Memo

To: CCB

From: Paul Richards, Relu Burlacu, and Mark Fisk (Columbia University Group 1 Consortium)

Date: May 17, 2002

Subject: Pn SSSCs for IMS and Surrogate Stations in Asia

Sponsor: Robert Woodward

CC:

Abstract

We propose that Pn Source Specific Station Corrections (SSSCs) for 14 seismic stations in Asia be installed into the CMR baseline processing configuration. The SSSCs are expected to improve the accuracy of location estimates of seismic events in Asia and reduce the uncertainties. The SSSCs were computed by the method of Bondár (1999) using regionalization (Figure 1) of 1-D travel-time curves versus distance, as described in detail in Appendix A. These *model-based* SSSCs were then refined by a kriging algorithm (e.g., Bottone et al., 2001), in which the SSSCs are updated at each gridpoint by a linear combination of travel-time residuals for ground-truth (GT) events, weighted by a distance-dependent correlation function. The kriging algorithm also estimates an uncertainty grid. For well-calibrated areas, the correction grid converges to the mean of local data and the uncertainty converges to the residual variance of local data. Far from calibration data, the correction grid converges to the *model-based* SSSC value, with larger uncertainty equal to the sum of the residual and calibration variances, which is the variance of the travel-time means averaged over all well-separated locations.

Several tests were conducted on the RDSS testbed to validate the SSSCs, with emphasis on model validation and evaluation of the kriged SSSCs. Two data sets were used for the validation: Kitov's data set of phase picks for nuclear weapons tests at Semipalatinsk and Peaceful Nuclear Explosions (PNEs) recorded by various combinations of 93 stations, available through Harvard's web site (*www.seismology.havard.edu/~ekstrom/Research/FSU_data/FSU_data.html*); and a second data set of 18 nuclear explosions in China, India, and Pakistan, and chemical explosions at Semipalatinsk recorded by a sparse network of IMS seismic stations. A more detailed description of the data sets is provided in Appendix A. Using Pn arrival times assembled by Kitov at the IDG in Moscow, and published GT locations and origin times, we relocated 156 events recorded by various combinations of 93 regional stations, with and without using SSSCs. Mislocations are

reduced for 63% of the events using the *model-based* SSSCs, and for 93% using the kriged SSSCs. The median mislocation improved from 12.2 km to 9.5 km and 2.7 km, respectively. The median area of the error ellipses was reduced from 1,596 km^2 to 450 km^2 and 196 km^2, respectively. Error ellipse coverage (percent of GT event locations within the corresponding error ellipses) is 97% without using SSSCs, 94% using *model-based* SSSCs, and 100% using kriged SSSCs. These results were obtained for source locations, stations, and paths that sample very extensive and diverse geological provinces of Central and Northern Asia. Thus, we believe the results indicate the general validity of the model and the resulting SSSCs for this region. We expect these SSSCs to perform, on average, as well as indicated by the validation test results for the *model-based* SSSCs, and substantially better for areas near the Lop Nor, Semipalatinsk, Indian and Pakistani nuclear test sites, and sites of historical Soviet PNE's, where calibration data have been utilized.

Statement of Objective

The objective is to install Pn SSSCs, computed by a regionalized travel-time model and kriging, for 14 IMS and surrogate stations in Asia into the CMR baseline processing configuration. These surface-focus (i.e., for depth = 0 km) SSSCs improve seismic event location performance in Asia by reducing mislocations and error ellipse areas while achieving at least 90% coverage.

Summary of Proposed Change

The proposed change is to install, under the CMR version control system (*ClearCase*), the Pn SSSCs for 14 IMS and surrogate stations in Asia, presented in Table 1, including stations AAK, AKTO, BRVK, KURK, MAKZ, NIL, ZAL, MAG, NRI (NRIS), SEY, TIK (TIXI), TLY, YAK, ULN (JAVM). Plots of the SSSCs and the corresponding modeling errors are presented in Burlacu et al. (2002).

Note that SSSCs for seven of these stations have already been delivered by the SAIC Group 2 Consortium. Although preliminary comparisons indicate that our Pn SSSCs for these stations perform significantly better for GT events in Asia, further work is needed to devise a strategy and thoroughly compare location performance using these duplicate sets of SSSCs. This evaluation work should be performed before these SSSCs are used in the operational system.

Expected Benefits

The off-line tests performed on the RDSS testbed and by the Columbia University Group 1 consortium demonstrate significant improvements in all location performance metrics recommended at the IDC Technical Experts Meeting on Seismic Event Location in 1999 (CTBT/WGB/TL-2/18). The methods of computing the SSSCs, the regionalization of 1-D travel-time curves, the GT data, and the results of testing are thoroughly documented by Burlacu et al. (2002). Validation tests performed by RDSS staff are documented by Bahavar (2002). Based on these validation test results for GT events in extensive and diverse provinces of Asia, we fully expect these Pn SSSCs to provide comparable improvements in location performance for the operational system.

Possible Risks and Dependencies

The SSSCs have potential impacts on the performance of *GA*, which uses *libloc*, and on *EvLoc*, which is called by automatic processing and *ARS*. Although we have not performed tests to assess the impact of our SSSCs on *GA* and *ARS*, the CCB Memo by Bondár (2001) addresses this issue. Their conclusion was that the impact of SSSCs, in general, is not considerable in terms of computational load and memory requirements. One possible issue is that larger SSSC files require increased read-in time. The SSSCs, computed by Columbia University Group 1 consortium, were generated on a rectangular grid with one degree spacing in longitude and latitude. As this is the same format as for previous SSSCs, we do not anticipate any risks of using the SSSCs in the *GA* and *ARS* environments. The off-line tests performed by RDSS staff and us showed no adverse impact of the SSSCs on *EvLoc*. However, we recommend that basic on-line testing be performed before the proposed Pn SSSCs are installed into the operational environment.

Note that not all events are affected by the proposed changes, but only those shallow events recorded by the 14 seismic stations in Asia with Pn phases.

Summary of Testing

Off-line testing was performed by the Columbia University Group 1 consortium and independently by RDSS staff. Appendix A and Appendix C provide the detailed results as Validation Test Reports from the Columbia University Group 1 consortium (Burlacu et al., 2002) and the RDSS testbed (Bahavar, 2002), respectively. Here we summarize the main results of those tests.

Figure 2 shows a map of the GT event locations (red stars) and the stations that recorded them (triangles), along with great circle paths between events and stations. There are 174 events shown on the map, including 156 explosions in Kitov's data set and 18 explosions in a separate data set that we have assembled. The green triangles represent the 30 IMS stations for which our consortium is tasked with generating SSSCs and the smaller blue triangles are stations that recorded events in Kitov's data set. The green curves in Figure 2 indicate the great circle paths for the 18 explosions from the second data set, along with paths for PNE's recorded by BRVK for which we have made our own phase picks from waveforms. The blue curves are great circle paths between events in Kitov's data set and the various 93 recording stations. This map illustrates that the source regions, station sites, and paths sample very diverse and extensive geological structures throughout Asia, making this data set extremely valuable for model validation.

The main objective of these tests is to use GT events to validate the Pn SSSCs by evaluating:

- travel time residuals before and after corrections;
- location performance (mislocation errors, error ellipse size, and coverage).

Figure 3 shows travel-time residuals versus epicentral distance for 145 Pn arrivals at station BRVK, corresponding to Soviet-era PNE's and UNE's at the Semipalatinsk and Lop Nor nuclear test sites. The residuals are relative to IASPEI91 without corrections (red squares) and after applying the *model-based* SSSCs computed by Bondár's method (green circles). It is clear the *model-based* SSSCs generally reduce the travel-time residuals. Figure 4 shows a similar plot using the SSSCs computed by Bondár's method and kriging, which shows that application of kriging provides further reduction of the Pn travel-time residuals at BRVK.

These results are quantified in Table 2 in terms of the mean and standard deviation of the Pn travel-time residuals for the various sets of explosions and the overall results. In all cases, both the mean travel-time bias and the standard deviation of the travel-time residuals are progressively reduced by applying the *model-based* SSSCs and the *model-based* plus kriged SSSCs. Although these results for BRVK were shown because of the geographical distribution of GT events and the quantity and quality of the Pn phase picks, which we carefully reviewed by inspection of the waveforms, they are qualitatively representative of the reductions in mean travel-time bias and residual variance that we obtain at other stations in Asia.

To evaluate the location performance we looked at two key aspects:(1) model validation and (2) evaluation of the kriged SSSCs. The first is to validate the regionalized travel-time model and *model-based* SSSCs computed by Bondár's method. The goal is to demonstrate that this model provides an effective representation of travel times in Central Asia. This is a critical step in the validation process because events may occur at locations far from calibration points used by the kriging algorithm, where the grids are asymptotically equivalent to the *model-based* SSSCs.

The second goal is to assess the location performance using the kriged SSSCs. To do this, we relocated the GT events using the kriged SSSCs with a leave-one-out procedure (to avoid using the same events to both compute and test the grids) and quantify the results in terms of the same performance metrics used in the model validation. The results are compared to those in which the relocations were performed without SSSCs and with the SSSCs computed by Bondár's method.

For model validation we used 156 events recorded at 93 stations (Kitov's data set). The test consists of relocating these events using Pn arrivals (2626 picks). All the relocations are performed with depth fixed at the surface. The relocation procedure is first applied using the IASPEI91 travel-time tables, without any SSSCs. This is followed by relocating the same events using the SSSCs. Both sets of relocation results are saved in a database at the CMR. Executing *EvLoc* with and without SSSCs resulted in 156 events with location estimates that converged.

Relocation performance is quantified using metrics that conform with the guidelines from the 1999 Location Workshop (CTBT/WGB/TL-2/18; also provided in Appendix D) held in Oslo, Norway, which include the following:

- the median mislocation of GT events should be significantly reduced;
- mislocation should be reduced by 20% or more for the majority of events;
- median area of confidence ellipses should be reduced, and the coverage should be the same or better;
- confidence ellipses should be reduced by 20% or more for the majority of events;
- variance of travel-time residuals should be similar or smaller.

Mislocation using Model-Based SSSCs

Mislocation is expressed as the distance between the GT location and the location obtained by *EvLoc*. Of the 156 events, the locations using SSSCs improved for 99 events (63%) and deteriorated for 57 events (37%). The median mislocation was reduced from 12.2 km to 9.5 km. For 82 events (53%) the solutions improved by more than 20%, while for 37 events (24%) the deterioration is more than 20%. Figure 5 shows the mislocation results. The green symbols represent the events for which the relocation with SSSCs is closer to the GT location than without SSSCs. The red symbols show events for which the mislocation without SSSCs is smaller than with SSSCs.

Error Ellipse Area and Coverage using Model-Based SSSCs

The error ellipses have systematic reduction in area by using the SSSCs than not. The difference in the error ellipse calculations for the two cases is due to a difference in the modeling errors. Since the modeling error for the SSSCs is always less than for IASPEI91, we expect the error ellipses for the SSSC case to always be smaller than for the IASPEI91 case. In fact, all 156 solutions (100%) are improved by more than 20% (Figure 6). The decrease in the median error ellipse area is 1,146 km^2 (from 1,596 km^2 to 450 km^2).

Error ellipse coverage is defined as the percentage of GT event locations that fall within the corresponding 90%-confidence error ellipse. For relocation solutions without using SSSCs, 151 events (97%) have 90%-confidence ellipses contain the GT locations. Using SSSCs, 146 events (94%) have 90%-confidence ellipses that contain the GT locations. Although the coverage is slightly lower when using the SSSCs, in both cases they are above the target of 90%, while the median area of the error ellipses is reduced substantially for all the events relocated with SSSCs.

The relocation results using the *model-based* SSSCs show the following:

- 63% of the events are located closer to the GT location than without using SSSCs;
- error ellipse area is smaller by 20% or more for 100% of the events;
- the coverage of the error ellipses is better than 90%.

Given the large number of source regions, stations, and ray paths that sample very diverse and extensive geological structures (represented by the 25 regions with corresponding travel times), we expect that SSSCs computed by Bondár's method for other stations in the same general area of Asia will, on average, perform as well as for the stations used to compile these evaluation metrics.

Mislocation using Kriged SSSCs

To evaluate location performance using the kriged SSSCs, we use a "leave-one out" procedure in which the event to be relocated is excluded from the kriging calculation of the SSSCs. We then relocate each of the 156 events with kriged SSSCs that are re-computed for each event so that the same data are not used to both compute and test the SSSCs. Since the kriged SSSCs approach the *model-based* SSSCs far from calibration data, we expect that the kriged SSSCs should perform at least as well as the *model-based* SSSCs, and much better for areas close to calibration data.

Of the 156 GT events, 145 solutions (93%) have smaller mislocation errors using kriged SSSCs than those obtained using just the IASPEI91 travel-time tables. Of these, 139 events (89%) have mislocation errors that are reduced by more than 20%. Only 11 solutions (7%) deteriorated, but not dramatically. The median mislocation is reduced from 12.2 km to 2.7 km when kriged SSSCs are used. Figure 7 shows a scatter plot of the mislocation distances, relative to the GT locations, obtained with (x-axis) and without (y-axis) using the SSSCs. As in Figure 4, the green symbols represent events for which location estimates using the kriged SSSCs are closer to the GT locations, while the red symbols show solutions that are better without using SSSCs.

Error Ellipse Area and Coverage using Kriged SSSCs

Using kriged SSSCs, error ellipse area is reduced for 153 of 156 solutions (98%), 152 of which (97%) are improved by more than 20%. Only 3 solutions (2%) do not have smaller error ellipses. The median ellipse area is reduced from 1,596 km^2 to 196 km^2. The results are shown in Figure 8. Error ellipse coverage, computed as the percentage of GT event locations contained within the 90%-confidence error ellipses, is 100% (all 156 GT events) when using the kriged SSSCs, as compared to 97% (151 GT events) without using SSSCs (i.e., using IASPEI91 only).

The relocation results using kriged SSSCs show significant improvements for all location performance metrics. Specifically,

- 93% of the events are located closer to the GT location with median mislocation errors reduced from 12.2 km to 2.7 km;
- error ellipse area is reduced by 20% or more for 97% of the events;
- median error ellipse area is reduced from 1,596 km^2 to 196 km^2, while achieving 100% coverage of the error ellipses with the GT event locations.

Location Results for 18 Additional GT Explosions

To directly evaluate the Pn SSSCs for IMS stations, we relocated 18 GT explosions in China, Kazakhstan, India, and Pakistan. Although this data set is small, comparable reductions in mislocations and error ellipse areas were obtained, as for the tests against Kitov’s data set (see Appendix A). Note that although these events were recorded regionally by a sparse set of IMS stations, the results are comparable to those obtained using a larger network of 93 stations for Kitov’s data set. In all cases, the test results demonstrate that our regionalization of 1-D travel-times curves, along with the computational methods of Bondár (1999) and kriging, have produced Pn SSSCs and modeling errors that improve the performance of location and uncertainty estimates in Asia.

General Remarks

It is important to note that location performance for events in areas far from existing calibration data should be, on average, comparable to the results obtained using the *model-based* SSSCs (i.e., without kriging). To illustrate the impact of kriging the travel-time residuals relative to the *model-based* SSSCs, we present in Figures 9-11 the kriged surfaces for stations BRVK, NRI, and YAK. In some areas the residuals are small and kriging has little impact, indicating that the *model-based* SSSCs are suitable. However, kriging can improve the SSSCs by up to several seconds.

Figure 12 shows Pn modeling errors as functions of epicentral distance for IASPEI91, our regionalized model (green curve), and three types of regions of Northern Eurasia (platform areas, paleozoic massifs and young platform, and tectonically active regions) defined by Kirichenko and Kraev (2001). Modeling errors were calculated as standard deviations of empirical data from the estimated travel-time curves in a 2-degree moving window with a 50% overlap (Kirichenko and Kraev, 2001). As an initial hypothesis, we defined our Pn modeling error as an upper bound of the modeling errors estimated by Kirichenko and Kraev (2001) for the various geotectonic provinces. To test the validity of our Pn model error, we computed average absolute travel-time misfits to the model-based SSSCs, binned by distance, for Pn phase arrivals in Kitov's data set (blue circles in Figure 12). While there are slight differences between the average misfit values and our modeling error curve, they are not significant with respect to the uncertainties. Furthermore, the validity of the error model was ultimately demonstrated by achieving appropriate coverage statistics. In the future we plan to refine this curve and, if data allow, to develop region-dependent modeling errors.

Schedule and Plan for Implementation

We recommend that the 14 Pn SSSCs be installed under CMR version control system (*ClearCase*) at the convenience of CMR staff. The SSSCs, in standard IDC format, are stored on the RDSS testbed under /home/rdtst/PROJECTS/G1/1/Install/SSSC_delivery. The naming convention of the files are *TT.$sta.$phase.reg.easia*.

Costs and Resources Required for Implementation

Implementation of the proposed changes is estimated to require less than one day of labor. No other costs or resources are required.

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Kirichenko, V. V., and Y. A. Kraev. Results of 1-D location calibration studies related to the territory of Northern Eurasia, *Proceedings of the 23rd Seismic Research Review*, 2001.

Bottone, S., M. D. Fisk, and G. D. McCartor. Regional seismic event characterization a using Bayesian formulation of simple kriging, in press, *Bull. Seism. Soc. Am.*, 2001.

Burlacu, V., M. Fisk, V. I. Khalturin, W-Y. Kim, P. G. Richards, J. Armbruster, I. Morozov, E. Morozova. Validation Test Report: Off-line Testing of a Regionalized Travel-Time Model and Source-Specific Stations Corrections for Asia., 2002.

Working Group B, Recommendations for seismic event location calibration development, CTBT/WGB/TL-2/18, 1999.

Table 1. IMS Stations for which Pn SSSCs were computed

IMS Code	Country	Station Name	Station Code
PS23	Kazakhstan	Makanchi	MKAR
PS25	Mongolia	Javhlant	JAVM
PS29	Pakistan	Pari	NIL
PS33	Russian Federation	Zalesovo	ZAL
PS34	Russian Federation	Norilsk	NRIS
AS57	Kazakhstan	Borovoye	BRVK
AS58	Kazakhstan	Kurchatov	KURK
AS59	Kazakhstan	Aktyubinsk	AKTO
AS60	Kyrgyzstan	Ala-Archa	AAK
AS86	Russian Federation	Seymchan	SEY
AS87	Russian Federation	Talaya	TLY
AS88	Russian Federation	Yakutsk	YAK
AS91	Russian Federation	Tiksi	TIXI
AS93	Russian Federation	Magadan	MAG

Table 2. Comparison of Pn travel-time residuals for station BRVK.

Case	IASPEI91		Model-Based SSSCs		Model + Kriged SSSCs	
	$\mu_{\Delta T}$	$\sigma_{\Delta T}$	$\mu_{\Delta T}$	$\sigma_{\Delta T}$	$\mu_{\Delta T}$	$\sigma_{\Delta T}$
Semipalatinsk UNE's	0.51	0.45	0.11	0.44	-0.02	0.30
Soviet PNE's	-3.91	1.96	-0.51	1.35	-0.05	1.09
Lop Nor UNE's	-2.52	0.04	0.85	0.04	0.02	0.04
Overall	-1.56	2.56	-0.15	1.01	-0.02	0.76

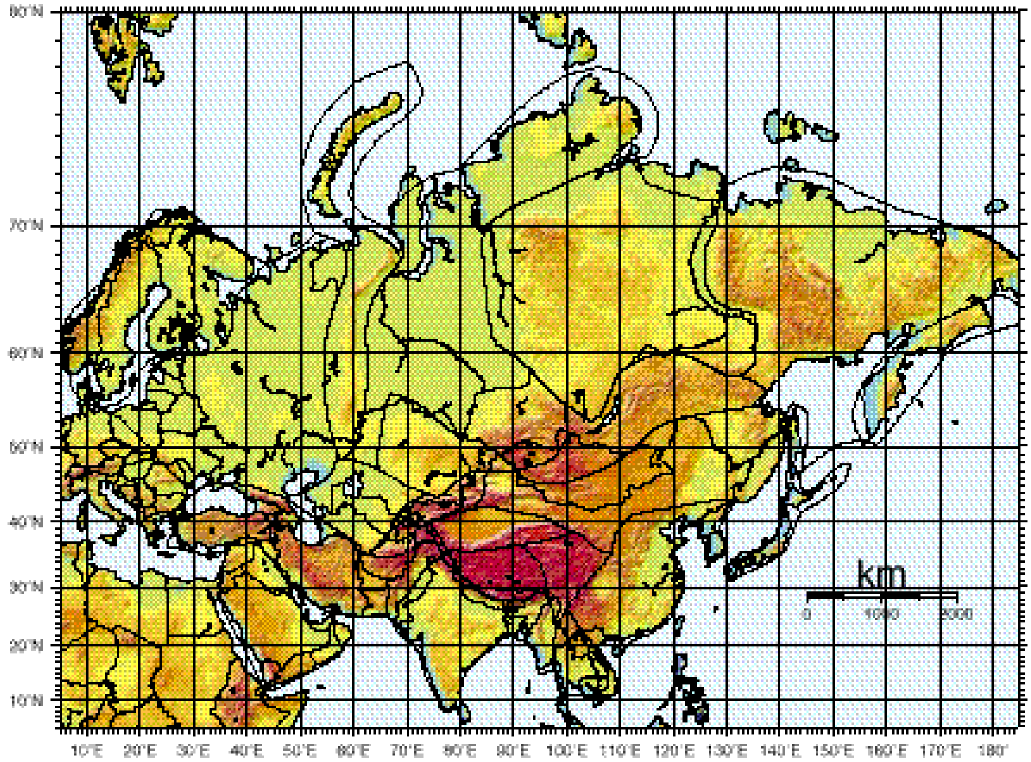

Figure 1. Map of topography and regionalization boundaries.

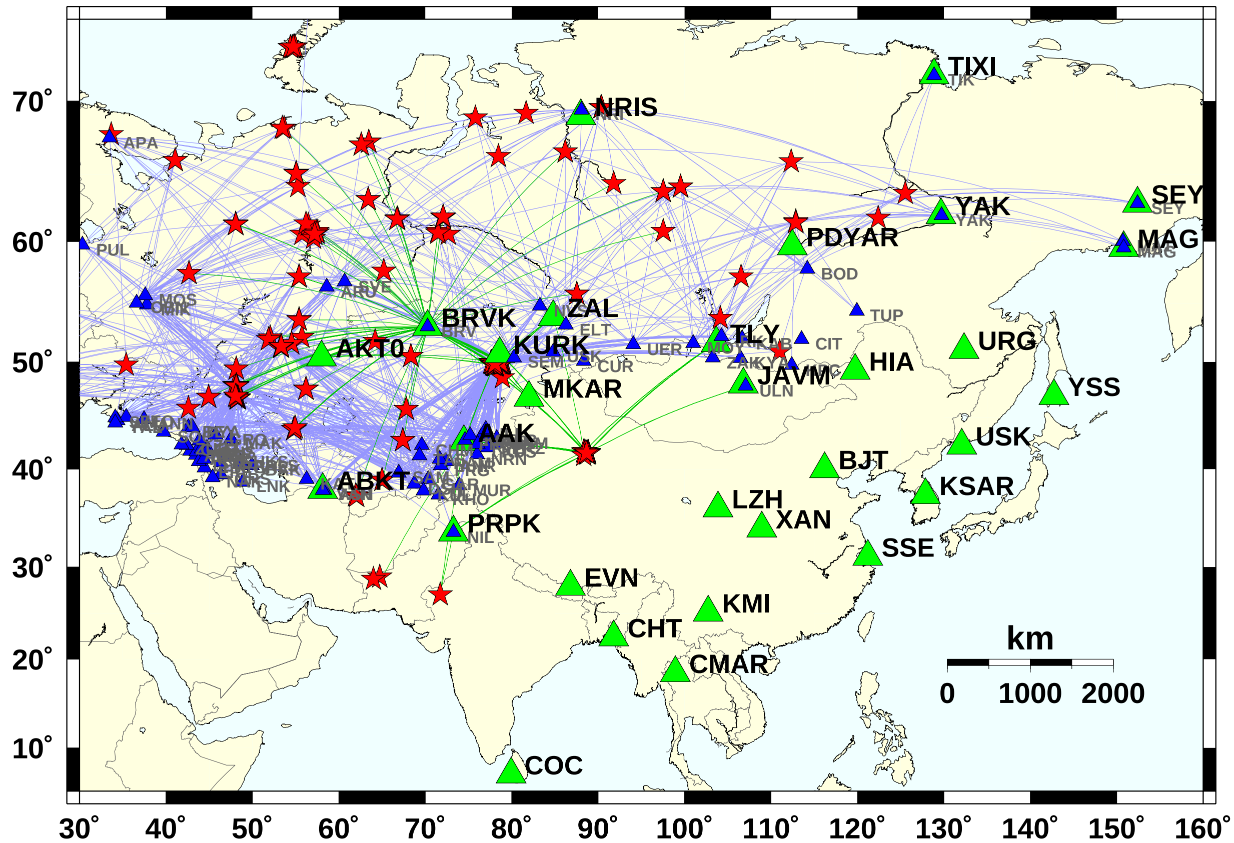

Figure 2. Map showing locations of 174 GT explosions (red stars) and the recording seismographic stations (green triangles) used for validation tests. Also shown are great circle paths between events and stations. The green triangles represent the 30 IMS stations for which our consortium is tasked with generating SSSCs. The smaller blue triangles represent stations that recorded events in Kitov's data set. The green curves indicate the great circle paths for the 18 explosions from our second data set, and for PNE's recorded by BRVK for which we have made our own phase picks from waveforms. The blue curves are great circle paths between events in Kitov's data set and the various 93 recording stations.

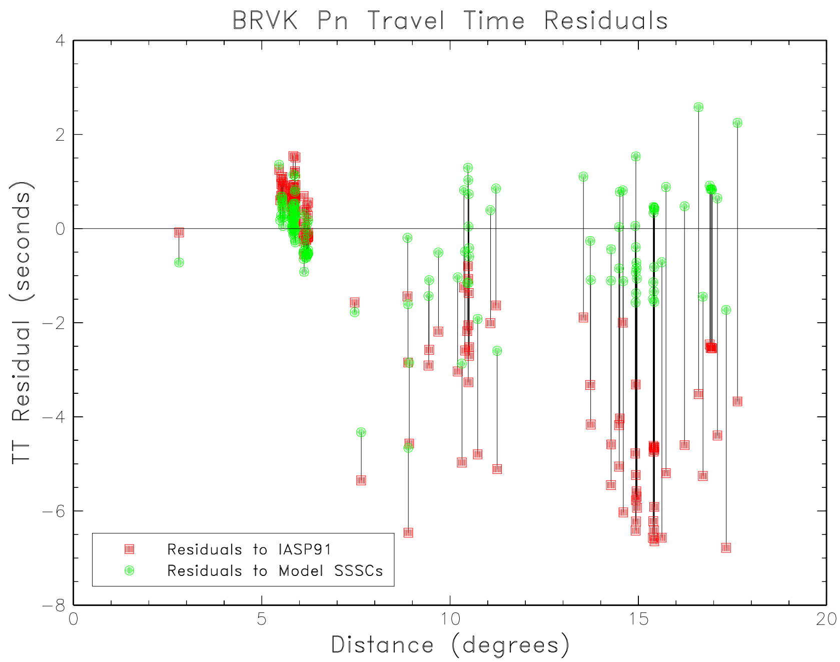

Figure 3. Pn travel-time residuals versus epicentral distance for station BRVK, before (red squares) and after (green circles) applying model-based Pn SSSCs computed by Bondár's method.

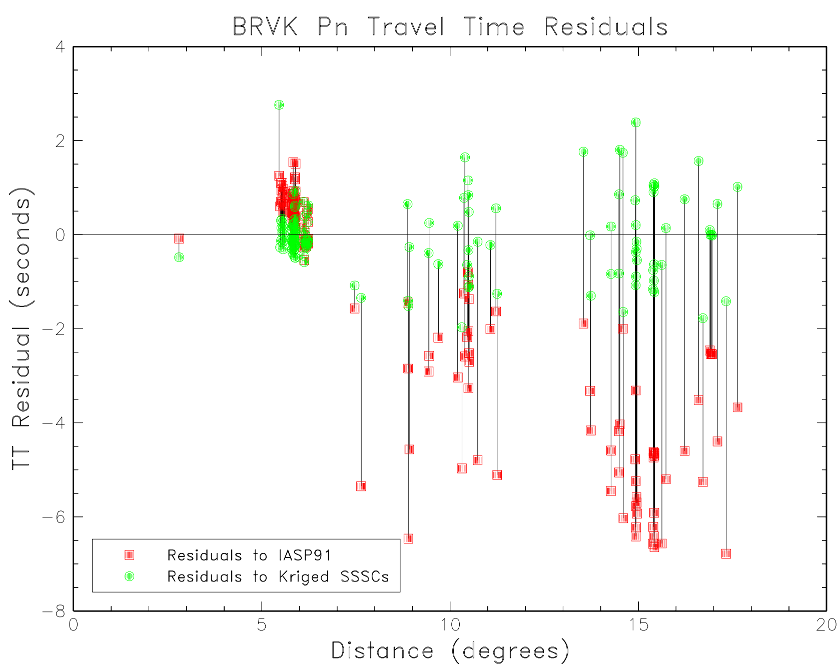

Figure 4. Pn travel-time residuals versus epicentral distance for station BRVK, before (red squares) and after (green circles) applying model-based plus kriged Pn SSSCs.

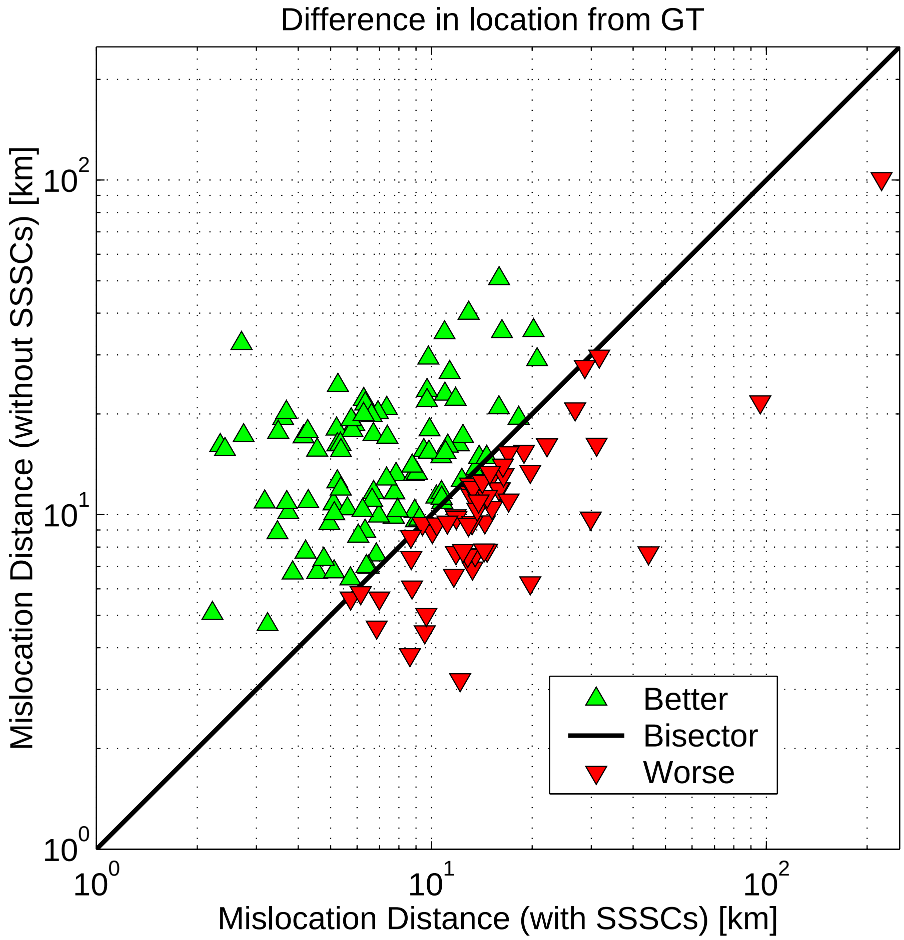

Figure 5. Mislocation distances with and without using model-based SSSCs with respect to corresponding GT locations. The green symbols show the events for which the mislocation error is smaller using SSSCs than without. Red symbols show the events for which the mislocation errors are smaller without using SSSCs. The bisecting line corresponds to equivalent mislocation errors for the two solutions (with and without SSSCs).

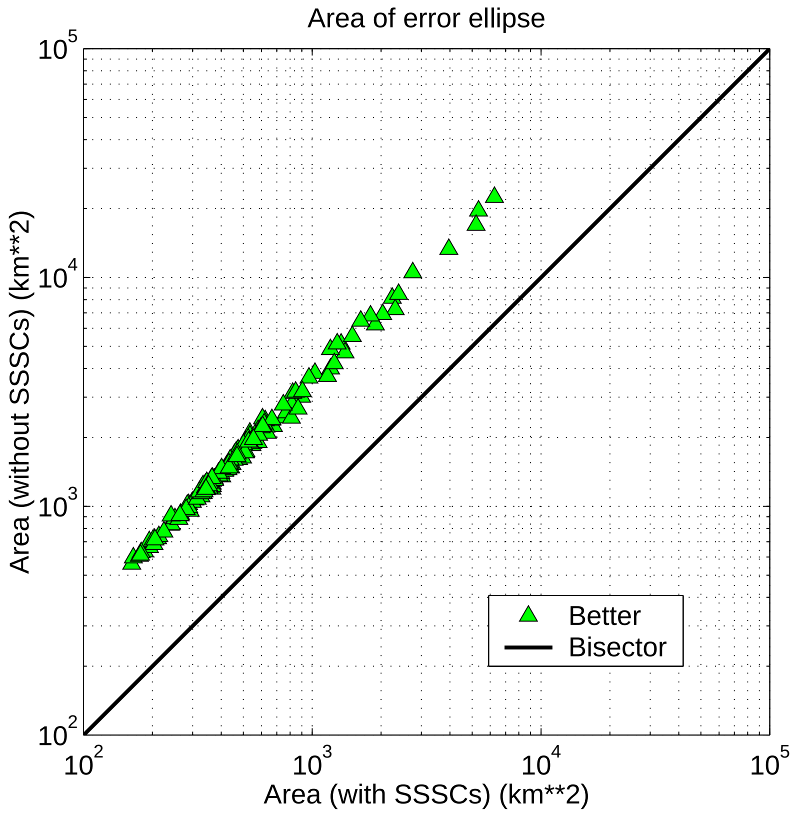

Figure 6. Scatter plot of error ellipse areas computed with (x-axis) and without (y-axis) using model-based SSSCs. Green symbols represent error ellipse areas that are smaller when using the SSSCs than without.

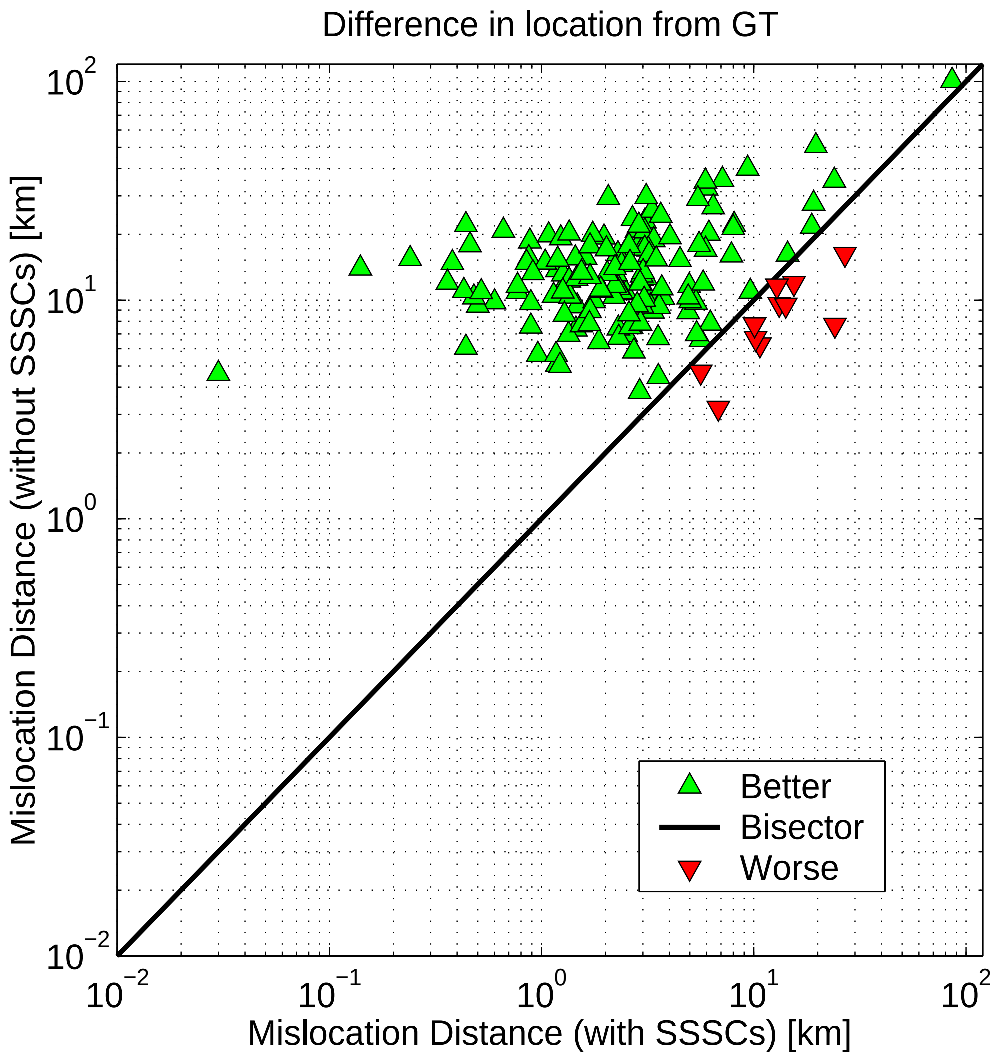

Figure 7. Mislocation distances with and without using kriged SSSCs with respect to corresponding GT locations. Markers and the line are defined as in Figure 5.

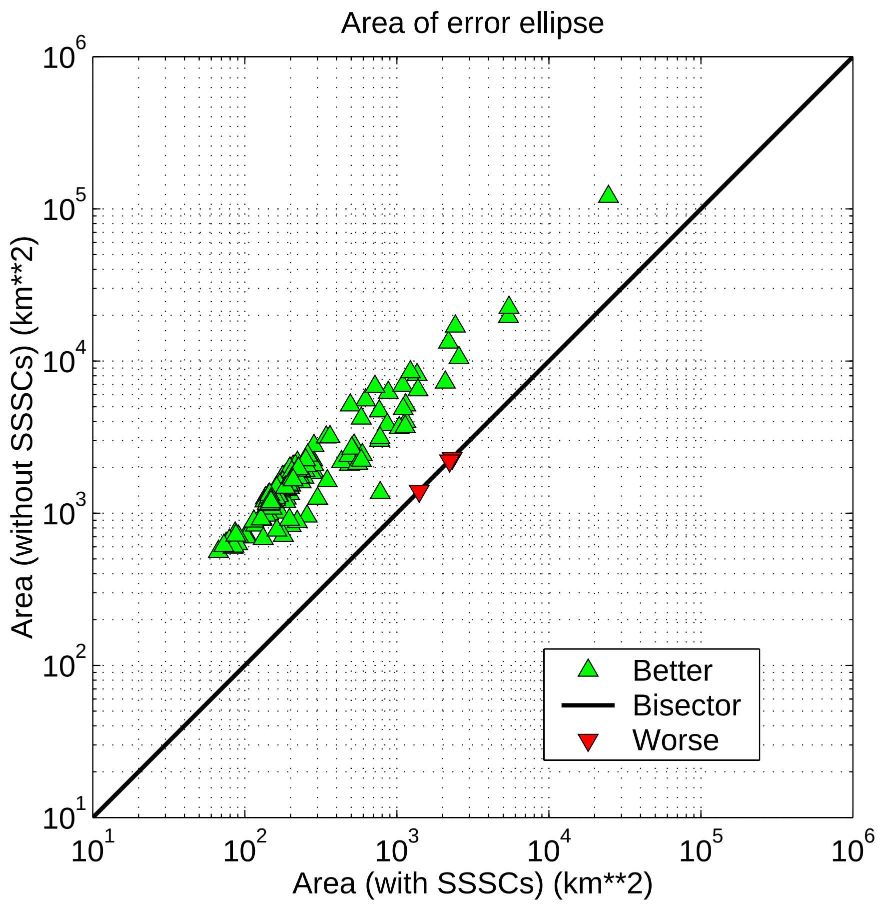

Figure 8. Scatter plot of error ellipse areas computed with (x-axis) and without (y-axis) using kriged SSSCs. Markers are defined as in Figure 6.

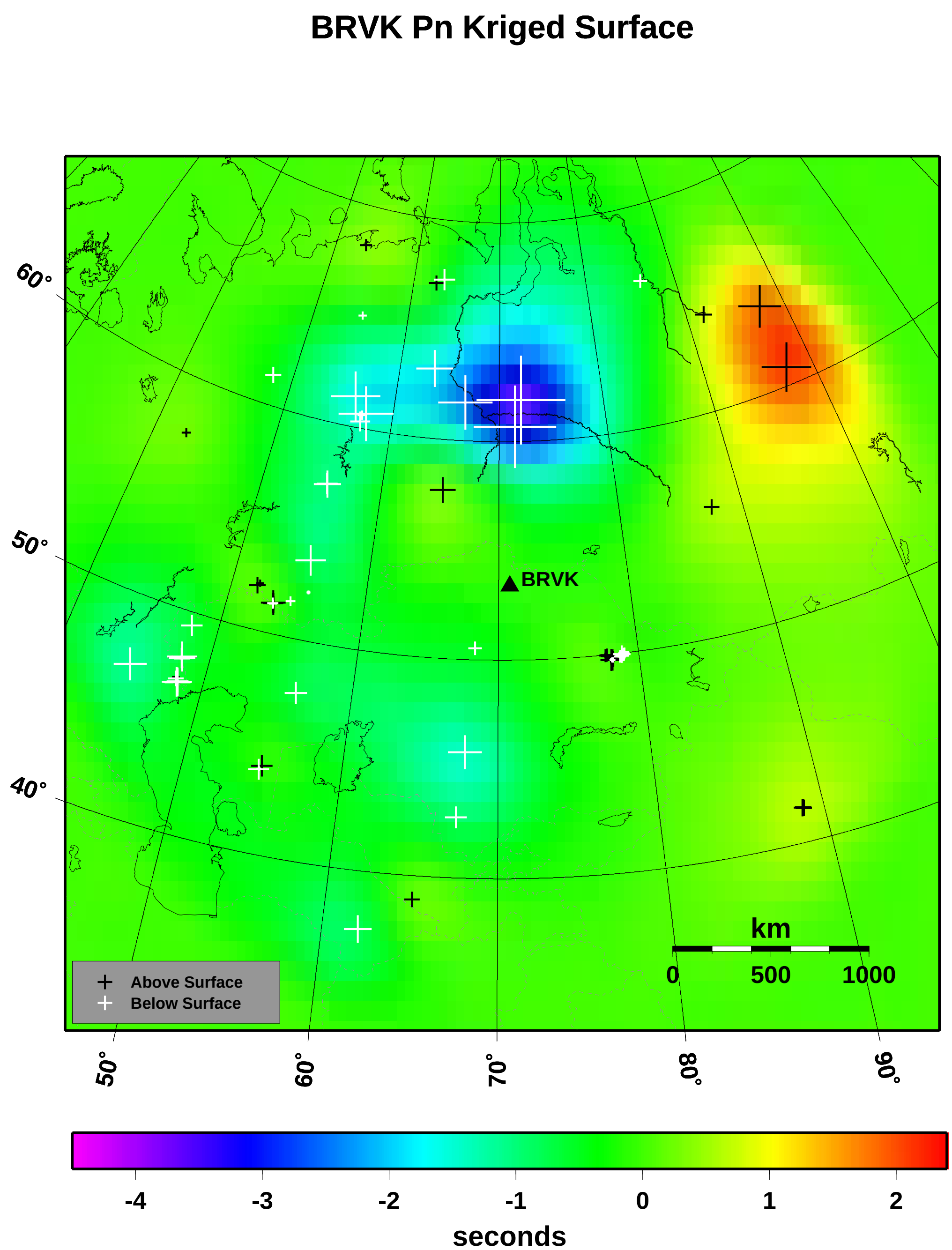

Figure 9. Kriged surface of Pn travel-time residuals relative to model-based SSSCs for station BRVK.

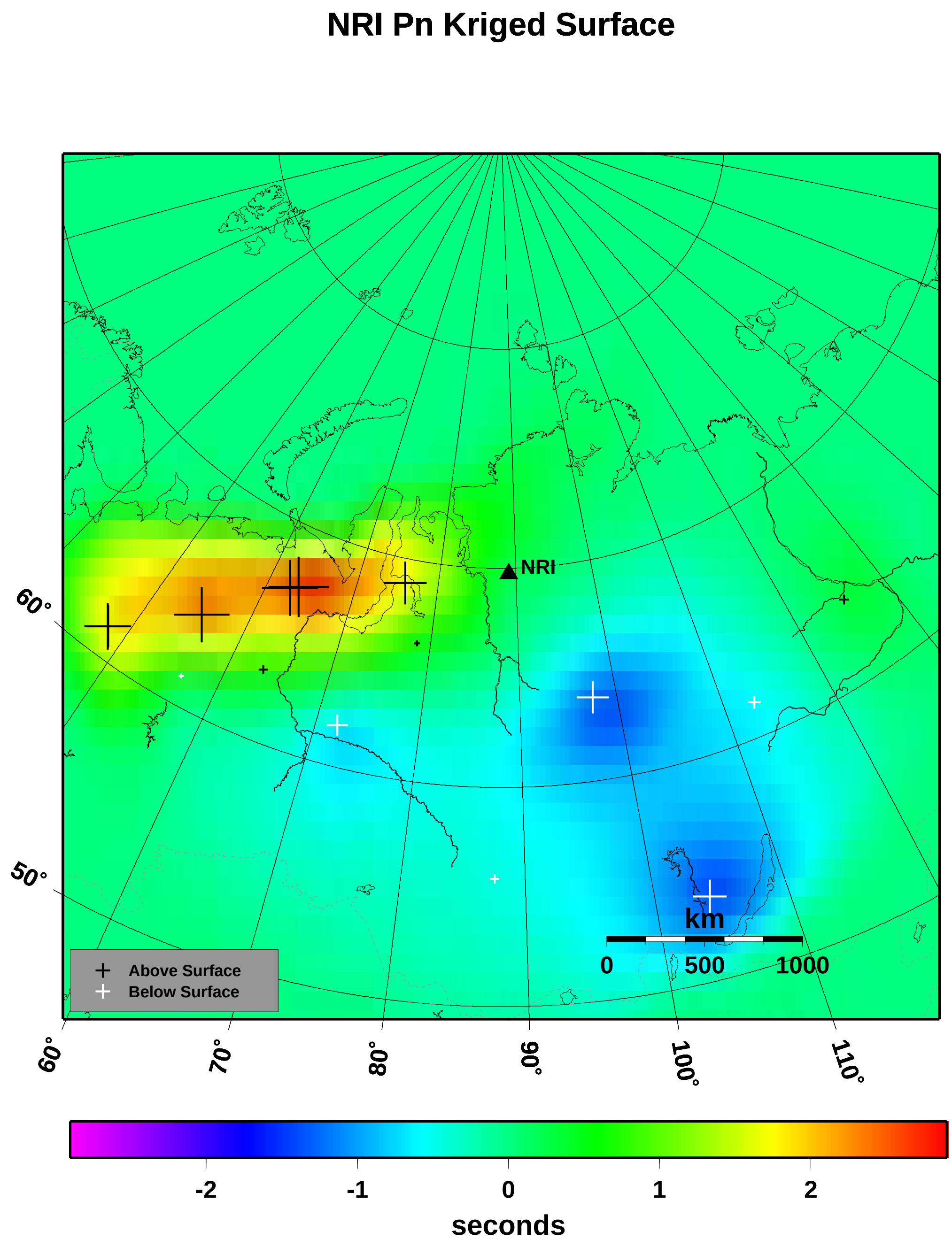

Figure 10. Kriged surface of Pn travel-time residuals relative to model-based SSSCs for station NRI.

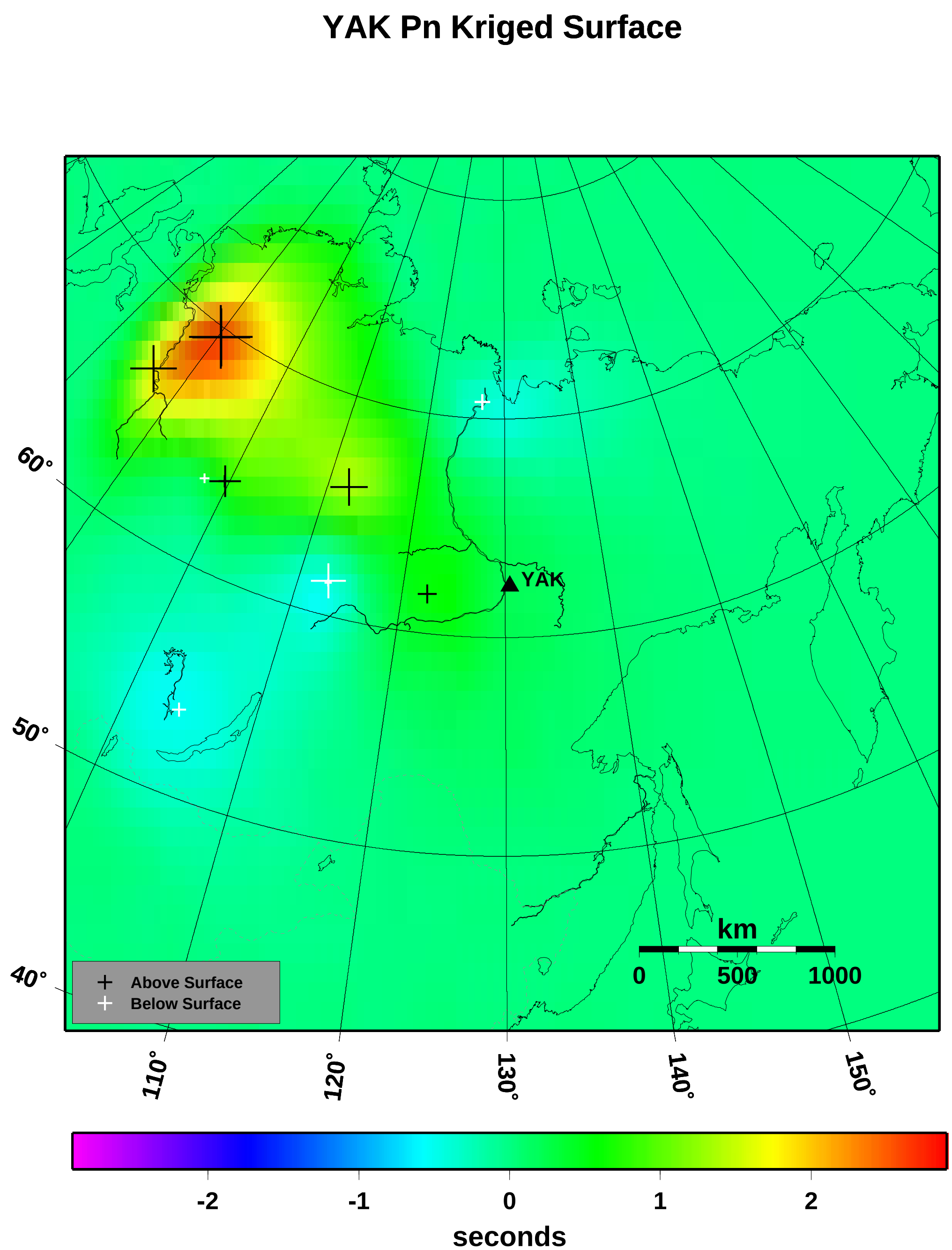

Figure 11. Kriged surface of Pn travel-time residuals relative to model-based SSSCs for station YAK.

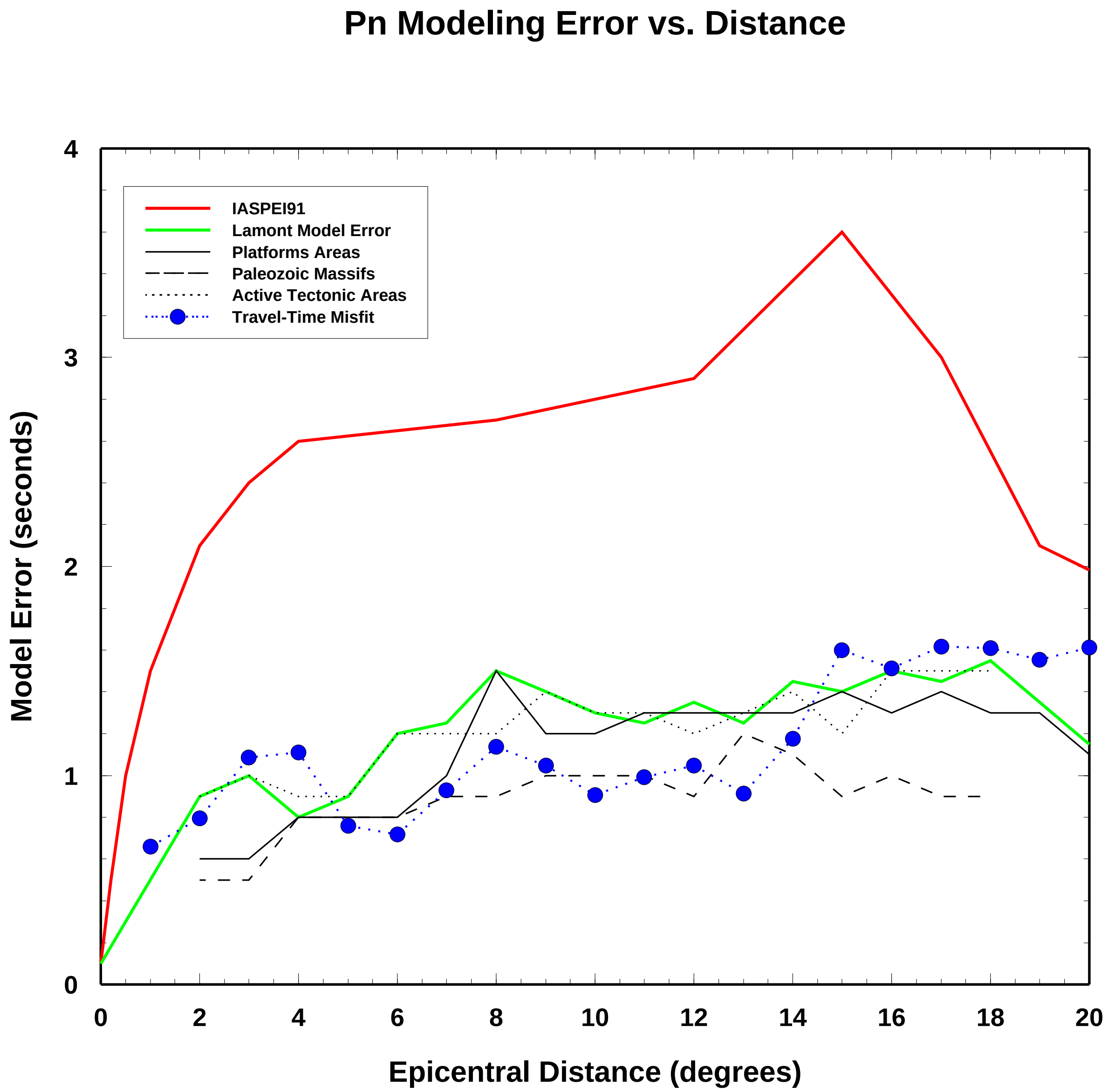

Figure 12. Pn modeling errors as functions of epicentral distance (total path length from event to station) for IASPEI91 (red curve), our regionalized model (green curve), and three types of regions of Northern Eurasia (black curves), defined by Kirichenko and Kraev (2001). Also shown are travel-time misfits to the model-based SSSCs, binned by distance, for Pn phase arrivals in Kitov's data set (blue markers).

Appendix A: Validation Test Report from Columbia University Group 1 Consortium

Appendix B: Validation Test Plan

Appendix C: Validation Test Report from RDSS

Appendix D: Recommendations from 1999 Oslo Workshop