images, thus the best performance is achieved if the number of the stencils is proportional to the stacking fold.

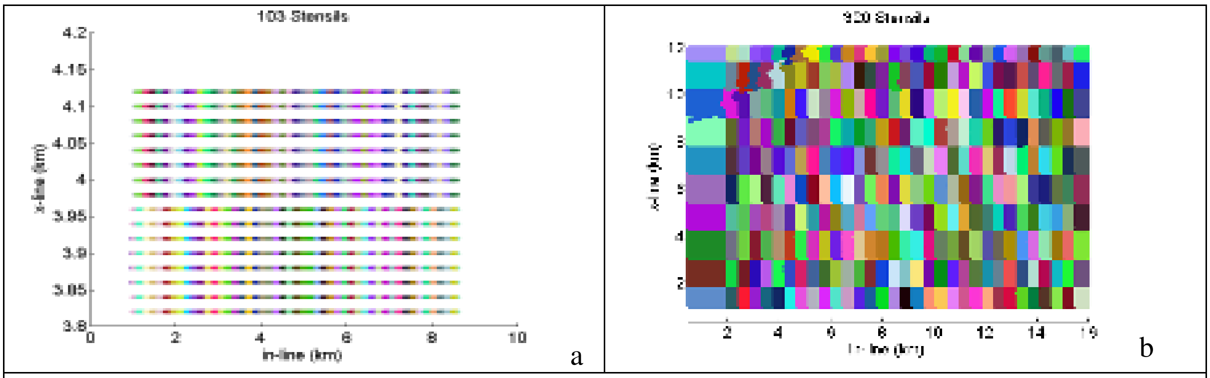

Figure 1. *Examples of the common image points for different stencils (datates division) used for the migration by a single node for SegSalt model (a) and for real land data (b).*

Implementation

First, we consider the SegSalt model with narrow azimuth dataset. The size of the model is 7980 m (InLine), 7920 m (CrLine), and 4000 m in vertical direction. We use the grid with the steps 20 m, 20 m, and 50 m to compute Green's functions and grid with steps 20 m, 20 m, and 5 m for images. We compute 17 common-offset vector images using 2600 stencils. Simulations are performed using 17 computational nodes, and the total computational time is 5000 node-hours. Examples of the staked images are provided in Figure 3.

Second, we apply the algorithm to compute images for the onshore field data. The size of the model is 15525 m (InLine), 11250 m (CrLine), and 5000 m in vertical direction. To compute the Green's functions we use the grid with the steps 25 m, 25 m, 50 m. The images are constructed on a grid with the steps 25 m, 25 m, 5 m. We considered 40 common-offset vector gathers. We use data division into 320 stencils, as presented in Figure 1 (b). We use 40 nodes for the simulation and perform 8 independent simulations. The total computational time for the images construction is 23000 node-hours. Examples of the 3-D common-image gathers reordered as 2-D common-offset are provided in Figure 4, whereas slalom-line section of the 3D stacked seismic image is presented in Figure 5.

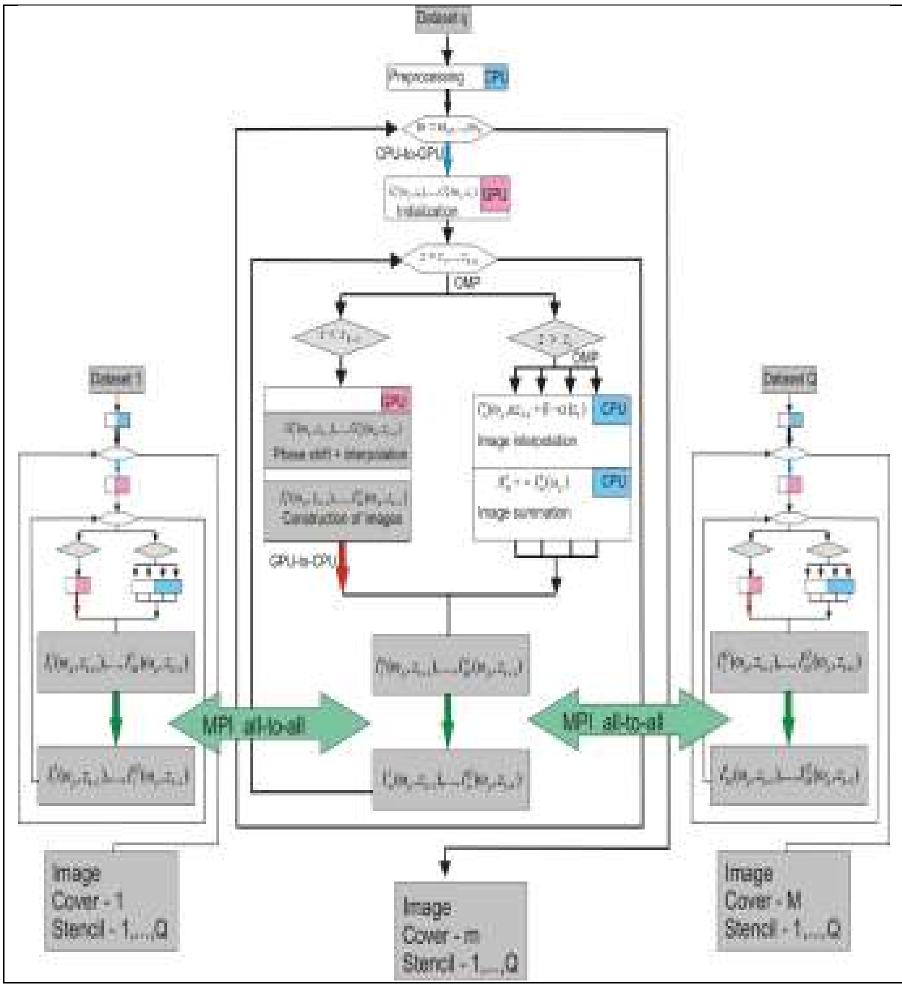

Figure 2. *The block-scheme of the algorithm*

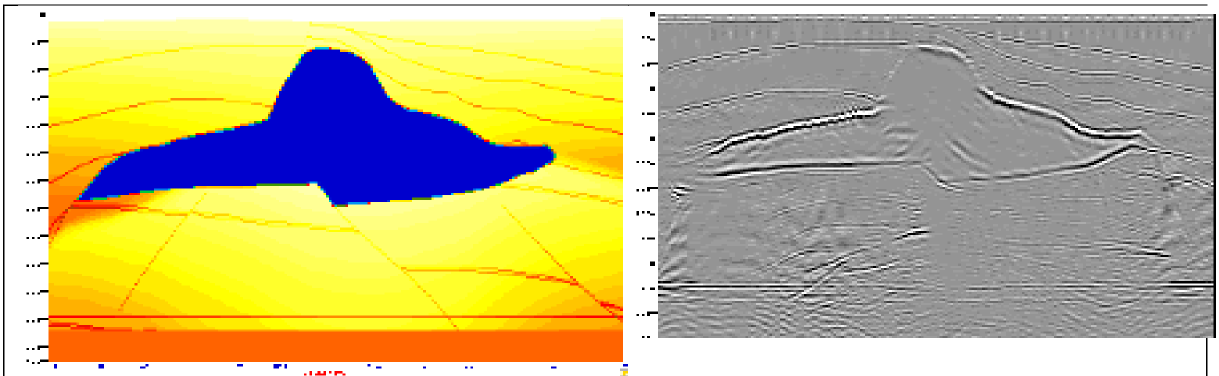

Figure 3. *2D cross-section (left) and staked image (right) for SEG Salt model (cross-line).*

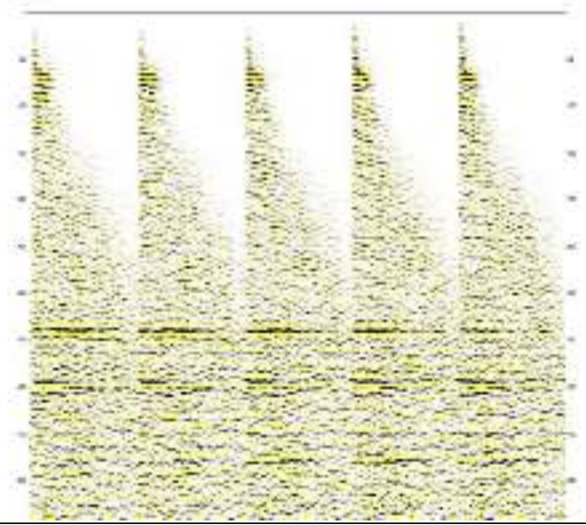

Figure 4. *3-D common-image gathers reordered as 2-D common-offset*

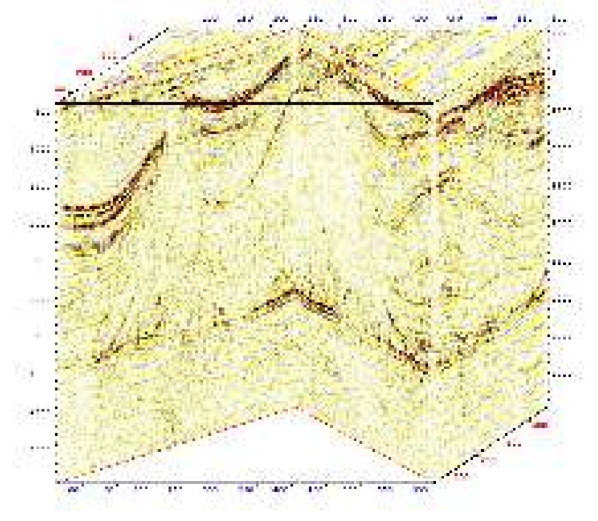

Figure 5. *Slalom-line section of the 3D stacked seismic image*

Conclusions

We presented a multilevel parallel algorithm for amplitude-preserving seismic migration of common–offset vectors-gathers based on the depth wavefield extrapolation by solving one-way wave equation. The solution is constructed by using pseudospectral method, thus the main computational effort is to perform forward and backward 2D FFT, which is done by use of GPU and qFFT. One-way wave equation is solved in frequency domain, thus can be computed for each frequency independently. Use of OWE allows simultaneous computation of the Green's functions for a set of sources/receivers, thus it let us migrate common-offset vector gathers with amplitude preserving due to the proper parallel data processing.

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References

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