METHODS FOR THE IMS REGIONAL KINEMATIC CALIBRATION

Nikolai A. Vasiliev

Laboratory of Experimental Geophysics
Joint Institute of Physics of the Earth
Russian Academy of Sciences

ABSTRACT

Among the problems related to CTBT a very important role belongs to the calibration of the regional travel times (regional kinematic calibration). The success in solving this task would significantly improve the accuracy of the weak seismic event location by the system. The methods that are applied to perform this kind of calibration are assumed in the present paper. All these methods can be broken into two principal groups: methods for direct calibration and those utilizing the velocity model of the media that is to be developed in an intermediate stage.

Direct methods are used to construct the time correction surfaces making use of previously learned seismological experience (regional travel time tables) or directly employing the experimental data. The first approach represents the try to perform the task through the linear combination of regional travel time tables (godographs) and their errors. Another technique is a kind of spatial interpolation of the regional observations for given station.

Indirect methods solve the calibration problem in two steps. Initially the 3-D velocity model of the media is being produced by the inversion of the observations. Afterwards the field of travel times is generated on the base of the velocity model. Methods inside the group differ depending upon what way is chosen for the reverse kinematic problem solution. Currently the velocity models are being built by “try-and-drop” technique or by tomographic inversion. The tomographic P-models developed till now do not possess the horizontal resolution enough to be successfully applied in a regional scale. The main reason of poor lateral resolution for the uppermost mantle comes from low amount and uneven distribution of regional P-wave observations used to produce the global tomographic models. The reliability of 3-D model constructed by “try-and-drop” method is unknown but its using is still reasonable unless enough data for the area to be calibrated have been collected.

Some investigators make the attempts to supplement the basic data by newly collected regional P-observations; others try to employ the S-models constructed on the base of the surface wave or the channel wave observations. The “try-and-drop” technique can be assumed as the attempt to compensate the lack of data by experience and intuition of the scientist.

The success of the efforts is defined by the availability of the regional P-wave observations and by proper choosing the method corresponding to the volume and geographic distribution of the data set. When and where the collected data density and geometry reach the definite threshold the seismic tomography will be able to resolve the problem of regional kinematic calibration in a comprehensive and optimal in given sense manner. In a meanwhile the composition of data availability, data distribution, geologic and tectonic complexity, and knowledge about the region define some role for each of calibration methods assumed.

OBJECTIVE

The quantitative target of the CTBT seismic monitoring is expressed by the requisite upper bound area of the 90% error ellipse around the detected seismic event. This area must be not more than 1000 km^2. Nevertheless the first evaluation of the IMS effectiveness revealed that the real results rarely fit 1000 km^2 requirement especially for the weak events that are mostly detected by the regional stations (within 2000 km circle around the event). Currently several methods to perform the regional kinematic calibration are being developed and the task of their classification rises. Such classification is aimed at better understanding the limitation of the methods and outlining the relevant areas of their application.

RESEARCH ACCOMPLISHED

All the methods related to the problem could be divided into two main parts. The first group constructs travel time corrections directly from observational data. The second group is characterized by two-stage way of solving the problem: the velocity model of the media is the result of the first step in which the reverse kinematic problem is being solved.

Methods for direct estimation of the regional travel times

Let us call direct that methods which aimed at producing the travel time corrections directly from experimental observations passing over the building the intermediate velocity model of the media. Depending upon the scale of the region the next types of corrections can be recognized.

Bulk corrections are those independent upon the azimuth and distance. They reflect features of crust and upper mantle underlying the seismic station.

Regional corrections are expressed by the regional travel time tables or godographs that are constructed for regions of the homogeneous tectonic structure of the upper layers of the Earth. Usually such godographs are calculated and utilized for a regional seismic network; their usage is helpful, but often it is impossible to track back a source of their appearance. We also put to this category the corrections developed for the relatively small areas when these areas are assumed to be homogenous. An example can be extracted from the history of nuclear explosion monitoring. The testing areas of the nuclear test sites were studied carefully enough to develop separate time corrections for them (Pahute Mesa and Yucca Flat inside Nevada Test Site of USA, Balapan and Degelen at the Semipalatinsk Test Site of former USSR, Mururoa and Fangataufa at the Pacific Test Site of France).

Continuos correction fields (point corrections, Source-Specific Station Corrections) are produced by different techniques of a spatial interpolation of experimental observations or regional travel time tables. The correction for new event inside the area covered by the correction surface is defined by the vertical projection of hypocenter to the surface.

The third type of corrections seems to be one of the highest importance for the monitoring the CTBT. Currently inside this group two main methods are being developed. The first (Proportional Godograph Method) is based on the knowledge of the travel time tables for the homogenous regions composing the complex terrain. The second approach is grounded on the direct using of the experimental data to construct the correction surface. The Kriging method is the most developed representative of the latter approach.

The Proportional Godograph Method

According to approach proposed by I. Bondar et. al., 1998, given a seismic ray intersects several homogeneous regions having their own travel time tables, the estimation for the total travel time is expressed as a weighted travel time table with the weights being proportional to the lengths of particular surface projections of the ray inside each region.

This estimation works good for a head wave model when seismic wave velocities are independent upon the depth and the travel in the crust is taken into account. Nevertheless the authors suggested this formulae for the real media since the shape of the experimental travel time - distances plots for regional distances is close to linear.

The Proportional Godograph Method (PGM) is very attractive to application for the kinematic calibration at least because it allows usage the many years experience of seismological observations expressed in regional travel time tables.

The calibration of some territory by this method includes the next steps.

1. Defining the homogenous regions composing the calibrated area;
2. Collecting all available information on the 1-D models (in time and velocity domains) related to given regions; data analysis and choosing the single model for each elementary province;
3. Regionalization that is positioning the borderlines between the elementary provinces;

4. The correction surface calculations;
5. An evaluation of corrections on the ground of the calibration events relocation.

The example of PGM application is described in the paper of Yang et. al., 1999. The method was used for the waves Pg, Pn, Sn, and Lg for the IMS American stations.

The reliable correction evaluation was made using 21 calibration events of known coordinates with the accuracy not worse than 2 km. The calculated epicenters uptrend takes place with 9.7 km median improvement for the events with enhanced epicenters and 4.7 km median deterioration for epicenters shifted out of the true event. The special attention was paid for two earthquakes located inside the Nevada Test Site. The corrections have worked out positively for both cases: the resulted deviation from the true epicenter is as small as 7-8 km. The good news is that the error ellipse area decreased from 1760 to 910 km^2. The negative effect is that the error ellipse coverage (the percentage of calibration events covered by the ellipse) went back from 84% to 74%. We can suggest that the underestimation of the modeling error is responsible for the both effects: the deviation of individual travel time tables from the median characterizes the scatter of mean for different populations rather than the general population scatter.

PGM is already in use for IMS calibration while its methodical error is still to be studied. We have investigated PGM by mean of Pn raytracing (program code "beam87" written by V. Cerveny, 1985). The case of compound media consisted of high-speed "platform", low-speed "tectonically-active" regions, and transmission zone between two regions was assumed. Separately we studied the PGM behavior for the different sharpness of the border between two regions [Vasiliev, 2000].

The PGM appears to be biased and sensitive to the epicenter distance and the distance between the source and media-dividing border. The biases vary from -0.3 s to +0.6s.

We investigated the influence of the regionalization error i.e. the error of location the borderline between different regions. PGM transfers this kind of error proportionally. For the border with transmission zone of 100 km width and distance event - border of 700 km each 100 km in error of border positioning causes PGM bias of 0.3 s ... 0.4 s for stations at epicenter distances 300...1700 km

Modeling for borders of different transmission widths reveals that PGM does not experience the notable dependency upon the sharpness of the border between two regions.

The behavior and quantitative scale of the PGM error allows its practical usage when the error is taken into account. We proposed the approach to do so by introducing both bias and pseudo scatter.

Kriging

The various procedures to construct the surface including scattered points are being widely applied in the mapping and visualization of geophysical data. Some of these are: 2-D bicubic interpolation, an adjustable tension continuous curvature surface gridding algorithm [Smith and Wessel, 1990], a "nearest neighbor" gridding [Smith and Wessel, 1999].

The latter algorithm employs the weighted mean taken through the points inside the correlation radii. Its realization in the GMT package [Smith and Wessel, 1999] additionally takes into account the individual measurement errors.

More developed weighted algorithm constitutes the ground of so called Kriging method. The main feature of the latter is the simultaneous producing of two surfaces: for travel time corrections and for their errors. This method is in practical use for geophysical field surfaces generation for knowledge database of USA Department of Energy developed for the needs of the CTBT [Hipp, 1997], [Young, 1998], [Schultz, 1998]. The Kriging has to satisfy the next requirements:

- To manage the different quality of the data;
- To make user able to effect the weight of each observation;
- To account spatial distribution of the background values for both the time corrections and their errors.

In the most modern release Kriging uses so called variogram reciprocal as the weight of the experimental datum. The variogram is the function assigned to the each station and is based on the correlation of the travel time deviation dependent upon the event-station distance. For stationary case, when the statistics of the process do not vary from point to point, the variogram is equal to background dispersion out of the correlation radii. Inside the circle of this radii the variogram equals to correlation of the observations in the different points subtracted from 1.

The complex regions that include high- and low-velocity provinces are of the most interest from kinematic calibration point of view. For these cases the background statistics vary from point to point and the procedure of Nonstationery Bayesian Kriging has been proposed [Schultz et. al, 1998]. In brief, the latter allows to come to different background models (travel time bias and dispersion) for different tectonic provinces.

The application of the Nonstationery Bayesian Kriging procedure is described in [Myers et. al., 1998] and includes the next steps.

1. One must collect sufficient for each station calibration event database. The number and density of such events are defined by the correlation radii. The latter value for the tectonic regimes is around 2 –3 deg. The authors of the assumed paper use teleseismically located events for calibration database. Selected events fit the next conditions:
    - The azimuth coverage is not less than 270;
    - The number of defining phases is not less than 50.
2. Following Sweeney, 1996 it is accepted that the conditions above guarantee the deviation of the calculated location from the true epicenter not more than 20 km with a 90% reliability.
3. The variogram for each station is constructed.
4. So called declusterization aimed at increasing the calculation effectiveness is to be done. This action averages the experimental observations inside the cell of size defined by condition that the correlation between observation of events occurred inside the circle of this radii is not less than 0.95 (usually about 50 km).
5. The travel time and modeling errors surfaces are constructed.
6. The evaluation of the calculated corrections is made using the set of checkpoints.

The application example of Kriging used to locate the earthquake swarm in Racha region (Armenia) by six IMS stations displays the sufficient enhancement of the calculated epicenters. The average error decreases from 51 km to 14-19 km [Myers et. al., 1998].

The features of the Kriging that limit its application are the next:

- The need to have big training population for each station;
- Relatively small area being calibrated by the method;
- Non portability of the calibration results from one station to others.

These requirements make the calibration scale of the Kriging pretty narrow when comparing to other known calibration methods. The most perspective area of Kriging seems to be the control of the test sites. It worth noting that while these places constitute only negligible part of the Earth surface, the monitoring practice learns us that the test sites are the points of the special attention and sensitivity especially when some event occurs in their vicinities.

Methods for travel time corrections estimation through the velocity model of the media

These methods assume solutions the reverse and afterwards the direct kinematic problem. On the first stage one has to build a velocity model for the media using the observation data. On the second step the correction surface around a station is generated from the velocity model. Doubtlessly, this approach serves to mutual enrichment of the geophysics and the seismological practice when is being applied correctly.

The methods can be divided into two groups depending upon what way is used to solve the reverse kinematic problem: whether it is the try-and-drop method for selection of the model or the tomography is used for this.

Try-and-drop method for the velocity model selection

This method of the velocity model selection comes from the Deep Seismic Sounding (DSS). It consists in selection the only model from the variety of physically valid models. The selected model should provide the minimum deviation from the observed data. For direct kinematic problem solution the separate task is the development of a software working with a global 3-D velocity model of the Earth crust and the uppermost mantle.

Petr Firbas has developed such software, has chosen the necessary resolution for crust and mantle, selected the initial models, and made the tentative adjustment of the model. He also calculated the tentative correction surfaces for the European IMS stations [Firbas et. al., 1997a,b,c]. The program deals with the global models of the Earth crust and the Moho discontinuity of 5 x 5 deg. resolution, and the mantle model of 2 x 2 deg. resolution. The composing background models are:

- The Earth crust model CRUST 5.1 [Mooney, Laskey, and Masters., 1998];
- The mantle model RUM [Gudmundsson and Sambridge, 1998] based on the upper mantle regionalization according to the rock ages and corresponding 1-D velocity models for each type of the tectonic provinces.

As velocity models for the definite regions become more developed they lay over the background model. The application results for North America and for some part of Northern Eurasia are described by Ryaboy et. al., 1998, 1999. Authors suppose that the Moho depth variations as well as the Earth crust velocity structure do not affect notably the travel times at the regional distances. On this ground the focused attention is paid to searching the uppermost mantle velocity model. To perform the regional kinematic calibration 8 PNEs inside USA terrain and 8 PNEs carried in the European Russia have been used. The information about the sources is known exactly.

In the every iteration of the whole procedure the next steps are to be done manually:

- The regionalization is introduced on the first step or is corrected on the succeeding steps; the new regions having specific 1-D velocity structure come into play if necessary;
- The parameters of 1-D velocity models are varied for the regions lying along the ray path surface projection;
- The direct kinematic problem is being solved for the newly adjusted complex model;
- The time correction surface is evaluated by comparison against the observation data.

These actions are being repeated for each explosion until the discrepancy between the model-generated travel times and observed data reaches about 1 second for each event after what one has to deal with the next explosion. After the complex model is corrected event by event (first pass of the inner loop is completed) one has to return to the first explosion because the 1-second difference between the model and experiment can become upset by the model changes involved by succeeding explosions. The procedure stops when the complex model fits experimental data for all the explosions.

The 1.5 second convergence in term of residual mean square was achieved for North America after 45 iterations (i.e. after 45 outer loop repetitions). The background 3-D model RUM contained only 4 typical 1-D velocity models for the continent. The resulted 3-D model includes 5 more mantle types, the borderlines and the models for the initial 4 elementary models have been changed sufficiently. The travel time deviations from IASPEI-91 vary from -5 s to +5 s that corresponds to the North America observation experience.

The calibration of the Northern Eurasia by this method is in the very beginning. There were carried out only 5 iterations; the discrepancies between the complex 3-D model and observations stay still as high as 2-3 seconds for some regions.

The evaluation of the IMS station correction fields modelled by this method was made using only few events. The corrections application leads to improvement of calculated epicenters while the statistics presented in the papers cannot be assumed as sufficient.

The try-and-drop selection method suffers from several unresolved limitations.

1. The model adjustment procedure allows too much subjectivity. The density of the data available is not even comparable to that of DSS where the method comes from. The investigator's fantasy becomes almost fully unleashed and the resulted model inevitably brings the authors understanding of the mantle structure in a fare more degree than the experimental data influence;
2. The combination of the huge labor-intensity and non-reproduction of the resulted 3-D model make the using of this very questionable;
3. There are no independent data to evaluate the corrections: the total number of 1-D model parameters is so big that all the regional experimental data are to be used for the 3-D model adjustment. In fact the model is evaluated using the residual mean square term characterizing the convergence to already used observations instead of using the control population.

We can suggest that the success of the first steps in this direction can be explained by availability and using of widely spread PNEs data, and on the other hand by good choice of the terrain to begin the calibration. North America consists of sharply divided two parts: low-velocity Western tectonic province and high-velocity Eastern platform. For such area one can expect the improvement in the event location even after simplest differentiation when comparing to global IASPEI-91 velocity model.

Transmission seismic tomography application to the problem of the regional kinematic calibration

The particularities of the regional kinematic calibration from point of view of the tomography application consists in the next:

- Relatively thin layer including the Earth crust and uppermost 100...400 km of the mantle is being investigated;
- Anomalies to be revealed are lateral; their amplitude is high (up to 5% of average velocity in the media);
- Characteristic size of heterogeneity is small (tens of km) comparing to the required global scale of the solution;
- P-velocity structure is of the main importance for the location improvement.

The problem occupies its specific place in a hierarchy of structure heterogeneity and earlier has never been solved in such a big scale by the tomographic method. At a time there is no P-velocity global model for the uppermost mantle that would directly allow to solve the regional kinematic problem.

Currently the tomographic approach to calibration is being developed by the geophysics working with the entire mantle P-velocity models and by investigators dealing with other than P wave velocity models for the lithosphere.

P-wave tomography

Kennett, 1998 analyzed the status of the P-velocity models development for upper mantle. He recognizes 3 kinds of approximation for such models; the order of the approximation depends upon the model ability to predict the velocity anomalies.

Author proposed to assume the RUM model [Gudmundson, Sambridge, 1998] as the 0-approximation. This model consists of 9 1-D velocity models corresponded to the different tectonic types of the continents and oceans. The geometry of the tectonic provinces is outlined by the seismic activity pattern and geological and tectonic structures on the Earth surface. The main merit of the model is its global scale. According to Kennett RUM is able to explain some 15% of velocity anomalies that is one third of the full tomography predictability.

The model developed by van der Hilst, Widiantoro, and Engdal, 1997 can be accepted as the model of the first approximation. The model was resulted from the tomography using the averaged rays between clusters of events and groups of neighboring stations. The approach stabilizes the result but smoothes the velocity anomalies. The model has resolution of 2 x 2 deg. on the surface and 100 km in the depth for the best covered terrain. The poor resolution and reliability occurs for oceans as well as for Africa, Eurasia, Antarctica, South America.

The tomographic model of Widiyantoro, 1997 is assumed to be the second approximation. The amount and quality of the data were sufficiently increased compared to the observation ground of the van der Hilst et. al. model. The events were relocated using pP phases; all available at that time ISC data were used (around 7,000,000 P-waves). No clusterization was employed. For the areas of highest data density the model resolution is 1 x 1 deg. and layer thickness of 50-75 km. The authors managed to build the velocity structure for as many as 14 regions, the patches are joined to construct the global 3-D P-velocity model of the mantle.

The second approximation differs from the first one by its resolution power, by amplitude of heterogeneity revealed, and by the coverage: the less detailed model describes the heterogeneity of lower amplitude but it is of wider coverage. The common feature of both tomographic P-models is defined by the very steep rays in the uppermost mantle used for the inversion. This leads to impossibility to resolve the low-scale lateral velocity anomalies, very uneven mosaic coverage defined by natural seismic activity and distribution of stations reporting to ISC.

Ekstrom et. al., 1998 analyzed the real resolution power of the modern tomographic P- models in sight of regional kinematic calibration. The analysis include some of the models assumed by Kennett. The starting point of analysis is the tomographic model of Su, Dziewonski, 1993 describing the large-scale mantle P-velocity heterogeneity on the ground of the spherical parameterization. Usage the model for the nuclear tests location [Smith, Ekstrom, 1996] sufficiently improved the calculated epicenters (the location error decreased by 40%) for the explosions situated inside the stable platforms. The same time relocation using this model does not work positively for the explosions located at the edges of platform where the lithospheric heterogeneity prevails, and the predictability of the model is poor.

To resolve smaller details of the velocity structure the block parameterization instead of spherical one should be involved. After this action far more unknown parameters to be estimated by an inversion appear, and the problem is usually regularized by different ways. Ekstrom et. al., 1998 tried to answer the question whether the real resolution power improves for the models of block parameterization comparing to those of spherical structure. Analysis of the block models [van der Hilst, Widiantoro, Engdal, 1997] and [Boschi, Dziewonski, 1998] comparing with the spherical harmonic model of Su and Dziewonski, 1997 led to the conclusion that the resolution power for formers increases indeed. Authors also stated that the inversion algorithm does not effect the result (SIRT and LSQR have been compared). Another important result is that the models of high resolution preserve the positive features of low-resolution models: the former can predict the big-scale low-amplitude velocity anomalies that are the base of the teleseismic travel time corrections. The latter means that the tomographic approach has a potential to perform the kinematic calibration in a comprehensive manner.

Authors came to the general conclusion that the uppermost mantle models of good lateral resolution should be built on the base of the regional data when the rays are sub-horizontal.

The same paper demonstrates the practical tomographic approach to study the uppermost mantle lateral heterogeneity. All the regional Pn phases stored at the ISC database at the time of study for the event-station distances from 2 to 11 deg. were used. The requirement serves to provide the head wave model workability. The "two station" technique [Berghoul, Barazangi, 1989] has been applied to estimate the P-velocity in the uppermost mantle under the stations. For circular area of radii 1 – 2 deg. around the stations the estimations for Pn velocity and velocity anisotropy have been obtained. We believe that the main results from the practical part of this paper are the next:

- The areas where the regional kinematic calibration can be performed using the earthquake data were outlined. One can expect the increase in ISC data volume and quality; this will necessary enhance the prediction power of the velocity model but will not spread the model to the stable platform regions.
- The anisotropy is notable and can be up to 5% of average Pn velocity. It has been proven the correlation between the anisotropy "fast" axis and the direction of the mountain chains at least in Europe. In other words one has to bear in mind this result when developing the 3-D velocity model covering the modern tectonic regimes: in fact the well pronounced anisotropy introduces 4th dimension into the model.

Tomography employing waves of the other types than P

Ritzwoller et. al., 1999 try to apply the S-velocity tomography to develop the P-velocity model. The well known advantages of the S-models comes from the observation base. Such models are usually deduced from the channel or surface wave data that spread horizontally and far from the epicenter therefore the S-models reflect the lateral heterogeneity of the uppermost mantle and are of wide (even global) coverage.

The authors develop the S-model on the base of group and phase velocity maps of LR and LQ waves for period range from 15 s to 20 s. Each particular 1-D model has 8 parameters to be adjusted (for each layer: thickness, average velocity , and velocity gradient) and are defined down to 400 km depth. All available information about the velocity structure for a given region is used for setting the best starting approximation and restrictions on the variability of parameters.

Authors pointed out good correlation between the revealed S-velocity anomalies, the tectonic structure, and the P-model of a low resolution [Bijwaard, 1998].The S-model conversion into the P-model is planned to be done on the future steps of a study. Nevertheless we assume such conversion as very doubtful. The main obstacle - an ambiguous relation between P and S velocities especially complicated in the uppermost mantle - could not be overcame by anyone so far while the whole row of continental and even global S-models is known.

We would propose to try developing the "SBPV" method (S-Borders, P-Velocity) that employs the tomographic S-model to construct the spatial border of the tectonic provinces. In turn the velocity structure of the province would be set from the P-wave tomography with the static borders.

CONCLUSIONS AND RECOMMENDATIONS

The simultaneous development of direct and indirect methods for calibration has sense as these approaches complement each other.

The success of the calibration efforts is defined by the trade-off between the complexity of the region to be calibrated and the amount and the geographic distribution of the data available. The relation of this type should be assigned to each region and will change with time. On the base of such relation the optimal calibration method could be chosen.

We also assume that to make the solution of the calibration problem more manageable some research laboratory should possess the technical ability to try all the tools being developed and to access all the data being collected.

Key Words: International Monitoring System, seismic calibration, regional kinematic calibration, 3-D P-velocity model.

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