# ACCURACY AND UNCERTAINTY IN SINGLE-STATION EVENT LOCATION

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**ABSTRACT**

To monitor compliance the Comprehensive Nuclear-Test-Ban Treaty it is desirable to locate and/or determine focal depths for seismic events with magnitudes of three or less; these events are often recorded by too few stations to locate them using conventional travel-time based methods. The principal objective of our research is to develop location and depth-determination methods that utilize signals from a single, three-component seismic station.

Success of waveform correlation methods for estimating focal depths depends on the accuracy of the crustal model used. Our efforts to constrain crustal models continue to exploit a receiver function method that employs a variant of the simulated annealing global search algorithm (SORVEC). Through a series of synthetic modeling experiments we are trying to determine the method's sensitivity to focal mechanism and depth, data frequency content, and the usefulness of models produced via teleseismic receiver functions in modeling regional seismic phases. An important question is whether the models determined by receiver functions, which utilize high-angle-of-incidence teleseismic signals as input, provide a reasonable basis for modeling seismic sources recorded at regional distances. The experiment described herein indicates that regional synthetics determined using the models provided by SORVEC are essentially similar to the "true" seismic signals, even when the SORVEC models are somewhat less complex than the "true" models.

We continue to investigate optimum methods to determine event-station bearings using single-station, three-component records of regional seismic events having magnitudes between 3.0 and 4.5. Since many such events do not have impulsive phase arrivals with high signal-to-noise ratios, it is not always feasible to determine azimuth using narrow time windows. We get much more reliable results using the entire P-to-Sn time window, which contains both P and P-to-Sv converted energy. Our present approach is to determine event-station bearing in two steps; initially we utilize horizontal components only to determine the event-to-station azimuth mod 180 degrees; then identify the proper direction from an analysis of the vertical-component and rotated horizontal component signals. Even for relatively small earthquakes that lack impulsive P arrivals, preliminary results indicate that we are determining event-station bearings with errors of about 10 degrees or less. Moreover, the uncertainties determined from statistical analysis are approximately equal to the observed error.

**Keywords:** single-station location, focal depth determination, regional seismology

## OBJECTIVE

Monitoring compliance with the Comprehensive Nuclear-Test-Ban Treaty (CTBT) provides the immediate impetus for improving single-station location (SSL) methods, as recent studies have indicated that monitoring decoupled explosions at the one-kiloton level would require detecting and identifying all quakes with mb above 3.0 or less. Travel-time based location methods are ineffective for small events since with the seismic station network currently in place for monitoring compliance to the CTBT, 82% of the earth's surface doesn't have three or more stations within 10°, and 99% doesn't have three within 5° (Frohlich and Pulliam, 1999). The situation is somewhat better for land areas, and would be very much better if we required only one station to obtain a location; in particular, only 7% of the land area has no stations within 10°, while 45% has none within 5°. Moreover, travel-time based location methods are notoriously inaccurate when the number of stations is small or when the epicenter is controlled by arrivals at a few 'key' stations. Finally, focal depths determined by traveltime-based methods are notoriously unreliable even when phase arrival times are numerous and properly identified. For CTBT purposes, it is desirable to obtain focal depths even if it isn't possible to determine an epicenter since any seismic event deeper than a few km is an unlikely candidate for a nuclear explosion.

## RESEARCH ACCOMPLISHED

Estimating Focal Depths at Regional Distances with a Single Station

We conducted a synthetic experiment to determine the usefulness of waveform correlation methods for determining focal depths in cases where the crustal structure is known only approximately. Our strategy has been to find the 1D crustal structure beneath a seismographic station with the SORVEC receiver function method (Zhao and Frohlich, 1996; Zhao et al. 1996), which conducts a global search using a modified simulated annealing algorithm, called Very Fast Simulated Annealing (VFSA). While the SORVEC method is quite successful at retrieving a crustal model that accurately predicts teleseismic phases, it is not obvious that the SORVEC model should also predict the regional phases that are most useful in constraining focal depths. The teleseismic phases used by SORVEC, including phases internally-reflected in crustal layers, are steeply propagating, while regional phases interact with the crustal layers at more oblique angles. Small discrepancies in model velocities, impedance contrasts, and depths to layer interfaces can result in large differences in regional waveforms.

To conduct a synthetic test of our waveform correlation method, we first computed teleseismic waveforms (30<delta<70) with the reflectivity method for both shallow (h<30 km) and deep (h>300 km) sources. These "data seismograms" were computed for various focal mechanisms and contain energy up to 5 Hz. Our input model consisted of eight crustal layers over the PREM mantle. Next, using the SORVEC method we determined the best-fitting crustal models having three, four, five, six, seven, and eight layers over a half-space (Fig. 1). While the synthetic "data" were computed with reflectivity, SORVEC uses a truncated generalized ray expansion to compute seismograms, evaluating on the order of 100,000 models to obtain the best-fitting model.

In all cases, the bulk properties of the crust--vertical travel times and crustal thickness-- were determined to within 4% of those of the input model. This result bodes well for attempts to use phases reflected at the Moho and the Earth's surface to constrain focal depths. However, depths to internal layers and layer velocities were more variable. S travel times were more accurate than P travel times in every case. Also, in some parameterizations, e.g., the 5-layer model, SORVEC determined velocities at the limits of the search bounds for some layers, indicating that the search bounds should be widened to allow a more complete search of model space.

Comparisons between the “true” radial synthetic seismograms (Fig. 2, solid lines) and the best-fitting radial seismograms computed by SORVEC indicate that the increasing model complexity beyond about five layers is not warranted in terms of error reduction alone. On the other hand, experiments with overparameterization--using 4 and 5 layers to model the "data" produced with three layers over PREM--indicate no serious consequences to high model complexity. In that case, two or more layers in the

SORVEC crustal model were so similar that a simple inspection would lead one to combine them. Note also that SORVEC's seismograms generally match the initial arrivals well, while later arrivals which often represent energy reflected between internal layers is modeled less well. This pattern carries through to the models, which generally show less accurate internal structure than bulk properties.

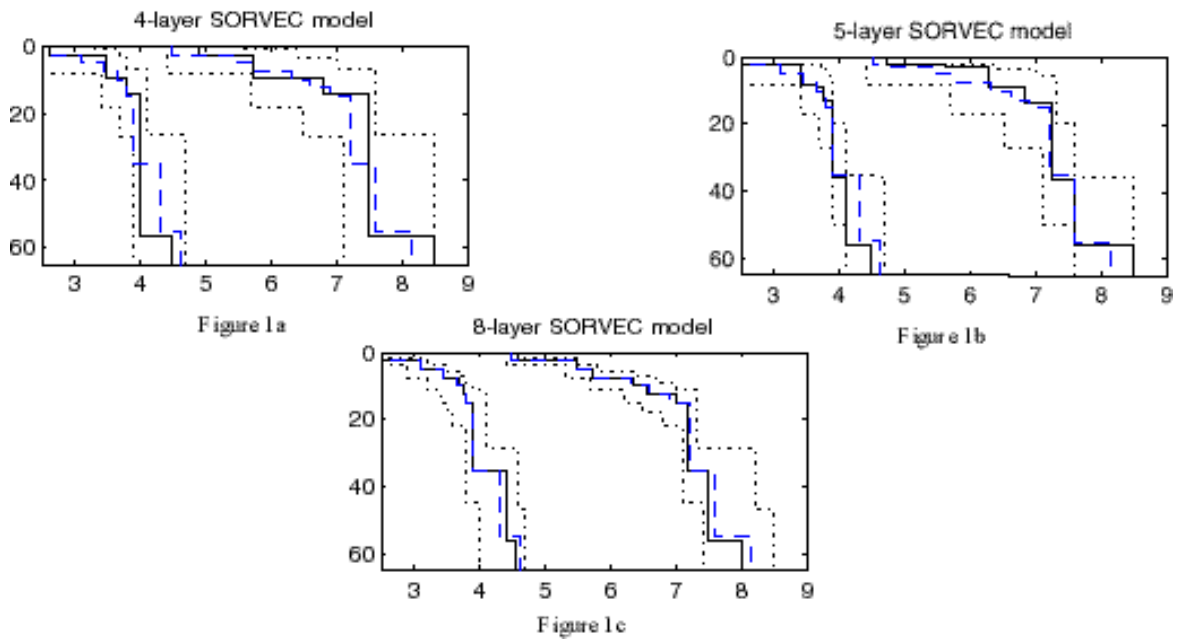


Fig. 1. Crustal velocity models produced by SORVEC using synthetic teleseismic seismograms (solid lines), the 8-layer velocity model used to compute these seismograms (dashed lines), and the search bounds input to SORVEC for each of three parameterizations (dotted lines). Each panel shows results when model is constrained to a different number of layers: (a) 4 layers, (b) 5 layers, (c) 8 layers. In each panel results for modeling S velocities are on the left, while P velocities are on the right.

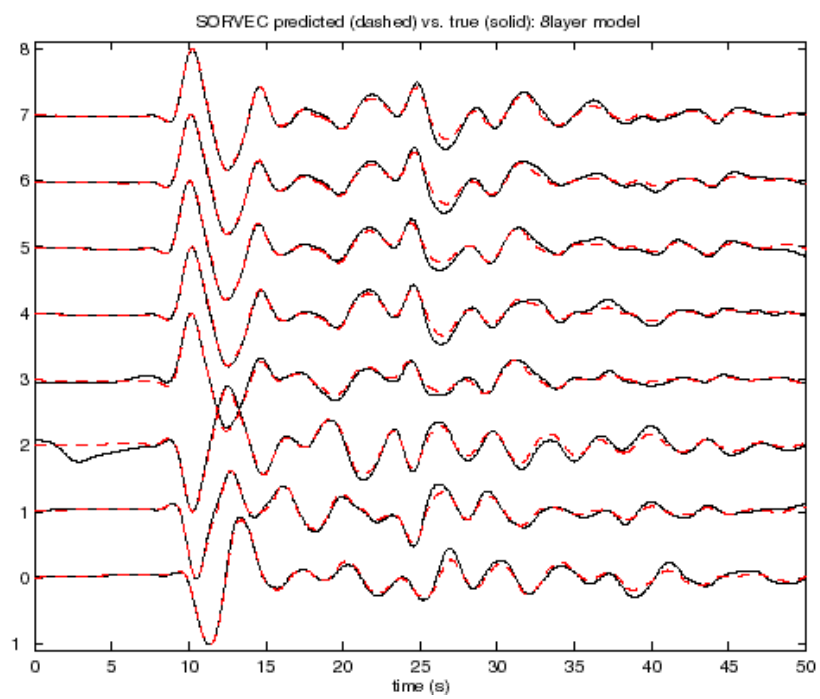


Fig. 2. Radial seismograms predicted by SORVEC for the best-fitting 5-layer velocity model (dashed lines) compared to the synthetic teleseismic "data" seismograms (solid lines). The fit was only slightly better for the best-fitting SORVEC seismograms for models having 8 layers.

Using the "true", eight-layer crustal model we computed seismograms for a focal depth of 5 km, distances of 200, 400, and 600, and various focal mechanisms (e. g., Figs. 3 and 4). With the five-layer SORVEC model, produced by fitting teleseismic synthetics to the eight-layer input model, we computed suites of radial and vertical seismograms for various focal depths (0-15 km depth in 2.5 km intervals) and distances of 200, 400, and 600 km (e. g., Fig. 5). Rather than assuming a single fault orientation, we compute seismograms for three fundamental faults (45 degree dip-slip, vertical dip-slip, and vertical strike-slip), which can be combined linearly to produce any double-couple source. Fault orientation essentially controls the energy emitted into any given phase in a direction that will reach the recording station. Some phases will not appear at a station that is situated on a source's nodal line. By computing each fundamental fault, and then attempting to correlate "data" synthetics with each, we automatically search for finite occurrences of every phase. We essentially assume that retrieving fault orientation in addition to focal depth using just a single station is unrealistic. Waveform correlation to fundamental faults is a strategy for simplifying the problem of single-station estimation of focal depths.

A second strategy for simplifying the correlation is to further minimize the effects of varying source orientations by computing and comparing energy envelopes (e. g., Fig. 4), rather than actual synthetics, which include positive and negative swings of the trace as determined by the focal mechanism. We find that pulses in energy envelopes are broadened by the combination of both positive and negative signals. In theory this broadening will decrease resolution. However, in practice it serves to make the procedure more robust. For demonstration purposes we have used focal depth increments of 2.5 km. Depth increments smaller than 2.5 km are generally indistinguishable when the procedure is applied to real data, so the slight loss of resolution with energy envelopes is insignificant.

Finally, we correlate the vertical "data" energy envelopes, computed for a distance of 200 km, with the vertical "fundamental fault" seismograms and plot the combined correlation function (Fig. 6). A clear peak can be seen at the expected 5 km focal depth, which indicates that the seismograms computed from the approximate (SORVEC) crustal model are sufficiently similar to those from the true (input) model to admit modeling of the regional phases that are most essential for determining focal depths. Fig. 7 shows a similar result for a distance of 400 km. However, distances of 600 (Figure 8) and 800 km did not work well, which suggests that the effects of model discrepancies become relatively more important with distance. This, in turn, implies that successful applications of single-station location methods may be limited to several hundred kilometers.

Determining the Station-Event Bearing

Our previous investigations focused on determining station-event bearing for small ($3 < M < 4.5$), regional (100 km < distance < 1000 km) events and on developing methods that were applicable to records from stations in a broad variety of tectonic environments (Pulliam and Frohlich, 1998). This research established that most reliable station-event azimuth information was obtainable from 1) the P-to-S time window; and 2) the high-frequency portion of the signal, i. e., we obtained best station-event azimuths when we high-pass filtered the three-component broadband signal with a corner frequency of 0.5 Hz. However, we were able to determine bearings only within about ±20° using conventional methods to determine bearing.

We have modified our approach to fully exploit the fact that the signal arriving between P and S combines both direct P arrivals and converted P-to-Sv arrivals. These have polarization directions 180° apart, which degrades the determination of azimuth if we employ the usual method of finding the bearing of the largest eigenvector of the 3-D covariance matrix. Instead, we now: 1) determine an initial bearing $\alpha$ from the 2-D covariance matrix formed from the E and N horizontal components; 2) rotate the horizontal-component signal along this bearing, and form the 2-D covariance matrix from this H- and the vertical Z-component signal; and 3) inspect this H-Z covariance to choose whether true signal bearing is $\alpha$ or $\alpha+180°$. This is theoretically similar to the 2-D method employed previously by Magotra et al. (1987) and Walck and Chael (1991). However, they applied this method to relatively impulsive signals in short (2 sec) time

windows, while here we evaluate rather noisy signals with well-developed codas in time windows of 25-100 sec duration.

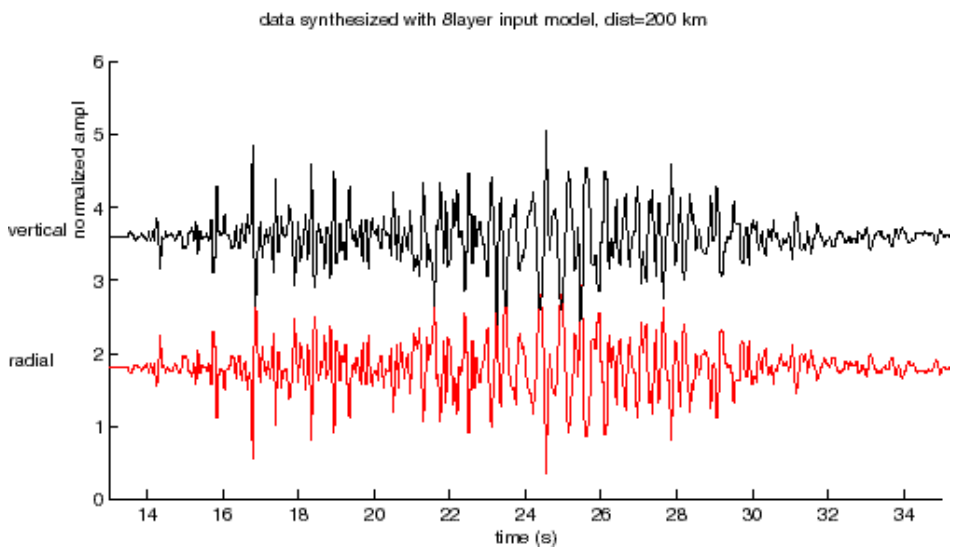


Fig. 3. Data synthesized with the eight-layer input model using a reflectivity method. The focal depth is 5 km; the distance is 200 km.

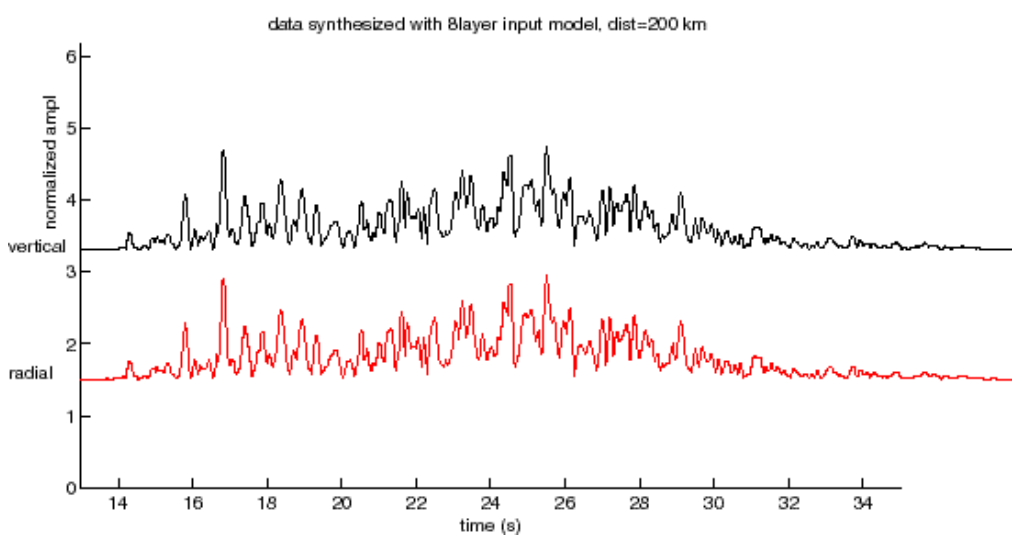

Fig. 4. Energy envelopes for the seismograms shown in Fig. 3.

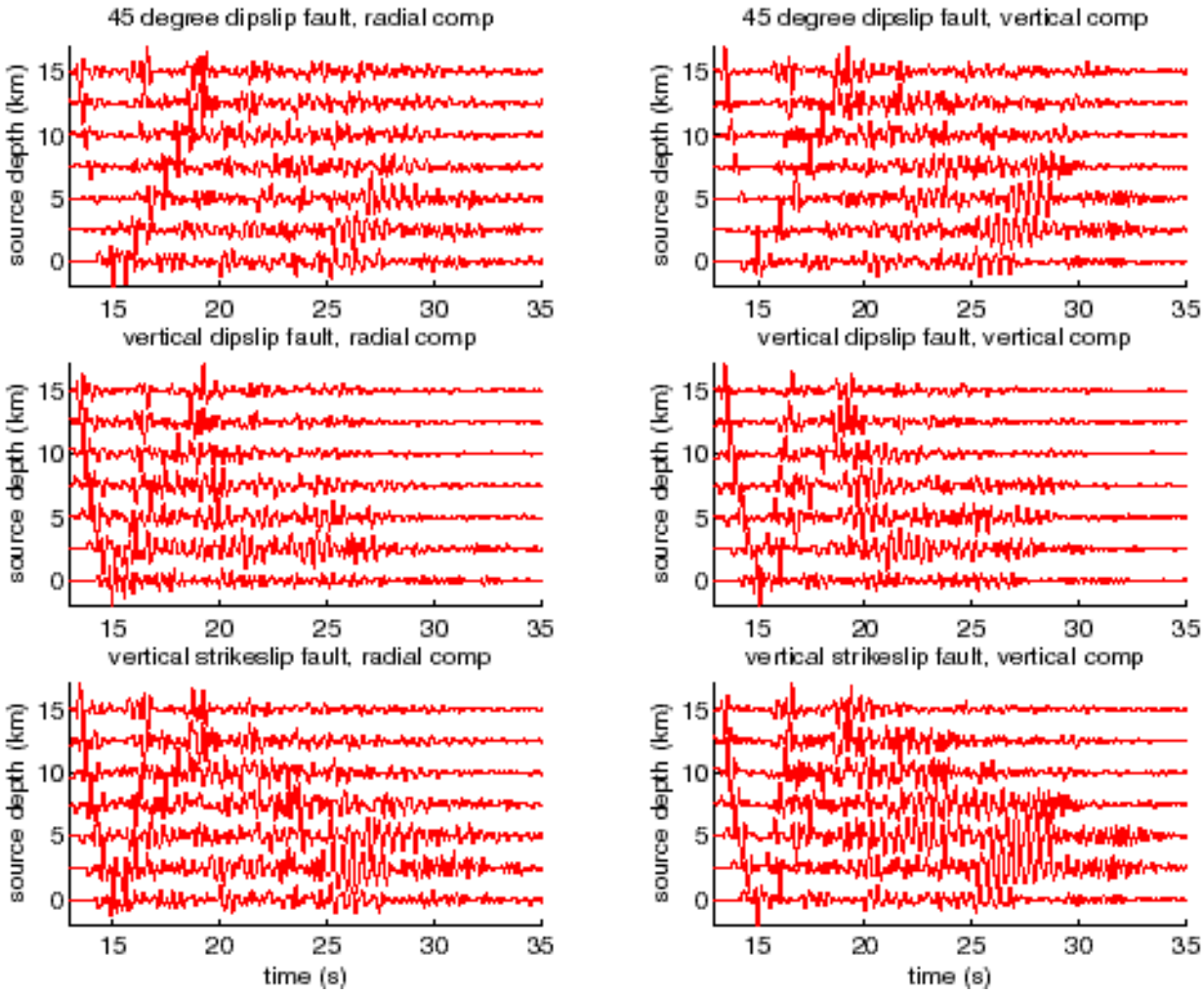


Fig. 5. Suites of synthetic seismograms computed for source depths of 0, 2.5, 5, 7.5, 10, 12.5, and 15 km at an epicentral distance of 200 km. The velocity model used was the best-fitting 5-layer model found by SORVEC.

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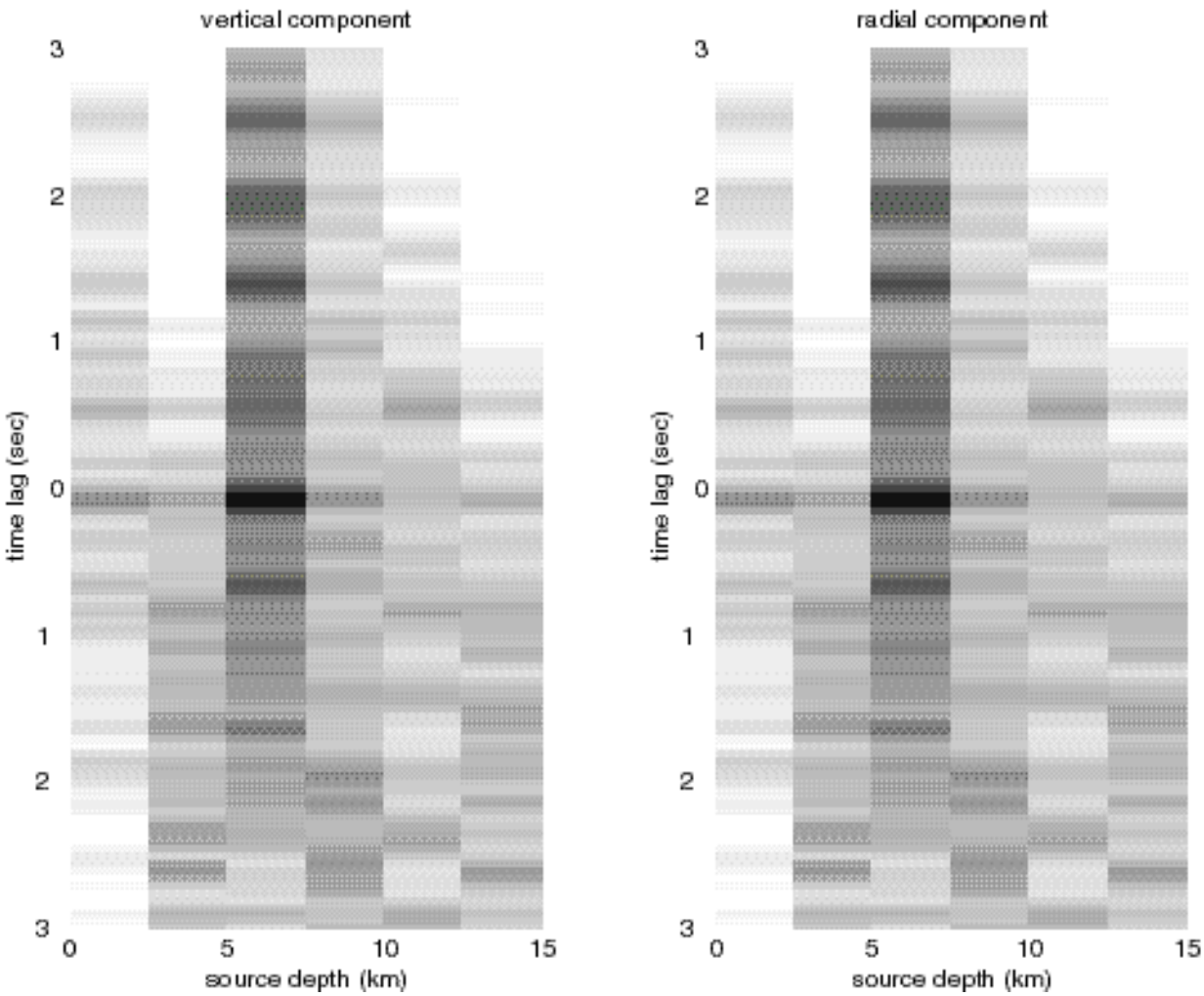


Fig. 6. Combined correlation functions for the vertical (left) and radial (right) data seismograms with the suites of synthetics computed with SORVEC's best five-layer model at 200 km epicentral distance. Note the peak at zero time lag and 5 km source depth, which indicates the correct source depth.

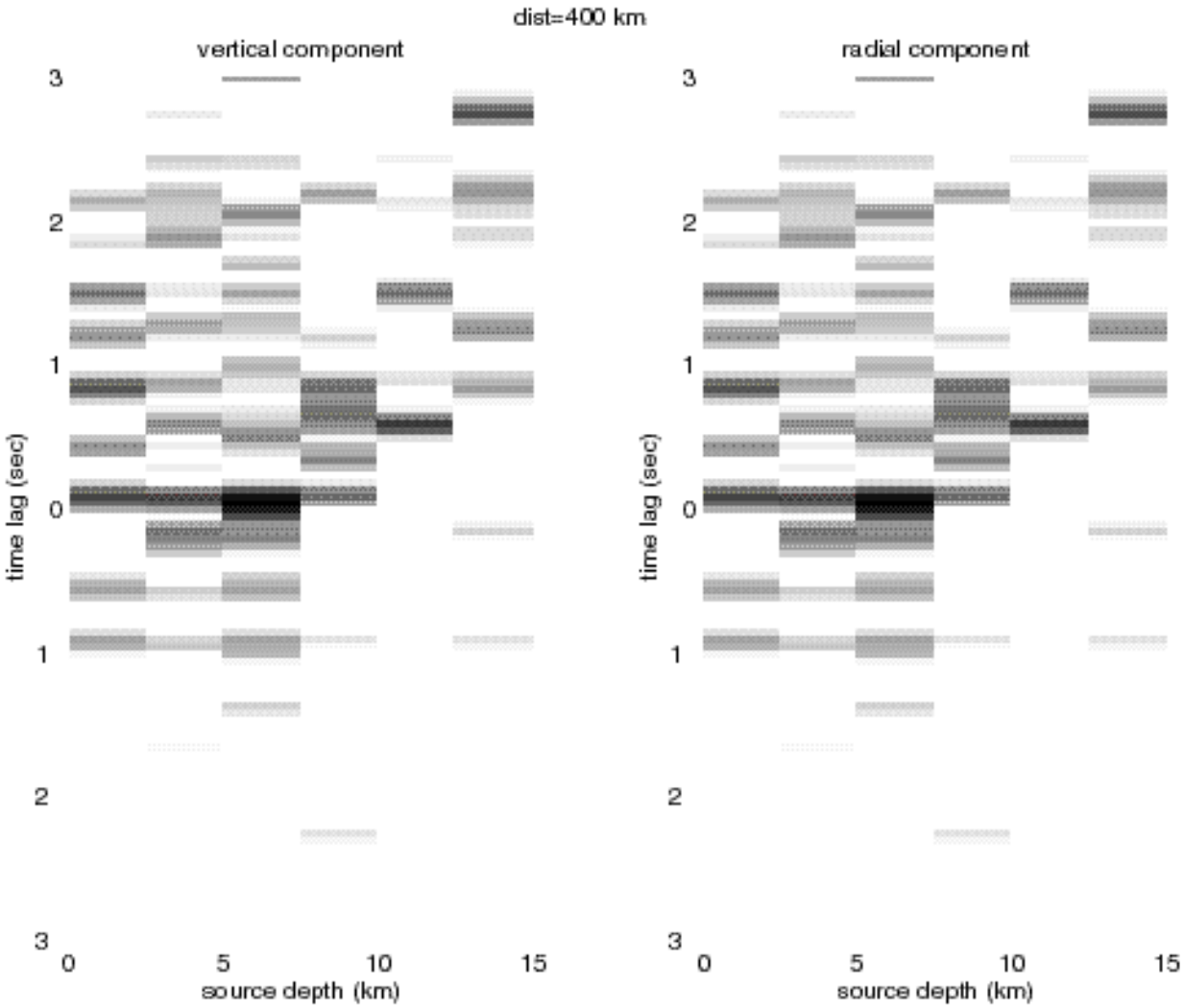


Fig. 7. Combined correlation functions for the vertical (left) and radial (right) data seismograms with the suites of synthetics computed with SORVEC's best five-layer model at 400 km epicentral distance. Note the peak at zero time lag and 5 km source depth, which indicates the correct source depth.

Our preliminary results indicate that the modified approach gives results that are similar to those obtained with to the previously-used method. In particular, the differences between the true bearing and the bearing determined by the modified approach are typically ±10° or less when the method is applied to signals with signal-to-noise ratios of 2.0 or more. Moreover, the differences between true and observed bearing are of approximately comparable size to our statistical estimates of the error, determined from the ratio of eigenvalues of the 2-D covariance matrix. This is important for CTBT concerns, as it suggests that we have some knowledge of the bearing uncertainty even for signals where the true bearing is unknown.

## CONCLUSIONS AND RECOMMENDATIONS

Most practical single-station location methods rely heavily on comparing real seismic signals recorded at regional distances to synthetics determined assuming a reasonably accurate crustal model. The present research demonstrates that crustal models determined using teleseismic signals and receiver-function methods are accurate enough. However, while our synthetic test is realistic in many respects, it fails to reproduce several types of real-world complexity, including laterally-varying crustal structure, surface topography, complicated source time functions, and non-stationary noise. We note that the waveform correlation scheme does not require that SORVEC be used to model the crust. While SORVEC finds a 1D model directly beneath the station and the waveform correlation assumes that that model represents structure between the source and the receiver, other, yet-to-be-determined methods for determining crustal structure may well produce a better average model between the source and receiver.

The most popular methods for determining event-station bearing rely on evaluating the 3-D signal covariance over a time window that contains an impulsive phase arrival, and generally has a duration of a few seconds or less. Our preliminary results suggests that if we use data from the entire P-to-S time window, we can obtain relatively bearing angle information with an uncertainty of ±10° or less for small events even though they lack an impulsive P and even though signal-to-noise ratios are low. Our ongoing research is focused on determining whether this conclusion will hold up for station-event pairs in a broad variety of tectonic environments. When the true event location is known, we are also investigating whether the statistical estimates of the error in bearing provide a meaningful estimate of the discrepancy between true and observed bearing.

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