Global Elastic Response Simulation

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Purpose of this project is twofold; (1) to solve inverse problem, that is, to perform waveform inversion for three dimensional (3-D) shear wave velocity (Vs) structure inside the Earth using the Direct Solution Method and (2) to solve forward problem, that is, to calculate synthetic seismic waveform for fully 3-D Earth model using the Spectral Element Method. As for the inverse problem, we implement the codes of the Direct Solution Method on Earth Simulator to compute synthetic seismograms of long period surface waves and their partial derivatives with respect to model parameters of 3-D Earth structure. We perform waveform inversion for 3-D Vs structure in the depth range from 11 to 888 km analyzing data in the frequency range from 2 to 4.1 mHz. Comparing to our previous applications, the parallel DSM calculation using 10 nodes improve the lateral resolution by 3×3 times. As for the forward problem, we use the Spectral-Element Method and calculate synthetic seismic waveform for a 3-D Earth model, which includes a 3-D velocity and density structure, a 3-D crustal model, ellipticity as well as topography and bathymetry. We use 243 nodes of the Earth Simulator and calculate synthetic seismograms accurate up to 5 sec for global seismic network stations.

The synthetic waveforms for 2002 Alaska earthquake using 243 nodes of the ES with SEM show that these synthetics can be used to obtain complex source processes during large earthquakes which occur in subductin zones where the seismic velocity structure is heterogeneous due to subducting oceanic plate.

Keywords: Synthetic seismograms, 3-D velocity structure of the Earth, Direct Solution Method, Spectral Element Method

1. Inverse Problem

We implement the codes of the Direct Solution Method (DSM. Hara et al., 1991) on Earth Simulator to compute synthetic seismograms of long period surface waves and their partial derivatives with respect to model parameters of 3-D Earth structure. We use auto-parallelization of the compiler together with directives for parallel computing in a single node. We employ MPI to perform parallel calculation using multiple nodes.

We use the implemented DSM codes to perform waveform inversion for 3-D Vs structure in the depth range from 11 to 888 km. We analyze observed spectra in the frequency range from 2 to 4.1 mHz. We use spherical harmonics to represent the lateral variation of 3-D structure and divide the region at the depths form 11 to 888 km into 4 layers.

Comparing to our previous study (Hara and Geller, 2000), we analyze more than 10 times larger dataset (5110 seismograms taken from 97 events) to improve the lateral resolution by 3×3 times (the maximum angular order is 24, while it is 8 in the previous study). Most of the CPU time is consumed for calculation of the partial derivatives, for which the vector operation ratio is about 99 per cent, and the parallel efficiency is about 76 % when we use 10 nodes (80 processing elements).

While the long wavelength patterns are consistent between the previous model and the model obtained in this study, the parallel DSM calculation makes it possible to look at finer scale features such as subducting oceanic plates for each subduction zone.

2. Forward Problem

We simulate global seismic wave propagation throughout a 3-D Earth model, which includes a 3-D seismic velocity and density structure, a 3-D crustal model, ellipticity as well as topography and bathymetry. The 3-D seismic velocity model we used in this simulation is S20RTS of Ritsema et al (1999). This model expands 3-D seismic velocity model of the Earth by spherical harmonics up to angular order 20, which means that the 3-D velocity structure in this model represents long wavelength heterogeneity. We use the spectral-element method (SEM) developed by Komatitsch and Tromp (2002). The method is based upon a weak formulation of the equations of motion and combines the flexibility of a finite-element method with the accuracy of a global pseudospectral method. The SEM uses a mesh of hexahedral finite elements on which the wave field is interpolated by high-degree Lagrange polynomials on Gauss-Lobatto-Legendre (GLL) integration points. Here we use fourth order

Lagrange polynomials. The Earth is first divided into six chunks. Each of the six chunk is divided into slices. Each slice is allocated to one CPU of the Earth Simulator. Communication between each CPU is done by MPI. Before the system can be marched forward in time, the contributions from all the elements that share a common global grid point need to be summed. Since the global mass matrix is diagonal, time discretization of the second-order ordinary differential equation is achieved based upon a classical explicit second-order finite-difference scheme.

To implement the SEM code on the Earth Simulator, we first test the code by using less than 10 nodes. We use 24 CPUs (24=6 ×2 ×2, therefore each chunk is divided into 4 slices) and 54 CPUs (54=6 ×3 ×3, therefore each chunk is divided into 9 slices). In this case, each slice is subdivided into 96 elements for 24 CPUs case and 64 elements for 54 CPUs case, respectively in a horizontal direction. This mesh is considered to be accurate to calculate seismic waves with periods up to about 40 second. We compare both 24 CPUs case and 54 CPUs case and get parallelization ratio of 99.86%. We could get this level of parallelization without major modification of the code, because it is already fully parallelized using MPI. However, the auto vectorization of F90 compiler of the ES could not fully vectorize the code and we need to modify the most inner loop of the program so that we can get high vectorization ratio. As a result of this modification, we could get the vectorization ratio of 98.6%. Because this parallelization ratio and vectorization ratio satisfy the Earth Simulator Center's criterion to request more than 10 nodes, we first request 48 nodes (384CPUs). Using 48 nodes (384 CPUs), we can subdivide each chunk into 64 slices (384=6 ×8 ×8). Each slice is then subdivided into 64 elements in one direction. Because each element has 4 Gauss-Lobatto points, then the average grid spacing at the surface of the Earth is about 4.8 km. The number of grid points in total amounts to about 1.3 billion. Using this mesh, it is expected that we can calculate synthetic seismograms accurate up to 8.75 sec all over the globe. To calculate 30 minute three components synthetic seismograms with 0.1 second sampling interval for all the grid points over the surface of the Earth, it took about 5 hours with 48 nodes of the ES. The SEM code has been developed by using PC cluster with 75 733 MHz dual-processor nodes and 75 gigabytes of memory at California Institute of technology. To simulate global wave propagation for one hour at periods greater than 18 seconds, it took more than 48 hours using this PC-cluster. Thus, the performance of the ES is quite astonishing. The performance we get with 48 nodes is about 1.0 Terra FLOPS, which is about one third of the total peak performance for 48 nodes.

Then we compare 96 CPUs and 384 CPUs for the same resolution of the mesh and get parallelization ratio of 99.97%. The vector ratio in this case is 99.3%. Based on these data, we next request 243 nodes (1944 CPUs). Using 243 nodes (1944 CPUs), we can subdivide each chunk into 324 slices (1944=6 ×18 ×18). Each slice is then subdivided into 48 elements in one direction. Because each element has 4 Gauss-Lobatto points, then the average grid spacing at the surface of the Earth is about 2.9 km. The number of grid points in total amounts to about 5.5 billion. Using this mesh, it is expected that we can calculate synthetic seismograms accurate up to 5 sec all over the globe. Before we start to calculate synthetic seismograms with 243 nodes of the ES, we first calculate the mesh files for this computation and store these mesh files on the magnetic tape mass storage system of the ES. It is because that once we calculate the mesh file and save it, then we should just read it when we calculate synthetics. The mesh files consist of elastic constants and coordinates at each grid point and the total amount of the mesh files becomes about 800 Gigabytes. To calculate 30 minute three components synthetic seismograms with 0.075 second sampling interval for all the grid points over the surface of the Earth, it took about 6 hours with 243 nodes of the ES. Using 243 nodes (1944 CPUs) we get about 5.0 Terra FLOPS, which is also about one third of the total peak performance for 243 nodes. This shows that when we increase the nodes from 48 to 243 the performance increases with a factor of five, which means that parallelization efficiency of this code is quite good.

When we calculate synthetic seismograms for the Earth, we need to have both body waves and surface waves all over the globe. Then it is desirable to have one hour synthetics for any seismic stations. In case of 243 nodes of the ES, the maximum CPU time allowed is about 6 hours, since 512 nodes × 3 hours is the upper bound determined by the ES center. Then we save the intermediate results of displacements for all of the grid points to the magnetic tape mass storage system, when we finish the first 30 min calculation. Then at the beginning of the next computation, we read both mesh files and these intermediate results from the magnetic tape system and restart the computation to get one hour synthetic seismograms.

The simulation of global seismic wave propagation has never been achieved before to calculate synthetic seismograms for fully 3-D Earth model with accuracy up to 5 sec. It should be noted that the typical normal-mode summation codes that calculate semi-analytical synthetic seismograms for 1D spherically-symmetric Earth models (e.g., Dahlen and Tromp, 1998) are accurate up to 6 seconds. In other words, the Earth Simulator now allows us to simulate global seismic wave propagation in fully 3D Earth models at periods shorter than current seismological practice for 1D spherically symmetric models.

We choose three earthquakes to calculate synthetic seismograms for fully 3-D Earth model using the SEM code and 243 nodes of the ES. They are: (1) September 2, 1997 Columbia earthquake (Mw 6.7, depth 213.2 km); (2) September 20, 1999 Taiwan earthquake (Mw 7.6, depth 21.2 km); and (3) November 3, 2002 Alaska earthquake (Mw 7.9, depth 15.0 km). To simulate synthetics seismograms for these earthquakes, we use two different ways to represent source mechanisms. For the Columbia event, we take Harvard University's Centroid Moment Tensor solution to represent the earthquake source, which means that the source is represented by a point source. This representation should be adequate if the earthquake size is less than about magnitude seven. However if the earthquake size becomes larger than about seven, the effect of finite source cannot be ignored. Because the earthquake source mechanism can be modeled by a series of fault rupture along a fault plane with finite dimension, we represent earthquake source for these two large earthquakes by a series of point sources distributed both in space and time. We use 210 point sources to represent source mechanism of Taiwan earthquake and 475 point sources for Alaska earthquake.

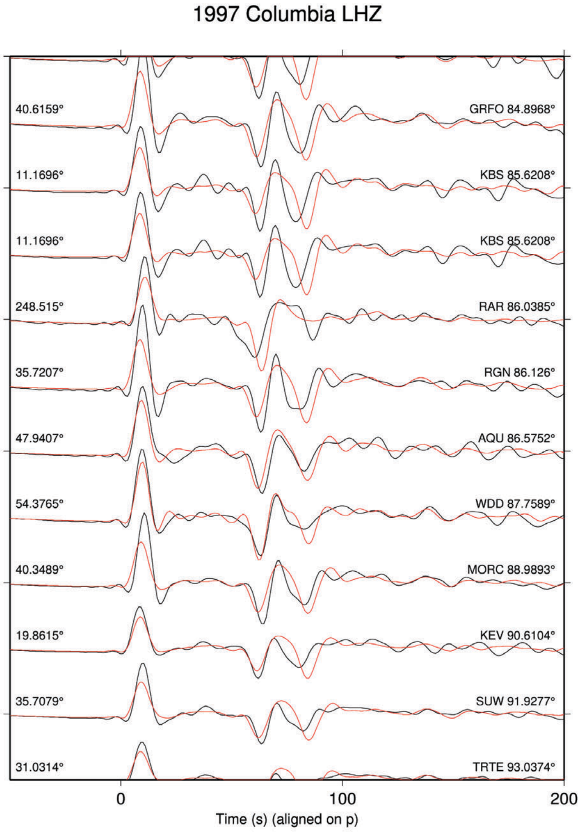

Fig. 1 Broadband data and synthetic displacement seismograms band-pass-filtered with a two-pass four-pole Butterworth filter between periods of 5 and 150 seconds for 1997 Columbia earthquake. Vertical component data (black) and synthetic (red) seismograms are aligned on the arrival time of the P wave. The azimuth is plotted above the records to the left, and the station name and distance are plotted to the right.

We show the results of our simulation for Columbia earthquake in Figure 1. Because there are now more than 500 seismic stations which equipped with the three component broadband seismometers, we may be able to directly compare our synthetics with the observed seismograms. Mapping of the 3D seismic velocity structure of the Earth is traditionally performed using a travel time anomaly of short-period body waves. However the validation of the 3D seismic velocity structure using the synthetic seismograms has never been done before. This is the first attempt to verify if the 3D seismic velocity model obtained by travel time anomaly models the observed seismograms well. Figure 1 compares the vertical component of synthetic seismograms and observed records for those stations with the epicentral distance about 90 degrees. The first peaks in these traces are the first arrival P waves. Because the depth of this Columbia earthquake is deep, there are two so called 'depth phases' after P arrivals. The first one is called pP phase, which means that the P wave from the hypocenter first travels upward and reflects at the surface of the Earth. The second phase is called sP phase, which means that the S wave from the hypocenter first travels upward and reflects at the surface of the Earth and then propagates to the station as P wave. The agreement of the arrival time of the synthetic seismograms and the observed records for P and pP phases is excellent for these stations, which means that 3-D seismic velocity model of P wave we used in this simulation is relatively good, even though the wavelength of this model is long. Therefore this simulation shows that the current 3-D seismic velocity model represents the general picture of the Earth's interior fairly well. However, at the same time, the arrival time for sP phases is not necessarily good for these stations, which shows that S wave velocity structure of this model is not good under the epicenter shown in Figure 1. This information can be directly used to further improve the current 3D seismic velocity model.

Figure 2 shows the results for Alaska earthquake. Because the rupture of this large earthquake has occurred along several hundred kilometers of strike slip fault with the source duration of about 80 seconds it shows strong directivity in amplitude of seismic waves propagating toward the rupture direction. The synthetics calculated by using SEM with 475 nodes of ES show that this directivity can be modeled quite well for both body waves and surface waves.

In summary, our SEM synthetics show that the 3-D seismic velocity model we used in this simulation is relatively good, and differences between data and synthetics can be used for further refining the 3-D Earth model. These synthetics can be used to obtain complex source processes during large earthquakes which occur in subductin zones where the seismic velocity structure is heterogeneous due to subducting oceanic plate.

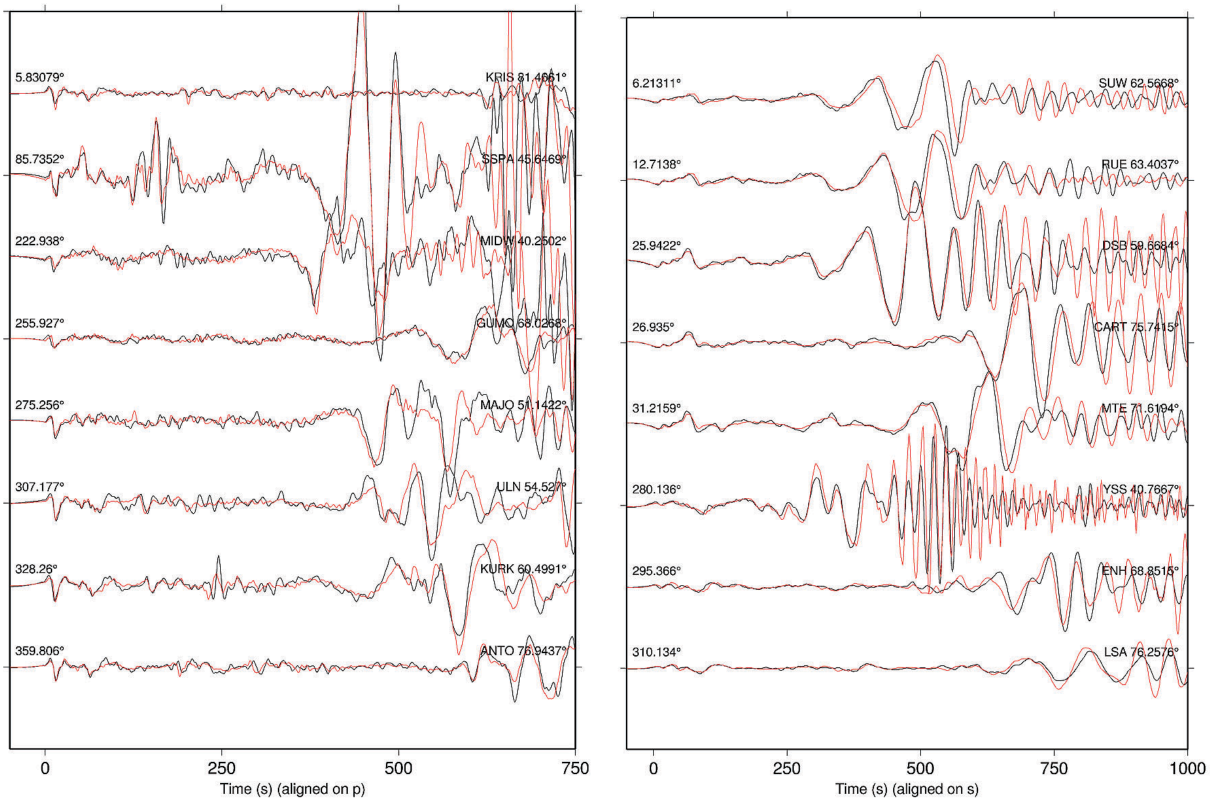

Fig. 2 Broadband data and synthetic displacement seismograms bandpass-filtered with a two-pass four-pole Butterworth filter between periods of 5 and 150 seconds for 2002 Alaska earthquake. Left: vertical component data (black) and synthetic (red) displacement seismograms aligned on the arrival time of the P wave. Right: transverse component data (black) and synthetic (red) displacement seismograms aligned on the arrival time of the S wave. For each set of seismograms the azimtuh is plotted above the records to the left, and the station name and distance are plotted to the right. The transverse component seismograms need to be multiplied by a factor of ten to compare them directly with the vertical component seismograms.

全地球弾性応答シミュレーション

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本研究課題は(1)地震波による地球内部構造のインバージョンと、(2)3次元地球モデル上の地震波伝播シミュレーションを行うことを目的とする。(1)については、長周期表面波の理論波形と内部構造モデルパラメタに対するその偏微分係数を計算するDirect Solution法のコードを地球シミュレータに移植した。移植したコードを用いて、深さ11-888kmの領域の3次元S波速度構造を推定する波形インバージョン解析を実施した。解析周波数帯は2-4.1 mHzである。DSMを使った以前の解析と比較して、10ノード使った計算により地球モデルの水平方向解像度を3×3倍上げることができた。(2)については、3次元地球モデルにおける地震波形を計算するSpectral Element法のプログラムを移植した。地球シミュレータの243ノードを用いて周期5秒まで計算した理論地震記録を、観測された波形記録と比較すると、両者は多くの観測点でよく一致しており、SEMにより計算した理論地震波形記録は地球内部構造及び震源過程の研究に非常に有意義であることを示している。特に、2002年のアラスカ地震に対して周期5秒までの理論地震記録を、有限の断層を破壊が伝播したことを考慮して計算した結果は、破壊の進んだ方向の観測点で地震波の振幅が非常に大きくなる現象をよく再現しており、沈み込み帯のような地震波速度構造の複雑な場所で起きる大地震の震源過程をインバージョンにより求める際にこのような理論地震波形記録が有効となることを示している。

キーワード：理論地震波形記録、3次元地球内部構造モデル、Direct Solution Method、Spectral Element method.