SEISMIC CALIBRATION OF GROUP 1 IMS STATIONS IN EASTERN ASIA FOR IMPROVED IDC EVENT LOCATION

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ABSTRACT

A Consortium of institutions which includes Maxwell Technologies, Inc., Massachusetts Institute of Technology's Earth Resources Laboratory (ERL), Weston Geophysical Corporation, the Russian Institute for Dynamics of the Geospheres (IDG), the Department of Geophysics of Peking University, and the Seismological Bureau of Sichuan Province has been assembled to conduct a research program directed toward the seismic travel time calibration of the 30 Group 1 IMS stations of eastern Asia. A carefully crafted scientific approach to this complex problem has been formulated in which rigorous seismological and statistical analyses of 3-D velocity models established for the regions surrounding the IMS stations of interest will be formally integrated with unique calibration data sets which will be provided by our international Consortium members to provide robust estimates of source-region specific station corrections (SSSCs), together with quantitative measures of the uncertainties in those estimates. A rationale for assigning priorities to the IMS stations to be investigated has been established, and a staged program of deliverables has been formulated in which preliminary calibration results for these priority stations will be provided six months after contract award and updated and refined on a regular basis throughout the three year performance period. We are currently assembling a preliminary 3-D velocity model of the entire region which is composed of a global background model on a 5°-by-5° grid (Stevens and McLaughlin, 1999), supplemented by more detailed models in regions where they are available. At the present time, such detailed models have been identified for a large portion of the Former Soviet Union (FSU) for which Deep Seismic Sounding (DSS) data have been used to define a 3-D velocity model of the crust and upper mantle on a roughly 40km-by-40km grid (Shchukin, 1989), and for an approximately 20°-by-20° area centered on the Pakistan/Afghanistan region for which a 3-D velocity model has been defined on a 1°-by-1° grid (Bernard et al., 1999). Regional phase travel times through these 3-D velocity models are being computed using the Podvin and Lecomte (1991) finite difference algorithm to obtain preliminary SSSC estimates with respect to the IDC default IASPEI91 model for each of the 30 Group 1 IMS stations. These preliminary estimates will be tested and refined using the various calibration data sets which are being assembled for this study. These include a unique set of regional arrival time data at 60 FSU permanent network stations from some 40 Soviet PNE tests, as well as 50 Semipalatinsk and Novaya Zemlya explosions with precisely known locations and origin times, including a number of stations which are either at or very near to Group 1 IMS station locations. The resulting SSSCs will then be thoroughly tested to quantify improvements to event locations in terms of uncertainty and location errors relative to the known locations of selected regional ground truth events. Our ultimate objective is to provide the IDC with the enhanced location capability which will be required to meet the CTBT monitoring objectives for this large Group 1 IMS station region.

OBJECTIVES

The purpose of this effort is to develop improved 3-D velocity models, Site-Specific Station Corrections (SSSCs), and Slowness-Azimuth Station Corrections (SASCs) for eastern Asia, to demonstrate the effectiveness of these models and corrections in improving locations of seismic events, to evaluate the uncertainties associated with these improved models and corrections, and to install these models and corrections at the Prototype International Data Centre (PIDC) of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) located at the Center for Monitoring Research (CMR) and evaluate their performance. The specific objectives are fourfold. The first is to collect appropriate calibration data and seismic events occurring in and around the calibration region. The second is to use these data to refine the regional velocity models and to define and refine SSSCs and SASCs for the 30 IMS stations within the region. The third is to use the new velocity models and SSSCs and SASCs with calibration data ["Ground Truth" (GT) data] to evaluate the location capabilities of the system. The fourth is to implement the SSSCs and SASCs into the location system at PIDC/CMR and to work with the CMR staff to evaluate their performance in that operational environment.

RESEARCH ACCOMPLISHMENTS

The determination of accurate seismic locations for detected events is one of the most important functions of the IDC because location plays such a key role in CTBT verification. Thus, for example, under the CTBT, the areas to be designated for potential onsite inspections are limited to 1000 km^2; and, consequently, this value has been adopted as the minimum performance requirement for uncertainties in IDC seismic locations. However, it has proven difficult to demonstrate that this level of accuracy can be routinely achieved, particularly for small events recorded by limited numbers of IMS stations. The principal reason for this difficulty is that the earth is laterally heterogeneous over a very broad range of length scales; and, therefore, travel time curves based on radially symmetric earth models, such as the standard IASPEI91 model employed at the IDC, can be seriously in error for some source and station locations. This problem is particularly acute at regional distances where the propagation paths of the seismic phases used in location are predominantly confined to the crust and upper mantle portions of the Earth which exhibit the greatest regional variability. Since many of the small seismic events which are of primary concern in CTBT monitoring will have to be located using regional seismic data, such variability places significant limitations on currently achievable location accuracy. It follows that in order to establish a robust CTBT monitoring capability, it will first be necessary to calibrate the IMS stations to account for such systematic deviations from the nominal travel time curves.

We are in the early stages of a three year program which has the objective of calibrating the 30 Group 1 IMS stations of eastern Asia. The map locations of these stations are shown in Figure 1, where it is indicated that they are composed of 11 primary and 19 secondary stations. It can be seen from Figure 1 that regional coverage circles extending to 2000 km radius surrounding these stations would encompass most of the Asian continent, with overlapping, multiple station coverage in most areas. Thus, the area under investigation is very large indeed. Of this total of 30 stations, 13 are currently active IMS stations and 7 more are in close proximity to permanent network stations for which significant historical calibration data are available. This subset of 20 stations has been designated as the "Priority 1" stations for the purposes of our investigation.

Our overall approach to this problem centers on the formulation of a 3-D velocity model of the region which can be used to define corrections to the default IASPEI91 model currently employed at the IDC. Thus, an initial velocity model is defined from currently available information and is then refined by performing joint tomography and multiple event locations using arrival time data collected for this region. Once an optimum average model has been developed, source-specific empirical travel time corrections for each station will be determined by interpolating between observed calibration event residuals relative to this 3-D model. Model-based travel times determined by ray tracing through the 3-D velocity model will then be combined with these empirical corrections to generate 3-D travel time tables for each Group 1 IMS station, and these predicted travel times will be differenced against the corresponding IASPEI91 travel times to define the required SSSCs as a function of source location around each station. This process will then be iterated to incorporate data from additional calibration events as they become available and the final models will be validated based on relocation experiments conducted using travel time data recorded from ground truth calibration events in the region.

Our preliminary model for the Group 1 region is a composite of three models: the long-period models of Stevens and Adams (1999) (model LP), the preliminary model of Bernard et al. (1999) for the Pakistan region (model OPM) and the Deep Seismic Sounding models for the former Soviet Union (model DSS). Each of these models is defined on a regular latitude/longitude grid of laterally homogeneous cells. The cells of model LP are 5 degrees by 5 degrees and cover the entire globe. The cells of model OPM are 1 degree by 1 degree and cover 24.5 degrees N to 43.5 degrees N in latitude and 54.5 degrees E to 80.5 degrees E in longitude. The DSS model cells are 0.3333 degrees wide in latitude and 0.5 degrees wide in longitude and cover 40 N to 72.33 N latitude and 30 to 140 degrees E longitude. Many of the DSS cells, however, are not defined. Each cell of each model is associated with a layered velocity versus depth profile. The LP profiles extend to 600 km depth. The OPM and DSS profiles extend to 30 km below the Moho depth, which is generally different for different cells. The areas covered by these three models are identified on the map in Figure 2, where the annotations in the 5 by 5 degree background model denote the different 1-D velocity models inferred by Stevens and Adams (1999) from their tomographic inversion analyses of observed IMS surface wave data.

The three models were assembled in hierarchy as follows. First, a master rectangular grid of latitude/longitude cells was constructed having variable cell dimensions and containing all the cell boundaries of the three input models. Each cell of the master grid was assigned a composite velocity profile defined to be the appropriate LP profile with the shallower depths replaced by an OPM profile or DSS profile, when either is defined. For a small number of master cells, both OPM and DSS profiles are defined; and we allowed the latter to take precedence. If the deepest velocity of a DSS or OPM profile exceeds the LP velocity at that depth, the velocities of LP layers below that depth were raised to this value. We point out that the master model, like LP, has profiles which vary from cell to cell in the number of total layers, number of crustal layers, etc.

The raytracing algorithm requires a grid of constant-velocity, cubic cells in a Cartesian coordinate system. We constructed such a grid for each station, extending 2000 km north, south, east and west of the station, and to a depth of 600 km. The cell size was 5 km. For each vertical column of cells in the Cartesian raytracing grid, we mapped the horizontal coordinates of the center of the column to a latitude and longitude, based on a sterographic projection centered at the station. This latitude and longitude is then located in the composite velocity model and the velocity profile at this point is extracted. The velocity profile is then translated into a uniform 5 km layering by calculating layer velocities that preserve the vertical travel time to each interface. This translation is done in conjunction with an earth-flattening transformation, which extends the legitimacy of Cartesian raytracing to greater distances from the station. The re-layered velocity profile defines the cell velocities for a column of the raytracing grid.

Ray tracing through this complex 3-D velocity model is being carried out using a code based on the finite difference algorithm of Podvin and Lecomte (1991). There are several advantages to using this approach in the current application. First, it permits the inclusion of secondary arrivals in the location problem; and secondly, it improves on previous modeling methods by being able to accommodate very large velocity contrasts of arbitrary shape, as high as 10:1. It is particularly convenient for estimation of SSSCs in that transmitted and diffracted body waves, as well as head waves, can be readily modeled for each possible hypocentral location in a Cartesian grid centered on a particular station. A first arrival criterion is then used to choose among the various types of waves to create the travel time tables. This algorithm has been extensively tested against a variety of models, including that corresponding to IASPEI91, and found to be accurate to better than 0.5 seconds over the entire range of source to station distances of interest in this project.

It is well known that there are extensive portions of the study area shown in Figure 1 which are essentially aseismic and, therefore, cannot be effectively calibrated using earthquake data alone. Fortunately, however, the U.S.S.R. did conduct an extensive series of PNE tests at widely dispersed locations throughout the territories of the FSU for which precise locations and origin times are now available (Sultanov et al., 1999). Travel time data from these explosions were observed at numerous stations of the U.S.S.R. permanent seismic network, and these data obviously constitute a primary resource for the calibration of Group 1 IMS stations in the FSU. Figure 3 shows the map locations of the approximately 60 U.S.S.R. permanent network stations for which travel time data are currently available from Soviet nuclear tests. Although all of these stations can provide ground truth data useful for calibrating subsurface velocity models for the region, there is a subset of 8 of them which are either at or very near to Group 1 IMS station locations; and these will obviously provide very important data for use in model validation studies. Particularly notable among these is the Borovoye station (BRVK) in Kazakhstan for which an exceptionally accurate

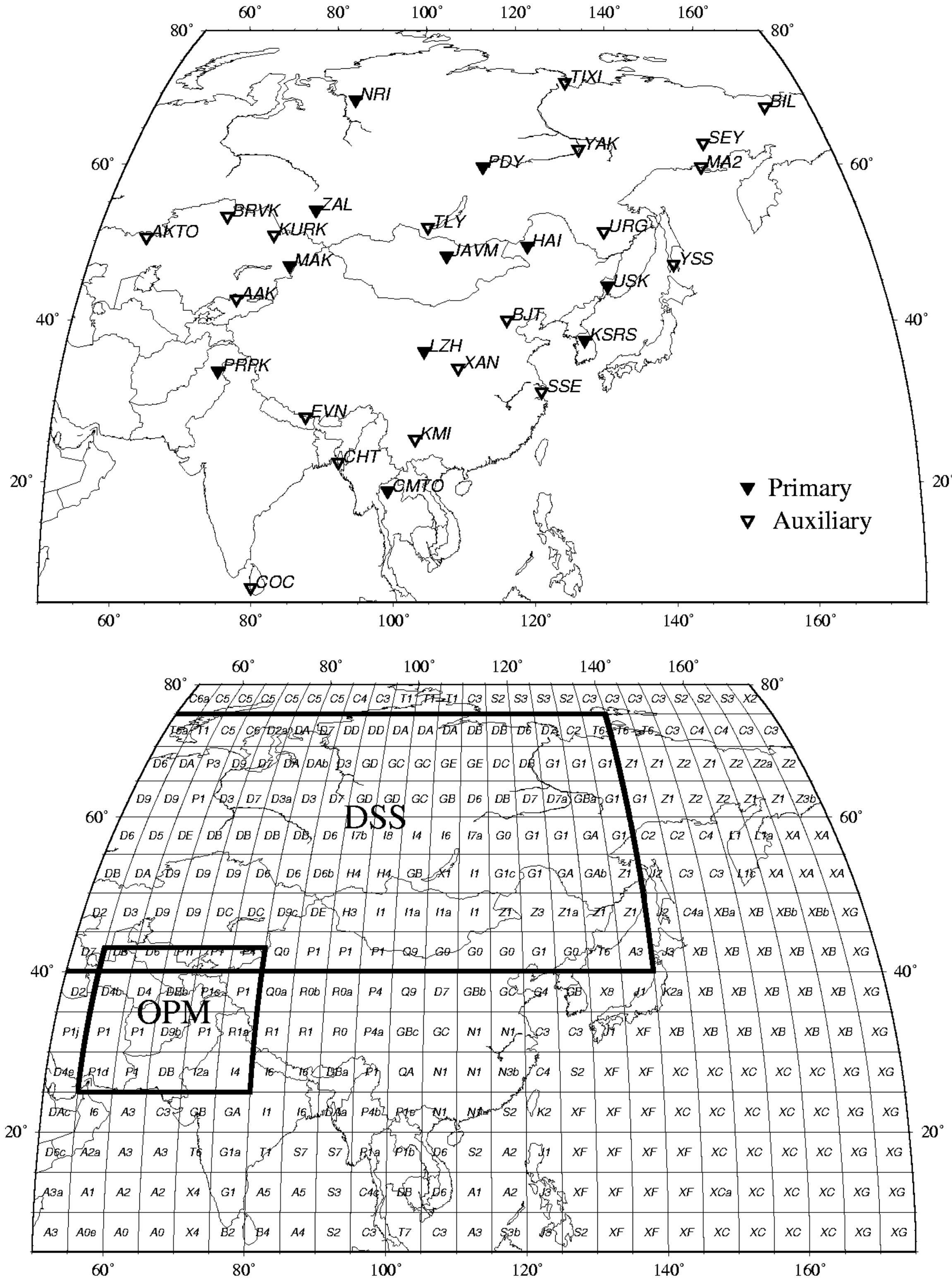

Figure 2.Map showing preliminary velocity models for Eastern Asia. The background model on the uniform 5 by 5 grid is the surface wave based model of Stevens and Adams (1999).

calibration database of regional ground truth data is available from over 100 nuclear explosions. This fact is illustrated in Figure 4 which shows the locations of underground nuclear tests within about 20° of the Borovoye station, together with the observed P wave travel time residuals with respect to IASPEI at BRVK for each test location. It can be seen from this figure that these regional calibration events are very well distributed about the BRVK station and that the observed travel time residuals with respect to IASPEI show a very complex pattern varying from about –8.0 to +1.0 seconds. It is probably fair to say that there is no other IMS station location for which a comparable amount of well distributed ground truth travel time data is currently available. Consequently, we have chosen to use BRVK as our benchmark station for the testing and evaluation of all of our calibration procedures.

As an initial test of our modeling procedures, we have estimated a preliminary SSSC for station BRVK by ray tracing through a 3-D DSS velocity model covering the region out to 20° around that station. Since DSS Pn velocities are not currently available for this entire area, we have adopted an upper mantle Pn velocity model which is consistent with the average observed PNE arrival times as a function of distance at BRVK for this initial application. A grayscale plot of the resulting surface focus SSSC is shown in Figure 5 where it can be seen that the preliminary 3-D velocity model predicts a complex pattern of corrections with respect to IASPEI, with a total range of variation extending from about –7.9 to +2.7 seconds. The extent to which this model predicts the observed PNE ground truth residuals of Figure 4 is illustrated in Figure 6, which shows the corresponding residuals computed with respect to the travel times predicted by the 3-D DSS velocity model. It can be seen that the residuals with respect to this latter model are greatly reduced relative to those of Figure 4, with the majority of residual values falling in the range of about ±1.5 seconds. This fact is illustrated more clearly in Figure 7, where the travel time residuals from Figures 4 and 6 are compared on an event by event basis. It can be seen that, while the residuals with respect to the original IASPEI model show an average bias of approximately –3.7 sec, those computed with respect to the DSS model are essentially unbiased, showing an average value of only –0.1 seconds. Moreover, the standard deviation of the residuals decreases from about 2.2 to 1.7 seconds in going from the IASPEI to the DSS model, indicating that the DSS model not only eliminates the average bias, but also accounts for more of the site specific variations between individual events. Thus, although further refinements are clearly required, the initial results obtained using the 3-D DSS velocity model are encouraging. We are currently proceeding to apply these same modeling procedures to the estimation of preliminary SSSCs for all 20 of our Priority 1 stations.

CONCLUSIONS AND RECOMMENDATIONS

We are in the early stages of a comprehensive program to calibrate the 30 Group 1 IMS stations of eastern Asia in an attempt to improve IDC seismic location capability in this area. A preliminary, composite 3-D velocity model for the entire region has now been formulated and an efficient finite difference ray tracing code for computing travel times through such models has been implemented and tested. A preliminary ground truth database consisting of arrival time observations at approximately 60 stations of the U.S.S.R. permanent seismic network from Soviet PNE tests has been assembled, including data at a number of stations which are either at or very near to Group 1 IMS station locations. Among these is the Borovoye station BRVK for which an exceptionally well distributed ground truth data set of regional arrival time observations from Soviet PNE events is available for testing of proposed calibration procedures. Initial tests of a 3-D, DSS-based velocity model for the region around station BRVK have been encouraging in that they indicate that such a model can account for virtually all of the observed travel time bias and a significant amount of the site to site variability associated with the predictions of the IDC default IASPEI91 model. Current efforts are directed toward the estimation of preliminary SSSCs for the subset of 20 Group 1 IMS stations which have been designated as the highest priority for calibration.

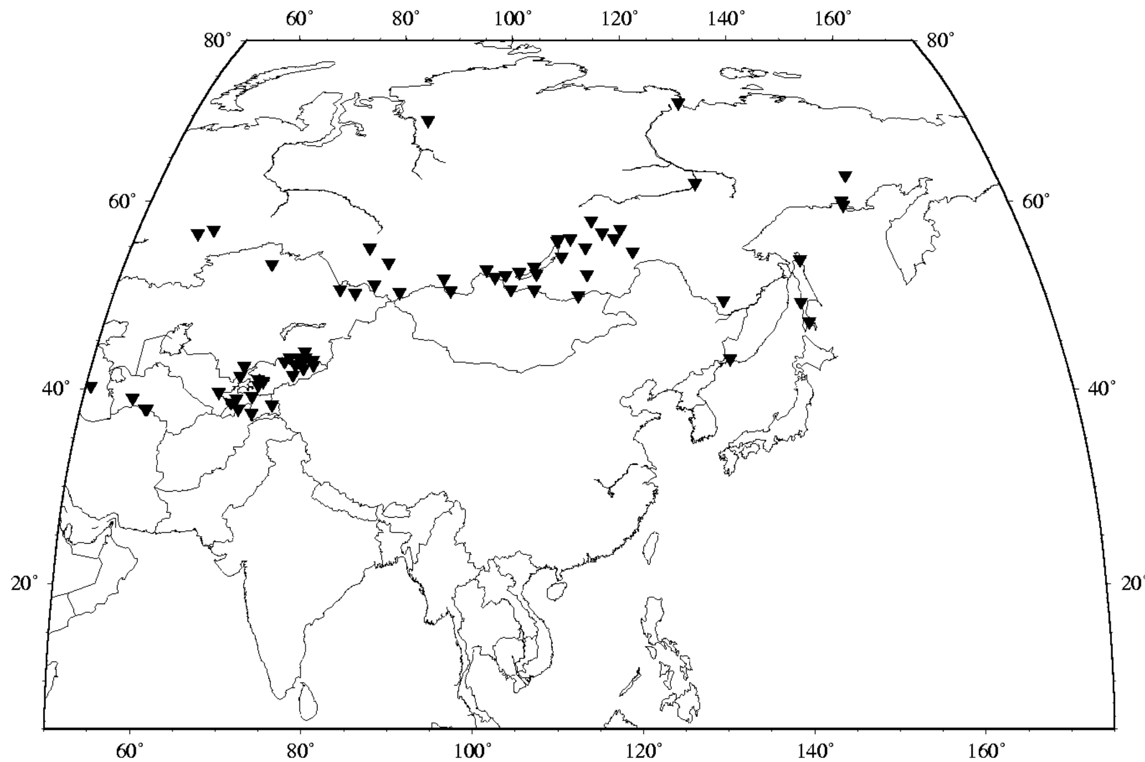

Figure 3. Map locations of U.S.S.R. permanent network stations for which travel time data are currently available from Soviet nuclear tests.

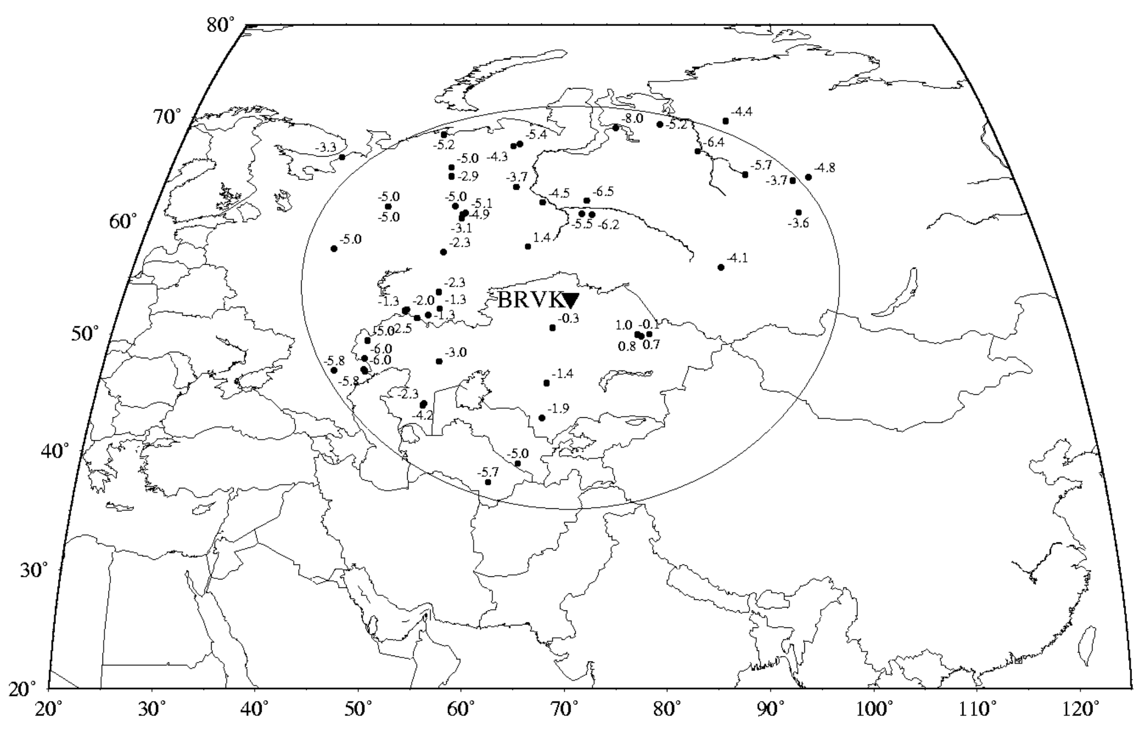

Figure 4.Map locations of regional distance underground nuclear tests recorded at IMS station location BRVK, together with associated observed travel time residuals with respect to IASPEI. The oval line marks a constant epicentral distance of 20° from BRVK.

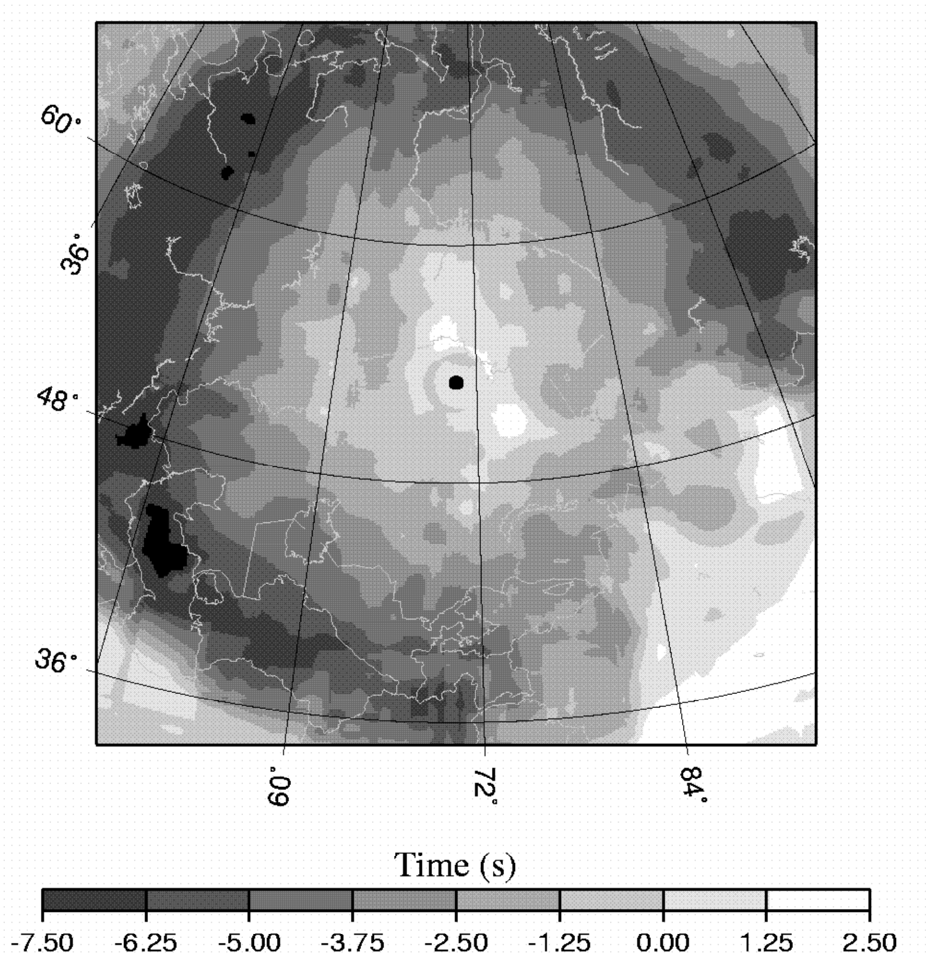

Figure 5. Surface focus SSSC for the Borovoye station computed using the DSS based 3-D velocity model for the surrounding region. Differential arrival times are computed with respect to the IDC default IASPEI91 model.

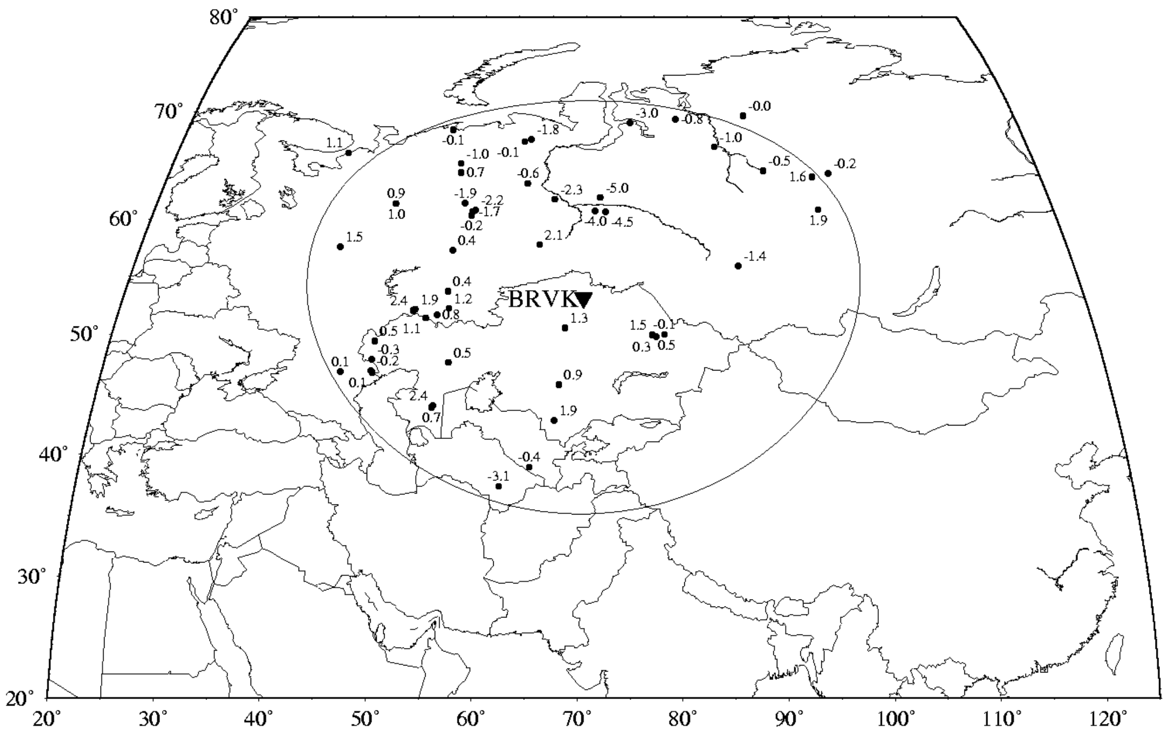

Figure 6. P wave travel time residuals for PNE ground truth events recorded at the BRVK station, computed with respect to the travel times predicted by the DSS based 3-D velocity model for the surrounding region.

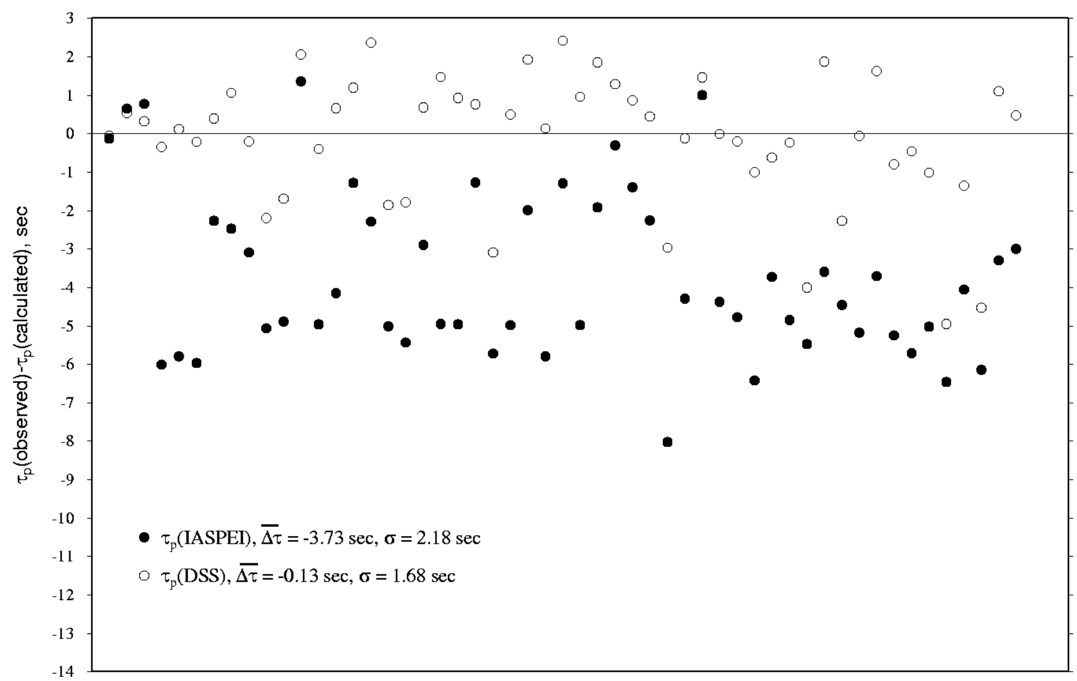

Figure 7. Comparison of P wave travel time residuals for PNE events recorded at the BRVK station, computed with respect to the IASPEI 91 and 3-D DSS velocity models, respectively.

Key Words: seismic, location, calibration, IMS, DSS, Soviet PNE, 3-D velocity models, SSSC

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