Calibration of 3D upper mantle structure in Eurasia using regional and teleseismic full waveform seismic data

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Abstract

We present progress in the development of a new approach to build and evaluate Earth models at the regional scale that utilizes full waveform seismograms.

Adequate path calibrations are crucial for improving the accuracy of seismic event location and origin time, size, and mechanism, as required for Comprehensive Nuclear-Test-Ban Treaty (CTBT) monitoring. There is considerable information on structure in broadband seismograms that is currently not fully utilized. The limitations have been largely theoretical. The development and application to solid Earth problems of powerful numerical techniques, such as the Spectral Element Method (SEM), has opened a new era, and theoretically, it should be possible to compute the complete predicted wavefield accurately without any restrictions on the strength or spatial extent of heterogeneity. This approach requires considerable computational power, which is currently not fully reachable in practice.

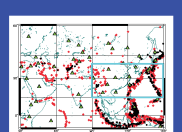
We have implemented an approach which relies on a cascade of increasingly accurate theoretical approximations for the computation of the seismic wavefield to develop a model of regional structure for the area of Eurasia located between longitudes of 30 and 150 degrees E, and latitudes of -10 to 60 degrees N. The selected area is highly heterogeneous, presenting a challenge for calibration purposes, but it is well surrounded by earthquake sources and a significant number of high quality broadband digital stations exists, for which data are readily accessible through the Incorporated Research Institutions for Seismology (IRIS) and the Federation of Digital Seismic Networks (FDSN).

The initial model is derived from a large database of teleseismic surface waveforms using well-developed theoretical approximations, the Path Average Approximation (PAVA) and Nonlinear Asymptotic Coupling Theory (NACT). Both approaches assume that waveforms are only sensitive to structure along the great circle path between source and receiver, which is adequate for the development of a smooth velocity model. This model is already parametrized and developed at relatively short wavelengths on the order of 200 km in the best-sampled regions and 400 km elsewhere.

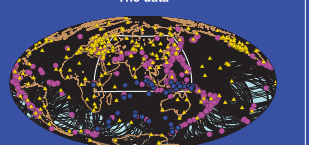
We are refining this velocity model in a smaller subregion using a more accurate theoretical approach. We utilize an implementation of a 3D Born approximation, which takes into account the contribution to the waveform from single scattering throughout the model, including points off the great-circle path, and which has been shown to accurately represent the wavefield in several situations where approximations such PAVA and NACT are problematic. The Born approximation has already been used to perform a preliminary inversion of regional waveforms for a smaller subregion between longitudes 90 and 145 degrees E, and latitudes 15 and 40 degrees N with a subset of the original dataset consisting of the source-receiver pairs contained within the region. However, to improve resolution, we are implementing an inversion scheme where PAVA and NACT are used to compute sensitivity outside the region and the Born approach inside the region. This inversion is being complemented by forward modeling of regional broadband waveforms using 2D and 3D finite element codes. This allows us to better constrain shorter wavelength and crustal structure.

There is also now a regional implementation of the SEM code available, and work is underway to refine the model further using a novel inverse approach where the synthetic seismograms in the inversion are calculated with SEM using a stacked-source approach.

The region



The data



The large Eurasian region of interest (above) is comprised between latitudes -10 and 60 degrees N and longitudes 30 and 150 degrees E. This area is highly heterogeneous and characterized by a wide spectrum of tectonic regimes. The large number of high quality broadband digital seismic stations (green triangle s) located in this area, for which data are readily accessible through the Incorporated Research Institutions for Seismology (IRIS) and the Federation of Digital Seismic Networks (FDSN), as well as the elevated seismicity (shallow (red) and deep (black) events with a Harvard CMT solution for the period 1998-2002) characterizing this region are the necessary requirements for the construction of a high resolution tomographic model for such a complex area. The bold blue lines delimit the region for which a refined velocity model is being built.

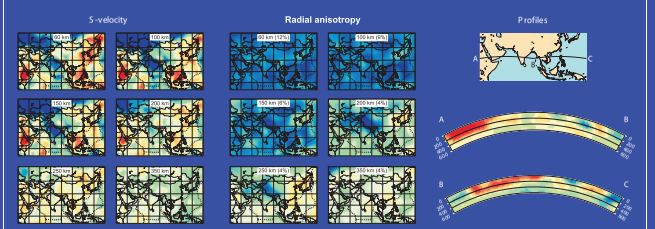
The used global dataset of surface waveforms cross ing the region of interest consists of waveforms from the existing database at Berkeley used over the last 10 years for global tomography (e.g. Li and Romanowicz (1996) and Panning and Romanowicz (2004)) and newly collected data. The used dataset contains 38,826 3-component waveforms from 393 teleseismic events (purple circles: events for which data existed in the database; blue circles: events for which data have been newly collected) recorded at 169 broadband seismic stations (yellow triangles). The data has been processed using a semi-automated algorithm, which removes glitches, and checks for many common problems (timing, instrument response, noise). Each seismogram is filtered (periods > 60 s) and divided into windows containing individual fundamental and higher mode energy packets.

References

Capdeville, Y. (2005) An efficient Born normal mode method to compute sensitivity kernels and synthetic seismograms in the Earth, Geophys. J. Int., 163 , 639-646.
Capdeville, Y., Y. Gung and B. Romanowicz (2005) Towards global earth tomography using the spectral element method: a technique based on source stacking, Geophys. J. Int., 162, 541-554
Fornberg, B., E. Lehto and C. Powell (1988) Stable calculation of Gaussian-shaped radial basis function, J. Comp. Phys., 115, 37-49
Komatitsch, D., and J. Tromp (1999) Introduction to the spectral-element method for 3-D seismic wave propagation, Geophys. J. Int., 139, 806-822.
Komatitsch, D., and J. Tromp (2002) Spectral-element simulations of global seismic wave propagation-I. Validation, Geophys. J. Int., 149, 390-412.
Li, X.D., and B. Romanowicz (1995) Comparison of global waveform inversions with and without considering cross branch coupling, Geophys. J. Int., 121, 695-709.
Li, X.D., and B. Romanowicz (1996) Global mantle shear velocity structure from the inversion of body, surface and higher mode waveforms, Geophys. J. Int., 101, 22245-22273.
Panning, M., and B. Romanowicz (2004) Inferences on flow at the base of Earth's mantle based on seismic anisotropy, Science, 33, 351-353.

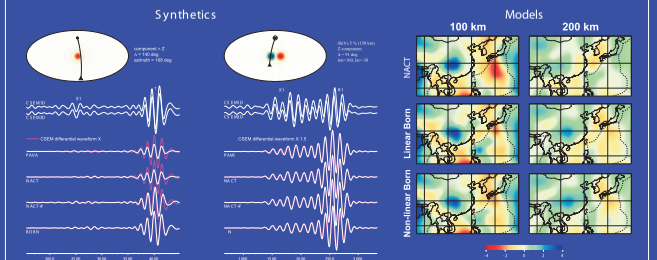
Starting model from 2D kernels

This radially anisotropic model, which covers the large Eurasian region, has been developed using the Path Average Approximation (PAVA) and the Nonlinear Asymptotic Coupling Theory (NACT - Li and Romanowicz, 1995). These approaches consider the 1D (PAVA) and 2D (NACT) sensitivity of waveforms to structure in the vertical plane along the great-circle path between the source and the receiver. The isotropic S-velocity structure (left) is parametrized laterally in level 6 spherical splines, which correspond to lateral resolution of ~200 km, and imaged anomalies are with respect to PREM. The radial anisotropic parameter $\xi = (v_{sh}/v_{sv})^2$ (center), which is less well constrained, is parametrized in level 5 splines, which have resolution of 400 km, and plotted anomalies are relative to isotropy (saturation level is given in %). Several tectonic features are clearly imaged in our model: slow back-arc basins (Japan and South China Sea), fast subducting slabs (e.g. Mariana, Japan and Philippine subduction zones), fast continental platforms (e.g. Eastern European Platform, Deccan province) and slow upwelling regions (Red Sea and Afar).



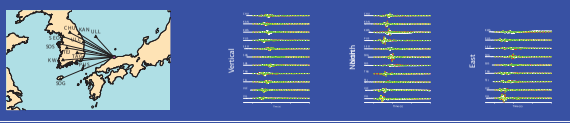
Preliminary models from 3D kernels

We are refining the above model in a smaller subregion between longitudes 90 and 145 degrees E, and latitudes 15 and 40 degrees N using a subset of the original dataset (vertical component records from 180 events where the source-receiver paths are contained within the larger Eurasian region). We utilize a more accurate theoretical approach that accounts for the 3D sensitivity of the waveform to velocity structure. 3D waveform sensitivity kernels are calculated using 2 different normal-mode based implementations of the Born (single scattering) approximation. The first approach maps the effect of structure into linear perturbations to the amplitude of the reference seismogram (Capdeville, 2005). The 3D sensitivity of this approach provides a great improvement over previous approaches which neglect off-path sensitivity for some complex paths (Synthetics, left). For some relatively simple paths through strong anomalies, however, a linear amplitude perturbation approach can be outperformed by an approach that instead perturbs the phase of the reference seismograms such as PAVA (Synthetics, right), which is non-linear in amplitude. For this reason, we chose to also explore a Born implementation where the effect of the average structure along the great-circle path is treated as a perturbation to the phase of the seismogram as in PAVA, while the effects of 3D sensitivity including off-path sensitivity are included as a linear amplitude perturbation. We developed 2 preliminary "low resolution" isotropic velocity models (level 5 spherical splines) of the subregion using these 2 Born implementations (Models, 4 bottom panels). Structure outside the subregion is modeled using NACT in both cases. Good agreement is observed between the models, which are also consistent with results obtained using the NACT approximation (Models, top 2 panels).



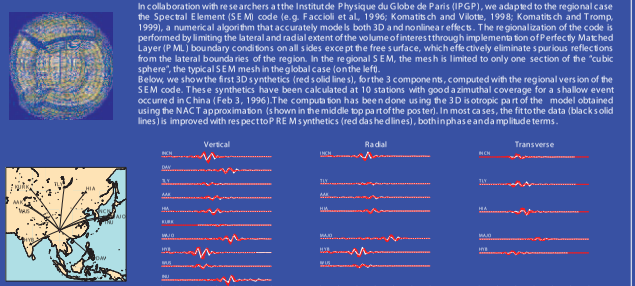
1D and 3D finite element synthetics

During the validation phase, 2D/3D forward modeling of regional waveforms will be performed using the e3d elastic finite difference code of Larsen and Schultz (1995). In particular, we will select paths displaying unmodeled waveform complexity to assess the level of additional calibration required especially concerning sharp discontinuities.
Below, we compare observed seismograms (solid white) at 11 stations in Korea, for an event in Japan (Oct 6, 2000), with preliminary synthetic waveforms computed for: 1D PREM for crustal and mantle structure (dashed yellow), 1D PREM for mantle structure and CRUST2.0 (dashed green), and the isotropic part of the 3D anisotropic model derived with NACT, for the mantle structure and CRUST2.0 (solid red).



3D spectral element synthetics

In collaboration with researchers at the Institut de Physique du Globe de Paris (IPGP), we adapted to the regional case the Spectral Element (SEM) code (e.g. Faccioli et al., 1996; Komatitsch and Vilotte, 1998; Komatitsch and Tromp, 1999), a numerical algorithm that accurately models both 3D and nonlinear effects. The regionalization of the code is performed by limiting the lateral and radial extent of the volume of interest through implementation of Perfectly Matched Layer (PML) boundary conditions on all sides except the free surface, which effectively eliminate spurious reflections from the lateral boundaries of the region. In the regional SEM, the mesh is limited to only one section of the "cubic sphere", the typical SEM mesh in the global case (on the left).
Below, we show the first 3D synthetics (red solid lines), for the 3 components, computed with the regional version of the SEM code. These synthetics have been calculated at 10 stations with good azimuthal coverage for a shallow event occurred in China (Feb 3, 1996). The computation has been done using the 3D isotropic part of the model obtained using the NACT approximation (shown in the middle top part of the poster). In most cases, the fit to the data (black solid lines) is improved with respect to PREM synthetics (red dashed lines), both in phase and amplitude terms.



Outlook

(1) Refinement, in the selected subregion, of the high resolution 3D anisotropic model derived with NACT, using the developed implementation of the 3D Born (single scattering) approach and the entire surface waveform dataset.
(2) Further refinement of the model obtained in (1), using the regional implementation of SEM for the calculation of synthetics (and a stacked-source method (Capdeville et al., 2005) to increase computational efficiency) and the Born approach for the computation of partial derivatives with respect to model parameters.
(3) Validation and improved calibration of the model obtained in (2) using Ground Truth datasets from the Knowledge Base, teleseismic receiver functions, broadband waveform forward modeling and surface wave group velocities.

Acknowledgements

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