Bureau International des Poids et Mesures

BIPM guidelines for GNSS calibration

V1.0 25/11/2013
V2.0 25/04/2014
V3.0 02/04/2015 V3.1 04/09/2015 V3.2 15/02/2016
V4.0 05/08/2021

Introduction to Version 4

As the BIPM has not enough resources to conduct calibration for all labs at any regular interval, collaboration started with the RMOs in 2014 to organize calibration of all time laboratories participating to UTC.

In this new calibration scheme, the BIPM maintains the calibrations of a set of stations distributed in the regions. These stations will provide the reference for the calibration trips organized by the RMOs. This procedure is based essentially on "differential calibration with closure", noted CC, [Esteban et al. 2012, Jiang et al. 2013] while "direct calibration"[1] exercises, noted DC, are also possible. In the first case the calibration trip starts and ends at the reference laboratory. In the second case, the station to be calibrated is calibrated directly at the site of the reference or at the user site, but without closure at the reference.

The Guidelines we present in this document establish the procedures for organizing, realizing and reporting to the BIPM the RMOs calibration trips. Although there is continuity between the successive versions, version 4 provides significant changes: Introduction of Galileo, refurbishment of Cal_Id numbering (A.3.3) and of uncertainty assignment (A.3.5), update of the Transfer of Calibration (A.3.6), new Time Department database (A.3.7), new Figure 2 with age of calibration. Therefore version 4.0 starts a new "clean" version of the Guidelines without highlighting changes between versions. Earlier versions of the Guidelines are available at https://webtai.bipm.org/ftp/pub/tai/publication/gnss-calibration/guidelines/archive/ .

A. General principles

A.1) Maintenance of the calibration of the time transfer facilities in laboratories contributing to time transfer for UTC.

All laboratories contributing to UTC are equipped with GNSS receivers, almost all of them providing the official time link, either by one-technique links (GPS or Galileo) of by combined-techniques links (GPS/GLONASS and TW/GPSPPP).

Most laboratories contributing to UTC operate redundant time transfer equipment, providing backups to the official UTC links. Having that equipment calibrated allows to alternatively making use of different receivers without taking care of their alignment.

The characterization of the delays in the time transfer equipment (here referred to as "calibration") is essential to the accuracy of time transfer and time dissemination. The set of GNSS equipment in laboratories used for time transfer in UTC needs to be calibrated, and the system is to be maintained through a programme of repeated calibrations over time.

The BIPM has always taken charge of organizing campaigns of calibration for UTC contributing laboratories. For this purpose, a set of "travelling" receivers of different types is maintained at the Time Department and submitted to long-term characterization (see section B). Over the years, due to the increasing number of labs and GNSS equipment, not all the labs have their GNSS equipment calibrated or regularly calibrated. To remedy this situation, the CCTF recommended collaboration between the BIPM and the RMOs for GNSS equipment calibration. To that aim, the present document provides the guidelines which will allow a better homogenization of the GNSS calibrations within the UTC community.

[1] This was referred to as "golden system calibration" in earlier versions of the Guidelines

A.2) Objectives of the cooperation between the BIPM and the RMOs, expected output.

Due to the huge number of GNSS stations distributed among the time laboratories for their participation to UTC, it is not possible for the BIPM to organize all the calibrations with a sufficient recurrence. The situation as of 2014-2015 is shown in Table 1 with some 150 receivers in 72 laboratories. In 2021, the BIPM database (https://webtai.bipm.org/database/gnss.html) lists some 225 receivers from some 85 laboratories, but not all of them are regularly reporting data.

Table 1: Number of participating laboratories and GNSS equipment for each RMO (as of 2014-2015).

RMO	N° OF PART. LABS (NMIs or DIs)	N° OF OTHER LABS IN THE REGION	N° of GNSS RECEIVERS in UTC	
			NMIs/DIs	OTHER
EURAMET	24	7	56	16
SIM	6	7	11	9
APMP	13	6	24	9
AFRIMETS	3	0	6	-
COOMET	4	0	3	1
GULFMET	1	1	3	-

The CCTF has therefore recommended that the BIPM implement guidelines for organizing coordinated calibration campaigns with the RMOs. Cooperation between the BIPM and the RMOs will allow a task sharing, and hence contribute to keep the calibrations of the GNSS equipment involved in the provision of UTC updated. The goals of the cooperation between the BIPM and the RMOs are

1. To have all GNSS equipment used in laboratories for time transfer in UTC calibrated;
2. To regularly repeat calibrations so as to maintain the accuracy of time transfer for UTC;
3. To seek reduction of the u_B by assessing the stability of the calibrations.

The BIPM will organize the calibration of some stations (called "group 1" here after) in each RMO, and the RMOs, together with these "group 1" laboratories, will organize calibration campaigns for the other laboratories of their region. All these results will be used for supporting the UTC system. A programme including repeated calibrations of the same equipment at regular time intervals will also allow better assessment of the stability of that calibration, consequently reducing its type B uncertainty u_B.

The guidelines presented here will assure that the calibration processes will all be consistent with those implemented at the BIPM. They contain the full procedure for organizing, running and computing the results of a calibration, and establish a prioritized programme for calibrations of equipment in the international system of time links.

A.3) Outline of the new system for GNSS calibrations.

The calibration scheme is presented in Figure 1. In each RMO some of the UTC laboratories will be selected as "Group 1" and the calibration trips involving these laboratories will be performed by the BIPM. Other laboratories will participate in "Group 2" calibration trips. The reference for these trips will be at least one "Group 1" system. Such "Group 2" trips will be performed under the responsibility of RMOs. In addition, the BIPM will conduct "Group 2" trips as necessary to accommodate special cases, using either one BIPM system or a "Group 1" system as a reference.

Each "Group 2" calibration trip will be announced in advance to the BIPM by the Proposing organization. The BIPM will attribute an identifier (Cal_Id, see A.3.3 below) to uniquely identify the trip, its participating systems and the calibration results. The report and results for the trip will be submitted to the BIPM that will validate them. The BIPM will assign an uncertainty to the trip results, and this uncertainty will be used to estimate the u_B uncertainty of UTC links for all participating systems (see A3.5).

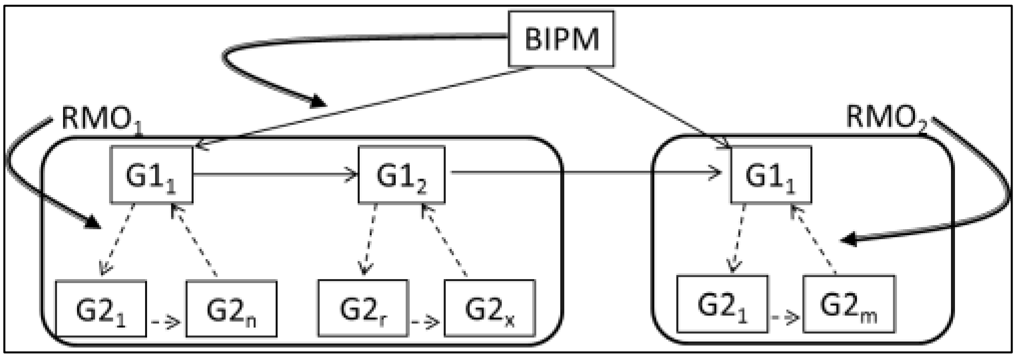

Figure 1: Schema of the GNSS calibration organization for the UTC generation. G1 and G2 refer to Group 1 and Group 2 laboratory, the curved arrows shows the organization responsibility. Solid arrows represent Group 1 trips and dashed arrows represent Group 2 trips.

While “differential calibration with closure” (CC) trips should provide the core of the BIPM calibrations, it is still possible to use “direct calibration” (DC) visits when a trip is not practicable. In practice, a system to be calibrated can visit a calibrated Group 1 system (at a Group 1 lab or the BIPM), or a calibrated Group 1 system can be sent to one laboratory, for side-by-side operation.

In the scheme described above, responsibility for a calibration exercise[2] is taken either by the BIPM or by a Group 1 lab. It is also possible for other entities to take responsibility of calibration exercises, e.g. a Group 2 laboratory, a manufacturer of GNSS receivers, a laboratory operating equipment for absolute calibration of GNSS receivers. It is required that such interested entities first have their calibration procedure validated by the BIPM to become an “authorized third party”. The calibration identifier (section A3.3) and the assigned uncertainty (section A3.5) will accommodate all validated procedures.

A.3.1) Presentation of laboratories in Groups 1 and 2, objectives of each.

Group 1: Those that operate more than one techniques (e.g. hosting several GNSS stations and /or TWSTFT) and which are or could be pilot laboratories or play a particular role at national/regional/international level. Their time transfer equipment will be calibrated in visits organized by the BIPM. The following RMOs are requested to propose laboratories (typically one to three, the exact number may be discussed) to be included in Group 1: SIM, EURAMET, APMP and COOMET.

AFRIMETS and GULFMET still have a small number of laboratories in UTC and are under organization. We do expect that these RMOs could provide calibration support in the future. In the meantime, calibrations in these regions could be provided by other RMOs or by the BIPM.

Group 2 includes other contributing laboratories not in Group 1. Their GNSS equipment will be calibrated primarily in visits organized by the RMOs (so called “Group 2 trips”), and alternately through other entities approved by the BIPM. Note that Group 2 includes laboratories contributing to UTC that are not NMIs, and it is desired that RMOs also take the responsibility for their equipment calibrations.

Any Group 2 calibration trip organized by an RMO should include at least the visit to a laboratory in Group 1 for the linking to the UTC system of calibrations.

The BIPM will participate as if it were in Group 1 for facilitating the link of laboratories in RMOs that cannot provide calibration support.

- *Policy for GNSS equipment calibration under the responsibility of the BIPM*

The BIPM will continue applying its usual policy to calibration campaigns under its responsibility. During the planning of a calibration trip, all participating laboratories will declare agreeing on the following procedure:

[2] The word “exercise” is taken to be more general than “trip”. In practice both may be used i.e. a “trip” does not necessarily imply travel of equipment.

- Custom formalities in each visited laboratory will be taken into account,
- The BIPM will cover the total costs of shipping and delivering its calibration equipment to the first visited laboratory,
- Every laboratory participating in a calibration trip will cover the total costs of shipping and delivering the equipment to the next visited laboratory, the last one being the BIPM.

A.3.2) GNSS codes considered for calibration

Calibration trips may cover one or several GNSS and codes, namely:

- GPS C1 , acronym GPSC1
- GPS P1-P2 , acronym GPSP3
- GAL E1-E5a , acronym GALE3 (since June 2020)

Group 1 trips organized by the BIPM will cover all codes. Group 2 trips are also encouraged to cover all designated codes. However, specific GPSC1 trips could be organized for laboratories not equipped with geodetic systems.

The list of GNSS codes considered will be extended as needed in the future.

A.3.3) Calibration identifiers

Calibration identifiers (Cal_Id) are meant to provide a unique identification of calibration results so as to easily refer to them. A data base (https://webtai.bipm.org/database/calib.html) will be maintained by the BIPM to link the Cal_Id to the participating laboratories and stations, to the report and results and to the assigned uncertainty. The data base will be open to all users of the UTC laboratories. Note that Cal_Id are meant to apply to all UTC time transfer calibrations, however only the use for GNSS is here considered.

The Calibration Identifier has the form znnn-YYYY where

- z identifies the type of calibration
- nnn is a number assigned by the BIPM;
- YYYY is the year number assigned by the BIPM (typically the start of the calibration exercise);

Presently defined types of calibration are:

z = 1: For GNSS calibration campaigns under the supervision of the BIPM; nnn then identifies a calibration report corresponding to a trip. Typically one report should correspond to a trip but there is the possibility of more than one report per trip. nnn will be 000 to 009 for Group 1 trips, 011 to 099 for Group 2 trips, 101 to 999 for other exercises by RMOs/labs/BIPM. Starting 2020, the range 101 to 199 is used for Transfer of Calibration, 201 to 299 for “Direct Calibration”, 301 to 999 reserved for other purposes.

z = 2: For GNSS calibrations by “authorized third parties” with other procedures (e.g. manufacturer calibration, absolute calibration, transfer using a calibrated link, ..).

Calibrations carried out before 2014 which are still valid are also referenced by a Cal_Id. Examples can be seen at https://webtai.bipm.org/database/calib.html by ordering results with the date of calibration.

All links used in the UTC computation are published in section 5 of the Circular T with the Cal_Id information, thus allowing reference to the original calibration reports. See https://webtai.bipm.org/ftp/pub/tai/Circular-T/cirthtm.

The calibration identifier is intended to provide reference to a unique set of calibration results (typically internal delay values) for an ensemble of receivers in an ensemble of laboratories participating to a given calibration exercise. Changes in the set-up of the participating laboratories are handled as follows (see section A3.6):

- If necessary, new receivers can later be added under the same Cal_Id through a Transfer of calibration.
- If a calibrated receiver is subject to set-up changes so that the calibration results should change (e.g. change of antenna or possibly firmware upgrades), the new calibration values can also be determined through a Transfer of calibration, but a new calibration identifier will be assigned by the BIPM.

- If a calibrated receiver is subject to set-up changes so that the calibration results should NOT change (e.g. change of reference delay), no specific action is required. It is advised to inform the BIPM of the set-up change.

A.3.4) Basic principles of the computation of the calibration results

Differential calibration trips are meant to transfer the values of hardware delays among different systems using a travelling (transfer) system. The following principles will be used to provide a reference value for the hardware delays:

For a “Group 1” calibration trip: Because we do not have (so far) an absolute reference, we propose to consider that the ensemble of the “Group 1” systems is itself the reference, as follows: For each new “Group 1” calibration trip, the delay values will be set so as to minimize, for the ensemble of participating “Group 1” systems, the variations of the values with respect to the previous calibration results. The procedure is described in TM266 at https://webtai.bipm.org/ftp/pub/tai/publication/gnss-calibration/guidelines/.

For a “Group 2” calibration trip, the reference is provided by the participating “Group 1” system that is visited at the beginning and end of the trip. The reference value is passed to the traveling system (e.g. as the average of the beginning and end-of-trip measurements), then to the other systems.

Detailed computation guidelines will be provided for each technique in order to have consistent practice for all calibration trips, see Section E.

A.3.5) Basic principles for assigning the calibration uncertainty of UTC links

Presently, GNSS time transfer data are entered in the TAI computation as “UTC links”, i.e. as [*UTC*(*k*)-*UTC*(*s*)]. We consider only the case where k is a Group 1 laboratory, covering the usual case where one laboratory (presently PTB) is chosen as pivot. The notation u_{CAL} will be used to represent the accuracy of an UTC link, i.e. this essentially covers the calibration of the receiving systems[3]. Adopting the simplified notation (A-B) for [*UTC*(*k*)-*UTC*(*s*)], we develop below how u_{CAL} (A-B) values will be assigned.

- Uncertainty from calibration

The general formula to compute the uncertainty from calibration of a link (A-B) at the time of calibration can be written as

$$u_{CAL}\,(A\text{-}B)(t0) = (u_{CAL0}{}^{2}\ [+\ \Delta u_{CAL}\ (A/B)\ ^{2}])^{1/2} \qquad (1)$$

where optional values Δu_{CAL} concern poor behavior during a calibration trip and are indicated in each calibration report. The value u_{CAL0} is chosen conventionally by the BIPM, following discussion in the CCTF Working Group on GNSS. As of July 2021 u_{CAL0} is as follows:

- 1.5 ns if the receiver in B has been calibrated in a Group 1 trip;
- 2.5 ns if the receiver in B has been calibrated in a Group 2 trip;
- 4.0 ns if the receiver in B has been calibrated in a “Direct Calibration” vs. a Group 1;
- 5.0 to 7.0 ns if the receiver in B has been calibrated by an “authorized third party”;
- 20.0 ns if the receiver in B has not been calibrated.

- Evolution of calibration uncertainty with time

After the calibration, the calibration uncertainty will evolve with time due to two factors:

- An ‘aging’ contribution u_{AG} computed with the age of the oldest calibration trip following the approach in [Jiang et al. 2011]. Since July 2020, the aging contribution in ns for the age Δt in months is

  $u_{AG} = \max\,(c_{AG} \times \Delta t^{1/2} - 1.0,\ 0.0)$

  where the aging coefficient for GNSS is $c_{AG} = 0.4$ ns. If Δt is larger than ten years, a conventional aging uncertainty of 10 ns will be used.
- An optional ‘transfer of calibration’ contribution u_{TC} that takes into account the contribution of changes in set-up that may occur over time (see details in the next section A.3.6).

[3] Note that it also includes, for single frequency links, the possible inaccuracy of the models used to compute the ionospheric delay. Therefore the u_{CAL} uncertainty of an UTC link may also depend on the link technique.

The general formula for the calibration uncertainty of a link, including optional elements within brackets, is then

$$u_{CAL}(t) = (u_{CAL0}^2 + u_{AG}^2 \; [+\Delta u_{TC}^2 + \Delta u_{CAL}^2])^{1/2} \qquad (2)$$

A.3.6) Evolution of a calibrated station between two calibration exercises

This section covers possible events that can affect a GNSS station between two calibration exercises, i.e. mostly a change in the set-up, a change in some elements of the receiving system itself or a replacement of the station. In the following, directions are given for the laboratory to take the necessary steps and for the BIPM to implement the results.

Changes in the set-up are discriminated between those that affect only the value of the “reference delay” (REFDLY in the CGGTTS format) and other cases, where values of the “internal delays” (INTDLY in the CGGTTS format) or of the antenna cable delay (CABDLY in the CGGTTS format) are affected. We can therefore identify two situations:

- If the change concerns only the REFDLY value AND if the calibration results are expressed as INTDLY or SYSDLY values, it is only necessary for the laboratory to measure the new value of REFDLY and to use it in reporting data. No change in Cal_Id nor in u_{CAL} results from this operation.
- In all other cases, it is necessary to change the calibration results for the station, either because the internal transmission delays have indeed changed or because the calibration results are expressed as “total delays” (TOTDLY in the CGGTTS format) and absorb the REFDLY value. The new results can be determined through a “transfer of calibration” (TC) performed by the laboratory. The value u_{CAL} is expanded to reflect the uncertainty of the transfer of calibration, as indicated in equation (2) above. The BIPM will estimate u_{TC} from the reported information.

The TC procedure determines calibration results for system 2 from the calibrated (reference) system 1. In practice, it should be based either (if possible) on the simultaneous operation of the two systems in common clock, or (if the two systems or the two set-ups cannot be operated simultaneously) on the operation of another system in common clock to bridge the gap. Such common clock operations should cover a significant comparison interval, at least several days. A report describing the operations and the computations of the relevant results shall be provided to the BIPM. As indicated in section A3.3, previously uncalibrated receivers can be assigned the Cal_Id of the reference receiver. Conversely, if a previously calibrated receiver obtains new calibration delays following a TC procedure, a new Cal_Id will be assigned to it by the BIPM.

A.3.7) Publication of calibration results in the Time department database

After validation by the BIPM Time department, the results of all calibration exercises will appear in the Time department database. There are several methods to access the results:

https://webtai.bipm.org/database/calib.html : The list of all GNSS calibration results, listed for each GNSS. Can be searched by Cal_Id, by laboratory or by receiver.

https://webtai.bipm.org/database/calid_gnss.html : The list of all Cal_Id with general information on each trip, also including trips not yet completed.

https://webtai.bipm.org/database/gnss.html : The GNSS equipment page gives access to the latest calibration identifier relative to all selected receivers (by default all receivers in the database). When only one receiver is selected, its complete history of calibrations is displayed.

In all pages, the Cal_Id will provide a link to a summary file of the trip, which will point to all available information.

All materials relative to the GNSS calibrations may also be directly accessed at https://webtai.bipm.org/ftp/pub/tai/publication/gnss-calibration/, see the readme file.

B. Characterization of the travelling systems.

B.1) BIPM systems

The long term characterization of BIPM GPS receivers (considering both traveling systems and systems remaining in the laboratory) had been presented in TM 204 (Petit, 2013). Since the start of the G1/G2 procedure in 2014, the BIPM reference stations are included in G1 results and their stability is assessed in TM266 at https://webtai.bipm.org/ftp/pub/tai/publication/gnss-calibration/guidelines/. The stability of the traveling systems is assessed through the observed closure of the repeated Group 1 trips.

B.2) RMOs traveling systems

Group 1 laboratories or third parties aiming at conducting calibration trips will present documented assessment of the stability of the traveling systems before conducting the first trip. The stability of the traveling systems should be evaluated over duration at least comparable to that of a calibration trip (i.e. several weeks to a few months) and should be documented. That evaluation can e.g. consist in comparisons with one, or ideally two, other independent systems. No specific format is required for this documentation. For a system that has already been used as a traveling reference, closure of past trips may also be used to assess the stability.

C. Organization of calibration trips

Each calibration trip will cover a number of laboratories contributing to TAI in the respective region, starting and concluding with the same laboratory in Group 1. The sequence of visits to the laboratories in Group 2 is proposed by the organizer of the calibration trip. At the end of the trip, closure measurements are to be performed and included in the report of the calibration. It could be an advantage to include more than one Group 1 laboratory in a calibration trip; nevertheless only one of them will be chosen as a reference, visited at the beginning and at the end of the trip.

The list of Group 1 laboratories (unchanged since its inception) is in Table 2. Note that there are no G1 laboratories in AFRIMETS and GULFMET. Figure 2, provided by Pascale Defraigne (ORB), lists the G2 laboratories and the date of the most recent calibration as of June 2021.

In general it is recommended to maintain a homogeneous age of calibration. The BIPM will provide Group 1 calibration typically every 2 years. The WG on GNSS has recommended in June 2020 to aim at a repeat of 3 years for the Group 2 calibration, however it is also necessary to fill the gaps and provide calibration to those not calibrated or which calibration is very old.

Table 2: List of Group 1 laboratories (as of July 2021)

EURAMET	SIM	APMP	COOMET	AFRIMETS	GULFMET
OP	NIST	NICT	SU		
PTB	USNO	NIM			
ROA		TL			

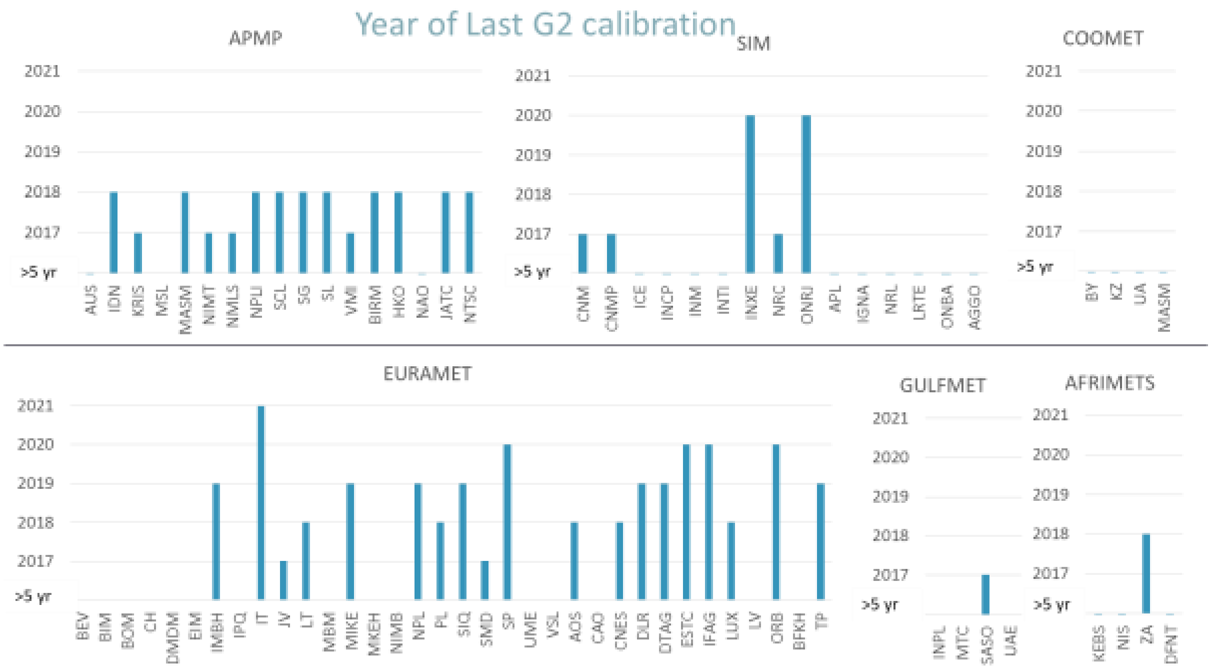

Figure 2: List of Group 2 laboratories (as of June 2021) including the year of calibration of the GNSS equipment typically used for UTC .

D. Operational guidelines

The Annex 1 of this document provides the operational procedures to be followed during a visit of the traveling equipment. It is initially established for "Group 1" calibration trips which are organized by the BIPM using BIPM traveling equipment. It therefore describes all steps of operations for the BIPM traveling equipment.

In addition, Annex 1 provides a description of the conventional internal reference, and of the measurements that allow accessing it, for all types of receivers (for which the information is available). These measurements are necessary to generate the REFDLY values for the receivers.

Annex 1 could be expanded, with the necessary changes, to any traveling equipment e.g. as would be used for "Group 2" calibration trips performed by RMOs or individual laboratories.

E. Data treatment, report and results (written report and electronic files)

E.1) Description of the process of calculation

Ready-to-use scripts and programs are provided to compute the difference in code measurements necessary for equipment calibrations. They will be used for Group 1 trips. If the responsible parties for Group 2 trips use other tools, they should describe the methods they use.

For trips calibrating geodetic receivers, using a traveling geodetic receiver, a procedure to generate code differences for all codes recognized in the CGGTTS format is described in Annex 3.

For trips calibrating GPS C1 time transfer receivers, using a traveling geodetic receiver, a procedure to generate code differences for GPS C1 is described in Annex 2.

GLONASS and BeiDou calibration are not yet covered in this version of the Guidelines (July 2021).

E.2) Final form of the report, submission to the BIPM

A Template of calibration report to the BIPM is presented in the Annex 4 to this document.

E.3) Application of the results

Results will be provided so as to be compatible with the CGGTTS format.

After validation by the BIPM, results of a trip should be applied by the participating laboratories to generate CGGTTS files, at a date agreed with the Time department. The calibration identifier should appear in the header of the data files, as specified in the CGGTTS V2E format, or in a COMMENT line if the V2 format is used..

By design, it is expected that Group 1 results should be updated more frequently than Group 2. **However, unless explicitly specified by the BIPM, new results for a Group 1 system should not be used to correct the results of past Group 2 trips for which the Group 1 system acted as a reference.** Exceptions could result from the discovery of an obvious significant error in the past results of a Group 1 system and will be treated on a case-by-case basis.

F. References

Defraigne P., Petit G., CGTTS-V2E: an upgraded standard for GNSS Time Transfer, Metrologia, 52-6, G1, 2015.

Esteban H, et al., 2012, EURAMET Project 1156, GPSCALEU: Results of two years GPS receiver calibration campaign, *Proc. EFTF 2012*, pp 354-360

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Petit G., "Values and uncertainties of the hardware delays of BIPM geodetic systems and estimation of the type B uncertainty of P3/PPP link calibrations", BIPM TM.172, December 2009, at https://webtai.bipm.org/ftp/pub/tai/publication/gnss-calibration/doc-soft/.

Petit G., "Differential calibration of BIPM P3 systems: Long term study", BIPM TM.204, Update June 2016, at https://webtai.bipm.org/ftp/pub/tai/publication/gnss-calibration/doc-soft/.

Petit G., "Continuity of GNSS "INTDLY" values of Group 1 geodetic receivers in successive Group 1 trips"; BIPM TM266 at https://webtai.bipm.org/ftp/pub/tai/publication/gnss-calibration/group1/.

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Annexes to the Guidelines

Annex 1- Operational procedures for a visit of the traveling equipment

Annex 2- Procedure for computing the difference of GPS C/A code measurements

Annex 3- Procedure for computing raw difference of GPS code measurements for geodetic receiver

Annex 4- Template for the calibration report to the BIPM