REGIONAL WAVE PROPAGATION AND INFLUENCE OF MODEL-BASED AND EMPIRICAL SSSCs ON LOCATIONS IN AND AROUND THE INDIAN SUBCONTINENT

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ABSTRACT

The primary objective of this study was to obtain reliable locations for earthquakes occurring in and around the Indian subcontinent to provide calibration parameters for the region. To this end, we compiled regional seismic bulletins from various seismic networks that operate in the region. We used P- and S-wave travel times contained therein to relocate events that satisfy the ground truth (GT) 10 event location criterion; thereby producing a set of good quality ground truth locations. Furthermore, we have reviewed the crustal structure models published by various authors based on the P-wave travel times from earthquakes and shots, and the surface-wave dispersion. Based on this review, we were able to identify ten distinct regions representing the study area. For each region, we have also developed one-dimensional (1-D) crustal models. For many events we also compiled regional short-period and broadband waveforms from stations in India as well as the Incorporated Research Institutes for Seismology (IRIS) broadband stations outside India, for example NIL, LSA, and KMI. The broadband data were primarily used to calibrate crustal structure and develop a 1-D model. We found that the model developed this way has the ability to generate P_{nl} and surface-wave synthetic seismograms that are consistent with the recorded seismograms. Suitability of this model was examined by generating the Lg waves up to 2000-km distance and comparing them with those recorded by the broadband stations in the Indian subcontinent.

To further investigate the influence of 3-D crustal models on the locations, we have combined Laske and Mooney's crustal model of the region separately with the regionalized upper mantle (RUM) and van der Hilst tomographic models for the mantle and computed travel times for all stations that lie within 20^o of the central India, Jabalpur, earthquake of May 21, 1997, the Chamoli earthquake of March 28, 1999, the Bhuj earthquake of January 26, 2001, and a few GT10 events from northeast India. We applied the finite-difference code of Podvin and Lecomte (1991) to calculate travel times through a full 3D model with a cell size of 1.5 km on each side, thus yielding accuracy up to 0.1 sec. To accommodate a large model (consisting of an area within 20^o of a target station), we divided the model into four quadrants and ran the calculations for each quadrant separately. We also developed a quasi 3-D scheme (Saikia *et al.*, 2001) in which we calculate travel times at many receivers using 2-D cross-sections constructed from the 3-D model. We use a total of 36 cross-sections (2-D) centered on a target station or an event to represent the entire model. This quasi 3-D calculation uses 1 km x 1 km cells and runs at least seven times faster than the full 3-D model and requires 200 Mbyte of memory compared to the 3.2 Gbyte memory required by the full 3-D calculation. Both yield the same level of accuracy. The quasi-3D algorithm is more efficient than the dynamic ray tracing code currently being applied to similar problems, in run time, and also avoids the problem of rays encountering shadow zones. Analysis of the travel-time residuals between 3-D and 1-D International Association of Seismology and Physics of the Earth's Interior (IASPEI) -91 calculations and empirical residuals relative to the IASPEI-91 model compare well within several degrees, but difference are as large as -3 to +2 seconds at larger distances in some areas. Our next goal is to estimate the improvements in locations of the earthquakes by using both model-based and empirical station-specific source corrections (SSSCs). This will be examined using the criterion that error ellipses reduce significantly without the loss of 90% coverage.

OBJECTIVE

Regional path calibration is primarily dependent upon the accuracy of hypocentral locations of seismic events. An objective is to obtain regional seismic bulletins from various seismic networks that operate in and around the Indian subcontinent, augment the International Seismic Centre (ISC) database of P- and S-wave travel times, and relocate events that satisfy the GT10 event-location criterion. In this report, we shall also present results of different models developed for various regions of the Indian subcontinent. In addition, we also demonstrate a numerical approach that is useful in generating Lg waves up to 2000-km distance. Another objective of our continuing study is to investigate the influence of 3-D models on the locations of seismic events. In this regard, we will present results of travel-time differences of two models, namely CRUST2.0+RUM and CRUST2.0+van der Hilst topographic models, relative to the 1-D IASPEI-91 model. The finite-difference code of Podvin and Lecomte (1991) is used to calculate travel times through a full 3-D model. Since the desired area around the selected International Monitoring System (IMS) stations is large (up to 20^o from the station), the model is large. Therefore, the cell size becomes crucial to accurately estimate the travel times to different stations.

RESEARCH ACCOMPLISHED

Figure 1 shows GT 5-10 locations of seismic events compiled for the geographical regions in and around the Indian subcontinent. This was done by locating seismic events using P- and S-wave travel-time data available from all sources. For many events we were able to estimate depths independently of the travel-time data. That is, depths were obtained by identifying and modeling depth-related pP and sP phases in the teleseismic waveforms and broadband P_{nl} and surface waves in the regional broadband waveforms. In the process, we were also able to develop localized crustal models. The origin time and location were then estimated with a fixed depth relocation using the depths established by the above procedure. The majority of the events shown in Figure 1 are of the GT 10 quality from the aftershock sequences of the Chamoli earthquake of March 28, 1999, and the Bhuj earthquake of January 26, 2001, which have ground truth accuracy of 5 km. Some of these high-quality ground truth locations are presented in Table 1.

We developed local crustal models for several regions by inverting travel-time data from local networks. These regions include the northeastern and northwestern regions of India and the Tibetan Plateau. Figure 1 shows the locations of many aftershocks following the 28 March, Chamoli earthquake (M_w 6.8). We merged the local and regional data with the phase data collected from the portable stations deployed following the main shock (Saikia *et al*., 2001). We started with the local models and locations and iteratively inverted for a 1-D model; this was done for both with a low-velocity zone (LVZ) and one without. The model with the LVZ resulted in smaller P-wave residuals than the residuals obtained using the local model and fixed locations (Figure 2). The greatest improvement is with the crustal P arrivals within 150 km. We found that local models require only a minor adjustment in fitting the time-domain data (Figure 3).

The model developed in this manner may not fit the high-frequency Lg waves, often lacking the characteristic features, such as the duration of coda waves, of the recorded data. However, it is possible to randomize the model around an average crustal model of a given region in order to generate the synthetic Lg waves consistent with data. In a recent study, Krishna (2002) investigated the propagational characteristics of regional seismic phases in the Indian shield and used a profile of broadband waveforms recorded from the May 21, 1997, Jabalpur earthquake by the stations of the India Meteorological Department. We used the same profile and investigated if the Lg waves can be generated by implementing the random velocity model using the source parameters developed in Saikia (2000). Figure 4 shows the waveform agreement of the simulated Lg waves with those recorded at the broadband stations installed in the Indian subcontinent.

We were able to identify many crustal models in the region from other published studies (Bhattacharya, 1974; Arora and Mannekar, 1969; Chaudhury, 1976; Chun, 1986; and others). Every model published was assessed for the geographical area that were covered by the data, including redundant ones. Based on the literature review, we were able to divide the Indian subcontinent into eight regions, namely the Himalaya, Gangetic Plains, west Gangetic basin, western India, central shield, peninsular shield, northeast India and Myanmar (formerly Burma) (Figure 4). The details of these crustal models will be presented at the Seismic Research Review.

We are also developing a capability to be able to compute travel times through 3-D crustal models. Earlier we applied the finite-difference code of Podvin and Lecomte (1991) to calculate travel times through a full 3-D model with a cell size of 1.5 km on each side yielding accuracy up to 0.1sec (Saikia *et al*., 2000). In this investigation, we are applying an additional method, which is called the quasi 3-D finite-difference scheme, to estimate the effect of 3-D structure on regional travel times using the extended graph based on the shortest path algorithm (Moser, 1998). The quasi 3-D is a calculation of travel times at many receivers through 2-D cross-sections constructed from a full 3-D model, centered on the target station. We use a total of 36 2-D cross-sections at an interval of 10^o in azimuth. Each 2-D cross-section uses 1-km x 1-km cells and the entire calculation is at least seven times faster than the full 3-D calculations. To evaluate travel time at a location, the 2-D travel times of the nearest two locations are linearly interpolated. Figure 5a shows an example of travel-time (TT) residuals between the full 3-D and the IASPEI-91 1-D model. These TT residuals were computed for all stations (circles) that recorded the Jabalpur earthquake (M_w 5.7) of May 21, 1997, in central India. The calculation used the full 3-D model, which consists of Laske, and Mooney's 1998; http://mahi.ucsd.edu/Gabi/rem/html crust model on top of the van der Hilst upper-mantle tomographic model (van der Hilst *et al*., 1997). The circles are the locations of stations for which travel times of P waves were reported in the ISC and local bulletins. Each circle is filled with color indicating the TT residuals between the recorded arrival times and travel times computed for the IASPEI-91 model. Any similarity in color-coding within the circle to its background indicated that the 3-D structure model is adequate for explaining the recorded travel times.

Also, note that the area encompassed in our calculation is large and was not practical to fit in the entire model in a single 3-D run with a cell size of 1.5 km on each side of the cube. A larger cell size will allow the incorporation of the entire model, but with increasing travel-time error. To keep the accuracy within 0.1sec, we therefore computed travel times for four sub-models, thus one model for each quadrant. This calculation required a memory of 3.2 Gbyte for each model and run time was about 180 minutes. Figure 5b shows the same TT residuals computed using the quasi 3-D method rather than the full 3-D model. In this calculation we used a curved grid that required only 200 Mbyte of memory. Each run required about three minutes and the entire calculation required about 108 minutes. These requirements make this quasi 3-D method very useful in computing travel times up to a large epicentral distance. In run time, the quasi 3-D algorithm is more efficient than the dynamic ray tracing code currently being applied to similar problems and also avoids the problems associated with the rays encountering the shadow zones.

We have also implemented the RUM model (Gudmundsson and Sambridge, 1998) by replacing the upper mantle tomographic model of van der Hilst. The RUM model has additional complexity introduced for the dipping slab structures. The RUM model parameterization is different from the tomographic model and warranted additional effort.

Figure 6a shows the quasi 3-D model residual variation with distance from the IASPEI-91 model. Figure 6 (b, c) shows two cross-sections showing the travel-time residuals of the RUM and van der Hilst models relative to the IASPEI-91 model. The short-wavelength variations seen in these calculations are primarily due to the crustal corrections from the CRUST2.0 models, whereas the longer wavelength anomalies (at great distances) are the results of both the crust as well as the mantle models.

Our main goal is to estimate the improvements in locations of the earthquakes by using both model-based and empirical SSSCs based on the principle that error ellipses reduce significantly without the loss of 90% coverage.

CONCLUSIONS AND RECOMMENDATIONS

We have completed development of regionalized crustal models in various regions of the Indian sub continent. These models can be used to compute travel times from different earthquake sources in the region using the technique presented by Bondar (Group B Oslo Workshop). We have also developed a list of ground truth events that will be useful for the calibration of the velocity model of the region. In Figure 1, we have shown locations of events that are of GT10 quality, or better. Many other events satisfy the criterion of GT25 events. The goal should be to refine locations of these GT25 events to the location accuracy of GT10 events. We expect the quasi 3-D approach will permit computing SSSCs reliably up to large epicentral distances (90^o) for the GT10 events in the region, and SSSCs so constructed will permit improvements to the location quality of the GT25 events.

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Table 1. Ground Truth Locations for Earthquakes in and around India

Date	hr:mn:ss	latitude	longitude	depth	mag	Region	
02/11/2001	02:33:20.6	23.366	70.576	19.9	4.0	Bhuj	GT5
02/11/2001	15:29:44.8	23.357	70.325	15.0	4.4	Bhuj	GT5
02/15/2001	10:04:42.4	23.371	70.362	15.0	4.8	Bhuj	GT5
02/19/2001	02:11:15.8	23.574	70.164	15.0	-.-	Bhuj	GT5
02/19/2001	08:24:19.7	23.597	70.229	1.0	5.1	Bhuj	GT5
05/21/1997	22:51:31.0	23.040	80.153	35.0	5.8	Jabalpur	GT10
06/04/1997	19:29:43.6	23.0283	80.1826	22.4	4.2	Jabalpur	GT10
03/28/1999	19:47:08.10	30.299	79.333	18.9	4.7	Chamoli	GT10
03/29/1999	08:49:47.00	30.301	79.302	9.8	4.3	Chamoli	GT10
04/06/1999	19:37:26.10	30.409	79.394	9.6	5.1	Chamoli	GT10
04/06/1999	20:46:42.10	30.413	79.406	7.3	4.6	Chamoli	GT10
04/07/1999	15:49:15.6	30.396	79.394	12.0	4.8	Chamoli	GT10
04/07/1999	16:23:30.0	30.471	79.319	11.0	4.4	Chamoli	GT10
08/29/1990	20:41:34.33	27.1763	92.7354	25.4	4.7	NE India	GT10
09/02/1990	06:29:26.05	26.5819	92.6700	57.3	4.6	NE India	GT10
06/23/1991	10:04:01.72	26.5883	93.1862	45.6	4.5	NE India	GT10
03/05/1996	09:27:37.30	26.434	92.935	49.6	4.0	NE India	GT10
05/14/1996	19:05:32.00	26.502	92.148	32.8	4.5	NE India	GT10
08/04/1996	13:51:32.6	26.452	93.186	43.4	4.3	NE India	GT10
11/19/1996	10:37:52.2	26.478	93.292	46.1	4.0	NE India	GT10
11/24/1996	00:52:11.80	26.859	92.685	43.1	4.2	NE India	GT10

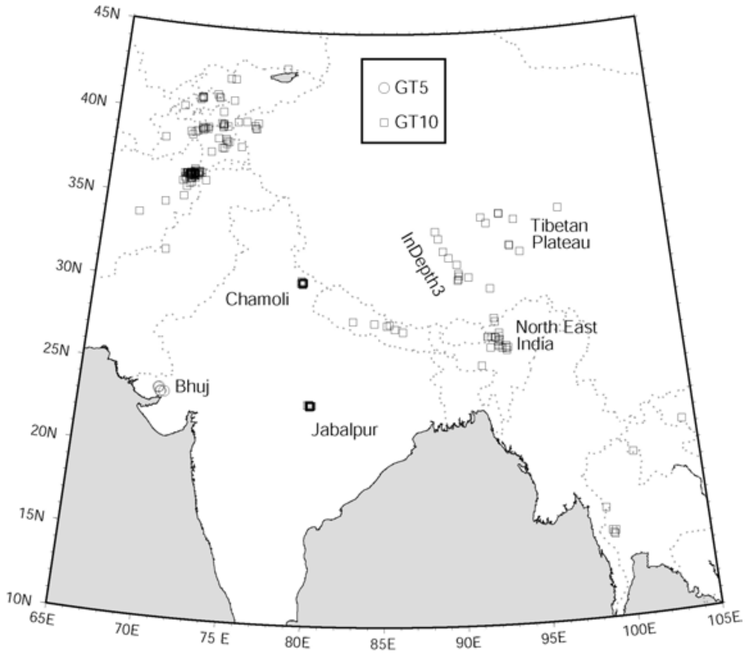


Figure 1. Map showing locations of a subset of ground truth events in and around the Indian subcontinent. The events shown by the boxes correspond to (GT)10 accuracy level and those by circles to (GT)5 accuracy level. The earthquakes were relocted using travel-time data from the local networks operating in the regions. The (GT)5 events were recorded by more than 15 stations surrounding the events within 50 km.

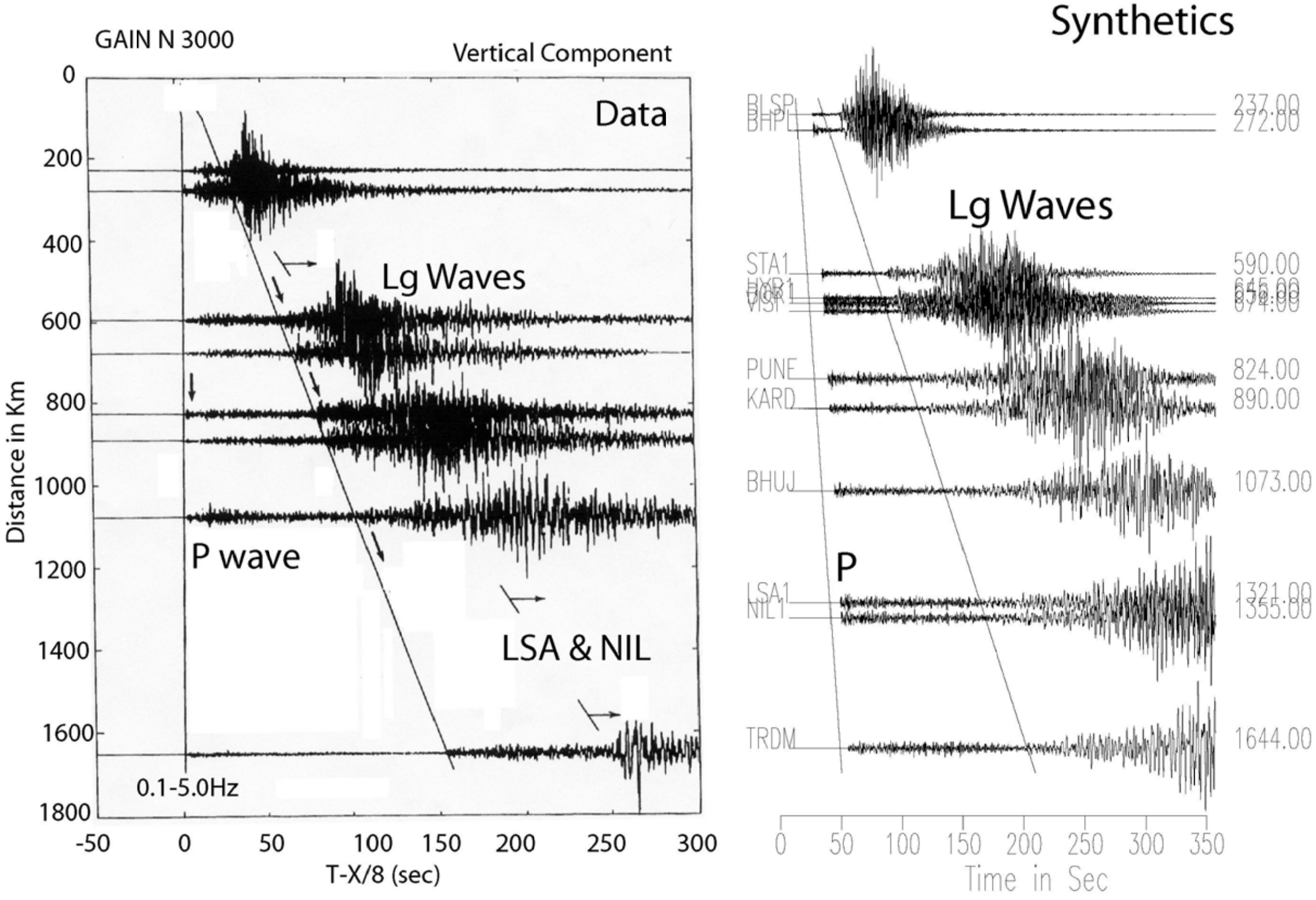
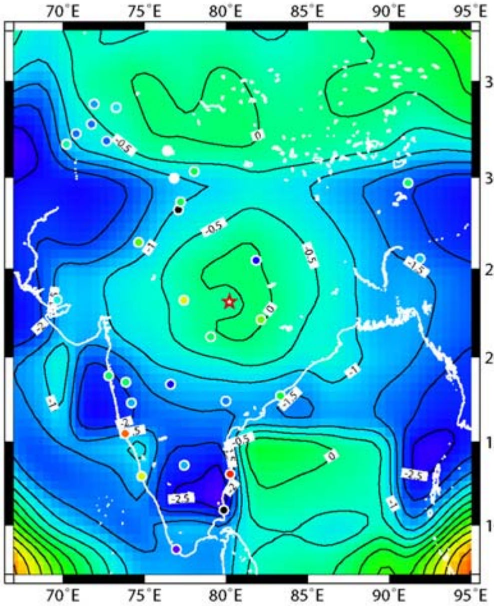
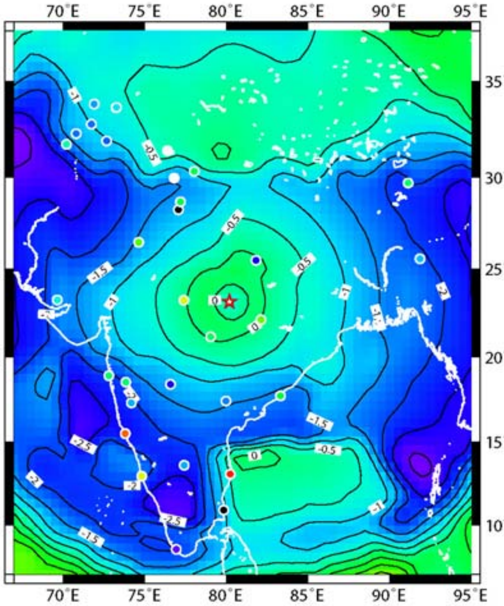


Figure 4. Lg waves as recorded by the broadband stations operated in the Indian Peninsula by India Meteorological Department (IMD). Left panel shows the data profile and on right is displayed the simulated Lg waves using laminar crustal model as discussed in Saikia (1994), a technique which was used successfully to model Lg waves recorded by the ECTN stations in eastern North America.



Travel time residuals for the Jabalpur earthquake.
Method of Podvin and Lecomte (1.5 km cell size)

Figure 5a Theoretical travel time residuals computed for the Jabalpur earthquake based on the tomographic model of van der Hilst overlain by the crustal model of Laske and Mooney. The circles represent observed travel-time residuals, with the same color coding as the theoretical residuals. All residuals with respect to the Iaspei model. The theoretical residuals were computed using the method of Podvin and Lecomte (1991).



Travel time residuals for the Jabalpur earthquake.
Quasi 3D method (1 km cell size)

Figure 5b Theoretical travel time residuals computed for the Jabalpur earthquake based on the tomographic model of van der Hilst overlain by the crustal model of Laske and Mooney. The circles represent observed travel-time residuals, with the same color coding as the theoretical residuals. All residuals with respect to the Iaspei model. The theoretical residuals were computed by interpolating 36 2D residuals sections radiating out from the epicenter.

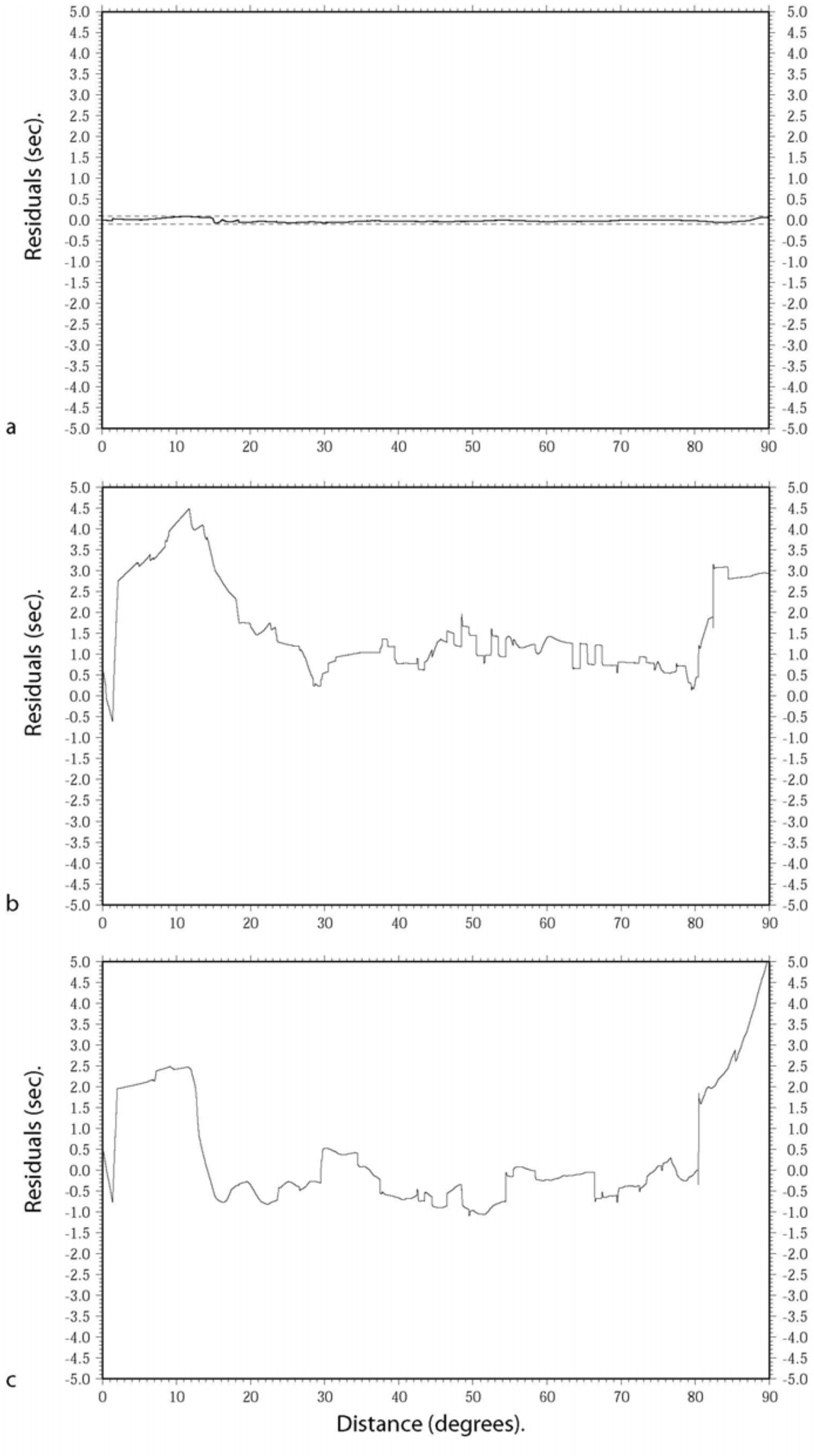


Figure 6. Traveltime residuals with respepct to tabulated IASP91 times as a function of distance from NIL at an azimuth of 20¡ for a - 1D model (IASP91 computed using the sortest-path algorithm), showing the ±.1 sec. interval with dashed lines, b - RUM/Crust2.0 and c - Vanderhilst/Crust5.1.