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 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 North. 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 exist, for which data are readily accessible through 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. This model is already parameterized 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 of the great circle path, which has been shown to accurately represent the wavefield in several situations where approximations such as 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.
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 has been developed from a large dataset of seismic waveforms using the PAVA and 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. We are now refining this model in a smaller region using a linear implementation of Born single-scattering theory (Capdeville, 2005), which more accurately represents the 3D sensitivity of the seismic wavefield, as well as comparing using a non-linear modified implementation of the Born kernels. Finally, we will utilize the SEM, a numerical approach that accurately models both 3D and non-linear effects (e.g., Faccioli et al., 1996; Komatitsch and Vilotte, 1998; Komatitsch and Tromp, 1999), which is now being adapted to the regional case. 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 Perfectly Matched Layer (PML) 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. While these additional datasets can help improve all aspects of the model, we anticipate the greatest improvement in the shallow structure, particularly the crust, which is not as well constrained by the longer-period data used in the initial model development.

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. 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 38,826 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 insure even distribution of data across the region.

We have developed a starting radially anisotropic model using NACT (Li and Romanowicz, 1995) which covers the large Eurasian region (Figures 1 and 2). This model is parameterized laterally in spherical splines. The isotropic velocity (Figure 1) is parameterized in level 6 splines, which correspond to lateral resolution of ~200 km, while the radial anisotropic parameter $\xi (V_{S\perp}^2/V_{SV}^2)$ (Figure 2), which is less well-constrained, is parameterized in level 5 splines, which have resolution of ~400 km.

We have nearly completed the technical work on developing the theoretical and numerical approaches which consider 3D waveform sensitivity. A regional version of the SEM code is in final debugging in collaboration with researchers at Institut de Physique du Globe de Paris (IPGP). This code takes the well-developed global SEM code, and modifies it to limit the lateral and radial extent of the volume by implementing PML boundary conditions on all sides except the free surface, which effectively eliminate spurious reflections from the lateral boundaries of the region. The final technical work on this code is some debugging on the implementation of attenuation and interpolation of the 3D velocity model. 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 coupled spectral element method (CSEM) inversion approach discussed in the proposal. As shown in previous reports for this project, 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. For this reason, we intend to use
this approach for definition of the partial derivatives with respect to model parameters for the development of the final model using SEM for the forward calculations, as using the numerical approach for partial derivatives becomes prohibitively expensive for models with large number of model parameters. We have also adapted this approach to directly invert our surface wave dataset until the availability of the SEM code. 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 1](image.png)

Figure 1. Starting isotropic shear velocity model derived using NACT. The lateral parameterization in terms of level-6 spherical splines, gives a resolution of ~200 km. Values are shown as percent perturbations to the isotropic velocity of the reference model, PREM.
Figure 2. Maps of $\xi (V_{SH}/V_{SV})$ for the starting model. Values are shown relative to an isotropic model ($\xi = 1.0$), including the anisotropy of the starting model above 220 km. Blue regions represent regions where $V_{SH}>V_{SV}$ and red regions where $V_{SV}>V_{SH}$.

While awaiting the SEM inversion, we have been exploring preliminary refinements of the model using 3D sensitivity in the subregion using vertical component records from 180 events where the source-receiver paths are contained within the larger region. For this preliminary work, we are focusing on isotropic velocity expanded in level 5 splines in order to determine what partial derivative approach will give the best results when used in conjunction with the regional SEM code. We explore two different implementations of 3D Born single-scattering theory. 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 (Figure 3). 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 seismogram such as the PAVA (Woodhouse and Dziewonski, 1984) (Figure 4), which is non-linear in amplitude. For this reason we choose to also explore an 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. This can be easily accomplished because we can show that the linearized version of PAVA is already included due to coupling between modes of different frequencies along a given dispersion branch (Romanowicz, 1987), and we can subtract this contribution from our linear Born kernels, and replace it with the non-linear contribution from PAVA.

Figure 3. Synthetic test of various theoretical approaches for a path grazing the edge of 5% slow anomaly. The top two traces are synthetics calculated in SEM for the 1D reference model and the 3D perturbation shown at top. The bottom four traces are differential seismograms (3D synthetic minus reference trace) calculated for 4 different theoretical approaches (solid) plotted over the SEM differential seismograms (dotted). PAVA and NACT are asymptotic approaches with 1D and 2D sensitivity respectively constrained to the great-circle path, while NACT+F uses derivatives of structure across the path to approximate the effects of focusing. Born is the 3D implementation of single-scattering discussed in the text.
While all approximations have similar performance, note that the first 3 approaches, which perturb the phase of the seismogram perform slightly better, particularly for the fundamental mode R1.

We develop two models of the subregion using these two Born implementations. Structure outside the subregion is modeled using NACT in both cases. Because the preliminary models are developed with only vertical component data, anisotropy is constrained to be equal to the reference model within the region. From depths of 100 km to 250 km, the two models (Figures 5 and 6) are in good agreement. At a depth of 60 km, the results are more unstable, with relatively large differences between models developed with linear Born (Figure 5), modified non-linear Born (Figure 6), and one developed with NACT using the same dataset and the same relatively low level of resolution (not shown). Work is ongoing to determine the origin of this instability. However, the stable structure at depth in agreement with other models of the region shows that the partial derivatives calculated in this manner should be useful when developing the final model using SEM. Further work is needed to determine whether there is an advantage to be gained by using the modified non-linear Born kernels rather than the linear partials in the final inversion.
Figure 5. Shear velocity model developed using linear Born kernels for 180 events recorded on the vertical component. Values shown are perturbations relative to the isotropic average of the reference model.
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, while potential improvements to the method are also explored. This approach should allow for relatively rapid calculation of partial derivatives for use in an inversion based on the regional implementation of SEM.

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


