INTERNATIONAL MONITORING SYSTEM LOCATION ACCURACY IMPROVEMENT IN NORTH AMERICA AND NORTHWESTERN EURASIA USING SOURCE-SPECIFIC STATION CORRECTIONS (3-D) FOR Pn, Sn, AND Pg PHASES

Russian Federation/United States Calibration Working Group*

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ABSTRACT

This study was carried out under the United States/Russian Federation (US/RF) Joint Program of Seismic Calibration of the International Monitoring System (IMS) in Northern Eurasia and North America. The main objective of the calibration efforts is to improve the IMS location accuracy of regional seismic events within North America (NA) and Northwestern Eurasia (NWE) utilizing Source-Specific Station Corrections (SSSCs) inferred from 3-D crustal and upper mantle velocity models. These corrections are hereafter referred to as SSSCs(3-D). The methodology for both NA and NWE was: 1). Collection and analysis of Pn, Sn, and Pg travel times and 1-D crustal and upper mantle velocity models, and assigning the 1-D models to tectonic regions to develop 3-D velocity models; 2). Feasibility study of 3-D travel-time modeling for development of SSSCs(3-D) corrections; 3). Relocation experiments for validation of SSSCs(3-D) developed by 3-D modeling. In the regions where no information on deep velocity structure was available, tectonic regionalization was used to extrapolate and/or interpolate seismic data from other regions where the velocity structure was known.

We developed SSSCs(3-D) for Pn, Pg, and Sn phases for IMS stations in NA and NWE and for several additional stations in NWE. Three-dimensional crustal and upper mantle P velocity models for NA and NWE were derived by fitting the models to observed travel-time residuals of Pn waves from ground truth zero (GT0) nuclear and chemical explosions, and from compiled seismic data. A 3-D modeling program “sssc2” developed by Dr. P. Firbas computes SSSCs up to 20 degrees for Pn and up to 8.5 degrees for Pg from these models. Corrections were derived for Sn by using a relationship between Pn and Sn travel times derived from ground truth (GT) events and IASPEI-91 tables. To validate the location accuracy improvement using SSSCs(3-D), we relocated four sets of calibration events for NA and NWE with approximately 90 events (announced chemical explosions and mine blasts from the Prototype International Data Centre (PIDC) GT0-GT2 database, historical nuclear explosions detonated in NWE, and GT10 events supplied by Dewey and others for western areas of the USA territory). These GT events were independent of the GT data that were used to derive the 3-D models. Results of the relocation experiments for GT0-GT2 and GT10 events in different regions of NA and NWE clearly indicate that the event location estimates were improved when SSSCs(3-D) were applied.

Generally we conclude that the application of the SSSCs(3-D) significantly reduces the error ellipse area and improves location accuracy. These corrections for NA have been accepted by the Configuration Control Board (CCB) of the PIDC to calibrate locations for IMS stations in NA. For the Lg phase, we propose that the existing corrections continue to be used. For teleseismic phases, no corrections have been developed for IMS stations in NA.

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KEY WORDS: earth crust, upper mantle, velocity structure, event location.

OBJECTIVE

The International Monitoring System (IMS) is being developed for global monitoring under the Comprehensive Nuclear-Test-Ban Treaty (CTBT). To help fulfill this task, seismic events should be located with high accuracy. To achieve the CTBT goal of 1000 km^2 location accuracy the IMS has to be calibrated, i.e.travel-times of seismic waves used in the location must take into account the 3-D structure of the Earth. This work is focused on calibration of IMS stations in NA and NWE. The main objectives are the following: 1). Pn travel-times data collection and analysis for different tectonic provinces of North America and Northwestern Eurasia; 2). Application of 3-D modeling for location of regional seismic events; 3). Demonstration of improvements achieved in location accuracy when 3-D models are used.

This work was carried out as part of the United States/Russian Federation (US/RF) Joint Program of Seismic Calibration of the International Monitoring System (IMS) in NWE and NA. This cooperation is useful irrespective of the CTBT.

RESEARCH ACCOMPLISHED

Our goal was to derive a 3-D crustal and upper mantle velocity model for continental NA and NWE capable of predicting Pn travel-times with an accuracy of approximately 1.0 s (RMS). The simplest 3-D velocity models were sought from a family of 3-D models that simultaneously fit the observed Pn travel-times for 8 GT0 events (nuclear and large chemical explosions) in NA and 20 GT0 events (nuclear explosions) and Fennolora long-range profile observational data for NWE. Figure 1 (top and bottom, respectively) shows the good coverage by deep seismic studies for southern and central regions of NA and for large parts of NWE.

The computer program “sssc2” (Firbas, 1997) was used to compute the SSSCs(3-D) for Pn and Pg, up to distances of 20 degrees and 8.5 degrees, respectively, based on developed 3-D velocity models. The methodology of location calibration based on 3-D modeling was recently summarized and published (Firbas, 2000; Ryaboy et al., 2001). The parametrization of the 3-D model employs an approach that allows combination of the best velocity information available from multiple sources. Block parametrization (i.e., division of geographic regions into blocks) is combined with a parametrization based on interpolation and permits substantial features of the Earth’s heterogeneities to be represented, including a laterally heterogeneous crust, an arbitrary curved Moho discontinuity, and a heterogeneous upper mantle. The base model covers the entire Earth and thus the SSSCs(3-D) for both regional and teleseismic phases can be consistently computed. All elements of the model (crust, Moho, uppermost mantle, etc.) are represented independently. An advantage of this approach is that the number of parameters to be varied during the iterative search for an improved 3-D model can be kept small and, furthermore, these parameters always have a clear physical interpretation.

As the first step, the initial 3-D models for P-waves for NA and NWE were based on a model of the Earth’s crust, CRUST 5.1 (Mooney et al., 1998), on Moho depths (Braile et al., 1989), and on the upper mantle velocity model RUM (Gudmundsson and Sambridge, 1998). As starting model for western areas of NWE, the 3-D model for P-waves developed by (Firbas, 1997a) was also used. In the search for the simplest 3-D model fitting the available data, the most accurate information (3-D crustal velocity model and the Moho depth) was kept fixed. The 3-D upper mantle velocity models of NA and NWE were then adjusted iteratively by comparisons of calculated and observed Pn travel times. Calculated Pn residuals based on the 3-D velocity models were tested against the maps of observed travel-time residuals and improvements to the 3-D model were made where necessary (Gordon et al., 2001; Ryaboy et al. 2001). This iterative procedure was quite straightforward, as the number of varied parameters could be kept relatively low. First, the 1-D velocity-depth sections were kept fixed and just the boundaries between tectonic units in the upper mantle were moved as needed. When the movement of the boundaries in the 2 x 2 degrees resolution model did not bring any further substantial improvements, new 1-D velocity-depth sections were added and/or existing 1-D velocity-depth sections were modified. We extrapolated 1-D velocity models within regions with similar geological structure. The 3-D velocity models fit the observed Pn travel times with a precision of 1 s (RMS). Figure 2 (top and bottom) shows proposed maps of the upper mantle velocity regionalization of NA and NWE, respectively. The 3-D crustal and upper mantle velocity models developed for NA and NWE (Gordon et al., 2001; Ryaboy et al. 2001) were used to produce maps of the SSSCs(3-D) for Pn and Pg for IMS stations and for several additional stations in NWE.

The SSSCs(3-D) for Sn waves were calculated from the SSSCs(3-D) for Pn waves using a relationship between Pn and Sn travel-times inferred from the Center for Monitoring Research (CMR) GT database and the IASPEI-91 travel-time tables. It is known that Vp/Vs ratio depends on many factors including depth and tectonic province (Alekseev et al., 1988; Hauser and Stangle, 1990). Since Vp/Vs ratio depends on depth, simple scaling of Pn travel times directly into Sn travel times is not possible as the Vp/Vs dependency on depth implies that Pn and Sn waves for the same station - source pair do not propagate along the same raypath. Statistically significant correlation was found between ratios TSn/TSn_iasp91 and TPn/Tpn_iasp91, where TSn and TPn are measured travel-times for GT events and TSn_iasp91 and TPn_iasp91 are corresponding IASPEI travel-times. A function was fitted to the distribution of all available points (TPn/Tpn_iasp91, TSn/TSn_iasp91) based on the CMR GT database. The correlation coefficient for this fit was 0.75, high enough to allow usage of this polynomial function for conversion of predicted Pn travel times into predicted Sn travel times. This approach, together with conservative estimates of modeling errors, proved to be successful and the location quality remained on the same level when TSn travel times were added to the locations based on Pn and Pg travel-times only.

We did not use the Lg phase in NWE due to large errors of discovered in arrival-time measurements. However, for NA, in agreement with current Prototype International Data Center (PIDC) procedures, we have used either CMR Lg travel times without SSSCs (for IASPEI-91) or Lg travel-times with SSSCs(1-D) (Yang and McLaughlin, 2000) as appropriate. Figures 3 and 4 show, as examples, the SSSCs(3-D) and modeling errors maps calculated for Pn waves for two IMS stations: PDAR (NA) and OBN (NWE). 1-D velocity-depth sections for the mantle were assigned to every grid point on 2x2 degree grid and the 3-D velocity distribution at any point is the linear interpolation of the four nearest 1-D velocity-depth sections. To obtain a reasonable resolution and size of the SSSCs files even for stations in northern areas, we calculated time corrections and modeling errors with different latitude/longitude grids for each station. SSSCs(3-D) files have grid 0.5 degree for latitude axis. Grid for the longitude axis has a constant value for each station within the range 0.5 degree to 1.2 degree depending on the latitude of the station.

To validate the calculated SSSCs(3-D) we have used two data sets of GT0-GT10 events for NA and two data sets of GT0 and GT2 for NWE. All these events were used only for relocation experiments and were not used for development of 3-D velocity models. We performed a careful analysis of travel times and, on occasion, waveforms to identify outliers at the level of events and at the level of individual arrivals, with the goal of eliminating their undue influence on the relocation experiments. Data quality analysis (visual inspection) of the GT0 and GT2 events for NA using waveforms (Baumgardt et al., 2000) largely confirms our results regarding identification of outliers based on the travel-times analysis. Altogether 15 GT0-GT2 events (mainly announced chemical explosions) were found for NA to have a sufficient amount of reliable regional arrival-time data to be used for the relocation experiments using regional phases only. The second data set for NA includes 29 GT10 events from the US calibration event data set with REB arrivals (Dewey et al., 1999). Figure 5 (top) shows the location of GT events used for relocation experiments in NA. Two sets of GT0-GT2 events were used for relocation experiments within Northern Eurasia. The first set of events includes 31 GT0-GT2 events from PIDC GT database, and the second set of events consists of 17 nuclear explosions detonated within western areas of NWE from 1965 to 1988 (Figure 5 bottom). These explosions were detonated when the IMS network did not exist, and we calculated SSSCs(3-D) and used for relocation experiments additional stations (“surrogate” IMS stations) located at distances of 150-200 km on average from the current IMS stations.

Relocation experiments were performed to evaluate the impact of the SSSCs(3-D) for Pn, Pg, and Sn on regional seismic event locations within NA and western areas of NWE and to asses the improvement both in terms of location accuracy and in the reduction of the size (area) of the 90% error ellipses. In line with the current PIDC procedures we used for NA all phases (i.e. regional Pn, Pg, Sn and Lg as well as the teleseismic phases). However, we used for relocation experiments within western areas of NWE only Pn, Sn, and Pg phases. The approach for the measurement errors used was identical to the current PIDC practice. As we are not proposing new SSSCs corrections for Lg, we used for North America either uncorrected Lg travel times or SSSCs(1-D) for Lg (Yang and McLaughlin, 2000). LocSAT program was used for the relocation experiments.

Results of the relocation experiments for GT0, GT2 and GT10 events located in different regions of NA and NWE clearly indicate that the event location estimates were improved when the SSSCs(3-D) were applied. For GT0 - GT2 data for NA was found that the median mislocation changed from 9.3 km for IASPEI-91 to 6.2 km for SSSCs(3-D), and the median 90% error ellipse area decreased from 2,011 km^2 for IASPEI-91 to 754 km^2 for SSSCs(3-D). For GT10 events in NA the median mislocation decreased from 16.7 km or IASPEI-91 to 11.4 km for SSSCs(3-D), and the median 90% error ellipse area decreased from 1,802 km^2 for IASPEI-91 to 725 km^2 for SSSCs(3-D). It is very encouraging that when using the initial SSSCs(3-D) fir 31 GT0-GT2 events in NWE the median mislocation decreased from 17.3 km for IASPEI-91 to 7.7 km for SSSCs(3-D), and the median 90% error ellipse area decreased from 4,113 km^2 for IASPEI-91 to 873 km^2 for SSSCs(3-D). For 17 nuclear explosions detonated within NWE the median mislocation decreased from 22.5 km for IASPEI-91 to 8.9 km for SSSCs(3-D), and the median 90% error ellipse area decreased from 2,811 km^2 for IASPEI-91 to 662 km^2 for SSSCs(3-D).

CONCLUSIONS

1. A 3-D crustal and upper mantle velocity models for NA and western areas of NWE based on previous results of deep seismic studies and derived by fitting 3-D velocity models to observed travel-time residuals of Pn waves from GT0-GT2 nuclear and chemical explosions were created to generate SSSCs(3-D).

2. SSSCs(3-D) for IMS stations in N A and for IMS stations and additional stations in western areas of NWE for Pn, Pg, and Sn phases are proposed based on the models in (1). SSSCs(3-D) corrections for Sn phase were derived by using a relationship between Pn and Sn travel-times derived from ground truth (GT) database and IASPEI-91 tables.

3. To validate the location accuracy improvement of the SSSCs(3-D), we relocated for NA a set of 15 GT0-GT2 events (announced chemical explosions and mine blasts) from the PIDC GT database and a set of 29 GT10 events supplied by Dewey et al. (1999). For western areas of NWE we relocated two sets of GT0-GT2 events: first set of the events includes 31 GT0-GT2 events from the CMR GT database, and the second set of events consists of 17 nuclear explosions detonated from 1965 to 1988.

4. The validation of the SSSCs(3-D) based on the comparison of the travel-times for the high quality GT0 events (mostly nuclear explosions) confirms that the predictions of the Pn travel-times using 3-D velocity models are of high quality (RMS 1.0-1.5 s).

5. Generally, we conclude that the application of the SSSCs(3-D) significantly improved location accuracy and reduced 90% error ellipses. These corrections developed for NA have been accepted by the Configuration Control Board (CCB) of the PIDC to calibrate locations for IMS stations in North America. The corrections for NWE are currently under further development and testing.

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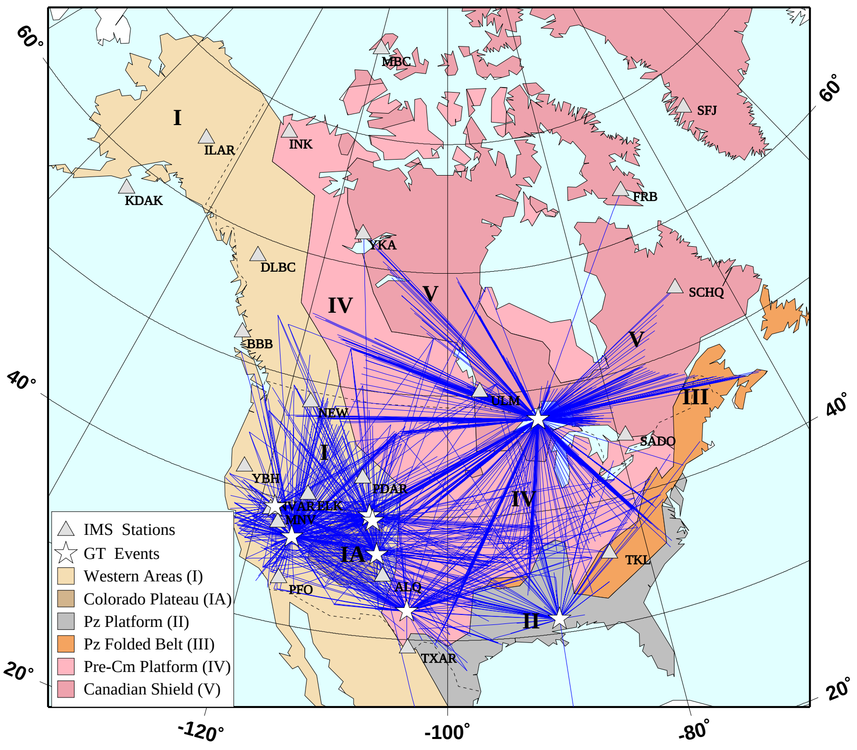
NORTH AMERICA



NORTHERN EURASIA

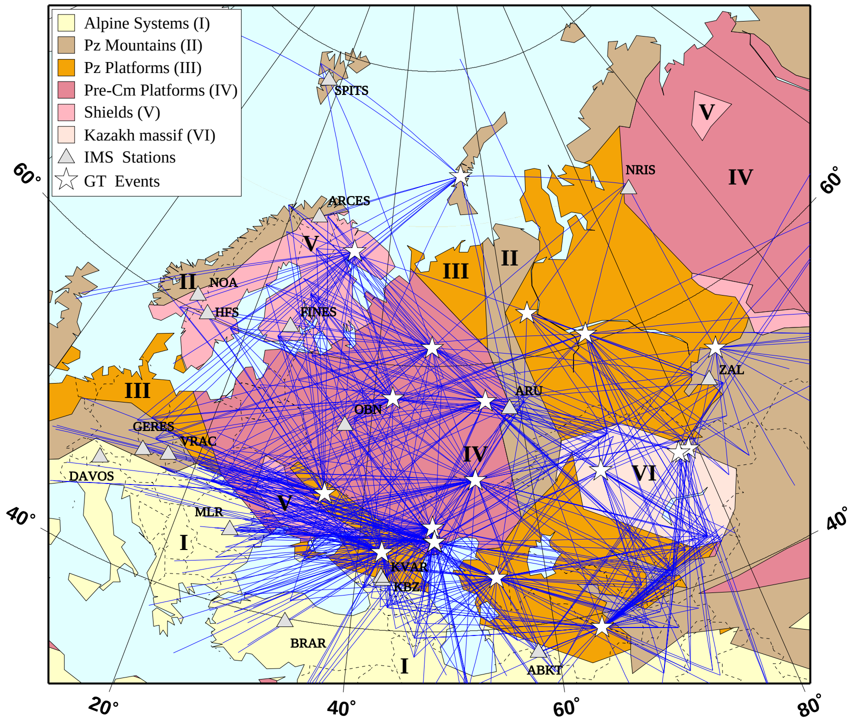
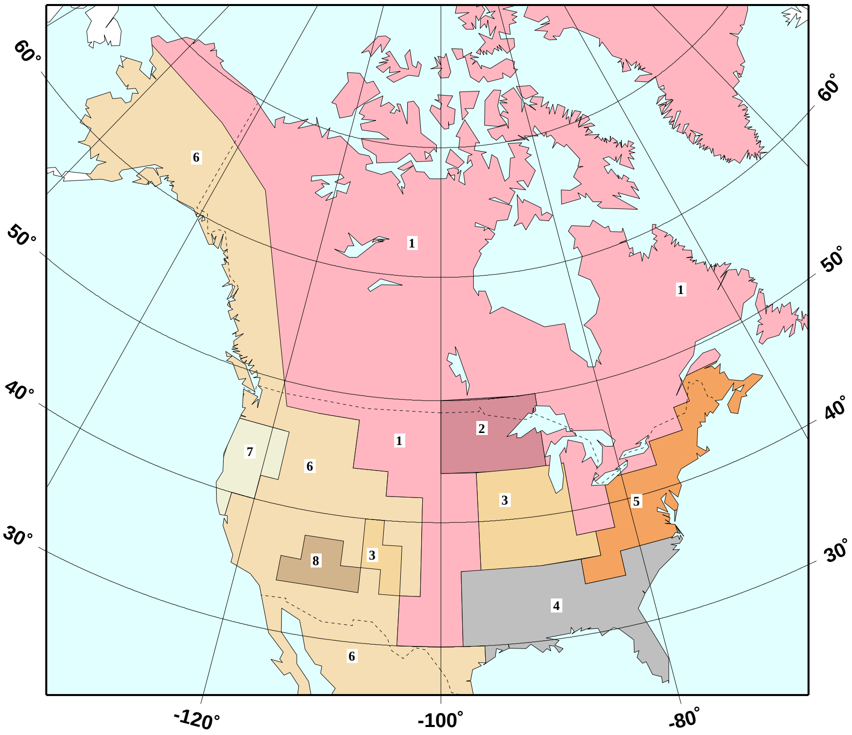


Figure 1. Calibration events used for development of 3-D velocity models. Lines are Pn event-station paths.

NORTH AMERICA



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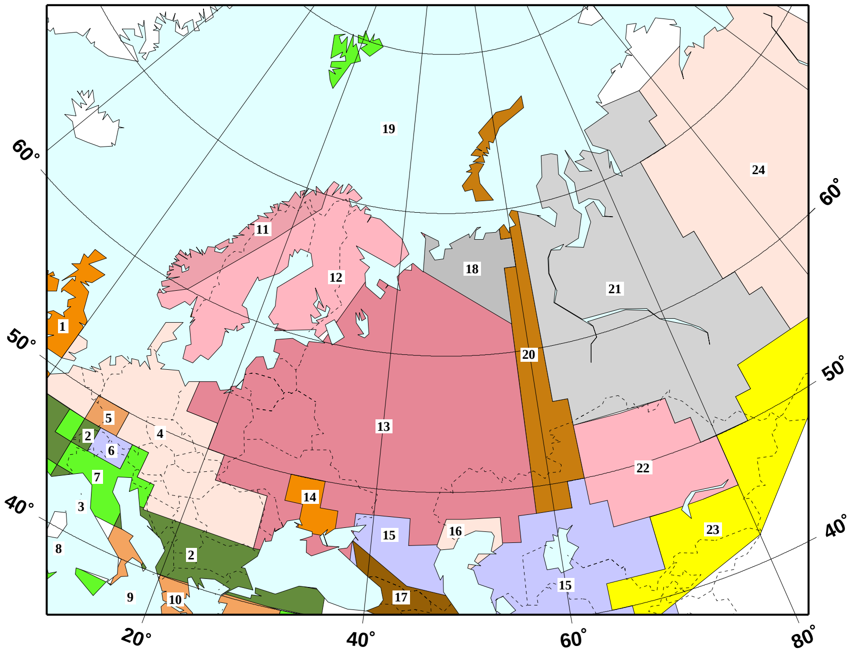
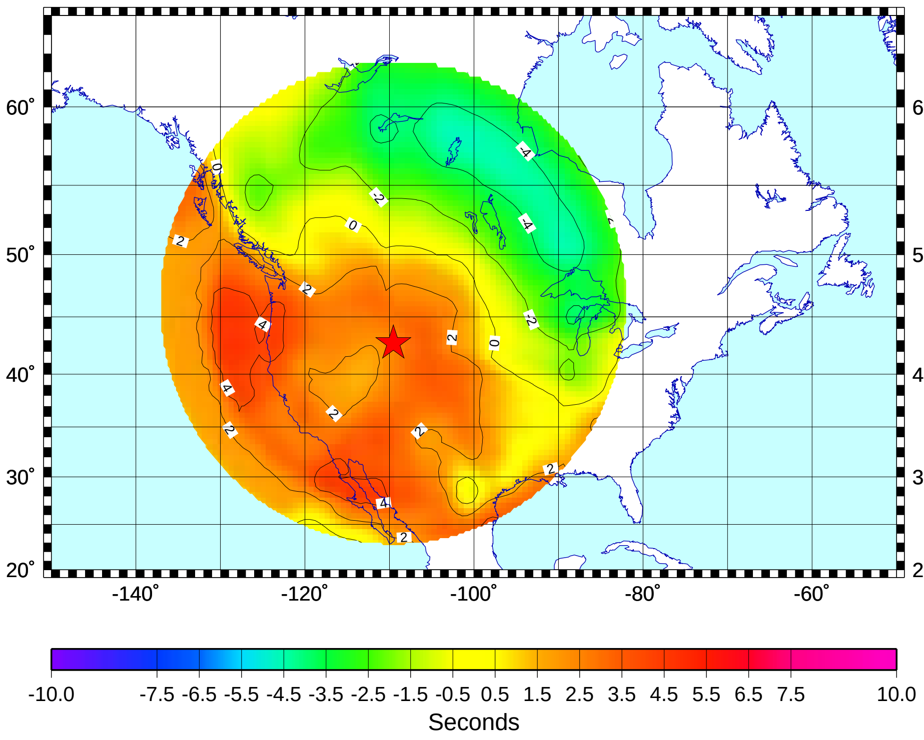


Figure 2. Upper mantle P-velocity regionalization maps. Each region is characterized by 1-D velocity model.

SSSCs for PDAR station at 42.77N 109.56W

Pn Time Deviations from IASPEI-91 (3D-model, Rev. 5.2)



Pn Modeling Errors

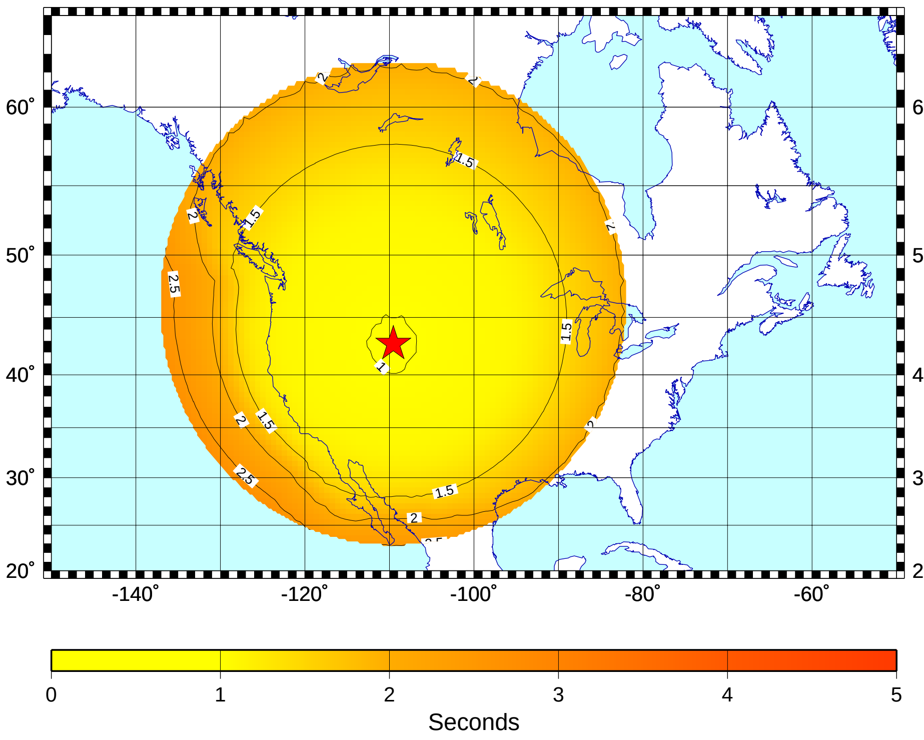
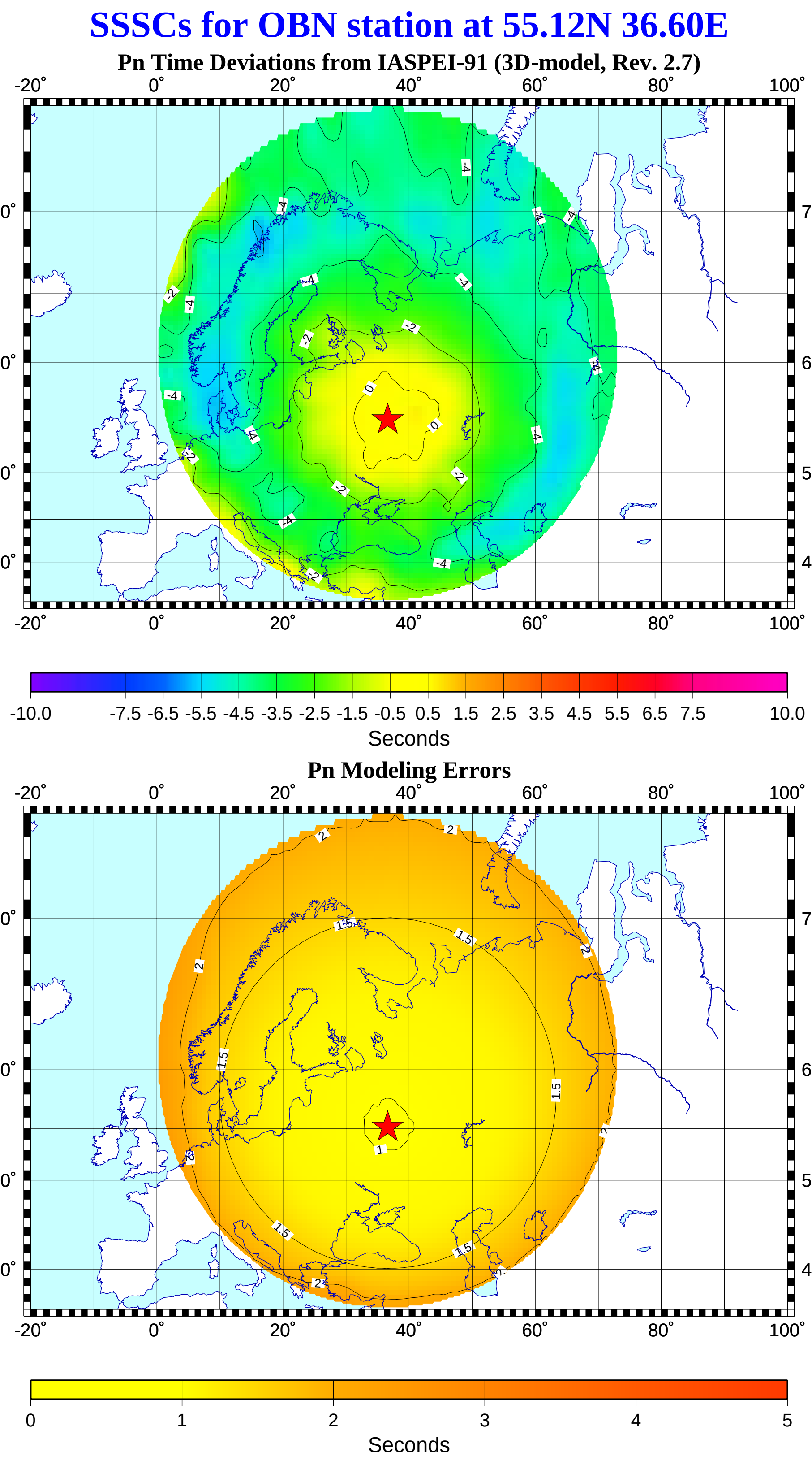


Figure 3. PDAR station, North America. Pn SSSCs and modeling errors.

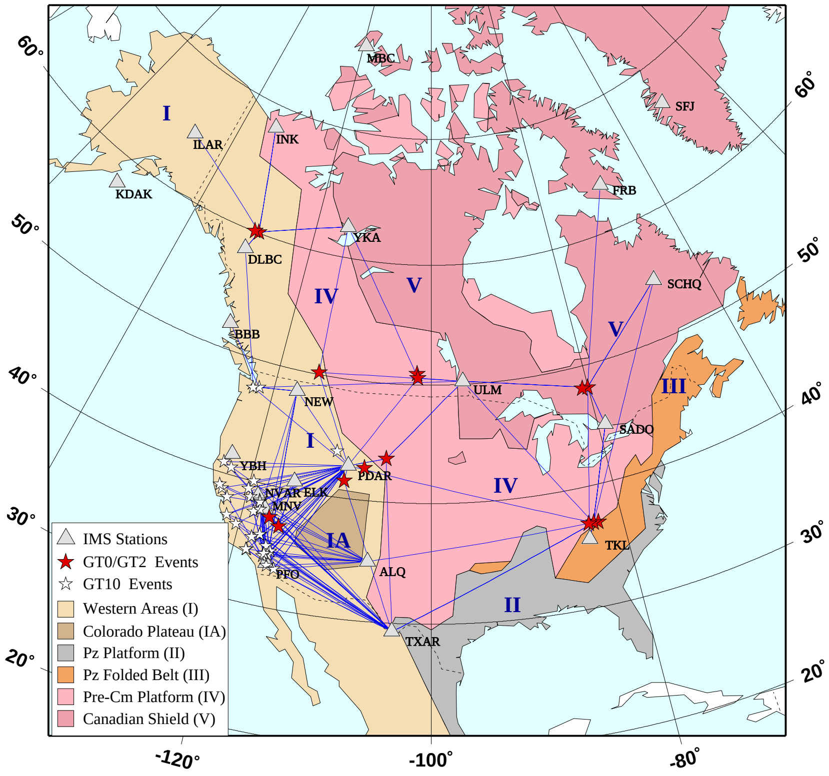

SSSCs for OBN station at 55.12N 36.60E

Pn Time Deviations from IASPEI-91 (3D-model, Rev. 2.7)

Pn Modeling Errors

Figure 4. OBN station, Northern Eurasia. Pn SSSCs and modeling errors.

NORTH AMERICA



NORTHERN EURASIA

Figure 5. GT events used for relocation experiments. Lines connect the events with seismic stations used for relocation experiments at regional distances.