SOURCE-SPECIFIC STATION CORRECTIONS MODELED BY DYNAMIC RAY TRACING IN 3-D EARTH MODELS

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ABSTRACT

Source-specific station corrections (SSSCs) to travel-time tables have been constructed for International Monitoring System (IMS) stations in Eastern Asia by ray tracing in three-dimensional (3-D) earth structure. Three-dimensional models are parameterized by tetrahedra, with linear interpolation of velocities between tetrahedron vertices. This parameterization allows analytic integration of kinematic and dynamic ray tracing equations. Two types of 3-D models have been tested: (1) a model consisting of 22 1-D velocity regions with lateral transition zones between regions and (2) a model constructed from CRUST 2 and RUM upper mantle. SSSC's are generated on 1 x 1 degree grids from 0-, 10-, 50-, 100-, and 150-km depth sources. In tests of relocation accuracy against ground truth locations, type (1) model, consisting of 1-D velocity profiles with lateral transition zones, performs better than the hybrid CRUST2 + RUM model. We find that travel times beyond the 1- to 2-degree range are more sensitive to structure in the upper mantle than the crust. A comparison of the SSSC's computed assuming a realistic Moho topography versus that predicted by lateral transitions between 1-D models is in progress.

OBJECTIVE

This work is a part of the Lamont-Doherty IMS calibration consortium. This consortium is charged with improving earthquake locations for 30 proposed stations in the International Monitoring System (IMS). The task assigned to the University of Connecticut is to develop algorithms for constructing three-dimensional models of the crust and upper mantle, to compute travel times, and to quantify the errors in estimated travel times for regional seismic waves propagating in these models. The incorporation of three-dimensional structure is needed to overcome the effects of off-azimuth paths on travel times and to estimate these effects. 3-D ray-tracing is particularly important in areas with strong lateral variations of velocity and/or Moho topography (e. g. Tibet). Three-dimensional modeling is also useful for SSSC computation for buried sources in regions where little ground truth information is available.

RESEARCH ACCOMPLISHED

Three-dimensional velocity models

Two types of velocity models were tested. One type is constructed from published models for the crust and upper mantle of eastern Asia. CRUST2 by Mooney *et al* (1998) incorporates many published refraction studies in a global 7 layer crust at 2 x 2 degree resolution and is a refinement of CRUST5.1. This crustal model was merged with the Regionalized Upper Mantle (RUM) model (Sambridge and Gudmundsson, 1998). Although this latter model is reported on 2 x 2 degree grid, it has been obtained primarily by inverting teleseismic data and therefore has lower resolution.

The second type of model is based upon partitioning of the whole region (Eastern Asia) into 22 sub-regions (Figure 1; Khalturin, unpublished). Each of these sub-regions corresponds to a geologic province with relatively homogenous lateral velocities. Available travel-time information (Kirichenko and Kraev, 2001) has been used to construct 1-D velocity model for each region (West, 2001). The 3-D model was then created with the assumption that each of the regions has a 1-D model with properties that change abruptly at region boundaries. Figure 2 shows velocity profiles corresponding to these models beneath station Borovoye. Seismic velocities in the upper mantle are higher for the regionalized model than for both the IASPEI-91 model and CRUST/RUM hybrid. This is important because Pn travel times computed with the IASPEI-01 model in Asia are typically longer than the ground truth travel times.

Parameterization and 3-D ray-tracing

The models, initially defined as functions of latitude, longitude and depth, were projected onto 3-D Cartesian grid tracking the spherical shape of the Earth. The earth was not flattened. Model input formats were converted for 3-D ray tracing codes (Menke, 2002), which requires quasi-layered structure with a constant number of nodes in each direction. The grid was discretized at 0.5 by 0.5 degrees. Each parallelepiped of 8 nodes is then divided into 5 tetrahedra with velocity defined in each vertex. The velocity inside each tetrahedron is a linear function of coordinates. A ray path in such medium is an arc of a circle and the travel time along such an arc can be computed exactly. The limitation of this method is that it requires non-zero velocity gradient in each tetrahedron and does not allow velocity discontinuities.

The error of this method is contributed by two major effects. The first source of errors is the tetrahedral parameterization of the Earth, which implies an approximation of the surface of the Earth by a multifaceted surface (Figure 3 b). It is possible to roughly estimate the magnitude of this error. Figure 3 c shows a simplified 2-D geometry for this case. The deviation of the model surface from the surface of the sphere at both source and receiver is $dz = R(1-\cos(\delta/2)/\cos\gamma)$, where R is the radius of the Earth, δ is the angular distance between nodes of the grid, and γ is the smallest angular distance to the node. This corresponds to a travel-time perturbation equal to $dt = dz\cos i/V_0$, where V_0 is the velocity at the source or receiver and *i* is a takeoff or arrival angle respectively. This type of error is largest in the center of a grid cell and gets smaller toward its nodes and goes to zero as we approach the nodes.

The second error comes from the velocity approximation. To examine the relative importance of these two types of errors, we compared the ray-tracing results using the well-known IASPEI-91 model with theoretical travel times. The results are shown in Figure 3c and d for grid sampling of 0.5 and 1 degree respectively. Subtraction of the theoretical error from the observed error yields the error caused by velocity approximation, which in the case of one-degree grid spacing was below 0.1 s for distances between 2 and 15 degrees. For distances less than 2 degrees, it can be as large as 2 s, and beyond 15 degrees, it becomes less than 0.05 s. For a 0.5×0.5 degree grid, the error beyond 2 degrees stays less than about 0.07 s. The velocity approximation error, however, stays large for distances less than about 2 degrees.

Results and ground truth validation

P-wave travel-time tables were generated for paths of regional seismic phases within and to area 1 IMS stations in Eurasia on 1 × 1 degree grid for different depths (0 km, 10 km, 50 km, 100 km and 150 km). Figure 4 shows travel-time differences between computed and theoretical (IASPEI-91) travel times for station Borovoye. For most stations the differences are ±8s. The magnitude of the corrections with respect to IASPEI-91 is greater for the regionalized model. CRUST/RUM hybrid converges with the IASPEI model as depth increases. Therefore the magnitude of the corrections decreases with growing distance.

The ray-tracing results for deeper sources suffer from lack of convergence at certain points of 1 × 1 degree grid. To overcome this problem, we are testing different schemes of travel-time interpolation to fill in shadow zones, including tension spline interpolation.

The validation of the travel-time estimates was performed using ground truth data from several sources (Murphy *et al*, 1997; Sultanov *et al*, 1999). The large part of the dataset comes from 83 Soviet peaceful nuclear explosions (PNE), 80 underground nuclear tests (UNT) from Semipalatinsk, and 7 UNT from Lop Nor (China). We also included data from Indian and Pakistani tests and well-located earthquakes (GT5-GT10, Yang et al., 2000). Another part of the dataset, which covers vast aseismic regions of Russia, comes from the Deep Seismic Sounding (DSS) program in the form of profiles from 19 PNEs and 2 weapon explosions (over 4600 travel-time picks made by the University of Wyoming research group).

The ground truth data were used for further refinement of the velocity model. We performed a travel-time inversion with software ray-traced (Menke, 2002). This software was chosen because it uses the same ray-tracing algorithm that was used to compute travel times. The model parameterization was performed as follows. We chose the regionalized model as a starting point. The model parameters were layer velocities in each region covered with data points. Each layer in the model was permitted to vary as a whole during the inversion. Overall 26% reduction of travel-time residuals was achieved as the result of the inversion. This improved velocity structure region was used to compute the SSSCs.

Performance of different velocity models in predicting actual travel times compared to the reference (IASPEI-91) model is summarized in Table 1. The travel-time residuals are the smallest for almost all of the stations, except NRI and FRU. The IASPEI 91 yields the best fit for NRI, and the CRUST/RUM hybrid gives good results for stations AAK and FRU. The overall mean and standard deviation of the travel-time residuals is the smallest for the regionalized velocity model. The IASPEI model has the greatest bias in estimate of travel times (mean residual is 1.53 s) and typically over predicts the true values.

Table 1. Travel time residuals for ground truth events for selected auxiliary stations, shown in Figure 1.

Station	Latitude	Longitude	IASPEI		CRUST+RUM		Regionalized	
	N	E	mean	rms	mean	rms	mean	rms
AAK	42.6300	74.4800	2.23	2.73	0.27	1.47	-0.92	1.01
ARU	56.4302	58.5625	1.29	2.16	-2.09	3.02	-0.16	1.04
BOD	57.8500	114.1830	-0.51	0.94	-3.67	4.23	-0.14	0.67
BRVK	53.0581	70.2828	1.28	1.87	0.30	1.93	0.33	1.18
ELT	53.2500	86.2670	1.69	2.06	0.75	2.00	0.79	1.38
FRU	42.8330	74.6170	2.12	3.26	0.21	0.89	-0.26	1.69
KURK	50.7000	78.6000	1.49	1.54	0.87	2.77	-0.18	0.64
MAKZ	46.8080	81.9770	2.12	2.17	1.19	1.68	0.51	0.93
NIL	33.6500	73.2512	3.56	3.87	0.7	1.24	-0.61	0.92
NRI	69.4430	88.0830	0.07	1.92	-2.68	4.34	0.33	2.34
OBN	55.1167	36.6000	1.16	1.59	-3.04	3.36	0.98	1.47
ZAL	53.9367	84.7981	2.01	2.04	2.69	2.71	1.24	1.29
Total	-	-	1.53	2.32	-0.45	2.34	0.03	1.56

CONCLUSIONS AND RECOMMENDATIONS

1. Source-specific station corrections (SSSCs) to travel-time tables have been constructed for IMS stations in Eastern Asia by ray tracing in three-dimensional earth structure. The ray-tracing procedure and velocity models were verified using available ground-truth information. The ground truth data were used for refining the velocity structure in the area of work. After testing different velocity models we found that the velocity model constructed of laterally homogeneous regions provided the best fit to the available data.

2. Ray-tracing in the medium with known travel times has shown that grid discretized at 0.5 by 0.5 degree provides adequate accuracy.

3. P-wave travel-time tables were generated for 30 IMS stations in Eurasia on 1 × 1 degree grid based upon the improved regionalized velocity model.

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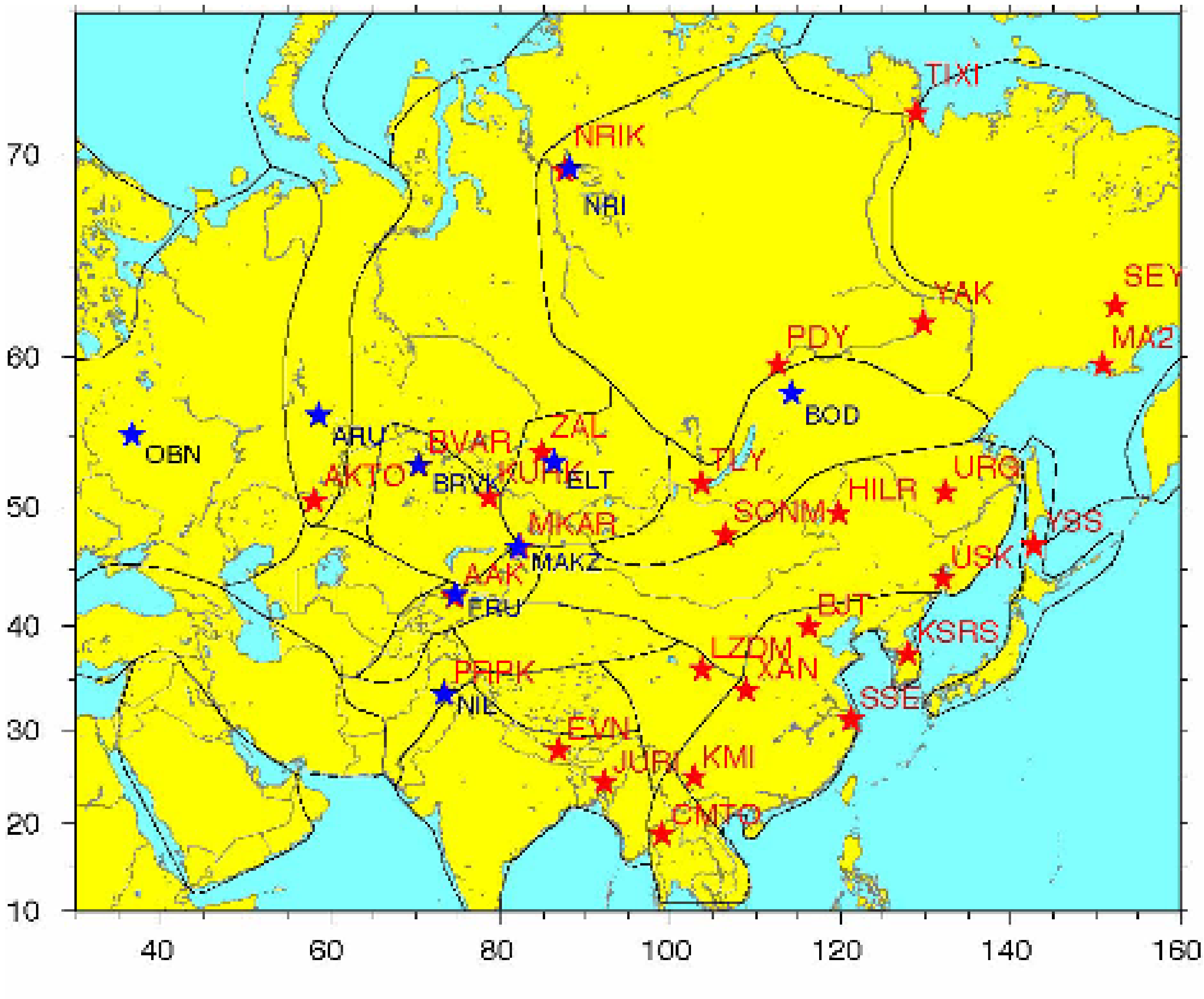


Figure 1. Map showing 30 IMS stations (red) and additional stations used for travel-time verification (blue).

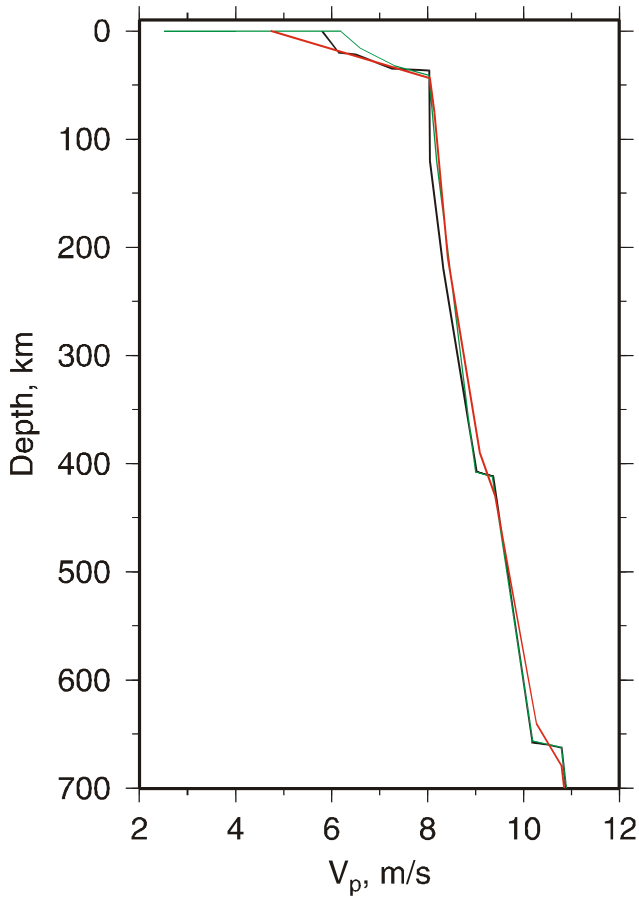
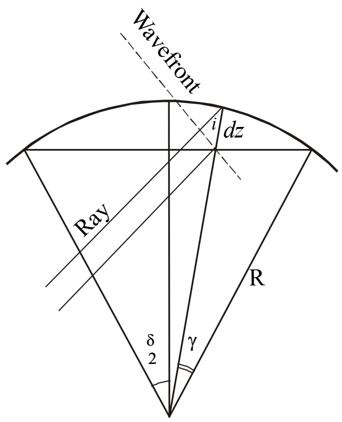


Figure 2. Velocity profiles beneath station Borovoye. Black line shows reference IASPEI velocity, red line – RUM/CRUST hybrid velocity, green line – 1-D velocity in the region surrounding station Borovoye.

a)



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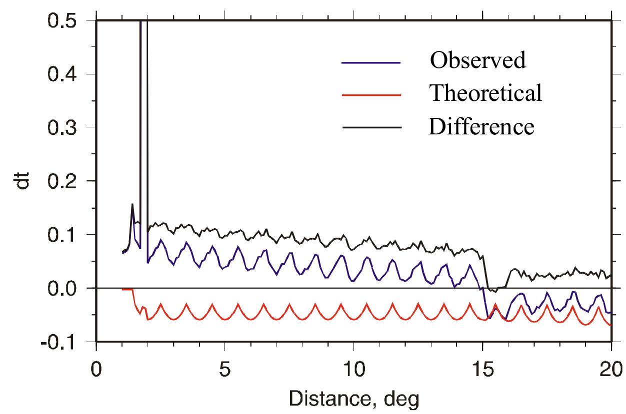

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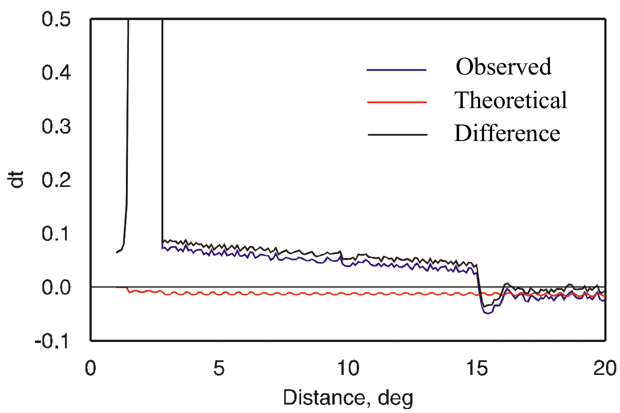

Figure 3. a) Geometry of a ray near the surface in the spherical earth approximated by tetrahedra. b) Difference between theoretical and computed travel times for IASPEI-91 model with 1 degree between nodes. Blue line shows the difference between ray traced and theoretical travel times, red line shows predicted error due to surface approximation, and black line is the difference between actual and predicted error. c) Same as b, except node spacing is reduced to 0.5 degree.

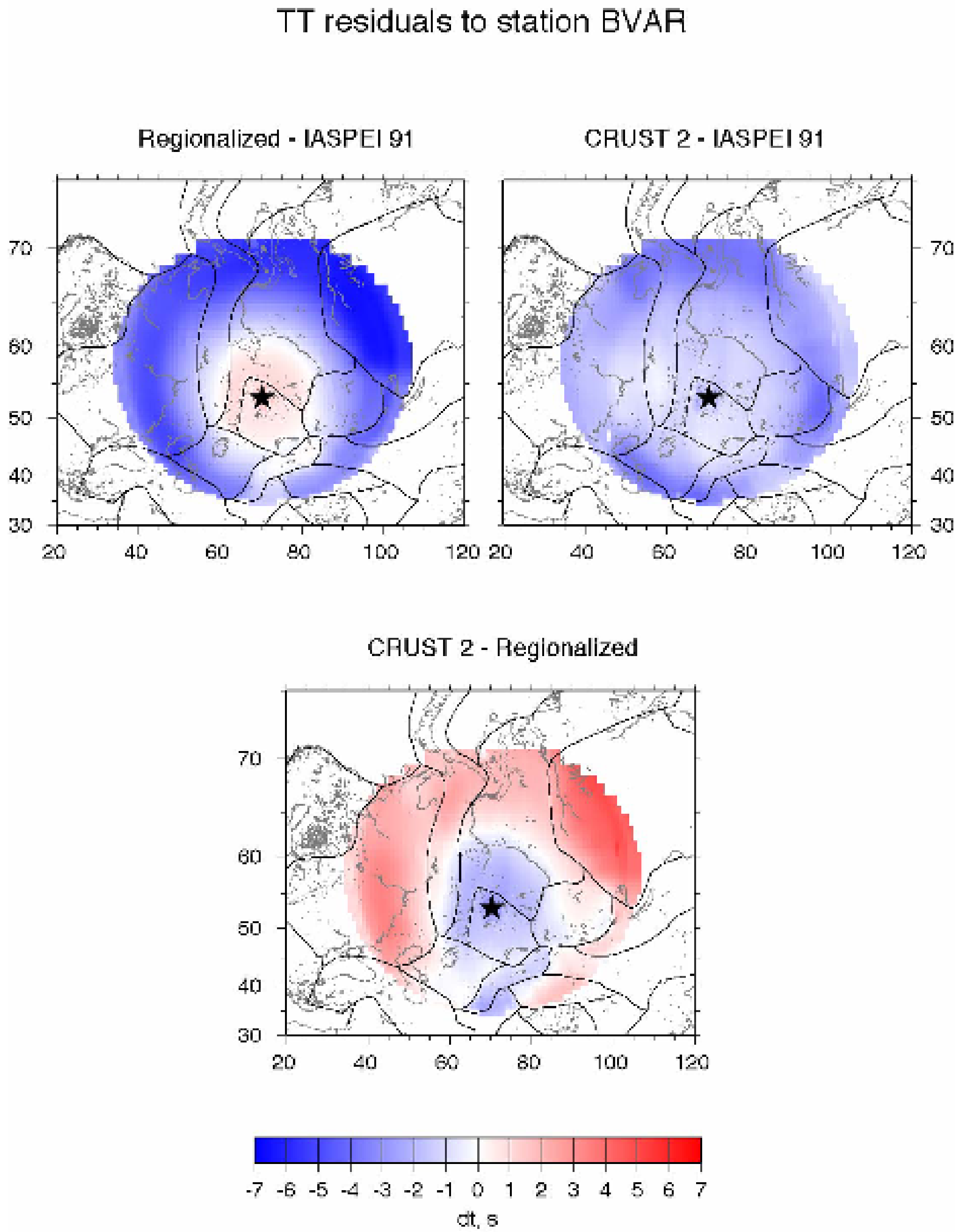

Figure 4. Travel-time differences between different velocity models computed for IMS station BVAR (Borovoye).