IMPROVING GLOBAL SEISMIC EVENT LOCATIONS USING SOURCE-RECEIVER RECIPROCITY

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ABSTRACT

The leading source of error in seismic event locations is travel time perturbations caused by three-dimensional Earth structure. The reciprocity of travel times between sources and receivers provides a method for testing the effectiveness of empirical methods for improving event locations that rely on nearby calibration events of known location. We apply this approach to travel time residuals obtained by Engdahl *et al.* (1998) for almost 100,000 teleseismic events. By analyzing the residual patterns at thousands of seismic stations of known location, we characterize the spatial coherence of station/event mislocation vectors. We find that, on average, calibration events are likely to improve locations only if they are located within 100 to 150 km of the target events. For 84 events of known location, we find that applying source-receiver reciprocity can significantly reduce location errors by correcting for the teleseismic residual pattern observed at stations close to the target events. These results have implications for efforts to improve event locations for nuclear explosion monitoring purposes.

Key Words: Seismic, Event Location, Source-Receiver Reciprocity

OBJECTIVE

The objective of this research is to experiment with new methods to improve seismic event locations, in support of monitoring efforts for the Comprehensive Nuclear Test Ban Treaty.

RESEARCH ACCOMPLISHED

Introduction

Improving seismic event locations is an important part of research to support nuclear test verification efforts. A goal of programs to monitor the Comprehensive Nuclear Test Ban Treaty (CTBT) is to achieve high-confidence absolute location uncertainties of less than 1000 km^2 (National Research Council, 1997). Errors in absolute event location in routine location methods using reference one-dimensional velocity models are typically dominated by the biasing effects of three-dimensional structure. Two main approaches have been applied to account for 3-D structure, both in teleseismic and regional event location problems. In the first, improved velocity models of the crust and mantle are developed that more correctly predict the seismic travel times used by the location algorithm. This includes models of crustal thickness variations, upper mantle Pn velocities, and full 3-D mantle tomography models. For example, Lienert (1997) demonstrated that a locally determined velocity model for regional phases in the western United States could improve the location accuracy of explosions at the Nuclear Test Site (NTS) in Nevada. Smith and Ekström (1996) showed that the rms location errors for 108 global events of known location could be improved by using a 3-D mantle model. Although this approach has achieved some success, global velocity models are still too smooth to fully account for the sharp local velocity changes that in many cases may dominate the location errors.

An alternative method is to apply empirical travel time corrections based on the residuals observed for calibration events of known locations. Because travel times to nearby events are likely to have similar patterns of residuals, their locations can be improved by using these station corrections, even if the details of the underlying 3-D velocity structure remain unknown. This approach would be straightforward if the "ground truth" events were in exactly the same places as the target events. However, in practice this is rarely the case, so considerable effort has gone into devising ways to interpolate the residuals between calibration events to create station correction "surfaces" that can be used to locate events at arbitrary locations (e.g., Cogbill and Steck, 1997; Schultz *et al.*, 1998). A fundamental difficulty of this approach is the sparse coverage of calibration events in many parts of the world.

In principle, due to reciprocity of travel times between sources and receivers, the residuals observed at seismic stations (which of course have known locations) from distant events provide information that could be used to improve the locations of nearby events as measured by distant stations. Here, we experiment with this approach to characterize how rapidly mislocation vectors change with position and to test whether source-receiver reciprocity can significantly improve global event locations. We use the recent teleseismic relocation effort of Engdahl *et al.* (1998) for nearly 100,000 events from 1964 to 1995 as a starting point, although the same approach could also be applied to regional or local event data. To test the accuracy of our locations, we examine the ground truth events tabulated by Smith and Ekström (1996).

We find that the scatter in computed station "mislocation vectors" is comparable to that seen in the ground truth events, suggesting that station locations can serve as a proxy for calibration events. Station mislocation vectors typically change rapidly over short scales; the correlation distance of station mislocation vectors is less than ~150 km, suggesting that, on average, calibration events are only useful for improving teleseismic event locations if they are located within 150 km of the target event. For 84 of the ground truth events, there is a suitable seismic station within this distance. For these events, median location errors are reduced compared to the original Engdahl *et al.* (1998) locations when travel time corrections are applied based on source-receiver reciprocity.

Data and preliminary processing

Engdahl *et al.* (1998) (henceforth termed EHB) devoted considerable effort to produce a cleaner version of the phase data collected by the International Seismological Center (ISC) and to relocate nearly 100,000 events (1964 to 1995) using an improved 1-D velocity model, later arriving phases, ellipticity corrections, and azimuth independent "patch" corrections to account for station terms. The EHB locations are widely recognized as one of the best sets of teleseismic event locations. For 104 ground truth events (both explosions and earthquakes) from Smith and Ekström (1996), the EHB mislocation rms, average and median are 10.5 km, 9.0 km and 8.1 km, respectively. These numbers compare quite favorably to the best overall results (rms = 13.2 km) obtained by Smith and Ekström (1996) using a 3-D Earth model and azimuthally varying station terms. At least some of the differences between the EHB and Smith and Ekström locations may be attributed to the inclusion of regional phase data in the EHB results (Smith and Ekström used data only at ranges greater than 30°).

We use the EHB location residuals as a starting point for our relocation efforts. We first relocate the events using the L1-norm, source-specific station term (SSST) approach of Richards-Dinger and Shearer (2000). The L1-norm may have some advantages in earthquake location due to its robustness with respect to outliers in the data (e.g., Kennett, 1992; Shearer, 1997). However, the EHB data are sufficiently clean that it is unlikely that the L1-norm makes much difference in this case compared to conventional least-squares approaches. To simply our algorithm, we use only P, Pn, pP, pwP, S, Sn, and sS arrivals (no core phases). We use the iasp91 (Kennett and Endahl, 1991) velocity model. We compute SSST corrections using an iterative procedure based on the median station residuals from the 20 closest events to each target event (see Richards-Dinger and Shearer, 2000, for more details). This method should improve the relative location accuracy among nearby events but does nothing to improve the absolute location accuracy of event clusters.

The SSST locations for 99,715 EHB events are available via anonymous ftp to mahi.ucsd.edu in the directory /pub/EHB_SSST. The SSST locations for 104 Smith and Ekström (1996) test events show a modest improvement over the original EHB locations; the mislocation rms, average and median are 10.1 km, 8.4 km and 7.5 km, respectively. In some regions the SSST locations appear to cluster more clearly into linear features that the EHB locations, but the improvement, if any, is generally very slight. A comparison between the EHB locations and the SSST locations is shown in Figure 1 for earthquakes in the vicinity of the Mendocino Triple Junction off the coast of California and Oregon.

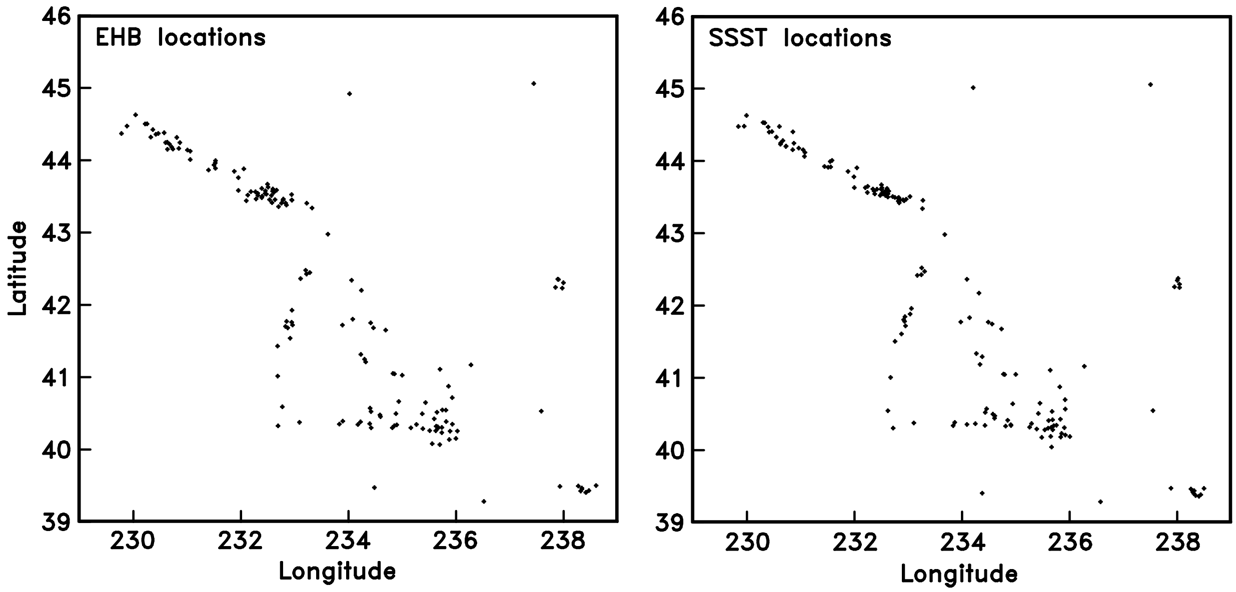

Figure 1. Earthquakes near the Mendocino Triple Junction (offshore northern California and Oregon) as located by (left) Engdahl *et al.* (1998) and (right) the source-specific station term (SSST) method.

Source-receiver reciprocity and station relocation

The reciprocity of travel times between sources and receivers means that the travel time from a source to a receiver is identical to the travel time that would be measured if there were a source at the station and a receiver at the event (see Figure 2). In practice, earthquakes or explosions are never located in exactly the same places as seismic stations. However, if a station is located close enough to a target event, then the teleseismic residual pattern observed at the station should be correlated to the residual pattern seen at the event. In this case, seismic stations could serve as proxies for ground truth events. The potential advantage of this approach is that there are data available for stations in many areas that are aseismic or currently lack ground truth events. If source-receiver reciprocity could be invoked, then these stations could be used to calibrate event locations in these areas.

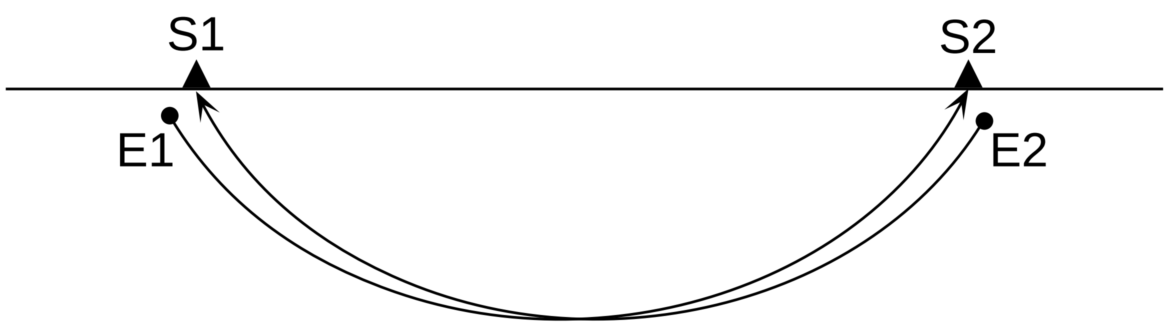

Figure 2. Source-receiver reciprocity implies that the travel time residual for a ray path from event E1 to station S2 will be approximately the same as the residual from source E2 to station S1, provided the corresponding events and stations are sufficiently close together.

To examine source-receiver reciprocity in the EHB data set, we first relocate the stations to see if they move significantly compared to their known locations. Our starting point is the residuals for the SSST locations (see above). We fix the event locations and origin times and adjust the station locations to give the best L1-norm fit to the travel times. We consider only changes in the latitude and longitude of the stations; we do not permit depth variations. We use both P and S arrivals when available; many stations have only P picks. To even out the very non-uniform event coverage, we compute summary ray residuals based on 10° bins in range and azimuth. One might object at this point by pointing out that because the true event locations are unknown, the station relocation procedure is not completely reciprocal to the event location procedure (which uses stations of known locations). Biases in the event locations might thus feed back into the station locations. However, this will only occur if the residuals resulting from the event mislocations have a systematic degree-one component around the target station. As we will see later, it appears that the strongest contributor to event mislocations is near-source structure. In most cases, therefore, the biasing effects of event mislocation on our station relocation method will be minimized by averaging over a wide range of azimuths.

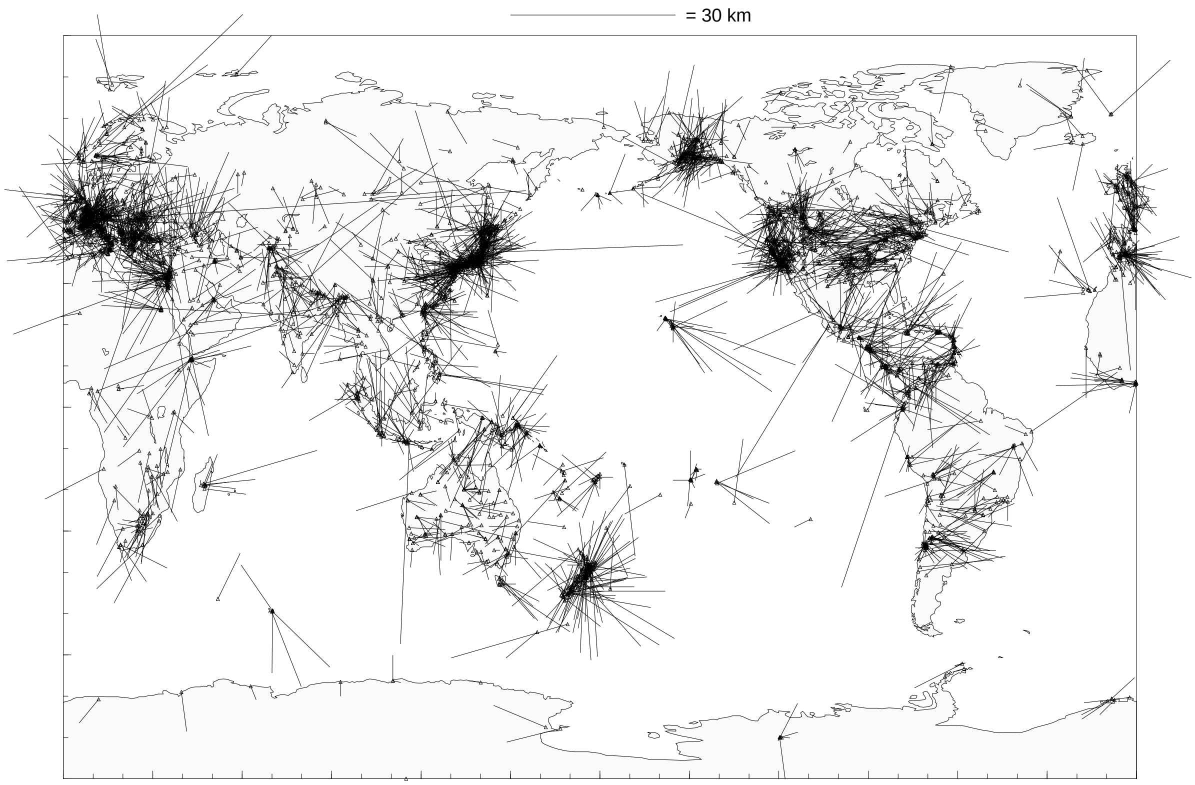

Figure 3. Mislocation vectors for 3004 global seismic stations as relocated using travel time residuals to distant events (see text). The true station locations are shown as triangles; the lines are drawn in the direction of the relocated stations. The lengths of the vectors are highly exaggerated; for reference a 30-km mislocation vector is shown above the plot.

We restrict our analysis to stations that recorded at least 100 events, from at least 10 different summary-ray source bins, and with no more than a 90° gap between summary ray azimuths. The resulting mislocation vectors for 3004 stations are plotted in Figure 3. The mislocation rms, average and median are 8.2 km, 6.2 km and 5.0 km, respectively. These station location errors are 13% to 33% less than the corresponding errors for the 104 calibration events in the SSST locations. The smaller errors in the station locations may be a result of: (1) differences in the station distribution compared to the 104 calibration events, (2) the fixed depth of the stations in the relocation procedure compared to the floating depths permitted in the event relocations, and/or (3) some of the residuals used in the station relocations being absorbed in event mislocations (see preceding paragraph). However, regardless of the exact size of the station mislocation vectors, it is instructive to to examine their directions and their degree of spatial coherence. This is illustrated in Figure 4, which shows the station mislocation vectors in detail across part of Europe.

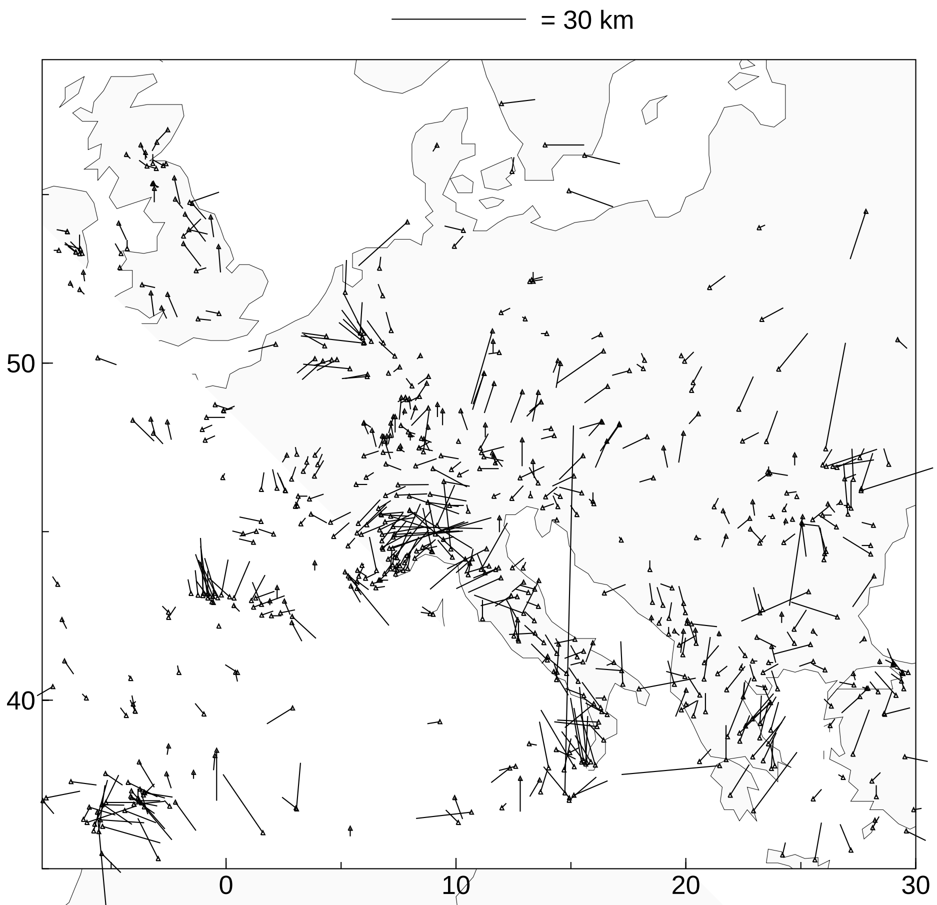

Figure 4. A closeup of station mislocation vectors in Europe. The true station locations are shown as triangles; the lines are drawn in the direction of the relocated stations. The lengths of the vectors are highly exaggerated; for reference a 30-km mislocation vector is shown above the plot.

The station mislocation vectors are correlated among nearby stations but often exhibit sharp changes over very short length scales. For example, notice the group of four southward pointing vectors in northwestern France (48°N, 3°W), about 150 km west of a group of six eastward pointing vectors (48°N, 0°E). Even greater incoherence in the station mislocation vectors can be seen across parts of Great Britain and Italy. The degree of spatial coherence of the mislocation vectors may be quantified by plotting the difference between pairs of mislocation vectors as a function of station spacing (Figure 5).

As one might expect, this plot shows considerable scatter. The globally averaged properties become clearer when the 50th (median) and 90th percentiles are plotted for 10-km averaging bins in station separation. The mislocation vector difference is reduced as the station pairs become close together but this effect only becomes significant for station separations of less than ∼300 km. For comparison, the dashed lines in Figure 5 show the 50th and 90th percentiles of the lengths of the individual station mislocation vectors.

When a calibration event is used to improve the location of a target event, a key question is how close the calibration event needs to be in order to significantly improve the target event location. We can address this question for teleseismic events on a global scale by using our station mislocation vectors as a proxy for event mislocation vectors. Thus, if we had travel time data from a station of unknown location we could attempt to improve our initial estimate for the station location by subtracting the mislocation vector for a nearby "ground truth" station. Figure 5 shows that, on average, this will only lead to an improvement in the station location if the calibration station is within 100 to 150 km of the target station. Further, the average improvement in the station location is fairly modest (less than 30%) even at much closer station spacing.

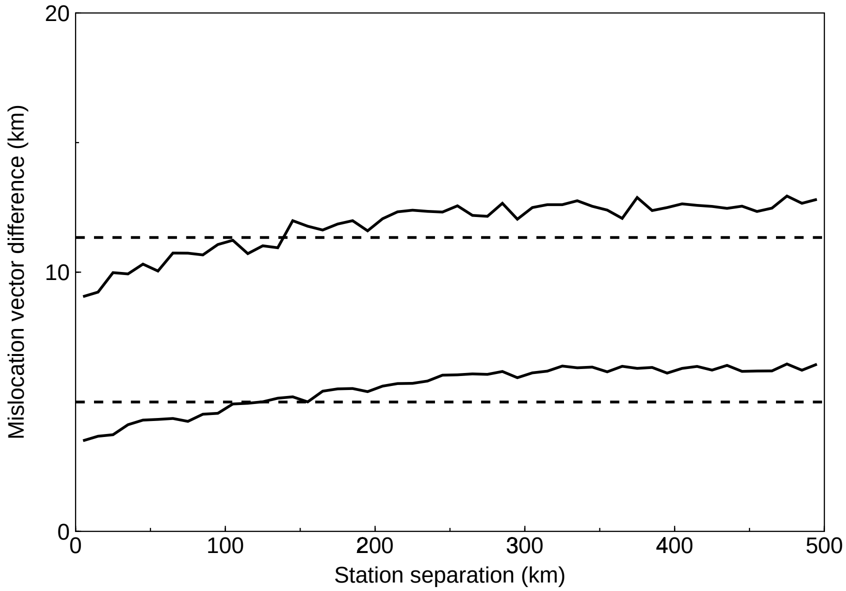

Figure 5. The difference in global station mislocation vector pairs plotted as a function of the distance between the true station locations. The solid lines show the 50th and 90th percentiles of the data, as binned in 10 km increments. The dashed lines show the 50th and 90th percentiles of the individual station mislocation vector lengths.

This is not to say that there are no regions where the station mislocation vectors show greater spatial coherence than the global average (presumably areas with relatively small local velocity perturbations). In these regions, calibration stations could be useful at distances greater than 150 km. But there also exist regions where the mislocation vector coherence is less than the global average. Calibration stations in these areas would only be useful if they were extremely close to the target stations.

Note that the observed residual patterns between stations are likely to be correlated at station separations far greater than 150 km, due to velocity perturbations near the distant source regions. It is only the degree-one part of the residual pattern that controls the station mislocation vectors. This part of the residual pattern appears to be dominated by local structures and can vary rapidly over minor changes in the station locations.

Of course, the true locations of seismic stations are already known so this analysis is useful only to the extent that is provides information relevant to the event location problem. In the next section, we compare the station mislocation vectors to mislocation vectors for the 104 ground truth events and test to see if the event locations can be improved by using travel time data from nearby stations.

Using source-receiver reciprocity to improve event locations

Figure 6 shows mislocation vectors for our SSST relocations of 104 ground truth events from Smith and Ekström (1996) compared to the station mislocation vectors discussed in the previous section. In some areas the event mislocation vectors correlate with nearby station mislocation vectors. For example in Figure 6, two events in the western United States (near 40°N, 252°E) are mislocated in the northeast direction, in approximate agreement with the mislocations of stations to the east and west of the events (stations to the south don't agree as well).

In other areas, however, the event mislocation vectors disagree with the trend of nearby station vectors (or the station vectors may be so incoherent that no clear conclusion may be drawn). At least some of the discrepancies between event and station mislocation vectors may arise from the mismatch between the surface stations and earthquakes at depth. Also, the distribution of events around the stations will differ from the distribution of stations around the events, so one would not necessarily expect the mislocation vectors to be exactly the same.

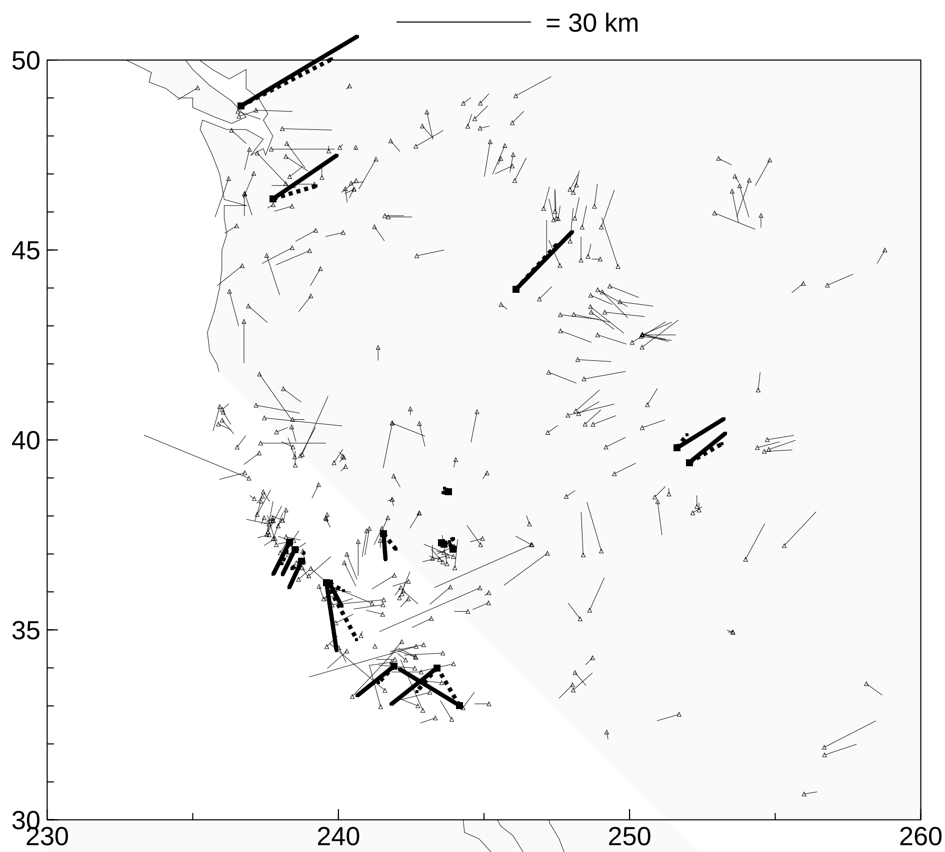

Figure 6. A closeup of station mislocation vectors (thin lines) in the western United States, compared to event mislocation vectors for ground truth events (thick lines). The SSST station mislocation vectors are shown as the solid thick lines; the mislocation vectors following application of corrections based on source-receiver reciprocity are shown as the dashed thick lines. The lengths of the vectors are highly exaggerated; for reference a 30-km mislocation vector is shown above the plot.

To more precisely apply source-receiver reciprocity in the case of target events with nearby stations, we attempted to improve the event locations by using the following procedure: We used only those target events for which there were nearby stations within 150 km, restricting our relocations to 84 of the ground truth events. For these stations, we then searched for distant events within 10° of a distant station that recorded the target event. Next, we computed the median residual for that distant station to apply as a correction in locating the target event. While we only relocated 84 events using this method, it was necessary to have access to residuals from most of the other events in the EHB data set in order to compute all of these path corrections.

The corrected ground truth mislocation vectors are plotted as dashed lines in Figure 6 for comparison to the original SSST mislocation vectors (solid lines). In the majority of cases the errors in the locations are reduced, although in a few examples the errors are increased. For the 84 events, the original EHB mislocation rms, average and median were 11.3 km, 9.8 km and 8.8 km, respectively. The SSST mislocation rms, average and median were 10.8 km, 9.0 km and 7.7 km. Following relocation using source-receiver reciprocity to the teleseismic residual patterns at nearby stations, these numbers were reduced to 9.1 km, 7.8 km and 6.6 km. The improvement compared to the SSST locations is fairly modest (about 15%), but consistent with the suggestion of Figure 5 that large improvement in locations will be achieved only if the station/event spacing is much smaller than 150 km.

CONCLUSIONS AND RECOMMENDATIONS

Source-receiver reciprocity can be used to gain insight into the effectiveness of using ground truth calibration events to improve teleseismic event locations. Perhaps our most significant result is that station mislocation vectors change rapidly over fairly short distances, with a globally averaged correlation length of about 150 km. This has sobering implications for the use of calibration events to improve teleseismic event location because source-receiver reciprocity implies that event mislocation vectors will behave in a similar fashion. In most regions, calibration events at distances greater than 150 km probably will have little or no benefit in improving the location of a target event (and may worsen the location). Interpolation of "correction surfaces" among calibration events will only be useful in teleseismic event location if the calibration events are spaced closely enough that their mislocation vectors are spatially correlated.

In regions where calibration events are missing, sparse, or poorly recorded, seismic stations could be used as substitutes for calibration events. These could be existing or archived stations, or new station deployments specifically designed for this purpose. All that is necessary is for these stations to record travel times at a range of event azimuths and ranges that are comparable to the station distribution used to locate the nearby events of interest. Because stations are restricted to the near-surface, reciprocity will be achieved most closely for shallow events, i.e., those that will be of greatest interest for CTBT monitoring purposes. In areas of little or no natural seismicity, it may be cheaper and politically easier to field temporary station deployments than to arrange for calibration explosions.

In principle, the effect of source-receiver reciprocity is naturally accounted for in tomographic inversions for three-dimensional Earth structure. However, as Smith and Ekström (1996) have shown, these models are currently of limited effectiveness in improving event locations. Our results suggest that the scale length of the heterogeneity that dominates teleseismic event mislocations is much smaller than the typical resolution of the tomographic models.

Our study examined both regional (e.g., Pn and Sn) and teleseismic phase data from the EHB data set. We also experimented with using only teleseismic arrivals at source-receiver ranges greater than 30°in hopes of minimizing location biases associated with the strong velocities heterogeneities in the crust and uppermost mantle. However, in this case the average location accuracy was reduced somewhat compared to the results obtained when the entire data set was used. The station mislocation vectors exhibited similar behavior to that shown here; on average the mislocation vectors were correlated only for station separations less than $\sim$150 km. Thus, it does not appear that the range of applicability of calibration events can be extended by using data only at longer source-receiver distances.

Our analysis was focused on teleseismic locations but many of the same concepts could be applied to purely regional location problems for smaller events, an increasing focus for CTBT monitoring efforts. The principles of source-receiver reciprocity apply at all length scales.

Acknowledgments

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