

A NEW REGIONAL 3-D VELOCITY MODEL OF THE INDIA-PAKISTAN REGION

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ABSTRACT

We have developed a 3-D velocity model for the crust and upper mantle in the India-Pakistan region (WINPAK3D) to improve regional event location. Results of extensive testing demonstrate that the 3-D model improves location accuracy for this region, specifically for the case of small, regionally recorded events, for which teleseismic data may not be available. The initial model for the region was developed by integrating the results of more than sixty previous studies related to crustal and upper mantle velocity structure. During the final year of this effort, we have developed a 3-D joint velocity tomography/event relocation to improve this preliminary velocity model. The algorithm applies an iterative, conjugate-gradients technique to minimize the misfit between calculated and observed travel times from multiple stations and events, subject to smoothness and geologic constraints. Events are relocated using the grid search location method of Rodi and Toksöz (2000) after each update of the 3-D velocity model. Travel times and their sensitivities to the velocity structure are computed with an extension of the 3-D Podvin-Lecomte (1991) method. We are applying our tomography algorithm to a suite of 580 events containing over 7,800 arrivals from the Engdahl *et al.* (1998) database.

A critical aspect of model development is validation, which we have addressed in three ways: (1) cross-validation analysis for a variety of events, (2) comparison of model-determined hypocenters with known event location, and (3) comparison of model-derived and empirically derived source-specific station corrections (SSSC's) generated for the International Monitoring System (IMS) auxiliary seismic station located at Nilore, Pakistan. The 3-D model provides improvement in regional location compared to a global 1-D model. For example, an event with a well-known location had an epicenter mislocation of only 6.1 km for the solution determined using the 3-D model, compared with a mislocation of 15.4 km for the IASPEI91 model (Kennett and Engdahl, 1991). These and other results demonstrate that 3-D models are a prerequisite for achieving improved location accuracies in areas with complex crustal and upper mantle structure.

KEY WORDS: 3-D velocity model, India, Pakistan, tomography, improved event location

OBJECTIVE

Improving seismic event location is particularly important for monitoring the Comprehensive Nuclear-Test-Ban Treaty (CTBT). The treaty requires a location accuracy of better than 1000 km² due to the restrictions defined both for on-site-inspections (OSI) and for using location as a discrimination tool. For small events ($m_b < 4.0$), meeting this requirement is problematic because of limited recordings and complicated crustal structure at regional distances not accounted for in the standard global 1-D models such as the IASPEI91 model (Kennett and Engdahl, 1991). Precise regional location of seismic events in the context of the CTBT requires a velocity model that accurately represents the real Earth structure, as systematic biases caused by unmodeled Earth structure are known to play an important role in earthquake location errors (e.g., Douglas, 1967; Dewey, 1972; Engdahl and Lee, 1976; Jordan and Sverdrup, 1981; Pavlis, 1992). Regional 3-D models that better represent the true Earth structure can be used to compute accurate travel times of regional seismic phases such as *Pn*, *Pg*, *Sn*, and *Lg*. Travel times calculated using 3-D models can then be used to develop source specific station corrections (SSSC's) that can be implemented by monitoring

organizations to provide improved regional event locations. Our goal is to develop a regional model of the crust and upper mantle for the India-Pakistan region that will improve event location accuracy and provide a set of improved hypocenter estimates based on that model. We are building an accurate 3-D model for the India-Pakistan region by updating a preliminary model through a joint velocity tomography and hypocenter relocation technique. Here we describe this approach in detail and our progress towards developing an accurate model for the India-Pakistan region.

RESEARCH ACCOMPLISHED

Preliminary Model

We have developed a regional 3-D velocity model of the crust and upper mantle structure, the Weston INdia/PAKistan 3-D model (WINPAK3D), to improve seismic event locations for the India-Pakistan region (Figure 1a). The region of interest has a complex tectonic history exhibited in the diverse geometries of crustal structures across the area. Using the available geophysical literature, we have compiled a detailed 3-D velocity model for the India-Pakistan region (Figure 1b). We synthesized data from approximately sixty published references relevant to the velocity structure, geology, and tectonics throughout the region. These references include data such as seismic reflection and refraction surveys (*i.e.* DSS profiles, *Pn* tomography, *Pnl* waveform inversion), interpretations of gravity data, surface wave studies, and receiver function analyses. Because these data sources vary in spatial coverage, resolution, and the number of constraints, the model varies in a similar manner. The velocity model is defined on a grid of one-degree by one-degree blocks and 5 km depth intervals from 0 to 75 km. We have appended the IASPEI91 model (Kennett and Engdahl, 1991) to the base of the preliminary velocity model, beginning at 80 km depth and extending to 700 km depth, to accommodate raypaths that travel into the upper mantle. See Johnson and Vincent (2001) for additional details on the development of the WINPAK3D model.

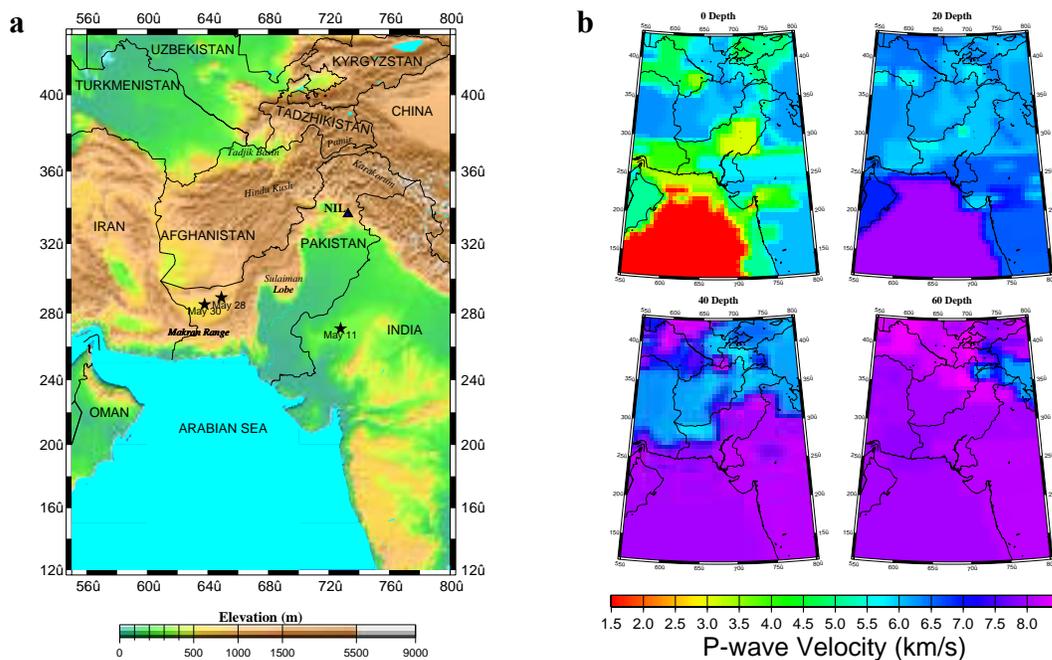


Figure 1. (a) Regional setting of the WINPAK3D velocity model showing the location of seismic station NIL at Nilore, Pakistan (future site of IMS station PRPK) as the black triangle and locations of the India and Pakistan nuclear test sites as black stars. (b) Slices of the velocity model at selected depths show the variability of velocity model resolution, as well as the large range of crustal thickness across this complex tectonic region.

Evaluating the Initial Model

The initial WINPAK3D velocity model was evaluated to ensure a reasonable model as a starting point for tomographic inversion. Testing and validation of a velocity model is a difficult task for several reasons: (1) the paucity of ground truth data, *i.e.*, explosions and earthquakes with known or well constrained location, as defined by Yang *et al.* (2000), (2) the pitfalls of using root mean square (rms) residuals to indicate improved location accuracy, and (3) the need to avoid circularity issues by ensuring that data used to generate the model are omitted from tests to validate the model. We evaluate our regional model's validity by comparing the hypocenter from a well-located event, recorded at a number of regional seismic stations, with model derived hypocenters. In addition, we implement a robust statistical procedure to further examine the validity of our regional model. We compare the performance of the 3-D model to the IASPEI91 model to determine the improvement over the global 1-D model for this region. Since the model was under development at the time of testing, the southern one-third of the current model was not included in the following model evaluation tests.

We begin by comparing our regional 3-D velocity model with the IASPEI91 model using the cross validation technique, a statistical method of evaluating a model. Cross validation obtains nearly unbiased estimators of prediction error in complicated problems (Efron and Gong, 1983). We performed this analysis for 6 events (Figure 2), chosen because they are well recorded and their epicenters are distributed across the model region. Applying the cross validation approach to the location problem, we repeatedly solved for the hypocenter of each event using unique subsets of 5 stations (simulating a sparse array) randomly selected from the set of regional arrivals. For each realization, we predicted the travel times to the omitted stations based on the hypocenter determination derived from the 5 stations. We calculated the average residual of predicted travel times at each station for all realizations and then evaluated the model fit in terms of the rms error for all stations. If the devised model is a physically relevant one, then it will yield accurate predictions for the omitted data.

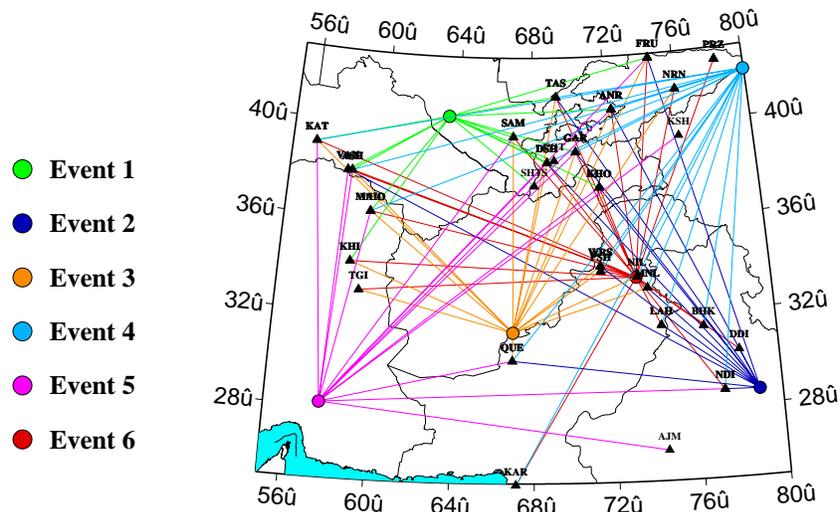


Figure 2. Events used for the cross validation analysis to test travel time prediction capabilities of the WINPAK3D model as compared with IASPEI91. Raypaths to the regional stations that recorded the events are shown.

We performed this analysis for both the WINPAK3D and IASPEI91 models and calculated the rms error for the travel time predictions made from each model (see Table 1). WINPAK3D achieves a smaller prediction error for the India/Pakistan region for 5 of the 6 events, with a large range of improvement in travel time prediction accuracy (22-83%) over IASPEI91. For event one, the prediction was the same for both WINPAK3D and IASPEI91. Although the rms prediction results demonstrate that WINPAK3D improves travel time prediction accuracy over IASPEI91 for events and raypaths throughout the model region, the amount of improvement that the 3-D model provides over IASPEI91 is quite variable. This is likely due to the varying resolution of the model discussed in the previous section. These results suggest

that WINPAK3D will serve as a good starting model for the tomography inversion, yet certain regions of the model will be subject to bigger updates than others.

Table 1. Cross Validation Results: RMS Prediction Error

Event	Stations	Realizations	Model Prediction Error (seconds)		Improvement
			WINPAK3D	IASPEI91	
1	5/14	2002	2.1	2.1	0%
2	5/13	1287	6.4	8.7	26%
3	5/17	5000	6.8	8.7	22%
4	5/18	5000	5.7	7.4	23%
5	5/14	2002	3.9	6.9	43%
6	5/23	5000	1.3	7.6	83%

Event 6 (m_b 5.2, USGS) in the cross validation analysis occurred on 14 February 1977 in the region near Nilore, Pakistan (Figure 2). This event was well recorded due to the presence of two temporary networks, Tarbela and Chasma, and a subarray of five stations centered on Nilore, Pakistan (NIL), all located in close proximity to the event. Based solely on data from these three networks, Seeber and Armbruster (1979) estimated the hypocenter of the event and conducted a detailed study of the aftershock sequence. Using teleseismic as well as regional data (not including the temporary networks), both the International Seismological Centre (ISC) and the U.S. Geological Survey (USGS) located the event within approximately 5 km of the epicenter reported by Seeber and Armbruster (S-A). The hypocenters of the main shock (depth = 14.46 km; John Armbruster, personal communication, 2000) and the 50 accurately located aftershocks determined by S-A indicate a rupture surface between 12 and 18 km depth. Given the high location accuracy estimated for this event as well as the large number of regional arrivals, we chose this event for a test of our model's location capabilities.

The S-A location (1979) for this event is one of the better constrained locations in the region due both to the local network coverage and to the detailed aftershock study. Though there have been several nuclear tests in the region, classified as ground truth (Yang et al., 2000) with known accuracies of 0 km and 1 km (GT0 and GT1), the regional data availability within our model area is limited. Arrival times for the 14 February 1977 event were reported to the ISC by 23 seismic stations within our model region. This event is additionally important due to its proximity to the seismic station at Nilore, Pakistan (NIL), the future site of the International Monitoring System (IMS) station PRPK.

Table 2. Location accuracy results of the 14 February 1977 Pakistan event

Reference	RMS			Mislocation (km)		
	Residual (s)	Lat.	Lon.	Depth (km)	Epicenter	Depth
Seeber and Armbruster	0.05	33.625	73.208	14.46	-	-
WINPAK3D	1.06	33.57	73.20	11.1	6.1	-3.3
IASPEI91	1.47	33.51	73.11	8.9	15.4	-5.5
NEIC	-	33.595	73.253	33	5.0	18.5
ISC	1.25	33.597	73.267	27	5.2	12.5

We believe that the velocity model should be validated using many source-station pairs prior to assessing model performance with sparse data. Using the 23 regional arrivals, we calculated the hypocenters predicted by both the WINPAK3D and IASPEI91 models (Table 2) for this event. The epicenter determined by WINPAK3D is 6.1 km from the "best" event location as determined by S-A (1979), while the IASPEI91 epicenter is approximately 15 km from the event. The depth is well determined for both models, due to extensive near-regional coverage when data from all stations are used. However, the cross validation results suggest that, in structurally complex regions, global models will be unacceptable for accurate location of small events not recorded teleseismically.

Therefore, we compare the locations for the event as determined by both the WINPAK3D and IASPEI91 models using only four stations, serving as IMS station surrogates. The four surrogate stations and their IMS counterparts are shown in Figure 3. The location determined using WINPAK3D and only arrivals from VAN, FRU, MNL, and TGI (Figure 4a, Table 3) is remarkably accurate (4.6 km). The IASPEI91

solution is within 14 km of the S-A epicenter. However, the surface projection of the 3-D 95% confidence region determined by the Monte Carlo simulation algorithm of Rodi and Toksöz (2000), encompasses the S-A epicenter for the WINPAK3D model, but not for the IASPEI91 model (Figure 5a). Furthermore, the epicenter calculated using the 3-D model and only four regional data is as accurate as the epicenters produced by both the ISC and the USGS (Figure 4a), which included teleseismic as well as regional data.

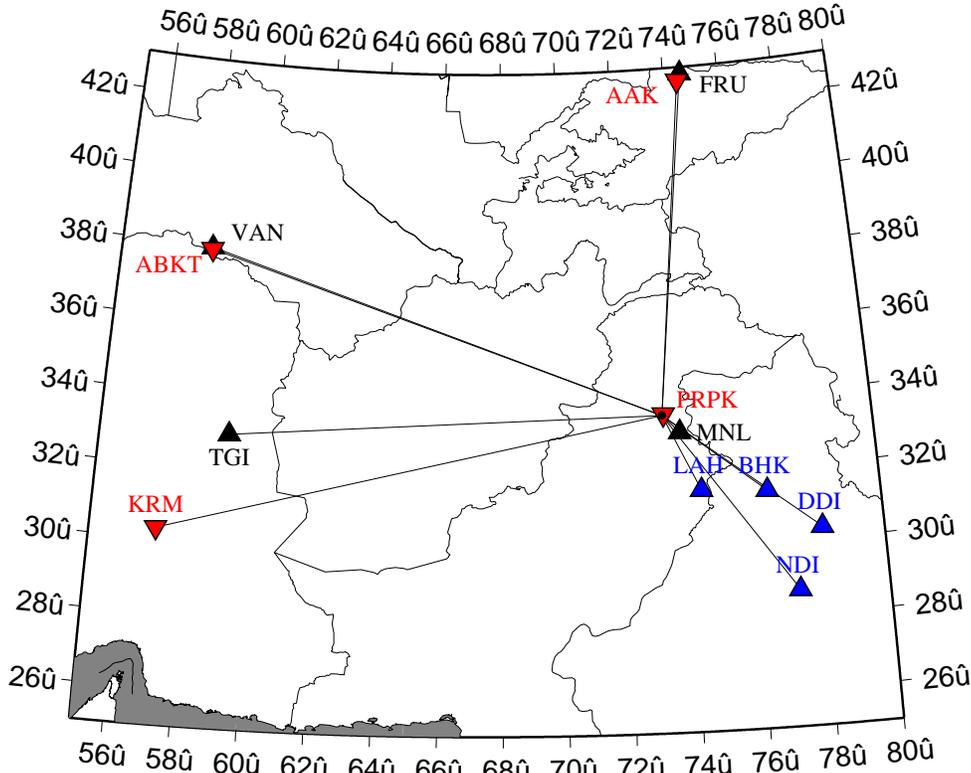


Figure 3. Location of the 14 February 1977 event (small circle plotted on top of PRPK) and the locations of regional stations VAN, FRU, MNL, and TGI (black triangles) used as surrogates for IMS stations (red, inverted triangles) for the sparse array locations. Blue triangles (LAH, BHK, DDI, and NDI) show stations used in the sparse array depth accuracy study.

We used the same four stations to determine the event location while fixing the depth to 15 km, the approximate depth of the S-A (1979) solution. With the hypocenter fixed at the approximate event depth, epicenter mislocation decreases to 2.9 km for the WINPAK3D model while it increases to 17 km for the IASPEI91 model. The confidence regions for fixed depth solutions are smaller, and again, the WINPAK3D confidence region encompasses the S-A location while the IASPEI91 confidence region does not. Interestingly, the solutions determined by both models, for both the fixed depth and free depth cases, lie within the 1000 km² region (17.8 km radius) required for CTBT monitoring protocol. We believe this is due to the close proximity of MNL to the event, helping to constrain the event depth.

Next, we next compare depth accuracy between WINPAK3D and IASPEI91 for the 4 station problem where different stations were substituted for MNL, the station closest to the epicenter (Figure 4). Given that the event is known to be a shallow crustal event, the only constraint imposed was to limit depth to less than 100 km depth. The results for the 4 station problem where depth is not controlled by a local station are shown in Table 3. The 3-D model provides much better constraint on event depth than the IASPEI91 model. WINPAK3D determined the depth of the event within 10 km of the S-A (1979) depth for all 4 variations of station coverage. However, all solutions calculated with the IASPEI91 model placed the event at the maximum allowed depth of 100 km. Epicenter mislocation was smaller for the WINPAK3D model as well, and in one case epicenter mislocation for the IASPEI91 solution exceeded the 17.84 km radius required for the 1000 km² OSI region. More importantly, the IASPEI91 based solutions could

falsely rule out this shallow event based on the erroneously deep hypocenters. Therefore, for this event, the WINPAK3D model has been shown to be extremely important for achieving the location accuracy required in nuclear monitoring.

Table 3. Location Accuracy for Sparse Arrays

Stations	WINPAK3D Mislocation (km)		IASPEI91 Mislocation (km)	
	Epicenter	Depth	Epicenter	Depth
IMS Surrogates	4.6	-14.5	13.5	-14.5
TGI, VAN, FRU, LAH	8.7	0.5	20.5	85.5
TGI, VAN, FRU, BHK	7.1	-9.4	10.5	85.5
TGI, VAN, FRU, DDI	1.9	-9.4	10.5	85.5
TGI, VAN, FRU, NDI	0.8	0.5	11.9	85.5

The International Data Center (IDC) currently uses the IASPEI91 global travel time curves as the default for event location. When the global model is insufficient for characterizing regional geology, the IDC sometimes applies path corrections (Yang *et al.*, 1999) in the form of SSSC's that are a function of source location for any station and phase. We derived SSSC's based on the WINPAK3D velocity model for the India-Pakistan region as described in Reiter *et al.* (2001). To account for the event depth, we calculated the anticipated SSSC for station NIL based on the WINPAK3D model for an event at 15 km depth.

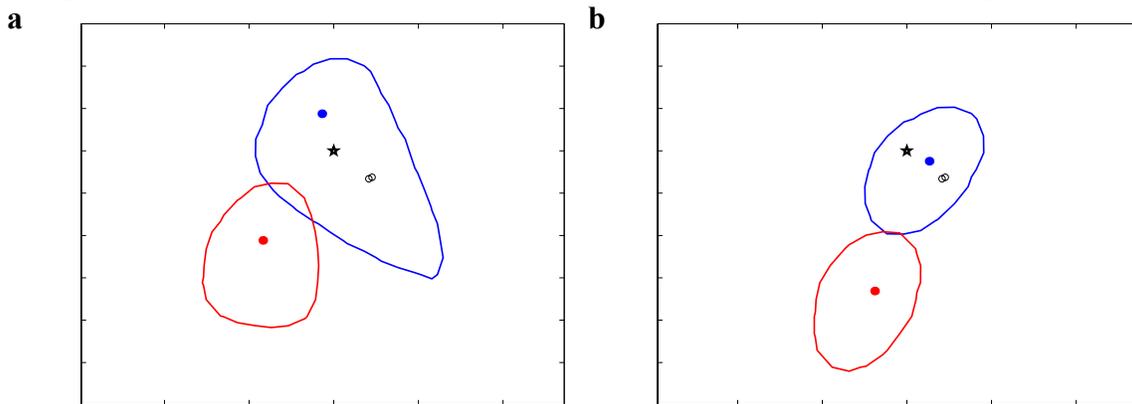


Figure 4. Location of 14 February 1977 event as determined by the WINPAK3D and IASPEI91 models using only arrivals from four stations (VAN, TGI, FRU, MNL) serving as IMS surrogates when (a) solving for hypocenter and (b) solving for epicenter only, with depth fixed to 15 km. The epicenter given by Seeber and Armbruster (1979) is indicated by the star. ISC and NEIC solutions determined using both regional and teleseismic data are shown by the open circles.

The 14 February 1977 event provides a unique reciprocity test of the 3-D velocity model, since it occurred very near the Nilore, Pakistan seismic station (NIL/PRPK). The residuals with respect to IASPEI91 at each station serve as empirical SSSC's. The differences between the empirical and model-based SSSC's at each station are less than 1 second for nearly half of the 23 stations and less than 3 seconds for the remaining stations. Since the SSSC values are as large as +/- 8 seconds in some parts of the region, discrepancies between the SSSC's of around 1 second are relatively small and show that the model-based and empirical SSSC's for NIL/PRPK are in very good agreement.

Tomography

A subset of 580 events were selected from the Engdahl *et al.* (1998) database of well located earthquakes and explosions. The selection criteria and processing of events in the Engdahl *et al.* (1998) data set results in location accuracy of 15 km or better in most continental areas, according to the IASPEI Working Group on Reference Events (<http://lemond.colorado.edu/~copgte/>). The subset of events were chosen in order to provide the best spatial distribution of events across the region, both in latitude-longitude and in depth.

Additionally, only events with 6 or more regional arrivals were selected from the database to insure sufficient data for hypocenter relocation. These events were recorded at 78 stations within our model region, amounting to over 7,800 arrivals (Figure 5). Travel times from these events will be used in an iterative velocity model tomography and hypocenter relocation procedure (described below) to update the preliminary model.

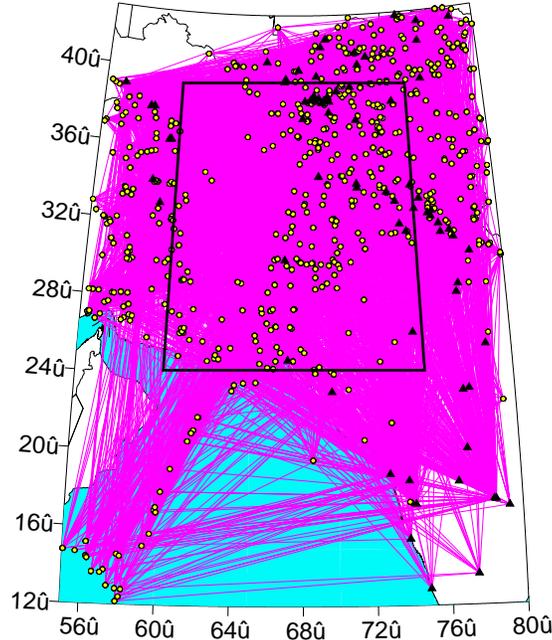


Figure 5. Ray coverage for tomography inversion provided by the 580 events (circles) recorded at 78 stations (triangles). The region outlined by the black rectangle is expected to have the best resolution in the tomographic update. Events and stations beyond this zone were included to provide optimal ray coverage in the primary model region. Ray coverage with depth is also very good.

We have re-parameterized WINPAK3D to reduce the number of model parameters to be solved for in the inversion. Our new parameterization is given in terms of a velocity vs. depth profile at each point on a geographic grid sampled uniformly in latitude and longitude. At each geographic grid-point, the velocity profile is given as velocity/depth pairs at nodes ranging from sea level to a depth of 760 km. Discontinuities in velocity are allowed at the ocean bottom, Moho and the major mantle discontinuities (410 and 660 km in the IASP91 model).

Our initial velocity model will be updated to fit the arrival times data from our database of 580 events. To accomplish this, we are developing an inversion algorithm that performs joint velocity tomography and multiple-event location. The algorithm will relocate the earthquakes in conjunction with revising the parameters of the velocity model. Initially, the model update will be restricted to the P_n velocity where we expect the greatest changes. Subsequent inversions will consider updates to the crustal thickness and other parameters.

Our inversion approach is formulated as follows. The unknowns are a vector \mathbf{m} containing the velocity model parameters to be estimated (e.g. P_n velocity at each point of the latitude-longitude grid), and the hypocenters and origin times of several events: (\mathbf{x}_j, t_j) , $j = 1, \dots, M$. The data are arrival times, d_{ij} , from each event to a subset of stations indexed as $i = 1, \dots, N$. The data and unknowns are related by

$$d_{ij} = t_j + T_i(\mathbf{x}_j; \mathbf{m}) + e_{ij}$$

where e_{ij} is the error in d_{ij} and T_i is a function that computes traveltimes to station i from an event hypocenter \mathbf{x}_j . This function depends on the model parameter vector \mathbf{m} . Our joint inversion criterion is to minimize an objective function of the form

$$\Psi(\mathbf{m}, \mathbf{x}_1, t_1, \dots, \mathbf{x}_M, t_M) = \sum_{ij} |d_{ij} - t_j + T_i(\mathbf{x}_j; \mathbf{m})|^2 / \sigma_{ij}^2 + \tau |\mathbf{Lm}|^2$$

with respect to all the unknowns. Here, σ_{ij} is the standard deviation of e_{ij} . The second term of ψ imposes a smoothness constraint on the velocity model, with \mathbf{L} being a regularization operator and τ a regularization parameter. The operator \mathbf{L} is chosen as a differencing operator with the effect that spatial derivatives of the model velocity are minimized. The parameter τ determines the degree of model smoothness.

Our algorithm minimizes ψ using a combination of conjugate gradients and grid-search techniques. The conjugate gradients method is used to update \mathbf{m} iteratively along a sequence of computed search directions. At each conjugate gradients step, grid search is used to minimize ψ with respect to the event origin parameters with \mathbf{m} fixed, thus updating the \mathbf{x}_j and t_j . The grid search for a given event is performed within a specified epicentral radius and depth range from its initial location, allowing us to handle events of varying ground-truth levels (e.g., GT0, GT5, GT15). Our grid search algorithm is described by Rodi and Toksöz (2000).

The forward model for this inverse problem is embodied in the traveltimes functions T_i . For fixed \mathbf{x} , we evaluate $T_i(\mathbf{x}; \mathbf{m})$ by interpolating a traveltime table stored on a 3-D hypocenter grid. The grid is created by applying the Podvin-Lecomte (P-L) finite-difference traveltime algorithm (Podvin and Lecomte, 1991) to the earth model defined by \mathbf{m} , using the location of the i th station as the "source" in the calculation. The forward P-L time calculation traces the wavefront propagation based on the Huygens' principle in the finite difference approximation. The model is discretized with an equally spaced grid comprised of constant velocity cells. Multiple arrivals (transmitted, diffracted, and head waves) are calculated at each grid node and the first arrival time is chosen. The time t at the current node is a function of the times t_n at some (3 or fewer) of the neighboring nodes and the slowness, s , in the cell traversed by the wavefront to reach this node. That is, $t = t(t_n, s)$.

We have extended the P-L algorithm to compute the sensitivities of traveltimes to cell velocities, as required for the inversion. When performing the forward calculation, we save the node pattern ("stencil") that shows which of the neighboring nodes were used to calculate the minimum time at the current node. The stencils are used to back-trace from any node of the grid to the source. The ray-tracing is done by identifying all of the grid nodes and the cells (slownesses) that contribute to the calculation of the time at the receiver. As the wavefront propagates away from the source, more nodes (and cells) are involved in the travel time calculation at each step. After the midpoint of the raypath, the propagation region narrows until it reaches the one node at the source location.

The sensitivity of the travel time to the slowness, $\partial t / \partial s$, is calculated at each grid node of the "ray" for the last cell traversed by the wavefront to reach that node. The weight of each neighboring node in the calculation of the time at the current node ($\partial t / \partial t_n$) determines the weight of the subsequent node-to-source subpath in the total travel time calculation for the ray. The sensitivities along each subpath are weighted by this term.

The ray-tracing algorithm and sensitivity calculation were tested by comparing the travel time computed as the sum of the weighted sensitivity-slowness products to the forward P-L calculated times. For rays with 10^5 nodes, the difference between travel times calculated by these two methods is on the order of 10^{-2} s when the calculation is done in single precision. Error of this magnitude for the number of nodes in the ray can be accounted for by the level of precision in the calculation, demonstrating that the ray-tracing technique is accurately tracing the minimum time P-L raypath.

We have developed the necessary algorithms for mapping our universal velocity model to a Cartesian block model needed by the P-L algorithm, and for mapping the 3-D Cartesian traveltime grids to geographic grids. The sensitivities are mapped from Cartesian blocks to the universal model parameterization.

We note that our joint inversion algorithm is fully nonlinear with respect to both the velocity model and event locations since traveltimes modeling and event relocation are performed for each update of \mathbf{m} . However, this comes at a high computational price and we are also allowing for multiple steps of the conjugate gradients iteration before the P-L modeling is repeated.

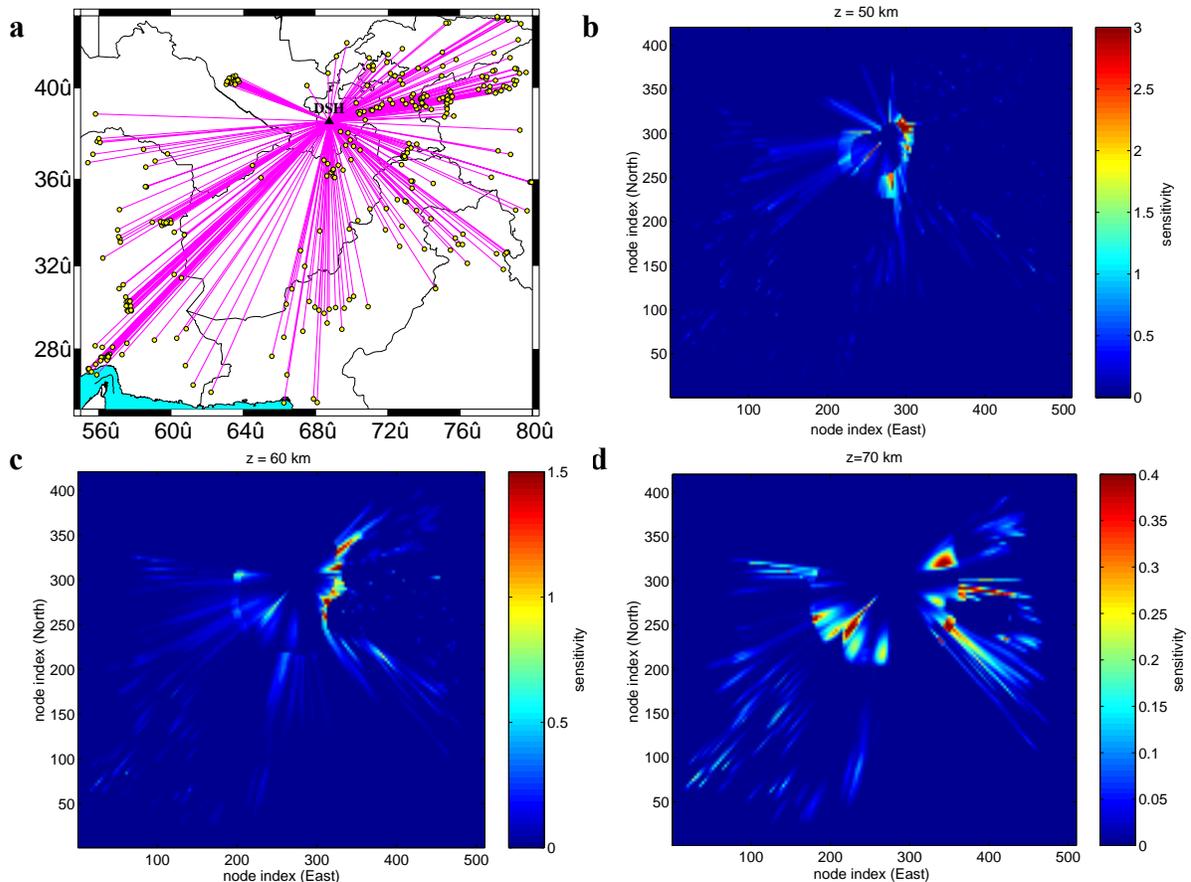


Figure 6. Ray sensitivities for station DSH. (a) Location of station DSH (triangle) and raypaths to events (small circles) within our model region that were recorded at DSH. Sensitivities of rays to model slices at (b) 50 km , (c) 60 km, (d) and 70 km depth.

Preliminary Analysis of Ray Sensitivities

We have performed a test of our ray sensitivity algorithm by computing the sensitivities to cell velocities of all the arrivals from our event database that were recorded at station DSH (Figure 6a). Selected depth slices of the sensitivities for DSH are shown in Figure 6b-6d. The rays have strong sensitivity to the model near the Moho boundary (presumably in the P_n velocity depth range). This suggests that updates to the P_n velocities as well as the Moho depth will provide the most significant improvement to the velocity model.

CONCLUSIONS AND RECOMMENDATIONS

Validation of the final, tomographically inverted, regional 3-D velocity model (WINPAK3D) will include more extensive application of the methods presented within this paper for testing of the preliminary model. We believe that all three techniques are important to the validation of any velocity model. Cross validation provides a statistical evaluation of the model's travel time prediction capabilities. Evaluation of location accuracy for a number of ground truth events is a very important aspect of model validation, as it will provide estimates of the model's location capabilities for location-based discrimination. Finally, model versus empirical based comparisons such as the comparison of the WINPAK3D SSSC for NIL with the

empirical SSSC derived from data for the 14 February 1977 event will provide a unique opportunity for validation when such events are available. Following the tomographic inversion and subsequent model validation, we believe that the updated WINPAK3D model will provide reliable, high-accuracy locations, for small events with sparse data, which will be critical for CTBT monitoring in the India-Pakistan region.

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