# METHODS OF IMPROVING REGIONAL SEISMIC EVENT LOCATIONS

Delaine Reiter[1], Carolynn Vincent[1], Michelle Johnson[1], and William Rodi[2]

Weston Geophysical Corporation[1]
Massachusetts Institute of Technology[2]

Sponsored by Defense Threat Reduction Agency

Contract No. DTRA-00-C-0098

## ABSTRACT

In this paper we investigate the effect that depth-dependent Source Specific Station Corrections (SSSC's) have on improving regional seismic event location accuracy. To accomplish this we have relocated events considered GT5 or less that occur within the region encompassed by Weston Geophysical's regional 3-D model of the India-Pakistan region (WINPAK3D) using different depth-dependent SSSC's. By comparing the hypocenters produced using SSSC's at different depths to the ground truth location, we have gained insight into the minimum number of depth-dependent SSSC's that must be implemented in current automatic processing routines for accurate and efficient regional event location.

For a crustal earthquake, we generated SSSC's for a suite of depths by calculating travel times for WINPAK3D relative to the global IASPEI91 model (Kennett and Engdahl, 1991) to all regional stations. We then estimated the event hypocenter using the International Seismological Center (ISC) location as an initial hypocenter and two different but closely related methods of SSSC application and hypocenter location. For both location procedures, we compared the location derived from application of the different depth-dependent SSSC's to the ISC location in order to determine if there were significant differences in the hypocenters. Our initial results suggest that two SSSC's, one for the crust and one for the mantle, may be the minimum number of SSSC's to achieve the current goal in location accuracy in our study region.

**KEY WORDS:** depth-dependent SSSC, regional event location, 3-D velocity model

## OBJECTIVES

### Introduction

The overall objective of this research is to produce a fully 3-D grid-search location algorithm that can more accurately locate seismic events using the International Monitoring System (IMS) network. Our current algorithm implements a regional event location method, one that incorporates 3-D velocity models and travel time predictions with a nested grid-search location technique. When high resolution regional 3-D velocity models are available for an area of interest, they can be used to compute accurate travel times of regional seismic phases such as *Pn*, *Pg*, *Sn*, and *Lg*. Travel times calculated from 3-D models can then be used to develop SSSC's that can be implemented by monitoring organizations to further improve regional event locations. One important question that remains to be answered in the operational usage of SSSC's concerns the role that depth-dependence plays in improving the seismic event location. We know from previous analyses (Rodi and Murphy, 2000) that SSSC's are neither constant nor linear as a function of focal depth. However, it is not clear if producing numerous SSSC's with depth using a small sampling interval will net significant improvement in event location. In this study we have initiated an investigation into the necessity and specifics of utilizing depth-dependent SSSC's. Our objectives are two-fold: (1) We want to determine the most efficient method for utilizing depth-dependent SSSC's in regional event location by considering two different techniques for their implementation, and (2) we want to determine the minimum number of depths for which SSSC's must be generated for efficient and accurate regional event location in the WINPAK3D region (Figure 1). In the following sections, we present the preliminary results aimed at completing these two research objectives.

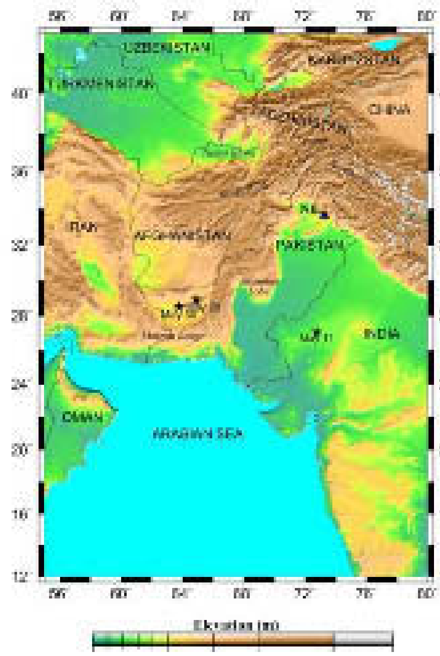


**Figure 1.** WINPAK3D (Weston India-Pakistan 3-D velocity model) study region. WINPAK3D encompasses a variety of different tectonic regimes from stable shield (southern India) to active collisional deformation zones. Crustal thickness varies between 15 km beneath the Arabian Sea to greater than 70 km beneath the Himalayas. The variations in crustal and upper mantle properties in this region provide an excellent testbed for this study aimed at examining the improvement in location accuracy offered by depth-dependent SSSC's.

## RESEARCH ACCOMPLISHED

### Setting

The Weston India Pakistan 3-D velocity model (WINPAK3D) is a 3-D P-wave velocity model of the crust and upper mantle developed to improve location estimation capability in the India-Pakistan region (Figure 1), especially for small, sparsely recorded regional events. The model was developed by intgrating the results of more than sixty previous studies related to crustal velocity structure in the region. Previous testing demonstrated that this model significantly improves location accuracy in this region, especially for small, regionally recorded events (Johnson and Vincent, 2001; Bernard-Johnson *et al*., 2000). This model has been used to calculate 2-D and 3-D SSSC's for stations within the region, including NIL, for use in regional event location, as described below.

On 14 February 1977, an $m_b$=5.2 (USGS) earthquake occurred in the region near Nilore, Pakistan. This event was well recorded by two temporary local networks (Tarbela and Chasma) in addition to the array at Nilore, Pakistan (NIL). Based on data from these three local networks, Seeber and Armbruster (1979) published a detailed study of the aftershock sequence and estimated the hypocenter of the event and associated aftershocks. The Seeber and Armbruster location is less than 5 km from the epicenters determined by both the ISC and the USGS using teleseismic and regional phase data. Based on these studies, we have assigned the Seeber and Armbruster location at least GT5 location accuracy. We compared the locations found in our study, calculated using only regional seismic phase data, to this Seeber and Armbruster ground truth location. The event was also recorded at 23 stations at regional distances

(Figure 2), and we used the bulletin data from these stations in the location efforts discussed in the following sections.

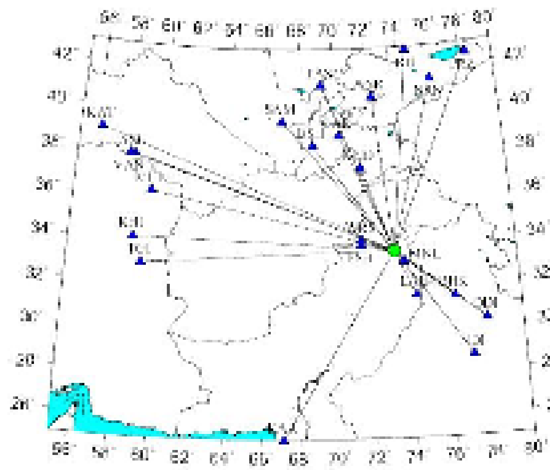

**Figure 2.** Regional ray coverage for the 14 February 1977 event near Nilore, Pakistan.

**Calculation of SSSC's**

We generated SSSC's for 23 stations within the India-Pakistan region using the WINPAK3D velocity model. Traveltimes through the WINPAK3D model were calculated from each station to all points in the 3-D space using a finite difference algorithm developed by Podvin and Lecomte (1991), as implemented by Lomax (1999). Traveltime tables were similarly calculated through a 3-D representation of the IASPEI91 velocity model (Kennett and Engdahl, 1991). The IASPEI91 traveltimes were then subtracted from the WINPAK3D traveltimes, resulting in fully 3-D SSSC's for each station. Figure 3 shows constant depth slices of the 3-D SSSC for station ASH in Turkmenistan. Note that there are significant variations in the SSSC's at different depths. 2-D constant depth slices were extracted from the 3-D SSSC's and were applied in two specific ways to the location process to investigate the requirements for applications of depth-dependent SSSC's.

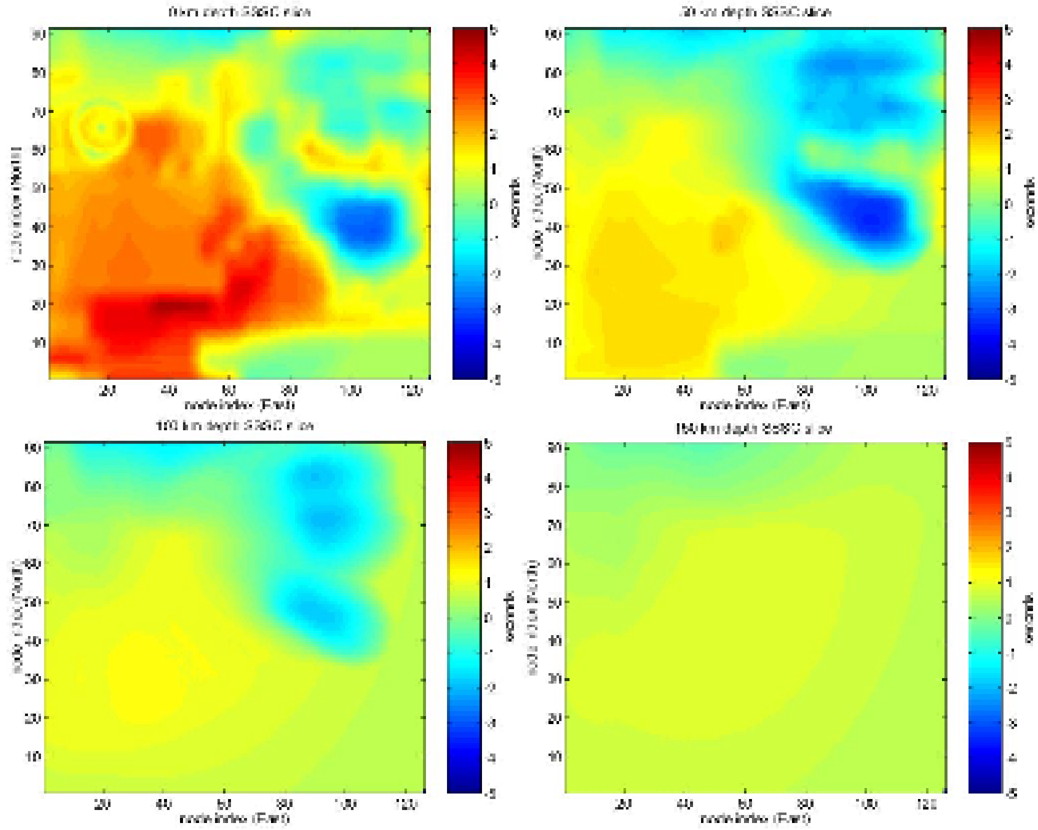

**Figure 3**. Constant depth slices (0 km, 50 km, 100 km, and 150 km depth) of the 3-D SSSC for station ASH derived from the WINPAK3D velocity model. The effect of the thick crust in the Himalayan region can be observed at depths greater than 100 km (blue region centered near node index 100E and 45N)

**Application of SSSC's to Location**

We have applied SSSC's to the location process in two different but closely related methods. For the first method, an iterative location procedure similar to current processing techniques at the prototype International Data Center (pIDC) was used to locate the seismic events with SSSC's. First, a preliminary epicenter is obtained using the network phase arrival time data. SSSC's are added to the arrival times based on the preliminary epicenter. The event is then relocated using GSEL, a 3-D grid search location algorithm (Rodi and Toksöz, 2000) and different SSSC's are added to the arrival time corrections to reflect the new location. The process is continued until the calculation converges. For the 14 February 1977 event, the hypocenter stabilized for each SSSC depth after a maximum of six iterations. The ISC hypocenter was used as the initial location.

The second method avoids the iterative process by adding the SSSC's directly to the set of traveltimes through our 3-D model, instead of to the arrival times. This results in a corrected set of travel time tables for input to a location program. GSEL is again used to locate the event within the 3-D corrected traveltime grids. However, for this method of depth-dependent SSSC application, only one computation of the grid search method is needed because the travel time grid itself was modified rather than the arrival times.

**Results**

We calculated locations for the 14 February 1977 event using the 23 regional *Pg* and *Pn* arrivals together with constant depth SSSC's ranging from 0 km to 180 km depth at 10 km intervals. These locations were calculated using both the one-step grid search and iterative grid search location methods. Figure 4 shows the results of these calculations. For each location, the depth mislocation, epicenter mislocation and hypocenter mislocation are shown (mislocation equals the calculated minus the Seeber and Armbruster (1979) location). For this event, which ground truth places at a depth of 14.46 km (Seeber and Armbruster, 1979), the most appropriate SSSC's range from 0 km to 30 km. For SSSC's 40 km and deeper, there is a marked increase in hypocenter mislocation, dominated by a jump in depth mislocation. This coincides with the Moho depth below the event of between 40 and 45 km. Also note that the epicenter mislocation varies by approximately a factor of 2 (between 6 and 12 km) for the entire range of depth-dependent SSSC's studied. For this event, the epicenter would have still met current CTBT location accuracy requirements of 1000 km$^2$. In fact, with hypocenter mislocation ranging from about 6 km to 15 km, this event is relatively well-located regardless of which constant depth SSSC is applied. However, it is important to note that the mislocation of the hypocenter calculated using uncorrected arrival times and the IASPEI91 velocity model is only 16.4 km. This is only slightly worse than that found with the least appropriate constant depth SSSC. For other events where the number of regional stations recording the event is significantly decreased, the range of mislocation may be broader, highlighting the potential need for appropriate depth SSSC's. We will continue to analyze events in this manner, particularly those with fewer regional arrivals, to further quantify the minimum number of depth-dependent SSSC's needed for efficient location algorithms.

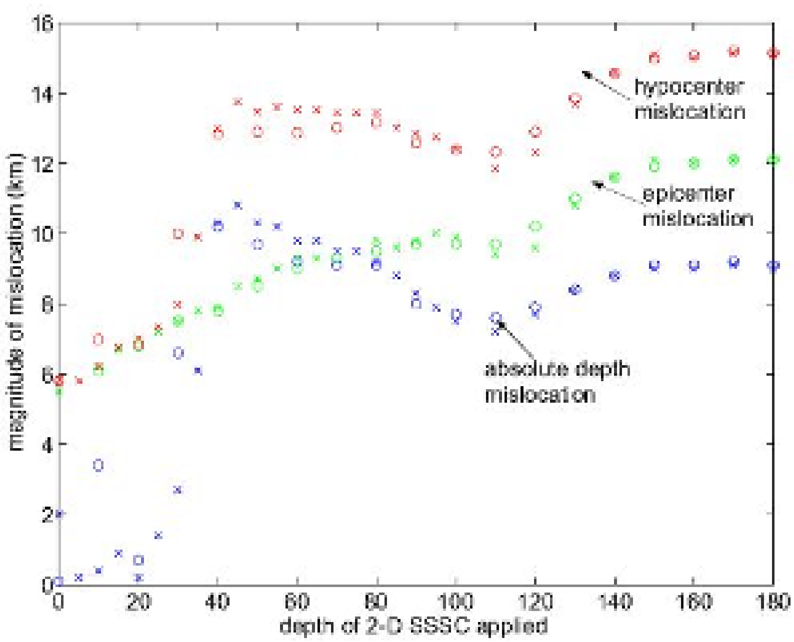


**Figure 4**. Mislocation of hypocenters calculated using constant depth SSSC's and 23 regional arrivals. Mislocations for hypocenters calculated by the iterative and one-step grid search are shown as circles and x's, respectively.

The differences in locations between the iterative and one-step grid search methods of location and SSSC application are minimal (Figure 4). Neither method produces locations that have consistently smaller errors. Mislocations from both methods follow the same trend, with both showing a significant jump for SSSC's 40 km and deeper. It is important to note, however, that a comparison of the rms norms produced for each hypocenter solution (Figure 5) reveals that the one-step grid search method is more successful than the iterative method at minimizing the residual norm in most cases. The one-step method is also more efficient in implementation, taking only a fraction of the time to produce a final solution compared to the iterative method used in this study.

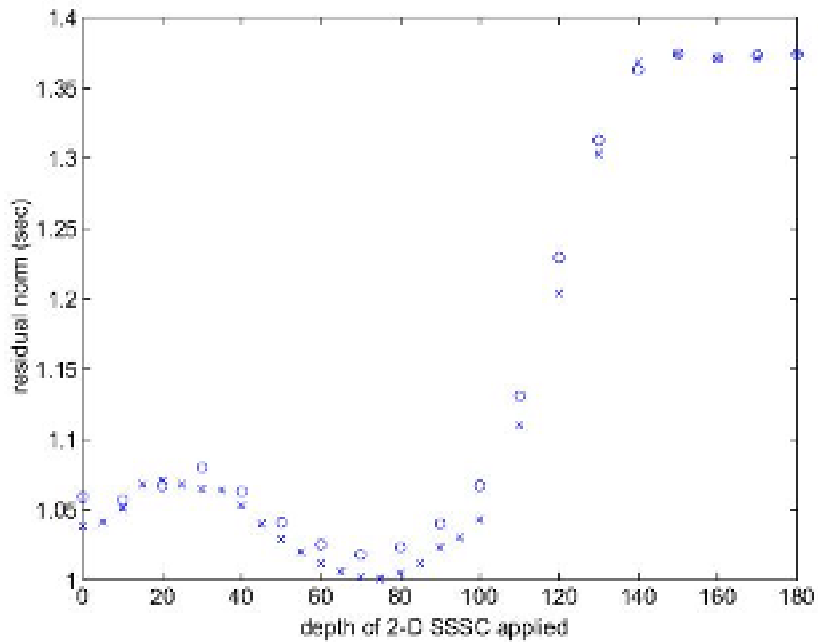


**Figure 5.** A comparison of rms norms for hypocenters calculated using the iterative grid search method of location plus SSSC application (circles) and the one-step grid search method for location plus SSSC application (x's). The one-step method has lower residual norms for most depths.

## CONCLUSIONS AND RECOMMENDATIONS

A primary goal of this research project is the improvement of our 3-D regional grid search location algorithm. In this paper we have investigated the best method for the application of depth-dependent SSSC's. Our preliminary results indicate that by adding the depth-dependent SSSC's directly to the 3-D travel time tables developed from fully 3-D raytracing, we can increase the efficiency of the event location alogrithm while reducing the rms in the hypocenters relative to iterative techniques currently used at the pIDC and IDC. For the crustal event presented in this paper (depth of 14 km), application of a single depth SSSC at any depth between 0 and 40 km leads to a more accurate location compared to the application of a mantle SSSC. Also, we see negligible differences in the hypocenter and epicenter mislocation regardless of which SSSC depth between 0 and 40 km is used. Further study is needed to determine how many depth-dependent SSSC's are necessary to locate both crustal and sub-crustal events with sparse data, and we are continuing research on this topic.

## REFERENCES

Bernard-Johnson, M., S. Rieven, C. Vincent, D. Reiter, and W. Rodi (2000), Empirical analysis of a 3-D Pakistan regionalized velocity model for improved seismic event location, *Proceedings, 22nd Annual DoD/DOE Seismic Research Symposium: Planning for Verification of and Compliance with the Comprehensive Nuclear-Test-Ban Treaty*, **02**, 06, 10pp.

Johnson, M. and C. Vincent (2001), Development of a 3-D velocity model of the India-Pakistan region for improved seismic event location, *Bull. of the Seismol. Soc. of Amer,* in review.

Kennett, B. L. N. and E. R. Engdahl (1991), Travel times for global earthquake location and phase identification, *Geophys. J. Int.*, **105**, 429-465.

Lomax, A. (1999), Probabilistic, non-linear earthquake location in 3-D media ( An online guide to software), http://iapetus.unice.fr/~lomax/nlloc.

Podvin, P. and I. Lecomte (1991), Finite difference computation of traveltimes in very contrasted velocity models: a massively parallel approach and its associated tools, *Geophys. J. Int.*, **105**, 271-284.

Reiter, D., W. Rodi, M. Johnson, C. Vincent, and A. Rosca (2001), A new regional 3-D velocity model of the India-Pakistan region, *Proceedings*, *23rd Annual DoD/DOE Seismic Research Review*.

Rodi, W. and J. Murphy (2000), Depth dependence of SSSC's, SAIC/Maxwell memo, 1 June 2000.

Rodi, W. and M. Nafi Toksöz (2000), Grid-search techniques for seismic event location, *Proceedings*, *22nd Annual DoD/DOE Seismic Research Symposium*, **02**, 39, 9pp.

Seeber, L. and J. Armbruster (1979), Seismicity of the Hazara Arc in northern Pakistan: decollement vs basement faulting, in *Geodynamics of Pakistan*, A. Farah and K. A. DeJong (Editors), *Geological Survey of Pakistan*, 131-142.