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## 6.1 Recommendations for Seismic Event Location Calibration Development

***Report from the Oslo Workshop 12-14 January 1999***

*Introduction*

During the May and August, 1998 meetings of Working Group B of the CTBTO Preparatory Commission, the International Data Centre (IDC) Expert Group identified the need for highly-focused work to provide regionalized travel times to improve seismic location methods used in the IDC. The Expert Group suggested that initial focus should be given to three geographical regions: North America, Eurasia and Australia.

To assist with the developments of the IDC applications software relating to the location calibration problem, an informal meeting of the IDC Technical Experts Group on Seismic Event Location was held in Oslo, Norway on 12-14 January, 1999. Forty technical experts, coming from nine signatory countries and the Provisional Technical Secretariat, participated in the meeting. Dr. Frode Ringdal of Norway chaired the meeting.

***Background and technical objectives***

The issue of regional location calibration has been discussed by seismologists for decades. While there is a general consensus that such calibration is necessary in order to significantly improve the location precision of internationally reporting earthquake agencies, no attempt has so far been made to include such corrections in routine location processing on a global scale.

The Oslo workshop 12-14 January, 1999 was convened to begin addressing this problem, by developing plans and recommendations for how such regional calibration could be incorporated into processing at the International Data Center (IDC) for the CTBT International Monitoring System (IMS). The Release 3 applications software will be developed during 1999 for delivery to the IDC prior to the start of the full-scale testing of the IDC. An important element in Release 3 capabilities will be the use of calibration information for event location in specific geographical regions.

Working Group B has previously encouraged States Signatories to support these location improvement efforts by supplying relevant location calibration information. The following types of calibration information were proposed in the document CTBT/WGB-6/CRP.26:

- Precise information on location, depth, and origin time of previous nuclear explosions or large chemical explosions
- Similar information on other seismic events that have been located by regional networks with sufficient precision.
- Data as appropriate on seismic travel-time models
- Any other information (e.g., geologic or tectonic maps) that would be useful
- Ground truth data from chemical explosions.

The primary task of the workshop was to assess the status and availability of such calibration information, and to develop recommendations for data, models and procedures for implementing regional location calibration at the IDC, both for Release 3 of the IDC applications software and for implementation in the longer term.

### Technical Objectives

Four technical objectives were addressed in the meeting:

1. Collection and collation of seismic event location calibration information:
   - Current location calibration information at the prototype IDC
   - Seismic event location "ground truth" information in the relevant regions available from open scientific sources and from States Signatories, including "ground truth" information, calibrated regional event bulletins and other data
   - Regionalized velocity models and seismic travel-time data for geographic-specific areas
   - Relevant regionalized tectonic and geologic information for consideration in Release 3 and for operational use
2. Assessing methods for the representation and application of event location calibration information:
   - Procedures currently used at the prototype IDC
   - Slowness and azimuth station corrections
   - Site-specific station corrections
   - One-dimensional travel-time models in combination with IDC standard earth models
   - Interpolation of individual data segments (tapering, boundary fitting, Kriging, etc.)
3. Providing recommendations for the validation and quality assessment of event location calibration data:
   - Current Configuration Control Board practices at the prototype IDC
   - Methods to assess the validity and usefulness of "ground truth" information
   - Quality control methods to be used at the IDC
4. Development of specific recommendations for incorporation into the Release 3 development program:
   - Region-specific location calibration information
   - Geographic limits on use of region-specific location calibration information
   - Methods for operational use of the location calibration information
   - Validation and quality control procedures to be implemented

### *Presentations during the workshop*

For each technical issue, the starting point was an introduction to the present procedures at the prototype IDC. Participants then proceeded to give specific presentations on each subject matter, followed by discussions and suggestions for improvements to current procedures.

### Collection of Calibration Information

Ground truth information is critical to testing and validation of calibration. Several useful databases are available at the prototype IDC in support of calibrations:

- The Reviewed Event Bulletin (REB) provides information for events worldwide within approximately 5 days after events occur.
- The Explosion database contains available information on all the 2041 nuclear explosions worldwide during 1945-1998.
- The Calibration Event Bulletin (CEB) consists of re-analyzed events especially selected from the REB on the basis of the recording quality, location, and magnitude of the events.
- The Ground Truth database includes four categories of events: GT0, GT2, GT10, and GT25, which correspond to location accuracies of 0 km, 2 km, 10 km, and 25 km, respectively.
- The Gamma Bulletin database are contributed by NDCs for events located by national networks. Quality information on locations is sparse in the Gamma Bulletin.

A number of papers relating to the collection of calibration information were presented by participants. Models for regionalization on a global basis were presented and discussed. Specific presentations were made by several experts describing regional velocity models and calibration data for the three general geographic regions being considered initially for calibration in Release 3: North America, Eurasia (Europe and Asia) and Australia.

It was noted that for some regions, information was incomplete or lacking, and the use of default "generic" velocity models for various tectonic regions was discussed in some detail. Valuable new data on ground truth information for seismic events was presented, and will be communicated to the IDC and the prototype IDC. Countries were encouraged to continue to provide relevant calibration data for the purpose of developing accurate seismic travel-time curves for various geographical regions.

The Expert Group on Seismic Event Location has the mandate to collect relevant information from all open scientific sources as well as requesting and compiling such information from all countries participating in the work to develop the IDC procedures. There is a wealth of information that could be relevant for the location calibration problem, and it will be a very large undertaking to assemble and apply essential parts of this information to the IDC processing.

### Application of Calibration Information

The goal of the current work at the prototype IDC is to improve estimates of location uncertainty (error ellipses) as well as to improve location accuracy. Location coverage ellipses are computed based on a-priori estimates of observational error. A-priori observation errors (arrival times, azimuths, and slownesses) are partitioned into measurement error and model error. Measurement error is considered a function of signal-to-noise ratio. Model error is a function of phase, depth, and distance. All corrections to observations (arrival times, azimuths, and slownesses) are also specified with model error.

There is a hierarchy of location calibration parameters. The software can accommodate, 1) slowness and azimuth station corrections as a function of station, phase, slowness, and azimuth, 2) bulk station travel time corrections for each station and phase, 3) one-dimensional regional phase models for each station, and 4) source specific station corrections as a function of station, phase, and source location. Model error must be specified for all such cases.

Reports were presented on a number of modelling studies, some of which showed significant improvement in location precision when applied to test sets of seismic events. For example, one-dimensional regional Pn, Pg, Sn, and Lg travel time curves were shown to provide improvements for the Baltic shield, the Barents region and North America. Three-dimensional models were introduced for North America and Europe and found to provide considerable improvements in location accuracy compared to standard (IASPEI-91) models.

Techniques for improved regional processing using sparse seismic networks as well as improved azimuth determination for regional arrays were presented and discussed. The application of special location techniques such as Joint Hypocentral Determination in a global context was also addressed.

### Validation of Calibration Information

Changes to the Operational System at the prototype IDC are subject to a rigorous review and approval procedure before implementation. A Configuration Control Board (CCB) that consists of senior staff of the prototype IDC is convened as needed to carry out this procedure. A proposal that addresses each of the following issues is required:

- Statement of Objective
- Summary of Proposed Change
- Expected Benefits
- Possible Risks and Dependencies
- Summary of Testing
- Schedule and Plan for Implementation
- Resources Required

The benefits of the change must be demonstrated through both unit testing and integration testing through a testbed system. Metrics have been devised that are appropriate for evaluating new sets of corrections to travel-time, azimuth, or slowness. They require sufficient "ground truth" events to measure the improvement in location and, where appropriate, depth and origin time. It is just as important that the location errors, as expressed for example in confidence ellipses, are realistic as that the locations themselves are improved.

The experience presented by participants included a review of relevant experience from the Experts Group on Screening. The development of event screening criteria for location and depth depends on the accuracy of their measurements and associated uncertainties. Comparisons of REB solutions to local and NDC network solutions indicates that:

- the REB 90% coverage ellipse does not contain the 'true' locations 90% of the time
- the depth uncertainties do not adequately represent the errors in depth

As a consequence the event screening criteria have been tailored to account for the errors in these measurements, resulting in depth and location not being as effective for screening as they could be. To make full use of these criteria, errors in the REB solutions need to be sorted out and the uncertainties minimized. The collection and analysis of calibration events will go a long way in achieving this goal.

**Working Group Discussions**

Three Working Groups were established to discuss the technical issues in detail during the meeting:

- Working Group 1: Collection of Calibration Information
- Working Group 2: Application of Calibration Information
- Working Group 3: Validation of Calibration Information

The results of the Working Groups were presented and discussed in a plenary session. These discussions have provided the basis for the recommendations presented below.

***Recommendations***

The IDC should locate events accurately, given the limitations of the IMS network and the current scientific knowledge, in support of the requirements for on-site inspection in the CTBT Protocol. The CTBT Protocol provides that the area of an on-site inspection shall not exceed 1000 square kilometers, with no linear distance greater than 50 kilometers in any direction. Therefore, this is the target for location accuracy in the Reviewed Event Bulletin as well as for special event analyses.

The recommendations listed below apply to IMS primary and auxiliary seismic stations. The question of Cooperating National Facilities is not addressed, but such stations could provide important additional calibration information.

Any changes in the parameters or processing algorithms at the IDC will be subject to formal procedures which will be established in the IDC Operational Manual.

**Technical Issue 1: Collection of Calibration Information**

*General*

1. Regional calibration of the IMS network will be required to achieve a location accuracy of 1000 sq km or better for well-recorded seismic events.
2. Calibration information for this purpose consists of ground truth information plus arrival data and/or waveforms. If the arrival data are not at IMS stations, station coordinates should also be supplied. For location calibration, GT0, GT2, and GT5 data are the highest priority. GT5 should be established as a new category. In general, an effort should be made to collect information for as many seismic phases as possible. Data quality information should be collected along with the ground truth data.
3. The IDC, within its structure, should maintain the calibration databases, coordinate and organize the acquisition of data, including contacts with the NDCs and liaison with non-governmental organizations, obtaining publicly available data, and remaining cognizant with the scientific literature.
4. Encouragement to States Signatories to cooperate in the location calibration of the IMS should be given by the PrepCom. This cooperation should encompass both supplying existing and available data and actively collecting new data through national or multilateral cooperative projects.

*Long Term*

1. Collection of data from the IMS stations and the NDCs for the Calibration Event Bulletin (CEB) should continue indefinitely. The IDC should maintain and update the CEB and make it available to the NDCs. The IDC should also collect ground truth data and organize and maintain it in appropriate databases. The IDC should provide direct access to the calibration and ground truth databases. NDCs should be encouraged to provide ground truth data.
2. The Calibration Event Bulletin should be supplemented by representative, carefully analyzed events from the explosion database, the Ground truth database and the Gamma bulletins. Based on this set of events, an Operational Location Calibration Database (OLCD) should be established (and continually updated). The OLCD should be made operationally available to be used for Joint Hypocenter Determination as required for regular REB production and special event analysis.
3. The ground truth database should be enhanced by collecting information on appropriate mining explosions and earthquakes, as described below. The explosion database should be maintained, updated, and added to as new data becomes available
4. For mining explosions, priority should be given to mines that produce detectable recordings on more than one IMS station. States Signatories should be encouraged to provide accurate timing for such explosions, e.g. by placing a recording instrument close to the mine, and to cooperate with the mining industry in the country to obtain details of charge size, configuration, etc., for explosions that are seen at more than one IMS stations.
5. For earthquakes, the IDC should seek to obtain publicly available information from aftershocks and dense network deployments, e.g. IRIS PASSCAL experiments, for earthquake of location quality of at least GT5 and of magnitude 4 and above. Earthquakes recorded by IMS stations are the most desirable.
6. The IDC should make an inventory of seismic refraction data, its nature and quality. The States Signatories should be encouraged to make appropriate data available to the IDC for location calibration through national or cooperative projects.
7. Even with these data collection efforts, it is not expected to be possible to calibrate the IMS to provide an accuracy of 1,000 sq km error ellipse area or better in all parts of the world. The only additional source of information is calibration explosions, and such future chemical explosions are encouraged. Explosions on land or in water are both suitable for location calibration; explosions in water are particularly effective in terms of charge size

*Short Term*

1. Collecting location calibration information is an important part of the IDCs work.
2. A transition plan needs to be developed to move the calibration databases and their operation and maintenance from the prototype IDC to the IDC. The IDC should identify the appropriate resources that will be needed both for the transition and for continuing operations. Formal collaboration and cooperation between the appropriate groups in the IDC and the prototype IDC will be needed.

3. Under present plans, the databases will be delivered in mid-1999 to the IDC. Upon the delivery, the IDC should start reanalyzing the CEB events that need to be reviewed. Data should be exchanged between the prototype IDC and the IDC in the transition period.
4. An initial version of the Operational Location Calibration Database, intended for operational use in Joint Hypocenter Determination as required for regular REB production and special event analysis, should be developed.
5. Recognizing the importance of auxiliary station data in locations, it is technically desirable to connect the auxiliary stations to the IDC as soon as possible.
6. A review of the scientific literature to identify appropriate ground truth data should be conducted.
7. A technical advisory group should be formed to identify appropriate sources of calibration information.
8. States Signatories should be encouraged to fund the collection of calibration information, including cooperative efforts.

**Technical Issue 2: Application of Calibration Information**

*General*

1. Seismic event location at the IDC will be made by developing a global geographic grid system, with station-specific calibration information for each grid point. This means that for each seismic station in the IMS, an associated grid will be implemented with values in each grid point corresponding to the best available phase information (travel times, azimuths, etc.) for regional as well as teleseismic phases.
2. Initially, this grid system may be spaced by 0.5-1 degree, but it could eventually be much denser. While the grid should in principle be equidistant on a global basis, it would in practice be advantageous to make the grid system denser in certain regions, for example, regions where the geology and tectonic structure is complex.
3. The grid system would encompass zero (or shallow) source depth on a global basis, and would be supplemented by grid systems at various depth intervals to allow for optimum processing in regions where deep earthquakes are known to occur.
4. A "generic" travel-time table (e.g. the IASPEI-91 table) is used to compute default travel times for each station-grid-phase combination. As regional velocity models are developed and validated, these models would be used to calculate refined travel times for the appropriate paths. These calculations could be done by modelling in one, two or three dimensions, and the guiding principle would be to include at any time the best validated model available.
5. In addition to these model-based data, a number of actually observed travel times for various phases, using validated calibration events, would be included, and would enable even more precise corrections to be made to the grid surface for events near these calibration sources. The global grid data could thus be continually improved as such events are accumulated. An interpolation mechanism, as well as a series of consistency checks, should be implemented to ensure that these new data retain consistency with the overall models.

6. Updates to the global grid should be made at regular intervals, and should be accompanied by extensive validation and evaluation to verify that they actually improve the location performance of the system.
7. The IDC and the prototype IDC should make all the calibration information openly available to participating National Data Centers (NDCs), so that each NDC can repeat the calculations and verify the results. Furthermore, a record of historical changes should be kept to enable changes to the calibration grid to be traced over time.

*Travel-time models*

1. The general goal should be predicted travel-time, azimuth, slowness, and a-priori uncertainties for each IMS station or array specified as a function of phase, source latitude, longitude, and depth. This should include regional and teleseismic phases. Resolution should allow for 0.5 to 1.0 degree sampling worldwide with embedded regions of higher resolution.
2. In order to reproduce locations, predicted travel times, slownesses, azimuths, and a-priori uncertainties (or corrections with respect to a standard one-dimensional model) should be available to users outside the IDC either in databases tables or through Web-pages.
3. While short term activities may emphasize calibration of regional phases it should be recognized that improved location in many regions depends upon improvements in both regional and teleseismic calibration.
4. Consistency of regional and teleseismic corrections will ultimately depend upon development of a single consistent three-dimensional velocity model for regional and teleseismic propagation.
5. A reasonable goal is to provide predicted travel times, azimuths, and slownesses with uncertainties better than the equivalent uncertainty of +/- 1 second for teleseismic P-waves.
6. Methods for development of travel time models may include interpolation of empiricial travel times from clustered or master events, or development of regional one-, two- and three-dimensional models (tomography, surface waves, deep seismic sounding, etc.) and tectonic regionalization. Model based and regionalization approaches must be validated by independent data sets that test the extension of the model beyond the limits of the original calibration data and phases to the intended phases and regions of applicability.

*Procedures*

1. The best available validated and tested model (for each region, station, or phase) should be included in each system release. The models should not be considered constant and static.
2. The calibrated location models should be updated as better validated models are approved for each region, station, or phase. Location calibration activities should continue indefinitely. Costs of activities should be shared by participating States and CTBTO to facilitate the process of developing, testing, and validating location models in all regions.
3. As location procedures (predicted travel times etc.) are updated, the historical set of procedural changes should be documented to permit unambiguous reproduction of old and new locations.

4. National Data Centers and other parties should be encouraged to provide calibration data, validation data, and cooperative proposals for location calibration. Proposals should be open and transparent for review and comment by outside parties. The US/RF cooperative effort is viewed as an excellent example of a cooperative effort that may include both calibration proposals (new travel time tables) as well as calibration data (original ground truth origins and arrival times) and validation data (additional ground truth origins and arrival times).
5. Calibration model development and testing/validation should be conducted with independent data sets.

**Technical Issue 3: Validation of Calibration Information**

*General*

1. A Configuration Control Board (CCB), similar in function to that currently at the prototype IDC, is an appropriate mechanism to validate calibration information and to define rules for acceptable ground truth data. The Provisional Technical Secretariat should establish a Configuration Control Board for the IDC.
2. A Location Calibration Board (LCB) should be established, with the responsibility to oversee the location calibration process. This Board should assess proposals for and recommend updates of relevant parameters and region-specific corrections, and forward its recommendations to the CCB for implementation. The Board should enlist the assistance of experts in each region being considered. It may be appropriate to make proposals related to a calibration of a particular region available to NDCs in that region for comments in advance.
3. Unit test metrics for the validation of proposed improvements should be primarily based upon sufficient relevant Ground Truth (GT) event locations, and should include the following requirements:
   - The median mislocation of GT events should be significantly reduced
   - Mislocation should be reduced by 20% or more for the majority of events
   - Median confidence ellipses should be reduced in area, and the coverage (% of GT events lying within the confidence ellipse) should be the same or better
   - Confidence ellipses should be reduced by 20% or more for the majority of events
   - Fit, as expressed by residuals or their variance, should be similar or better
4. For each area studied, a set of ground truth events, the majority of which should be located by sufficient (for location) IMS stations, should be established. Historic events recorded by sufficient surrogate IMS stations may be included, but should comprise less of half the events used. Any validation should use a set of events that do not include those from which the proposed corrections were determined.

*Data Base Development and Validation*

1. Proposed new calibration parameters should be subject to integration testing in an online (testbed) system with real time data for a period of more than one week, and for at least long enough that the corrections are applied to some events and location improvements demonstrated.
2. Any change in software or parameters that affect the location of events should be approved by the CCB. A complete record of changes in both software and calibration

corrections relevant to location of events should be maintained at both the prototype IDC and the IDC.

3. The Location Calibration Board should recommend criteria for designation of ground truth events and related phase data, and forward these recommendations to the Configuration Control Board for approval. For GT0 and GT2 events, such criteria should include supporting references and/or documentation for each event. For GTx where x>2, specific criteria on station coverage should be met or documentation should be provided. Criteria should also be established for the use of non-IMS stations as surrogates for IMS stations.
4. Responsibility for the Calibration Events Database (CEB) will be transferred from the prototype IDC to the IDC in mid-1999. The IDC should maintain and update the CEB, including carrying out additional waveform analysis, and make it available to NDCs and the prototype IDC. Both the IDC and the prototype IDC should collect ground truth data and exchange it on a regular basis.
5. The IDC and the prototype IDC should provide direct access to the archive database, including calibration and ground truth databases. Full responsibility for calibration work and associated databases should be assumed by the IDC after the final software release is delivered to the IDC by the prototype IDC. NDCs should be encouraged to provide ground truth data, accompanied by supporting documentation.
6. Statistics on the Calibration and Ground Truth databases should be reported to NDCs. Such statistics should include the numbers of events added and analyzed, and the geographical coverage of these databases.
7. CCB proposals and minutes, and related technical reports, should be made available to NDCs, preferably through a convenient Web page mechanisms. An annual report should provide metrics on mislocation and confidence ellipse size and coverage on a region by region basis, taking into account the most recent ground truth information.
8. Expenses associated with the validation of calibration information and results are to be covered by the NDCs and the prototype IDC on a voluntary basis, but some work needs to be funded by the CTBTO if full global coverage is to be accomplished.

**Technical Issue 4: Specific Procedures for IDC Release 3**

1. In the work towards developing IDC Release 3 software, the general recommendations described above concerning the collection, application and validation of calibration information should be taken into account.
2. The infrastructure being established for location calibration will enable systematic, ongoing improvements and updates to be made for all areas of the world. IDC Release 3 should begin this development by initially including regional calibration information for North America, Eurasia (Europe and Asia) and Australia.
3. For each region, validated travel-time and velocity models should be incorporated as available. For subregions where no specific such information is available, a generic velocity model (e.g. IASPEI-91) should be used.
4. The best available validated and tested model for generating travel times should be used for each region to be calibrated.

5. Regional calibration information should be implemented only after the corresponding improvements in location accuracy has been documented in accordance with criteria specified in the recommendations provided above for the validation section.
6. An initial Operational Location Calibration Database, intended for operational use in Joint Hypocenter Determination as required for regular REB production and special event analysis, should be delivered as part of Release 3.
7. A transition plan should be established for transferring responsibility to the IDC from the prototype IDC in connection with the Release 3 developments. This plan should incorporate a schedule for the establishment of appropriate infrastructure at the IDC, such as a Configuration Control Board and a Location Calibration Board.
8. Signatories are requested to provide, as early as possible, all relevant location calibration information that they may have available for the regions listed in item 2 above. Experts from Signatories are encouraged to work closely with the prototype IDC, the IDC and the coordinator to assist in the collection and validation of data. This new calibration information should be included to the maximum extent possible in the IDC Release 3 applications software.
9. Additional slowness-azimuth station corrections should be included in Release 3, and such corrections should as a minimum be developed for all existing primary seismic stations.
10. All existing 3-component primary stations should be calibrated with respect to the orientation of the components for Release 3.

**Frode Ringdal**

***Reference***

Technical Documentation from the Workshop on IMS Location Calibration, Oslo, Norway 12-14 January 1999, NORSAR, Kjeller, Norway