ANNEX B

CTBTO Calibration Programme – Phase 1

Terms of Reference (TOR):

These Terms of Reference contains the description of work for the “CTBTO Calibration Programme – Phase 1”.

1. Background

During the Sixth (May-June 1998) and Seventh (August-September 1998) sessions of Working Group B (WG B) of the Preparatory Commission for the CTBTO, the International Data Centre (IDC) Technical Experts Group on Seismic Event Location Calibration (hereafter Experts Group) identified the need for highly-focused work to provide regionalized travel-times to improve seismic location methods used at the CTBTO/IDC.

To assist with the developments of the CTBTO/IDC application software relating to the location calibration problem, an informal meeting of the Experts Group was held in Oslo, Norway on 12-14 January 1999. A paper CTBT/WGB/TL-2/18 contains the report on the outcome of this meeting to the Eighth (February 1999) session of WG B. These TOR are based upon this report.

The Experts Group has received many reports from a number of countries on activities useful to the Calibration Programme. For example, the Experts Group received a report on the work carried out by a joint Russian Federation/United States Working Group on seismic location calibration for Northern Eurasia and North America. This report was provided to the Ninth (August 1999) WG B session as paper CTBT/WGB/TL-2/35. The Experts Group considered this report to be a valuable contribution to the IMS location effort, and recommended that the data and procedures described in this report be tested and evaluated in the next Release of the CTBTO/IDC application software. The Experts Group encouraged all CTBT Signatory States to follow this example by conducting national or co-operative research efforts relevant to the location calibration problem, following the recommendations for seismic event location calibration developments presented in CTBT/WGB/TL-2/18. As other examples of activities useful to the Calibration Programme, the information on Kazakhstan calibration explosions and Dead Sea calibration explosions can be mentioned.

The overall objectives of the CTBTO Calibration Programme are:

1) *Collection of seismic event calibration information;*
2) *Enhancing the location capability of the IDC through use of calibration information.*

The ultimate goal for the Calibration Programme is the development of high-resolution regionalized velocity models and travel-time corrections, referenced to the IMS network. In Phase

1 of this Programme the emphasis is on regional seismic phases, but eventually travel-time, azimuth and slowness corrections for all seismic phases will be needed. The event location uncertainty, as defined by the 90% uncertainty ellipse, should not exceed 1000 km^2 for events of sizes near the estimated threshold of the future IMS (mb 3 – 4).

The general approach for this Programme follows the paper *"Recommendation for Seismic Event Location Calibration Development"* (CTBT/WGB/TL-2/18) attached to these TOR. Under this approach, the final calibration product shall be a geographic grid of travel-time and, if possible, azimuth (slowness) corrections for regional phases for each IMS station. The grid point spacing should not exceed 100 km, but could be much smaller. For the regional phases Pn and Sn the grid should extend to 20 degrees from the station, or at least out to the farthest point at which Pn is a first arrival in the area. The grid system should cover sources at depth as well as surface sources. While the grids can be model-based, they will have to be validated by regional observations from reference events with known origin parameters (ground-truth data). Velocity models, data used to derive them, and data for reference (ground-truth) events, etc. shall be deliverables. Inventories and analysis of available and new long-range profile data are encouraged. The research products shall be delivered to the PrepCom CTBTO in Vienna, Austria.

2. Scope of the Work

The activities that shall be performed under the Contract are described here below as Tasks.

The Contractor shall perform only the Task/s defined in its Contract.

Task 1: *Collection of ground-truth data and inventory of long-range profiles; Calibration events;*

Task 2: *Collection of regional / teleseismic travel-times; Collection of regional / teleseismic azimuth and slowness data;*

Task 3: *Collection of results for tectonic and seismological regionalization for the Earth's crust and mantle;*

Task 4: *Collection and/derivation of basement depth maps, Moho depth maps, Pn (Sn) velocity maps, attenuation and Lg blockage maps;*

Task 5: *Collection and/or derivation of regional (global) 1-D, 2-D or 3-D high-resolution velocity models of the Earth's crust and mantle; collection of Lg and surface wave velocities;*

Task 6: *Derivation of travel-time, azimuth, and slowness corrections for the relevant IMS stations;*

Task 7: *Validation of the derived travel-time, azimuth, and slowness corrections.*

The work to accomplish any of the above-identified Tasks shall be performed observing closely the detail specifications and definitions given below, and in accordance with Contractor's Statement of Work. Paragraphs in TOR are numbered for easy referencing them in the proposals.

3. Reporting and Co-operation with CTBTO

1. For any activity with duration longer than six (6) months a "Semi-annual Technical Status Report" is to be submitted within 30 days following the completion of the first six months period from the signature of the Contract, providing a description of all achievements in the first six months of work. It should include all relevant deliverables available at this stage in digital form and in the agreed formats.
2. At the end of the work, a Final Report is to be prepared and provided to the Commission not later than one (1) month after the end date of the work. This report has to include all deliverables in digital form and in agreed formats.
3. If the duration of the activities under the Contract exceeds twelve (12) months (and provided the Contract is extended for year 2 and 3 by the CTBTO in accordance with the Optional extension defined in the Contract), then every six months a "Semi-annual Technical Status Report" is to be provided to the CTBTO (always not later than one (1) month after the end date of each six month period). Any such report has to include all the relevant deliverables in digital form and in agreed formats, available at this stage.
4. As a general rule, the Schedule for provision of the deliverables (in digital form) described in the Statement of Work shall be followed, unless otherwise agreed with the Commission in the course of the activity.
5. All formats for provision of deliverables shall be agreed in advance with the Commission.
6. The Semi-annual and Final Reports and deliverables will be evaluated by the Commission taking into account the purposes of the work under these Terms of Reference. Before accepting the Reports, the Commission may request clarifications, additional information or corrections within 6 months from the date of their submission to the Commission.
7. Optional activity 1: Following the acceptance of the Reports, the Commission reserves the right to ask the Principal Investigator to provide a presentation and/or further clarifications/explanations on any part of the Reports or any related deliverable within a period of 18 months from the submission of the Final Report. If additional work is connected with such an explanation which exceeds substantially the Statement of Work agreed for the Contract, the Commission has the option to request the performance of such additional work at terms and conditions to be agreed upon in advance (including possible reimbursement of costs for the Principal Investigator, or any Contractor staff identified by the Principal Investigator).

   Subject to agreement on the additional cost, the Commission may also request the explanation (presentation of results) is provided in Vienna, Austria and/or at a specific workshop.

   It is anticipated that the Commission will mainly consider covering round-trip economy class air tickets and per diem for the period of engagement (at the Commission staff rate) for the persons involved in the additional activity.
8. Optional activity 2: If the Contract already includes (as part of the Terms of Reference or Statement of Work) the provision of corrections and validation of corrections (Tasks 6 and 7), the Commission has an Option to request (following the acceptance and within a 18 month period after the Final Report is submitted) the Principal Investigator to co-

operate with the Commission in the verification of the corrections, and on unit-, integration- and any other further testing of the deliverables. Such Option, if exercised by the CTBTO, may be for up to two man-months in total duration (unless agreed otherwise) in one or multiple visits to the CTBTO in Vienna and may involve the Principal Investigator and/or any other relevant contract staff assigned by the Principal Investigator.

Terms and conditions for this optional activity shall be agreed upon in advance (including possible reimbursement of costs for the Principal Investigator, or any Contractor staff identified by the Principal Investigator). It is anticipated that the Commission will mainly consider covering round-trip economy class air tickets and per diem for the period of engagement (at the Commission staff rate) for the persons involved in the additional activity.

9. All information and data contained in the reports and in all deliverables provided by the Contractor to the Commission in the frame of the work under the Contract are subject to the License defined in the Contract. Reports and deliverables will also be available, on request, to all States Signatories to the CTBT. Detail Specifications of Tasks

<u>For Task 1:</u>

- *Collection of ground-truth data and inventory of long-range profiles*
- *Calibration events*

10. Ground-truth (GT) events are defined as those with well-known uncertainties in origin parameters. The GT classification scheme used for this Calibration Programme is described below. Contractors are to use this GT classification scheme as a guidance and they should use the evidence at hand and their best judgement to assign events to GT categories.

11. GT events useful for the Calibration Programme are those for which travel-times, azimuths, and/or slownesses with acceptable accuracy can be provided for a set of measurement points (stations / arrays / sensors along long-range profiles) in regional and/or teleseismic distances. This implies that GT events must be large enough to be clearly recorded at such distances.

12. For the purpose of the Calibration Programme it is essential that each GT event be assigned a <u>GTx (x = 0, 2, 5, 10, 25) category</u>. Evidence and reasoning for the GT classification have to be carefully documented for each GT event. Trustworthy documentation on each GT event is a mandatory deliverable whenever a GT event is used in the contract fulfilment. The way in which the origin parameters have been obtained (direct measurement, seismic location, stations and input data used to locate the event, etc.) must be clearly specified. The GT events, for which no suitable documentation does exist and/or cannot be provided, should not be used. To guarantee the transparency and trustworthiness of the Calibration Programme, absence of appropriate documentation for a GT event is a reason for its non-acceptance by the CTBTO/IDC and any such event used to derive corrections justifies the non-acceptance of those corrections for any further validation. When in doubt as to what constitutes trustworthy documentation on a GT event and its origin parameters and how to proceed in some more complex situations, the CTBTO/IDC should be consulted.

13. Each event can be assigned only to one GTx category. For any event in a GTx (x>0) category the epicentre must be known with an accuracy of x kilometres (at least at 90% confidence level). The depth for any event in GTx category must also be known with an accuracy of x kilometres (at least at 90% confidence level). It is advisable to consider also the criterion that the origin time of any GT event be known with an accuracy of x / 8 seconds (at least at 90% confidence level).

14. The special case is the GT0 category that can comprise events for which the origin parameters are known with minimal uncertainties (90% confidence level applies). These uncertainties should not exceed a few hundred meters for latitude, longitude. Because of the special importance of these events, some special consideration is given to depth and origin time. The GT0 category is subdivided into two subcategories GT0-HYP and GT0-EPI.

15. The GT0-HYP subcategory will contain events for which all origin (*hypocentre*) parameters (i.e. latitude, longitude, depth, and origin time) are known with the above-defined GT0 uncertainties.

16. The GT0-EPI subcategory will contain events for which only the latitude and longitude (*epicentre* parameters) are known with the above-defined GT0 uncertainties. Estimates of uncertainties for depth and origin time have, however, to be provided as well (90% confidence level applies).

17. In the best case the GT0-HYP event origin information is known based on direct measurements (not seismic location) and with minimal measurement errors in latitude, longitude, origin depth, and origin time. These events are mostly large chemical or nuclear explosions, some which have been used for long-range seismic profile measurements. Information on the GT0-HYP events is most valuable for the Calibration Programme.

18. In some cases the latitude, longitude, and depth are known with the accuracy of the GT0 category, but the origin time is not known from direct measurements and it can be only estimated (e.g. by seismic location using a dense local network). This group of events may include some nuclear or chemical explosions, mine blasts, quarry blasts, rockbursts, etc. In situations where the origin time can be derived reliably with an accuracy of a few tenths of a second (90% confidence level applies), such an event may be used along with the other GT0-HYP events. If such accuracy cannot be achieved, these events can still be very useful for validation of the derived travel-time corrections (e.g. by relocation experiments). These events must be assigned to the GT0-EPI category or, if not considered sufficiently well constrained even for GT0-EPI category, be included in one of the other GT categories (see below).

19. An inventory of all long-range profiles, detailing locations of shot points, shot times, and relevant charges are assets for the Calibration Programme as the shots are typically GT0 events. Collection of this data is strongly encouraged. All long-range profiles providing information on any substantial part of the Earth's crust and on any part of the upper mantle are of interest to this Calibration Programme. Of special interest are profiles which were measured using large explosions (including in-water explosions) and, in particular, using "peaceful nuclear explosions" (PNEs) or kT-level explosions.

20. Of special importance for the CTBTO Calibration Programme are calibration explosions designed specifically for the purpose of calibrating the IMS network. These explosions are always expected to be GT0-HYP events. In all cases the institution planning / executing such an explosion should liase with CTBTO/IDC. Under current

CTBTO budgetary constraints, the CTBTO is not, however, planning funding of any calibration explosions. It is expected that in the long-term these calibration explosions may help to fill the gaps where under current circumstances zero or very few high quality GT events can be identified. The calibration explosions may be exploded in water, where possible, to achieve improved explosion energy coupling into Earth. It would be an advantage to continue projects for explosions in the shallow regions of the world's oceans where a 10 ton explosion is assumed to produce excellent seismic signals, not only within 20 degrees, but also in the teleseismic zone. Some industrial and military underwater explosions may approach the quality of the specifically planned calibration explosions. If possible, such explosions should be considered for inclusion in the GT data sets. Some large explosions in (open-pit) mines and quarries may be also helpful, and efforts should be made to provide their exact location and measure the origin time. Preferred mine explosions and quarry blasts are those which are fired as a single shot. Nevertheless, some of the ripple-fired explosions may also be useful, in particular if they are very large. For ripple-fired explosions, information on the geometry of charges and explosion timing delays should be provided, if available.

21. Besides the GT0 event category, GT event categories GT2 and GT5 were identified by experts as the most useful ones for the location calibration. They represent events for which the hypocentral parameters are guaranteed to be known within two and five km accuracy respectively (at least at 90% confidence level). The GT5 category was established as a new one by the experts at the Oslo 1999 workshop. Some of these seismic events can be those located with sufficient accuracy by densely spaced local and/or regional networks.

22. In some cases the location of events is known only from satellite photography, but with accuracy of at least GT2 category. These events can be very useful for validation of the derived travel-time corrections. It may even be proven that some advanced cluster analysis method can help in estimating the origin time with the accuracy of the GT0 category. Also information on some of the PNEs and historical nuclear explosions may correspond to the GT2 category.

23. GT events of category GT10 (GT25) may be useful, in particular, for azimuth and slowness correction derivation and validation. Some of these events may be very well located, based on teleseismic observations at many stations with excellent azimuthal distribution and/or relocated events from aftershock studies supported by additional evidence (observed macroseismic effects, fault location, etc.). For some shallow events in the oceans their estimated location can be compared with the detailed ocean bottom topography and morphology.

24. To achieve good coverage of an area by GT events, highest priority should be given to providing all available GT0 and GT2 events. If events of GT5 and GT10 categories are available then the spatial distribution of these events is to be considered, i.e. if many of these events have identical (similar) hypocentres, then only a reasonably sized subset of all available GT5 and GT10 is to be provided (e.g. five to ten GT events per one degree square or a cluster). It is, however, important to stress that it is valuable to provide certain redundant events so that spread of values for the derived travel-times (azimuths, slownesses) for origin – station combination can be estimated and thus indirectly the accuracy and reliability of the provided data can be assessed.

25. There are many areas of the world (oceans, subduction zones, areas lacking proper network coverage, etc.) where, at least in the near future, it will not be possible to observe GT5 events. For these areas, GT10 events well constrained by sets of reliable

stations may temporarily be considered in order to approach the global coverage for calibration and attempt to verify the time corrections. These events and associated arrival-time data should be thoroughly quality checked and always given lower weight compared to any GT0, GT2 and GT5 data.

26. In some cases aftershock sequences can help to collect evidence that a particular event may be considered a GT10 event (correlation with observed macroseismic features may be very useful). Joint hypocentre determination (JHD) or other modern cluster analysis approaches can be beneficial for estimating the uncertainties for the event location.

27. Events from the period of GSETT-3, i.e. since January 1995, and events recorded by the IMS and GSETT-3 stations are preferred, but any historical high-quality GT events (for which there is any reasonable documentation) are of interest to this Calibration Programme.

28. In general, the emphasis should be on events of magnitude of 3 and above, since the small magnitude events (not visible beyond a few hundreds of kilometres) are of limited value for the IMS calibration. It is, however, expected that there will be important exceptions to this rule for various reasons (e.g. long-range profile shots, events unique for a region).

29. It is worth mentioning that earthquakes of very large magnitude may not be well suited for the Calibration Programme. The extended fault plane (extending more than several kilometres) and complex (multi-)source mechanism can make the origin parameters uncertain and the travel-time patterns difficult to use, in particular, for regional S-waves. Some ripple-fired chemical explosions, despite having quite large total charges, may also be problematic for the Calibration Programme and care should be exercised in their use.

30. Shallow events (with hypocentre depth not exceeding 10 km) seem to have a higher chance to be characterized by very tightly constrained epicentre locations. Zero depth and shallow GT events seem to be preferable for the derivation of the initial version of travel-time corrections.

31. If the events are supported by clear and reliably identified depth phases, then some of the deep events may prove to be quite useful as well.

32. For some GT events multiple origin estimates are available (for example obtained by different agencies and published). In such a case, the Contractor is encouraged to provide all the origin estimates along with the reference information. If possible, one of the solutions should be assigned the status of " preferred origin".

33. If a location procedure was used then information has to be provided whether any of the origin parameters were or were not fixed when locating the events. If any parameter is kept fixed, the explanation for this action has to be provided.

34. The origin parameters (all provided origin estimates, if multiple of them exist for an event) are to be provided in digital form. The CTBTO/IDC will accept formats that will contain the information requested above. The formats have to be, however, fully described and agreed with CTBTO/IDC. The formats covering some parts of the information requested are, for example, the CSS3.0 "origin" and "origerr" table formats, and/or the GSE2.0 / IMS1.0 origin formats.

35. If a location procedure was used for calculating the origin parameters of a GT event then all the input data used (phase, station, arrival-time, etc.) and their uncertainties are to be provided in digital form and in the format(s) described in the part on Task 2 (see

below). Furthermore, all available arrival data are to be provided for those events whose location is known from direct measurements (GT0 category) as well. (If waveform data are available then these should be also provided – see Task 2 below.)

36. If a location procedure was used then the algorithm for calculating weights based on arrival-time (azimuth, slowness) uncertainty, phase, range, etc. must be described.

37. If a location procedure was used then the used velocity model(s) should be provided in digital form. Provision of this information should follow the specifications on velocity models given in the part on the Task 5 (see below). Furthermore, information on all relevant corrections applied (station corrections, elevation corrections, timing corrections, etc.) must be provided.

38. If a location was used then all output data on the calculated origin (including all relevant uncertainties – 90% confidence level applies), the maximum azimuthal gap, distance to the nearest station, magnitude(s) (if known), and all the residuals must be provided in digital form and in a bulletin format (for example: the GSE2.0 or IMS1.0 bulletin format). The CTBTO/IDC is willing to accept various bulletin formats, but the format has to be agreed with CTBTO/IDC before it is used and must be fully described.

39. If a location software was used then a reference to a publication (if published in an international journal) or a copy of a report describing the location software has to be provided. If a widely used location software has been customised then information on differences against the original published version have to be provided. The CTBTO has the Option (within the contract period and 18 months after submission of the Final Report for the contract) to request a copy of the location software (including its source code) for free use in CTBTO. If CTBTO exercises this Option then the Contractor will deliver this location software to CTBTO within one month and the delivery will include relevant documentation.

40. If a location procedure was used then a detailed description of the algorithm used for calculation of origin parameter uncertainties (uncertainty ellipses, uncertainty ellipsoids, irregular uncertainty areas, origin time uncertainty, etc.) is to be provided along with parameters used (standard errors, weighting schemes, etc.).

41. Care should be exercised when using seismic location to estimate the origin parameters of GT events. Ideally, the location should be based close seismic stations having good azimuthal distribution. Data for difficult ranges (Pn and P in range 17 – 23 degrees; the crossover zone of Pg and Pn as the first onset in a range dependent on the local Moho depth) should be weighted down (or avoided) in location. It may be useful to test locations based on P-type arrivals only and compare them with locations based on both P and S arrivals. Conclusions may be drawn from comparison of these multiple location results.

42. For events well recorded both at regional and teleseismic distances with sufficient azimuthal station distribution in both regional and teleseismic distances, it may be useful to calculate independently the locations based on regional and based on teleseismic phases. Conclusions may be drawn from comparison of these multiple location results.

43. It is worth checking the level of coupling between the calculated depth and spatial coordinates (latitude and longitude) for the individual GT events. Repeated relocation with different fixed values of hypocentre depth can help in estimating of the level of such coupling. The same applies to the coupling between the calculated depth and the origin time.

44. If an event is assigned to a GTx category based on a seismic location then the validity of such an assignment should be verified (documented) in a trustworthy way. Among possible ways are: (a) systematic relocation of the GT events with many subsets of arrivals, (b) relocation experiments with random errors applied to its associated arrivals, (c) relocation experiments using different initial event location estimates, (d) relocation experiments to eliminate solutions that represent local minima (e.g. search in the parameter space around the received location), (e) relocation experiments with different weights applied to the arrival data, (f) series of fixed depth locations for various origin depths, (g) use of waveform modelling to estimate a reasonable hypocentre depth and its uncertainty, (h) use of joint hypocentre determination, hypocentroidal decomposition method, and other modern event clustering methods, etc. Other approaches are also mentioned in the paragraphs above. Usage of more than one of the above-mentioned approaches is strongly encouraged.

45. The type of event (single explosion, ripple fired, rockbursts, shallow earthquake, etc.) should be provided along with additional information on charge (yield), magnitude(s), organization performing the blast, location of the blast (country, nearest town, mine, quarry, etc.), etc.. This information should be provided, where available, to support and complement the GT event origin parameters. If any information on the GT event has been published (in a scientific journal, report, etc.) then a reference (if published in an international journal) or copy of this publication has to be provided.

<u>For Task 2:</u>

- *Collection of regional / teleseismic travel-times*
- *Collection of regional / teleseismic azimuth and slowness data*

46. Collection of trustworthy regional and teleseismic travel-times for all primary and secondary phases and for different hypocentre depths is essential for the Calibration Programme. In the Phase 1 of the Calibration Programme the emphasis is directed towards regional phases (Pn, Sn, Pg, and Lg) as these phases have substantial impact on event location accuracy once IMS stations in the regional zone (within 20 degrees from the epicentre) are used. For understanding the complex travel-time curves at far regional and near teleseismic ranges (i.e. within 16 – 30 degrees from the epicentre) careful review of data in these ranges is encouraged.

47. Azimuth and slowness information is used at the CTBTO/IDC in the event location process along with the travel-time values. Reliable azimuth and slowness values may improve, in particular, the performance of the event building stage in the CTBTO/IDC automatic processing.

48. Only quality-checked arrivals (travel-times, azimuth, and slowness) should be provided and only such arrivals can be used in any subsequent operations leading to derivation of velocity models and/or corrections. Should there be any doubts about phase identifications or any other concerns regarding the quality of the arrival data, these are to be documented and extreme care should be exercised when considering of use of such data. Care should be exercised and checks performed as needed for possible occurrence of some timing errors (wrong timing at some stations, wrong timing for the whole local/regional network, etc.).

49. When working with travel-time (arrival-time) data, the ultimate goal of the Calibration Programme (i.e. an area of uncertainty 1000 km^2 or less at the 90% confidence level in the event location) is to be kept in mind. Though it is difficult to specify just one number for requested travel-time accuracy, one second (or better) for primary P arrivals (Pg, Pn, and P) and two seconds (or better) for S arrivals and other secondary arrivals of body waves are considered reasonable limits. These limits (in the root mean square sense) are to be used as a guide for the required accuracy of the travel-times and derived travel-time corrections.

50. The accuracy limits for azimuth and slowness data are more difficult to specify. Nevertheless, for both regional and teleseismic phases, the azimuth values should be known to few degrees.

51. As the GT arrival data used to derive the velocity models and/or travel-time (azimuth and slowness) corrections are to be stored at the CTBTO/IDC indefinitely, every effort should be undertaken to avoid including unreliable data in the CTBTO/IDC databases. The procedure used for cleaning the arrival-time (azimuth, slowness) data sets and performing data quality analysis have to be clearly documented. The same applies to the arrival-times (azimuths, slownesses) to be used to validate the derived time (azimuth, slowness) corrections.

52. If the phase identification is questionable or the pick accuracy is quite low then this has to be flagged and such phase readings should not be used in relocation experiments.

53. Estimates of the picking (measurement) errors are to be provided with all arrival-times (travel-times, azimuths, slownesses). It has to be kept in mind that the error of any provided travel-time value (i.e. the difference between the arrival-time and the corresponding event origin-time) is a combination of the picking error for a phase and the error (uncertainty) in the origin-time. If there is any uncertainty in phase identification (e.g. in the range of Pg – Pn cross-over zone, Pn triplication & Pn – P cross-over zone, etc.) this has to be taken into account and the error associated with arrival-time and/or travel-time value has to be correspondingly adjusted. This is particularly important when the travel-time values are used to derive travel-time curves and/or travel-time corrections and their related uncertainties.

54. The arrival-times (travel-times, azimuths, and slownesses) for GT events are best documented by provision of the raw waveforms with arrival picks. Thus, if possible, the relevant waveforms in digital form should be provided. The preferred digital waveform formats are CSS3.0, GSE2.0, and IMS1.0. Other formats can be used when agreed with the CTBTO/IDC. If waveforms cannot be provided in digital form, then at least the provision of good-resolution hardcopies of waveforms (e.g. long-range profile time-sections using optimal reduction velocity) is strongly encouraged.

55. The arrival-time information should be provided in digital form as well. The preferred formats include CSS3.0 “arrival” and “assoc” table formats, GSE2.0 or IMS1.0 bulletin and/or IMS1.0 “associated arrival” formats. Other formats may be used when agreed with the CTBTO/IDC. Provision of related information on applied filters, beams, etc. used for arrival picking is encouraged.

56. When only arrival-time (travel-time, azimuth, slowness) and not the waveform information can be provided, a very careful data quality analysis of arrival-times (travel-time, azimuths, slownesses) and checks on their mutual consistency (internal consistency of the data set) is to be performed and documented.

57. For all seismological stations for which arrival-time (travel-time, azimuth, slowness) information is provided / used, the information on the station code and station location (latitude, longitude, elevation) has to be provided. The Contractors are encouraged to provide additional information on the stations: for example country, nearest town, agency operating the station, network the station belongs to, type of station, instrumentation at the station, type and depth of sensor emplacement, sensor response, sensor orientation, station on- and off- times, geology at the station, P and S velocity – depth profile at the station, thickness of sediments and their velocities, type of timing equipment, etc., if available. Care should be exercised when reporting the station coordinates and elevation, as this is a known source of errors. The latitude, longitude, and elevation of the station (corrected for the emplacement depth of the sensor) are to be given with an accuracy better than 100 meters (~0.001 degrees).

58. Graphical representation of the range and azimuth dependency of travel-times (as well as azimuth and slowness) for any source (station) and phase is encouraged – i.e. provision of a contoured (colour-coded) travel-time (azimuth, slowness) “surface”. In all cases both plots of original data points and plots of interpolated travel-time (azimuth, slowness) “surfaces” are requested.

59. In situation where the travel-time data for any selected source (station), phase, and region do not allow consideration of a full range and azimuth dependency, the summary azimuth independent (only range dependent) numerical and graphical representation is encouraged – i.e. provision of a travel-time curve for a given phase and source (station). In all cases both plots of original data points and plots of interpolated travel-time curves are requested.

60. Travel-time information from specifically planned calibration explosions is of great interest to this Calibration Programme. Strenuous efforts should be made to get travel-time information for the existing and planned IMS sites. All seismic stations in the regional zone (up to 20 degrees) should be requested to provide waveforms and arrival-times for all observed phases. Portable instruments should be deployed in the regional zone to improve the azimuthal and distance coverage. Deployment of some of the portable sensors along several radial lines (profiles) from the epicentre is also encouraged as this can help to properly correlate phase onsets and correctly identify phases. Data from ocean bottom seismometers and hydrophone stations should be provided.

61. Where long-range profile travel-time data are provided, either travel-time curves (for the individual phases and shot points) or the travel-time values for individual instruments along the profile, together with their locations in latitude and longitude can be provided. The documentation should specify whether elevation corrections have been applied. If not, the elevation information has to be provided. In some cases, profile measurements recording “off-profile” nuclear and large chemical explosions have been undertaken. Such data are very useful and should be reported if available.

62. Many regional travel-time curves were constructed in the past and used for event location in specific regions (countries). Most of these travel-time curves were not based on GT events, but on various statistical approaches. It is useful to make an inventory of these existing regional travel-time curves for all types of phases and different hypocentre depths. To permit compiling a well-documented inventory of these travel-time curves as much documentation as possible should be provided. This should include any publications or reports on the derivation and use of these regional travel-time curves. If original data on which the travel-time curves were derived are available, these

should be provided. The area over which such travel-time curves are assumed to be applicable should be provided. If possible, at least a limited number of ground truth events should be used to assess the validity of these travel-time curves.

63. Many teleseismic and / or regional azimuth (slowness) correction patterns were constructed in the past and used (mostly) for array stations. Most of these travel-time curves were based not on GT events, but on various statistical approaches. It is useful to make an inventory of these teleseismic and / or regional azimuth (slowness) correction patterns for all types of phases and hypocentre depths. To permit compiling a well-documented inventory of these teleseismic and / or regional azimuth (slowness) correction patterns as much documentation as possible should be provided. This should include any publication or reports on the derivation and use of these teleseismic and / or regional azimuth (slowness) correction patterns. If original data on which the teleseismic and / or regional azimuth (slowness) correction patterns were derived are available, they should be provided. The area over which such teleseismic and / or regional azimuth (slowness) correction patterns are assumed applicable should be provided. If possible, at least a limited number of ground truth events should be used to assess the validity of these teleseismic and / or regional azimuth (slowness) correction patterns.

<u>For Task 3:</u>

- *Collection of tectonic and seismological regionalization for the Earth's crust and mantle*

64. Geological (geophysical) information regarding the Earth's structure on regional and global scales, both for the crust and mantle, is useful for the Calibration Programme. The tectonic and "seismological" regionalization is to be provided with supporting evidence (copies of published papers, reports, maps, etc.). It is expected that provision of this information will frequently be in a hardcopy form, but provision of digital information is preferred. (Formats for digital data should be agreed with the CTBTO/IDC.) Furthermore, if information on gravity measurements and their interpretation in terms of structure (and density) is known, this information is to be provided.

<u>For Task 4:</u>

- *Collection and/derivation of basement depth maps, Moho depth maps, Pn (Sn) velocity maps, attenuation and Lg blockage maps*

65. Information on the basement depth, Moho depth, Pn (Sn) velocity, lithosphere thickness, attenuation, and Lg blockage is essential for the understanding of the calibration data. Maps are preferred, but information provided as a set of values for specified latitude-longitude points is also considered valuable. The information is requested in digital form. The simplest format is an ASCII file with records containing latitude, longitude, and relevant value(s). Other formats can be used after agreement with the CTBTO/IDC. Any information provided must be presented along with the relevant documentation (original publications and/or reports, etc.).

66. The emphasis is on original values (before interpolation and filtration) and the provision of sets of these values is particularly encouraged. If any maps were constructed from the above-specified values, they should be provided as well. It is, however, necessary to specify as many details as possible on how the maps were constructed (original raw data, methods applied for cleaning the data sets, area for which data were available, interpolation and extrapolation procedures, etc.).

For Task 5:

- *Collection and/or derivation of regional (global) 1-D, 2-D or 3-D high-resolution velocity models of the Earth's crust and mantle*
- *Collection of Lg and surface wave velocities*

67. Information on studies with (or leading to) derivation of regional (global) velocity models is essential for the calibration, both on regional and global scales. Generally, velocity models can be used to generate consistent travel-time corrections for all seismic phases and for arbitrary origin depths. Models can also be used (following tectonic regionalization) for extrapolation into those regions for which there is insufficient GT information.

68. Currently, the globally averaged IASP-91 velocity model is used at the CTBTO/IDC as a background (default) velocity model both for P and S body waves. Despite the fact that the travel-time curves used at the CTBTO/IDC are represented as travel-time tables, they have been consistently generated (at the prototype IDC) for all body waves using this velocity model. The internal consistency of all travel-time data used at the CTBTO/IDC should be preserved even if moving towards more complicated sets of travel-times in the framework of the Calibration Programme.

69. The set of phases for which IASP-91 travel-time curves (tables) are generated also includes those phases (e.g. pP, sP, PcP, etc.) for which GT data will hardly ever be collected in a sufficient quantity, quality, and geographical coverage to direct calibration of travel-times. These phases are very important for the event depth determination. It is important to guarantee that the travel-time differences for all phases including pP-P, sP-P, etc. are kept consistent (e.g. both travel-times must be consistently corrected and/or correspond to single velocity model). Departure from the internal consistency of travel-times for different phases would have serious negative implications for the proper functioning of the CTBTO/IDC event location subsystem and also of the CTBTO/IDC event screening subsystem.

70. An inventory of available regional velocity models (both for P and S) is essential for the Calibration Programme. The areas of applicability of the regional velocity models must be clearly stated. If possible, these velocity models should be validated, based on independent GT data (performing either relocation experiments or, at least, travel-time calculations and comparisons).

71. Many long-range profile data have been interpreted to derive 2-D (1-D) velocity models along with basement and Moho depth sections (maps). An inventory of these 2-D (1-D) models would be a valuable asset for the Calibration Programme. Critical analysis of these velocity models is needed to compare these velocity models for the same (similar) tectonic provinces.

72. Furthermore, it would be valuable to verify the derived velocity-depth sections (based on the long-range profile data) at any crossing points of long-range profiles. Care should be exercised to avoid overestimating any effects of anisotropy (but where present, they should be carefully assessed and the extent of the effects of anisotropy on travel-times is to be evaluated and validated).

73. Contributors are encouraged to construct and verify composite 3-D regional velocity models, if available sets of 2-D regional velocity models are dense enough and permit this. The resulting 3-D velocity models should be verified, where possible, using independent GT data.

74. The 1-D, 2-D and 3-D velocity models may be provided in various parametrizations and formats, but any parametrization and format must be well described. The velocity models should be provided in digital form. Formats of digital data have to be agreed with CTBTO/IDC. Exceptional cases when only hardcopy is provided should be kept to minimum.

75. In cases where a set of 1-D velocity-depth sections representing a 2-D velocity model (a grid of these for 3-D velocity models) is used as the "native" velocity model parametrization, these 1-D velocity-depth sections are to be provided along with their geographical positions (latitude and longitude). Geographical areas of applicability of any velocity models are to be provided as well. Graphical representation (contour plots, colour-coded sections) of the velocity distribution(s) are to be provided for the 2-D and 3-D velocity models. For the 3-D models the suitable graphical representation includes both vertical and horizontal 2-D sections with emphasis on figures representing the most important features of the region (e.g. subducting slabs). The Contractors are encouraged to provide information on resolution and uncertainty of the velocity models including suitable graphical representation of these quantities.

76. Global (P and S) 3-D velocity models are of special interest for the Calibration Programme. Validation of these models, using well-defined and well-documented sets of GT events, is essential. These models may be very useful in particular for (deeper parts of) the Earth's mantle and provision of these velocity models is encouraged. (It is understood that most of the global velocity models are not based on GT events.)

77. The Calibration Programme would benefit from information on Lg and Rg velocities and travel-times and their regional (or even 2-D) distribution (in correlation with the tectonic units, geological structure, and P/S velocities). Original publications / reports, documenting how (and based on which data) these velocities were derived, are to be provided. Information on how the travel-times were picked is to be provided.

78. To allow the testing of the provided multidimensional (both regional and global) velocity models, it is requested that, along with the velocity model in digital form also a software module (along with source code in C or FORTRAN) is provided, permitting calculation of the (P and/or S) velocity value (and layer/block number if relevant) for any point characterized by latitude, longitude, and depth. The software module has to be provided both with in-line documentation (comments in the source code) and with sufficient user documentation (manual, man page, etc.). The software is to be delivered for free use at the CTBTO and at no additional costs.

79. When providing a 2-D and, in particular 3-D, velocity model it is recommended to provide a software module (with source code in C or FORTRAN) to calculate travel-times of all relevant phases to permit comparison with other methods of travel-time calculation. (The reason for this request is that in many cases any re-parametrization of

a multidimensional velocity model to allow its usage by another ray-tracing Programme may lead to substantial differences in the calculated travel-times.) The software module has to be provided both with in-line documentation (comments in the source code) and with sufficient user documentation (manual, man page, etc.). The software is to be delivered for free use at the CTBTO and at no additional costs.

80. It is emphasized that any velocity model should be provided along with the original publications / reports documenting how (and based on which data and after which data quality control) the velocity model was derived.

For Task 6:

- *Derivation of travel-time and azimuth and slowness corrections for the relevant IMS stations*

81. Under the approach specified in CTBT/WGB/TL-2/18, the final calibration product shall be a geographic grid of travel-time and, if possible, azimuth, and slowness corrections (for all phases used in event location) for each IMS station, along with estimates of the uncertainties for the travel-time (azimuth, slowness). This should include both regional and teleseismic phases. The grid point spacing should not exceed 100 km, but could be much smaller. For the regional phases Pn and Sn the grid should extend to 20 degrees from the station, or at least out to the farthest point at which Pn is the first arrival in the area. The grid system should cover sources at depth as well as surface sources. While the grids with corrections can be model-based, they will have to be validated by regional observations from reference events with known origin parameters (GT data).

82. While the grids can, in principle, be equidistant on a global basis, it will be advantageous in practice to make the grid system denser in certain regions, for example, where the geology and tectonic structure is complex. The grid systems at various depth intervals should allow optimal processing in regions where deep earthquakes are known to occur. Consistency of regional and teleseismic corrections may ultimately depend upon development of a single consistent global three-dimensional velocity model for regional and teleseismic propagation.

83. The travel-time corrections requested have been sometimes called “Source Specific Station Corrections” (SSSC). The azimuth and slowness corrections requested have been sometimes called “Slowness-Azimuth Station Corrections” (SASC).

84. The approach used to obtain the grids with the time (azimuth, slowness) corrections and their related uncertainties has to be described in detail. Also the approaches used for interpolation of individual data or segments with the corrections (tapering, boundary fitting, kriging, extrapolation, etc.) have to be described. The description of the process must be done in such a way that it can be considered trustworthy by experts and can be used by other Parties (e.g. representatives of States Signatories) and by the CTBTO/IDC for validating the corrections.

85. All the GT data and/or velocity models used for the derivation of the corrections and used in their testing / validation must be provided in digital form. The standards and formats for the provision of the GT data and velocity models described in the specifications above for Tasks 1 - 5 must be followed.

86. To allow the first level of assessment of the reliability of the corrections, information on spatial density of supporting data is to be provided for every set of corrections and over the whole area for which the corrections are being provided. This information can be provided, for example, in the form of a map of corrections with an overlay of points for which the travel-time (azimuth, slowness) GT data values were available and used.

87. The corrections and related error estimates (so called modelling errors) have to be provided to the CTBTO/IDC in digital form. The testing and operational use of any of the corrections at the CTBTO/IDC will require that these corrections and the related error estimates be in a standard IDC format. The details of the standard IDC format will be provided by the CTBTO/IDC on request. Provision of the corrections in the CTBTO/IDC specific format is strongly encouraged in order to avoid the uncertainties potentially stemming from different interpolation / extrapolation schemes. (Note that the Release 2 of the IDC software, used at the CTBTO/IDC at the time when the TOR is released, does not contain the full functionality to use all the above-specified corrections and thus the full description of the IDC-standard format is not available at present.)

88. The CTBTO/IDC will be accepting the corrections and related error estimates in various digital data formats, but agreement with the CTBTO/IDC regarding the format is requested before it is used. The format must be well described. If the delivered corrections are not in IDC-standard format, then the deliverables have to include source code of a software module (in C or Fortran) which provides the time (azimuth, slowness) correction and the related error estimate for any relevant (IMS) station and any relevant seismic phase as a function of latitude, longitude and depth of the event. The software module has to be provided both with in-line documentation (comments in the source code) and with sufficient user documentation (manual, man page, etc.). The software is to be delivered for free use at the CTBTO and at no additional costs.

For Task 7:

- *Validation of the derived travel-time, azimuth, and slowness corrections*

89. Any provided corrections can be considered for use within the CTBTO/IDC operational system only when properly validated. The validation should be done by relocation experiments, which can demonstrate the location improvement when the corrections are applied. For GT0-HYP events it should be demonstrated that the travel-time (azimuth, slowness) after application of corrections is closer to the GT travel-time (azimuth, slowness) data.

90. The relocation experiments should be based on as many GT data as possible. The GT data set used for validation of corrections should ideally include events that were not used (either directly or indirectly) in the derivation of corrections.

91. If corrections for teleseismic phases are to be validated, then an experiment should be set-up to use only teleseismic phases in location (any corrected and/or uncorrected regional arrivals should not contribute to the location estimation, but they can be associated with the events and predicted travel-times for them can be calculated).

92. If corrections for regional phases (Pn, Pg, Sn, and Lg) are to be validated, then an experiment should be set-up to use only regional phases in location (any corrected and/or uncorrected teleseismic arrivals should not contribute to the location estimation,

but they can be associated with the events and predicted travel-times for them can be calculated).

93. If corrections are provided both for the teleseismic and regional phases, then first the independent above-described relocation experiments (a) using only regional phases and (b) using only teleseismic phases should be set up. Only if both these experiments are successful and both document substantial improvements in event location should a relocation experiment using both regional and teleseismic corrected arrivals be performed.

94. The relocation experiments should clearly demonstrate the utility of the proposed travel-time (azimuth, slowness) corrections for the calibration of the IMS network. The final relocation experiments, intended to show the effect of the proposed corrections, should only use data for IMS stations or relevant "surrogate" stations. (Surrogate stations are non-IMS stations located reasonably close to the planned/existing IMS stations.) Surrogate stations used instead of IMS stations will be needed in situations where historical data are used for relocation experiments. (A justification should be given to show reasons why a particular station was selected as a surrogate one.)

95. Ideally, only the most reliable data (preferably GT0 and GT2 events) should be used in the relocation experiments. If events for multiple GTx categories are used in the relocation experiments then the results and their evaluation shall be provided independently for each GTx category.

96. No bad or unreliable data should be used in any validation experiments. Events with very poor azimuthal distribution of recording stations should not be used for relocation experiments.

97. Use of GT10 events for validation of travel-time corrections in event relocation experiments (if attempted because of absence of higher quality GT events, i.e. GT0, GT2, and GT5) is to be done with utmost care. The uncertainty area (at 90% confidence level) for these GT10 events can be quite comparable with the requested accuracy of 1000 km^2 (equal to an equivalent uncertainty circle of 17 km radius at 90% confidence level). Use of GT10 events for validation of travel-time corrections may be useful in situations where the known event mislocations in a region, based on the IASP-91 travel-times, substantially exceed 25 km. It may, however, become of very little use and provide very little (if any) evidence on event location refinement through calibration when the known average mislocations before calibration are 15 km or less.

98. The modelling errors provided with the corrections have to be checked for consistency with the 90% calculated uncertainty error ellipses. (The definition of 90% uncertainty ellipse is: "The 90% uncertainty ellipse contains 90% of computed epicentres for GT events.") In other words, where a relocation experiment does not result in 90% of GT epicentres being inside the 90% uncertainty ellipses, the error estimates controlling the size of the uncertainty ellipses should be re-considered to achieve reasonable consistency between the definition of the 90% uncertainty ellipse and the percentage of GT epicentres inside of the respective 90% uncertainty ellipses. (Where the number of GT events used in relocation experiment is small, the statistical relevance of the percentage of GT events falling into the 90% uncertainty ellipses may be less statistically significant. In such cases the modelling errors can hardly be verified for consistency with the 90% uncertainty ellipse definition.) In every case, however, the exact percentage of epicentres of GT events falling within the calculated 90% uncertainty ellipses is to be provided.

99. Furthermore, the calculated depth uncertainties must properly reflect the depth uncertainties for the GT data (the 90% confidence limit should also be considered here). The regional station coverage for many GT events may be not sufficient to calculate origin depth and its uncertainty reliably – in these cases it will only be possible to use fixed depth relocation.

100. For GT0-HYP events (and perhaps for some GT0-EPI and GT2 events) evaluation of the relocation experiments should also include a comparison of the origin time calculated in the relocation with the "GT origin time". If the calculated origin time is substantially different from the "GT origin time" for GT0-HYP events then the corrections used should be re-considered.

101. To evaluate the level of improvement after the proposed corrections have been applied, the characteristic parameters are to be calculated and analyzed. The provided characteristic parameters must include:

a) *Percentage of all event locations moved closer to the GT epicentres;*

b) *Percentage of all event locations moved closer to the GT epicentres by 20% or more;*

c) *Percentage of all event locations moved away from the GT epicentres;*

d) *Percentage of all event locations moved away from the GT epicentres by 20% or more;*

e) *Average and median mislocation ,in km, based on locations with and without corrections applied for all relocated events;*

f) *Average and median improvement in epicentre estimation for all relocated events, in km;*

g) *Exact percentage of GT epicentres within the calculated 90% uncertainty ellipses;*

h) *Average and median uncertainty ellipse area, in km^2, for all events located with and without corrections;*

i) *Average and median decrease of 90% (normalized) uncertainty ellipse size, in km^2, for all events;*

j) *Average and median improvement of depth estimation, in km, for all events where the depth was not fixed in the relocation experiment;*

k) *Average and median improvement in origin-time estimation, in seconds, for all GT0-HYP events.*

102. Similar characteristic parameters will need to be used for the validation of the azimuth (slowness) corrections.

103. Histograms demonstrating the distribution of event mislocations and of the improvements (for azimuth, slowness misfit, etc.) are useful not only to display the distribution for the rather well located events, but also to identify special cases and/or mislocations. Such histograms shall be provided.

104. The results of the relocation experiments should be provided both in printed (tabular and/or text) form and in digital form (along with description of the used format). Tables

have to show the time, GT location, number of regional and teleseismic phases used in relocation, mislocation for relocation without corrections and with corrections, etc. Appropriate figures clearly showing GT locations and locations obtained with and without corrections applied should be provided.

105. All data, scripts (preferably for a UNIX environment), software modules (including source code), etc. used for the validation of the corrections (for relocation experiments) by the Contractor are considered deliverables and have to be provided to the CTBTO along with a suitable description (documentation) to facilitate rapid verification of the provided validation results. The software is to be delivered for free use at the CTBTO and at no additional costs.