APPLICATION OF A GLOBAL 3D MODEL TO IMPROVE REGIONAL EVENT LOCATIONS

A.L. LEVSHIN AND M.H. RITZWOLLER

Center for Imaging the Earth's Interior, Department of Physics, University of Colorado at Boulder[*]

ABSTRACT

Accurate location of weak seismic events is crucial for monitoring clandestine nuclear tests, for studying local seismic structures, and for assessing possible seismic hazards. Outside of a few regions with dense seismic networks, weak seismic events (with magnitude less than 4) are usually sparsely recorded at epicentral distances less than 20°. Because of lateral variations in crustal and upper mantle structures, observed travel times of seismic phases deviate significantly from predictions based on 1-dimensional (1D) seismic models. Accurately locating weak seismic events remains a difficult task for modern seismology. Perhaps the most promising solution to this problem is the use of a 3-dimensional (3D) model of the Earth. Here we present the results of a validation test in which, using the 3D model SR2002 of the crust and upper mantle and regional phase data alone, we relocate ~ 200 earthquakes and nuclear explosions in Eurasia. The 3D model is constructed using surface wave dispersion data. The event locations using the 3D model are compared with so-called Ground Truth data, either known by non-seismic means or validated by cluster analysis, with location accuracy mostly 5 km or better. Typically, the 3D model reduces the location errors to about half the values attained with the 1D model; i.e., ~ 18 km location errors are reduced to about 9 km. This test indicates that the location of regional events can be significantly improved by using a global 3D model.

Keywords: Earthquake location, 3D model, 1D model, source-specific station corrections, nuclear test monitoring.

1. INTRODUCTION

Locating low-magnitude events with the accuracy required for nuclear monitoring is a challenging task. These events are usually recorded by a sparse network of stations only at regional distances where the effects of lateral variations of the crustal and upper mantle structure can be significant. This is especially true for Central and Southern Asia which are a mosaic of tectonic blocks of different sizes with highly varying deep structures. One-dimensional (1D), radially symmetric models such as iasp91 (*Kennett & Engdahl, 1991*) or ak135 (*Kennett et al., 1995*) do not provide accurate prediction of travel times for local and regional distances. One possible way to account for the effect of lateral heterogeneity

* Campus Box 390, Boulder, CO 80309-0390, USA (fax: +01-303-492-7935, e-mail: levshin@ciei.colorado.edu)

is to construct empirical source-specific station corrections (SSSCs), which is possible in regions with numerous well located events. Such events are commonly called Ground Truth, and if location accuracy is better than 5 km they are identified as GT5 (e.g., *Bondar et al., 1999*). However, such events are missing from large regions of the Earth. In these circumstances, it is possible to construct SSSCs using reliable 3-dimensional (3D) regional or global models. Our work demonstrates that continental- and global-scale 3D models are emerging with sufficient reliability and resolution to warrant their use in locating events using regional phase data alone. We investigate the use of one such global model constructed by *Shapiro and Ritzwoller (2002)*, thereafter referred as SR2002. To compute SSSCs from this model we use a 2D raytracing shooting code based on algorithms developed by *Červený and Pšenčík (1984)*. The accuracy and efficiency of this code in computing SSSCs is entirely adequate for the problem at hand.

To investigate the usefulness of the global model SR2002 for locating small regional events we present the results of a validation test, in which we use SR2002 beneath Eurasia and regional phase data alone to relocate 193 GT5 earthquakes and nuclear explosions. In the following sections we describe the model SR2002 and the location procedure based on this model. We close with comparisons between the Ground Truth locations (*Engdahl and Bergman, 2001*) and those obtained using model SR2002.

2. CONSTRUCTING THE 3D MODEL

Broadband surface wave dispersion data are used to construct the global 3D model SR2002 of the crust and upper mantle on a $2° \times 2°$ grid. The techniques used for model construction are described in detail by *Shapiro and Ritzwoller (2002)* and *Ritzwoller et al. (Global surface wave diffraction tomography, submitted to J. Geophys. Res, 2002)*. The inversion for SR2002 involves two principal steps: (1) surface wave tomography and (2) the inversion of the tomographic maps for a shear velocity model.

In the first step, the processed group and phase velocity dispersion measurements are converted to 2D dispersion maps. The data processing has been described by *Ritzwoller and Levshin (1998)*, and the tomographic method is discussed by *Barmin et al. (2001)*.

The second step is a multi-stage process that starts with the selection of an 'Initial Model'. This model is based on a variety of sources of global information, including the sediment model of *Laske and Masters (1997)*, the crustal model CRUST5.1 of *Mooney et al. (1998)*, and the mantle shear-wave velocity model S20A of *Ekström and Dziewonski (1998)*. We use a uniform parameterization over the whole globe. Not all model parameters have equal freedom during the inversion. Some are explicitly constrained, e.g. crustal velocities, the depths to Moho, and the bottom of the anisotropic mantle. The perturbations to the mantle velocities are implicitly constrained by the use of cubic B-splines. The v_p velocities in the mantle are determined through the logarithmic scaling relation $\delta ln v_p / \delta ln v_s = 0.5$.

The procedure culminates in a Monte-Carlo inversion for an ensemble of acceptable models at each spatial node. The middle of the ensemble ('Median Model'), together with the half-width of the corridor deffined by the ensemble, summarizes the results of the inversion. Two vertical slices through the model are shown in Figure 1.

The main advantages of the use of surface wave data for constructing a 3D model is the dense coverage of the Earth by surface wave paths and constraints placed on uppermost mantle structure. Vertical resolution is reached due to use of broadband surface wave data in the period range 16-200 s.

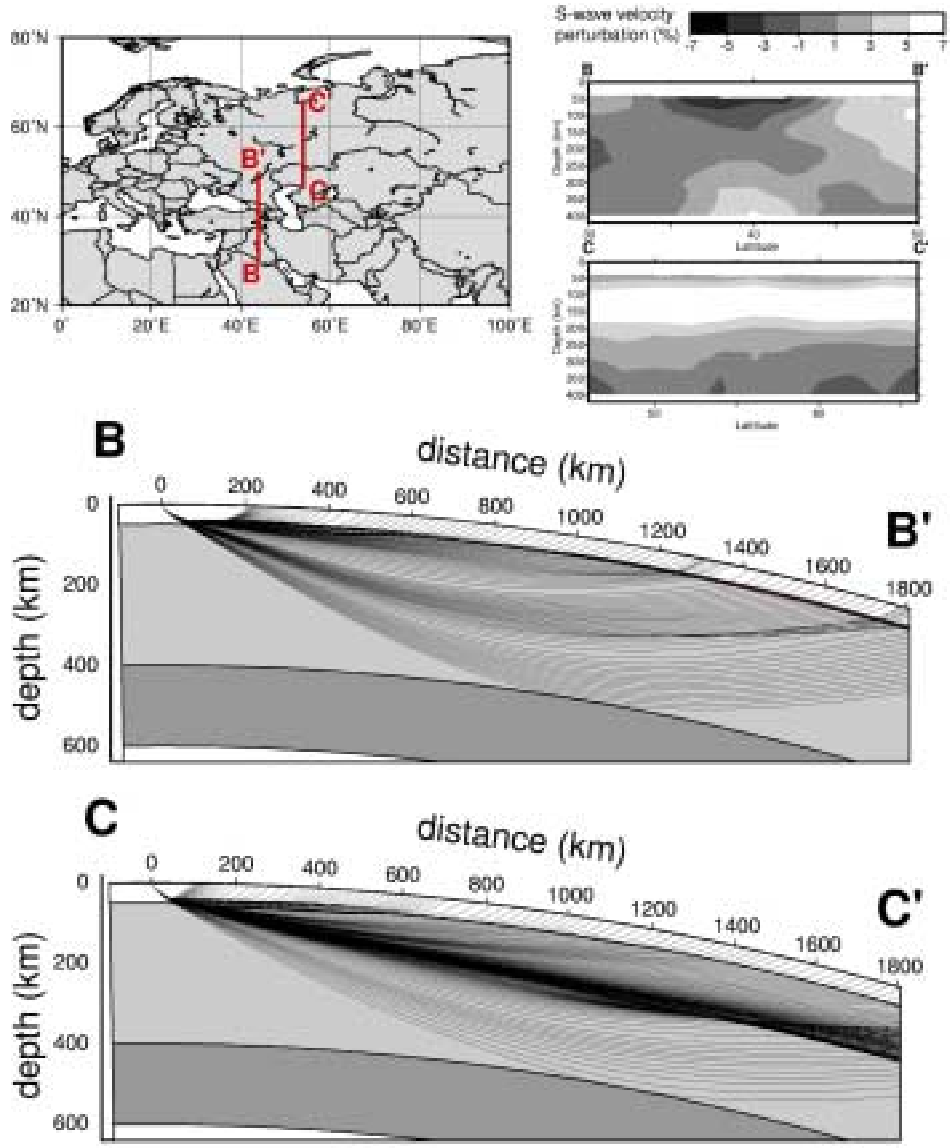

Fig. 1. The two-dimensional (2D) raytracing through the 3D model SR2002 along profiles BB’ and CC’ shown on the map. Vertical shear velocity slices for two profiles are shown in the upper right corner.

3. CONSTRUCTING SOURCE-SPECIFIC STATION CORRECTIONS

We used the model SR2002 described above to construct Source Specific Station Corrections (SSSCs) for 1050 seismic stations in Eurasia and North Africa. The SSSC for a given seismic phase is defined for a particular station as the difference between travel times t_{3D} calculated using SR2002 and t_{1D} from the reference 1D model ak135 (*Kennet and Engdahl, 1995*):

$$SSSC(\theta,\varphi,h) = t_{3D}(\theta,\varphi,h;\theta_0,\varphi_0) - t_{1D}(\Delta,h) \ . \qquad (1)$$

Here θ, φ, h are the source latitude, longitude, and depth; θ_0 and φ_0 are station coordinates; and Δ is epicentral distance from (θ, φ) to (θ_0, φ_0). Travel times in the 3D model are computed using a 2D raytracing algorithm (*Červený et al., 1977*; *Červený and Pšenčík, 1984*; *Červený, 2001*). We found that effects of off-path propagation in the 3D model of the medium are relatively small in comparison with observational errors and errors produced by the inaccuracy of the model (*Villaseñor et al., Computation of*

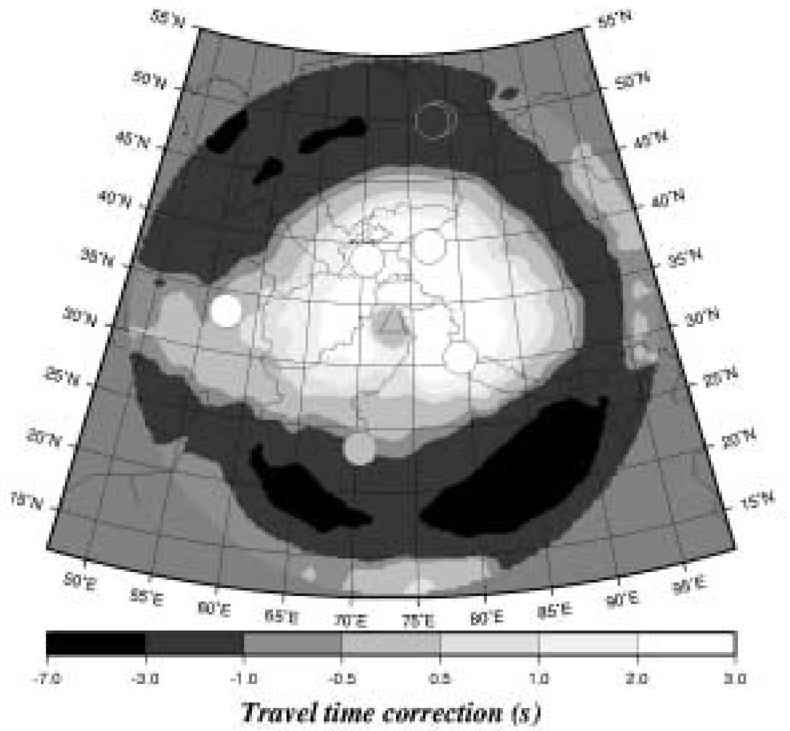

Fig. 2. Example of a SSSC for the seismic station NIL (Pakistan). Also shown are empirical path corrections (circles) for several clusters of seismic events (nuclear explosions and earthquakes) inside the region (*Engdahl and Bergman, 2001*). Travel times are relative the 1D model ak135 (equation (2)).

regional travel times and station corrections from three-dimensional velocity models, submitted to Stud. geophys. geod., 2002). This justifies the use of 2D-raytracing code (*Červený and Pšenčík, 1984*, significantly modified by M.P. Barmin for this specific application). Computations are made in a Cartesian (flat Earth) reference system, and an earth-flattening transformation is applied to the model. The code provides travel times for Pg, Pn, and P phases on a grid along a set of profiles radiating from the station. The grid steps are 25 km for Δ, 5° for profile azimuth, and 5 km for source depth.

Examples of raytracing through the model SR2002 are shown in the lower part of Figure 1. An example of a SSSC for the first arriving P waves at epicentral distances less than 20° for station NIL (Pakistan) is shown in Figure 2. The empirical path corrections found by *Engdahl and Bergman (2001)* for several clusters of seismic events situated in this region are shown in the same figure. The empirical corrections are generally similar to those predicted using the 3D model.

4. LOCATION PROCEDURE

The location procedure is based on a grid-search, in which rms misfit to observed travel times is the functional we seek to minimize. Epicentral latitude and longitude are the two unknowns searched across a spatial grid. The third unknown, origin time, is found for each trial location by minimizing the rms residual. Event depth is fixed to the Ground Truth value because it trades off strongly with origin time and, to first-order, is independent of the epicentral location for shallow crustal events. Fixing event depth, therefore, has little effect on the error in the epicentral location in most cases. The grid is centered at a starting location (usually the teleseismic PDE location). Only first arriving mantle P phases at epicentral distances less than 20° are used. The spatial grid is usually 1 km × 1 km and covers 2500 km^2. For each grid point, the difference between the observed and predicted time for each observation is found following

$$dt_{3D}^{i} = t_{obs}^{i} - SSSC^{i} - t_{1D}^{i} \ , \qquad (2)$$

where *i* is the station index ranging to *N*, the number of reporting stations for a particular event. Observations with residuals having absolute values above a certain threshold (3 s) relative to the starting location are discarded. The distance between the best spatial node (with minimal rms) and the Ground Truth location for a given event is considered as the relocation error.

To compare results of relocation using the 3D and 1D models we apply a similar procedure to the residuals relative to the 1D reference model

$$dt_{1D}^{i} = t_{obs}^{i} - t_{1D}^{i} \qquad (3)$$

Examples of the rms misfit grid for a nuclear test at Azgir (Kazakhstan) using equations (2) with the 3D model and (3) with the 1D model are shown in Figure 3.

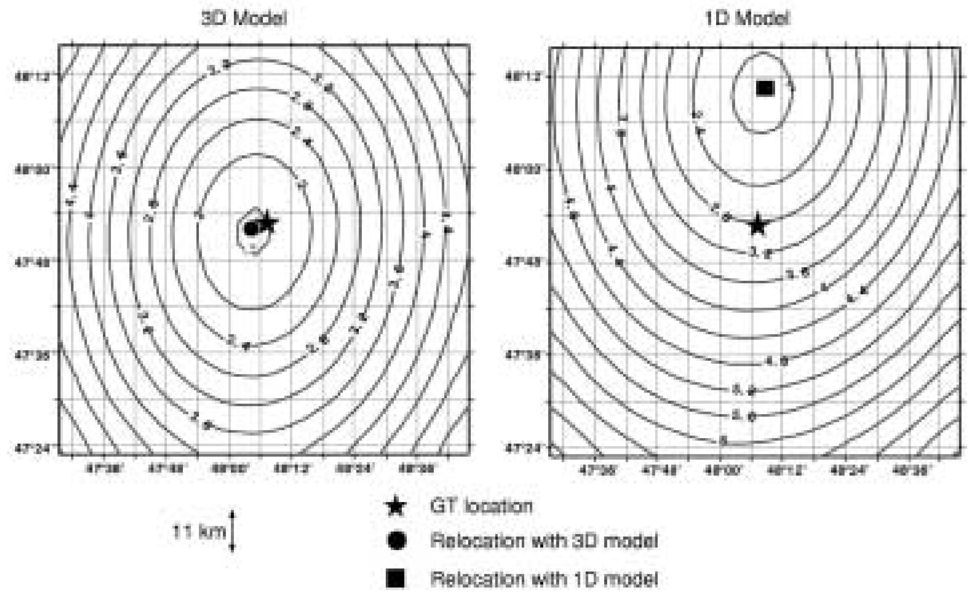

Fig. 3. Comparison of the results of relocation using the 3D model SR2002 and the 1D model ak135 for a nuclear test at Azgir (N.W. Kazakhstan). Errors in location are 4 km with the 3D model and 32 km with the 1D model. Contours are rms values in seconds.

5. RESULTS OF VALIDATION TESTS

The validation tests reported here are based on GT5 seismic event locations of earthquakes and nuclear explosions that have been located specifically for these tests using cluster analyses by *Engdahl and Bergman (2001)*. The locations of the event clusters are shown in Figure 4. Table 1 indicates the number of events and the median value of the number of stations in each cluster. Also indicated are the median values of the open azimuth (i.e., the largest azimuthal gap between stations observing a given event) in each cluster. We use phase travel time data from the EHB bulletin (*Engdahl et al., 1998*). An overall summary for each of the 15 event clusters is presented in Table 1. Location error and rms misfit for each cluster are presented. Typical location error for a 3D model location is 8.5 km, with errors larger than 12 km in only one cluster. Rms misfit averages about 1.11 s. Typical location error using ak135 is 18 km, and the rms misfit average is 1.17 s. Location using the 3D model are better than those with the 1D model for 88% of the individual events. The small difference in the rms values for 1D and 3D locations reflects the fact that in many cases the observed travel time patterns are very simple, and even with a 1D model one can fit the data well by varying epicenter location and origin times. The point is that the inferred location will be erroneous, as the 18 km average location error for the 1D model indicates. Among 193 relocated events, only 25 events have less than or equal to 10 reporting stations. For 20 of these 25 events (80%), the 3D location is better than for the 1D location.

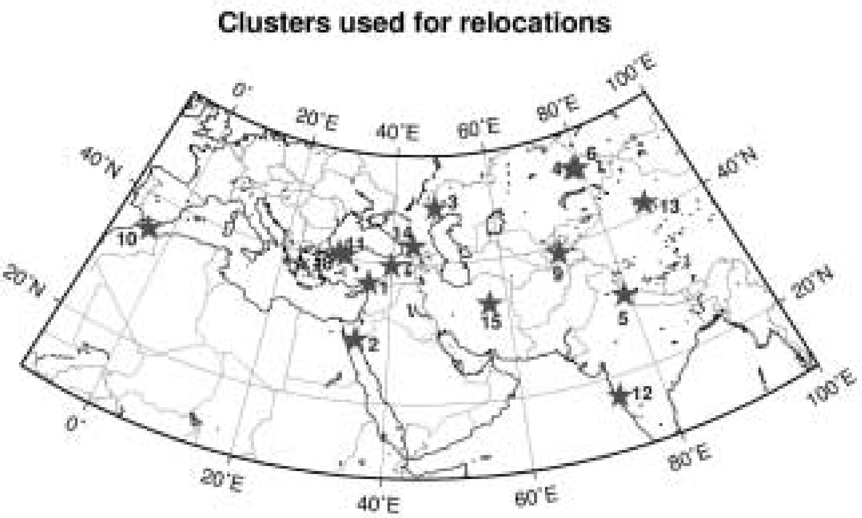

Fig. 4. The location of 15 event clusters containing 193 events that are relocated. The clusters are: 1 Adana (Turkey); 2 Aqaba (Gulf of Aqaba); 3 Azgir (Kazakhstan); 4 Balapan (Kazakhstan); 5 Chamoli (India); 6 Deglen (Kazakhstan); 7 Duezce (Turkey); 8 Erzin (Turkey); 9 Garm (Tadzhikistan); 10 Hoceima (Morocco); 11 Izmit (Turkey); 12 Koyna (India); 13 Lop Nor (China); 14 Racha (Georgia); 15 Tabas (Iran).

Table 1. Results of relocations using the 3D model SR2002 and the 1D model ak135.

					3D model		1D model	
	Cluster	#events	Median # of stations	Median of open azimuths (deg)	Error (km)	rms (s)	Error (km)	rms (s)
1	Adana	20	19	153	11.4	1.07	13.5	1.02
2	Aqaba	25	46	154	14.7	1.09	22.4	1.21
3	Azgir	7	15	215	6.1	1.41	29.2	1.76
4	Balapan	11	24	125	5.1	1.03	17.5	1.22
5	Chamoli	10	16	135	6.0	0.93	10.8	0.80
6	Deglen	8	8	259	8.5	1.05	27.7	1.07
7	Duezce	16	37	115	6.5	1.31	13.7	1.23
8	Erzin	6	41	64	8.1	1.21	14.4	1.40
9	Garm	16	16	86	9.3	1.15	12.8	1.20
10	Hoceima	22	22	33	9.9	0.88	19.3	0.86
11	Izmit	8	84	85	8.4	1.12	11.7	1.03
12	Koyna	8	9	217	10.5	0.75	16.1	1.02
13	Lop Nor	13	23	117	8.3	1.02	18.8	1.09
14	Racha	11	66	55	5.3	1.45	25.2	1.42
15	Tabas	12	25	117	9.8	1.23	19.2	1.29
	all clusters	193	23	117	8.5	1.11	18.2	1.17

To estimate, statistically, the effect of the number of reporting stations on location accuracy, we carried out a simulation using the same observational data. We located events using various random selections of a given number of reporting stations from available data sets. The simulation demonstrates that the difference in the accuracy between the 3D and 1D locations reduces appreciably if the number of reporting stations is less than 10. These tests show that if there are fewer than 15 reporting stations, the 3D locations are more accurate for about 67% of the events. If the number of reporting stations is greater than 15, the 3D locations are better than the 1D locations for about 80% of the events. Another predictive variable is open azimuth, which is correlated with the number of reporting stations. For the 3D model, if open azimuth is less than about 180°, location error is nearly independent of open azimuth and equal to about 10 km. If open azimuth is larger than 180°, location error is higher and grows with decreasing station number. Similar trends are apparent for the 1D locations. One of the main reasons for such instability is uncertainty in the origin time or the source depth which may cause significant bias in location if the station distribution is one-sided.

We described, above, the performance of the 3D global model SR2002 in comparison with the 1D global model ak135 in location of regional events. It is possible that regional 1D models will significantly improve locations in comparison with the global 1D model. To address this question we should define what is a regional 1D model. Taking into account that we use travel time measurements at regional distances up to 2200 km, a regional model should correspond to an area ~ 4400 km in diameter. It is doubtful that the regional model, especially if it includes tectonic provinces and internal seas, will accurately predict travel times. We test this hypothesis by taking the vertical velocity profiles from SR2002 beneath each cluster as the surrogate regional 1D model for the region surrounding each cluster. For each cluster we located events using its regional 1D model exactly as has been done with the 1D global model. The resulting average error in location for the 15 clusters in Table 1 is 16 km, which is slightly smaller than for the global 1D model (18 km), but still significantly worse than obtained with SR2002 (8.5 km). Results of location using the 3D model are better than using the 1D regional models for 78% of the individual events.

6. CONCLUSIONS

Relocation of 193 events in 15 event clusters using regional Pn and P data yielded two principal conclusions. First, the 3D model SR2002 of the crust and upper mantle delivers improved regional locations over the 1D model ak135 on average and for 88% of individual events. The use of surrogate 1D regional models instead of the global 1D model does not change the main results: the 3D model SR2002 still provides better locations on average and for 78% of individual events. Second, as statistical tests demonstrate, the key predictor of location accuracy is the number of reported regional Pn and P phases used in the location. If the number of reported phases is greater than ~ 15, the 3D model improves the location for about 80% of the events and location error relative to ground-truth averages about 9 km compared with 18 km for ak135. If the number of reported phases is less than 15, the differences between the locations using the 3D and the 1D models becomes less distinct. Still, the 3D location provides better results for ~ 67% of the events.

Further studies are needed to improve estimates of the statistical characteristics of location errors and to clarify the location bias due to uncertainties in the origin time and source depth as a function of source-station geometry. We note in conclusion, however, that the accuracy of location using the 3D model is better than prescribed by the Comprehensive Nuclear Test Ban Treaty (18 km).

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