SOURCE-SPECIFIC STATION CORRECTIONS FOR REGIONAL PHASES AT INTERNATIONAL MONITORING SYSTEM STATIONS

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ABSTRACT

The software at the prototype International Data Centre (pIDC) allows for a hierarchy of calibrations relevant to location improvement. The IASPEI91 global travel-time curves have been used as the default for event location at the pIDC since 1995. A series of corrections can be made, including ellipticity and elevation corrections (for each arrival), Bulk Time Station Corrections (for each station and travel-time phase), and Slowness and Azimuth Station Corrections (for each station and array). Separate regional travel-time curves (distance less than 20 degrees) may be designated for Pn, Pg, Sn, and Lg for each International Monitoring System (IMS) station. It may also use path corrections, or Source Specific Station Corrections (SSSC), to apply corrections relative to IASPEI91 as a function of source location for any station and phase. Where a single model is insufficient for characterizing the regional geology, SSSCs are more appropriate for event locations. The travel-time corrections and modeling errors are specified on a latitude/longitude grid in the pIDC location software. We have adopted an approach developed by Bondár in deriving SSSCs for regional phases. This method is based on regionalization and regional travel times for different tectonic regions surrounding each station. The predicted travel times are calculated as the weighted sum of total travel times in each region along the source-station path. The development and validation of the SSSCs rely on the 1-D regional models/regionalization and the ground truth testing events, respectively. Further development in 1-D velocity models and travel time curves can improve such SSSCs, event locations, and uncertainties. Ground truth events with high location accuracy are essential in demonstrating the expected improvement in event locations when applying SSSCs.

Fennoscandia is the only region where the 1-D travel times (Baltic model) were implemented in location processing at the pIDC. We have developed SSSCs for regional phases at the Fennoscandian stations by interpolating travel times through different 1-D models using Bondár's method. SSSCs for stations NRIS and SPITS are also derived given the fact that paths from both stations to high-latitude events are within the Fennoscandia regionalization as Baltic. Validation testing using ground truth events shows significant reduction in error ellipses by applying the SSSCs (from 3830 to 1120 km^2). When using the SSSCs mislocations have also been reduced for events outside the shield while the improvement within the shield is similar to that using the 1-D Baltic model (9 km improvement on average for GT2 events). The SSSCs for these stations were implemented at the pIDC for Reviewed Event Bulletin (REB) location in April 1999.

Regional SSSCs for North American IMS stations have been developed and have undergone initial testing by Bondár. For ground truth events with location accuracy better than 10 km, the median improvement in location due to SSSCs is 7 km, and the median reduction of error ellipse areas is about 800 km^2 (from 3700 to 2900 km^2). Currently we are evaluating the 1-D travel times and regionalization used in deriving the SSSCs for the North American IMS stations. We are also collecting high-quality ground truth events in North America for further validation testing of the SSSCs.

Key Words: prototype International Data Centre, pIDC, IASPEI91, SSSCs, location, calibration, 1-D model, travel times, Baltic model, Fennoscandia, North America, International Monitoring System, Reviewed Event Bulletin.

OBJECTIVES

Our goal is to improve event locations using regional travel time corrections for IMS stations relative to the IASPEI91 model. Miss-locations and error ellipses have recently been reduced in Fennoscandia region by operational use of regional SSSCs at stations ARCES, FINES, HFS, NOA, NRIS, and SPITS (Yang and McLaughlin, 1999a). Similarly we develop regional SSSCs in North America based on regionalization and 1-D models to reflect the differences in geology and tectonics in eastern and western North America. New regional SSSCs are derived for 21 IMS stations in North America, including ALQ, BBB, DLBC, ELK, FRB, ILAR, INK, KDAK, MBC, MNV, NEW, PDAR, PFO, SADO, SCHQ, SFJ, TKL, TXAR, ULM, YBH, and YKA. Validation testing for regional SSSCs in North America is conducted using ground truth events to verify event location improvement relative to GT and location error ellipse coverage.

TRAVE LTIMES FOR 1-D MODELS IN NORTH AMERICA

We employ regionalized 1D models in deriving the regional SSSCs for the IMS stations in North America (distance less than 20 degrees). The travel time corrections are a weighted sum of the travel times in each region along the source-station path (Bondár et al., 1998; Yang et al., 1998). There are large variations in upper mantle (Moho to 300 km) velocity structures and travel times between the stable central/eastern and the tectonic western North America. The upper mantle velocities are low in the tectonic region and high in the shield/platform region. We collected and compared a number of velocity models/travel times in search of suitable models to use for SSSCs in North America. In the shield/platform region of North America there may be no or only a thin low velocity zone. In contrast, there may be a thick low velocity zone below tectonic western North America. Compared to the IASPEI91 model, the travel times are up to 4 seconds faster in the stable region but are up to 3 seconds slower in the tectonic region than the IASPE91. In this paper we summarize our findings and more details are given in Yang and McLaughlin (1999b).

Western North America. We collected 15 velocity models/travel times for tectonic western North America from the literature and a number of agencies. For instance, Archambeau et al. (1969) constructed P-wave velocity models of the upper mantle, CIT109, CIT110, CIT111, and CIT112 from LRSM profiles running east-southeast and east-northeast from two nuclear explosions (Shoal and Bilby) and an earthquake (Fallon) in Nevada. Their Moho Pn velocities range from 7.72 to 8.048 km/s. Archambeau et al. modeled the arrival times of Pn out to 1200 km and used an upper mantle triplication to explain Pn from 1200 to 2000 km. Their data and models serve as an excellent set of travel times for seismic sections starting in Nevada and ending in the eastern shield and platform regions. The CIT111 model is slow at distances less than 10 degrees and then becomes fast at distances greater than 10 degrees. This model seems particularly suitable for paths across different geology regions in North America. ISC data for six GT0 Nevada nuclear tests and an earthquake at Borah Peak in 1983 (ground truth information is available for all 7 events) generally agree with the CIT111 model, but there are no data beyond 12 degrees. Kovarch and Robinson (1969) derived an S velocity model (STAN3) for the Basin and Range province of western North America using LRSM array data. Their S model (Sn of 4.5 km/s) is compatible with P velocity models of Archambeau et al. (1969). The STAN3 mode is roughly the median of the group of S travel time curves that we compiled for western North America.

Eastern North America. Over 15 velocity models/travel times are collected from the literature and a number of agencies. In general the shield models in North America as well as in other regions are in good agreement with each other; they are all faster than the IASPEI91 model. For instance, Kremenetskaya and Asming (1999) extended the NORSAR model (e.g. Ringdal et al., 1997) for the general Barents Sea region. The median of our compiled travel times for eastern North America are almost identical to those generated using the Barents Sea model. ISC arrival time data for 54 well-located events in eastern North America also generally agree with the shield model. For Sn in

North America, the travel times for the Barents Sea model are within a reasonable range of other curves.

Regionalization. Mooney et al. (1998) compiled crustal data from the literature to produce a 5 degree by 5 degree grid of discrete models for the globe. Their goal was to compile regionalized crustal thicknesses and velocities for inclusion in worldwide tomographic inversions. Compilation of upper mantle Pn velocities was a secondary goal to their study. The 139 discrete models span a range of Pn velocity of 7.9 to 8.2 km/s. Mooney et al. report that this is only a fraction of the worldwide range from 7.6 to 8.6 km/s. Models assigned to stable North America have Pn velocities of 8.0 - 8.2 km/s. Models assigned to western tectonic North America are assigned Pn values of 7.9 to 8.0 km/s. Pn velocities below 7.8 km/s reported by many authors for the region are not represented. Braile et al. (1989) provided a summary on Pn velocity, crustal thickness, and average crustal P velocity in the US and adjacent Canada from the literature. Their contour maps clearly show variations across the continent corresponding to the geological and tectonic features. From the west to the east the medians are about 35 to 40 km in crustal thickness, 7.8 to 8.1 km/s in Pn velocity, and 6.2 to 6.4 km/s in average crustal P velocity. From Braile et al. map of Pn velocities we can see that it is not possible to construct a path greater than 10 degrees from the tectonic west to the stable east without crossing the 8.0 km/s contours.

Pg and Lg. Fewer studies are available for Pg and Lg velocity models and these phase detections are less common than Pn and Sn. We use velocities of 6.2 km/s for Pg and 3.55 km/s for Lg for the tectonic region, and velocities of 6.4 km/s for Pg and 3.6 km/s for Lg for the shield/platform region. The Pg velocities are roughly the medians of the average crustal velocities for the eastern and western North America, respectively, given in Braile et al. (1989). The Pg and Lg modeling errors for the Baltic model were used as guide for the Pg and Lg errors in North America.

Selected Models. Based on our review of the literature and examination of recent data, we chose the Barents Sea model for both Pn and Sn in the shield/platform region, and CIT111 for Pn and STAN3 for Sn for the western tectonic region. We construct modeling errors using the standard deviations of each model relative to the median of each group of our compiled models (10 for Pn and 6 for Sn in eastern North America; 11 for Pn and 7 for Sn in western North America). The modeling errors also account for the expected variations due to the difference in crustal thickness: 0.25 seconds for Pn, assuming a crust thickness of 7 km, and P velocities of 6.5 and 8.2 km/s; 0.4 second for Sn, assuming a crust thickness of 7 km, and S velocities of 3.58 and 4.5 km/s. Figure 1 shows the Pn, Sn, Pg, and Lg travel times and modeling errors for the shied/platform region. Figure 2 shows those for the tectonic region.

The regionalization of North America is shown in Figure 3. For the US (except Alaska) we use the Braile et al. Pn map to outline the tectonic region following contours of ~ 8.0 km/s. We extended this tectonic region slightly further north to include Vancouver Island where reported velocities are low. In this tectonic region the CIT111 and STAN3 models are used for Pn and Sn, respectively. We use faster travel times for the rest of North America, including eastern US, most of Canada, and Alaska. Although Alaska is far more complex than the shield geologically, there are reports that the P velocity in Alaska is higher than 8.1 km/s. However, currently only GT10 events are available in our ground truth data set for validation testing for this region and only one or two IMS stations are within regional distances for each event. The Alaska/Yukon region requires additional study.

RELOCATIONS USING REGIONAL SSSCs AT NORTH AMERICAN IMS STATIONS

We have derived SSSCs for Pn, Sn, Pg, and Lg for IMS stations in North America using Bondár's method. In our regionalization, North America is divided into two regions, stable shield/platform region and tectonic region (Figure 3). We use travel times faster than IASPEI91 for the shield/platform region (Figure 1), and travel times slower than IASPEI91 for the western tectonic region (Figure 2). Modeling errors are also shown in Figures 1 and 2. An example of Pn, Sn, Pg, and Lg SSSCs and modeling errors are given in Figures 4 and 5 for IMS station PDAR.

We relocated events in the same ground truth data set as studied by Bondár et al. (1998). We reassign the 34 P and 4 S defining phases with distances less than 20 degrees to Pn and Sn, respectively. Among the 49 events in the US (excluding Alaska), the testing and validation metrics are as follows:

- 55% of events moved closer to the GT locations with a median improvement of 5.5 km,
- 45% of events moved away from the GT with a median deterioration of 4.2 km,
- 31% of events moved closer to GT by 20% with a median of 10.8 km,
- 33% of events moved away from GT by 20% with a median of 6.3 km,
- error ellipse areas decreased for 92% of events, with a median decrease of 760 (from 1760 to 910),
- the 90% ellipse area coverage decreased by 10% (from 84% to 74%).

Given that most of the validation events are GT10 and the median miss-location distance is 15 km, we would expect the coverage to be significantly less than 90%. Assuming we were comparing to GT0, the sampling statistics would expect coverage between 75% and 100% at the 1 sigma level, and we do not consider the reduction in coverage as statistically significant. The results further emphasize the need for ground truth events better than GT10.

Among the 49 events in the data set, 21 events are GT2 or better (including 4 GT0 events). For these GT0-GT2 events, the median improvement of GT locations is 9.7 km and the median deterioration is 4.7 km; the median improvement and deterioration by 20% are 11.6 km and 8.9 km, respectively. The error ellipses for all these events are smaller by at least 20% with a median improvement of 1740 . Ground truth events with accuracies better than 5 km are vital for validation testing of location improvement using SSSCs.

We further relocated two recent GT2 events at NTS (Figure 6). Both are earthquakes that occurred in January 1999. Using SSSCs both events moved closer to the GT locations. For the event on 01/25/99 the miss-location decreased from 10 km to 6.7 km; for the event on 01/27/99 the miss-location decreased from 14 km to 8.6 km. In particular, the error ellipse for the 01/27/99 event now includes the GT location. In both cases the error ellipses are significantly smaller when using SSSCs.

CONCLUSIONS

SSSCs were implemented for the Fennoscandia region to improve event locations at the PIDC in April 1999. We are currently developing SSSCs for North American IMS stations using regionalized travel times. Validation testing using ground truth events shows that event locations are improved using SSSCs and location error ellipses are significantly reduced. Compared with previous studies using different regionalization and travel times, the location results here show better improvement. In particular, median deterioration is reduced. The validation testing further emphasizes that ground truth events with accuracies better than 5 km are important for validation testing of SSSCs to event locations.

REFERENCES

Archambeau, C. B, E. A. Flinn, and D. G. Lambert (1969), Fine Structure of the Upper Mantle, J. Geophy. Res., 74, 5825-5865.

Bondár, I, X. Yang, K. McLaughlin, R. North, V. Ryaboy, and W. Nagy (1998), Source Specific Station Corrections for regional phases at IMS stations in North America and Fennoscandia, EOS Trans. AGU, 79(45), Fall Meet. Supple., F839.

Braile, L.W., W.J. Hinze, R.R.B. von Frese, and R.G. Keller (1989), Seismic properties of the crust and uppermost mantle of the conterminous United States and adjacent Canada, Memoir-Geol. Soc. Am., 172, 655-680.

Kovach, R.L., and R. Robinson (1969), Upper mantle structure in the Basin and Range province, western North America, from the apparent velocities, Bull. Seismo. Soc. Am., 59, 1653-1665.

Kremenetskaya, E., and V. Asming (1999), Location calibration of the Barents region, Calibration Workshop, January 12-14, Oslo, Norway.

Ringdal, F., E. Kremenetstkaya, V. Asming, and Y. Filatov (1997), Study of seismic travel time models for the Barents region, NORSAR Sci. Rep. 2-96/97, 102-114.

Yang, X., K. McLaughlin, and R. North (1998), SSSCs for regional phases at IMS stations in North America and Fennoscandia, CMR Technical Report, CMR-98/46.

Yang, X. and K. McLaughlin (1999a), SSSCs for regional phases at Fennoscandian and other stations, CCB memo, CCB-PRO-99/03.

Yang, X. and K. McLaughlin (1999b), SSSCs for regional phases at North American IMS stations, CMR Technical Report (in preparation).

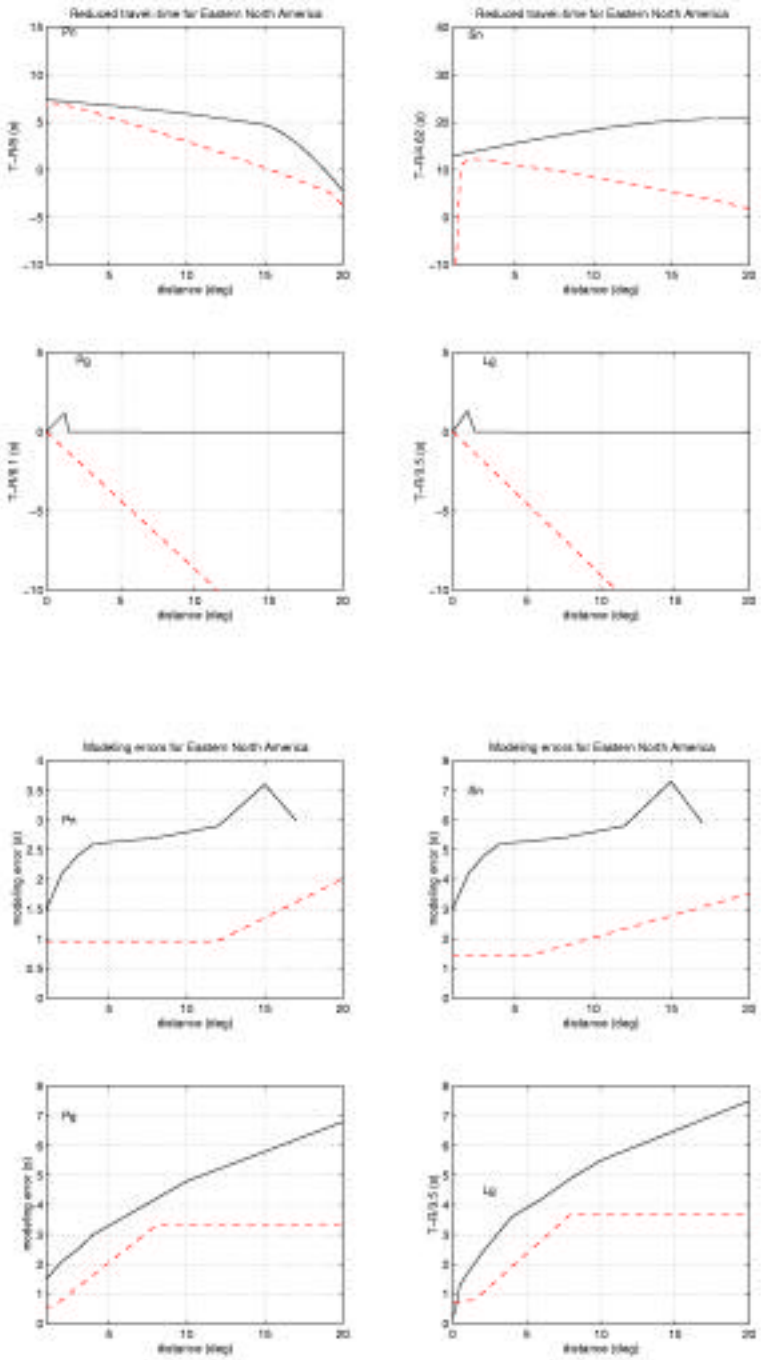

Figure 1. Pn, Sn, Pg, and Lg reduced travel time and modeling errors for eastern North America (dashed line) compared to the IASPEI91 travel times. The Pg and Lg travel times correspond to constant velocities of 6.4 km/sec and 3.6 km/sec, respectively. The Pn and Sn modeling errors are derived from the standard deviation of a suite of travel time curves (10 Pn and 6 Sn), plus expected travel time variations due to variations in crustal thickness (0.25 and 0.4 seconds, respectively). The Pg and Lg modeling errors are default values.

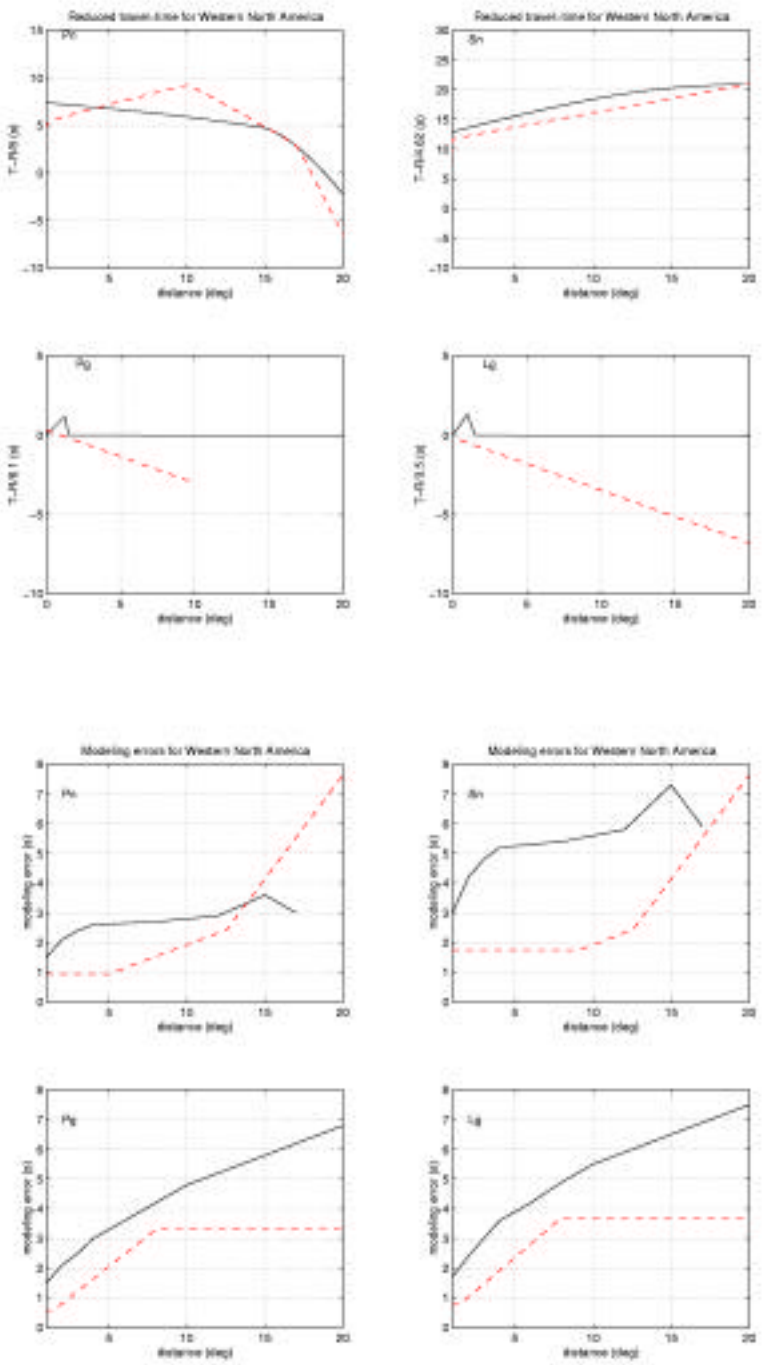

Figure 2. Pn, Sn, Pg, and Lg travel times and modeling errors that are used for SSSCs in western North America (dashed line) compared to the IASPEI91 travel times. The Pg and Lg travel times correspond to constant velocities of 6.2 km/sec and 3.55 km/sec, respectively. The Pn and Sn modeling errors are derived from the standard deviation of a suite of travel time curves (11 Pn and 7 Sn), plus travel time variations due to differences in crustal thickness (0.25 and 0.4 seconds, respectively). The Pg and Lg modeling errors are default values.

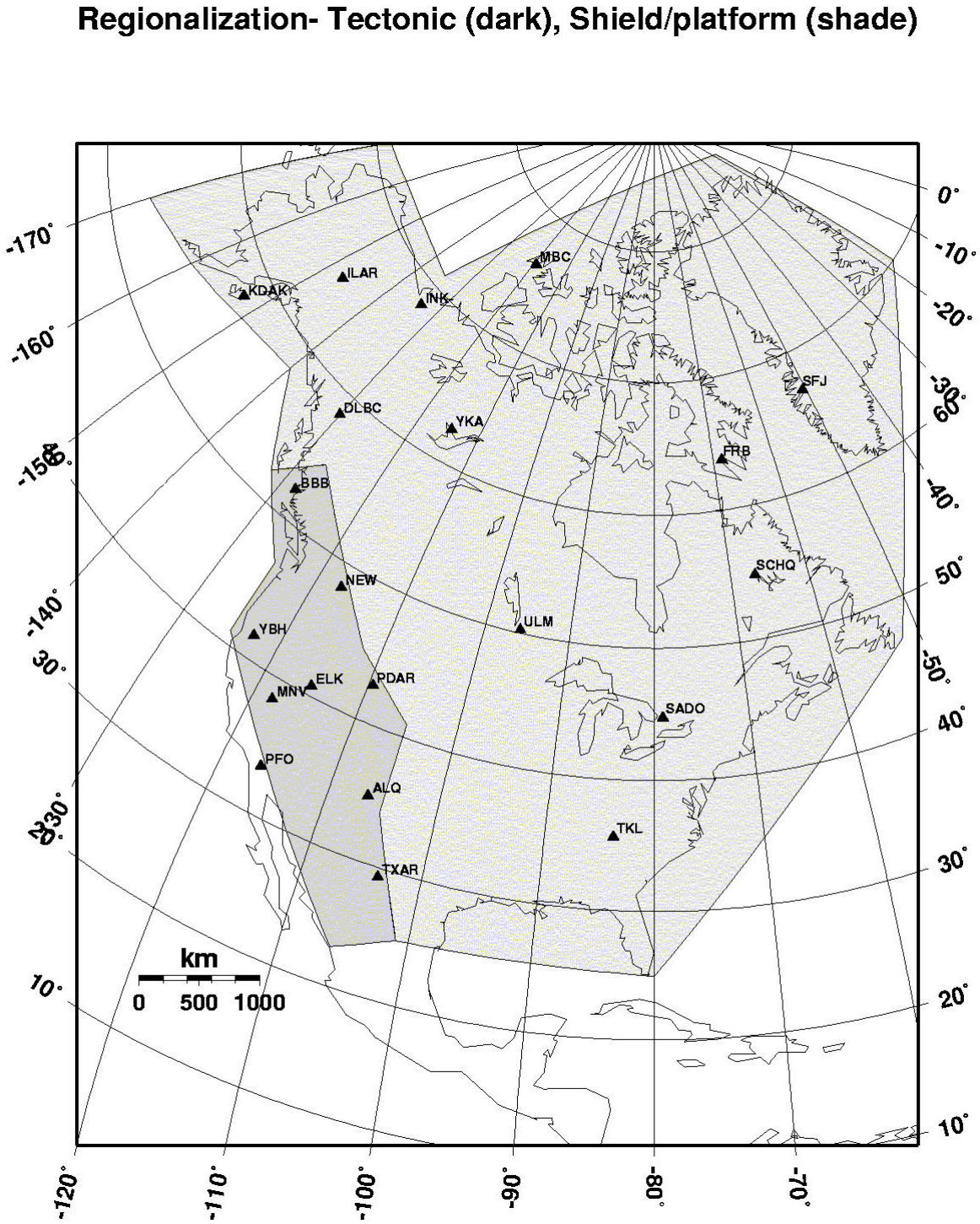

Figure 3. Regionalization of North America. In the tectonic region (dark) the CIT111 P model and the STAN3 S model are used (Figure 2). In the shield/platform region (shade) the Barents Sea model is used (Figure1). The IASPEI91 model is used for the rest of region.

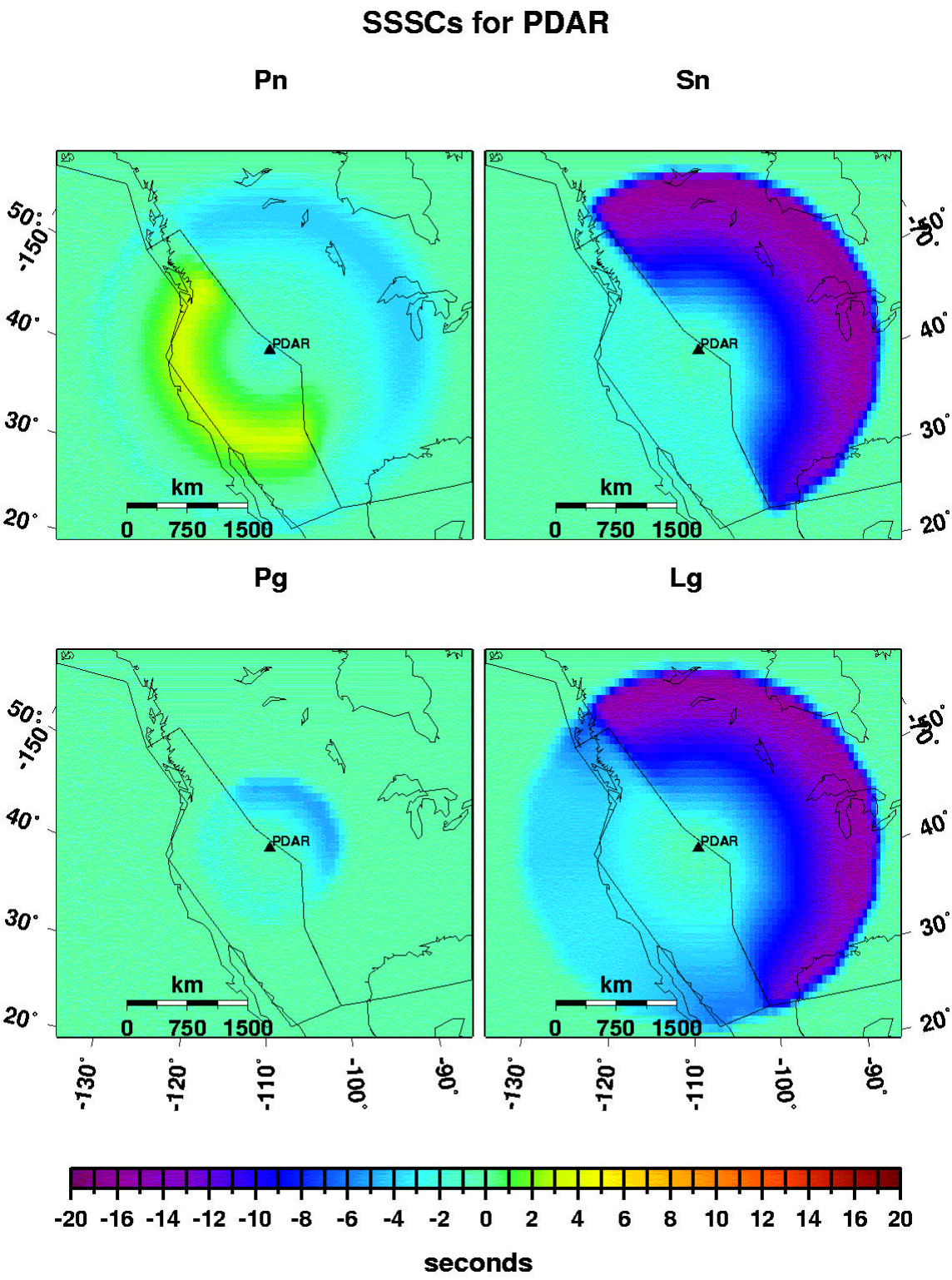

Figure 4. Pn, Sn, Pg, and Lg regional SSSCs for PDAR (Pinedale array) out to 20 degrees. Predicted travel times are fast to the east and slow to the west, so the travel time corrections are negative in the east and positive in the west.

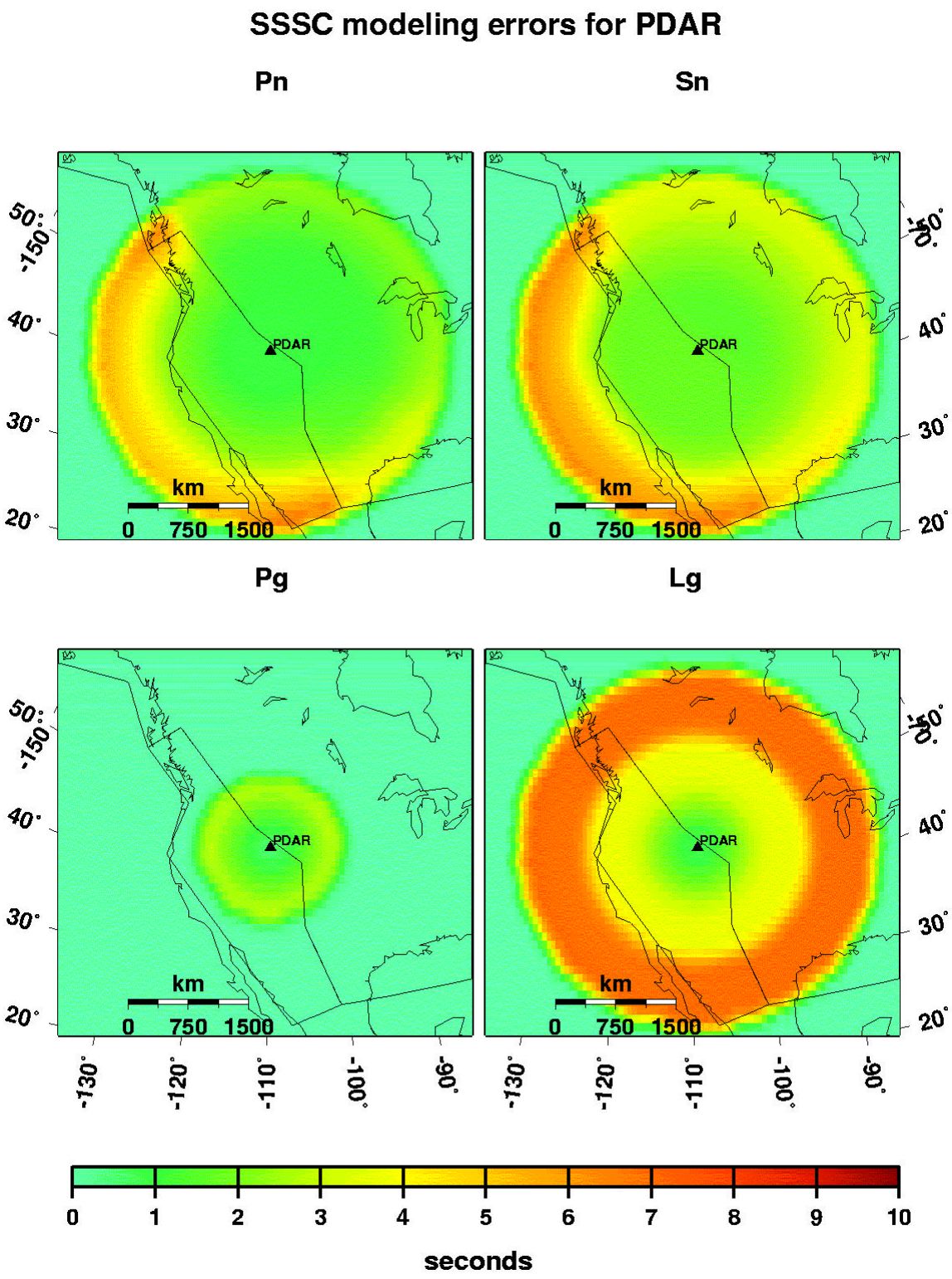

Figure 5. Pn, Sn, Pg, and Lg a-priori modeling errors for PDAR. Modeling errors increase with distances and they are larger in the west than the east for Pn and Sn (see also Figures 1-2).

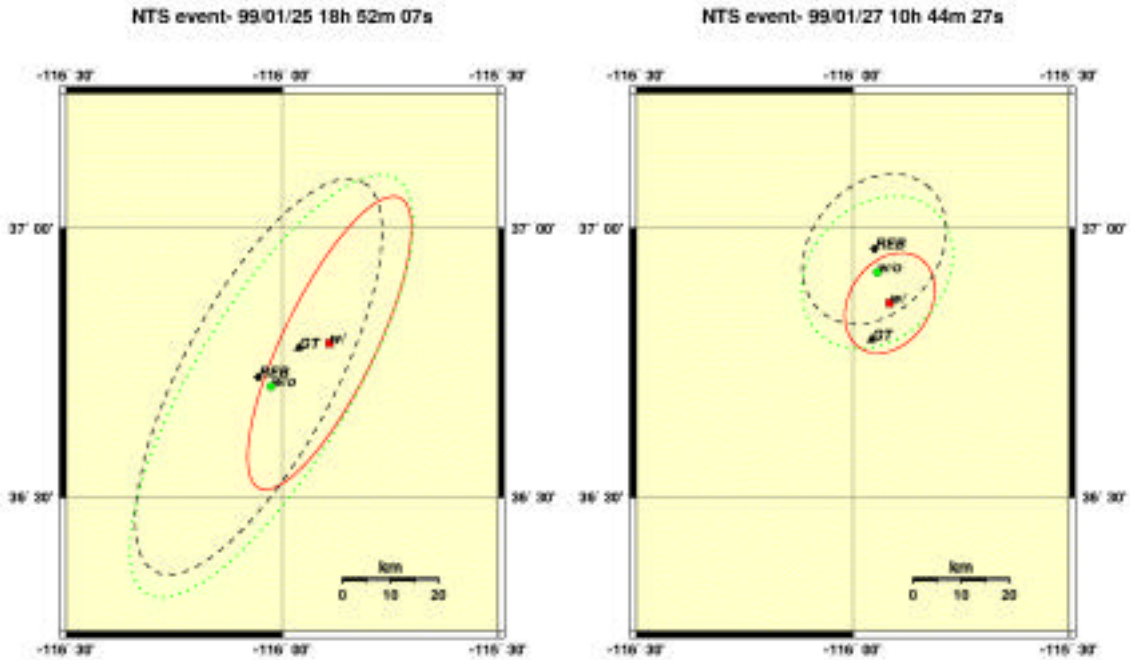

Figure 6. Location comparisons for earthquakes at NTS on 01/25/99 and 01/27/99. The GT locations have accuracy better than 2 km. Locations obtained without SSSCs are not identical to the REB locations due to fixed zero depth. All IMS stations in the REB are used in locations. The distances to GT locations and error ellipses are reduced when using SSSCs. (a) The distance to the GT location is improved 3.3 km using SSSCs (from 10 km without SSSCs to 6.7 km with SSSCs). SSSCs for 3 of the 8 IMS stations are applied, including MNV (Pn, Pg, Sn, Lg), PDAR (Pn), and TXAR (Pn). (b) The distance to the GT location is improved 5.4 km using SSSCs (from 14 km without SSSCs to 8.6 km with SSSCs). SSSCs for 4 of the 16 IMS stations are applied, including MNV (Pn, Pg, Lg), ELK (Pn, Sn, Lg), PDAR (Pn, Pg, Lg), and TXAR (Pn).