SEISMIC LOCATION CALIBRATION IN THE MEDITERRANEAN, NORTH AFRICA, MIDDLE EAST, AND WESTERN ERUASIA

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ABSTRACT

The goal of our Consortium's work is to improve event location in the Mediterranean, North Africa, Middle East, and Western Eurasia by calibrating travel times used in the location process by the International Data Centre (IDC). We develop 3-D velocity models and compute predicted regional travel times using ray tracing. The Source-Specific Station Corrections (SSSCs), relative to the IASPEI91, are obtained for regional P and S phases within 20 degrees at each International Monitoring System (IMS) station. SSSCs and modeling errors can be applied in the IDC location process to improve event location in calibrated regions, as demonstrated in previous studies in Fennoscandia and North America (e.g. Yang et al., 2001). We perform validation tests of the SSSCs by comparing them with empirical corrections from cluster analyses and by relocating ground truth (GT) events that possess location accuracies better than 5 km (GT0-GT5). This three-year project, starting in 2000, is divided into two phases, and we are currently at the transition between the two. The 3-D models, SSSCs, and GT events developed in Phase 1 will be delivered to the Prototype IDC this year.

In Phase 1 two separate 3-D velocity models are developed and SSSCs are computed. One is a 3-D hybrid model constructed by combining global mantle models with global crust and upper mantle models using improved group and phase velocity data sets and inversion methodology (Villaseñor et al., 2001). A second is a regionalized crustal model, developed from published tectonic maps and 1-D velocity models, combined with a 3-D mantle model parameterized in terms of radial and horizontal cubic splines using a combination of direct and differential travel times and surface-wave phase measurements (Antolik et al., 2001). The two models are compared for cross-validation and model error evaluation. SSSCs have been computed for the IMS stations as well as for IMS surrogates and other stations for validation testing. GT0-GT5 events collected for the study region are relocated with and without SSSCs applied and results are compared. Detailed evaluations on location improvement are conducted using a suite of evaluation criteria and metrics as recommended by the Oslo Workshop in 1999 (CTBT/WGB/TL-2/18, 1999). Preliminary results show that, when SSSCs are applied, events move closer to their GT locations and error ellipses are reduced without significant loss of coverage.

KEY WORDS: location calibration, SSSCs, travel-times, 3-D velocity models, IASPEI91, GT, IDC.

OBJECTIVE

The objective of this work is to improve IMS seismic event locations in the Mediterranean, North Africa, Middle East, and Western Eurasia using more accurate travel-time information. We develop regional path-dependent travel-time corrections ($\Delta \leq 20°$) for IMS stations in the study region to be incorporated into the PIDC/IDC location process.

RESEARCH ACCOMPLISHED

Introduction

The Group-2 Consortium carries out seismic location calibrations for IMS stations in the Mediterranean, North Africa, Middle East, and Western Eurasia using 3D models. Source Specific Station Corrections (SSSCs) for IMS seismic stations are developed to improve location accuracy and reduce error ellipses. Our goal is to develop SSSCs for Pn, Sn, and Lg phases out to 20° and the Pg phase out to 8° for all IMS stations in the study region (Figure 1). Previous studies have demonstrated that event locations and uncertainties can be improved by applying regional travel time corrections in event location (e.g. Yang et al., 2001a).

This work consists of two phases, preliminary and refined corrections, respectively. In Phase 1 we develop preliminary Pn and Sn SSSCs for a source depth of 10 km. In Phase 2 we will refine and improve the models and methods to obtain final SSSCs, including depth dependence. Pg and Lg SSSCs will also be developed in Phase 2. In both phases, validation testing is conducted using ground truth (GT) events to demonstrate improvement on event locations when using the corrections. In this report we describe preliminary Phase 1 validation testing results which are currently being delivered and tested on the DTRA CMR R&D Testbed.

Two separate 3D models are developed in Phase 1. A 3D hybrid model (CUB model) is constructed by combining global mantle models with global crust and upper mantle models using improved group and phase velocity data sets and inversion methodology (Villaseñor et al., 2001). A second model (SAIC-HRV model) is a regionalized crustal model, developed from published tectonic maps and 1D velocity models, combined with a 3D mantle model parameterized in terms of radial and horizontal cubic splines using a combination of direct and differential travel times and surface wave phase measurements (Antolik et al., 2001). The two models are compared for cross validation and model error evaluation. SSSCs are calculated for a given station using 3D ray tracing. Validation testing of the model-based SSSCs is conducted by relocating GT0-GT5 events. GT10 events may also be used to extend the coverage of the region where GT0-GT5 events are not available. They are recorded at IMS stations and/or surrogate stations as well as other stations, and distributed throughout the study region. We evaluate reductions in mislocations and error ellipses by applying SSSCs in event location. Results discussed in this report are for Pn and Sn SSSCs from the CUB model only.

Regional SSSCs are defined on rectangular 1°x1° latitude/longitude grids where both a travel-time correction and a modeling error are given at each grid point. The corrections are relative to the IASPEI91 travel times used in the PIDC/IDC location process. Modeling errors, the uncertainty in the predicted travel times, are estimated to ensure 90% ellipse coverage. In Phase 1 modeling errors (Figure 2) are estimated from the variance of the travel time residuals, with respect to the 3D model, in the EHB catalog (Engdahl et al., 1998).

In addition to the relocation testing described in this report, validation testing is also carried out using other methods, e.g. cluster analyses. The JHD/HDC cluster analyses are used to derive path-dependent corrections from event clusters. Comparison are made between these empirical corrections and model-based SSSCs for cross validation (Figure 2). Station corrections and statistical scatter of clusters are used as one source of information in estimating modeling errors.

Validation Testing

Validation testing for regional SSSCs in the Group-2 Consortium region is conducted by relocating events using SSSCs to verify event location improvement relative to the GT and location error ellipse coverage. The events used in validation testing are GT0-GT10 events and are not directly used in the model development.

We evaluate statistics on mislocation, error ellipse area, 90% error ellipse coverage, origin time differences from GT, origin time error, and standard deviation of observations. When SSSCs are applied, event location should be improved and error ellipses should be significantly reduced without loss of 90% coverage.

SSSCs from a large set of stations are applied in event location to validate the models and model errors. To assess IMS location improvement SSSCs are applied to only IMS stations and surrogate stations. The effect of mixing calibrated and uncalibrated regional and teleseismic data is also tested. Four sets of tests are conducted, including calibrated regionals only, calibrated and uncalibrated regionals, calibrated regionals and uncalibrated teleseismics, and calibrated regionals and uncalibrated regionals and teleseismics.

Our major evaluation metrics include those recommended by the 1999 Oslo Location Workshop (CTBT/WGB/TL-2/18, 1999). Additional metrics are also developed to measure the performance of the SSSCs. Both the L1 norm (median, spread, minimum, maximum, 20,40, 60 80 percentiles) and the L2 norm (mean, variance, standard deviation, average deviation) are calculated for the distance from GT, size of error ellipse, 90% ellipse coverage, origin time, origin time error, and misfit obtained with and without SSSCs. Student and Wilcoxon significance tests of paired samples are also applied, and statistics significant at least at 95% level are included in this report. Besides applying the evaluation metrics to an entire data set, we further divide each data set into several classes based on the GT accuracy (i.e. within vs. beyond the GT accuracy when located with and without SSSCs), and on mislocation (i.e. within vs. beyond x km). We also compare the numbers of events in a data set which are located within 1000 km^2 error ellipses that contain the GT and within 25 km distance from the GT with and without SSSCs.

Test Data Sets

Four data sets are used in validation testing of the Pn and Sn SSSCs developed for the study region. They are GT0-GT10 events collected by the Consortium, the Fennoscandian GT events used in a previous study (Yang et al., 2001a), GT10 Mid-Ocean Ridge and Transform (MORT) events, and estimated GT5 EHB events. Since the expected improvement in location is on the order of 10 km, the location of reference events should preferably be within 5 km accuracy or better. We mainly focus on GT0-GT5 events for relocation and error ellipse validation, but other events are also used for validation testing to extend coverage of the region.

The GT0-GT10 events from the Consortium database include nuclear explosions, chemical explosions, and well-located earthquakes, particularly from JHD/HDC cluster analyses (Engdahl and Bergman, 2001). Arrival data are merged from the PIDC REB, EHB catalog, as well as national and local network bulletins in the region. Events with at least three Pn (Sn) arrival data are used in validation testing. There are 11,000 Pn and 860 Sn defining arrivals in the test data set. Figures 3-4 show the GT0-GT10 event locations and Pn and Sn paths.

The Fennoscandia data set was previously used in testing 1D SSSCs for the Fennoscandian stations. It mainly contains 425 GT events in Fennoscandia, originally considered as GT2. Thirty-five MORT events in the Gulf of Aden and North Atlantic are included for testing to extend the coverage. These events are referenced to the bathymetric features and are estimated as GT10. Candidate GT5 events are also selected from the EHB catalog for the study region based on the candidate GT5 selection criteria. Estimated GT5 locations were obtained for 448 events relocated using phases recorded only within 300 km.

Test Results

The Fennoscandian data set and 1D SSSCs serve as a benchmark of the SSSCs developed using the 3D model by raytracing. The location results for the GT events are similar when the CUB and 1D Pn and Sn SSSCs are applied. With the CUB SSSCs 60% of events are improved, and the median ellipse area is reduced by 1900 km^2 (from 3700 to 1800 km^2) without loss of the 90% coverage (99%).

Our major validation testing is conducted using the GT0-GT10 events. To assess the effect of SSSCs in event location, several sets of relocations are done in order to separate factors that affect event location, and in each set there are multiple runs. Depth is fixed to zero in all relocation tests since these events are mostly shallow. Given the uncertainty in the location accuracy of GT events, at this stage we evaluate the location results for both GT0-GT5 and GT0-GT10 events. To be complete and objective we also include all locatable events in the current evaluation. Events near the boundary of the study region may be poorly located since we do not use any stations outside the region (Figure 1). A total of 571 GT0-GT10 events are relocated using only Pn and Sn phases, with and without SSSCs, for all stations:

- 60% events are improved in mislocation with a median of 8 km, and 47% are improved by more than 20%. 40% events are deteriorated with a median of 6 km, and 31% are deteriorated by more than 20%.
- The median improvement in ellipse area is 2360 km^2 (from 4600 km^2 without SSSCs to 2240 km^2 with SSSCs). The 90% coverages are 97% without SSSCs and 91% with SSSCs.
- 24% of the events are located with less than 1000 km^2 error ellipses that contain the GT locations and within 25 km mislocations, compared to 11% events without SSSCs.
- Origin time errors are reduced for 99% of the events. The median improvement, relative to the “GT” origin time, is 0.8 seconds, and the overall medians are 3.1 seconds without SSSCs and 2.2 seconds with SSSCs. The standard error of observations is improved for 61% events with a median of 0.2 seconds.

In this test, relocation results are similar between all GT0-GT10 events and GT0-GT5 events since there are only 25 GT10 events (all in the Aden and Koyna clusters). The median improvement in mislocation is larger for the GT0-GT2 events (10 km) while smaller for the GT5 events (6 km). Figure 5 compares mislocations with and without SSSCs. There is large improvement in mislocation and error ellipse area for low ndef (number of defining phases used in locating the event) events (Figure 6). Figures 7-10 show some examples of events in this data set using only Pn and Sn phases from all stations with and without SSSCs.

For IMS improvement validation the GT0-GT10 events are relocated using only IMS and IMS/surrogate stations with and without SSSCs. The results are similar to the previous one, but the median deterioration is larger for the case of IMS stations only, indicating that locations may be biased when only few stations with poor station geometries are used. When the SSSCs are applied to both IMS and surrogate stations, 59% events are improved by a median 8 km and the rest are deteriorated by a median 6 km. Error ellipses are reduced by ~60% while maintaining the same 90% coverage. This test shows that the SSSCs will effectively improve regional event locations when the full IMS network is deployed. Further testing using the GT0-GT10 events is also conducted to evaluate the effect of mixing calibrated and uncalibrated regional and teleseismic phases in event location. In general there is small improvement in mislocation and error ellipses.

For better path coverage, we also test the MORT events in validating the regional SSSCs. When the MORT events are relocated using Pn and Sn phases only, the majority of events have significant reductions in both mislocation and error ellipses using SSSCs. However, there are large mislocations and poor ellipse coverage, possibly due to poor station geometry. Relocation of the GT5 EHB events using Pn and Sn phases shows small improvement with SSSCs for all stations due to good azimuthal coverage. Using IMS stations with SSSCs, the majority of GT5 EHB events have large improvement in location and ellipse area, but the ellipse coverage is less than 90%.

CONCLUSIONS AND RECOMMENDATIONS

Validation testing of preliminary Pn and Sn SSSCs is conducted by relocating reference events in the Group-2 study region (Figures 3-4), with and without SSSCs. Four data sets are used in the offline testing, including the Fennoscandian GT events, Group-2 GT0-GT10 events, MORT GT10 events, and GT5 EHB events. To separate various factors that affect event locations, multiple sets of tests are conducted for each data set. Each set of tests is further divided between IMS stations, IMS/surrogate stations, and other stations. We include all events in our evaluation in order to be objective and to reveal potential problems.

Relocation results using SSSCs show overall improvement in event locations and error ellipses. As expected, low ndef events generally have larger improvement/deterioration. When 571 GT0-GT10 events are relocated using only Pn and Sn phases with SSSCs for all stations, 60% of the events are improved with a median improvement in mislocation of 8 km (10 km for GT0-GT2 events). All events have reduced error ellipses without losing 90% coverage. The median reduction in ellipse area is 2360 km^2 (from 4600 km^2 without SSSCs to 2240 km^2 with SSSCs). The improvement is similar when only calibrated IMS/surrogate regionals are used, but the deterioration is larger when only calibrated IMS regionals are used due to poor station geometry. When mixing calibrated and uncalibrated regionals and teleseismics, relocation results show less improvement in general.

Compared to previous studies, the relocation results are similar to those for Fennoscandia (Yang et al., 2001a), and both are better than those for North America (Yang et al., 2001b). Note that the current results have only used Pn and Sn SSSCs while Pg and Lg were also used for the two other regions. Further, in this report we show statistics for all events, including events along the border of the study region which may be poorly located since we only use regional phases from stations within the study region.

Several lessons have been learned from the validation testing about the data and model. Improvement on these aspects is expected in Phase 2. More details may be found at http://g2calibration.cmr.gov.

- Despite our effort in collecting GT5 or better events throughout the study region, currently the path distribution is still limited. In Phase 2 more data will be collected for better coverage. At present, the data quality in our collections also varies. For instance, within a cluster the reference events may be better than the derived events. Relocation results show better improvement for the reference cluster events when SSSCs are applied. Since the median improvement in event location is less than 10 km using SSSCs, it is important to assess the GT events as accurately as possible. In addition, the event, arrival, and station information is collected and merged from a variety of data sources. Currently inconsistencies may still exist in the data sets. We will continue our effort vetting the information for further studies.

- Some poorly relocated events may be due to poor model predictions in travel times. We are identifying the areas where the model needs improvement. In Phase 2, the emphasis in model development will be placed on improving the model in certain areas and refining the model in general. It is undesirable to mix calibrated and uncalibrated data in event location, particularly to mix calibrated and uncalibrated regional phases for a given station. Developing Pg and Lg SSSCs has a high priority in Phase 2. Teleseismic phase calibration may also be explored since teleseismics play a dominant role in IMS event location. At present the SSSCs are generated for the source depth of 10 km and we mostly fix depth to 0 km in relocating events. In Phase 2 we will explore depth-dependent SSSCs. In addition, the modeling errors currently used are conservative, invariant in azimuth, and station-independent. More realistic modeling errors are expected in Phase 2 that are closely coupled with the 3-D model and stations.

REFERENCES

Antolik, M., G. Ekström, and A.M. Dziewonski, Global event location with full and sparse data sets using three-dimensional models of mantle P-wave velocity, Pure Appl. Geophys., 291-317, 2001.

Engdahl, E.R., van der Hilst, R.D., and Buland, R.P., 1998, Global teleseismic earthquake relocation with improved travel times and procedures for depth determination, Bull. Seism. Soc. Am.,88, 722-743, 1998.

Engdahl, E.R., and E. Bergman, Validation and generation of reference events by cluster analysis, this Volume, 2001.

Villaseñor, A., M.H. Ritzwoller, A.L. Levshin, M.P. Barmin, and E.R. Engdahl, Shear velocity structure of central Eurasia from inversion of surface wave velocities, Phys. Earth Planet. Int., 169-184, 2001.

Yang, X., I. Bondár,, K. McLaughlin, and R. North, Source Specific Station Corrections for regional phases at Fennoscandian stations, Pure Appl. Geophys., 158, 35-57, 2001a.

Yang, X, I. Bondár,, K. McLaughlin, R. North, and W. Nagy, Path-dependent regional phase travel-time corrections for the International Monitoring System, Bull. Seism. Soc. Am., in press, 2001b.

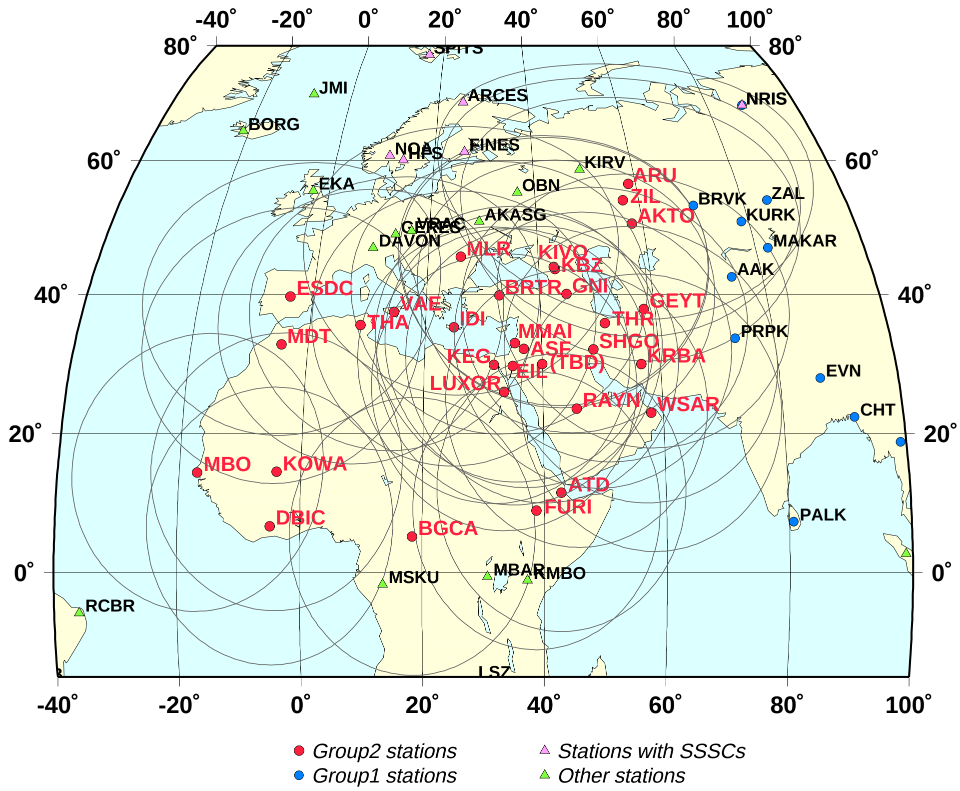

Figure 1. Group-2 Consortium region of interest. There are 6 IMS stations with existing regional SSSCs in this region (Yang et al., 2001a).

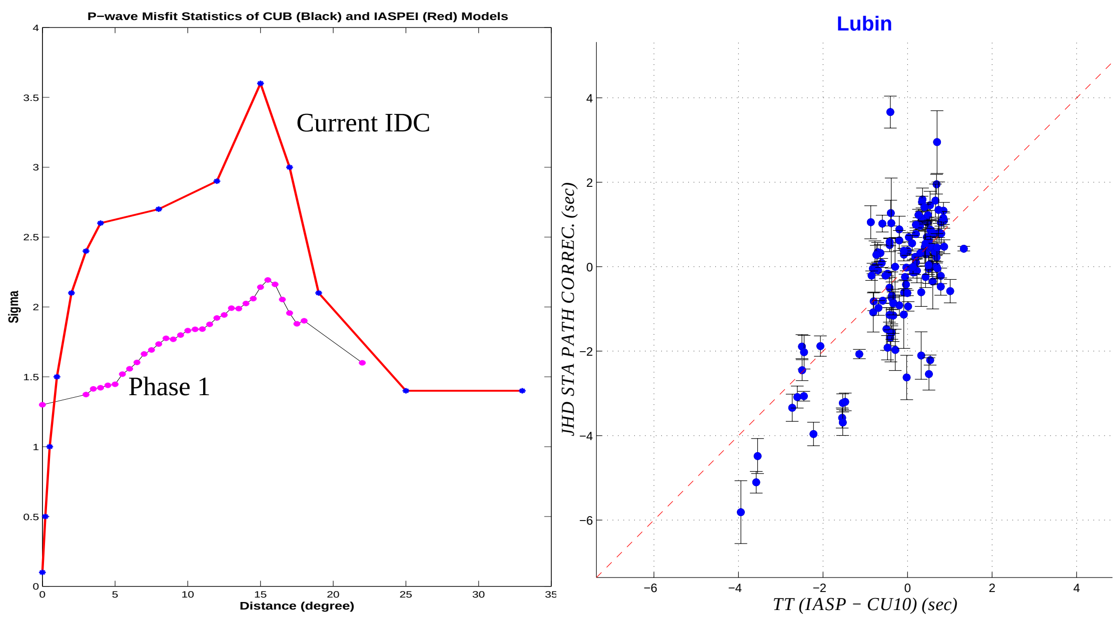

Figure 2.(Left) Modeling errors used in Phase 1 (thin line) compared to that used at the PIDC/IDC currently (thick line). (Right) Empirical path correction comparisons of the Lubin, Poland, cluster and the CUB model. There is good agreement between the empirical JHD path corrections and the model predictions (correlation coefficient of 0.8).

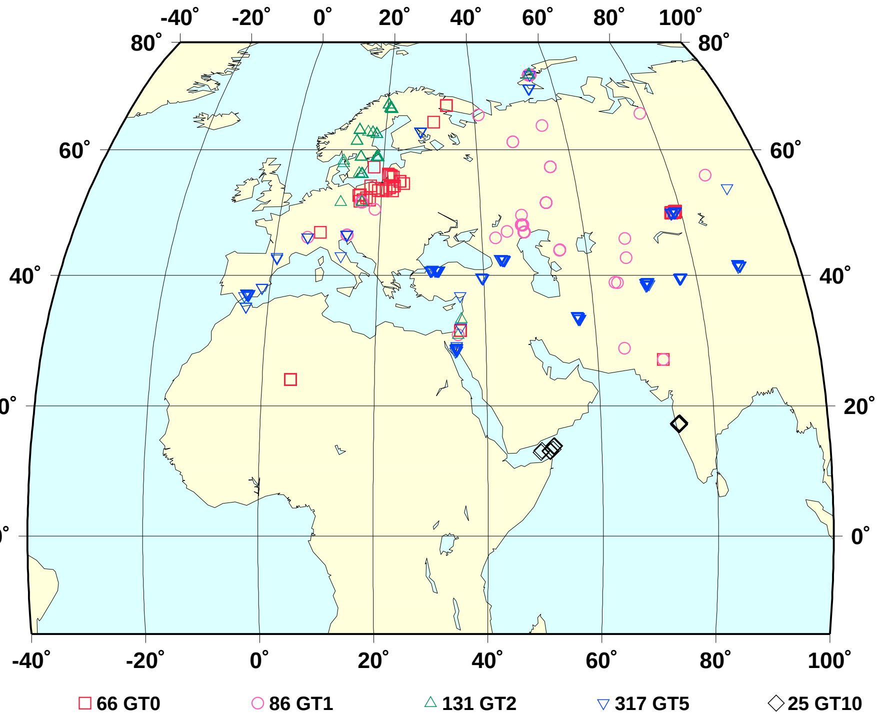

Figure 3. 625 GT0-GT10 events in the Group-2 Database used in relocation (http://g2calibration.cmr.gov).

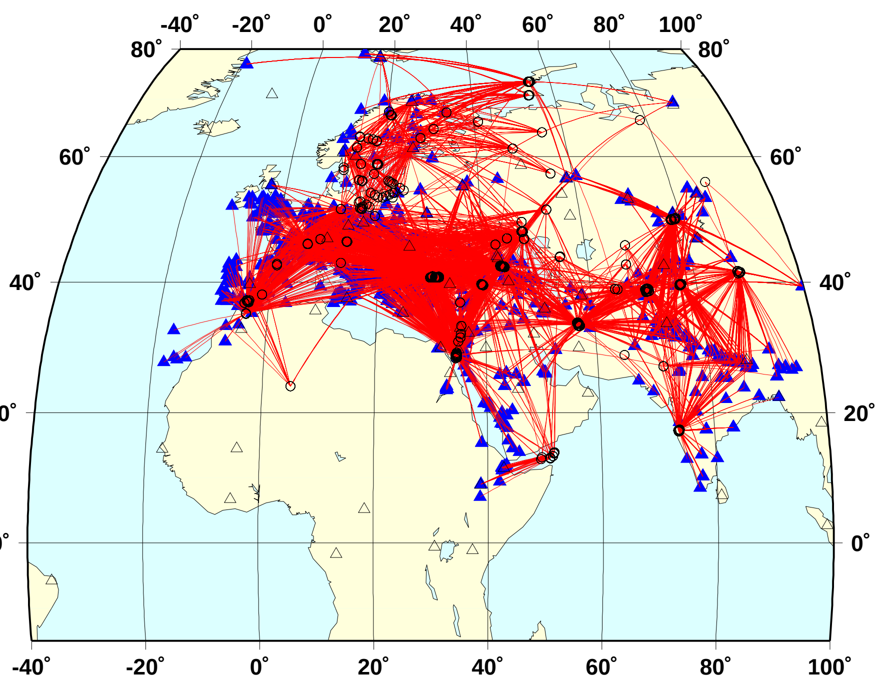

Figure 4. 11,000 Pn and 860 Sn path coverage in the Group-2 GT0-GT10 data set. Events (circles) and stations (open triangles for IMS; solid triangles for other stations) are also plotted.

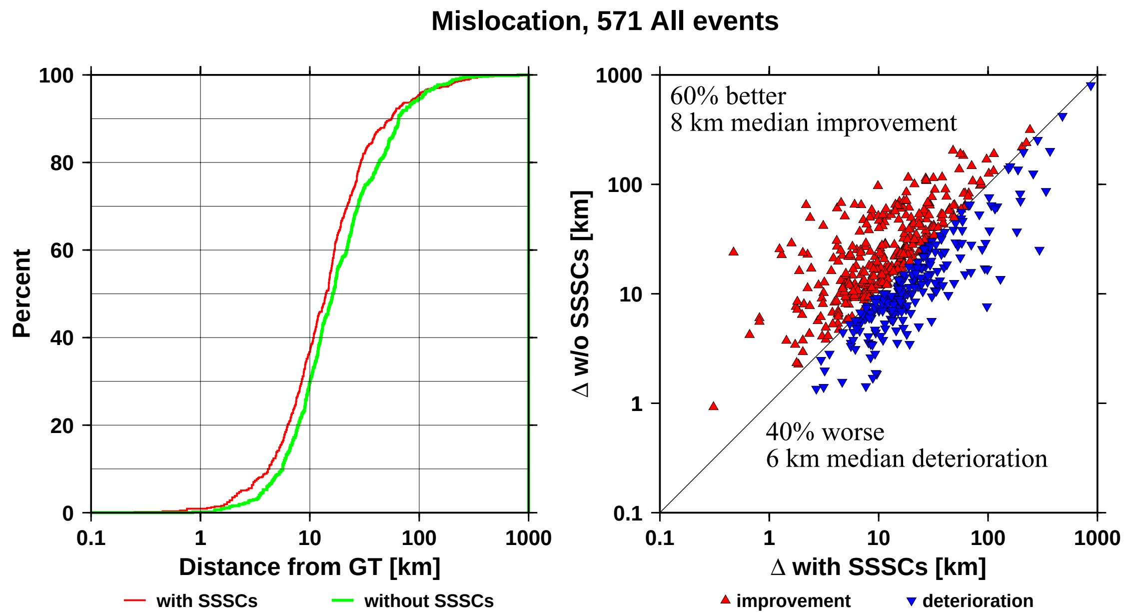

Figure 5. Mislocation comparisons of the GT0-GT10 events with and without SSSCs. (Left) Cumulative plot showing location improvement using SSSCs compared to without SSSCs. The 80 percentile mislocation is reduced from 43.0 to 29.2 km (32% reduction), and the median mislocation is reduced from 16.5 to 14.1 km (15% reduction). (Right) Comparison of mislocations with and without SSSCs. Symbols above the diagonal line indicate improvement with SSSCs.

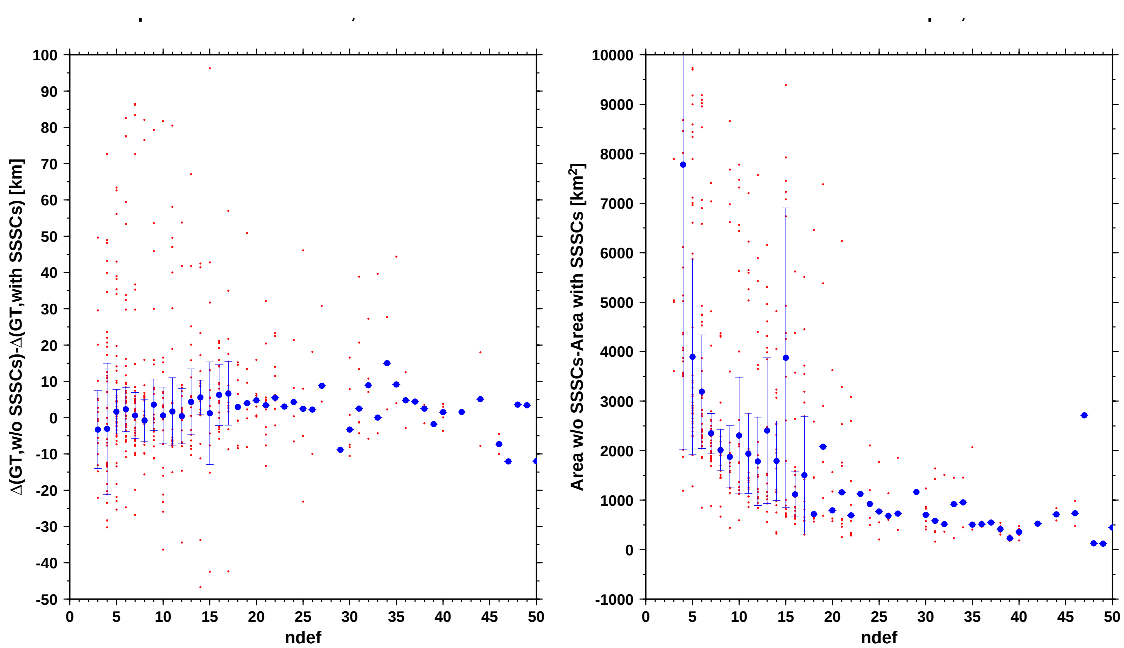

Figure 6. Improvement on mislocation (Left) and error ellipse (Right) vs. ndef for the GT0-GT10 events with and without SSSCs. Positive numbers indicate improvement. Low ndef events show large scatter in improvement/deterioration of mislocation.

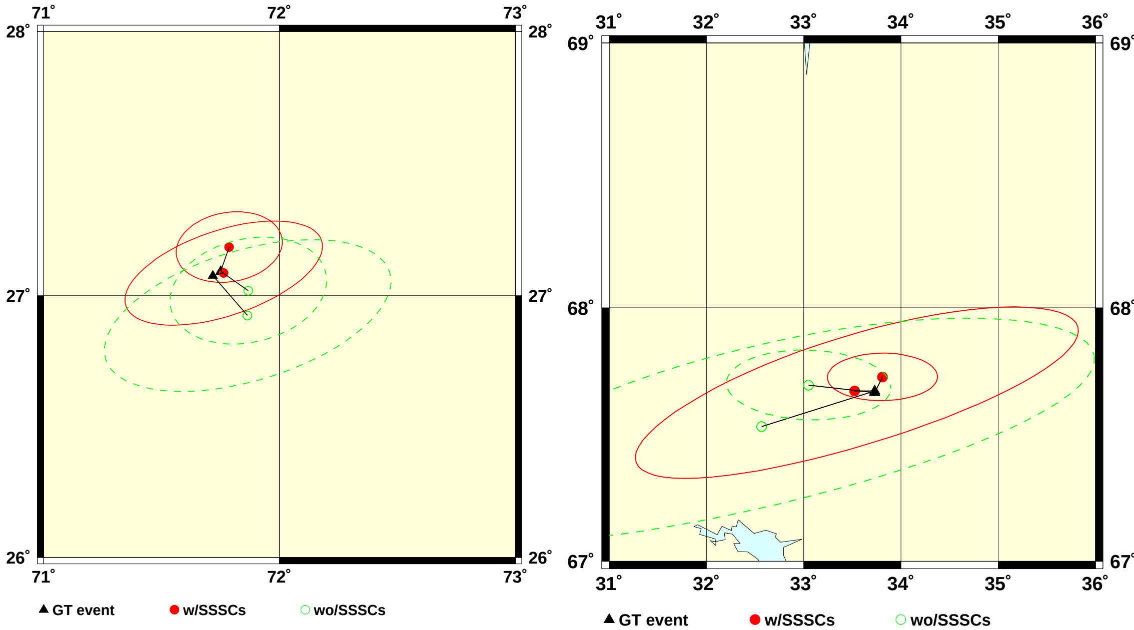

Figure 7. Relocations of the 1974 and 1998 Indian nuclear explosions (Left; GT0) and the 1996/09/29 and 1997/10/12 Kola calibration shots (Right; GT0) using Pn and Sn phases only, with (solid) and without SSSCs (dashed).Using SSSCs the mislocations are 4.6-10.8 km for the former, improved by 3.4 -17.6 km, and 7.6-8.8 km for the latter, improved by 21.4-43.2 km.

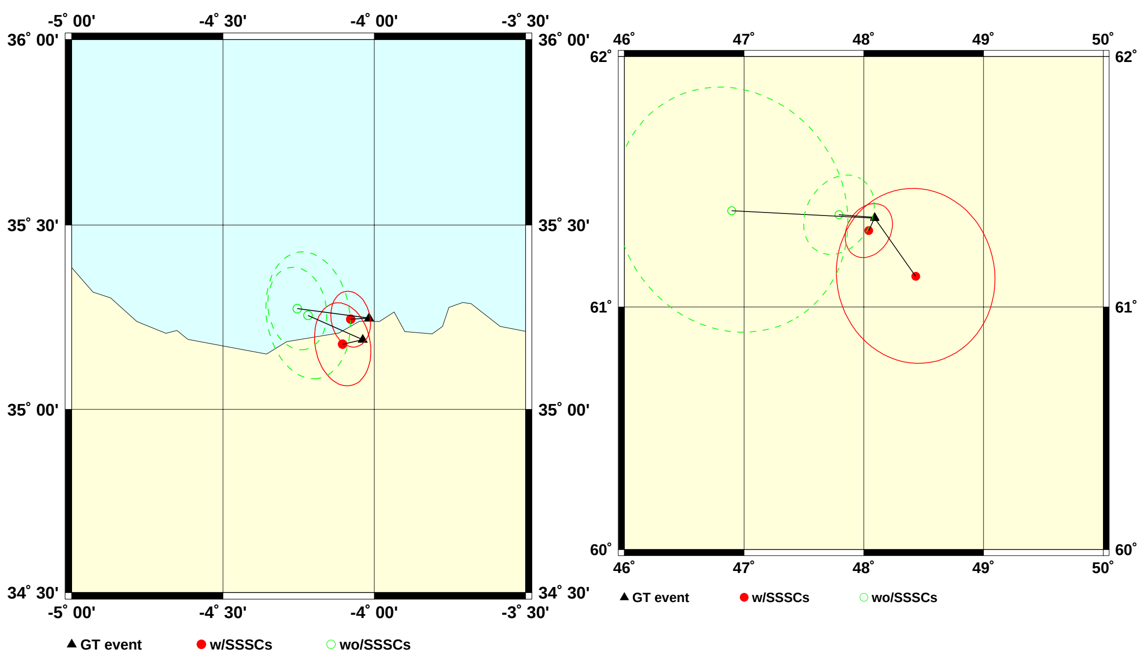

Figure 8. Relocations of the Morocco cluster (Left; GT5) and two PNEs on 1971/10/04 and 1988/09/06 (Right; GT1) using Pn and Sn phases only, with (solid) and without (dashed) SSSCs. Using SSSCs the mislocations are 5.6-6.2 km for the former, improved by 11.8-16.2 km, and 3.7-29.2 km for the latter, improved by 12.4-35 km.

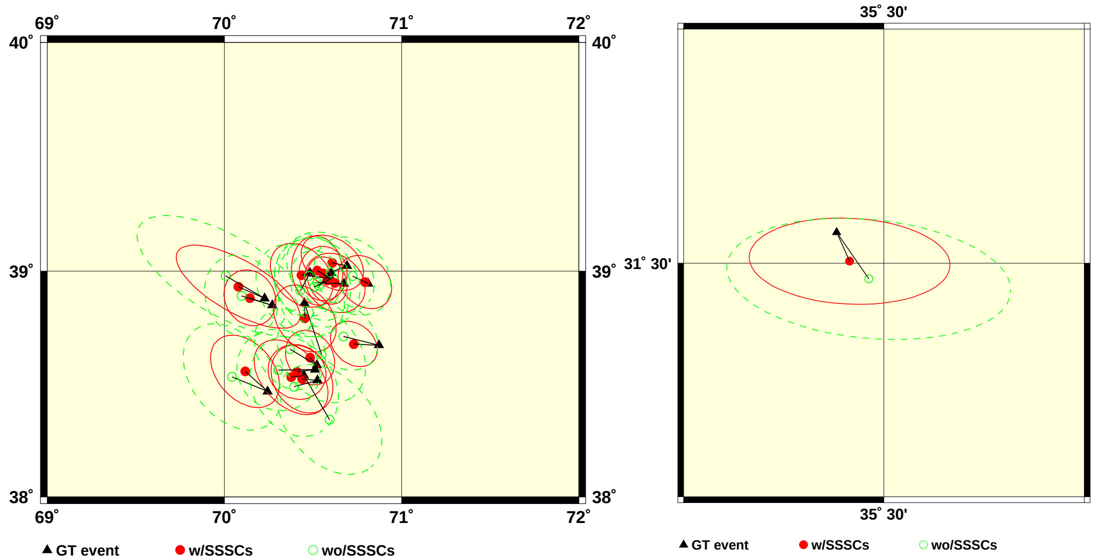

Figure 9. Relocations of the Garm earthquake cluster (Left; GT5) and the 1999/11/11 Dead Sea shot (Right; GT0) using Pn and Sn phases only, with (solid) and without (dashed) SSSCs. With SSSCs the median mislocation is 7.5 km for the former, improved by 5.9 km. The mislocations is 3.8 km for the latter, improved by 2.9 km.

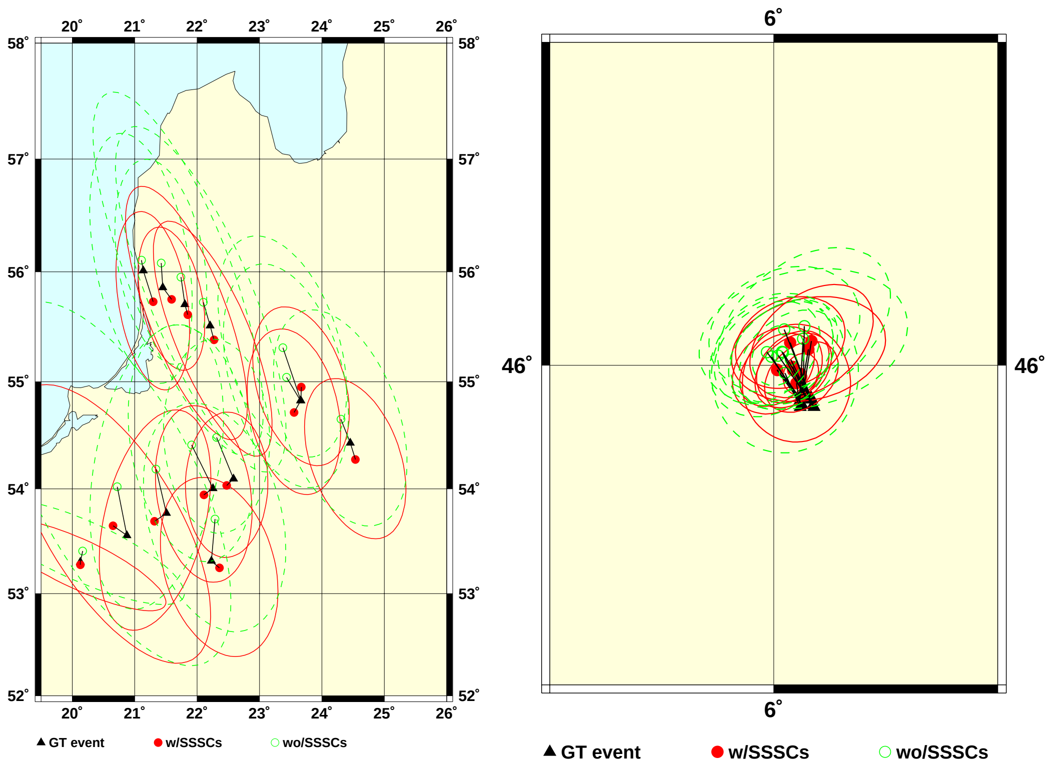

Figure 10. Relocations of the 1997 Polonaise and 1995-1996 Eurobridge shots (Left; GT0) and the French earthquake cluster (Right; GT5) using Pn and Sn phases only, with (solid) and without (dashed) SSSCs. Using SSSCs the median mislocation is 14 km for the former, improved by 24.7 km, and 6.2 km for the latter, improved by 2.8 km.