SEISMIC LOCATION CALIBRATION FOR THIRTY INTERNATIONAL MONITORING SYSTEM STATIONS IN EASTERN ASIA

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ABSTRACT

We review preliminary results of 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 Eastern Asia.

We have developed and tested Station-Specific Source Corrections (SSSCs) for Pn travel times at IMS stations (or suitable surrogates) in Asia, including AAK, AKTO, BRVK, KURK, MAKZ, NIL, ZAL, MAG, NRIS (NRI), SEY, TIXI (TIK), TLY, YAK, JAVM (ULN), and about 90 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 by Khalturin et al. (2001) after extensive review of published studies including many from the Russian literature. 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.

Using Pn arrival times for our GT events, we relocated 157 explosions (most from the Soviet era) recorded by various combinations of 94 regional stations. Mislocations were reduced for 63% of the events using the model-based SSSCs, and for 93% of the events using model-based and kriged SSSCs. Median mislocation improved from 12.2 km to 9.5 km and 2.7 km, respectively. Median error ellipse area was reduced from 1,596 km^2 to 450 km^2 and 196 km^2, respectively. Error ellipse coverage (percentage of GT locations within 90% error ellipses) was 97% without using SSSCs, 94% using model-based SSSCs, and 100% using kriged SSSCs.

Working with Cormier and Stroujkova (see their separate paper, this meeting — they are part of our Lamont consortium), we are now able to use 3D ray tracing (rather than the Bondár method) to obtain model-based SSSCs. Future efforts will focus largely on generating and testing SSSCs at IMS stations in China and nearby countries, and for secondary regional phases (Pg, Sn, Lg). To obtain reference events in China, we have carried out several studies of the Lop Nor underground nuclear explosions (UNEs) using waveform cross-correlations and IKONOS satellite images as well as conventional phase pick data, allowing us to obtain locations that are of GT1 quality or better for almost all these events.

We have also begun a series of studies based on phase pick data contained in the Annual Bulletin of Chinese Earthquakes (ABCE). Preliminary SSSCs for stations BJI, CHG, HLR, KMI, LZH, SSE, and XAN are computed from the reported first-arriving phase travel times of earthquakes within 2000 km from each of these stations. To improve the relative location of events within the ABCE we use the double-difference (DD) approach to relocate multiple events simultaneously. We have applied the DD method to several areas on mainland China where seismicity is dense enough to link earthquakes together over short distances (< 10 km). Twenty clusters of 50 or more events are formed, the largest of which is located in western China and includes more than 450 events. Initial results indicate that within these clusters the average relative location precision is improved by more than an order of magnitude, and averages about 500 m and 850 m in the horizontal and vertical directions, respectively. In some areas the seismicity correlates with surface traces from a fault map. It is also possible to use intensity maps to infer absolute locations. In this way we are building up numerous reference events, expected to be of GT5 quality.

OBJECTIVE

The goal of this project is 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 in March 2000. It is a three-year collaborative academic-industry research project led by Lamont Doherty Earth Observatory and involving a consortium of five institutions. Details of our work are described in Richards et al. (2000) and Conrad et al. (2001).

Web pages at http://www.LDEO.columbia.edu/~richards/consortium.html include the list of 30 stations we are studying, their locations, relevant maps, comments on pertinent datasets, and downloadable files describing our work in some detail. During the second year of work, we have focussed on the derivation of Pn SSSCs for 14 IMS stations in and near Russia and Central Asia, and we have begun to develop similar results for IMS stations in and near China. Table 1 lists these stations. This paper describes results from our second year.

Table 1. IMS stations for which preliminary Pn SSSCs have been 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

Our overall plan has been:

a. to develop regional models with their associated travel times for about 25 sub-regions of East Asia;
b. to compute regional travel times for paths that cross between sub-regions and thus to obtain model-based SSSCs;

c. to obtain empirical travel times for IMS stations (or their surrogates), using reference events (ground truth);
d. to apply kriging methods (with the model-based SSSCs as background) to obtain new SSSCs.

Then
e. there is the final work of assessing relocation performance, which again uses ground truth, and sampling methods (leave-one-out, etc.). This final step is by far the hardest, since, for example, it entails iterations back to the earlier steps, especially in the context of seeking additional data to improve results in particular sub-regions. Our two previous papers (Richards *et al*., 2000; Conrad *et al*., 2001) have covered items (a) – (c) and have described our principal datasets. In this paper, we present preliminary results for (d) and (e).

We have quantified relocation performance using metrics that conform with the guidelines from the 1999 IMS Location Calibration Workshop (CTBT/WGB/TL-2/18) held in Oslo, Norway, which stipulated that:

- the median mislocation of ground truth (GT) events should be significantly reduced;
- mislocation should be reduced by 20% or more for the majority of events;
- median confidence ellipses should be reduced in area, 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.

Our preliminary model-based SSSCs were computed by the method of Bondár (1999), using regionalized 1-D travel-time curves for Asia based on published studies. We then applied a kriging algorithm (e.g., Bottone *et al*., 2002) to empirical travel-time observations from events with ground truth locations. The resulting kriged SSSCs (grid files with one-degree resolution, extending out to 20 degrees from a given station) represent travel-time corrections relative to the IASPEI91 travel-time tables. We want IASPEI91 travel times plus SSSCs plus origin time plus possible corrections for elevation and ellipticity to predict observed arrival times.

Description of Results from Off-line Testing

Figure 1 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 underground nuclear explosions (peaceful nuclear explosions [PNEs] and weapons tests) in the Former Soviet Union and 18 explosions (chemical explosions in Kazakhstan and UNEs in China, India, and Pakistan) in a separate data set that we have assembled. Further details on these datasets are given in Conrad *et al*. (2001) and from files available at http://www.LDEO.columbia.edu/~richards/consortium.html

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

BRVK Pn Travel Time Residuals

Case	IASPEI91		SSSC		SSSC+Kriging	
	$\mu_{\Delta T}$	$\sigma_{\Delta T}$	$\mu_{\Delta T}$	$\sigma_{\Delta T}$	$\mu_{\Delta T}$	$\sigma_{\Delta T}$
STS 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

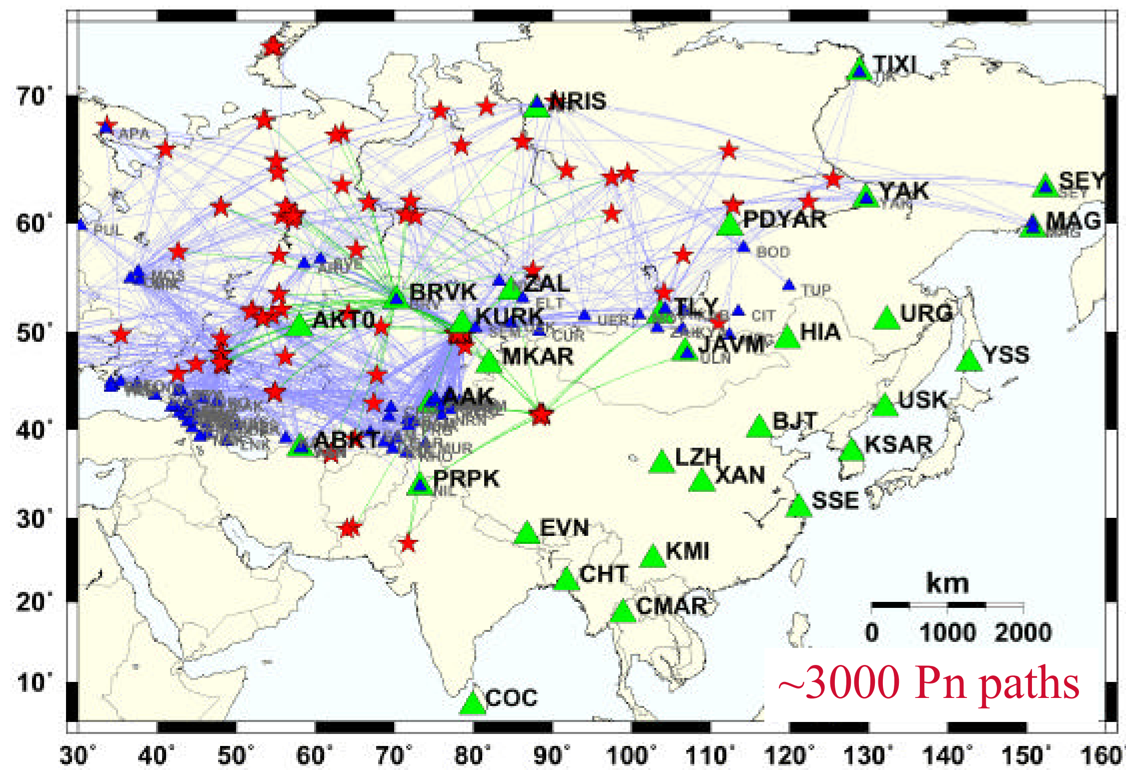


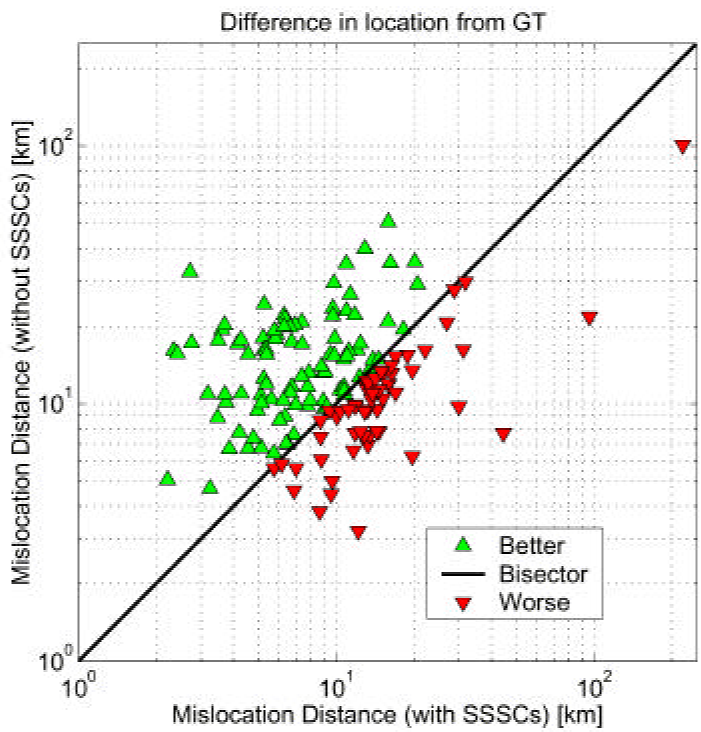
Figure 1. Map showing locations of 174 GT explosions (stars) and the recording seismographic stations (triangles) used for validation tests. Also shown are great circle paths between the events and 93 stations for which we have obtained arrival times for these events. The large (green) triangles represent the 30 IMS stations for which our consortium is generating SSSCs.

The main objective of off-line testing was to use GT events to validate the Pn SSSCs by evaluating:

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

Table 2 shows travel-time residuals for 145 Pn arrivals at station BRVK, corresponding to Soviet-era PNEs and UNEs at the Semipalatinsk and Lop Nor nuclear test sites. These results are given 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 are shown because of the good geographical distribution of GT events and the quantity and quality of the Pn phase picks for this station — which we carefully reviewed by inspection of the waveforms — they are qualitatively representative of reductions in mean travel-time bias and residual variance that we obtain at other stations in Asia.

To evaluate location performance of our SSSCs, 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 here is to demonstrate that our regional model and our method of computing travel times provide 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 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 we then quantified our results in terms of the same performance metrics used in the model validation. The results were compared to those in which the relocations were performed without SSSCs, and with the purely model-based SSSCs computed by Bondár's method.



63% improved

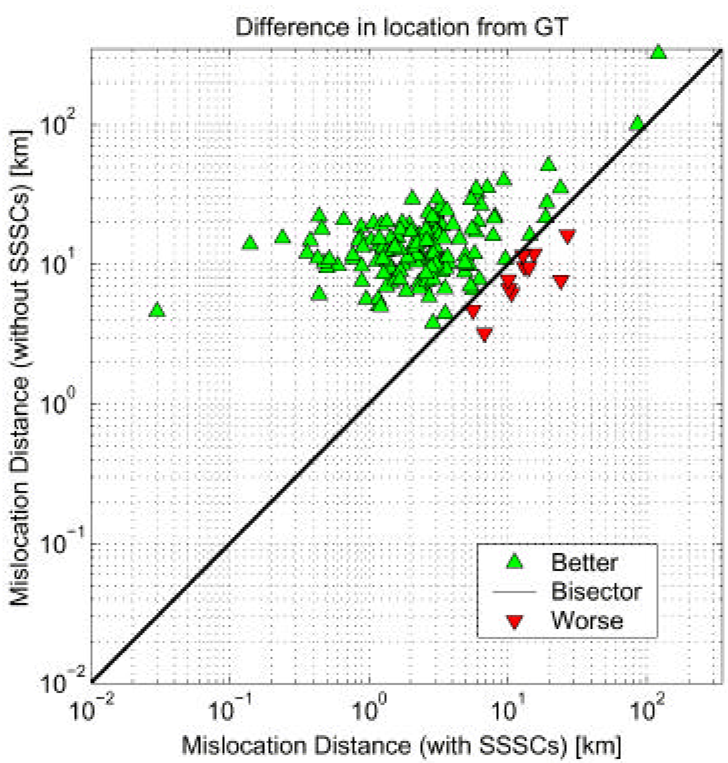
37% deteriorated

53% improved by > 20%

24% deteriorated by > 20%

Median mislocation:

12.2 km → 9.5 km



93% improved

7% deteriorated

90% improved by > 20%

6% deteriorated by > 20%

Median mislocation:

12.2 km→ 2.7 km

Figure 2. Map showing reductions in mislocation. The upper panel and summary results show the reduction using model-based SSSCs. The lower panel/results shows the reduction using kriged SSSCs.

For model validation we used 156 events recorded at 93 stations (a major subset of Figure 1, namely the underground nuclear explosions in the Former Soviet Union for which we have good ground truth and numerous regional phase picks). The test consisted of relocating these events using Pn arrivals (2626 picks). All the relocations were performed with depth fixed at the surface. The relocation procedure was first applied using the IASPEI91 travel-time tables, without any SSSCs. This was followed by relocating the same events using the SSSCs. Running the program EvLoc with and without SSSCs resulted in 156 events with location estimates that converged.

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%. The upper panel of Figure 2 shows these results. To evaluate location performance using the kriged SSSCs, we used a "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 156 events with kriged SSSCs that were re-computed for each event so that the same data were 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. The lower panel of Figure 2 shows significant improvement with kriging. The median mislocation has been reduced from about 12 km to about 3 km.

Figure 3 (upper panel) shows the differences of mislocations, without and with the model-based SSSCs, versus number of defining phases (on the left) and azimuthal gap (on the right). Green (red) markers indicate solutions with smaller (larger) mislocations when SSSCs are used. Large mislocation errors when using the SSSCs generally occur when the number of defining phases is less than 6 and the gap is greater than 200 degrees. In such cases the locations are poorly constrained with or without use of model SSSCs. Figure 3 (lower panel) shows corresponding results with kriged SSSCs, and again there is great improvement over the use of purely model-based SSSCs.

The error ellipses are systematically reduced in area by using SSSCs. The difference in the error ellipse calculations for the two cases (with and without SSSCs) is due to a difference in modeling errors. Since the modeling error for the SSSCs is always less than for IASPEI91, we expect the error ellipses using our model SSSCs will always be smaller than for the IASPEI91 case. In fact, all 156 solutions (100%) are improved by more than 20% (Figure 4, upper panel). 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 that contain the GT locations. Using our model 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.

Given the large number of source regions, stations, and ray paths that sample very diverse and extensive geological structures (represented by our 25 sub-regions of Eastern Asia 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.

Using kriged SSSCs, the error ellipse area as shown in the lower panel of Figure 4 is reduced for 153 of 156 solutions (98%), 152 of which (97%) are improved by more than 20%. Only three solutions (2%) do not have smaller error ellipses. The median ellipse area is reduced from 1,596 km^2 to 196 km^2. 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, Figure 4 shows that

- 93% of the events are located closer to the GT location (median mislocation errors down 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.

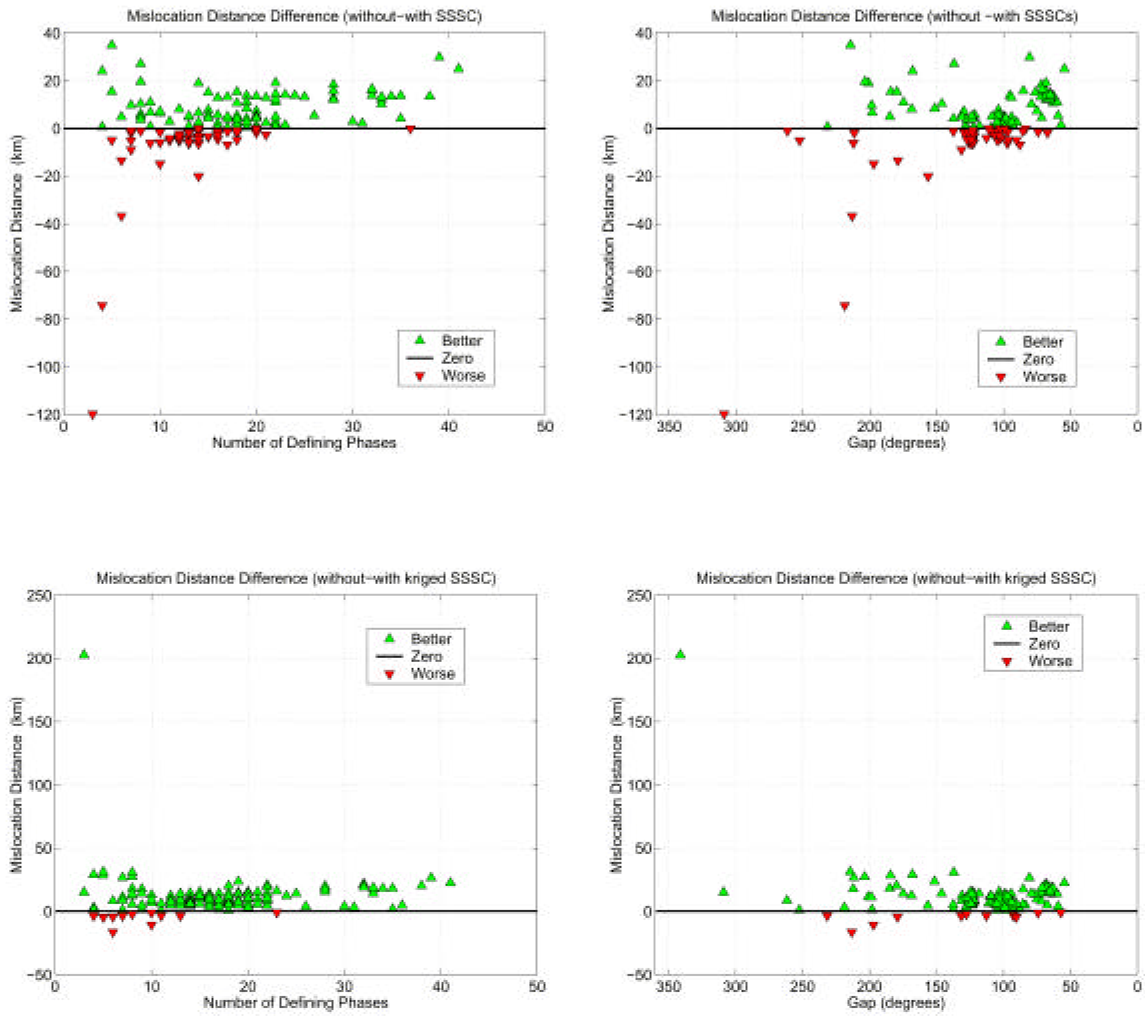
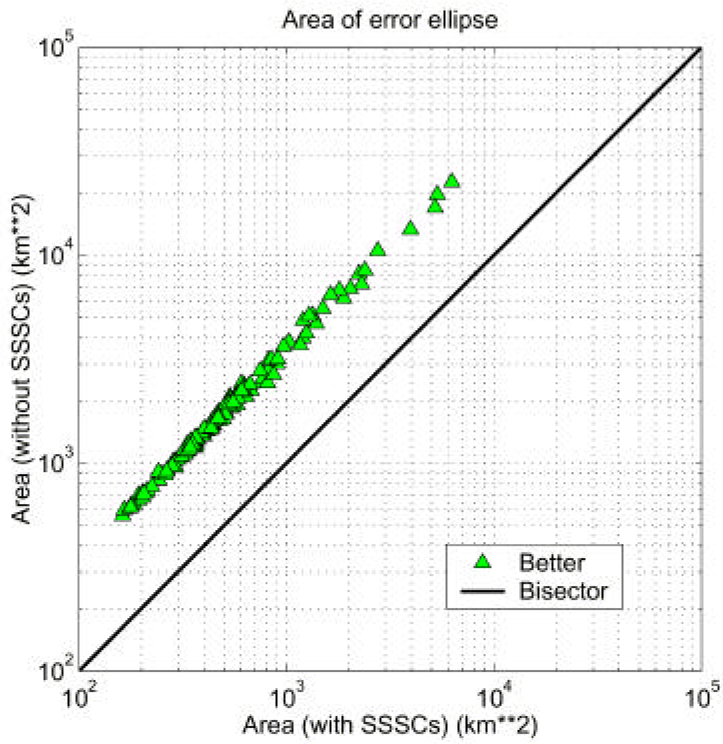


Figure 3. Mislocation distance differences (without SSSCs – with SSSCs), shown as a function of the number of defining phases (on left side), and as a function of gap (right side). The upper panel is for model-based SSSCs. The lower panel is for kriged SSSCs. Kriging gives significantly improved results.

Because we had regional Pn phase data for about 100 stations in our analysis of the phase associated with Figure 1, we developed SSSCs for far more than the 14 IMS stations (or IMS surrogates) listed in Table 1. Figure 5 shows the dependence of error ellipse area on the number of defining phases (using various subsets of the available stations), and on the gap. Again we see a notable improvement with use of kriged SSSCs. Because we are using Pn only in this analysis, the number of defining phases is equal to the number of stations.

The work summarized here in Figures 2, 3, 4, 5 was presented on May 23, 2002, as a proposal to the Configuration Control Board of the Center for Monitoring Research, and accepted as the basis for 14 Pn SSSCs of IMS stations listed in Table 1. The actual (kriged) SSSCs are available from the authors, along with extensive documentation.

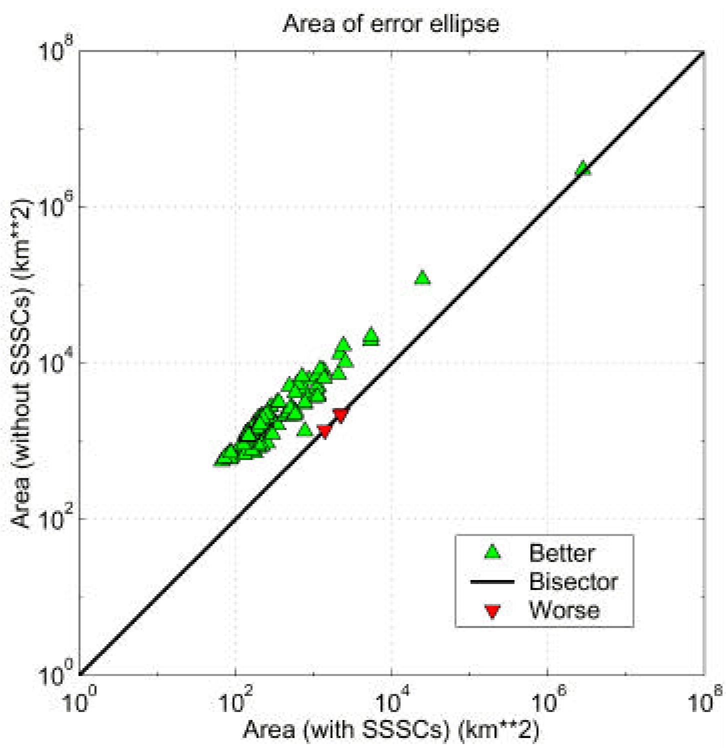


100% improved by > 20%

Median area:

1,596 km² → 450 km²

Coverage 97% to 94%



98% improved

2% deteriorated

98% improved by > 20%

0% deteriorated by > 20%

Median area:

1,596 km² → 196 km²

Coverage 97% to 100%

Figure 4. Illustration of the reduction in error ellipse area, with use of SSSCs. The upper panel shows results using model-based SSSCs. The lower panel shows even better results with kriged SSSCs.

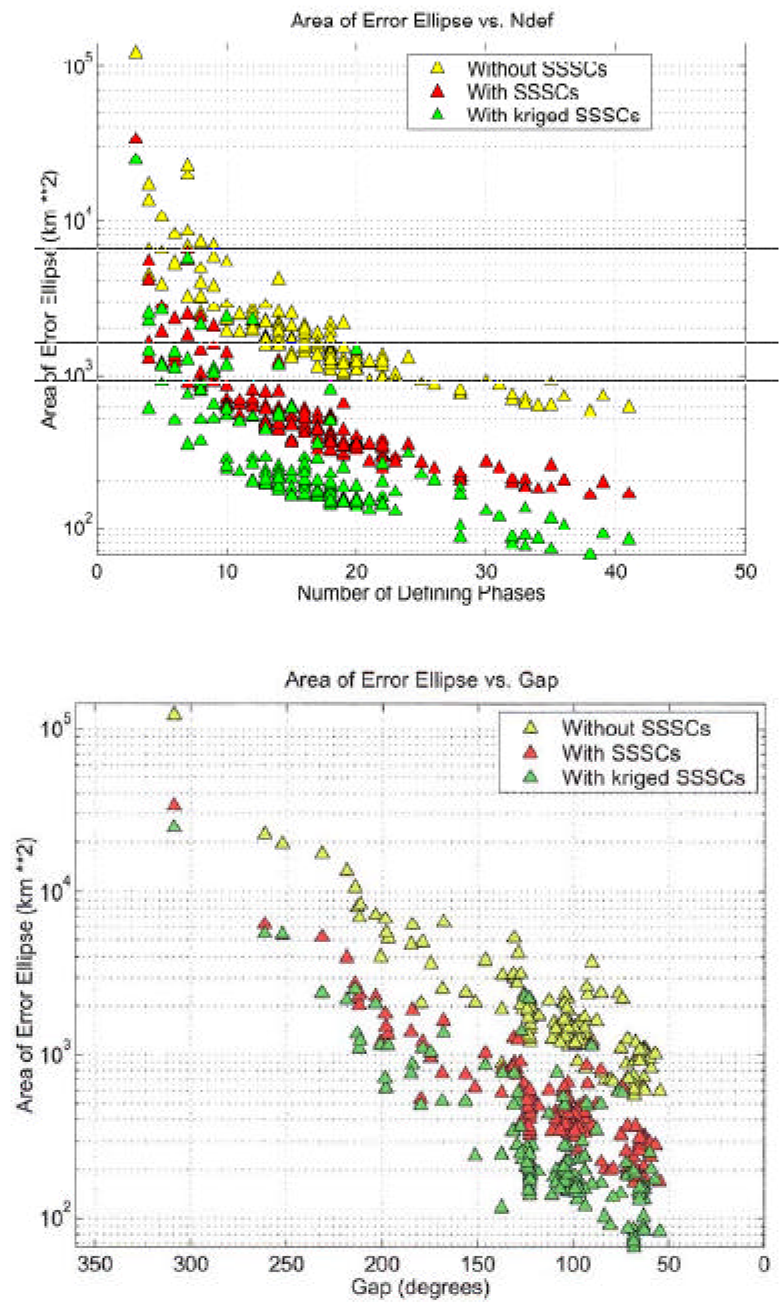


Figure 5. Illustration of the reduction in eror ellipse area, with use of SSSCs. The upper panel shows results as a function of the number of defining phases. The lower panel shows results as a function of gap.

Brief review of our work on GT events in China, and on empirical SSSC for an IMS station in China

We have worked with about 500,000 Pn phase picks for seismic events in China during 1985–1999 reported by 170 stations in and near China. These are derived from the Annual Bulletin of Chinese Earthquakes (ABCE). We are using these data to obtain GT5 quality events and empirical SSSCs in this major sub-region of East Asia. Figure 6 shows the great merit of locating events, with these data, not one-at-a-time, but all together using the double difference algorithm of Waldhauser and Ellsworth (2000). Also shown in Figure 6 are fault traces from data provided by the US Geological Survey, derived from the volumes on regional geology of China provinces published by the Geological Publishing House (Beijing, 1984 – 1993). In this case, knowledge of the position of a major fault enables us to have some confidence in treating our relocations as absolute relocations.

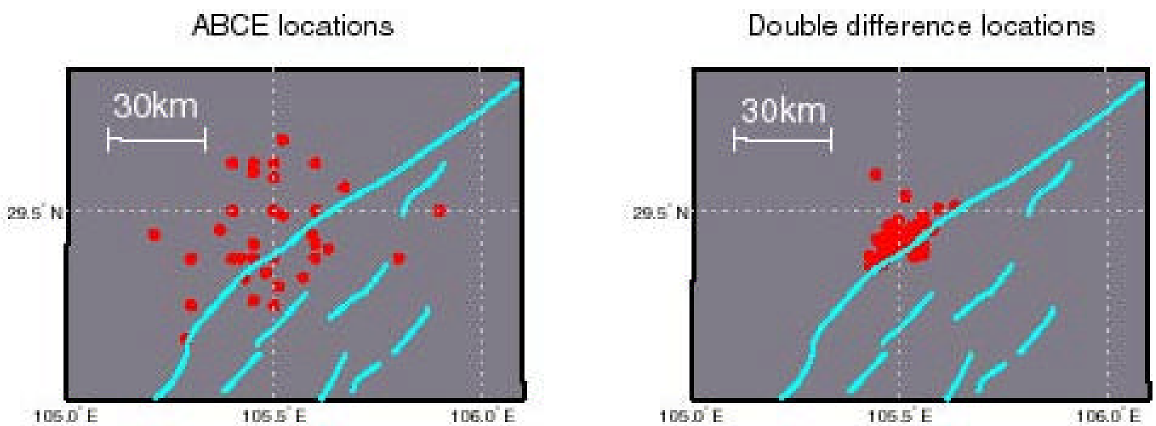


Figure 6. On the left are shown locations of a cluster of earthquakes in China, published in the Annual Bulletin of Chinese Earthquakes, compared (right) with results of a multi-event relocation.

We have carried out a similar analysis for several earthquake clusters in China. Because all of the IMS stations planned for China are at sites that have long operated as stations used for the ABCE, we can use numerous reported phase picks at these particular stations, together with ABCE event locations, to obtain empirical SSSCs for all IMS stations in China. Thus, Figure 7 shows empirical SSSCs for two stations in China that have been identified as sites for IMS stations: HLR (Hailar) as a primary station and XAN (Xi'an) as an auxiliary. Black dots are seismic events reported by the station in the ABCE (4324 for XAN, 154 for HLR). We use the reported arrival times to obtain empirical SSSCs as observed arrival times minus expected (on the basis of ABCE hypocenters and the IASPEI91 model). Of several stations for which we have made these plots, the coverage is best for XAN and worst for HLR.

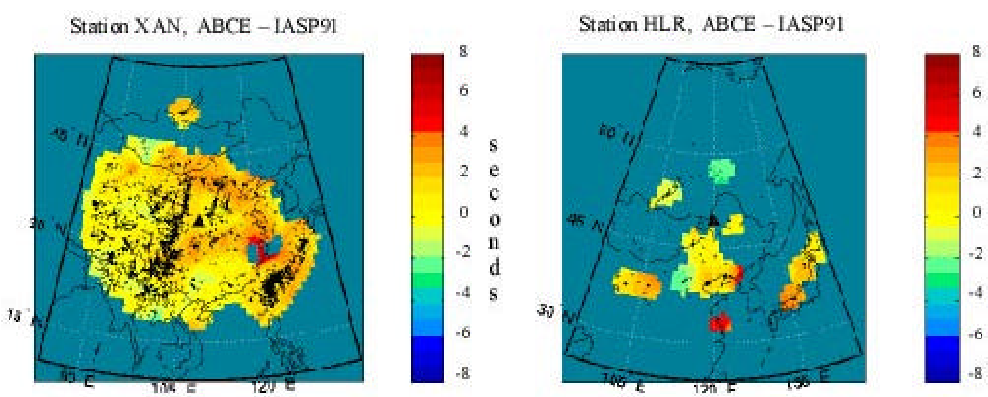


Figure 7. Empirical SSSCs based on phase picks reported in the Annual Bulletin of Chinese Earthquakes.

CONCLUSIONS AND RECOMMENDATIONS

Our principal conclusions are that ground truth data described in Figure 1, for stations in and near Russia and Central Asia, are a basis for obtaining Pn SSSCs at stations listed in Table 1, using analysis presented in Figures 2 through 5. Using these data, we have documented significant location improvement. Use of kriged SSSCs results in median mislocation error being reduced down from 12.2 km to 2.7 km, error ellipse areas reduced by 20% or more for 97% of the events, and median error ellipse area reduced from a median of 1,596 km^2 down to 196 km^2, while achieving 100% coverage. We recommend that continued analyses of these data be applied to phases other than Pn to obtain SSSCs for additional phases.

Because of the extensive experience (since 1966) of seismometer operation with digital recording at the Borovoye Geophysical Observatory, Kazakhstan, and the associated archive of sets of digital records for more than 700 underground nuclear explosions from this site, we conclude that when this site begins operation as an IMS station, it has the potential to become the best calibrated of all IMS stations. Because the station has demonstrated a capability to detect a significant fraction of global seismicity, it will have, as an IMS array station, the potential to have a significant effect upon the performance of the global system for monitoring nuclear explosions.

We have also found that regional phases routinely reported in the Annual Bulletin of Chinese Earthquakes are likely to be an adequate basis for location calibration of IMS stations in and near China. These data may be used both to establish a significant number of reference events, and to obtain empirical SSSCs for IMS stations.

ACKNOWLEDGEMENTS

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REFERENCES

Bondár, I (1999), Combining 1-D models for Regional Calibration, in *Proceedings of a Workshop on IMS Location Calibration*, Oslo, January 1999.

Bottone, S., M. Fisk, and G. McCartor (2002), Regional Seismic Event Characterization using a Bayesian Formulation of Simple Kriging, in press, *Bull. Seism. Soc. Am*.

Conrad, C., M. Fisk, V. Khalturin, W.-Y. Kim, I. Morozov, E. Morozova, P. Richards, D. Schaff, and F. Waldhauser (2001), Seismic Location Calibration for 30 International Monitoring System Stations in Eastern Asia, in *Proceedings, 23rd Seismic Research Symposium*, Jackson Hole, Wyoming.

Richards, P., W.-Y. Kim, and V. Khalturin (2000), A Plan for Seismic Location calibration of 30 IMS Stations in Eastern Asia, in *Proceedings, 22nd Seismic Research Symposium*, New Orleans, Louisiana.

Waldhauser, F. and W. Ellsworth (2000), A Double-Difference Earthquake Location Algorithm: Method and Application to the Northern Hayward Fault, *Bull. Seism. Soc. Am*., **90**, 1353–1368.