SEISMIC LOCATION CALIBRATION FOR 30 INTERNATIONAL MONITORING SYSTEM STATIONS IN EASTERN ASIA: FINAL RESULTS

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ABSTRACT

We have completed a three-year consortium effort to improve the capability to locate seismic events based on data acquired by 30 International Monitoring System (IMS) stations in East Asia.

We have developed and tested Source Specific Station Corrections (SSSCs) for Pn and Sn travel times at these 30 IMS stations (or suitable surrogates), and for 127 other stations used for validation testing. The SSSCs were initially computed by the method of Bondár (1999), using regionalized 1-D travel-time curves established after extensive review of published studies including many from the Russian literature. Subsequently we developed a 3-D model of the P-wave velocity for East Asia (using a set of 36 different regions in each of which we obtained velocity as a function of depth), and used 3-D ray tracing in the latter model to compute SSSCs. These model-based SSSCs were refined empirically by applying a kriging algorithm to travel-time residuals for ground-truth (GT) events. Off-line validation tests were performed by evaluating travel-time residuals and by relocating GT events, with and without using SSSCs. To test the validity of the model directly, relocation tests were first performed using model-based SSSCs without kriging. Tests were then performed to evaluate the kriged SSSCs, using a leave-one-out approach so that events were not simultaneously used to both compute and test the SSSCs.

Nuclear explosions dominated our ground-truth datasets in the first two years of this project. In particular we used source parameters for Soviet-era Peaceful Nuclear Explosions (PNEs). But this approach, while quite satisfactory for calibrating stations in much of Russia and Central Asia (which made up approximately half the IMS stations we studied) could not be extended to the remaining stations, for which it was necessary to develop GT information on significant numbers of earthquakes. By use of the double-difference method and detailed fault maps, we obtained 64 GT5 earthquakes by re-analyzing the Annual Bulletin of Chinese Earthquakes (ABCE) for a 15-year period (1985 to 1999). It contains phase picks for approximately 1000 earthquakes in and near China, each year. A preliminary examination of digital waveforms for about 14,000 events, in and near China, shows that approximately 9% of them (1301 events) have the property that any one event has almost the same Lg waveform as at least one other event. These events are grouped into 494 sets of events, each of which has essentially the same short-period waveform and thus the events of each set must be within about 1 km of each other. These event sets provide a good method for assessing the quality of standard event catalogs. When combined with other information, they can provide high-quality absolute locations.

Using Pn and Sn arrival times for our GT data sets, we relocated 525 events recorded by various combinations of 140 regional stations. Mislocations were reduced for 66% of the events using the model-based SSSCs, and for 85% of the events using model-based SSSCs refined by kriging. Median mislocation improved from 16.9 km to 11.4 km and 6.5 km, respectively. Median error ellipse area was reduced from 2,616 km^2 to 1,633 km^2 and 722 km^2, respectively. Error ellipse coverage (percentage of GT locations within 90% error ellipses) was 89% without using SSSCs, 91% using model-based SSSCs, and 92% using kriged SSSCs. These results were obtained for source locations, stations, and paths that sample very extensive and diverse geological provinces throughout much of Asia. The SSSCs are expected to perform, on average, as well as the test results using the model-based SSSCs, and substantially better for areas where GT calibration data were utilized to refine the SSSCs.

OBJECTIVE

The goal of this project has been to improve the accuracy of estimates of the location of seismic events — and to reduce the uncertainty of such estimates — on the basis of an interpretation of the arrival times of regional seismic waves observed at 30 stations of the International Monitoring System (IMS) located in Eastern Asia.

RESEARCH ACCOMPLISHED

Introduction

Our project began as a three-year effort in March 2000 and has now been completed. It has been a collaborative academic-industry research project led by Lamont and involving a consortium of five institutions. We developed a structural model of East Asia built up from 36 sub-regions, shown in Figure 1, and we also developed the capability to compute travel times in this model by 3D ray tracing. We developed a set of 525 ground-truth events (almost all them of GT5 quality or better), and their associated phase picks. In addition to calibrating 30 IMS stations we calibrated another 110 stations in East Asia. The total set of 140 stations and GT locations, and the Pn paths between them, are shown in Figure 2. We derived a set of model-based Source-Specific Station Corrections (SSSCs) for Pn and Sn from 3D ray tracing in our regionalized model, and we then used empirical arrival times and GT information to refine the model-based SSSCs by kriging. In this paper, we emphasize the end-to-end validation of our claims of significant location improvement when our SSSCs are applied to relocate seismic events in East Asia.

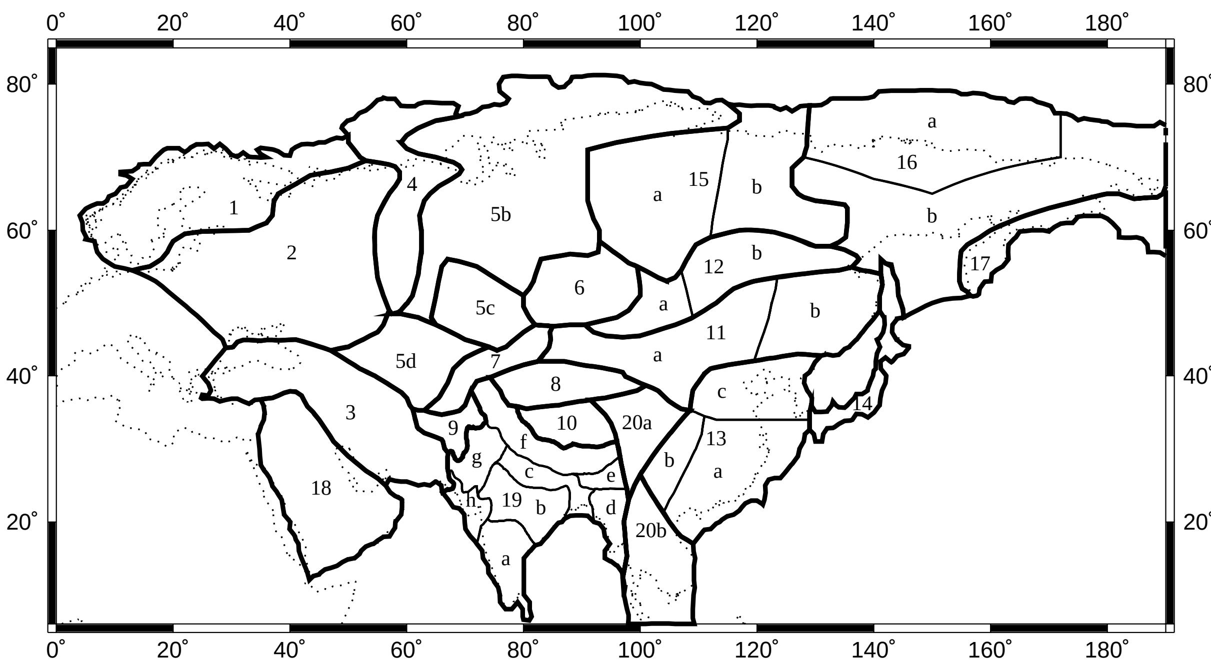

Figure 1. The region boundaries and numbering system used for 36 1D regions in East Asia and surrounding areas, which together make up the 3D velocity model in which 3D ray tracing was used to give our model-based SSSCs.

Further details of our work, including much information on how we obtained our regionalized model and numerous new GT events in East Asia (mostly, in and near China), are contained in Fisk (2002), Waldhauser and Richards (2003ab), Schaff and Richards (2003ab), Yang et al. (2003), and Burlacu et al. (2003). A CD has been prepared with our main final report (Burlacu et al., 2003) and 1871 additional files giving our data, including details of our 3D model, our GT events (including phase picks in CSS 3.0 format), and our model-based and kriged SSSCs. Our work has also been described in 11 papers presented at four Oslo workshops on location calibration organized by NORSAR from 1999 to 2003 (and appearing in the proceedings of those workshops), eight presentations at meetings of the American Geophysical Union, the Seismological Society of America, and the International Association of Seismology and Physics of the Earth's Interior, and in Seismic Research Review meetings of 2000, 2001, and 2002.

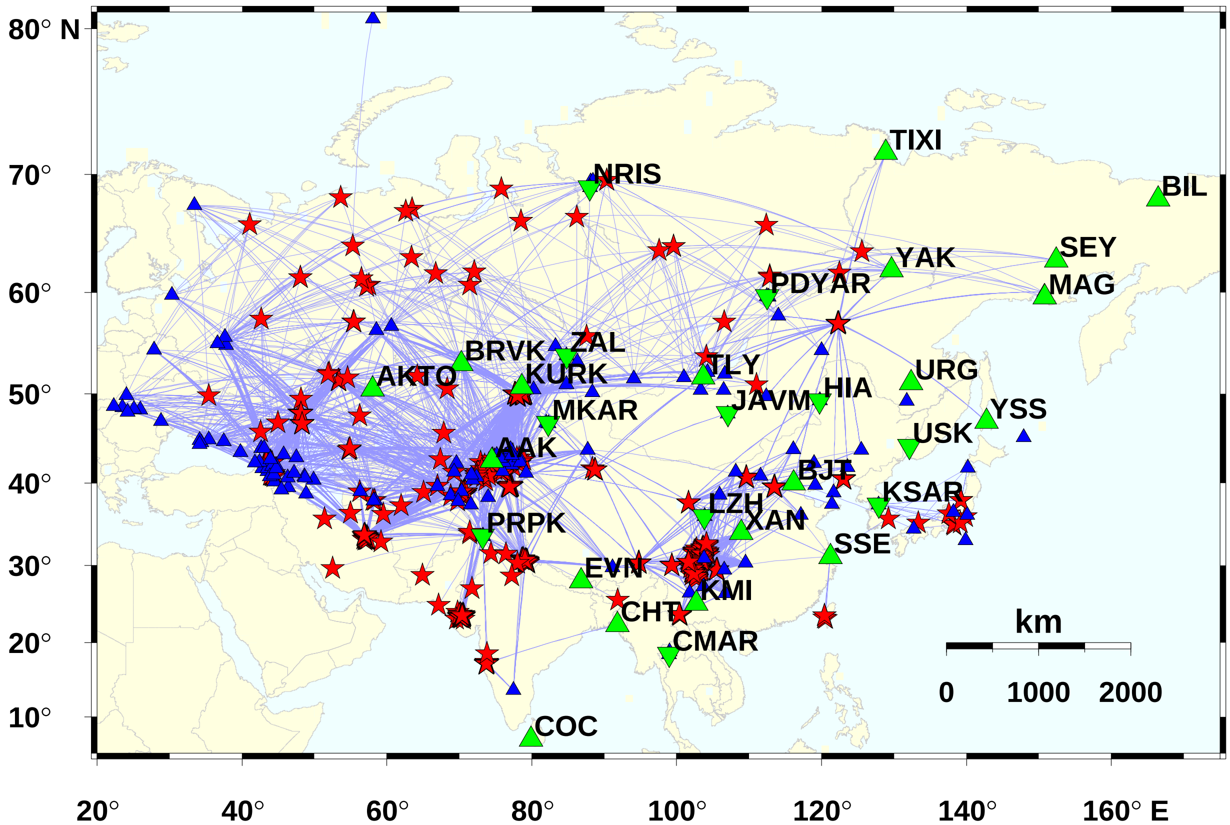

Figure 2. Map of events (red stars) and recording seismic stations (blue triangles) of the data set used for model validation. The green triangles represent the 30 IMS stations that our consortium was tasked to calibrate. Also shown are great circle Pn paths between events and stations.

Table 1. Mean and standard deviation of Pn and Sn travel-time residuals, in seconds, for all the stations that recorded at least 3 GT events.

Case	IASP91		Model-Based SSSCs		Model + Kriged SSSCs	
	$\mu_{\Delta T}$(s)	$\sigma_{\Delta T}$(s)	$\mu_{\Delta T}$(s)	$\sigma_{\Delta T}$(s)	$\mu_{\Delta T}$(s)	$\sigma_{\Delta T}$(s)
Pn	1.89	1.77	1.33	1.48	0.22	1.01
Sn	6.08	4.24	3.08	3.76	1.34	3.76

The tables and figures in this paper contain descriptions of our claims of location improvement, which have been the subject of a successful integration test conducted in May 2003 by the Research and Development Support System staff of the group then known as the Center for Monitoring Research.

As an overall indication of how well our SSSCs reduce the misfit between observed and calculated arrival times, Table 1 shows RMS values for the mean and standard deviation of the Pn and Sn travel-time residuals for all the stations that recorded at least 3 GT events. The kriged results were obtained via a leave-one-out approach in the generation of SSSCs, so that the arrival times from any one event were not used to provide the location estimate in that case. From this Table, we see that a very significant reduction of residuals is obtained by kriging.

In sections that follow, we describe a discovery concerning broad area seismicity of China which proved useful in generating ground truth reference events and which points the way to a future in which seismicity will be located by making use of waveforms rather than being based on phase picks. We then describe our model validation, and end-to-end validation of our kriged SSSCs, before giving our conclusions and recommendations.

A discovery concerning broad-area seismicity

As part of our work to generate ground-truth reference events in East Asia, we found that whole waveforms of regional signals, from a few seconds prior to the P arrival and running to several tens of seconds after the Lg arrival, were very similar for certain clusters of events. This result was first obtained for events (foreshocks, aftershocks) associated with a magnitude 5.9 earthquake in 1999 in the Xiuyan region of Liaoning Province, China (Schaff and Richards, 2003a). The correlation coefficient was above 0.9, for a time window of a few hundred seconds (recorded in the band from 0.5 to 5 Hz for stations several hundred km distant from the events). Because it was possible to measure relative arrival times with precision of a few milliseconds (about three orders of magnitude better than traditional Lg phase picks), relative locations accurate to about 150 m could be obtained.

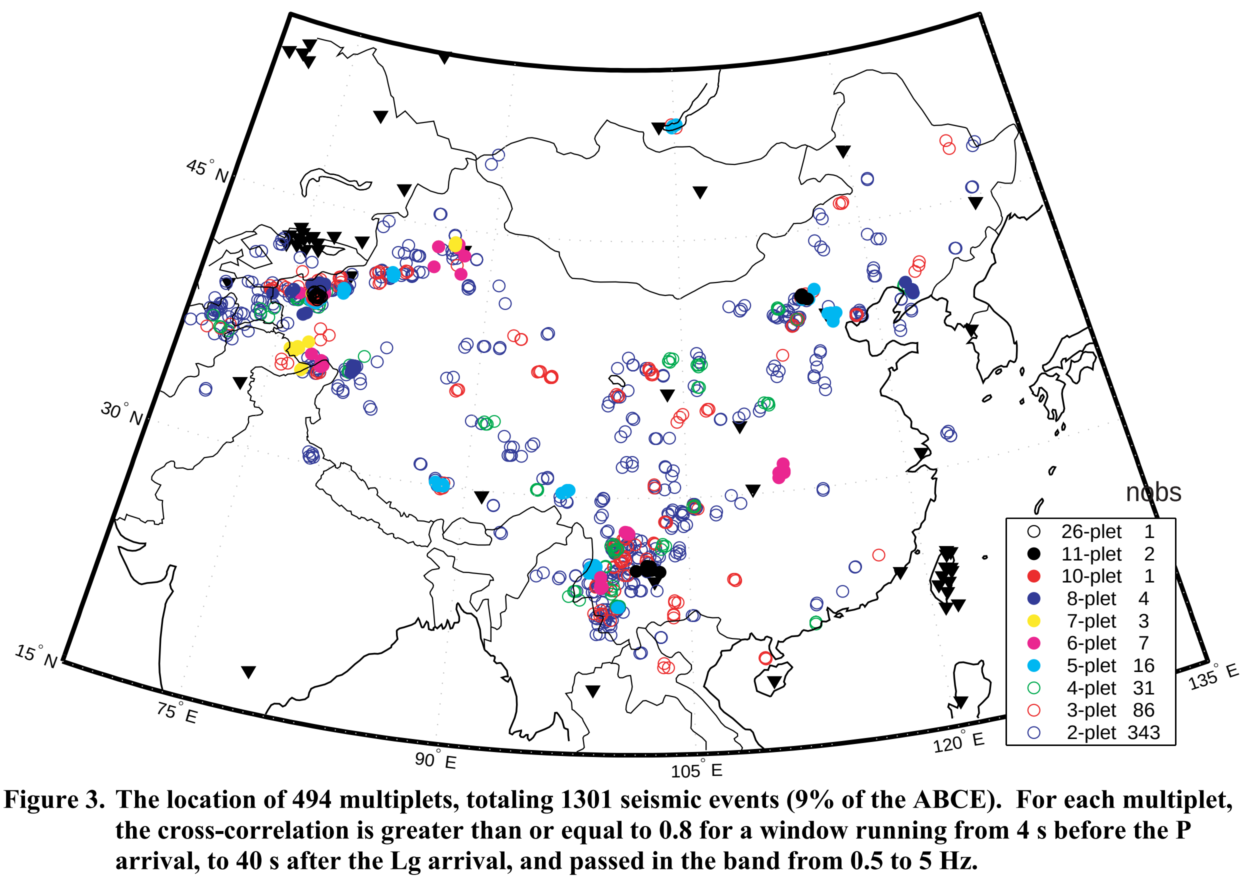

Figure 3. The location of 494 multiplets, totaling 1301 seismic events (9% of the ABCE). For each multiplet, the cross-correlation is greater than or equal to 0.8 for a window running from 4 s before the P arrival, to 40 s after the Lg arrival, and passed in the band from 0.5 to 5 Hz.

Our studies of Chinese seismicity for the years 1985 to 1999 included analysis of about 15,000 events reported in the Annual Bulletin of Chinese Earthquakes (ABCE), and allowed us to derive 64 GT5 quality events as documented by Waldhauser and Richards (2003a). Knowing the approximate location of these 15,000 events, we made a major data request to the IRIS (Incorporated Research Institutes for Seismology) Data Management Center for the regional waveforms of about 14,000 events in and near China, as recorded by all digital stations within 20° for each event (a total of 115 stations). When this dataset (about 12 Gbytes) was searched for repeating waveforms, it was found that a set of 1301 events had the property that each event had almost exactly the same seismograms as at least one other event. These 1301 events, about 9% of the ABCE, were composed of 494 subsets of repeating signals (Schaff and Richards, 2003b). Each subset (in most cases composed of just a pair of events, i.e. a doublet) must consist of events that were within 1 km of each other, given the time window and bandwidth of the signals that were cross-correlated.

Numerous different uses may be made of our discovery that a significant fraction of seismicity in a broad region is made up of repeat events. Excellent relative locations may be obtained for the events within a cluster. The clusters may in some cases be located in an absolute sense (enabling their use as GT events). And the fact that each cluster is so small in size (less than 1 km across) enables a simple evaluation of the precision of event catalogs that locate the events one-at-a-time (Schaff and Richards, 2003b).

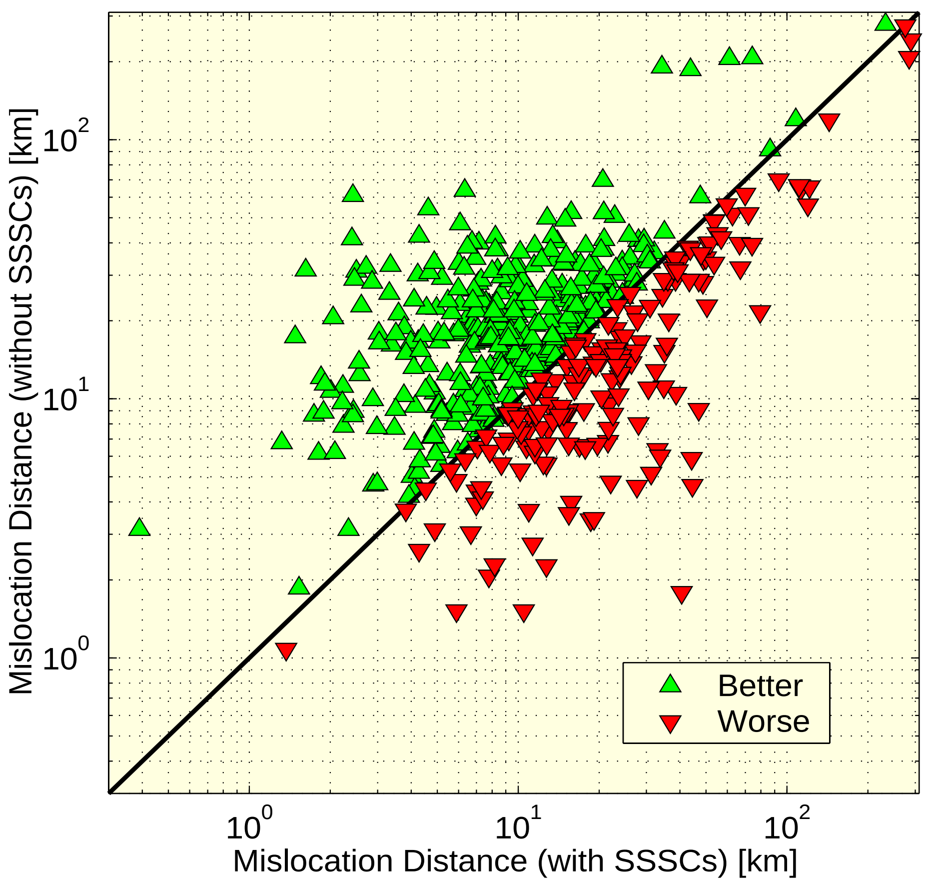

Figure 4. Mislocation distances with and without using model-based SSSCs with respect to corresponding GT locations. The green symbols show the events for which the mislocation error is smaller using SSSCs than without. Red symbols show the events for which the mislocation errors are smaller without using SSSCs. The bisecting line corresponds to equivalent mislocation errors for the two solutions (with and without SSSCs).

Evaluation of our travel time model

For model validation we use 525 events recorded at 140 stations. The test consists of relocating these events using Pn (5677 picks) and Sn (1586 picks) arrivals. All the relocations are performed with depth fixed at the surface. Figure 2 shows the distributions of events and seismographic stations used in this analysis. Also shown in Figure 2 are great circle Pn paths between events and stations. The relocation procedure is first applied using the IASP91 travel-time tables, without any SSSCs. This is followed by relocating the same events using the SSSCs. Executing EvLoc with and without SSSCs resulted in 525 events with location estimates that converged.

First we look at the mislocations, then at the travel time residuals, and then at the size of the error ellipses and their coverage, when using our model-based SSSCs.

Mislocation is expressed as the difference in distance between the GT location and the location obtained by EvLoc. Of the 525 events, the locations using SSSCs improved for 348 events (66%) and deteriorated for 177 events (34%). The median mislocation was reduced from 16.9 km to 11.4km. For 276 events (53%) the solutions improved by more than 20%, while for 140 events (27%) the deterioration is more than 20%. Figure 4 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 the events for which the mislocation without SSSCs is smaller than with SSSCs.

The standard error of observations, a measure of the fit that depends on the root-mean-squared (rms) travel-time residuals, shows improvement for 304 solutions (58%) and deterioration for 221 solutions (42%). 186 solutions (35%) are improved by more than 20% and 147 solutions (28%) deteriorated by more than 20%.

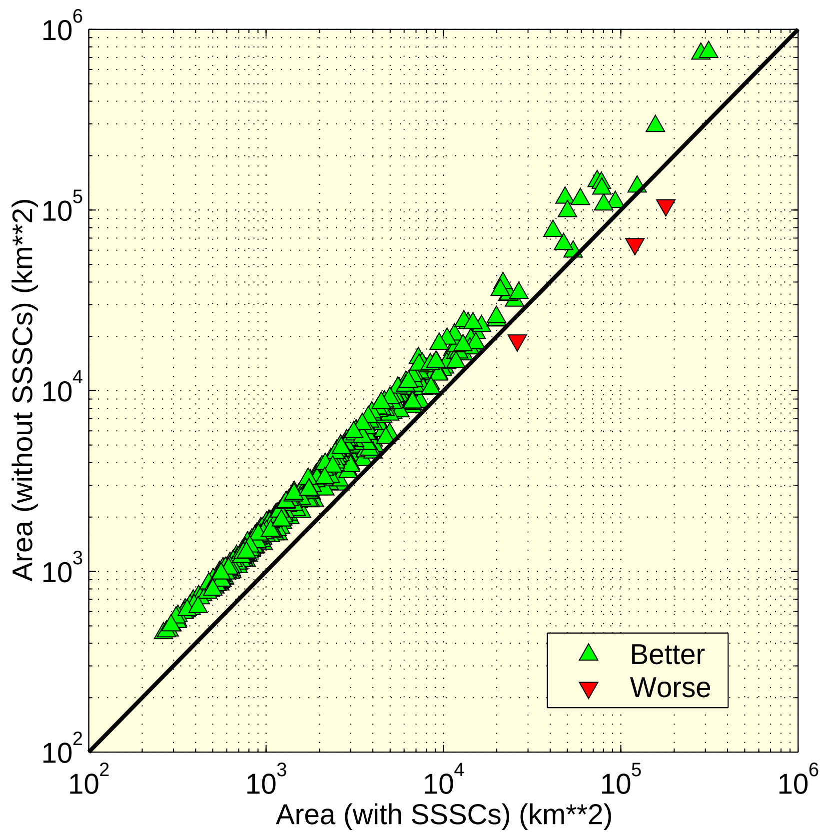

Figure 5. Scatter plot of error ellipse areas computed with (x-axis) and without (y-axis) using model-based SSSCs. Green symbols represent error ellipse areas that are smaller when using the SSSCs than without.

Our SSSCs lead in general to smaller error ellipses. Thus, using model-based SSSCs, error ellipse area is reduced for 522 of 525 solutions (99%), 498 of which (95%) are improved by more than 20%. Only 3 solutions (1%) do not have smaller error ellipses. The decrease in the median error ellipse area is 953 km^2 (from 2,616 km^2 to 1,633 km^2). Figure 5 shows the scatter plot of error ellipse areas computed with and without SSSCs.

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, 466 events (89%) have 90%-confidence ellipses that contain the GT locations. Using SSSCs, 476 events (91%) have 90%-confidence ellipses that contain the GT locations. In both cases the coverage is near the target of 90%, while the median area of the error ellipses is reduced significantly when relocating with SSSCs.

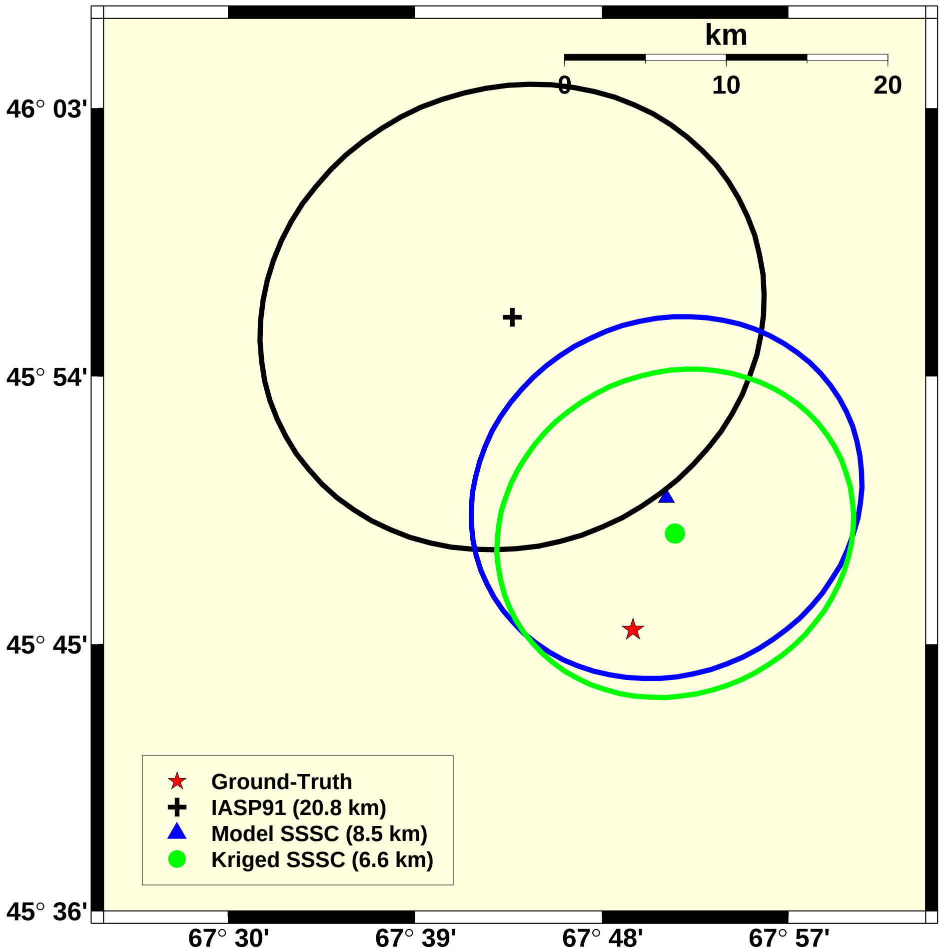

Figure 6. Relocation results, with and without using SSSCs, for a PNE (Meridian-2) in the Former Soviet Union on 19 September 1973. Mislocation errors relative to the ground-truth location are 20.8 km without using SSSCs, 8.5 km using model-based SSSCs, and 6.6 km using kriged SSSCs. The error ellipse areas are 710 km^2 without using SSSCs, 425 km^2 using model-based SSSCs, and 357 km^2 using kriged SSSCs.

Evaluation of our kriged SSSCs

We evaluated location performance using the kriged SSSCs. At locations near calibration data, the kriged corrections converge to the mean of the nearby data values and the uncertainty converges to the residual (i.e., local) variance. For grid points far from calibration data, the correction surface approaches the model-based SSSC, with larger uncertainty that is the sum of the calibration and residual variances. Thus, the kriged SSSCs should perform at least as well as the model-based SSSCs, and much better for locations close to calibration points. In this analysis, we used a computationally intensive but necessary "leave-one out" procedure in which the event to be relocated was excluded from the kriging calculation of the SSSCs. We then relocated each of the 525 events with kriged SSSCs that are re-computed for each event so that we do not use the same data to both compute and test the SSSCs.

As an example, Figure 6 shows relocation results without SSSCs, with model-based SSSCs, and with kriged SSSCs for a PNE, Meridian-2, which was detonated on 19 September 1973 in the Former Soviet Union. The kriged SSSCs reduce the mislocation error from 20.8 km to 6.6 km and reduce the error ellipse area from 710 km^2 to 357 km^2. For this event, the relocation results do not differ significantly when using the model-based or kriged SSSCs. Note that

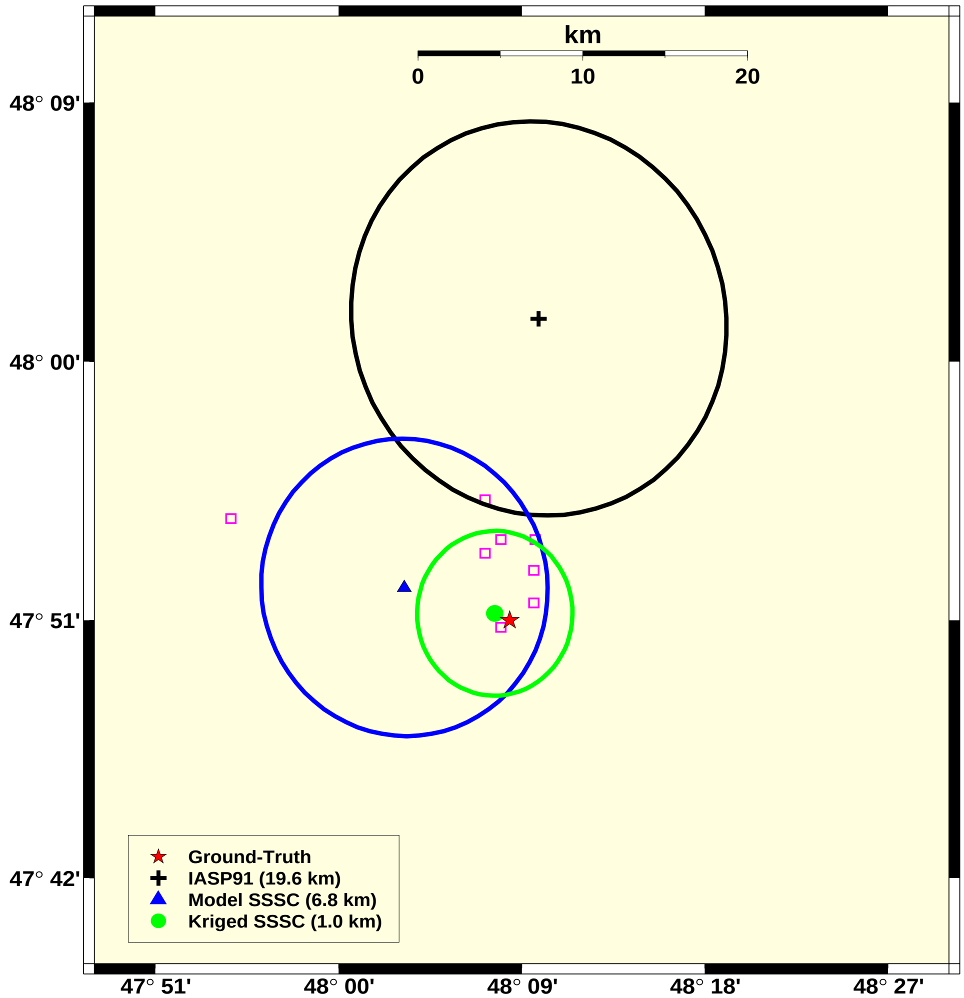

Figure 7. Relocation results, with and without using SSSCs, for a PNE (Azgir-10) in the Former Soviet Union on 24 October 1979. Mislocation errors relative to the ground-truth location are 19.6 km without using SSSCs, 6.8 km using model-based SSSCs, and 1.0 km using kriged SSSCs. Magenta square markers represent calibration points. The error ellipse areas are 455 km^2 without using SSSCs, 264 km^2 using model-based SSSCs, and 79 km^2 using kriged SSSCs.

the error ellipses are smaller when using either version of the SSSCs, and contain the GT location, unlike the error ellipse based on IASP91 without SSSCs. Another case, depicted in Figure 7, shows that kriging, when calibration points are near the event to be located, can have a significant impact. In this case again, the error ellipse based on IASP91 without SSSCs does not include the GT location. What is different in this case is that there are 23 GT events inside a 4° radius around the Azgir-10 PNE and only one in the previous case (Meridian-2). With magenta squares we display in Figure 7 the nearby GT reference events. The residuals of the 23 GT events are being used in the kriging process. The kriged SSSCs, used in relocation, contribute to a solution that is 1 km distance from the GT location compared to 6.8 km when model-based SSSCs are used in the relocation process. The improvement of results shown in Figure 7, compared to the results in Figure 6, is an indication of the effectiveness of empirical data, in a situation where such data are available.

Next we look at the mislocations in general, then at the size of the error ellipses and their coverage, when using our model-based SSSCs refined by kriging.

Of the 525 GT events, 445 solutions (85%) have smaller mislocation errors using kriged SSSCs than those obtained using just the IASP91 travel-time tables. Of these, 410 events (78%) have mislocation errors that are reduced by more than 20%. Only 80 solutions (15%) deteriorated and 53 solutions (10%) deteriorated by more than 20%. The median mislocation is reduced from 16.9km to 6.5 km when kriged SSSCs are used. Figure 8 shows a scatter plot of the mislocation distances, relative to the GT locations, obtained with (x-axis) and without (y-axis) using the SSSCs.

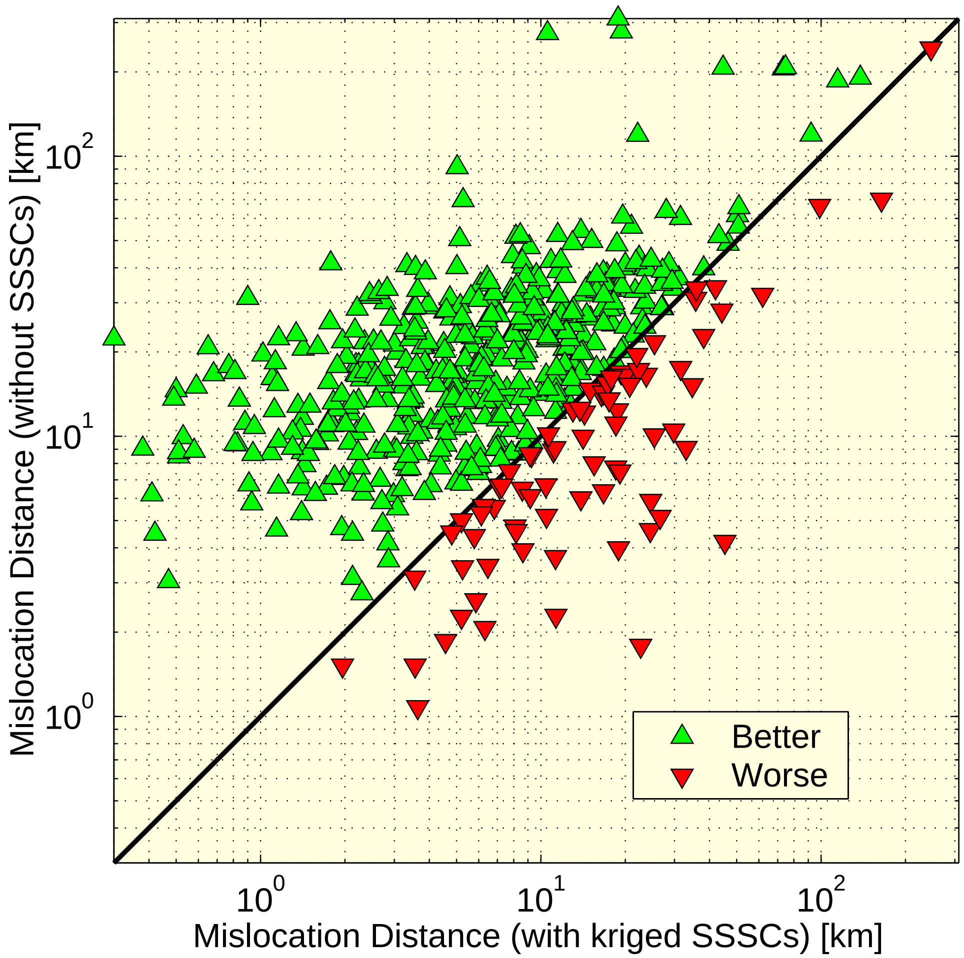

Figure 8. Mislocation distances with and without using kriged SSSCs with respect to corresponding GT locations. Markers and the line are defined as in Figure 4.

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. Using kriged SSSCs, error ellipse area is reduced for all the 525 solutions (100%), 523 of which (99.6%) are improved by more than 20%. The median ellipse area is reduced from 2,616 km^2 to 722 km^2. The results are shown in Figure 9. Error ellipse coverage, computed as the percentage of GT event locations contained within the 90%-confidence error ellipses, is 92% (483 GT events) when using the kriged SSSCs, as compared to 89% (466 GT events) without using SSSCs (i.e., using IASP91 only).

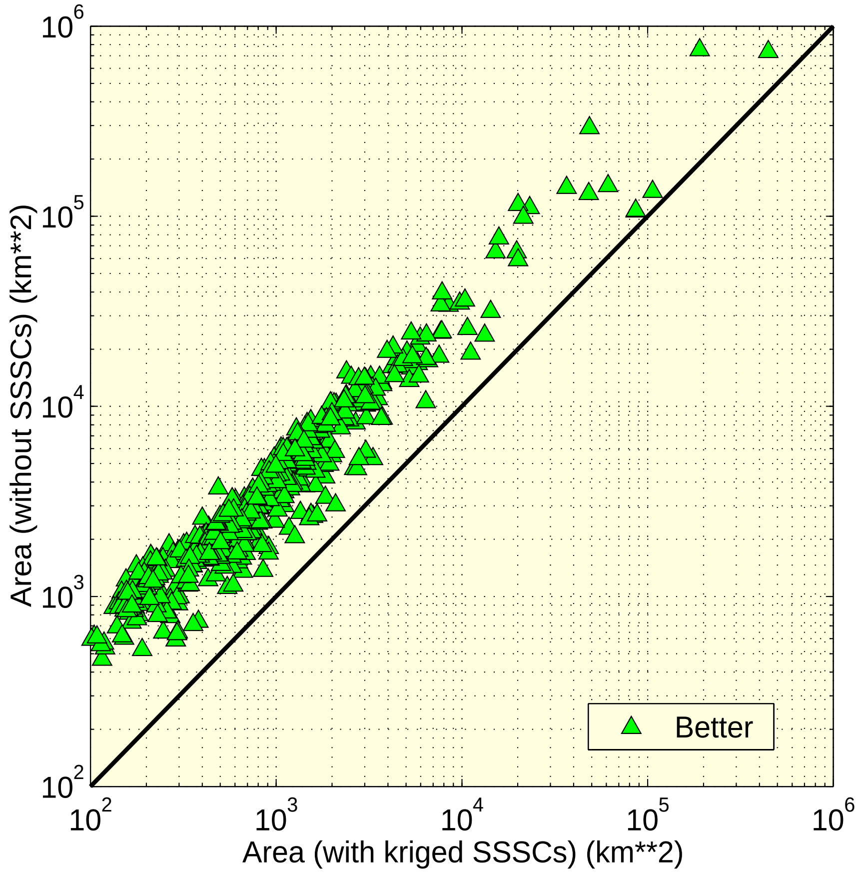

Figure 9. Scatter plot of error ellipse areas computed with (x-axis) and without (y-axis) using kriged SSSCs. Markers are defined as in Figure 5.

CONCLUSIONS AND RECOMMENDATIONS

In this paper we have briefly presented results validating our regionalized travel-time model of East Asia and evaluating the effectiveness of the regional Pn and Sn SSSCs developed by the Lamont Consortium for Group 1 IMS stations. In Table 2 we summarize the main location performance metrics when Pn and Sn arrivals were used with and without SSSCs. More extensive documentation is available.

We believe the results indicate the general validity of the model and the resulting SSSCs for this region. In all cases, the results demonstrate that the regionalization and travel-times curves, developed by the Lamont Consortium for Group 1 stations, along with the computational methods of 3D ray tracing and kriging, developed by the Consortium, have produced Pn and Sn SSSCs and modeling errors that improve the performance of location and uncertainty estimates in East Asia. We expect that these SSSCs will perform, on average, as well as indicated by the validation test results for the model-based SSSCs, and substantially better for regions surrounding the Lop Nor, Semipalatinsk, Indian and Pakistani nuclear test sites, where high-quality calibration data have been utilized.

We note that the degree of location improvement using our SSSCs significantly exceeds the criteria developed at Location Workshops held in 1999, 2000, 2001, 2002, and 2003 in Oslo, Norway (see for example CTBT/WGB/TL-2/18 for 1999). In part, this is a reflection of the fact that the IASP91 travel times are a poor representation of regional travel times in much of the region we have studied. We therefore recommend that any users of regional signals recorded by the 140 stations that we have calibrated consider our SSSCs for seismic event location in East Asia. In particular, we recommend that our SSSCs be considered for use in operational systems that interpret seismic arrival-time data from these stations. Finally, we note that our overall method (of first obtaining model travel times and then kriging with empirical data) is well suited to calibration of any stations in East Asia that have a significant archive of reliably measured arrival times.

Table 2. Location performance metrics for Pn and Sn.

Case	IASP91	Model-Based SSSCs	Model + Kriged SSSCs
Median mislocation (km)	16.9	11.4	6.5
Events with reduced mislocation		66%	85%
Median error ellipse area (km^2)	2,616	1,663	722
Events with smaller ellipses		99%	100%
90% coverage	89%	91%	92%

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