ON THE USE OF KRIGED P-WAVE TRAVEL-TIME CORRECTION SURFACES FOR SEISMIC LOCATION

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ABSTRACT

Accurate location of seismic events remains a critical issue for global nuclear explosion monitoring. Herein we present some observations on the nature of kriged P-wave travel-time correction surfaces and their application to improving seismic event location in China. We have adopted the correction surface approach due to ease of implementation and the fact that empirical correction surfaces can be constructed without detailed knowledge of crustal structure. However, correction surfaces can be built on any velocity model, no matter how detailed, so that when such models do become available, surfaces can be recalculated for that model. This, in turn, enables prediction of corrections in regions lacking seismicity. We use the modified Bayesian kriging method to construct surfaces for 76 stations around Asia, analyzing travel-time data from seismic events in the United States Geological Survey Earthquake Data Reports (EDR) and the International Seismic Center (ISC) catalog. Due to limited data, we gather residuals for events throughout the crust (as defined by the 1-D global model employed) whose location accuracies range from 2-25 km. The correction surfaces are used with the EvLoc algorithm to perform regional relocations of several thousand events in the region around China.

Correction surfaces dramatically improve the clustering and linearity of regional seismicity and increase the stability of EvLoc. About 50% more events are successfully relocated when surfaces are used. Comparing regional relocations to high-quality ground truth also reveals a significant quantitative improvement in location accuracy. In an effort to further improve our location ability, we are creating a comprehensive merged database for the China region, comprised of EDR, ISC, Reviewed Event Bulletin, and several regional catalogs. This database will provide the most complete record of arrivals for events in eastern Asia, and its location performance will be validated against current databases.

One measure of the robustness of the kriged surfaces is their correlation; nearby stations should have similar P-wave correction surfaces. We find that surface correlation is high for nearby stations but drops off beyond about 250 km, implying that, on average, crustal structure varies rapidly across Asia. This length scale may be useful for assessing whether or not surrogates should be used in developing correction surfaces for new stations. Moreover, this correlation length can also be used to constrain the model correlation length parameter in the kriging procedure.

We have performed a suite of sensitivity tests to examine the effect of depth and epicentral mislocations on travel-time residuals. These tests were performed using four closely spaced high-quality ground truth events as observed by the 76 stations for which we calculate correction surfaces. Fixing the latitude and longitude of the events and letting the origin time and depth vary, we find that there is about 0.13-sec deviation in residuals for every 10 km of depth error. Epicentral mislocations result in P-wave residual errors of about 0.75 sec per 0.1^{o}. When compared to the root-mean-square residual value of about 1.9 sec, effects due to depth errors and depth averaging are minimal.

KEY WORDS: location, validation, calibration, regional

OBJECTIVE

Accurate seismic event location remains a key element for monitoring the globe for nuclear explosions. It is particularly difficult to obtain accurate locations at lower magnitudes using sparse global networks. One approach towards improving location is to use travel-time residuals of well-located events to correct travel times for other events in the same region. This approach, which accounts for inadequate Earth models, has been used to calibrate spatially limited regions of interest, most notably at nuclear test sites in various countries. However, in the present context we must monitor vast regions of the Earth's surface, and hence have begun constructing surfaces of travel-time corrections that will ultimately span entire continents, if not the globe. This aspect of the approach is relatively new, and we present some observations on the use, and nature, of P-wave travel-time correction surfaces, testing their application to improving regional seismic event location in Asia.

We have adopted the correction surface approach for a number of reasons, including ease of implementation and the fact that empirical correction surfaces can be constructed without detailed knowledge of crustal structure. In the implementation we discuss here, empirical travel-time corrections are determined with respect to a 1-D base model, and corrections are not predictable beyond the correlation length of the geologic structure. It is important to note, however, that correction surfaces can be calculated for any base model, no matter how detailed, so that when detailed crustal structure is obtained, surfaces can then be recalculated for that model, in turn enabling travel-time correction prediction in regions without empirical data. To construct our correction surfaces, we use the modified Bayesian kriging (MBK) method of Schultz et al (1998).

The MBK method creates an interpolated surface from residuals using correlation lengths of the background model and the data. The correlation of the data can be determined empirically using variogram analysis, presuming the data are isotropic. The correlation of the background model is more difficult to estimate, but we propose a method below that may prove effective. MBK also produces an error variance surface associated with the correction surface. MBK marks an improvement over standard kriging in that it is able to blend back to the variance of the background model beyond the empirically derived correlation lengths. This method has been applied successfully for *P*-waves travel times for seismic location in the Middle East (Schultz et al., 1998; Myers and Schultz, 1998) and in Asia (Steck et al., 2001), and we refer the reader to Steck et al. (2001) for details of our particular implementation. Certainly, the effectiveness of the correction surface method is dependent on the accuracy of the trave-time residual data used. In this study, we use several levels of ground truth, ranging from events located with an accuracy of 2 km (nuclear tests located with the aid of satellite imagery), to events located to an accuracy of about 20-25 km. The latter range is for events whose locations have maximum azimuthal gaps of less than 90 ^{o} and 180^{o}, and numbers of defining phases greater than or equal to 50 and 30, respectively [E. R. Engdahl, personal communication; Bondar et al (2001); Sweeney (1996)].

RESEARCH ACCOMPLISHED

Empirical Kriged P-wave Travel-Time Surfaces

In this paper we elaborate on the performance of empirical kriged *P*-wave travel-time correction surfaces that were developed by Steck et al (2001). The surfaces cover a region between 20ß-55ß latitude and 65ß-115ß E longitude, and were developed for 76 regional seismic stations around Asia. Figure 1 shows the station locations. The propagation path corrections are source-to-station corrections, where each station has its own set of corrections, and the corrections vary depending upon geographic position of the source. Because we are most interested in surface sources, we have restricted our investigations to crustal events, and the correction surfaces are not applicable to sources below the Moho. For this paper the travel-time residuals are calculated with respect to a regional 1-D velocity model based on results published in Li and Mooney (1998) and reported in Steck et al. (2001).

The best constrained ground truth information available for the region is that from nuclear explosions. We include locations for explosions from two test sites: the Chinese test site at Lop Nor (Gupta, 1995) and the former Soviet Union test site at Balapan, Kazakhstan (Thurber et al., 1993). Because the origin times for these events are not known, these events are considered to be accurate within 2 km, although the reported location error is typically less than 2 km. We also examined 26 events that have independent depth constraints, ultimately using only about a third of them as ground truth to construct our travel-time surfaces. While perhaps not as valuable as epicentrally constrained ground truth for calibration purposes, these data nevertheless offer some improvement over events for which the depth is poorly constrained, and this is a point that we will return to.

The most abundant data we have are constrained events that have been recorded by at least 30 stations with an azimuthal gap < 180^{o}, and have a sum of depth plus depth error less than the moho depth of the model. Applying the 30/180 criteria results in 917 useable ground truth (GT)20 events for the *China_LM* model. If we instead constrain our data using a 50/90 criterion, the number of useable events decreases to 689; see figure 2 for event locations. From these sets of events we then gather residuals by station, discarding residuals larger than 5 s (for 30/180) or 10 s (for 50/90) in absolute value, and kriging the declustered data to obtain an interpolated surface for each station. Declustering the residual data accelerates and stabilizes the kriging procedure.

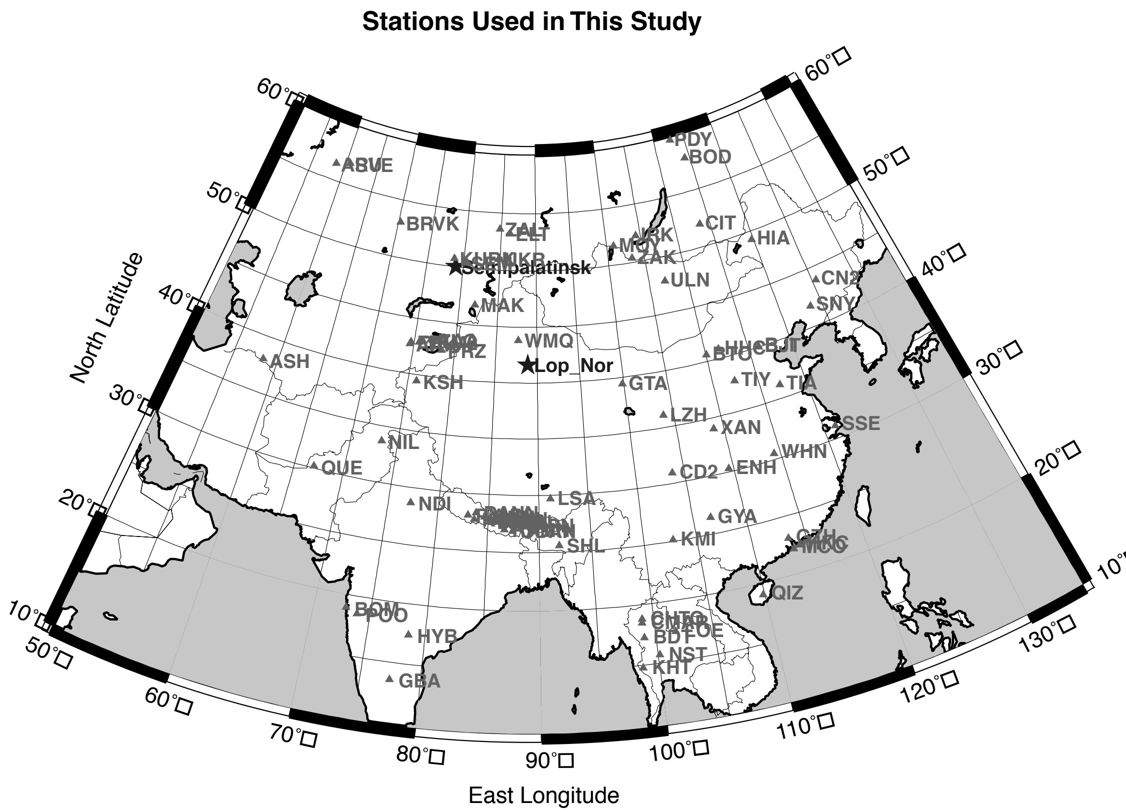

Figure 1. Map of 76 seismic stations used in this study.

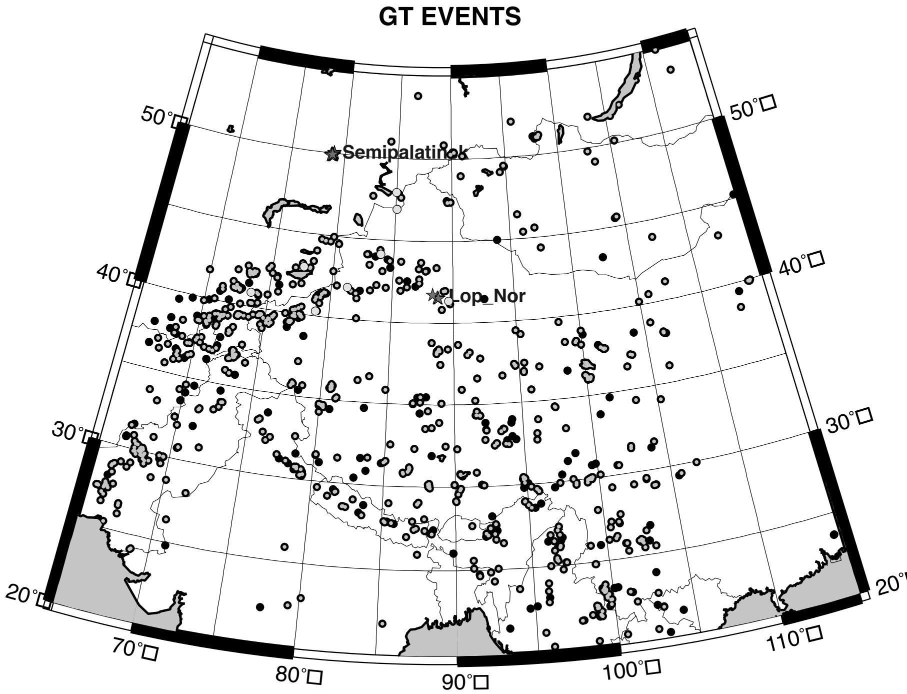

Figure 2. Locations of GT2-20 events used to create correction surfaces. Black dots show the 917 30/180 data, small gray dots within the black dots show 689 50/90 data. Stars show GT2 nuclear tests and larger gray circles indicate depth-constrained events, primarily in the Tien Shan area.

Regional Location Using Kriged P-wave Travel Time Surfaces

Travel-time correction surfaces are used to relocate 6748 events from the United States Geological Survey (USGS) Earthquake Data Reports (EDRs) and the International Seismic Centre (ISC) catalogs, for the region around China, using the EvLoc algorithm (Bratt and Bache, 1988; Nagy, 1996). In this case only stations for which corrections were available are used. Figure 3 shows our relocations without using correction surfaces (top), and relocations with corrections (bottom). While qualitative in nature, comparing these two plots shows that the use of correction surfaces improves the tightness and linearity of events and clusters. The use of correction surfaces improves our ability to relocate events with sparse data by stabilizing the location procedure. When correction surfaces are not applied (and the same stations are used), only about 70% of the original 6748 events converged to a solution. Quantitative location improvement can be obtained for regions having high-quality ground truth. Regional relocations with corrections are better than either corrected or uncorrected teleseismic locations.

Correlation of Kriged P-wave Travel-Time Surfaces

One measure of the robustness of the kriged surfaces is the correlation between surfaces for nearby stations. If the number and locations of events from which the surfaces are derived are similar, one might expect that surfaces for nearby stations would be well correlated, while the correlation would be somewhat random for more distant stations. To investigate this, we look at all possible station pairs for the 76 stations in Asia. Our measure of surface correlation is the simple expression:

$$\rho_{jk} = COV_{jk} / \sigma_j \sigma_k$$

where ρ is the correlation, COV is the covariance, σ is the standard deviation, and j,k represent the two kriged surfaces (Davis, 1986). Figure 4 shows the correlation, ρ, versus inter-station separation distance, x, for two

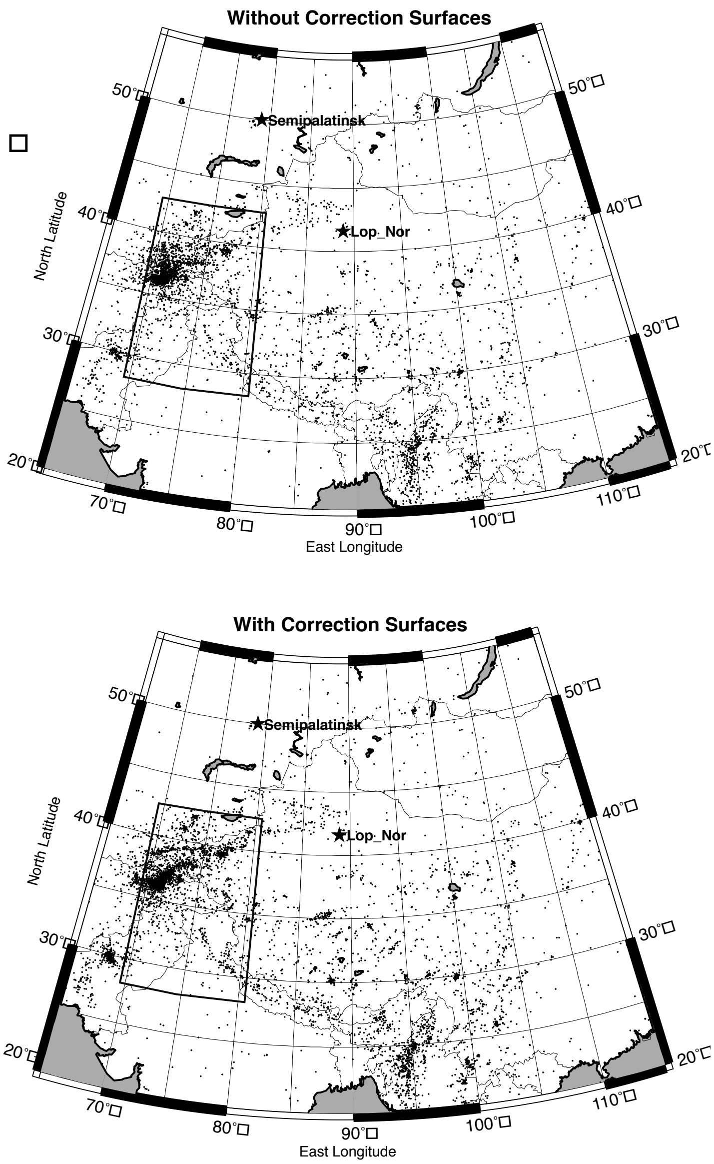

Figure 3. (top) 4630 successful relocations without kriged correction surfaces, (bottom) 6748 successful relocations with kriged correction surfaces based on 30/180 data. In both cases, only stations for which corrections were available were used in the relocations. Note greater event clustering and linearity, particularly within the boxed region.

sets of data, those with 50 stations or greater and an azimuthal gap < 90^o and those with 30 or more stations and an azimuthal gap < 180^o. Curves of the form:

$$\rho = A_0 10^{(A_1 x)} - A_2$$

are fit to the data as well, with very similar results. The y-intercept was slightly higher for the 50/90 data (.8633 versus .8109) suggesting a higher correlation for the better constrained events. Perhaps the most striking observation here is that correlation drops off dramatically beyond 250 km, and even within that distance, there are several largely uncorrelated surface pairs. The lower correlations inside 250 km largely arise from correlating surfaces with little data or from surface pairs with limited overlap in event coverage. The 250-km correlation range agrees qualitatively with results from Shearer (2001) where reciprocity is used to assess a global average correlation range of about 150 km. The swift drop-off in surface correlation suggests that on average, geology varies rapidly in this region, with a structural correlation range of about 250 km. This may be valuable for assessing whether or not surrogates should be used in developing station correction surfaces for new stations, though the inter-station geologic terrain should be evaluated first if at all possible. Since the correlation of the surfaces is really a measure of the correlation of surface geology between stations, we propose that a more effective estimate of model correlation length can be obtained from the surface correlation length, ρ.

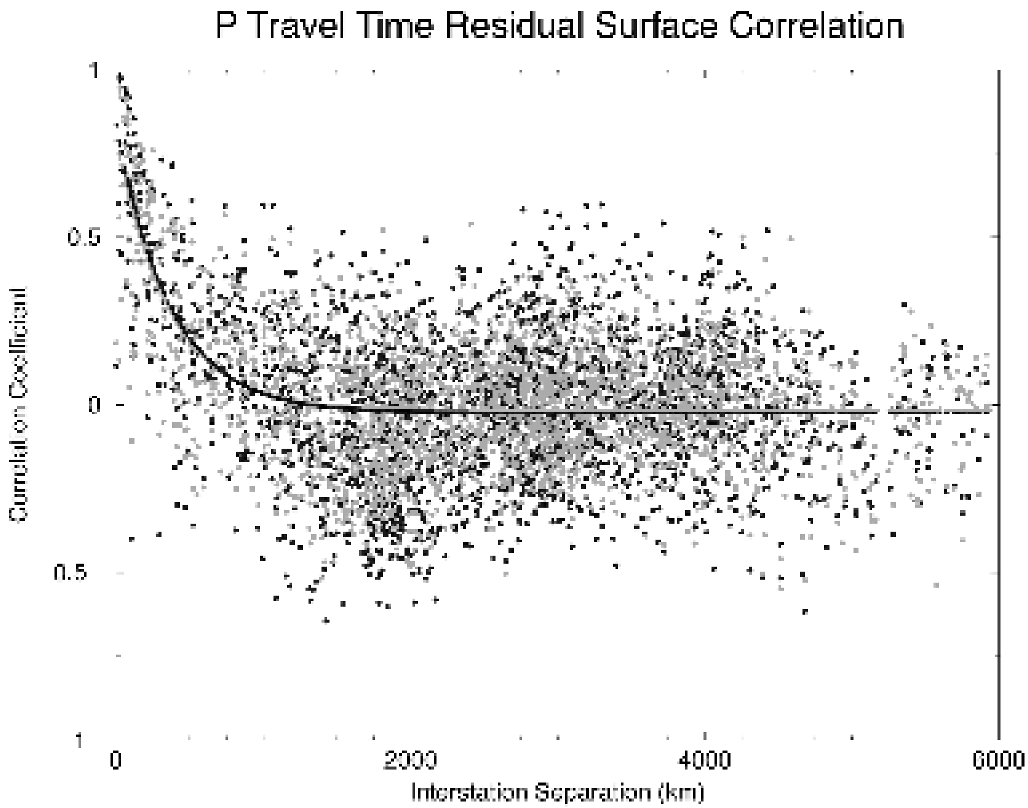

Figure 4. Correlation of kriged surfaces for station pairs, plotted as a function of inter-station distance. Gray circles are for seismic events with 30 or more defining phases (one per station) and maximum azimuthal gap less than 180^o; black circles for events with 50 or more defining phases and maximum azimuthal gap less than 90 ^{o}. Curves fit to both sets of data are also shown.

Effects of Mislocation on Travel -Time Residuals

To produce our correction surfaces, we use a combination of events located to within 2 km or 20-25 km of their true location, where the former is for nuclear explosions located with JED methods and satellite imagery, and the later is for well-located earthquakes. We also have some earthquakes for which depths have been constrained by a number of different methods, from waveform fitting and inversion, to depth phase analysis. To investigate the value of using depth-constrained events and events whose location is known only to within some limit, we ran synthetic tests in which either depth or epicenter was perturbed from its initial ground truth estimate. In EvLoc, we then calculate new travel times for the perturbed hypocenters, and solving for a new origin time if depth was perturbed. Travel-time residuals are then calculated and compared to residuals for the unperturbed case. We investigate this using four high-quality ground truth events in western China, as observed by the 76 stations for which we have calculated correction surfaces. For the depth-perturbed events, we fix the latitude and longitude and let origin time vary. For increments of 10 km in depth, we then re-gathered the station residuals, and find the average deviation of the residuals from the residuals at zero depth. These data are shown in Figure 5. One can see that there is about 0.13-s deviation in residuals for every 10 km of depth error.

Epicentral errors are explored by perturbing the epicenter to the north, east, south and west by increments of 0.05°, 0.1°, 0.25°, and 0.5°. Origin time and depth are held fixed. The differences between the residuals from the shifted epicenters and those at the correct epicenter are calculated and grouped by distance bin. From these a standard deviation is determined for each distance bin, and results are shown in Figure 6. We find about 0.75 s standard deviation in travel time residual per 0.1° of mislocation.

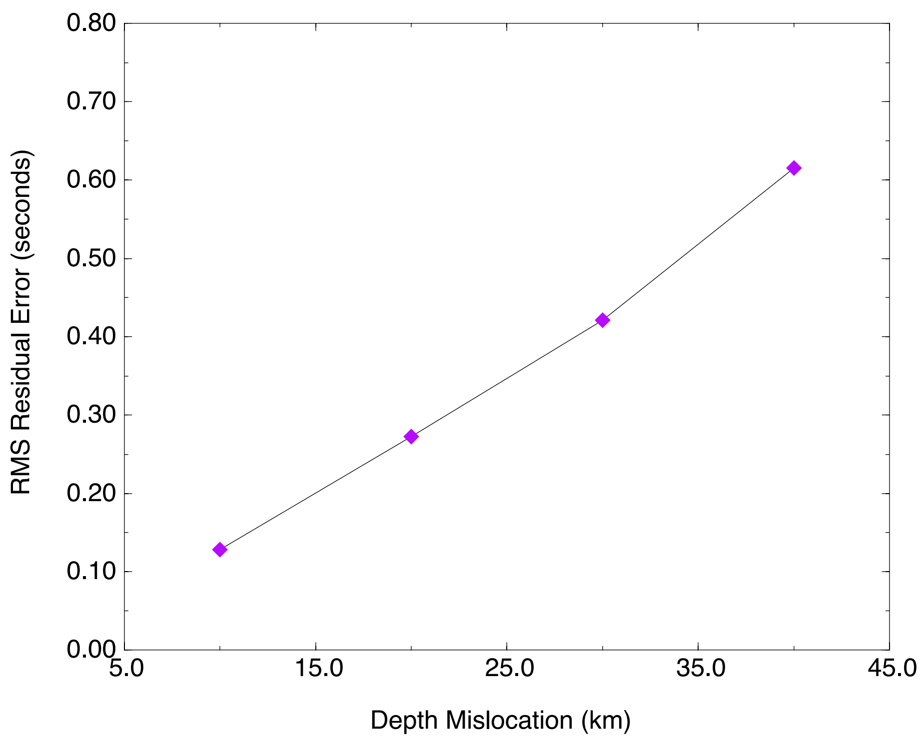

Figure 5. Standard deviation of residuals from those at zero depth, as a function of depth mislocation.

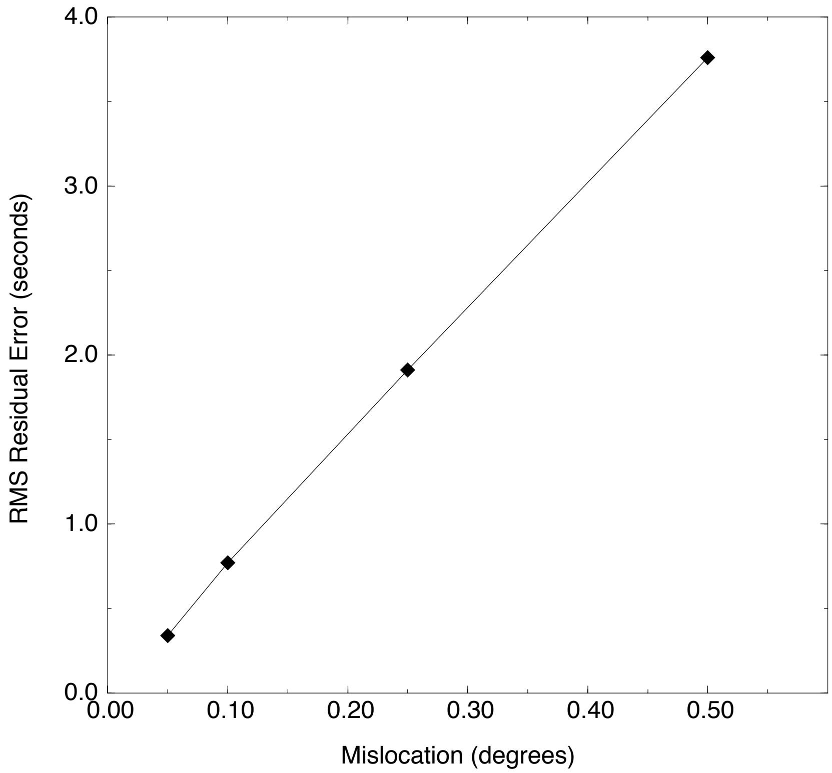

Figure 6. Standard deviation of residuals from those at ground truth epicenter, as a function of epicentral mislocation.

As seen in figure 3, even using travel-time residuals from seismic events having locations accurate to only 20 km can dramatically improve our regional location ability in Asia. In this study we have combined residuals for events located throughout the crust, using all events for which depth plus depth error is less than crustal thickness. This was motivated in part by our need for data but also by the overall lack of strong constraints on depth for this region. Results shown in Figure 5 suggest that the errors introduced by this approach are small, on the order of a few tenths of a second, compared to the overall size of the residuals, which are on the order of a few seconds (see figure 7). This effect has also been reported by S. Myers (Pers. Comm.). Errors in residuals are larger for epicentral mislocation, at about 1.5 seconds for a 22-km location error. While 1.5 s is approaching the size of an average root-mean-square (RMS) residual (1.85 s), it is smaller than the smallest standard deviation assigned to the residuals, and there are nevertheless improvements in our locations using data at, or under, this level of ground truth accuracy. This may result from the larger residuals dominating the improvement, or it may be that we are simply improving the clustering of events, while their absolute location is still off by about 20 km. In either case, this suggests that mislocation biases for regional events are significantly larger than those of teleseismically located events, and that the use of teleseismically located event P-wave residuals can be used to improve regional locations.

Developing Regional Seismic Databases for Improving Event Location and Ground Truth

The use of two-dimensional kriged travel-time correction surfaces requires ground truth information, which can be in the form of known explosion locations and well-located teleseismic events. To develop a ground truth data set, we rely on existing catalogs and our own travel-time information. There are many global and regional seismic catalogs with earthquake information for Asia used in location studies, each containing origin and arrival information that may or may not overlap with the other catalogs. In order to obtain the most accurate earthquake locations, all available arrival information should be combined into a single data set, including derived travel times from digital stations. We have developed a seismic location database for the China region,

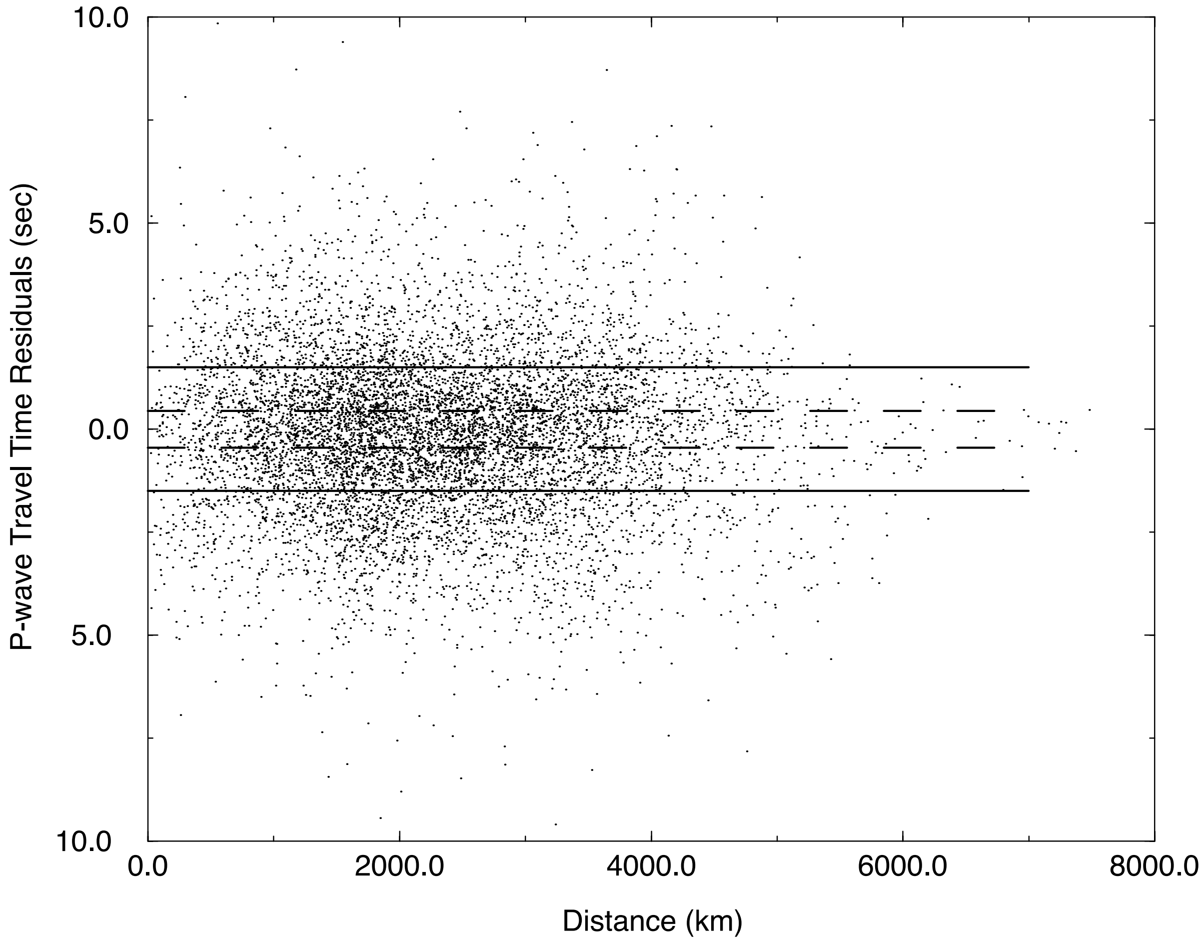

Figure 7. P-wave travel-time residuals versus distance for all 76 stations. The dashed lines represent the RMS residual error for depth mislocation of 30 km (– 0.40 sec). The solid lines are RMS residual error for an epicentral mislocation of 22 km (–1.5 sec). This compares to an RMS residual of –1.85 sec.

combining origin and arrival information from a number of global catalogs, including the prototype International Data Center (pIDC) Reviewed Event Bulletin (REB), USGS Earthquake Data Reports (EDR), International Seismic Centre (ISC), as well as several regional catalogs. Regional arrivals obtained from digital data in Asia are also included. We also include ground truth information from previous research efforts for nuclear test sites and regional mining information. This merged database will provide more arrival data in which to improve location studies such as developing and utilizing empirical travel-time corrections surfaces.

As a first step, the above catalogs are joined based on origin location and time to produce a master table listing common origins by event ID (evid). This master origin table provides the basis for merging the arrival tables from different catalogs and deleting redundant arrivals based on a catalog hierarchy. Certain catalogs are known to have errors in arrival times from truncation and machine versus manual picking. Traits such as this go into determining a suitable catalog hierarchy in which to remove duplicate information. The final location database will thus have the most accurate arrival information available and contain origin, origin error, association, and arrival tables, all without redundant information.

CONCLUSIONS AND RECOMMENDATIONS

We find that kriged P-wave travel-time correction surfaces dramatically improve seismic event locations in Asia. Correction surfaces stabilize the location procedure such that 50% more events are located when surfaces are used, and clustering and linearity of seismicity are more pronounced. Because the input P-wave residuals are derived from events located to only 20-km accuracy, the locations themselves may still contain biases despite improvement in relative locations. If the seismicity used to create the surfaces is in fact unbiased but simply contains random errors on the order of 20 km, then the final locations may not be biased. By perturbing known event depths and epicenters by varying amounts, we are able to assess that errors in depth do not have a significant effect on the construction of the surfaces, being an order of magnitude smaller than typical residuals. Errors in epicenter will contribute significant error to the correction surfaces, but these errors still do not dominate the surfaces' effects on location. This may arise through the averaging effects implicit in our surface construction, or through the corrections being dominated by the larger values present in the surfaces themselves. Nevertheless, the more accurately one knows the locations of the events whose residuals are being used, the more effective the surfaces will be in improving locations. Through investigation of the correlation of our correction surfaces with each other, we find that an average structural correlation length for Asia is about 250 kilometers.

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