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 develop 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 begun work on an approach that 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 North. The selected area is particularly suitable for the purpose of this experiment, as it is highly heterogeneous, presenting a challenge for calibration purposes, but it is well surrounded by earthquake sources, and, even though they are sparsely distributed, a significant number of high quality broadband digital stations exist, 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 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.

We plan to refine this velocity model 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 situated outside of the great circle path. We perform verification tests of this approach for synthetic models and show that it can accurately represent the wavefield as predicted by numerical approaches such as SEM in several situations where approximations such as PAVA and NACT are insufficient.

The Born approximation will be used to perform an inversion of regional waveforms for a smaller subregion between longitudes 90 and 150 degrees E and latitudes 15 and 40 degrees N. The waveforms are a subset of the original dataset consisting of the source-receiver pairs contained within the region to avoid aliasing structure from outside the region into the model.

In future work, the model will be further refined using a novel inverse approach utilizing a regional implementation of the SEM code for calculation of the synthetic seismograms used in the inversion.

OBJECTIVES

The primary objective of this research is to develop and apply an approach to utilize increasingly advanced theoretical frameworks and numerical methods in order to obtain improved regional seismic structure calibration. Specifically, a large-scale regional Eurasian model will first be developed from a large dataset of seismic waveforms using the path-average approximation (PAVA) and Nonlinear Asymptotic Coupling Theory (NACT) (Li and Romanowicz, 1995), which are well-developed normal-mode based approaches which consider 1D and 2D waveform sensitivity respectively along the great-circle path between source and receiver. This model will then be refined in a smaller region using an implementation of Born single-scattering theory (Capdeville, 2005), which more accurately represents the 3D sensitivity of the seismic wavefield. Finally, we will utilize the Spectral Element Method (SEM), a numerical approach that accurately models both 3D and nonlinear effects (e.g., Faccioli et al., 1996; Komatitsch and Vilotte, 1998; Komatitsch and Tromp, 1999). To conserve computational resources for this step, we will restrict the use of spectral elements to the upper mantle by coupling to a normal mode solution (Capdeville et al., 2002) and applying appropriate boundary conditions. Additionally we plan to utilize a novel approach with stacked sources (Capdeville et al., 2003) to further speed computation.

A further objective of this research is to perform validation and improved calibration of the model described above using a variety of approaches and datasets, including ground truth datasets from the Knowledge Base. Specifically, we plan to apply teleseismic receiver function modeling, regional broadband data forward modeling, and surface wave group velocity measurements to test and improve the model using data not included in the original inversion.

This research can then serve as a proof of concept for applying a similar approach to the calibration of seismic structure in other regions of the Earth.

RESEARCH ACCOMPLISHED

A global dataset of surface wave waveforms crossing the region of interest was collected (Figure 1). We started from the existing waveform database that was collected at Berkeley over the last 10 years for the construction of global mantle tomographic models (Li and Romanowicz, 1996; Megnin and Romanowicz, 2000; Gung et al., 2003; Panning and Romanowicz, 2004). The goal was to complement this global database in the region of interest. After choosing data from 20 new events, and adding in the data from the existing dataset, we now have 38826 3-component waveforms from 393 events recorded at 169 stations. The data has been processed using an automated algorithm, which removes glitches, and checks for many common problems related to timing, poor instrument response, and excessively noisy windows. A weighting scheme has been applied to ensure even distribution of data across the region.

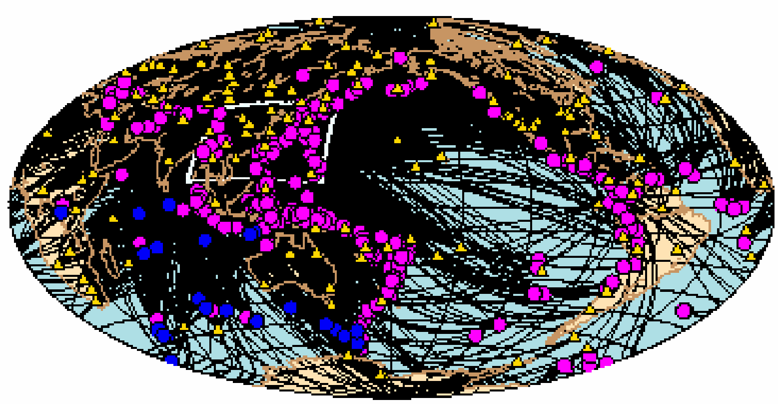

Figure 1. Source-receiver paths of waveforms included in the dataset. Receivers are shown as yellow triangles, events that are part of the previously existing waveform collection are shown by purple circles, and newly collected events are shown with blue circles. The region of interest is shown by the white rectangle.

Technical work continues on developing the theoretical and numerical approaches that consider 3D waveform sensitivity. Work is underway to adapt the SEM code, which will be used in the final inversion step to the regional case. Because coupling the SEM solution to a 1D mode solution at a spherical interface is a key feature of the coupled SEM (CSEM) code we plan to use, limiting the region to the upper mantle is easily accomplished using previously existing versions of the code and has been done. Limiting the 3D portion of the model to a selected region, however, requires larger changes to the code. Currently, work is underway to most efficiently integrate this into the code using the latest algorithms to apply boundary conditions at the boundaries of the region of interest for the SEM code. However, while preparation of that code continues, we have proceeded to develop a complementary 3D inversion approach, which incorporates many of the advantages of the CSEM inversion approach discussed in the proposal. As shown in Figure 2, very similar accuracy in defining the partial derivatives with respect to model parameters can be obtained using a 3D implementation of the Born (single scattering) approximation. We are adapting an implementation of this approach to be used for inverting our surface wave dataset. Because the Born approach is somewhat less numerically intensive than the CSEM-based inversion, an added benefit is that stacking of sources is no longer required, and therefore the waveforms can be divided into packets. Using packets is advantageous as it allows us to only use the highest quality data from the waveform dataset, while removing noisy portions of the seismograms.

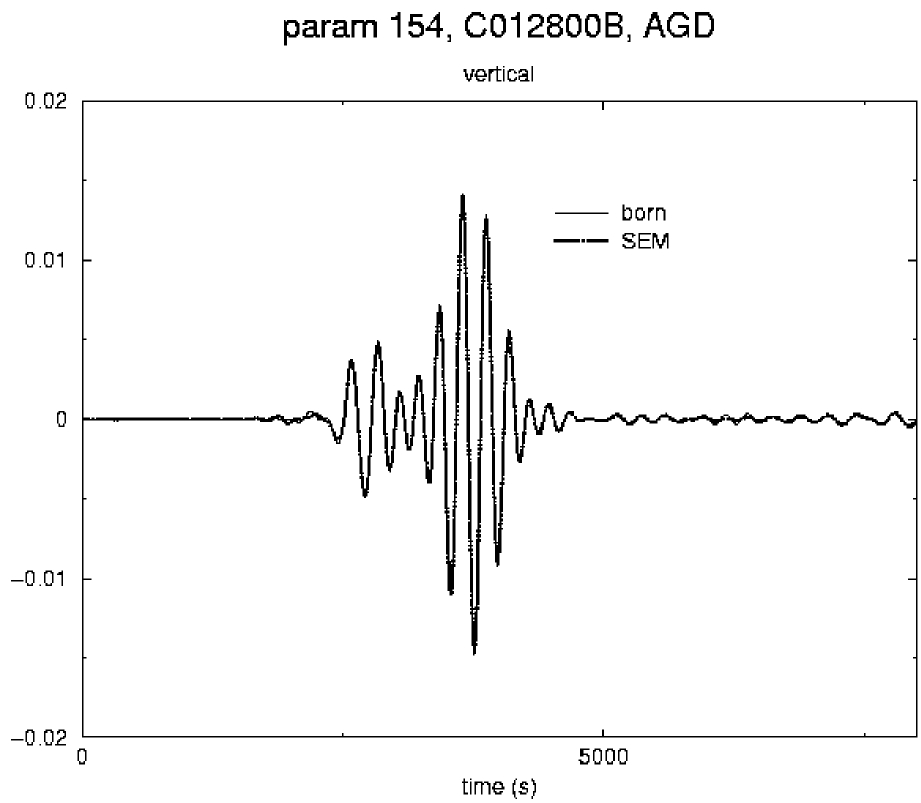

Figure 2. Comparison of partial derivative seismograms computed with SEM (dotted line) and normal modes Born approximation (solid line) for an epicentral distance of 92 degrees. The model parameter with respect to which partial derivatives are computed is between the source and the receiver, slightly off path.

To further test the effectiveness of the Born code, we have performed several tests which compare the Born code with other theoretical approximations. For example, for a case of a source-receiver path passing through a single slow anomaly centered at 220 km depth (Figure 3), all theoretical approaches produce seismograms consistent with those predicted by CSEM. However, when the path passes just outside the anomaly (Figure 4), PAVA and NACT, which only consider structure along the great-circle path, do not accurately map the phase or the amplitude of the fundamental mode differential seismogram. NACT plus focussing (NACT+F), an additional theoretical approximation that also includes sensitivity to across-path derivatives of structure, and the Born code both do a better job of reproducing the CSEM data. Another slightly more realistic case to consider is when a path passes through both positive and negative velocity anomalies along the source-receiver path (figure 5), as would certainly occur for many source-receiver paths across Eurasia. In this case, PAVA sees nothing, as the two anomalies cancel out, while the 2D sensitivity of NACT predicts the amplitude but not the phase of the overtone phase (X1), or the fundamental mode (R1). NACT+F does a reasonable job of predicting the amplitude of the differential seismogram but does not match the phase well, particularly in R1. The Born code, on the other hand, correctly predicts the phase of the differential seismogram throughout, although it overpredicts the amplitude of the R1 portion of the seismogram.

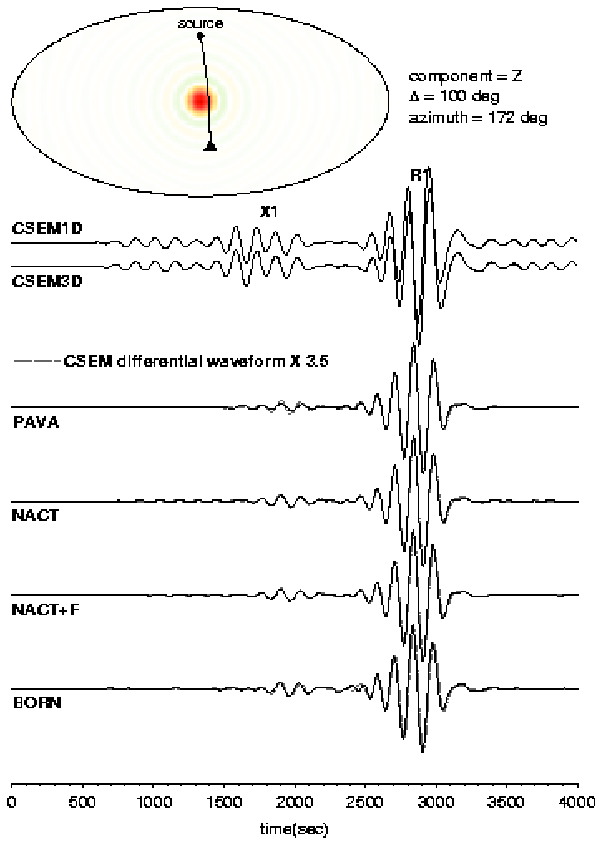

Figure 3. Comparison of performance of several mode-based approximations used in tomographic modeling. The map shows the source-receiver geometry and the velocity model, which consists of a ellipsoidal anomaly 5% slower than the background centered at 220 km depth. The top two traces are the SEM synthetics calculated from the 1D background model and the 3D model. The remaining traces show the differential waveforms obtained by subtracting the waveform produced by the 1D model. For each of the approximations shown, the differential SEM waveform is shown as a dotted line, and the waveform from the approximation. Results are shown for the PAVA, NACT, NACT plus a higher-order focusing approximation (NACT+F), as well as the 3D Born approximation.

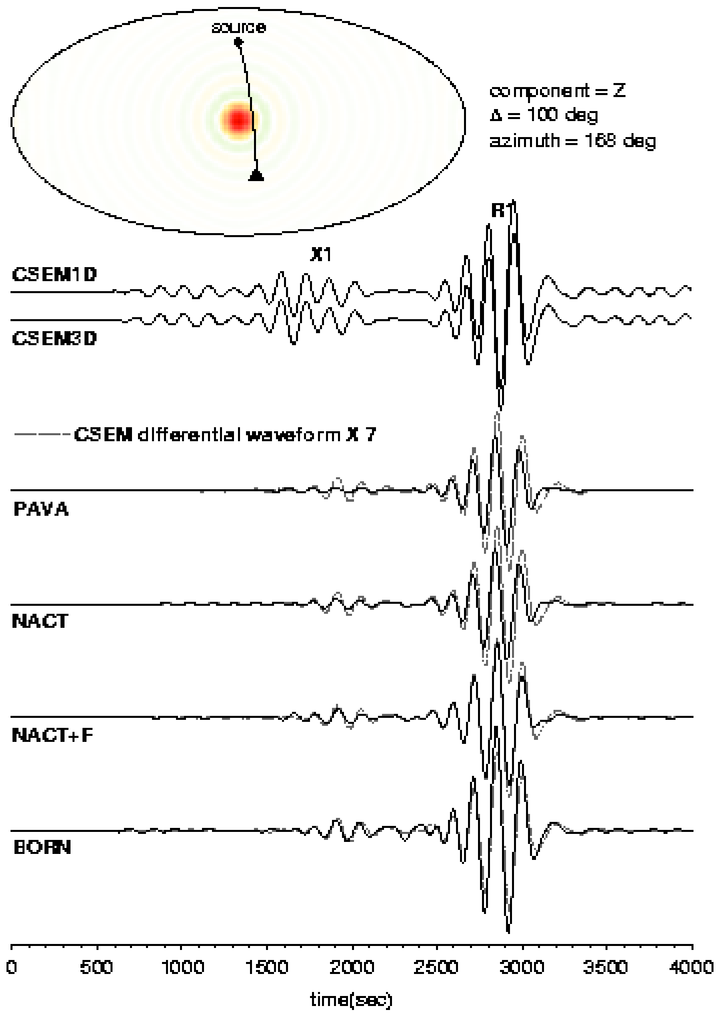

Figure 4. Same as Figure 3 for a path that passes slightly east of the anomaly.

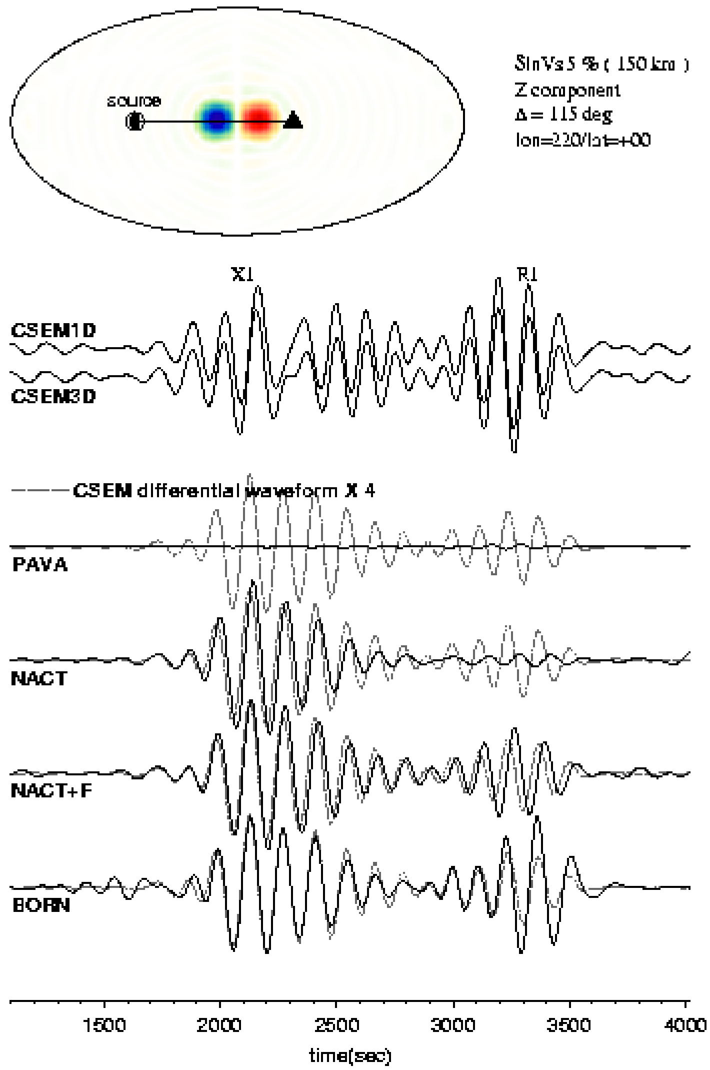

Figure 5. Similar to Figure 3 and 4, but for a model with two ellipsoidal anomalies of +/- 5% centered at 150 km depth and also using a realistic moment tensor source.

With the success of the Born code in predicting the 3D effects of structure in these particular paths, we have begun work to implement this theory into an inverse approach. The starting 3D S velocity model for this inversion will be based on our existing 3D global models. We have converted the global parameterization used in our global tomography to one based on local functions, specifically spherical splines. This parameterization is now available for inversions using the approximate NACT methodology to develop the first iteration model and is now also implemented for an inversion using the Born code.

CONCLUSIONS AND RECOMMENDATIONS

Using better theoretical and numerical approaches in regional tomographic modeling is very important for adequate seismic path calibration. Here a 3D implementation of Born scattering theory is shown to accurately model 3D effects for a few particular structures. Utilizing this theory in combination with the dataset of waveforms already gathered should allow for an improved model of Eurasian upper mantle velocity structure.

Further work on using SEM, a numerical approach which takes into account 3D and nonlinear effects, in an inversion should offer continued improvement of the model. Additionally, other approaches and datasets, including ground truth datasets from the Knowledge Base, teleseismic receiver functions, broadband waveform forward modeling, and surface wave group velocities allow for validation and improvement of the model.

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REFERENCES

Capdeville, Y., E. Chaljub, J. P. Vilotte, and J. P. Montagner (2002), Coupling the spectral element method with a modal solution for elastic wave propagation in global earth models, *Geophys. J. Int.* 152: 34–66.

Capdeville, Y., B. Romanowicz, and Y. Gung (2003), Global seismic waveform tomography based on the spectral element method, abstract, joint AGU/EGS/EUG Meeting, Nice, April 2003.

Capdeville, Y. (2005), An efficient Born normal mode method to compute sensitivity kernels and synthetic seismograms in the Earth, submitted to *Geophys. J. Int.*

Faccioli, E., F. Maggio, A. Quarteroni, and A. Tagliani (1996), Spectral-domain decomposition methods for the solution of acoustic and elastic wave equations, *Geophysics* 61: 1160–1174.

Gung, Y., B. Romanowicz, and M. Panning (2003), Anisotropy and lithospheric thickness, *Nature* 422: 707–711.

Komatitsch, D. and J. P. Vilotte (1998), The spectral element method: an effective tool to simulate the seismic response of 2D and 3D geological structures, *Bull. Seism. Soc. Am*. 88: 368–392.

Komatitsch, D. and J. Tromp (1999), Introduction to the spectral-element method for 3-D seismic wave propagation, *Geophys. J. Int.* 139: 806–822.

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 model developed using nonlinear asymptotic coupling theory, *J. Geophys. Res.* 101: 22,245–22,273.

Megnin, C. and B. Romanowicz (2000), The 3D shear velocity structure of the mantle from the inversion of body, surface and higher mode waveforms, *Geophys. J. Int.* 143: 709–728.

Panning, M. and B. Romanowicz (2004), Inferences on flow at the base of Earth's mantle based on seismic anisotropy, *Science* 303: 351–353