IMPROVING REGIONAL SEISMIC EVENT LOCATION IN CHINA

Lee K. Steck, Aaron A. Velasco, Allen H. Cogbill, and Howard J. Patton
Los Alamos Seismic Research Center
Earth and Environmental Sciences Division
Los Alamos National Laboratory

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ABSTRACT

In an effort to improve our ability to locate seismic events in western China using only regional data, we have developed empirical propagation path corrections (PPCs) and applied such corrections using traditional location routines. Thus far, we have concentrated on corrections to observed P arrival times for crustal events using travel-time observations available from the U.S. Geological Survey Earthquake Data Reports, the International Seismic Centre catalogs, the prototype International Data Center Reviewed Event Bulletin, and our own travel-time picks from regional data. Location ground truth for events used in this study ranges from 25 km for well-located teleseismic events, down to 2 km for nuclear explosions located using satellite imagery. We also use eight events for which depth is constrained using several waveform methods. Using the EvLoc algorithm, we relocate events from a region encompassing much of China (latitude 20º-55ºN; longitude 65º-115ºE). Using *iasp91* as our base model, we find that travel-time residuals exhibit a distance-dependent bias. For this reason, we have developed a new 1-D model for China, which removes a significant portion of the distance bias.

For individual stations having sufficient P-wave residual data, we produce a map of the regional travel-time residuals from all well-located teleseismic events. Residuals are used only if they are smaller than 10 seconds in absolute value and if the seismic event is located with an accuracy better than 25 km. From the residual data, PPC surfaces are constructed using modified Bayesian kriging. Modified Bayesian kriging offers us the advantage of providing well-behaved interpolants, but requires that we have adequate error estimates associated with the travel-time residuals. For our P-wave residual error estimate, we use the sum of measurement and modeling errors, where measurement error is based on signal-to-noise ratios when available, and on the published EDR estimate otherwise. Our modeling error comes from the variance of travel-time residuals for our 1-D China model. We calculate PPC surfaces for 74 stations in and around China, including six stations from the International Monitoring System. The statistical significance of each PPC surface is evaluated using a cross-validation technique. We show PPC relocation results for a Tibetan earthquake that has been located using InSAR. The use of PPC surfaces in regional relocations significantly reduces seismic event mislocations, and eliminates distance bias in travel-time residual curves.

Key Words: location, calibration, seismic regionalization, kriging

OBJECTIVE

Seismic detection and location of small events remains a key issue for effectively monitoring the Comprehensive Nuclear-Test-Ban Treaty (CTBT), which has an implicit goal of locating seismic events within a contiguous area smaller than 1000 km^2. In China, where station coverage is sparse and crustal structure is strongly heterogeneous, this goal presents a significant challenge. Our objective is to improve regional seismic location in China, by developing spatially varying corrections to P-wave travel-time observations for shallow events. We have chosen the propagation path correction approach both because the limited seismicity makes three-dimensional inversion for velocity structure difficult, and because the pIDC and the U. S. National Data Center both utilize this method in their standard analysis proceedures. For our study we use bulletin data from the United States National Earthquake Information Center Earthquake Data Reports (EDRs), the International Seismological Centre (ISC) bulletin, the prototype International Data Center's (pIDC) Reviewed Event Bulletin (REB), and our own travel-time picks from regional data. We have chosen to locate events within a region defined from 20º-55º N latitude and from 65º-115º E longitude, using the EvLoc algorithm (Bratt and Bache, 1988; Nagy, 1996). While our intent is to calibrate all regional seismic stations in Asia, many of the stations of interest, particularly those of that will be part of the International Monitoring System (IMS), have not been in operation long enough to acquire sufficient data for our empirical approach. To circumvent this problem we use data from stations reporting to the EDR and ISC as surrogates for those of the IMS.

RESEARCH ACCOMPLISHED

For the China region, we have gathered an extensive database containing both traveltime information and waveforms for regional stations located in China, Pakistan, India, Kyrghyzstan, Kazakhstan, Mongolia, Russia, Korea, and Thailand. For the years between 1986 and 1989, we use data from the ISC bulletin. Between 1990 and January 1998, we use the EDRs. P-wave residual means and variances at stations reporting to both catalogs are similar, which suggests that we are not introducing any additional biases by combining these data sets. We supplement these data with travel-time picks from the REB, and our own travel time picks from regional data. Our digital waveforms were retrieved from the IRIS database using the event origin information from the global catalogs mentioned above, and are the result of a large regionalization effort (Hartse et al., 1997). Travel-time picks and amplitude measurements of regional phases have been made on broadband channels when available; otherwise, short-period channels are used (Hartse et al., 1997). For the locations, we use only first-arriving P travel-times, and have added about 6800 of these picks to our data set. We base the quality of the pick on the signal-to-noise ratio (SNR) of each phase, using the convention of Nagy (1996). These same criteria are used to define measurement error for REB picks. We begin our analysis using the global velocity models *ak135* (Kennett et al., 1995) and *iasp91* (Kennett and Engdahl, 1991). However, as discussed below, our research has expanded to incorporate analysis using 1-D regional models for China.

A critical element of our location effort lies in improving our ability to accurately estimate the errors in travel-time measurements. This is important both for determining the location confidence region, and for providing accurate estimates of travel-time for interpolation. To aid in this, we have refined estimates of modeling and measurement errors. Modeling error is defined as the travel-time variance of a particular model as a function of distance, while the measurement error is defined as the picking error associated with each phase. Optimally, SNR should be used to determine the measurement error, and we use this when available. When SNR is not available, we use a uniform measurement error of 2 s^2, as is done in the EDRs Modeling error is the more difficult of the two types of error to determine. We begin by using estimates of the modeling error developed from arrivals compiled by the pIDC for *iasp91* (Swanger, personal communication). This estimate of modeling error does not account for intrinsic biases present in our locations, arising from differences in network geometry and from using a 1-D base model when the true structure is laterally variable. Steck et al. (1998) show that for distances < 20º, travel-time residuals exhibit a distance trend, suggesting that standard global velocity models do not adequately reflect the crustal structure of China.

To properly construct the travel-time residual surfaces, we must remove this trend. For this reason, we have attempted to develop unbiased, 1-D, regional velocity models for China before PPC surface construction. The three models we look at are based on data from Li and Mooney (1998), Kosarev et al. (1993), and Jih (1998), and we call them *China_LM*, *Asia*, and *China_RSJ*, respectively. The *China_LM* model is developed by averaging seven crustal models based on deep seismic sounding results for China (Li and Mooney, 1998). Our strategy was to assume a three-layer crust with each layer having the average crustal thickness and velocity of the three thickest layers of each of the seven models. Thin sedimentary layers and anomalous mid-crustal zones were eliminated. For these regional 1-D models, we place their crustal structure on top of the *iasp91* mantle structure. Figure 1a shows the P-wave models used in this study.

Travel time residuals from our 1-D models show a slight reduction in distance bias (Figure 1b), with the *China_LM China_RSJ* models providing the most improvement. Figure 1c shows the standard deviation of the residuals, which represents the modeling error for each of the models. Also plotted is the original estimate of modeling error from *iasp91* P-waves (Swanger, personal communication). The global and regional 1-D model errors appear to be consistent at regional distances, where modeling errors are largest. At teleseismic distances, all of our models are consistent with each other, but the errors are on the order of 0.4 s larger than that provided by the pIDC. At regional distances, the modeling error differences between all regional 1-D models are not significant, but we obtain a slightly higher modeling error for *iasp91.* The primary impact of applying these new modeling errors will be to change the error ellipse sizes. When we compare our iasp91 locations with the new and old modeling error differences, we find that that the error ellipses grow on average by only 0.4 ± 0.7 km for the semi-major axis and 0.3 ± 0.5 km for the semi-minor axis. Note that none of the 1-D models is able to completely eliminate the distance bias in the residuals. Cogbill and Steck (1997) show that by applying PPCs, most remaining bias can be removed.

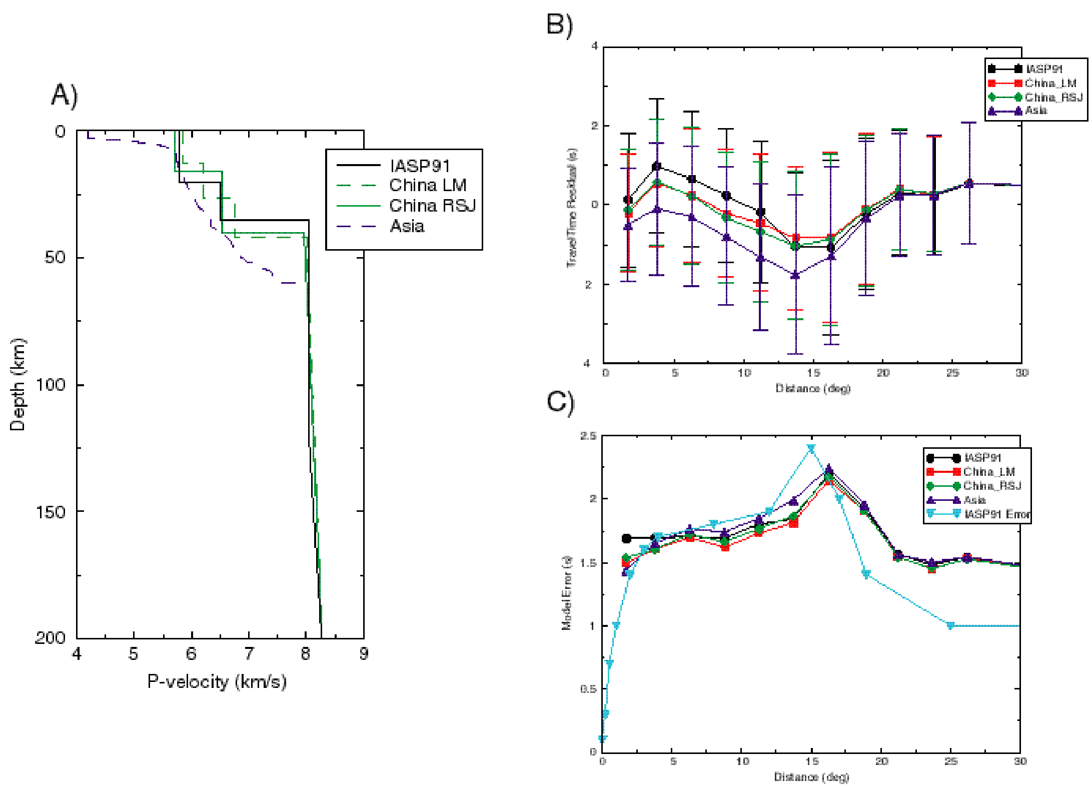

Figure 1. See text for discussion

Seismic Event Relocations

We perform our initial relocations using 9500 events with over 300,000 P-wave arrivals spanning 11 years. We relocate all events using the four velocity models described above, letting the algorithm remove outliers based on travel-time residual size. To ensure high quality locations to be used in our 2-D correction surfaces, events must have been recorded by at least 30 stations, have maximum azimuthal gap < 180°, and have a sum of depth plus depth error less than the moho depth of the model. Applying these criteria reduces the number of useable events to 705, 915, 907, and 1074 for the *iasp91*, *China_LM*, *China_RSJ*, and *Asia* models, respectively. From these sets of events we then gather residuals by station, discarding residuals larger than 10 s in absolute value. Thus, our data set is teleseismically constrained. By employing the previous two criteria, we restrict ourselves to residuals from events located with an accuracy of about 25 km (E. R. Engdahl, personal communication). Average epicentral differences between the various models are less than a fraction of a kilometer, while origin times and depth vary depending on the routine practices applied at the locating institution and on the relative speeds of model used. For nuclear explosions that were located by Gupta (1995) and Thurber et al. (1993), we constrain the latitude, longitude, and depth and invert only for origin time. We do this for all velocity models. For our depth-constrained events, we set the depth and let the program invert for latitude, longitude, and origin time. While the main effect of constraining depth is to more accurately determine origin time, we expect some improvement in epicentral location as well.

Ground Truth

To test and validate our travel-time corrections and relocation algorithms, ground truth information is needed. The best-constrained ground truth information available for the region is that from nuclear explosions. We include explosions from two test sites: the Chinese test site at Lop Nor and the former Soviet Union test site at Balapan, Kazakhstan. Gupta (1995) relocated many Lop Nor nuclear explosions using satellite imagery and a relative location algorithm. Thurber et al. (1993) obtained locations for 20 explosions at Balapan, Kazakhstan, also using a joint epicentral determination (JED) technique in conjunction with SPOT satellite images. Because the origin times for these events are not known, these events are considered to be accurate within 2 km.

Our ground truth database also includes surface rupture information obtained for a large earthquake (M_w = 7.5) that occurred on Nov. 8, 1997, approximately 750 km south of the Lop Nor nuclear test site. The mainshock is a shallow, strike-slip, intraplate event (Velasco et al., 1999). Velasco et al. (1999) obtain a consistent source model over a wide range of frequencies, from a wide variety of seismic data. However, mapping of the actual ground rupture was obtained from InSAR data for the mainshock (Peltzer, personal communication). The rupture length is approximately 180 km, showing a very linear fault (Figure 4). Because the mainshock is an east-west striking fault, we can use the mainshock rupture as a guide for validating our path correction surfaces since the depth and latitude are well-constrained.

Finally, we have looked at using 26 central Asian seismic events that have independent depth constraints as ground truth. While perhaps not as valuable as epicentrally-constrained ground truth for calibration purposes, these data never-the-less offer an improvement over events for which the depth is poorly constrained. This approach of establishing ground truth is sometimes the best means available to verification seismologists for calibrating a region. Furthermore, much can be learned about the performance of seismic techniques from comparative analysis, and such knowledge can be used to design improvements in techniques and/or to identify new data requirements. Focal depths from a variety of methods are reported in Patton (1998) and Woods et al. (1998). There are nine depth estimates for the 26 events, from (1) ISC hypocenter determination, (2) pP - P travel time delays, as reported by the ISC, (3) hypocenter determinations in the NEIC Preliminary Determination of Epicenter (PDE) and EDR, (4) simultaneous focal depth and moment tensor determination reported by the NEIC based on Sipkin's method (Sipkin, 1982), (5) Harvard centroid moment tensor catalog, (6) pP - P modeling from Woods et al. (1998), (7) broadband modeling of regional seismograms in the time domain from Woods et al. (1998), (8) modeling regional surface-wave spectra (Patton, 1998), and (9) depth phase determinations from Engdahl et al. (1998). We compute focal depth by taking the weighted average of all estimates available for each event, except those from the centroid moment tensor-- they seem to be bounded at 15km.

The largest variance from the weighted mean focal depth is found for regional surface-wave estimates (RSS), while the depth estimates from the NEIC moment tensor inversion have the smallest variance. Their variances translate into standard deviations of 14.0 km and 2.0 km, respectively. The other standard deviations are: 11.5 km for the ISC location, 5.5 km for the ISC pP, 7.7 km for the NEIC PDE, 2.0 km for the NEIC moment tensor, 8.7 km from the Harvard moment tensor, 12.0 km for the Woods et al. (1999) pP, 11.0 km for the Woods et al. (1999) regional body wave, and 4.9 for the depth phase solutions of Engdahl et al. (1998). In selecting depth-contrained events for use as ground truth, we check the difference between the free- and fixed-depth solutions for hypocentral location. For models *iasp91*, *China_LM*, *China_RSJ*, we find 8 events within 5 km depth for the fixed and free depth solution. The latitudes and longitudes are also within 0.1 km of each other for these solutions. Thus, we use these eight events for our 2-D surfaces below. For the Asia model, we find 11 events that meet our criteria.

Propagation Path Correction Surfaces

Propagation path correction surfaces are created by interpolating the residuals onto 2-D surfaces using modified Bayesian kriging (Schultz et al., 1998) for 68 stations reporting to the ISC and/or EDR catalogs, plus 6 of the pIDC stations. Unfortunately, the limited phase data available from the pIDC stations, due to their more recent installation, makes construction of correction surfaces for these stations of reduced value at this stage. Using modified Bayesian kriging, the value of the PPC surface goes to zero at distances greater than a specified correlation length away from the data points, and an estimate of the variance associated with the surface is calculated based on user-supplied residual variances and an estimate of the background variance. We use 5º for both the model and data correlation lengths.

To explore the validity of the kriged surfaces, we apply a method called cross-validation. There are two principal questions we wish to address: how well do the kriged surfaces describe the data, and how well can kriging predict surface values at data points that have been left out? Our approach is to perform a leave-one-out scenario, whereby for each surface we sequentially recalculate the surface, deleting a different data point each time for all points in that surface. We then determine the mean and variance of the differences between the value of the cross-validated surface at the deleted point and the value at that point for the original surface. The averages of these means and variances are 0.1 s and 1 s^2, respectively, suggesting that the surfaces are robust. For comparison, the average variance of the input residual data is about 5 s^2. The kriged surfaces reduce the variance of the data significantly (an average of 65%) and the average variance reduction of the surfaces themselves from the data is about the same, 70%. In areas were data are plentiful, there is good correlation between the cross-validated surface and the original kriged surface. Where data points are isolated, there is little correlation. Eliminating stations where a cross-validated surface has low correlation with the original surface is unnecessary, because the kriging process itself accounts for the relative accuracy of the input data points.

To illustrate the effect of the PPCs on epicentral location, we show a relocation of the Tibetan earthquake whose surface rupture was identified with InSAR. Figure 2 compares the NEIC epicenter to the relocation using PPCs in EvLOC. Generally, the use of PPCs has two effects. The first is that location bias is reduced, and the second is that the EvLoc algorithm is more likely to converge successfully to a solution. When teleseismic data are used along with PPCs to locate large nuclear explosions, the solutions tend to be dominated by the more plentiful distant data, and the positive effects of using PPCs are much reduced. While this result shows that PPCs can greatly reduce mislocation errors, we have very little other ground truth in the China region. Therefore, the applicability of our correction surfaces cannot be assessed in other geographical provinces. We have found that relocations using a mixture of PPC and non-PPC stations are not successful.

CONCLUSIONS AND RECOMMENDATIONS

We have developed empirical P-wave propagation path corrections for 74 seismic stations in and around China. Some distance dependence is observed in our correction surfaces when locations are performed with the *iasp91* velocity model. To remove this bias we have developed a simple 1-D model for China. Application of PPCs based on our average China model successfully eliminates all remaining bias, except at distances less than 2.5º. We have shown that these corrections improve regional event location for an earthquake in Tibet; we find similar results for nuclear tests at the Balapan and Lop Nor nuclear test sites. Because of sparse seismicity in some areas of China, and a lack of data at some critical stations, we have begun looking at alternative methods of predicting PPCs. We suggest that efforts be undertaken to generate 3-D velocity models in order to be able to predict PPCs in areas where no data is available.

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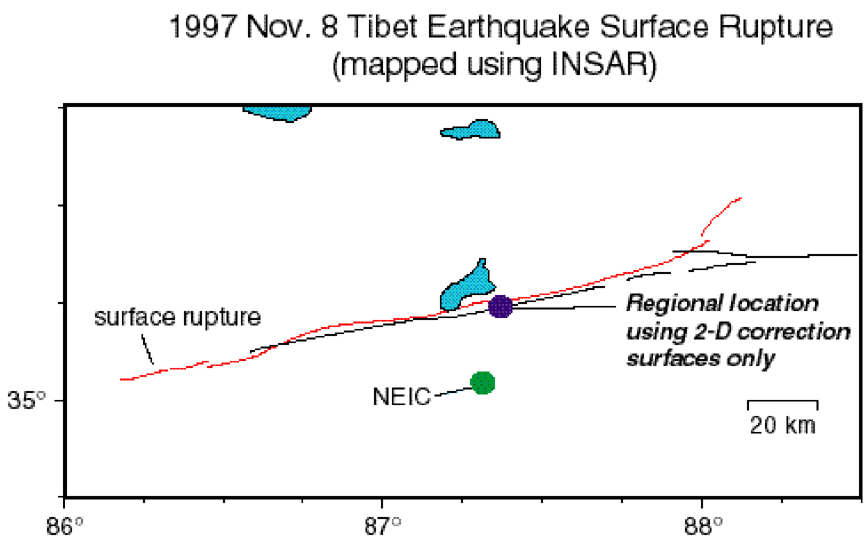

Figure 2. See text for discussion (courtesy of Gilles Peltzer).

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