Challenges in Computational Seismology

In December 2004 the big and disastrous Sumatra earthquake, magnitude M9.3, has alerted the public worldwide and drawn attention to the science related to such phenomena. For seismologists, this event provides a unique high quality dataset and therefore better insight to the processes inside the Earth. One of seismology's major tasks is to resolve the structure of the Earth's interior. For decades it is known that the earth, by first approximation, can be described by a spherically symmetric model consisting of a crust, mantle, an outer and an inner core. Since then the challenge has been to extend this model, allowing for lateral variations, such as plumes (hot material arising from the core mantle boundary to the surface) or subduction zones (typically, oceanic crust forced beneath continental crust, when different tectonic plates collide, which subsequently sinks to the core).

In the last 20 years seismologists have developed a variety of techniques to solve this problem resulting in the first three dimensional images of the Earth. One approach is “seismic tomography”, which is comparable to medical tomography. Seismic waves inside the earth are represented as rays penetrating the earth along various paths and recorded with seismometers at different positions all over the globe. In this way the interior of the Earth is illuminated from all directions and angles leading to the construction of a 3D image of seismic velocities inside the Earth.

An alternative approach that arose with the development of computer technology is the simulation of full 3D wave propagation using numerical techniques. Simulation of seismic wave propagation with recent supercomputers that allow for the solution of the complete wave fields through 3D structures, are currently revolutionizing seismology and related fields. Wave propagation on a planetary scale has so far predominantly been carried out using quasi-analytical approaches (e.g., spherical harmonics) and perturbation theory. Only recently the impact of 3D structures on the observed wave field is being addressed as computational power has reached a state where the simulated wave fields can be directly compared to observations.

With the tools developed in the seismology group of the LMU Munich (axi-symmetric approach [1] and spherical sections [2]) as well as a spectral element approach [3] that was developed at the California Institute of Technology, but extended and installed on the Munich supercomputer facilities of the Leibniz-Rechenzentrum Munich, a new era of global seismic data modeling is just beginning.

In the last years the spectral element method (SEM) has become one of the most important tools in computational seismology. Being a modified finite element method it provides a very flexible way of implementing geological structures, which are usually quite irregular and complex in shape. First introduced for fluid dynamics, it was further developed in the 1990's for seismological applications.

Today the SEM can be used to simulate the wave propagation in quite realistic global spherical Earth models including various features such as topography/bathymetry, laterally heterogenous velocity structures in the crust and the mantle, attenuation (anelasticity), anisotropy and also second order effects, as for example Earth's rotation, gravity or the influence of ocean water on the wave field. The advantages of the method are not only the capability of dealing with complex structures, as mentioned above, but also its high accuracy and the possibility of program implementation on parallel computers.

In this method, the model for global wave propagation is built using the “cubed sphere” approach. This is illustrated in Figure 1, where the initial cube is gradually distorted from left to right, until its six faces match the surface of the sphere. The clue in this procedure is to keep a small cube in the interior of the mesh undistorted thus avoiding singularities in the center at r=0. The applied velocity model S20RTS is shown along the faces of the six “chunks” of the cubed sphere in Figure 2 together with a close up look of the spectral element mesh used in our simulations.

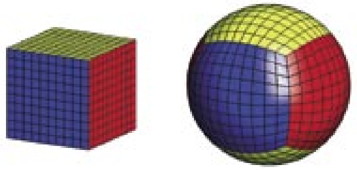

Figure 1: Creation of a global Earth model by expanding an initial cube to the sphere (i.e., cubed sphere mesh). Keeping a small central cube undistorted avoids singularities at r=0.
(Picture courtesy of Peter Danecek)

At the moment we use a model setup that resolves periods down to 20 seconds for standard applications. This setup uses 19 nodes (152 processors) of the HITACHI SR8000 supercomputer of the LRZ. The typical memory needed by our models, is between 60 to 90 GB, depending on whether attenuation is incorporated or not. The typical total runtime is 19 hours (25 including attenuation) for the calculation of a 90 minute seismogram. Figure 3 shows a simulated complex wavefield inside the Earth.

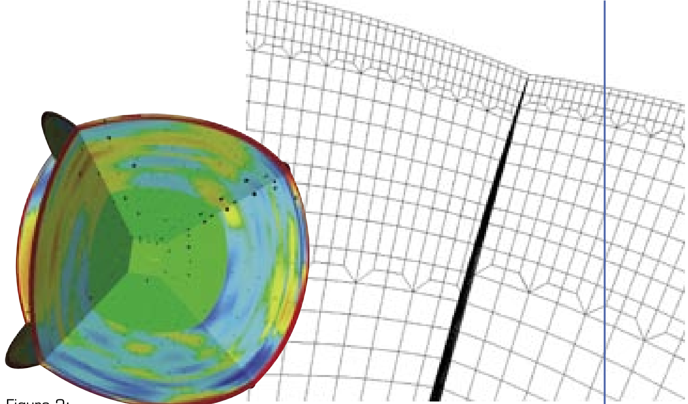

Figure 2:
(a) Cut planes along the borders of the six cubed-sphere chunks showing the three-dimensional S-wave velocity structure S20RTS and
(b) part of the numerical mesh used in the spectral element code

The possibility of calculating wave propagation in all kind of media and structures, opens the way for many applications. Studying the amplification effects of sediment basins beneath large cities for earthquake hazard assessment, looking at the effects of several different theoretical models of earth structures on the wave field, or trying to understand the physics of faulting, just to mention a few. One big challenge in the next decade will be to create a link between seismology and geodynamics, as seismology can provide a snapshot of Earth's current state of convection. This can be used as boundary condition for modeling the dynamical behaviour of the mantle. In turn, one can use the results of geodynamical simulations (Figure 4) and study the wave field going through those models in comparison to purely seismologically constrained models.

However, as stated above, the major goal of global seismology is to improve current Earth models and provide realistic images of our planet's interior. Today, numerical simulations are considered to be the right instrument for this full 3D wave form inversion.

Recently, an idea dating back to 1984 was rediscovered, which suggests combining simulations of wave propagation with its mathematical adjoint. One can think of this as the wave field, that is generated by sources at the receivers and traveling backward in time to the former source. Doing so, one can illuminate those parts of the numerical model that are incorrect compared to reality. Nevertheless, this procedure implies a vast amount of memory storage and even higher memory requirements during runtime. Many of those demanding computations will be necessary to obtain a reliable and high resolution image of the Earth. (For further information please visit www.geophysik.uni-muenchen.de)

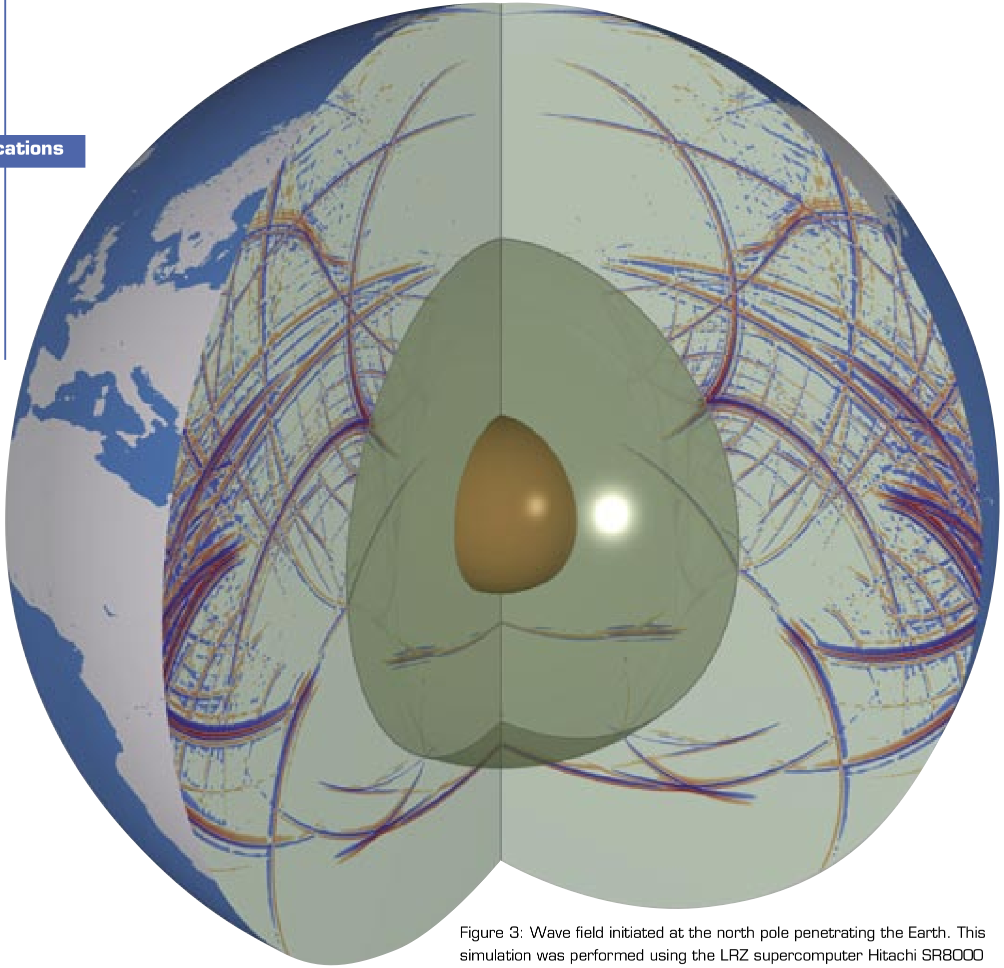

Figure 3: Wave field initiated at the north pole penetrating the Earth. This simulation was performed using the LRZ supercomputer Hitachi SR8000 with a program developed by the seismology group of the LMU Munich

Acknowledgements

We like to acknowledge funding through the KONWIHR Project, and the Leibniz-Rechenzentrum and its steering committees for providing access to the Hitachi SR8000. We also want to thank the LRZ supporting staff for their help. These projects were partly supported through the DAAD (IQN-Georisk) and the German Research Foundation.

References

[1] **H. Igel, T. Nissen-Meyer, G. Jahnke**
Wave propagation in 3D spherical sections. Effects of subduction zones. Phys. Earth Planet. Int., 132:219-234, 2002

[2] **G. Jahnke, H. Igel**
High resolution global wave propagation through the whole Earth: the axi-symmetric PSV and SH case. In EGS General Assembly, Nice, France, 2003

[3] **D. Komatitsch, J. Tromp**
Spectral-element simulations of global seismic wave propagation – I. Validation. Geophys. J. Int., 149:390-412, 2002

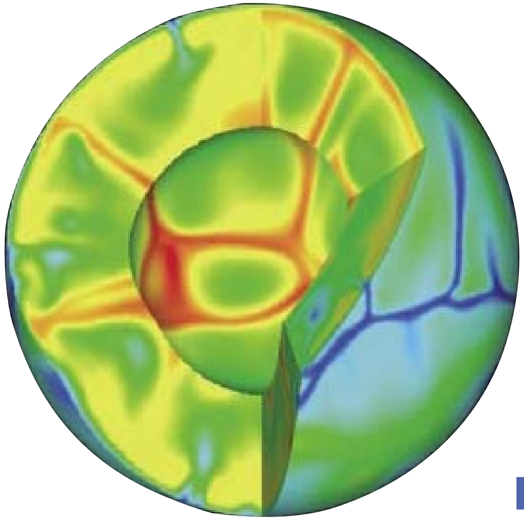

Figure 4: Temperature field inside the Earth resulting from a geodynamical mantle convection model. Numerical Simulations of wave propagation through such models is thought to better provide a link between seismology and geodynamics

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