VALIDATING 3D GEOPHYSICAL MODELS FOR USE IN GLOBAL TRAVEL-TIME CALCULATION FOR IMPROVED EVENT LOCATIONS

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ABSTRACT

Towards developing a fully global, seamless travel-time calculation and event location capability, we evaluate existing 3D velocity models to test their ability to correctly predict travel times for ground-truth (GT) data. We have identified 513 GT5 or better events within the Los Alamos National Laboratory (LANL) seismic database, which provide us with 58,970 arrivals for our study.

We first verify that calculated travel times through our global, 3D ellipsoidal parameterization of the AK135 model are within our tolerance of 0.2 s to Tau-P predictions. Subsequently, we compare observed teleseismic P-wave travel times for our GT dataset to those predicted by dynamic ray tracing through a variety of crustal models superimposed on an AK135 mantle. These models were developed either through ad hoc combination of regional models, or through fitting of straight-ray propagation through a Cartesian system with smoothing over 1 to 3 degree grids. We examine the improvement to travel-time predictions for these models compared to the AK135 alone.

We next examine a recently published 3D, global mantle model (MITP08). This model was developed by inverting travel-time residuals along fixed rays for an AK135 model, with a Crust2.0 correction. When we adhere to the AK135 ray paths to calculate our GT event residuals, we find that the MITP08 model provides significant improvement to travel-time prediction compared to other models tested to date. Not surprisingly, when we calculate the travel times using dynamic rays, the performance is poorer.

GT travel times are best predicted through any given model when the calculation is performed using a method close to that used in generation of the model, as expected. Such considerations as Earth ellipticity correction, fixed ray vs. dynamic ray tracing, crustal corrections (for mantle models) and mantle values (for crustal models) need to be applied appropriately for a fair evaluation. Conversely, any model made available to the community is of little practical use unless the method of its derivation is also provided, or clearly explained so that it may be replicated for travel-time calculation and location procedures. Due to the existing heterogeneity in models and their methods of derivation, we conclude that towards our development of a seamless, global model and locator, existing models may best serve as starting models for a global inversion using a single, consistent ray tracing and travel-time calculation approach.

OBJECTIVES

The nuclear monitoring community strives to continually improve its ability to estimate seismic event locations and associated uncertainties through a variety of means. Nonlinear location algorithms, relative event relocation, waveform matching, and a plethora of seismic velocity models have all been applied to the problem over many years. The fundamental goal critical to obtaining better locations is the ability to better predict seismic phase travel times through the earth. Thus the creation of improved seismic velocity models is of paramount importance to solving the problem, yet the models themselves are of little use to the monitoring community if their derivation and method of travel-time fitting are not also available.

For many practical reasons, individual research groups often focus only on a particular region when producing their models, and these models are often not tested in a fully global paradigm due either to the incompatibility of their methods (small regions modeled in Cartesian systems, fixed great-circle paths assuming horizontal propagation, and so forth). It is our assertion that for truly robust and comprehensive location capability, the monitoring community must move towards fully integrated, global 3D models capable of fitting all types of observables (phases) that may be recorded and reported for seismic events. The model will be seamless, and no *ad hoc* switching among models (local to regional to teleseismic) should be employed within the location algorithm.

In concert with the global ray bending development of Sandia National Laboratories (Ballard et al., 2009), we begin testing the travel-time prediction capabilities of various models delivered to the monitoring community and we explore the adjustments required to incorporate these models into the fully elliptical whole-earth structure.

RESEARCH ACCOMPLISHED

Validation Dataset

To explore the travel-time prediction capabilities of test models, we have compiled a catalog of travel times for 513 events in the LANL Ground-Based Nuclear Explosion Monitoring database (Begnaud et al., 2004; Begnaud, 2005), which comply with a Ground Truth (GT) level (Bondár et al., 2004) of less than 5 km. Sources at this GT level are largely man-made, and are comprised of both chemical and nuclear explosions, including the Peaceful Nuclear Explosions (PNE's) recorded during the U.S.S.R. Deep Seismic Sounding (DSS) campaigns (Morosov et al., 2005). Sixty-seven very well-located earthquakes are also included. We report on preliminary tests using this dataset, whose initial examination is applied to teleseismic *P* arrivals. Figure 1 shows the ray coverage for Eurasia for the 58,970 source-receiver *P*-arrival pairs that we include in our study.

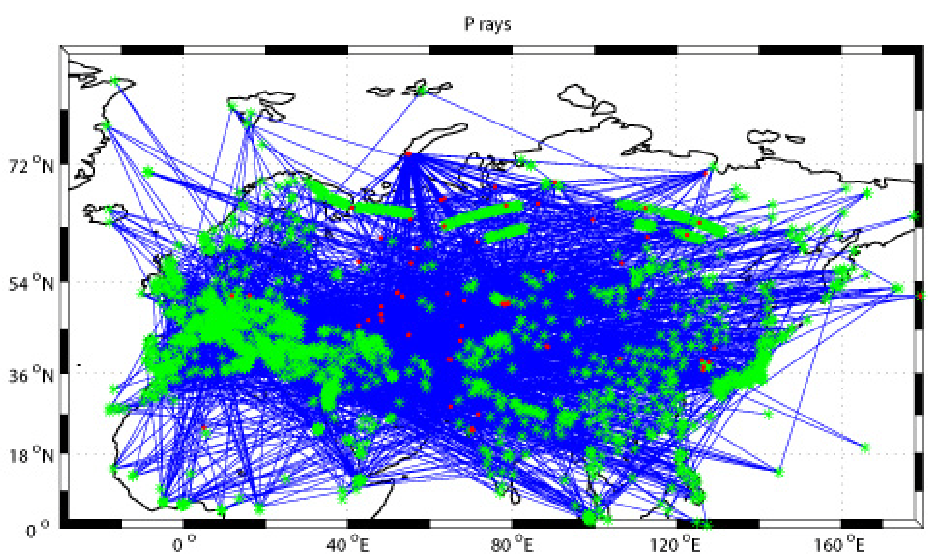

Figure 1. 58,970 *P*-wave paths in our validation dataset of 513 events of GT5 and less (Begnaud et al., 2004; Begnaud, 2005). Sources are shown as green asterisks; receivers as small red dots.

Test Models

We first explore the application of the ray bender to an elliptical representation of the standard AK135 (Kennett et al., 1995) model in our global, tessellated parameterization. We compare the calculated travel times through this model with those derived using TauP (Buland and Chapman, 1983; Crotwell et al., 1999). We then demonstrate the variations in these residuals from a global AK135 model that has had its crustal layers replaced by Crust2.0 (Bassin et al., 2000), a global crustal model generated at two-degree grid spacing using a variety of available sources: seismic tomography results, analyses from refraction profiles, and some assumptions derived from other topographic, geological and geophysical parameters. We then will examine the MITP08 model, which is a three-dimensional, global mantle model recently published by Li et al. (2008).

AK135

We begin with a simple test to validate the ray bender results in an AK135 model that has been parameterized in our global tessellation method, with ellipticity included in the model geometry (an oblate spheroid). The travel-time residuals we calculate in this model are compared against residuals calculated using the standard TauP Toolkit (Kennett and Gudmundsson, 1996) for source and receiver pairs, to ascertain how closely our travel-time calculations match the standard 1D approach currently in use. The TauP Toolkit results are corrected for ellipticity using the standard ellipticity corrections (Dziewonski and Gilbert, 1976; Kennett and Gudmundsson, 1996).

For teleseismic *P*-wave arrivals, the median difference between the 3D ray bender and TauP estimations (Figure 2) is 0.135 s, with a standard deviation of 0.0505 s. These differences are within our tolerances of 0.2 s, which gives us confidence in the bender results for *P* arrivals. Some minor differences are inevitable due to the parameterization of the model tessellation and geometry of the ray bending.

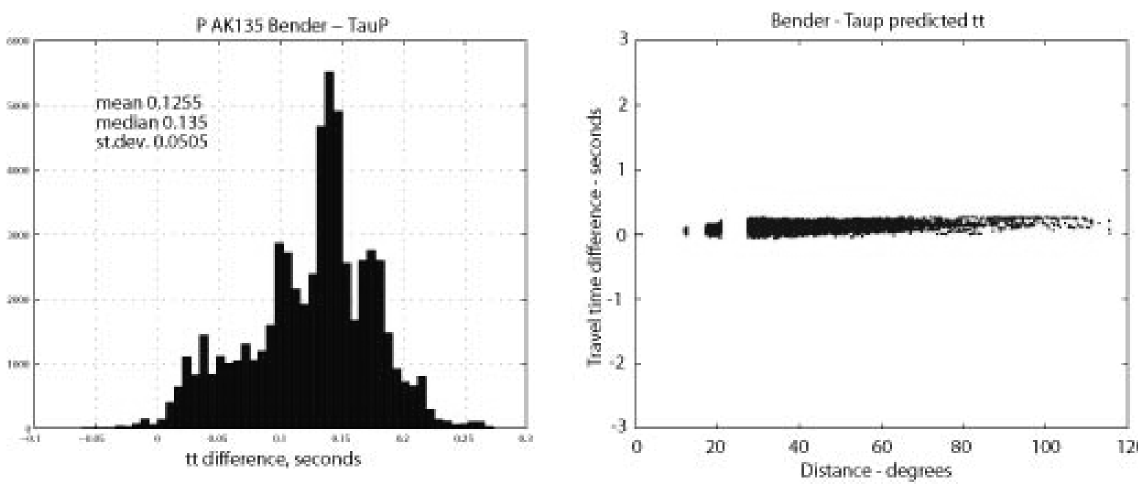

Figure 2. Ray bender calculated travel times for the GT dataset minus TauP calculated travel times for *P* (teleseismic) arrivals. Calculations performed using the AK135 earth model. Left: histogram of travel-time differences, with statistics. Right: travel-time differences as a function of distance.

Crustal 3D models over AK135

A preliminary examination of available regional crustal models superimposed on an AK135 core and mantle are compared to the globally averaged AK135 to explore the improvements to teleseismic *P* travel times that can be realized with some accommodation for the known variability in the crust. We recognize that any effect will be most pronounced in dealing with *Pn* and *Pg* phases, as teleseismic arrivals will have spent most of their time in the mantle. Our preliminary analysis is shown in Figure 3, in which we present the difference between predicted and observed travel times for our 58,970 arrivals in the GT dataset when we substitute crustal velocities of the AK135 with the Crust 2.0 model of Laske and Masters (1997), with the crustal *P*-velocity model of Sun et al. (2004) and the crustal *P*-wave values found in the DoE Unified model (Begnaud et al., 2004; Flanagan et al., 2007; Pasyanos et al., 2004). The figure presents histograms of the travel time differences for each case, along with the mean, median and standard deviations. It is immediately clear that the poorest performance is found with the simple AK135 model. Much of the problem may lie in mantle variation that is unaccounted for in this 1D radially symmetric model; however, some of the travel-time residuals are no doubt the result of its failure to account for crustal variations.

For our GT dataset, the mean *P*-arrival residual for an AK135 model is 0.3796 s, with a median of 0.478 and a standard deviation of 1.6824 (Figure 3a). Figure 3b presents the results for an AK135 model whose outermost layers and Moho depths have been replaced by the Crust 2.0 values. We see an improvement over AK135 of better than 50%, with a mean residual of 0.1437 s, a median of 0.219 and standard deviation slightly improved at 1.6786, suggesting slightly fewer outliers. The Sun et al. (2004) China crustal model (Figure 3c) embedded in a Crust 2.0 outer layer over AK135 reduces the AK135 values somewhat from a mean of 0.3796 to 0.3384, a median from 0.478 to 0.402 and standard deviation of 1.6824 to 1.6721. We note that some of our rays may not be representative of the Sun et al. model's influence alone, as it is only valid for China, whereas our data cover Eurasia; thus, a more accurate analysis will require a study restricting data to that region.

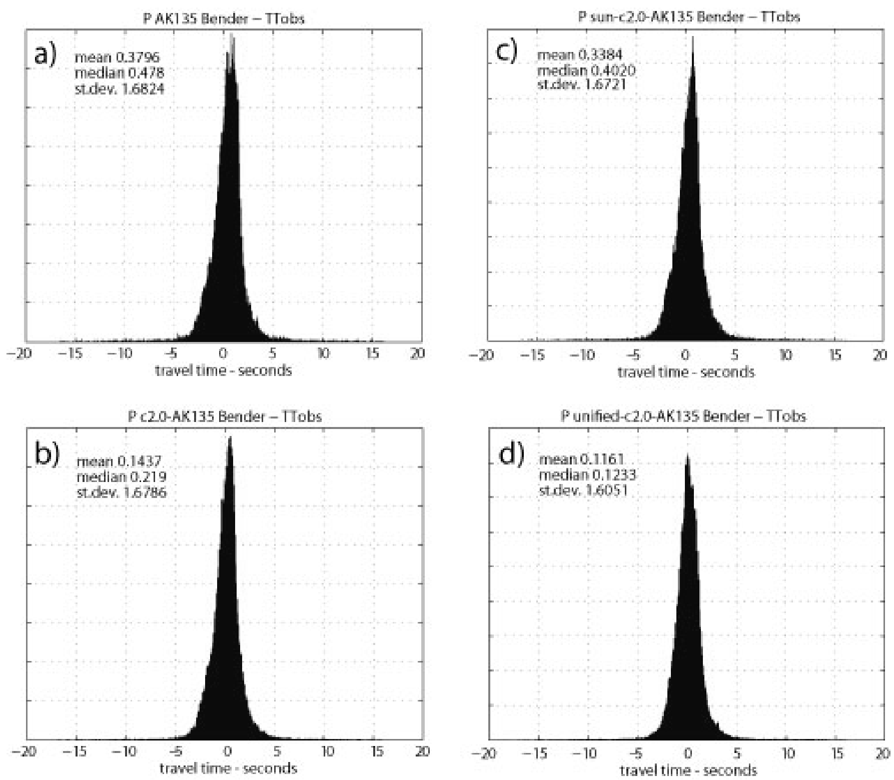

Figure 3. Predicted minus observed travel times for *P* waves using four models: a) AK135; b) Crust 2.0 overlying AK135; c) Sun et al. (2004) embedded in Crust 2.0 over AK135; and d) DOE Unified model embedded in Crust 2.0 over AK135.

Finally, modeling the *P* rays through an AK135 mantle and core overlain by Crust 2.0 with the DoE Unified Model gives rise to a reduction from AK135 for travel-time residuals as follows (Figure 3d): mean from 0.3796 to 0.1161, median from 0.478 to 0.1233 and standard deviation from 1.6824 to 1.6051. Among these models it appears that the Unified Model exhibits the sharpest reduction in residual for our GT dataset for *P* waves.

Mantle Model

We explore the improvements possible in our travel-time calculations by employing a fully three-dimensional, global P-wave model for the Earth's mantle, whose known variability is not addressed in the AK135 earth model. Li et al. (2008) have devised such a mantle model, which we test against the GT dataset travel times in our 3D tessellated parameterization. This seismic velocity model was developed to image in as much detail as possible the tectonic variations in the Earth's mantle as a whole. The model has succeeded in revealing a number of interesting yet not unexpected mantle features, including subduction zones.

Figure 4 illustrates the details of mantle structure obtained in this model, in a series of cross-sections through Western Pacific subduction zones. We are keenly interested in adopting such a model in our global 3D location algorithm to replace the AK135 or iasp91 (Kennett and Engdahl, 1991) default models used in routine location practice, for seismic phases that pass through mantle depths between source and receiver. Appropriate use of the model is needed, however.

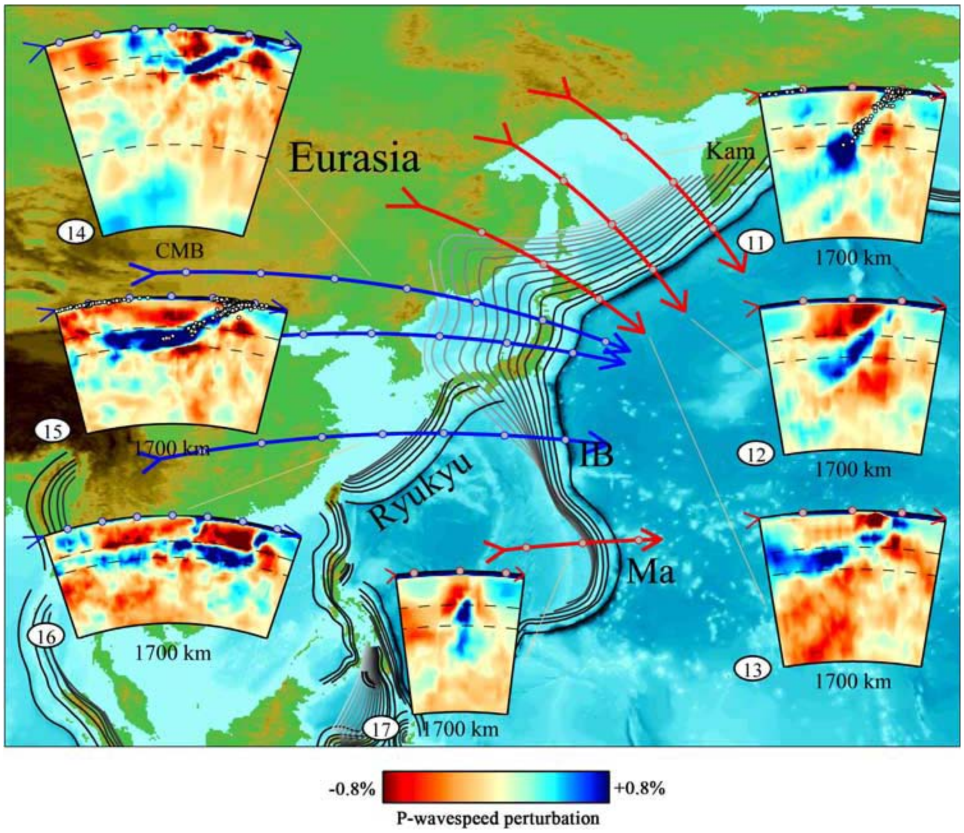

Figure 4. Selected cross-sections of mantle *P*-wave velocity variation across Western Pacific subduction zones (from Li et al., 2008).

Through discussions with the authors we have determined that the following considerations must be accommodated:

- The model was derived by calculating rays for source-receiver pairs through an AK135 earth model then inverting for mantle slowness variations by integrating along these fixed rays.
- Crustal variations were removed by assuming that Crust2.0 (Laske et al., 2001) perturbations account for travel-time variations for the rays passing through the crust.
- Ellipticity corrections were applied to the assumed rays after tracing.

The ray tracing algorithm we are using (Ballard et al., 2009) employs dynamic rays by default, so we needed to modify the code so that a requirement for fixed AK135 rays could be applied to testing of the MITP08 model. We built a 3D global model consisting of AK135 for inner and outer core, MITP08 mantle and fixed crustal corrections at all geographic points based on assumed travel-time through Crust2.0. We applied the ray bending algorithm to calculate travel times along the fixed AK135 rays integrated through our tessellated parameterization of the MITP08 model, and we examine the residuals between these predicted travel times and observed travel times for our test dataset.

In Figure 5, we show differences between observed and predicted *P*-wave arrivals for our GT dataset, to compare the performance of the MITP08 global mantle model for two different calculation methods: dynamic rays (left panel) and fixed AK135 rays (right panel). Both mean and median travel-time predictions are approximately five times better when using the fixed rays, as applied in the tomographic inversion by Li et al. (2008) when developing the model. Travel-time standard deviations are roughly equal in both applications.

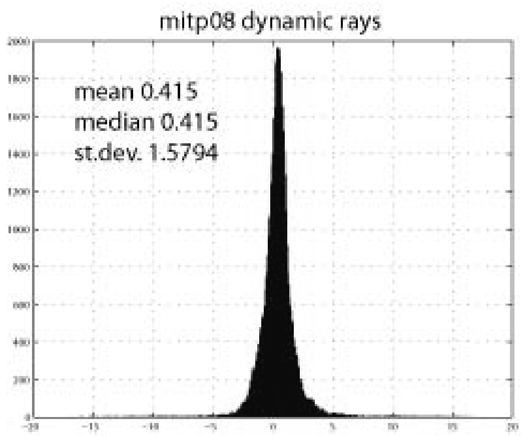

Figure 5. Comparison of performance of MITP08 global mantle model for *P* waves using the ray bender. Left panel: predicted travel times using dynamic ray bending. Right panel: predicted travel times using fixed AK135 rays.

Discussion

For teleseismic *P* waves we see that the use of a three-dimensional, variable crustal model over the standard AK135 model reduces the travel-time residuals compared to those computed through only AK135. This result is not unexpected and has been traditionally corrected for using station-centered correction surfaces that accommodate not only path residuals from the crust but also from mantle variations. Through our exploration of three crustal models available to us, we note sometimes significant reduction in residual. We note here that in all three cases, the crustal models are being used in a manner inconsistent with their derivation, so optimal performance is not expected. In the case of the Crust 2.0 and Unified models, velocities were estimated based on information from a variety of sources and these models cannot be said to have been data-driven. For example, the Unified model arose from literature searches, local tomography results, refraction profile, and was pieced together as a patchwork of broad, terrain-based, one-dimensional models which were smoothed at the terrain boundaries. The Sun et al. model was generated in a Cartesian system with no corrections for sphericity or ellipticity. Velocities were determined at each grid point over a 1 degree grid by a Monte Carlo search within prescribed velocity ranges for raypaths contained within one to three degrees of each grid point, providing implicit smoothing. Although the ranges over which seismic travel times were averaged are small enough to argue that earth curvature corrections were unnecessary, we have parameterized it in an ellipsoidal, triangular tessellation and we apply dynamic raytracing through it, which is inconsistent with its derivation; thus optimal results are not expected. The improvement demonstrated in the *P*-wave travel times for all our crustal examples are thus in some ways inevitable simply because the models must necessarily come closer to the true velocities compared to the globally averaged AK135 values, but in none of these cases can we be certain that the models are optimal for direct application to our location problem with our travel-time calculation method.

Examining mantle models, we have compared the residuals for predicted minus observed travel times both when using a model blindly and also using it appropriately for the manner in which it was derived. The MITP08 model was parameterized in our global, 3D tessellation. We then calculated travel times for teleseismic *P* waves using our default: dynamic ray bending. Clearly, based on Figure 5a, use of the model in this fashion does not provide good results. In fact, AK135 alone does nearly as well (see Figure 4a) and the Crust2.0 over AK135 performs noticeably better (Figure 4b). Use of the dynamic ray tracing, however, is inappropriate for calculating travel times through this MITP08 model, given that the velocity perturbations in the model were obtained with respect to fixed rays through an AK135 model. We therefore apply the travel-time calculation to our GT dataset through the MITP08 model using fixed rays and obtain a mean residual of -0.0986 seconds, with a median of -0.0923. This is approximately 20% improvement over the Unified model results.

CONCLUSIONS AND RECOMMENDATIONS

In our preliminary tests of the ray bender in the 3D global tessellated application, we have validated the predicted travel times compared to standard, 1D TauP travel-time predictions for our GT dataset. We have explored the influence on teleseismic *P* waves of 3D crustal models, and we find that they provide added value to the reliability of travel-time predictions, although their improvements vary and their methods of development are not necessarily consistent with the manner in which we will be using them. We find that for models such as the MITP08, it is crucial for operational travel-time prediction that we apply this model using methods appropriate to the manner in which it was developed. Inappropriate use of the model, however, results in poorer performance. Because researchers use a variety of methods in developing their models to image mantle and lithospheric structure, we cannot expect uniform performance of models obtained as deliverables on DOE/AFRL contracts, using a single travel-time calculation method.

This raises questions regarding the usefulness of models developed for the monitoring community. Routine event location will ultimately be performed with a single, global 3D model, but the model must be appropriate for the method in which the seismic travel times will be calculated for location. We conclude that the many models being provided by the community can best be tested and validated only if their methods of derivation are provided with the models; even in cases where all the information is available, the best of these models may not be optimal as-is for implementation in routine travel-time calculation. We propose that the best global, 3D model for routine event location will be one that is derived using identical travel-time estimation to that in the location algorithm, using the best of the models from the monitoring community as starting models for this inversion.

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