ELSEVIER

Physics of the Earth and Planetary Interiors 113 (1999) 11–24

PHYSICS OF THE EARTH AND PLANETARY INTERIORS

Development of calibration techniques for the Comprehensive Nuclear-Test-Ban Treaty (CTBT) international monitoring system

István Bondár [a,b,*], Robert G. North [a]

[a] *Science Application International, Center for Monitoring Research, Suite 1450, 1300 N 17th Street, Arlington, VA 22209, USA*
[b] *Seismological Observatory, Hungarian Academy of Sciences, Meredek u. 18, H-1112 Budapest, Hungary*

Received 25 November 1997; received in revised form 10 August 1998; accepted 10 August 1998

Abstract

A prototype International Data Centre (pIDC) is developing and testing concepts for the International Monitoring System that will be put into place to monitor compliance with the recently-signed Comprehensive Test Ban Treaty (CTBT). The testing includes the routine production of a daily bulletin of global seismic activity, several days after real time, since the beginning of 1995. A wider variety of seismic phases are used for location than is the practice of existing agencies producing global bulletins at greater delays, and another difference is that observed slowness vectors are used in addition to arrival time. Comparisons of pIDC bulletins with those provided by national agencies that operate denser networks have demonstrated both random and systematic errors in location that often exceed the formal error estimates. The pIDC is developing and testing techniques to reduce systematic biases through region- and path-dependent corrections to travel-time and slowness, and to better account for random errors. Initial results from this very long-term project are encouraging.

Keywords: pIDC; CTBT; International Monitoring System

1. Introduction

Region- and path-dependent calibration of seismic travel times to improve event location has been practised to some extent by a number of national earthquake monitoring agencies, but until recently no attempt has been made to implement such calibration on a global scale, despite a large number of publications advocating such an approach using, for example, velocity models derived from tomographic inversions. Existing agencies that produce global bulletins, such as the US National Earthquake Information Service (NEIS) and International Seismological Centre (ISC) continue to use older (Jeffreys–Bullen) global travel-time models for location. This is because of an inherent conservatism needed to maintain a stable long-term baseline, further justified by ill-fated short-term experiments with alternative

* Corresponding author. Comprehensive Nuclear-Test-Ban Treaty Organization, International Data Centre, Vienna International Centre, P.O. Box 1200, A-1400 Vienna, Austria.

0031-9201/99/$ - see front matter
PII: S0031-9201(99)00033-3

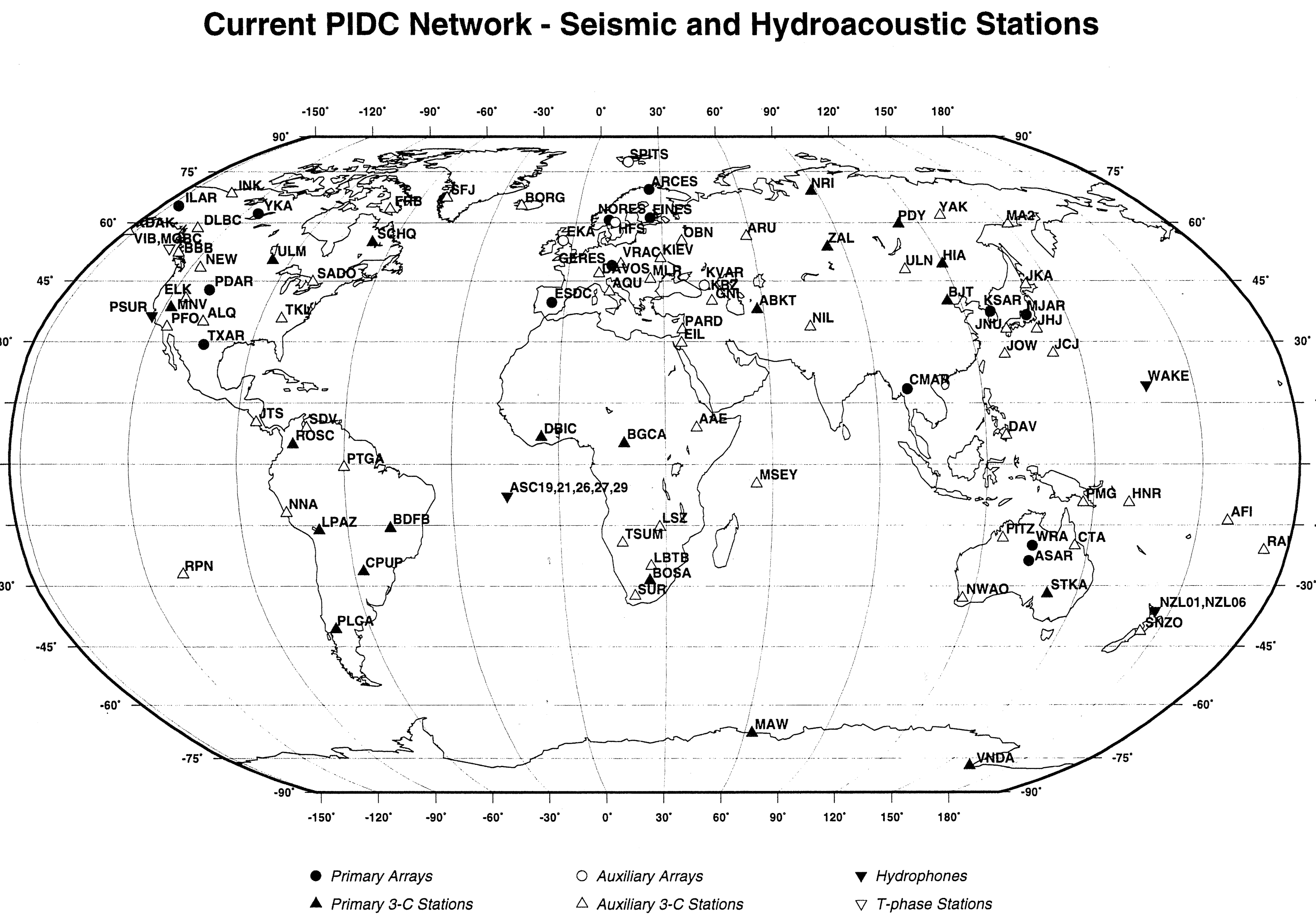

Fig. 1. Current pIDC seismic and hydroacoustic network. Primary station are shown as black (arrays as circles, 3C stations as triangles) symbols, auxiliaries as hollow symbols.

global models, and because of limited resources to develop and test changes to existing procedures.

With the negotiation, and subsequent signature in September 1996, of the Comprehensive Test Ban Treaty (CTBT) additional resources were made available for the development and extensive testing of new location procedures, including regionalized travel times, in an operational setting. The approach to and aftermath of the CTBT have also engendered an unprecedented amount of international cooperation. This cooperation has included the rapid provision of national seismic bulletin information, and research on the location problem by scientists from many countries at an international facility. That research has been focused upon the calibration of the International Monitoring system (IMS) that is now being established to provide the data needed to ensure compliance with the CTBT.

2. IMS seismic network

The IMS network will consist of 50 primary seismic stations (29 of which are arrays), providing continuous real-time data, 121 auxiliary seismic stations, that provide data upon request in order to improve location and event characterization parameters, 11 hydroacoustic stations (five hydrophones, providing continuous real-time data and six T-phase seismic stations) to locate underwater events, 60 infrasound stations, providing continuous real-time data that is processed to locate atmospheric events and 80 radionuclide sites that provide daily samples of particulates and noble gases to monitor and locate releases of radionuclide materials. While not all stations are in operation yet, the seismic network, shown in Fig. 1, is the most complete. It can be seen that the IMS network is a sparse, teleseismic network.

An International Data Center (IDC), to be located in Vienna will receive data from all these sites, process them and provide both the raw data and products (summaries, event bulletins, list of signal detections, event characterization parameters, etc.) to signatories. A prototype IDC (pIDC) has been operating in Arlington, VA, USA as part of the GSETT-3 experiment since January 1, 1995.

The pIDC issues a Reviewed Event Bulletin (REB) every day, within 72–120 h of the end of each data day. The REB contains an average of 60 events per day, with a maximum of over 300 events. Nearly all events are recorded to teleseismic distances—more than 95% of the events have mb calculated, from observations at distances larger than 20°. As the number of stations is limited, the pIDC utilizes not only the first arriving phases as does the ISC or NEIC, but the phases Pg, Pn, Sn, Lg, P, pP, sP, PKP, pPKP, PcP PP, S, ScP and SKP are also used in the locations as well as the slowness and azimuth measurements. An event is built if it has at least three first arriving phases at primary stations, the 'weighted count' of observations exceeds a threshold value and it passes review by both a leading analyst and a seismologist. In the locations the iasp91 travel-time tables are used, and the default depth is set to 0 km.

Table 1 compares the NEIC and pIDC bulletins to the ISC bulletins for the first 6 months of 1995. The ISC bulletin, which is released after a 2-year delay, contains twice as many events as either the NEIC (6–9 months delay) or the REB (5–7 days delay). However, the REB provides the most events with mb (in 1995 the proportion of such events in the REB was only 86%, now it is over 95%). Of the events with mb in the ISC bulletin the NEIC did not report 2851 events (mostly on oceanic ridges, Japan, Indonesia and the Pacific), and the REB 1230 events (Japan, Central America, Indonesia and the Pacific). Fig. 2 illustrates the differences. Here the number of reported events are plotted as a function of number of defining stations—the REB reports far more events recorded by three to four stations, but obvi-

Table 1
Bulletin comparisons, January–June 1995

	ISC	NEIC	pIDC
Total events located	22926	10110	9641
Total with mb given	7602	5047	8201
Percentage with mb given (%)	33	50	86
Matching ISC events	22926	9763	7173
Matching ISC events with (ISC) mb			
Number	7602	4751	6372
Number with mb calculated	7602	4625	6222
Number with ML calculated	0		34
Number with no magnitude calculated	0	126	116
Not reported	0	2851	1230

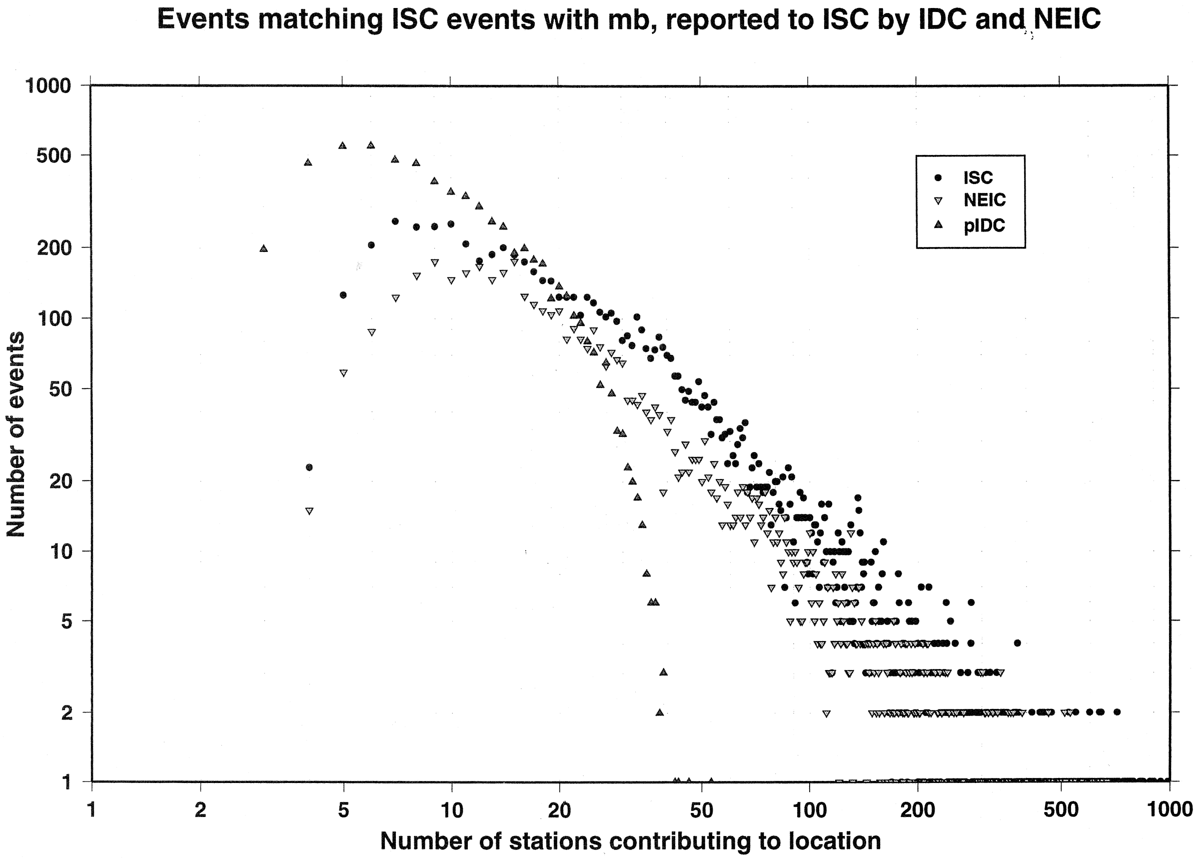

Fig. 2. ISC events with (ISC) mb reported by pIDC and NEIC, January–June, 1995.

ously it cannot use more stations than those in the IMS network.

3. Location calibration of the IMS seismic network

The CTBT provides an On-Site Inspection (OSI) option if a possible violation is claimed by a signatory. The area covered by an OSI cannot exceed 1000 km^2. With a sparse, teleseismic network like the IMS, it is extremely difficult to meet this requirement. Not only would the error ellipses often exceed 1000 km^2 in area, but a study (Bondar, 1997) has shown that during the Conference of Disarmament Group of Scientific Experts Third Technical Test (GSETT-3) experiment only 50% of the REB 90% coverage ellipses contained the true locations—assuming that the error of local network solutions is about 5 km. The comparison of REB locations to National Data Center (NDC) locations has also revealed systematic mislocations in several regions of the world.

These observations initiated the location calibration effort of the IMS network in May, 1996. The Group of Scientific Experts (GSE) prescribed the collection of ground truth locations, i.e., exactly known locations (explosions) or very well located events (local network solutions) to be used to generate and test location corrections. The location calibration includes the determination and testing of station and path corrections, derived either empirically from GSETT-3 results or based on other data, such as travel times or models from long-range

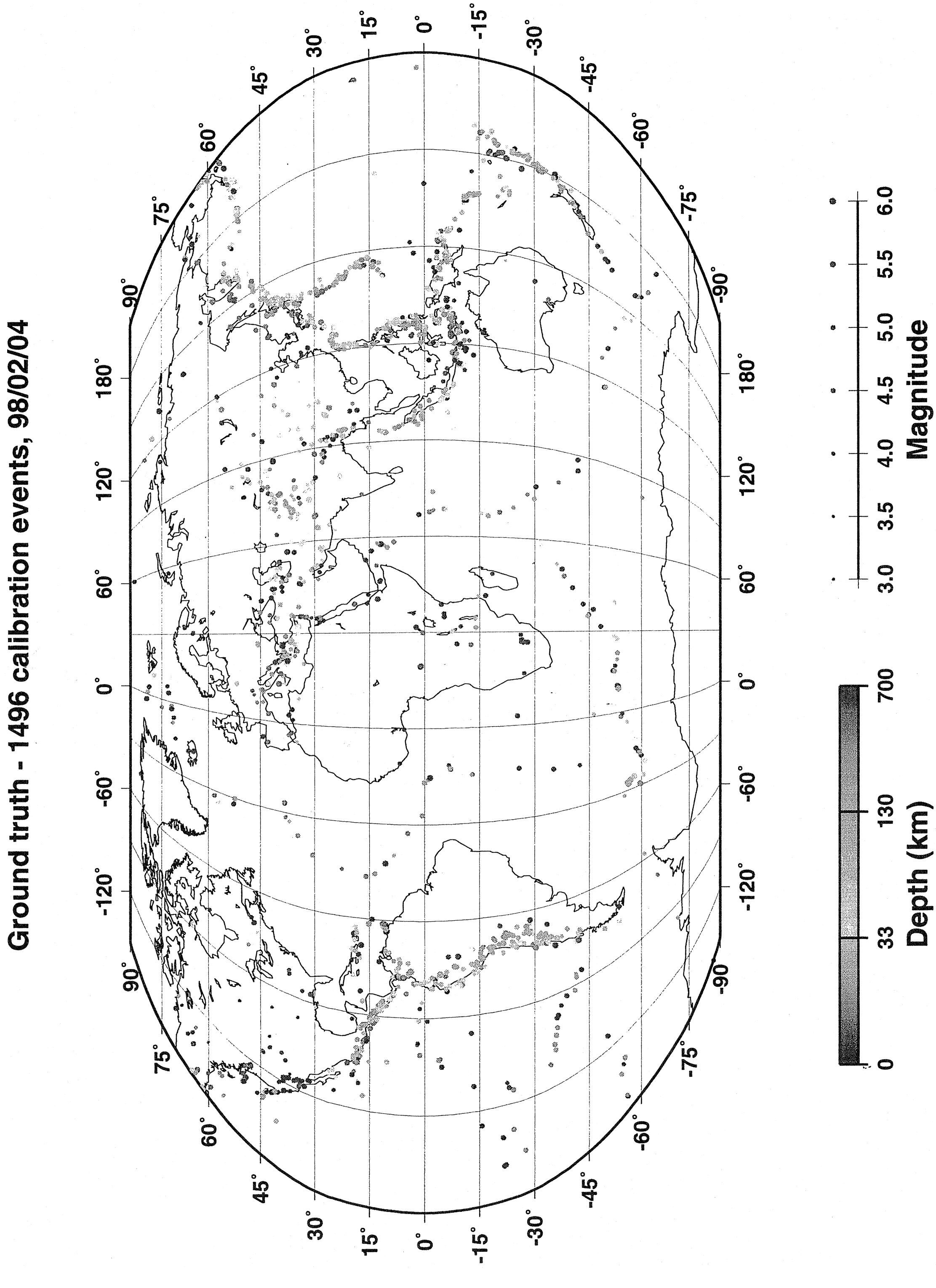

Fig. 3. Map of calibration events collected so far at the pIDC.

profiles, very accurate locations, etc. The calibration of the IMS network is a very long-term project. In the following we describe the limited results accomplished so far.

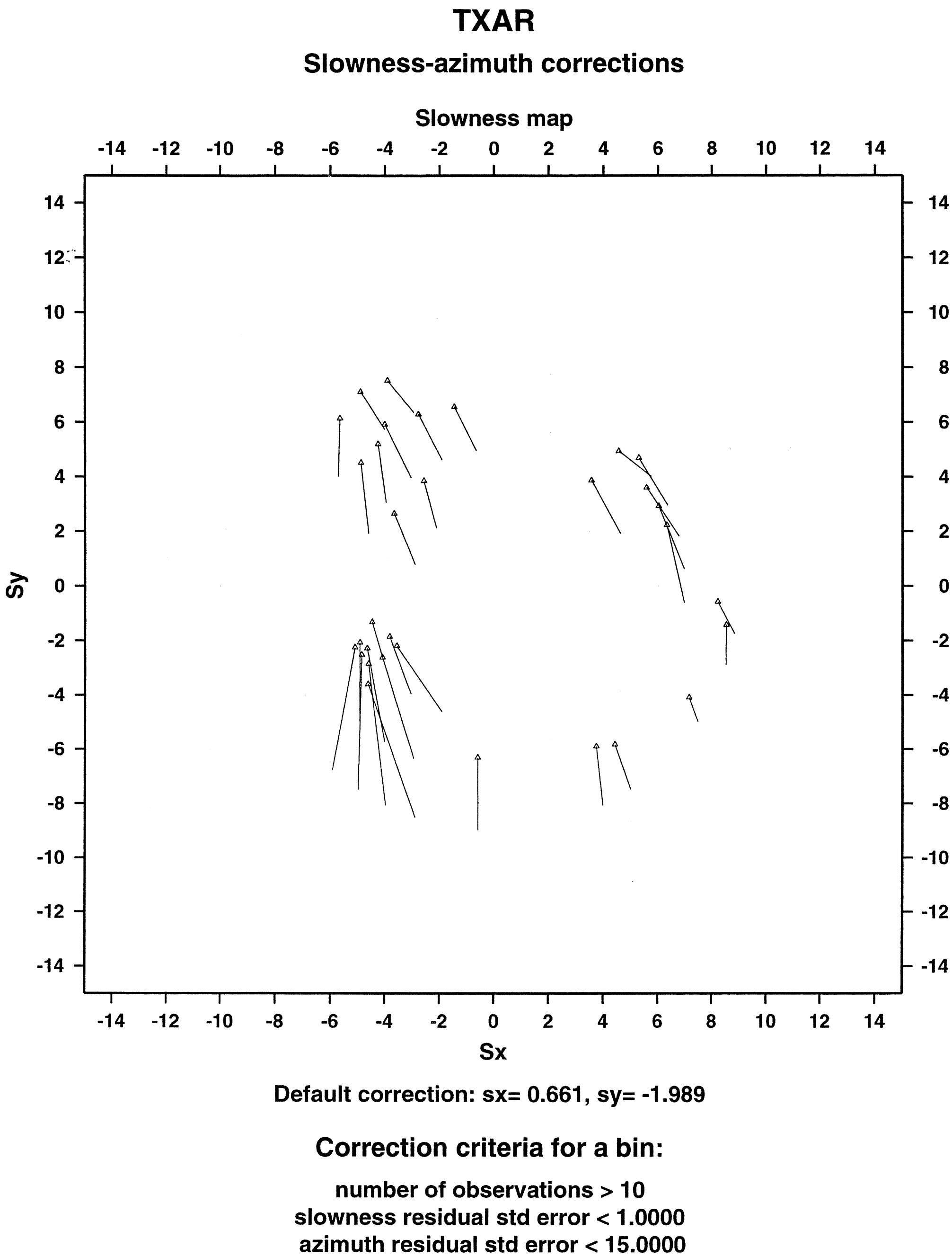

Fig. 4. Slowness–azimuth station correction (SASC) map for the TXAR array, USA.

3.1. Ground truth event selection

The selection of calibration events is done on a daily basis. Whenever a daily REB is ready, an automatic procedure selects calibration event candidates from the REB. Only events with body wave magnitude between 4 and 6 are selected, i.e., events above the IMS detection threshold and small enough to disregard the effect of extended sources. The acceptance of an event in the automatic selection depends on the number of defining phases where each geographic (Flinn–Engdahl) region has its own self-adjusting acceptance threshold, which ensures the selection only of the 'best' events in high seismicity areas while allowing rare events from low seismicity areas to be selected.

From the automatic daily selection one or two events on average are picked manually as calibration events. The waveforms of the selected events are requested from all auxiliary stations and are carefully reanalyzed. If an event occurred within regional distance of a local network, the NDC is asked for the location and phase readings for the event. The event is then relocated using all available information, that is the phase picks from the reanalyzed IMS waveforms and those from the NDCs. The calibration

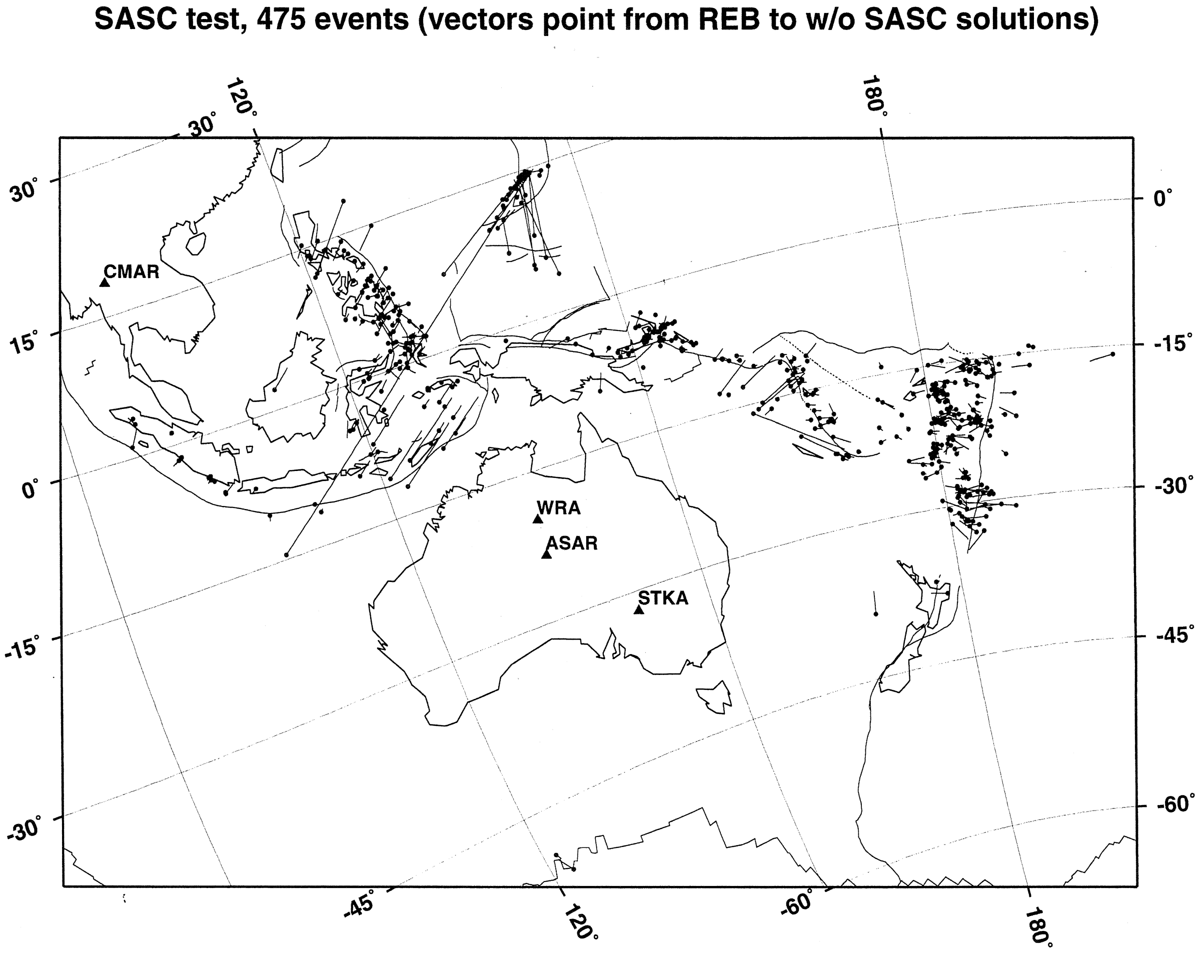

Fig. 5. Relocated events without applying SASCs, using only arrivals from the primary stations ASAR, CMAR, STKA and WRA. The vectors point from the original REB location toward the location without SASCs (black dots), thus showing the mislocation vector.

event bulletin (CEB) is available through the pIDC web page, www.pidc.org. The currently selected calibration events are shown in Fig. 3.

Besides the calibration event selection, countries may nominate events. Canada, Israel, the Russian Federation, South Africa, Switzerland and the USA have already provided ground truth information.

It is recognized that not all calibration events may meet the location accuracy requirements when testing different corrections. Obviously, it is futile to use events with 25 km location error if the expected location improvement of a correction is about 10 km. Therefore, different ground truth categories have been constructed. Each category has its advantages and limitations. For direct calibration of the IMS network, only recent events are useful.

GT0 consists of events with exactly known location and origin time. These are usually calibration shots or announced chemical explosions (the exact location and origin time of nuclear explosions are rarely made public). There are just a handful of such events, few of which are recorded teleseismically.

GT2 consists of mainly mine explosions and quarry blasts where the size of the mine is about 2 km. The origin time may be biased. Although there are several hundreds of such events, they are concentrated in specific areas and as for GT0 events, are usually recorded only to regional distances. Thus,

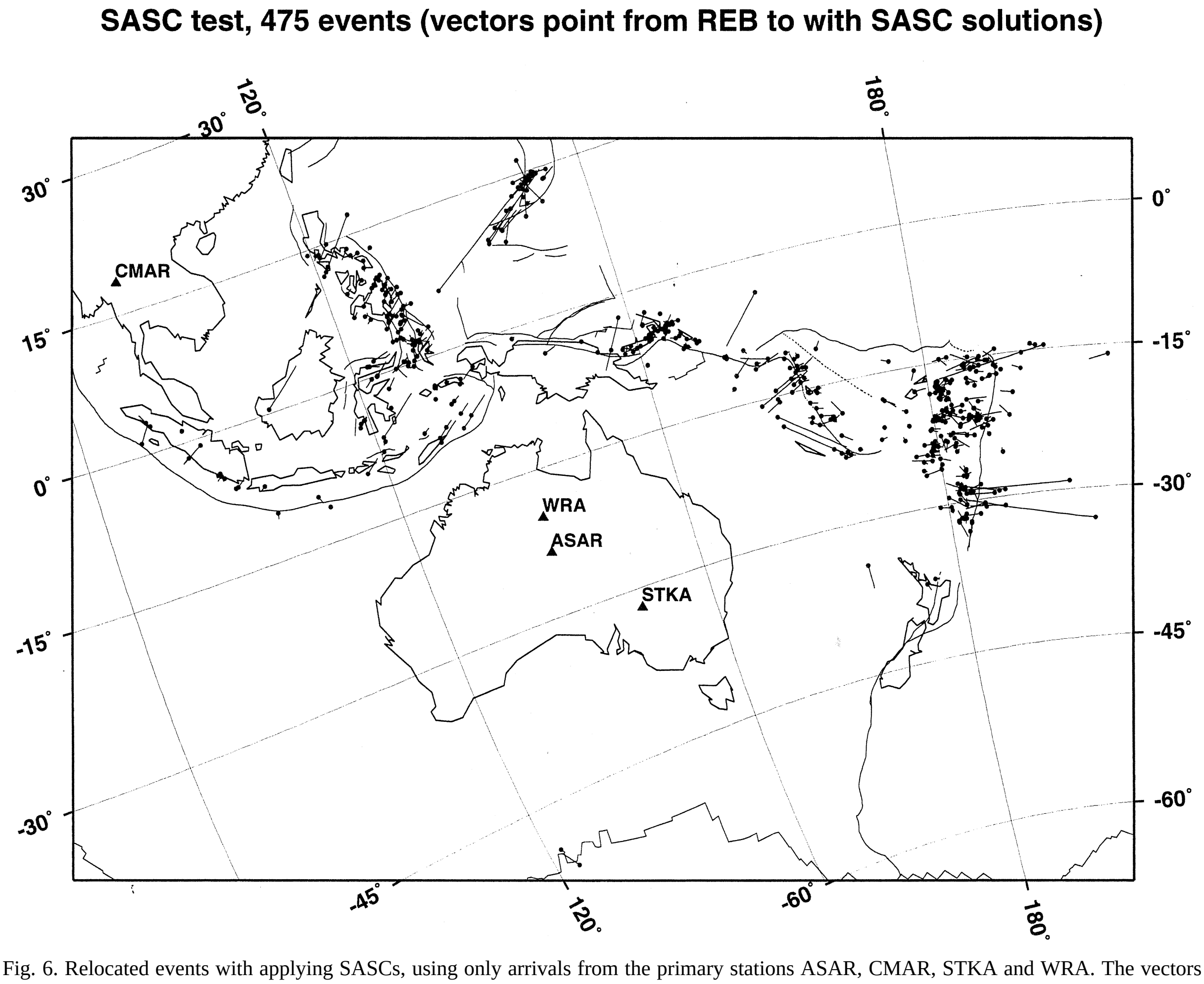

Fig. 6. Relocated events with applying SASCs, using only arrivals from the primary stations ASAR, CMAR, STKA and WRA. The vectors point from the original REB location toward the location with SASCs (black dots), thus showing the mislocation vector.

they cannot be used for deriving and testing teleseismic corrections.

The presumed location accuracy of the GT10 and GT25 events is 10 and 25 km, respectively. These are seismic network locations where both the location and origin time are biased. The selection is not restricted to the CEB but locations from the NEIC and ISC bulletins are also accepted if at least three IMS stations recorded the event.

The acceptance criteria for a GT10 event are that it is recorded at least by five stations within 3° distance, and the largest azimuthal gap between the recording stations within 5° distance is less than 180°. The GT10 events are well-constrained local network solutions but only a few regional networks (California, Alaska, Japan, Europe, Chile, South Africa) can satisfy the above requirements.

An event falls into the GT25 category if the number of defining phases is at least 40, and the largest azimuthal gap is less than 90°. As the more relaxed criteria for GT25 events allows teleseismic locations, the Earth's seismicity is quite well represented by these events. However, because of their relatively large location errors, their use for calibration purposes is rather limited.

3.2. Modeling and measurement errors

The size and orientation of the coverage error ellipse depends upon the station geometry and the

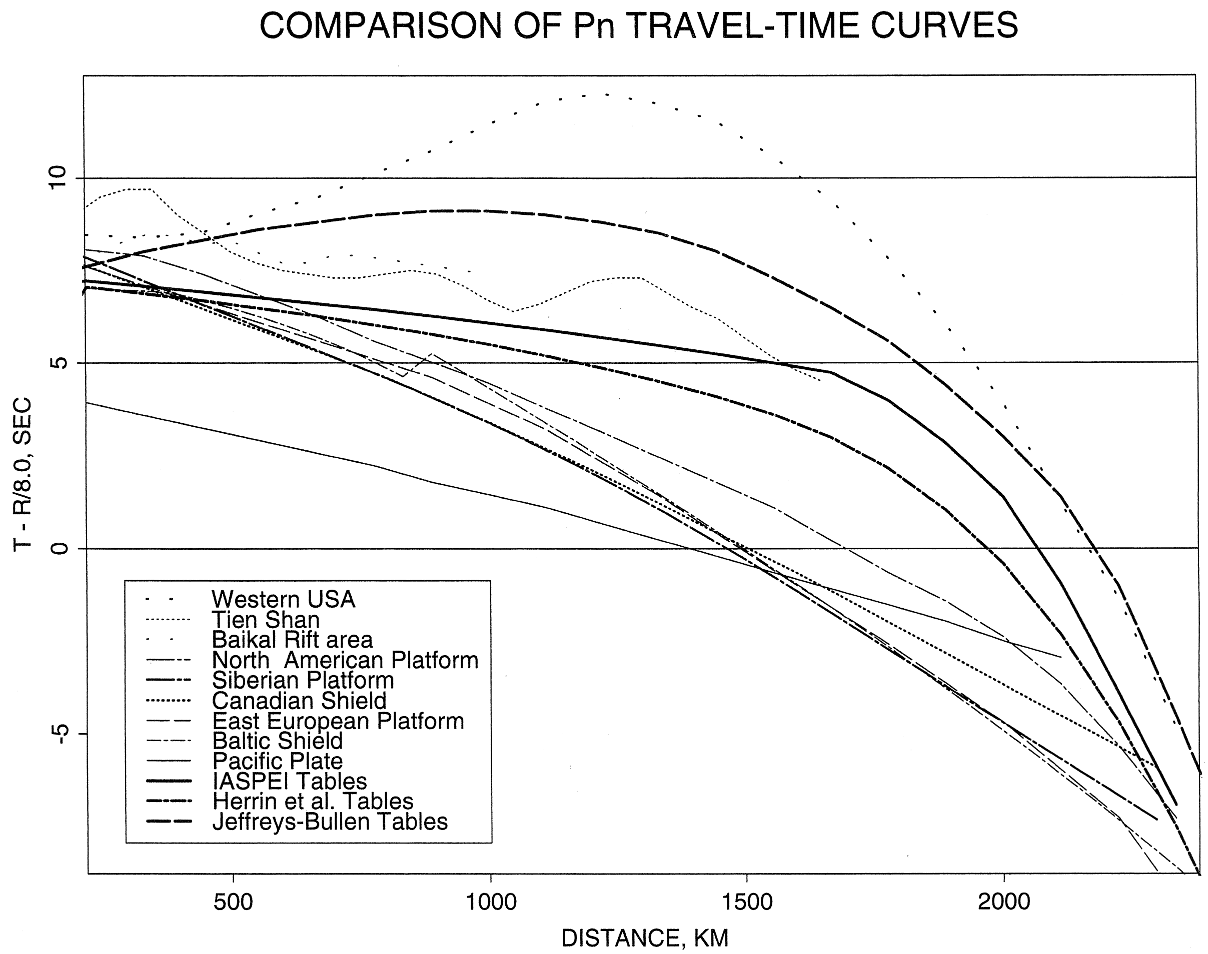

Fig. 7. Comparison of IASPEI travel-times at local and regional distances to those obtained from explosion seismology at different tectonic provinces.

total errors. The total error consists of the measurement errors that are a function of signal-to-noise ratio, and the modeling errors that measure the uncertainty in the model itself. With the revision and better estimation of both the measurement and modeling errors (Beall et al., 1997) that were imple-

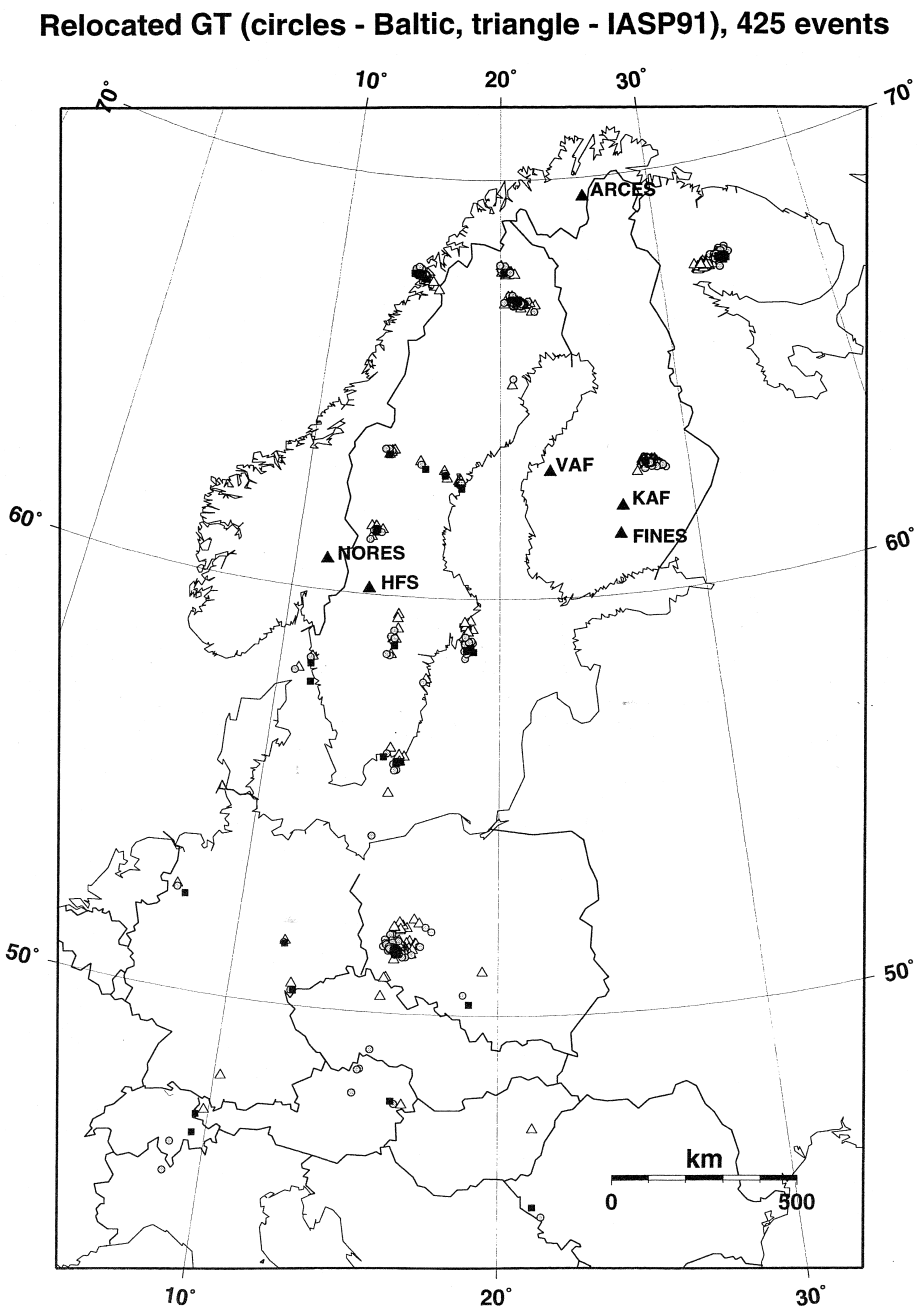

Fig. 8. Relocation results in the Fennoscandia region with the Baltic shield model (circles) compared to the solutions with the iasp91 travel-time tables (triangles). The ground truth locations in the region (mostly mines) are shown as black squares.

mented in routine operations at the pIDC in August 1997, the error ellipses are now a more reliable measure of location errors.

3.3. Slowness–azimuth station corrections

Unlike the NEIC or ISC solutions, the IMS network locations also utilize the slowness and azimuth measurements. Their contribution is most essential when only two or three stations record an event and the number of time defining phases is low. However, the slowness measurements can also be biased. Therefore, the removal of systematic bias from the slowness estimates has a beneficial effect on the locations.

The IMS network being primarily teleseismic, it does not frequently provide regional phases and therefore slowness–azimuth station corrections (SASCs) are determined only for teleseismic phases. Fig. 4 shows the SASC map for the TXAR array, USA. As can be seen, the SASCs are defined over a circular grid in slowness space, and a correction is assigned to a bin if the observations exhibit a consistent bias from the theoretical values.

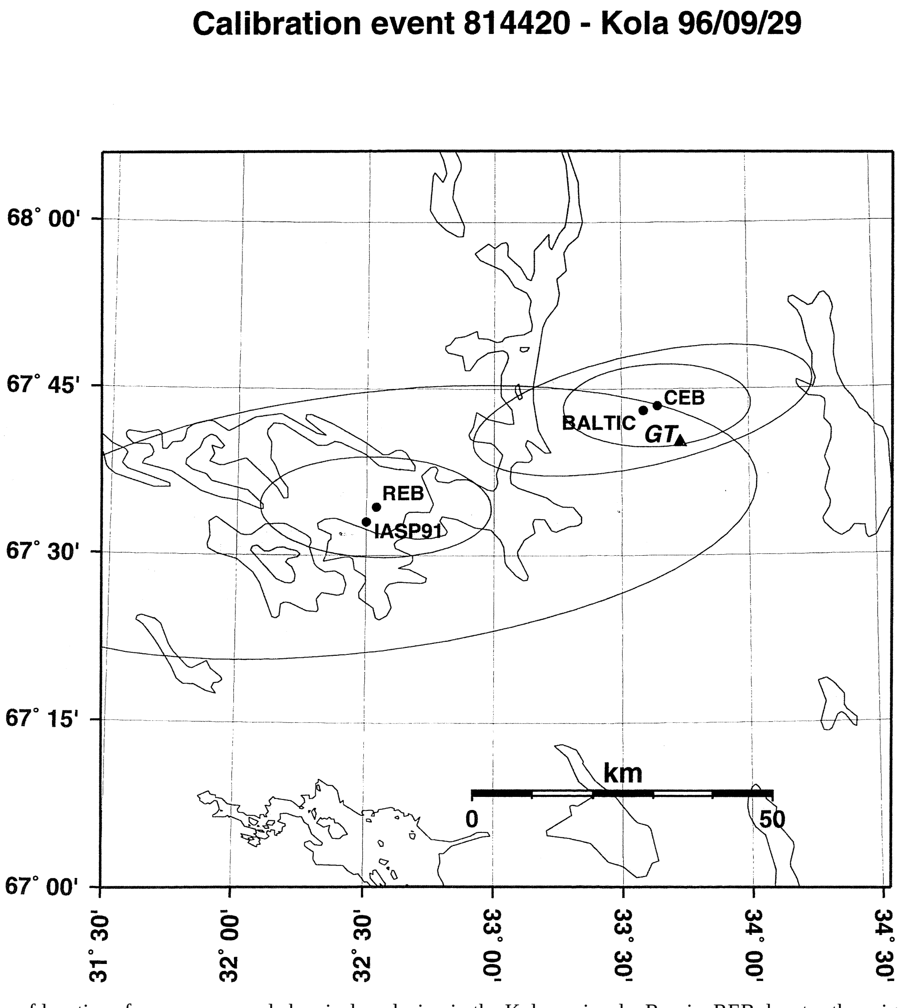

Fig. 9. Comparison of locations for an announced chemical explosion in the Kola peninsula, Russia. REB denotes the original REB solution, IASP91 is the solution with the new estimates of modeling and measurement errors for the IASPEI model, BALTIC is the solution provided by applying the Baltic shield model, CEB is the same as BALTIC but with additional stations and phases from the Finnish and Norwegian NDCs, GT indicates the ground truth location.

To illustrate the effect of SASCs on the locations, 7-weeks worth of data have been selected from the region around Australia that includes Indonesia, the Philippines, the Marianas, Fiji, Tonga and New Zealand. This area is the most prone to events recorded only by two or three primary stations, and thus having very few defining time defining phases. In these cases the slowness measurements are used to provide a better constraint on location. The events were relocated with and without applying SASCs, using only the arrivals from the four primary stations in the area. The original REB locations were used as reference locations. Fig. 5 shows the mislocation vectors from the REB solutions when no SASCs were applied, while Fig. 6 shows the mislocations with SASCs. Comparison of the figures reveals that the mislocation errors are substantially reduced around the Mariana, Philippine, Java, Timor trenches and became smaller around the Solomon, New Hebrides and Kermadec trenches when SASCs are applied. The application of SASCs also reduces the area of error ellipses, without increasing the number of 'true' (REB for this study) locations that would fall outside the ellipse.

3.4. Regional travel-time tables

Although the iasp91 travel-time tables work quite well for teleseismic distances, they may not fit travel time curves at regional distances, especially in Pre-

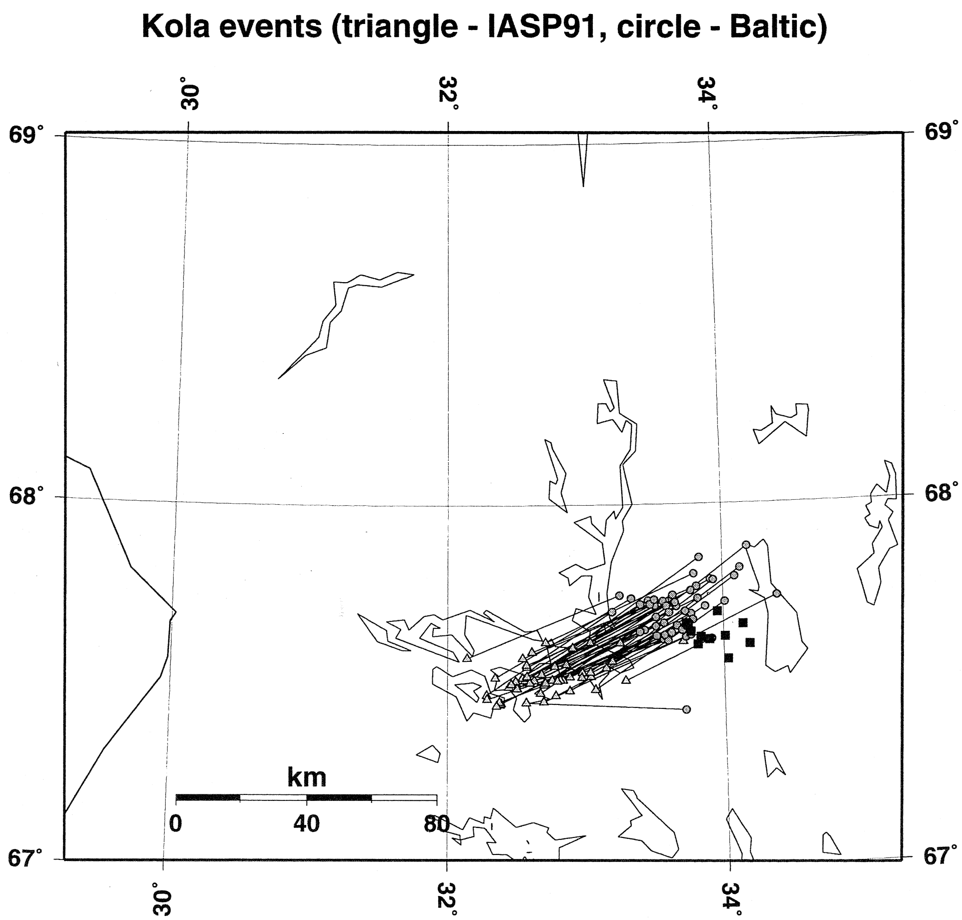

Fig. 10. Relocation results in the Kola peninsula with the Baltic shield model (circles) compared to the solutions with the iasp91 travel-time tables (triangles). The mine locations (ground truth) in the region are shown as black squares.

cambrian shields and platforms. As Fig. 7 shows, the difference can be as much as 8 s, resulting in systematic location errors. Fortunately, shield and platform areas can be considered homogeneous enough to apply one-dimensional velocity models. Even with this simple approach, systematic mislocations can be dramatically reduced.

We applied one-dimensional travel-time curves for the regional Pn, Sn, Pg and Lg phases recorder at stations in Fennoscandia, derived from long range seismic profiles (North et al., 1997). As most of the events are mine-related ones in the region (Grant et al., 1993, Tarvainen, 1996), the mine locations can be accepted as ground truth. Fig. 8 illustrates the relocation results with the Baltic shield model shown as circles. The solutions with the iasp91 travel-time tables are shown as triangles and the mine locations as black squares. In both cases the new modeling and measurement errors are applied. Inside the network, where the station coverage is good, the improvements are not so spectacular, but at far regional distances—Kola peninsula, Poland, Norway—the mislocation errors are greatly reduced. Furthermore, the sizes of the error ellipses are substantially less (all below the 1000 km^2 limit) while still containing the ground truth locations.

Fig. 9 shows a case study from the Kola peninsula. A chemical explosion announced by the Russian authorities took place on September 29, 1996. The ground truth location is shown as a black triangle, together with the original REB, the iasp91 and the Baltic shield model solution. The CEB location, besides the data from IMS stations, utilized phase arrivals provided by the Finnish and Norwegian NDCs. Here also the travel-time tables derived from the Baltic shield model were applied. It can be seen that the REB solution was not only about 50 km away from the real location but its error ellipse did not contain the ground truth location. The iasp91 solution remained basically the same as the original REB solution but owing to the new modeling and measurement errors, its error ellipse now included the true location—at the expense of a huge error ellipse. The Baltic shield model solution moved really close to the ground truth, and its error ellipse became reasonably small. The CEB location did not improve the location substantially, but because of the additional stations that took part in the solution, the error ellipse shrank further. It should be mentioned that this is not an exceptional example, but rather typical, as Fig. 10 shows. The figure illustrates how the Baltic shield model solutions (circles) move toward the ground truth mine locations (black squares) as compared to the iasp91 solutions (triangles).

4. Conclusions

Since the IMS network consists of relatively new stations (many of them have not been deployed yet), its location calibration will definitely be a long project. The success of the calibration effort strongly depends on cooperation with the national data centers. So far Australia, Bolivia, Brazil, Canada, Chile, Colombia, Costa Rica, Croatia, the Czech Republic, Finland, France, Germany, Great Britain, Hungary, Israel, Italy, Japan, Norway, Pakistan, Peru, Romania, the Russian Federation, Slovenia, South Africa, Spain, Switzerland and the USA have contributed to the calibration effort.

As ground truth information and data from the IMS stations accumulate, we can proceed with location calibration from geologically better known areas to less known parts of the world. Encouraged by the success of the Baltic shield model, which was implemented in routine operations in August 1997, we are going to derive and test one-dimensional regional travel-time tables for other platform and shield areas, such as Eastern North America, Australia, South Africa, the Russian platform and Siberia. We will also make efforts to derive path-dependent corrections in tectonic areas, such as Western North America. Once the corrections are evaluated and the testing results warrant, they will be implemented in routine operations.

Acknowledgements

The authors would like to thank Greg Beall, Petr Firbas, Jan Gaudaen, Hans Israelsson, Walter Nagy, Vlad Ryaboy, Henry Swanger, Matti Tarvainen and Nikolay Vasiliev for their contribution to the calibration effort, Ron Cook and Daud Shah for the reprocessing of the waveforms of calibration events, and especially the personnel at the NDCs who have provided invaluable data on the calibration events.

References

Bondar, I., 1997. Comparison of REB locations with NDC solutions during the GSETT-3 period, Center for Monitoring Research. Technical Report CMR-97/11.

Beall, G., Israelsson, H., Swanger, H., 1997. New style measurement and model errors, Center for Monitoring Research, CCB Memo CMR-97 July.

Grant, L., Coyne, J., Ryall, F., 1993. CSS Ground-Truth Database: Version 1 handbook, Center for Seismic Studies, Technical Report C93-05.

North, R.G., Bondar, I., Ryaboy, V., 1997. New regional traveltime tables for the Baltic Shield inferred from DSS observations for calibration of the International Monitoring System, Proceedings of the 19th Annual Research Symposium on Monitoring a Comprehensive Test Ban Treaty, September 23–25, 1997, Orlando, USA pp. 115–124.

Tarvainen, M., 1996. Personal communication.