DEVELOPMENT OF SSLOC3D: A TOOL FOR SINGLE-STATION LOCATIONS OF SMALL SEISMIC EVENTS USING REGIONAL 3D VELOCITY MODELS

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Sponsored by National Nuclear Security Administration
Office of Nonproliferation Research and Engineering
Office of Defense Nuclear Nonproliferation

Contract No. DE-FG02-02ER83572 and W-7405-ENG-48

ABSTRACT

Regional monitoring of low-yield nuclear explosions requires detection, location, and discrimination of small seismic events. Locating accurate epicenters for these small-to-intermediate magnitude (2.5 < m_b < 4.5) seismic events with traditional network location techniques can be problematic because only one or a few stations may record the event. To facilitate the monitoring of low-yield nuclear explosions, we developed SSLOC3D, a prototype system for determining single three-component (3C) station epicenter locations using epicentral distance estimates and back-azimuth corrections determined from 3D velocity models. Software components developed for SSLOC3D include a polarization analysis tool for 3C back-azimuth estimation, Lg phase picking tools to improve analyst picks, travel-time grids for P-, S-, and Lg-waves, station-dependent back-azimuth corrections, and calibrated error analyses used to generate confidence ellipses. SSLOC3D compares observed travel time differences for secondary and primary phases (e.g., Lg - P) with modeled travel time differences generated from regional and global velocity models. The models tested include the 1D-IASP91 global model, the WINPAK3D regional model (developed by Weston Geophysical), and the CRUST2.0 3D global model. Currently, we have developed travel time grids, back-azimuth corrections, and error analyses for stations NIL (Nilore, Pakistan) and HYB (Hyderabad, India). In the future, we plan to calibrate more stations and incorporate arrays, which have been shown to provide more reliable estimates of back-azimuth by using techniques such as beam-forming and cross-correlation.

We used SSLOC3D to determine single-station locations for 39 events in southern Asia classified as GT15 or better. The events include 38 earthquakes occurring in four separate clusters and a nuclear explosion at the Pokhran Test Site, India. For single-station locations performed using observed regional S-P travel times, the use of the CRUST2.0 model to generate travel times for both phases resulted in an average of 14 km less distance error than IASP91. The results for Lg-P show a 5 km improvement in the distance error when using 3D models in contrast to the 1D-IASP91 model. For the nuclear explosion and two of the four clusters, SSLOC3D locations have approximately 20 km or less average total mislocation and compare favorably with traditional network locations. The remaining two clusters have large back-azimuth errors that cause larger total mislocations. Back-azimuth error is the largest source of total mislocation in all four clusters, and results show that the application of 3D model-based back-azimuth corrections was only partially successful at improving these locations. We anticipate reducing the back-azimuth errors in the future with the use of arrays. The results indicate the need for additional development of phase modeling tools such as 3D modeling of Lg velocities. Our findings also suggest that empirical calibrations of both travel-times and back-azimuths can further improve the SSLOC3D methodology.
OBJECTIVE

In order to monitor low-yield nuclear explosions at regional distances, the detection, location, and discrimination of small seismic events recorded only at regional distance seismic stations or arrays is required. Prior to classifying a small, regionally recorded seismic event as a nuclear explosion, the event must be located and the spectral characteristics of the signal must be evaluated for discrimination purposes. Location of the event on or near a known nuclear test facility plays an important role in determining the processing steps used to discriminate the event. Thus, the accurate location of small seismic events in both space and time plays a vital role in nuclear monitoring efforts.

For global network locations, such as those computed by the United States National Data Center (USNDC), the United States Geological Survey (USGS) National Earthquake Information Center (NEIC), and the International Data Center (IDC), as well as the International Seismological Centre (ISC), the preferred solution is to have multiple observations (at numerous seismic stations around the globe) of relatively few of these recorded phases (i.e., only the $P$ waves). In regions with relatively few seismic stations and small-to-intermediate ($2.5 < m_b < 4.5$) magnitude events, the traditional location methods cannot always satisfy the location accuracy requirements for monitoring because only one or a few stations may record the event. We addressed this problem by developing and testing a model-based prototype single-station location software system, known as SSLOC3D (Single-Station LOCations determined from 3D velocity models), for achieving accurate epicentral estimates based on observations made at single seismic stations or arrays. This system is an innovative and practical approach to determining locations for small-to-intermediate magnitude seismic events using three-component (3C) single-station data.

RESEARCH ACCOMPLISHED

Introduction

To locate an event with a single seismic station or array, the slowness vector for the various seismic phases recorded (e.g., $P_n$, $P_g$) must be estimated. For a single three-component (3C) station, the horizontal projection of the slowness vector is the back-azimuth, and the vertical projection gives the angle of incidence that can be converted to an apparent phase velocity if a crustal velocity near the station is known. In contrast to typical location routines for moderately sized events that use a single scalar observable for one component of ground motion, this method incorporates the important information contained on all three components of the ground motion. Our method consists of complete three-dimensional (3D) ray tracing through regional 3D velocity models to determine off-azimuth propagation and travel time differences between secondary phases, such as $L_g$, $S_n$, and $R_g$, and primary phases, including $P_n$ and $P_g$. These predicted arrival times are compared with travel time differences observed on three-component seismic stations or arrays in order to determine the epicentral distance. Back-azimuth estimates for the primary and secondary phases are determined with polarization techniques (3C) or waveform crosscorrelation methods (arrays) and corrected for off-azimuth propagation determined by 3D ray tracing and empirical calibration. Using the back-azimuth and distance estimates, an epicentral location is estimated using standard geometrical formulae and appropriate error distributions are used to define confidence regions around the epicenter. A schematic of the system is presented in Figure 1, which shows the software input requirements from two components. The first component consists of travel-time grids and azimuth corrections derived from 3D velocity models. A database of observed data, consisting of regional phase picks (e.g., $L_g$, $S_n$, and $P_n$) and back-azimuth estimates form the second component of the system. The two components are then combined to determine a single-station location and an error ellipse estimate for each event in the database. To develop the prototype SSLOC3D system, we:

- Compiled a waveform database of regional seismic events in southern Asia recorded at NIL (Nirole, Pakistan) and HYB (Hyderabad, India) with varying ground truth classifications.
- Examined different methodologies for phase picking and back-azimuth estimation using 3C stations.
- Tested various 2D and 3D ray tracing methods of estimating regional phase ($P$, $S$, and $L_g$) travel times.
- Calculated theoretical back-azimuth corrections.
• Developed a 3D seismic velocity model-based single-station location algorithm.

• Completed testing of the algorithm using various 3D and 1D velocity models and events in our ground truth database.

Figure 1. Schematic showing the processing components for locations formed with \( Lg \) and \( P \) phases using SSLOC3D. The procedure can also be modified with 3D travel time grids for \( S \) replacing the \( Lg \) results.

**Database Development**

To develop and test our location software we compiled a database of events with the most accurate ground truth locations for our study region of southern Asia, downloaded regional waveforms for these events at the 3C stations NIL and HYB, and picked the regional phases observed on the seismograms. The database consists of 85 events with location accuracy characterized by GT-1 (4 events), GT-5 (31), GT-10 (7), GT-15 (17), and GT-25 (23). The sources for the catalog data included the GROUP2 reference event list (REL) (McLaughlin et al., 2002), the EHB bulletin (Engdahl et al., 1998), and the Center for Monitoring Research’s Reference Event Data Base (CMR REDB; Yang et al., 2000). Data from NIL and HYB were downloaded from the Incorporated Research Institutions in Seismology (IRIS) Data Management Center (DMC), and the locations of the stations and events are shown in Figure 2. Figure 2 also marks the locations of the Koyna, Bhuj, Jiashi, and Chamoli earthquake clusters, which together with the Indian nuclear test at the Pokhran Test Site (PTS) of 11 May 1998 were all GT-15 accuracy or better and the focus of the study.

**3C Station Phase Picking and Back-azimuth Estimation**

The next stage consisted of an analyst picking all regional phases observed on each waveform and creating an arrival database that includes \( Pn, Pg, Sn, \) and \( Lg \) onset times. While onset determination for \( Pn, Pg, \) and \( Sn \) is relatively straightforward for our study region of southern Asia, the onset of \( Lg \) varies from simple, impulsive arrivals in the shield regions of India to complex, emergent arrivals in tectonic regions such as the Himalayas. In order to verify the accuracy of the analyst \( Lg \) picks, we extended the Jurkevics (1988) phase detection method, which calculates the ratio of the radial component to the vertical and transverse components, to include spectral analyses. Abrupt changes in these ratios, together with changes in the frequency content of the signal, are often associated with \( Lg \) arrivals (Figure 3). We also verified the analyst \( Lg \) picks using the WAVELET detector of Tibuleac et al. (2003). The analyst results were typically within 2 seconds of the picks suggested from the Jurkevics (1988) and WAVELET methods. In a couple cases, the two techniques helped highlight an analyst error resulting in a re-picking of the phase.
Figure 3. SSLOC3D technique for picking $L_g$ arrivals using a modified version of the Jurkevics (1988) method. Jurkevics noted that the $L_g$ arrival is often associated with abrupt changes in the ratio of the radial component to the vertical and transverse components. We note similar results when applying the technique to data recorded at HYB as shown in the upper two subplots. The final subplot shows the change in frequency content associated with the $L_g$ arrival, the solid vertical line at 226 seconds in the plot.

We determine the back-azimuth of the $P$-wave arrival by using a polarization technique developed by Jurkevics (1988). Using this technique, we developed a polarization module for SSLOC3D that calculates the back-azimuth and rectilinearity for overlapping windows of three-component seismic data. An example of the analysis is shown in Figure 4. We search for the largest value of the rectilinearity within the $P$-wave
arrival window, and we determine the mean back-azimuth in a one-half second window following the time of the maximum rectilinearity. When compared to another method of three-component back-azimuth estimation, the frequency-wave number method as coded in MatSeis (Young, 1997), we find the polarization technique is computationally faster and offers more accurate back-azimuths for the events from our study region with location accuracy better than GT15. Thus, the polarization technique was the preferred method to estimate back-azimuths for all events in our database.

![Image](image_url)

**Figure 4.** SSLOC3D polarization analysis for an event recorded at HYB. The upper subplot presents the back-azimuth calculated while the middle subplot displays the rectilinearity. The $P_n$ and $P_g$ arrivals are shown in the bottom subplot. The mean back-azimuth was determined to be $267.1^\circ$ with one standard deviation equal to $0.5^\circ$.

**Regional Phase Travel Time Estimation**

We calculated theoretical travel times to a single station in complex 3D models for the regional phases $P$, $S$, and $L_g$. The resulting 3D travel time grids are differenced (e.g., $L_g-P$) and compared to observational data using SSLOC3D.

**WINPAK3D.** Weston Geophysical Corporation compiled a detailed initial 3D velocity model through synthesis of pertinent data from approximately 69 published references on the velocity structure, geology, and tectonics throughout the region of southern Asia (Reiter et al., 2001). The model is referenced as WINPAK3D for its coverage of INdia and PAKistan, however the extents also include Afghanistan and sections of Iran. The references utilized to develop the model included data such as seismic refraction and reflection studies, interpretations of gravity data, surface wave studies, and receiver function analyses. Reiter et al. (2001) completed a fully 3D tomographic update of the $P$-wave model and subsequently converted the model into an $S$-wave model using a depth-dependent Poisson’s ratio equivalent to that in the IASP91 (Kennett and Engdahl, 1991) model. The fact that the $P$-wave velocity model was developed using GT data from southern Asia (Reiter et al., 2001) was an advantage for using WINPAK3D. However, we also examined the performance of a global model, CRUST2.0.

**CRUST2.0.** The global 3D model chosen for evaluation, CRUST2.0, was developed by Bassin et al. (2000) from an extension of CRUST5.1 (Mooney et al., 1998). CRUST2.0 is a prototype 2-degree crustal model developed using large databases of crustal and sedimentary basin structure, compressional wave and shear wave velocities, and densities determined from field and laboratory studies. Rigorous statistical methods were used to predict crustal structure in regions without data. In addition to global coverage, the advantages to using this model are that it has more detailed crustal structure than WINPAK3D; however, the disadvantage is that the mantle lid velocities are not updated by a tomographic inversion using data in our study region.
Body Wave Travel Time Grid Calculation. To determine the values of the travel time grid for $P$-waves and $S$-waves, we applied the Podvin-Lecomte (P-L) finite-difference travel time algorithm (Lomax, 1999; Podvin and Lecomte, 1991) to the earth models using the location of the station as the source in the calculation. The Podvin-Lecomte method solves the eikonal equation in a 3D medium using a finite-difference approximation. It can accurately model different propagation modes, such as transmitted and diffracted body waves or head waves. It estimates accurate travel times in the presence of severe, arbitrarily shaped velocity contrasts, as those occurring across the Moho discontinuity. This is an improvement over similar methods (Vidale, 1988; Moser, 1991), which can encounter serious difficulties in the presence of sharp, first-order velocity contrasts. The model is discretized on an equally spaced grid composed of constant velocity cells. Multiple arrivals (transmitted, diffracted, and head waves) are calculated at each grid node and the first arrival time is chosen. This computation produces a complete grid of travel times considerably faster than two-point ray tracing, while allowing the sources and receivers to be located anywhere within the model. The P-L computations are then output in the form of a 3D travel time grid for the $P$- and $S$-phases at the station of interest.

$Lg$ Travel Time Grid Calculation. Before theoretical $Lg$ travel-times could be estimated, we first examined the published definitions of this important phase. The phase was first described by Press and Ewing (1952) as a transverse impulsive phase traveling across the North American continent with average crustal $S$-wave velocities. Since then, $Lg$ has been described as refracted and reflected $S$-waves within the crust (Bouchon, 1982; Olsen and Braile, 1983) as well as higher-mode surface wave propagation (Oliver and Ewing, 1957; Kovach and Anderson, 1964). We have used these definitions to determine the theoretical travel-times for the phase in southern Asia, and the results of using each method in SSLOC3D will be shown in the location results section.

Masked $S$-Wave Models. We have examined the effects of constraining the $S$-wave model velocities to small values at depths below the lower and mid-crustal levels. We refer to this concept as “masking” the $S$-wave model. For this method, we calculated travel-times through the masked models using the P-L ray tracing technique. This concept tests the hypothesis that $Lg$ travel-times can be modeled as $S$-waves refracted within the crust at different depths.

Crustal-Averaged 2D $Lg$ Grids. Another technique we developed for modeling $Lg$ travel-times involved computing the average of the $S$-wave velocities in the upper 30 km of the crust for the WINPAK3D and CRUST2.0 $S$-wave models. We chose 30 km because displacement eigenfunctions for 1 Hz higher-mode Rayleigh-waves are normally confined to the upper 30 km of crust. For regions where the crustal thickness was less than 30 km, the averaging was completed for the layers above the Moho. The averaged velocity at each model node was then used as the input to a 2D extension of the P-L ray tracing method, and the $Lg$ travel times were estimated. Figure 5 shows the results for this methodology at station NIL.

Constant $Lg$ Velocities. We generated modal summation synthetics (Herrmann, 2002) for the first five (5) Rayleigh-wave higher modes using the WINPAK3D velocity profile beneath each of the stations NIL and HYB. The results are shown in Figure 6. After fitting a straight line to the higher-mode onsets, we determined $Lg$ velocities of approximately 3.5 km/sec and 3.6 km/sec for NIL and HYB, respectively. We used these constant velocities to generate the $Lg$ travel time grids at NIL and HYB. This modeling tests the assumption that $Lg$ can be modeled as higher-mode Rayleigh-wave propagation, and we are currently proposing to extend this technique to 2D and 3D models using synthetic data from the Generalized Fourier Method.

Back-azimuth Correction Estimation

Our technique for deriving back-azimuth corrections was designed by Bill Rodi (MIT) and is again based on the P-L finite difference method, which we use for our travel time calculations. Using reciprocity, travel times are calculated between a particular station location and all points in a 3D grid of event locations. The slowness and azimuth observed at a station from a given event are the length and direction of the slowness vector defined by taking the gradient of travel time with respect to the station location. Our approach is to approximate this gradient by subtracting travel times computed for the actual station location from travel times calculated for perturbed station locations. Specifically, we compute travel times to each point in a 3D grid, using the P-L algorithm, from three different “station” locations: (1) at the proper station location, (2) displaced from the station by one node to the north, and (3) displaced from the station by one node to the east. We have chosen one-node displacement (5 km) for initial testing of this technique, but we are exploring varying the displacement amplitude for accuracy. Slowness is
calculated in seconds/km and then converted to seconds/degree. Note that with this approach we obtain the slowness vector for each point in the 3D grid. To determine the slowness corrections at each node, we subtract the back-azimuth values based on the theoretical back-azimuth from those predicted for the 3D model.

**Figure 5.** $L_g$ group velocity map for station NIL (star) developed by averaging the CRUST2.0 S-wave velocities in the upper 30 km and ray-tracing through the resulting 2D model. Features to note include increased theoretical $L_g$ velocities in the Indian Shield and the Himalayas with reduced $L_g$ velocities associated with basin structures.

**Figure 6.** Modal summation synthetics for velocity profiles extracted from WINPAK3D at the HYB and NIL station locations. The fundamental mode and the first five higher modes were filtered between 0.5 and 2 Hz and plotted. The resulting $L_g$ group velocities were measured at the onset time of the higher modes as approximately 3.6 km/sec and 3.5 km/sec for HYB and NIL, respectively.

**Single-Station Location Methodology**

The objective of the single station location program, SSLOC3D, is to locate events recorded at only a single station and to provide realistic error ellipses. It requires an observed back-azimuth and differential phase arrival time, such as $L_g$-$P$. The program utilizes theoretical 3D modeled travel time grids, described earlier, to determine the epicentral distance and uses 3D modeled back-azimuth grids to apply a correction to account for structural effects on the observed back-azimuth. SSLOC3D combines the estimated distance with the corrected back-azimuth to locate the
event. Then the $P$ travel time is determined from the 3D travel time models and an origin time is obtained. Finally, SSLOC3D calculates the 95% confidence interval for the location error ellipse.

The prototype SSLOC3D program was designed to work with HYB and NIL and uses custom models and parameters for these stations. The next generation of the program will be expanded to additional stations/arrays. The travel time grids, back-azimuth corrections, and error uncertainty bounds must be calculated and calibrated using any available ground truth data for each station. The 11 May 1998 Indian nuclear test and 38 GT15 or better events from four clusters were used to calibrate and test SSLOC3D for stations HYB and NIL. With the ground-truth data, mislocations were calculated for each 3D model to determine the most appropriate model. These mislocations allow quantification of the errors that are used when locating non-GT events.

For each SSLOC3D location, we define a 95% confidence interval in the form of an ellipse empirically determined from back-azimuth and distance errors. First, the back-azimuth error is defined as the difference between the theoretical (station to ground truth location) and observed back-azimuth. Thus, our back-azimuth error includes both the measurement error in the polarization technique as well as off azimuth propagation caused by structural complexities. This error varies as a function of back-azimuth and some clusters have larger errors than others do. HYB shows the smallest back-azimuth errors for the clustered events near Koyna and larger errors at Bhuj, while NIL has smaller errors at Jiashi and PTS than at the Chamoli cluster. In order to determine the 95% confidence interval, two standard deviations of back-azimuth error are calculated for HYB and NIL using all clustered events (Figure 2) recorded at those stations and determined to be 6.2 degrees and 17.5 degrees for HYB and NIL, respectively.

The epicentral distance error is more complicated and is a function of incorrect phase picks and model error. Rather than assume values for the model and pick errors, we chose to empirically determine the distance error. Thus, the observed back-azimuth for every event in the database was fixed to the true back-azimuth and the event was relocated. The mislocation due only to distance errors is a combined function of the pick errors in both $Lg$ (or $S$) and $P$ and model uncertainty. For CRUST2.0, two standard deviations of the distance errors were 42.22 km and 63.05 km at HYB and NIL, respectively. We have also calculated the distance errors (model + pick) for all other models considered during the study.

**Location Results in Southern Asia**

We examined the performance of our single-station location methodology on the 11 May 1998 Indian nuclear test and 38 GT15 or better events located from four clusters (Koyna, Bhuj, Jiashi, and Chamoli; Figure 2). The resulting mislocations were determined as the difference in distance between the station and ground truth locations, and the best results are compiled in Table 1. We present two mislocations in Table 1; the first is the total mislocation in km due to both back-azimuth and distance errors, while the second mislocation is due to distance error only. One standard deviation of the mislocation is presented in the parentheses.

The Koyna region of west-central India is well known for the clustered seismic activity that started in 1962 after the impoundment of the Koyna reservoir. We formed single-station locations for 10 events from this region ranging from $4.2 < m_b < 4.9$ using HYB data. Nine of the ten events were listed as GT5 in the GROUP2 Reference Event List (REL) (McLaughlin et al., 2002) while the remaining event was listed at GT15 in the EHB bulletin. For the Koyna events, the best locations (Table 1) were determined from the WINPAK3D $P$-wave model and the 2D WINPAK3D averaged $Lg$ travel times. For these models, we observed an average of 9.4 km of total mislocation, which is less than 2% of the total travel path.

The Republic Day earthquake of 26 January 2001 was the mainshock for the Bhuj earthquake cluster. We formed single-station locations for 8 events from this cluster ranging from $4.5 < m_b < 6.9$, and the cluster mislocations are presented in Table 1. Data from station HYB, which is approximately 1080 km southeast of the cluster, were used for these locations, and the events were listed as GT5 in the GROUP2 REL. For the Bhuj events, the best locations were created using the constant velocity $Lg$ travel times and $P$-wave travel times determined from the WINPAK3D model. For these models, we averaged 49.6 km of total mislocation, which is less than 5% of the total travel path. Most of the mislocation is due to back-azimuth error as only 11.2 km, 1% of the total travel path, is caused by distance error.
We created a single-station location for the Indian nuclear test of 11 May 1998 as recorded at NIL (Table 1). NIL is 743 km north-northeast of the Pokhran Test Site (Figure 4), and the event is listed as GT1 in the GROUP2 REL. For this event, the best location was obtained for the CRUST2.0 P-wave and crustal-averaged Lg (2D CRUST Lg) travel-times. For this combination, we observed 0.6 km of total mislocation, which is less than 1% of the total travel path. There was essentially no mislocation due to back-azimuth error for this event.

The Jiashi cluster in northwest China had twin mainshocks occurring on 21 January 1997 with Ms magnitudes of 6.2 and 6.5. We created single-station locations for 6 aftershocks with 3.7 < mb < 5.4 using regional seismograms from NIL (Table 1). NIL is 740 km southwest of the Jiashi cluster, and the events are listed as GT10 in the GROUP2 REL. For this cluster, the best locations were created from the CRUST2.0 P-wave and crustal-averaged Lg travel times (2D CRUST Lg). For this combination, we have 22.5 km of total mislocation, which is approximately 3% of the total travel path. Of this mislocation, only 9.4 km was due to distance error. We note that the S-P results for this cluster were significantly worse than those determined using the observed Lg-P data.

The Chamoli mainshock was a magnitude 6.8 earthquake that occurred in northern India on 29 March 1999 (Figure 4). We created single-station locations for 14 aftershocks with 3.8 < mb < 5.1 using regional seismograms from NIL (Table 1). NIL is approximately 670 km northwest of the Chamoli cluster, and the events are listed as GT5 in the GROUP2 REL. For this cluster, the best locations were created for the CRUST2.0 P-wave and masked Lg travel times. For this combination, we have 101 km of total mislocation, which is approximately 15% of the total travel path. Most of this mislocation is due to error in the observed back-azimuths as 33.9 km, 5% of the total travel path, is due to error in the epicentral distance.

Table 1. Best model combinations and associated errors for the nuclear test and each cluster.

<table>
<thead>
<tr>
<th>Cluster</th>
<th>P-wave Model</th>
<th>Secondary Phase</th>
<th>Secondary Phase Model</th>
<th>BAZ Correction Applied</th>
<th>Total Mislocation Error in km (Distance+BAZ) Mean (STD)</th>
<th>Mislocation Error in km (Distance only) Mean (STD)</th>
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<tbody>
<tr>
<td>KOYNA (HYB)</td>
<td>WINPAK3D</td>
<td>Lg</td>
<td>2D WINPAK3D Lg Average</td>
<td>Y</td>
<td>9.4 (5.7)</td>
<td>4.4 (4.5)</td>
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<td>BHUJ (HYB)</td>
<td>WINPAK3D</td>
<td>Lg</td>
<td>Constant Lg Velocity</td>
<td>Y</td>
<td>49.6 (31.9)</td>
<td>11.2 (8.5)</td>
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<tr>
<td>PTS (NIL)</td>
<td>CRUST2.0</td>
<td>Lg</td>
<td>2D CRUST2.0 Lg Average</td>
<td>N</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>JIASHI (NIL)</td>
<td>CRUST2.0</td>
<td>Lg</td>
<td>2D CRUST2.0 Lg Average</td>
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<td>22.5 (15.8)</td>
<td>9.4 (8.7)</td>
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<tr>
<td>CHAMOLI (NIL)</td>
<td>CRUST2.0</td>
<td>Lg</td>
<td>CRUST2.0 Lg Mask</td>
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<td>101.0 (55.2)</td>
<td>33.9 (16.3)</td>
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CONCLUSIONS AND RECOMMENDATIONS

We used SSLOC3D to form single-station locations for 39 events in southern Asia classified as GT15 or better. For single-station locations performed using observed regional S-P travel times, the use of the CRUST2.0 model to generate travel times for both phases resulted in 14 km less distance error than IASP91. The results for Lg-P show 5 km improvement in the distance error when using 3D models as opposed to the 1D IASP91 model. WINPAK3D performed the best for clusters recorded at HYB while CRUST2.0 performed better at clusters recorded at NIL. Further work needs to be done to understand which regions of each model give the most accurate locations and use that information to develop new models.

It is clear from Table 1 that back-azimuth error is still the largest source of the total mislocation error, and results show that the application of 3D model-based back-azimuth corrections were not consistently successful at improving these locations. Only 3 of the 5 region mislocations improved with the use of back-azimuth corrections (Table 1). We examined the effects of empirical calibration of the back-azimuth error by fitting an experimental cosine curve to the observed NIL back-azimuths following a method similar to Tibuleac and Herrin (1997). Using this technique, we reduced the mean residual (theoretical-observed) back-azimuth from 3.0 to 0.1 degrees and reduced the standard error from 7.1 km to 6.9 km. Application of the empirical corrections to the Chamoli cluster
reduced the total mislocation from 101 km to 82 km. We plan to further examine additional azimuthal calibration techniques.

The single station location system used in this project yields locations that compare favorably with results from traditional multi-station location techniques but with the added benefit of being able to locate events recorded at only a single station. Single-station mislocations for four of the five event regions studied were less than 6% of the total epicentral distance. In addition, while many of the nuclear test sites have calibrated single-station location formulae, our single-station method improves location capability in broad and/or aseismic regions where little or no calibration data exists. The current $L_g$ models, crustal averaged, “masked”, and constant velocity, performed equally well. Yet, the results indicate that the development of additional phase modeling tools, such as 3D modeling of $L_g$ travel times, and empirical calibration of both 3D travel-time grids and back-azimuth correction grids should further improve the methodology. We note that these locations are model dependent and will improve as we develop better knowledge of the regional velocity structure.

REFERENCES


