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Abstract

The Lawrence Livermore National Laboratory (LLNL) CTBT R&D program has made significant progress towards improving the ability of the IMS seismic network to locate small-magnitude events in the Middle East and North Africa (ME/NA). Given that high-grade ground truth (such as known explosions) has been difficult to obtain in these regions, we have placed a significant effort towards the development of a teleseismically constrained seismic database that provides event locations good to within 20 km. This data set is used to make an initial evaluation of the effectiveness of calibration on the proposed seismic IMS network in the ME/NA. Utilizing a surrogate IMS regional network in the Middle East, we find that when a seismic event lies within the footprint of the recording network, the uncalibrated event locations are good to within about 25 km of the teleseismically constrained (TC) location. Using region-specific static station corrections further reduces this difference to about 20 km. To obtain further improvement in location accuracy we have used the modified kriging technique developed by SNL to interpolate new travel-time corrections. We compare this technique with other robust linear interpolation techniques with the goal of enhancing the estimation of travel-time corrections. This is important for TC events which we find can have large uncorrelated uncertainties. Finally, we are making a large effort to incorporate LLNL analyst picks on primary and secondary phases and develop azimuth and slowness estimates from current IMS arrays to improve/supplement the NEIC picks.

Key Words: seismic, regional location, kriging

Objectives

The primary objective of this study is to improve our ability to locate seismic events in the Middle East and North Africa (ME/NA) by generating travel-time corrections for the IMS seismic station network. These corrections should reduce both the bias and variance error in the location estimate. In order to assess the effectiveness of our corrections and location techniques, accurate locations of seismic events must be obtained. To avoid circularity there must be enough events so that the events tested are independent of the events used to generate the original corrections. For large areas of the ME/NA this poses an immediate difficulty, since good recordings of explosions in the region are scarce. Thus, to calculate preliminary corrections for travel-times we utilize the best constrained data set of locations currently available. This data consists of well-recorded large (teleseismic) events that have occurred at relatively shallow depths (Cogbill and Steck, 1996). By restricting this data set to only those events having very good, worldwide station coverage we can generate a higher-grade ground truth set of event locations that are known with a measurable level of uncertainty.

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In the first section, we focus on the development of this teleseismically constrained data set, demonstrating that these seismic event locations have an uncertainty of about 20 km. We then make a preliminary evaluation of the effectiveness of the proposed IMS network by designing and testing a surrogate network that has a similar geometry. Finally, we demonstrate the need for better 1-D velocity models and more detailed source-specific station corrections in the ME/NA.

Research Accomplished

Teleseismically constrained database. Generating travel-time corrections for improved location requires well-located events in terms of origin time, epicenter, and hypocentral depth. In the Middle East and North Africa, there is a hierarchy of ground truth that can be obtained. This hierarchy ranges from explosions with exact locations to carefully studied aftershock sequences, events located by dense local networks, and teleseismically constrained events such as CMT and EDR bulletin events. Although the location accuracy goes from better to worse as we work through this list, the ease of obtaining these locations and the abundance of data increases greatly. Given that there are many thousands of TC events in the ME/NA and only a scarce number of higher-grade events, we begin with the development of the TC data set. LLNL has an active effort in obtaining new ground truth and this information is being incorporated continuously as it becomes available.

The work of Sweeney (1996) shows that teleseismic events can give event locations with a known uncertainty. His work focused on four different regions of the Middle East and North Africa. In this study accurate locations based on aftershock and dense array studies were compared with the corresponding teleseismic locations for those same events, as reported by the ISC and NEIC. Figure 1 shows the location error as a function of the number of defining P phases used in the location. Also shown is the location error as a function of the maximum azimuthal gap. This work shows that if one uses an acceptance criterion of ndef>50 and azgap<90 (50-90 criterion), the teleseismic event locations are good to within 20 km. In addition, Sweeney's work shows that even though fewer picks are used by the NEIC for their final location their picks give more accurate locations than the ISC picks. For this reason, we restrict this study to teleseismic events located using only the NEIC EDR picks and our own supplemental analyst picks.

The NEIC bulletin locations are referenced to the Jeffreys-Bullen velocity model. To be consistent with the International Data Center (IDC), whose standard is the AK135 velocity model, we have relocated all EDR events that fit the 50-90 criterion using this velocity model. Relocation was done using EvLoc which operates on the LLNL Oracle database. Figure 2 shows all of the teleseismically constrained events relocated in one portion of the Middle East, while Figure 3 shows the difference in epicentral location and origin time resulting from the use of this new velocity model. These plots show a convergence of the two teleseismic locations as the number of stations increases and a shift of about 2 s in the origin time. These horizontal differences all lie well within the uncertainty of the initial teleseismic location suggesting consistent TC locations. All of the AK135 relocations shown in Figure 2 have been incorporated into the LLNL hierarchical ground truth database with a 20 km uncertainty assigned to the location.

Surrogate IMS network. The TC data set developed above can allow for an initial evaluation of the effectiveness of the IMS seismic network in the ME/NA. Unfortunately, many of the stations have not been installed and the poor geometry of currently installed IMS stations makes it difficult to obtain an initial estimate of the proposed networks ability to locate events accurately. Thus, a preliminary evaluation of the network is made by designing a surrogate network. This surrogate network is close, but not identical, to the proposed IMS network. Such a network may perform either better or worse than the proposed IMS system. Figure 4 illustrates the surrogate IMS network as utilized in this study. Stations were chosen such that the actual IMS stations was used if it exists. If an IMS station does not yet exist then the nearest station is used. For reference, the map also shows those stations that are within 50 km from a proposed IMS station and those that are greater than 50 km away.

Evaluating the effectiveness of this surrogate network can give a preliminary estimate of how the actual IMS may perform for regional events. We assume here that the TC events are recorded only at the corresponding regional and near teleseismic stations making it a regional event. These regional events are then separated into two sets. The first set consists of those events recorded with good regional station coverage. In this case the maximum azimuthal gap was required to be less than 180°. In other words, the event lies within the footprint of the locating stations. The first plot in Figure 5 shows the predicted location assuming no station calibration. The second plot shows the location given an optimal set of static station corrections that were estimated and applied using a leave-one-out robust statistical approach. Without any calibration the surrogate network locates to within 25 km. Static station corrections generate only a mild improvement, reducing the maximum horizontal error to about 20 km which is within the uncertainty of the known location of the TC event locations. The second set consists of those events that are outside the footprint of the recording regional stations, so that station coverage is poor. This is the case where the maximum azimuthal gap is greater than 180°. Figure 6, showing the resulting regional locations, demonstrates that this poorer station coverage results in much larger location errors. Horizontal differences reach values greater than 100 km, showing that large mislocations can occur when station coverage is poor. We are currently developing more robust nonlinear location techniques that can help to improve these regional locations.

A summary of the surrogate networks effectiveness is given in Figure 7. This plot shows that the locations appear to be good to within 20 km of the TC location when the azimuthal gap is less than 200°. Once the gap exceeds this value large mislocations can result. Clearly, static station corrections account for only a mild improvement in the regional locations.

Source specific travel-time correction surfaces. The station corrections utilized in the surrogate study were static station corrections, meaning that only a single correction was applied at each station. Given that such corrections appear to lead to only a mild improvement in location, we are currently working with SNL to evaluate the effectiveness of kriging and other geostatistical techniques as a means of estimating site-specific, travel-time corrections.

Examination of travel-times from seismic sources to a particular station reveals that spatially clustered sources tend to have similar residuals, and the distance between events to which residuals are correlated can be quantified. Such spatial statistics of sampled data can be used to extrapolate residuals (and uncertainties) of sampled points to unsampled regions. Figure 8 is an example of using a modified kriging technique developed at SNL to estimate travel-time residuals for the station SHI in Iran. Although this example shows (to first order) that corrections to travel times produce a spatially coherent pattern, kriging and other geostatistical techniques may be improved upon by accounting for data characteristics that are common to seismological data sets. Specifically, the variance of travel-time residuals can change for each datum and current techniques do not use this information when estimating unsampled points. Additionally, some regions are sparsely sampled, forcing extrapolation of known data points far beyond average correlation distances. We are currently considering further modifications to the kriging technique that address these issues. Once statistical techniques are tailored to the special considerations of seismological data sets, these techniques will likely be useful for estimating a range of seismological parameters including discriminant corrections (e.g. Pg/Lg spectral ratios).

Conclusions and Recommendations

LLNL is working to develop improved IMS location estimates in the ME/NA through the use of ground truth calibrations. A ground truth hierarchical data base has been developed that includes more than one thousand TC events with event locations accurate to within 20 km. Utilizing this data base, static station corrections, 1-D regionalized velocity corrections, and more elaborate source specific station corrections are being developed and evaluated in this region.

Preliminary tests show that region-specific static station corrections lead to only a mild improvement in regional locations. Thus, we are utilizing one-dimensional regionalized velocity models and more sophisticated correction surfaces to completely describe the final correction surfaces for each station. Initial estimates of these surfaces have been generated in conjunction with SNL using their modified kriging interpolation algorithm and performance of these correction surfaces is being assessed. We find that given the variable and somewhat large uncertainties associated with our hierarchical ground truth data base, it is clear that additional modifications need to be made to the kriging approach. These modifications need to allow for a better statistical estimate of the final correction surface when variable uncorrelated errors are present. We are currently examining a number of robust interpolation modifications and will present their ability to estimate and predict the uncertainty of source-specific travel-time corrections.

References

Cogbill, A. & Steck, L, 1996, Regional location in Western China, Proceedings of the 18th Annual Seismic Research Symposium on monitoring a CTBT, p. 685-694.

Sweeney, J., 1996, Accuracy of teleseismic event locations in the Middle East and North Africa, Lawrence Livermore National Laboratory, UCRL-ID-125868.

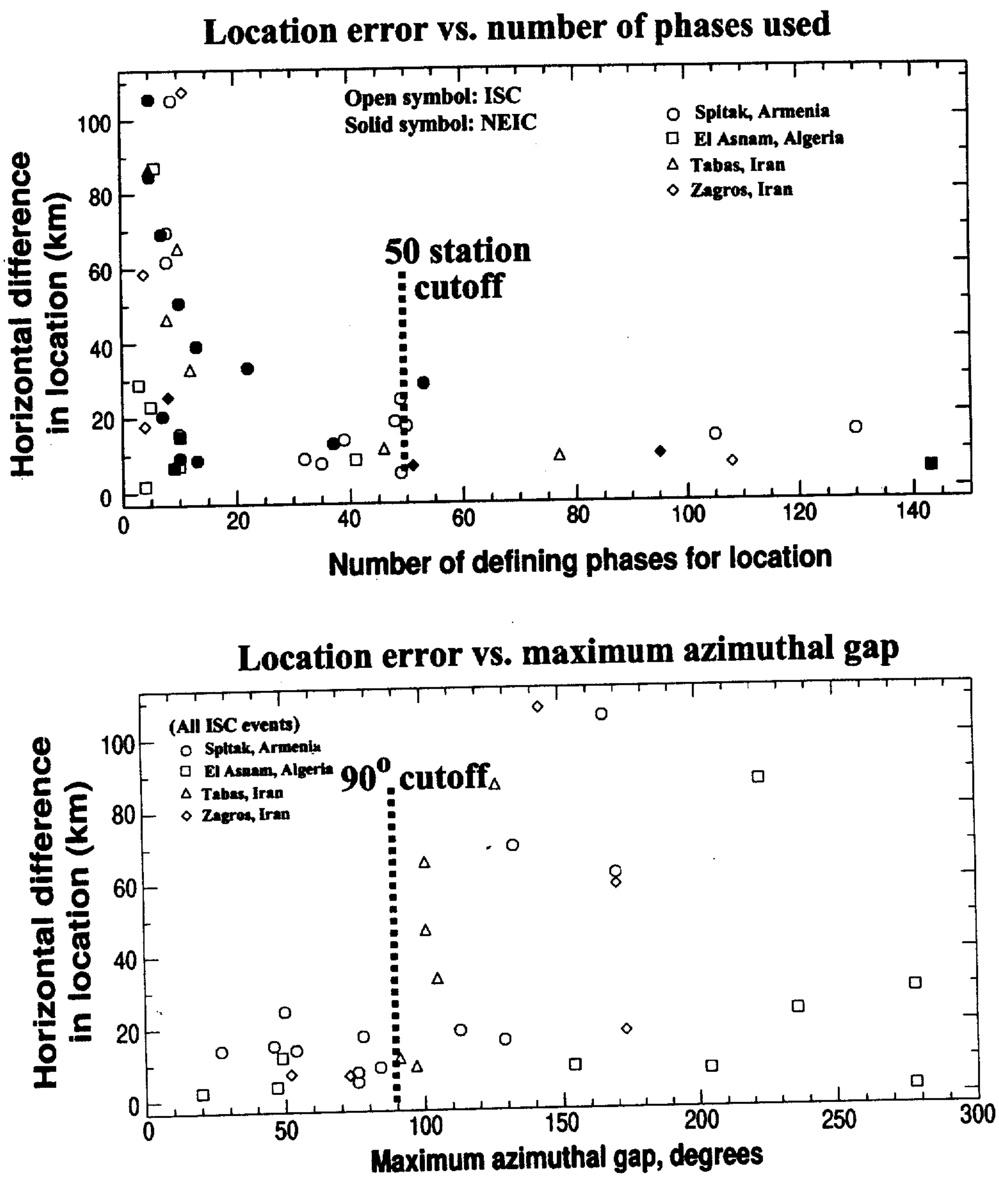

Figure 1. Summary of the results from Sweeney (1996) showing the horizontal difference between teleseismically constrained ISC/EDR event locations and more accurate aftershock/dense network locations. The horizontal difference is shown both as a function of (a) number of defining phases and (b) maximum azimuthal gap.

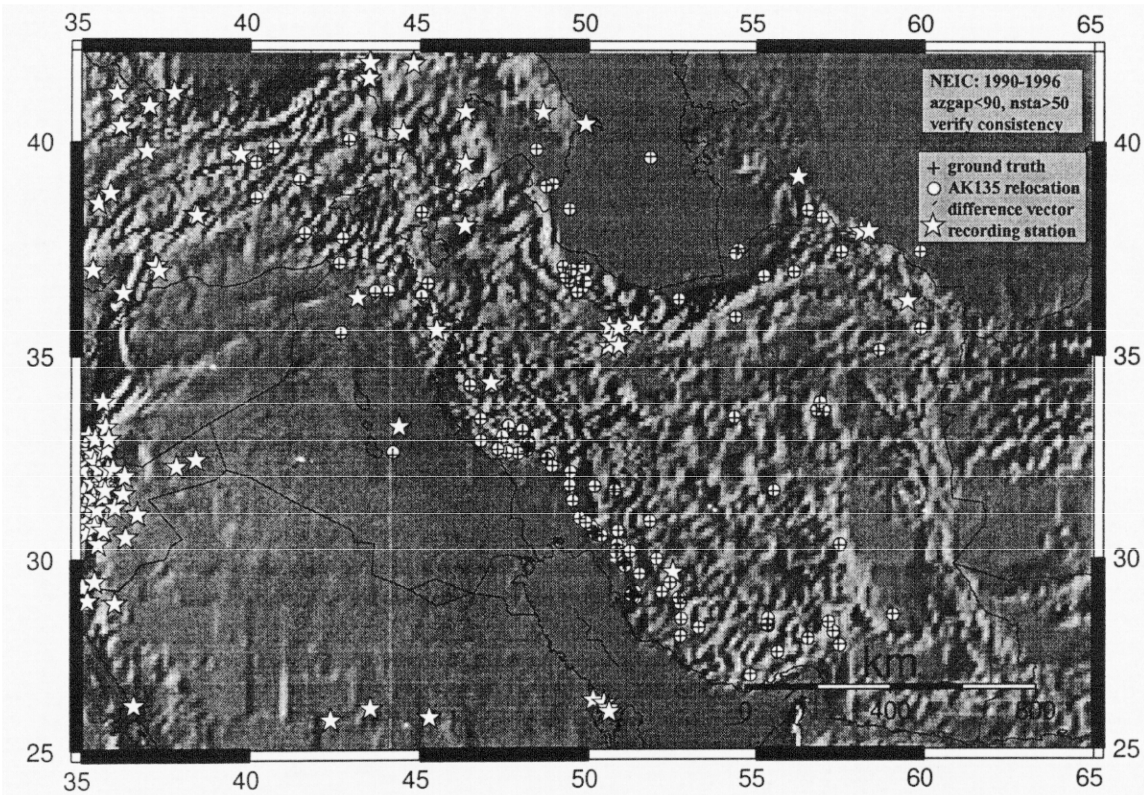

Figure 2. Plot showing teleseismic events relocated in a portion of the Middle East. Each of the events shown matches the 50-90 criterion based on the work of Sweeney (see Figure 1).

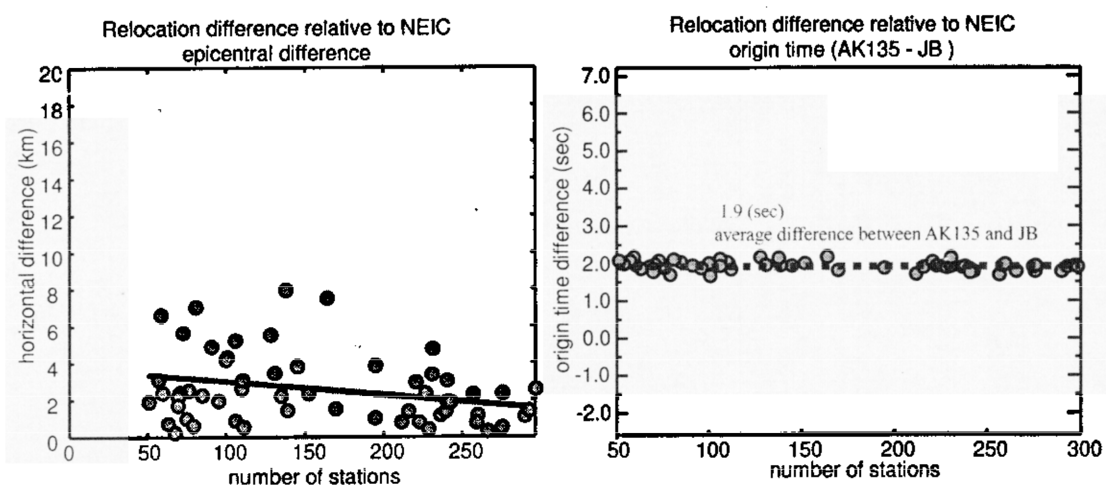

Figure 3. (a) horizontal difference and (2) origin time error for relocation of teleseismic events using AK135 velocity model and EDR travel-time picks.

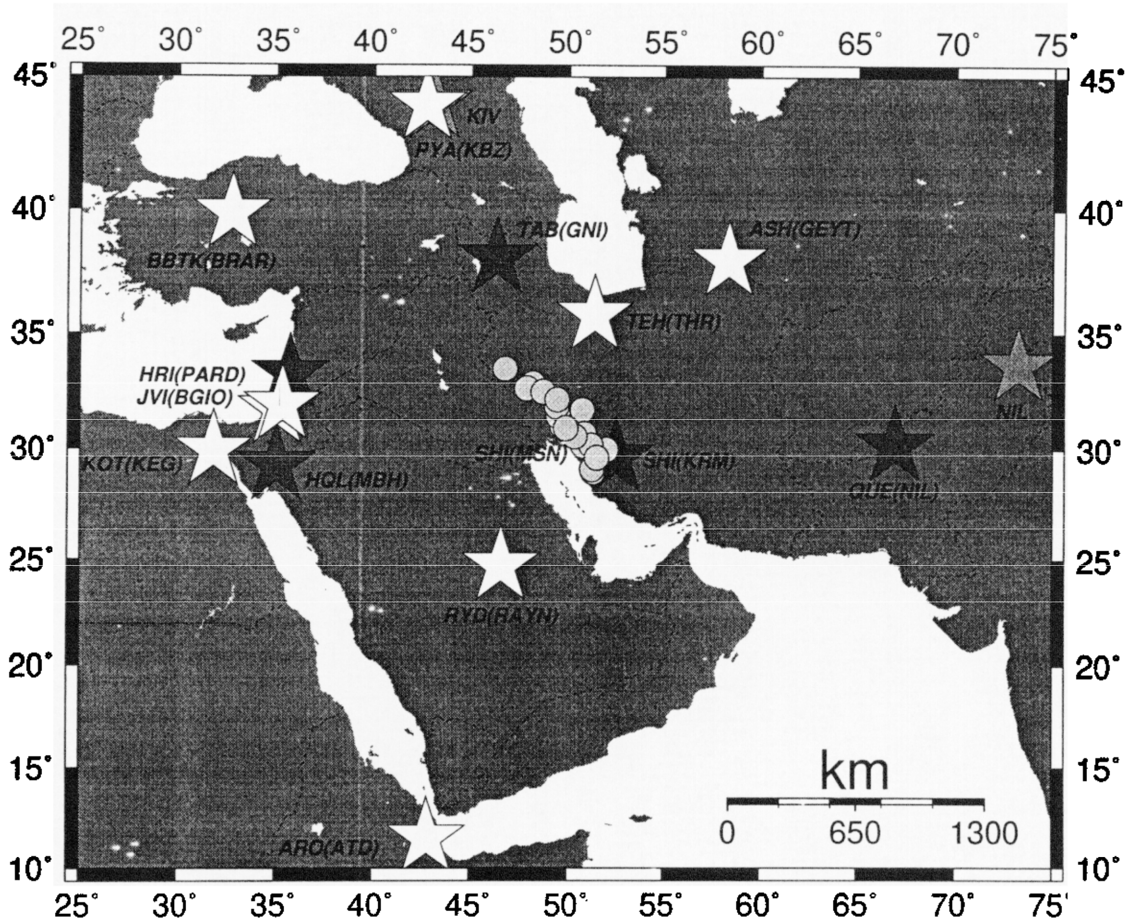

Figure 4. Map view of the surrogate IMS network used to make a first-order estimate of the networks effectiveness. The stars show actual IMS stations (light gray), EDR reporting stations that are within 50 km of a proposed IMS station (white), and EDR reporting stations that are greater than 50 km from a proposed station (dark gray). The circles show the events that to be relocated in the Zagros region.

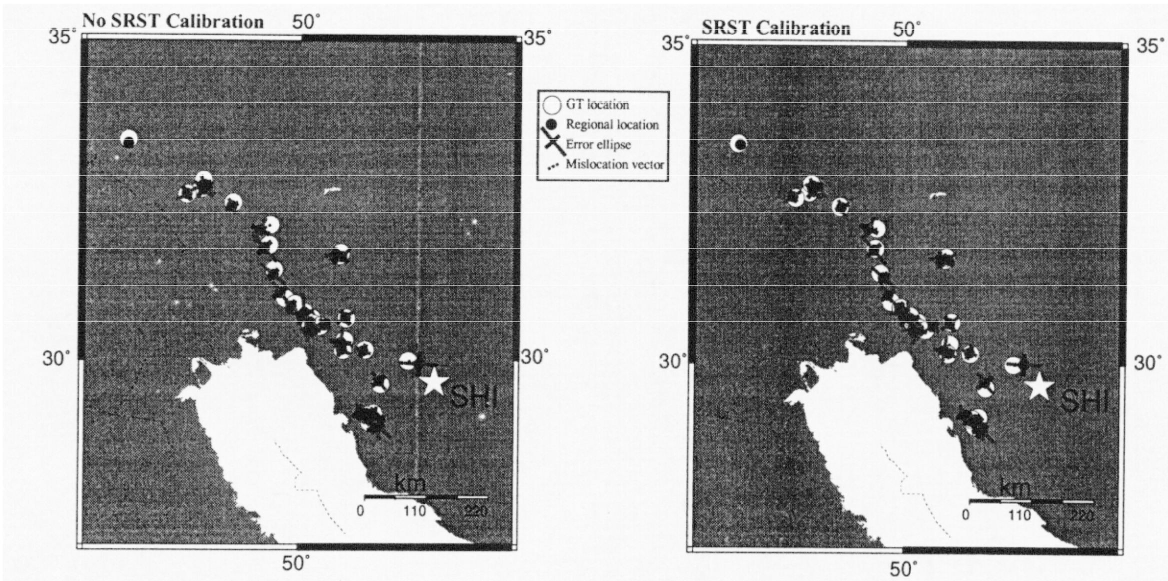

Figure 5. Map view of regional relocations plotted over the teleseismically constrained locations for the case that the event was within the footprint of the recording stations (AzGap < 180°). The locations are shown for the case of no station calibration and the case of an optimal static station calibration. At least three regional P recordings were required for a location and station calibrations were applied only if 10 or more independent events were available for the correction.

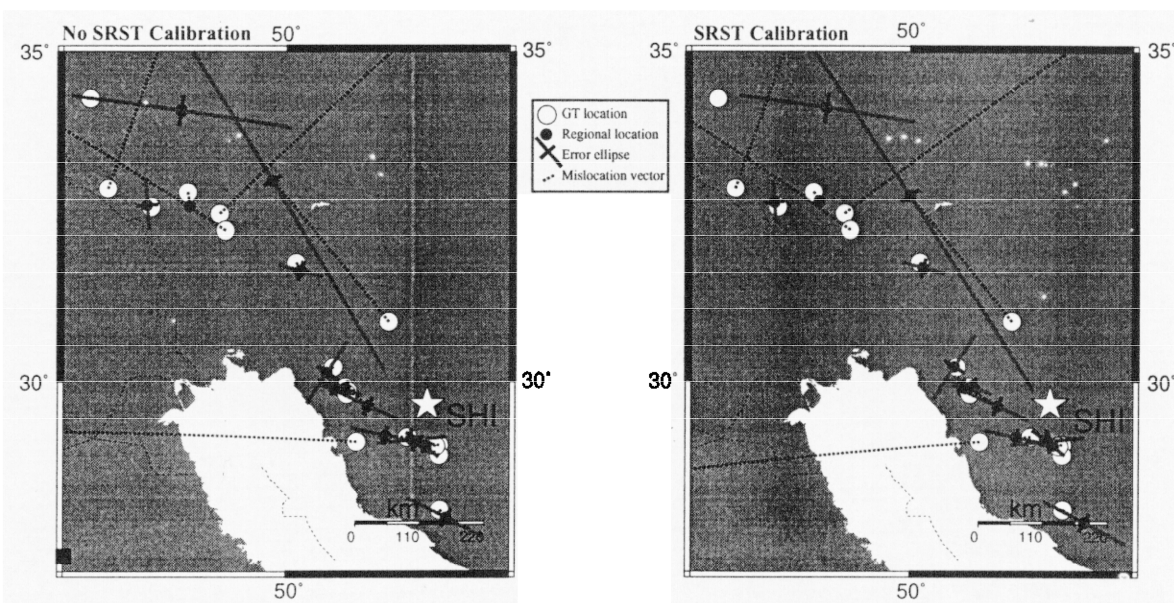

Figure 6. Similar to Figure 5, except that the events lie outside the footprint of the recording stations (AzGap>180°).

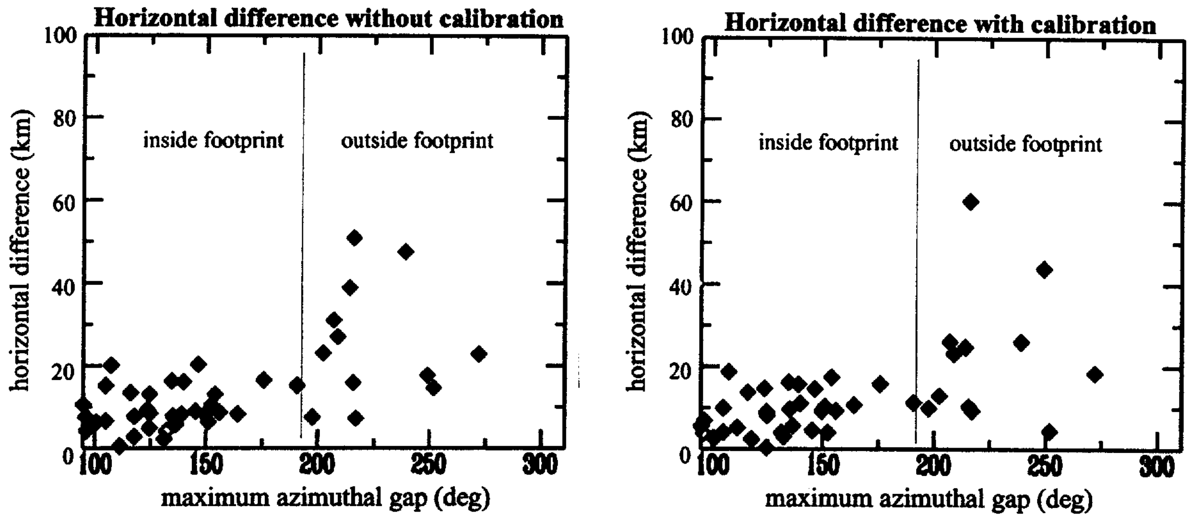

Figure 7. Summary figure showing the horizontal difference between the regional surrogate network and the teleseismically constrained location. Both the case of no calibration and the case of incorporating a static station correction are shown.

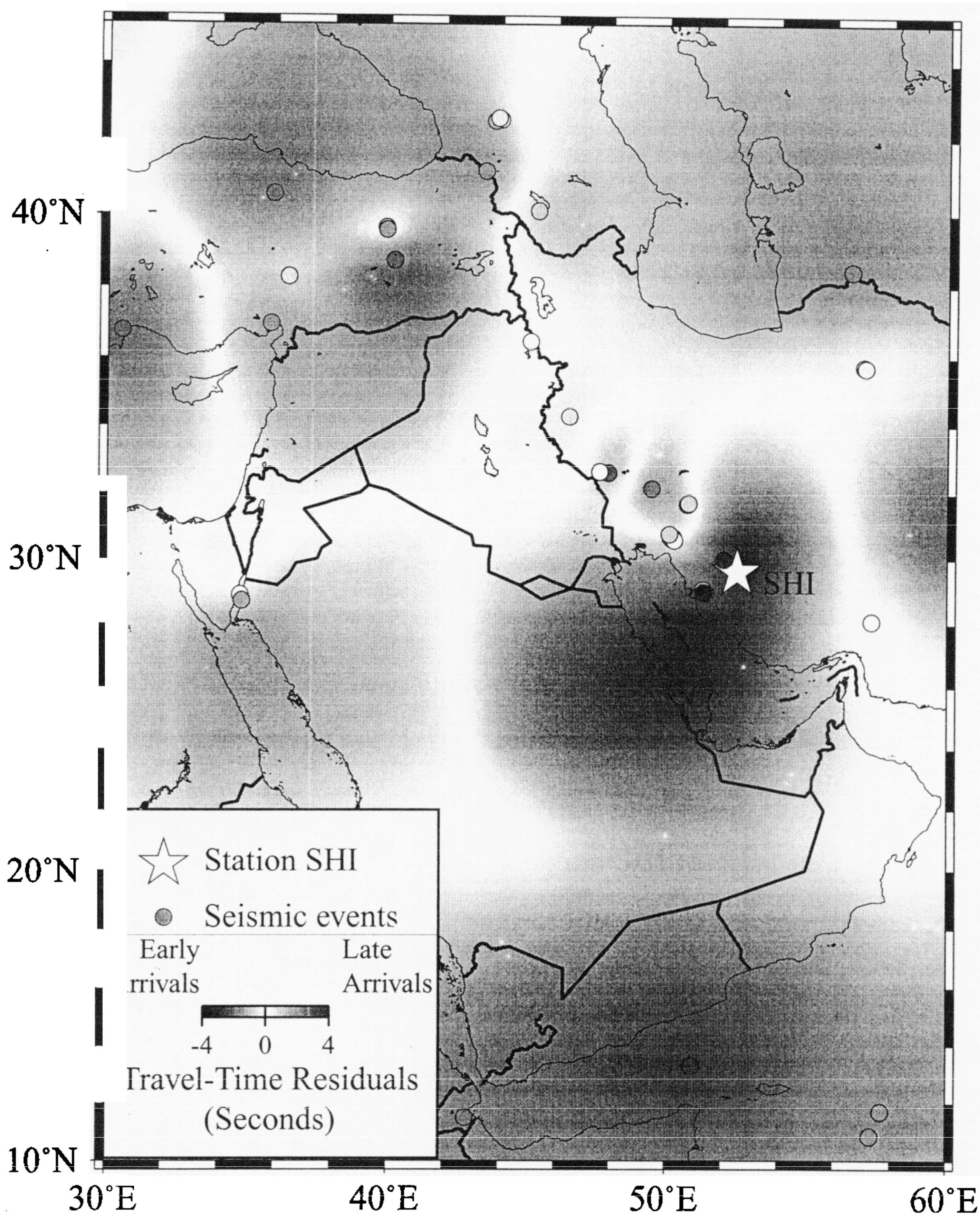

Figure 8: Kriged surface of travel-time residuals calculated using data from the events shown. Residuals of events and kriging results are color coded with red and blue representing late and early arrivals, respectively.

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