BIPM guidelines for GNSS calibration

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Introduction

The system of calibration procedures for GNSS equipment that has been in operation at the BIPM over the past many years is twofold:

1. For GPS C/A code-only receivers, since the 1980s, the procedure is based on differential calibration trips with a closure at a reference receiver in LNE-SYRTE (OP), i.e. the trip begins and ends by visiting OP. In this procedure, the traveling receiver is just a transfer system between the reference receiver and the receivers in the visited laboratories. Results for laboratory k are expressed as a correction to add to [UTC(k) – UTC(OP)].
   The same kind of procedure is used since ~2009 for GLONASS C/A receivers, with another GPS/GLONASS receiver at OP acting as a reference.
   See http://www.bipm.org/jsp/en/TimeCalibrations.jsp in "Archive" under GPS C/A code or GLONASS C/A code.
2. For geodetic receivers providing GPS P3, since 2001, the procedure is based on the transfer of calibration from one reference receiver of the BIPM (sometimes called "golden receiver") to receivers in the visited laboratories. The traveling "golden receiver" is itself the reference. The initial BIPM "golden receiver" had been absolutely calibrated in 2001 but, over the years, the status of traveling "golden receiver" was transferred to new BIPM receivers. The traveling receiver provides reference values of the (receiver+antenna) internal delays for the P1 and P2 code and results are expressed as (receiver+antenna) internal delays for the P1 and P2 code for all visited systems.
   See http://www.bipm.org/jsp/en/TimeCalibrations.jsp in "Archive" under GPS P3 code.

In this document we name "differential calibration with closure" the first procedure where a traveling system serves as a transfer between all systems visited during a trip and where the trip begins and ends at the same location. We name "golden system calibration" the second procedure in which the calibration of the golden system is transferred to other systems, each one independently of the others (whether the golden system travels to the site of the system to be calibrated, or the system to be calibrated visits the golden system).

Although the use of C/A-only receivers is declining, such equipment will still be in use at some labs and some calibration procedure needs to be maintained.
On the other hand, the use of geodetic receivers is increasing. However the "golden system calibration" procedure chosen so far, though conceptually simple, has some drawbacks: it is not adapted to a large network and it does not allow reaching a time link accuracy as low as can be achieved through "differential calibration with closure", see e.g. [Esteban et al. 2012, Jiang et al. 2013].
Furthermore, the BIPM has by far not enough resources to conduct "golden system calibration" visits for all labs at any regular interval. RMOs and laboratories have already proposed to help by performing "differential calibration with closure" trips but this could not be considered so far because it would mix the two types of calibration procedures thus it would not ensure a better global consistency.
The BIPM now proposes a new procedure in which the BIPM, the RMOs and laboratories can cooperate. This procedure is based essentially on "differential calibration with closure" trips with the reference values provided by a set of systems operated in selected laboratories. In the new calibration scheme, the BIPM will maintain the calibrations of a set of equipment distributed in the regions. These systems will provide the reference for the calibration trips organized by the RMOs. The Guidelines we present in this document establish the procedures for organizing, realizing and reporting to the BIPM the RMOs calibration trips.

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) 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 (known 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 the 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). In the current system, time links are assigned a calibration uncertainty u_B[1] as follows: u_B = 5 ns is assigned for links between systems that have been calibrated by the BIPM, with the age of the calibration presently not taken into account. This procedure takes into account the instability of a calibration as resulting from the repeatability of the delay measurement in different campaigns over time. Arbitrarily, u_B = 20 ns is assigned to links involving at least one non-calibrated equipment. In between, values as u_B = 7 ns are given to links involving equipment pre-calibrated by the manufacturer and sometimes by an external laboratory. However, for assigning a value to u_B coming from a calibration external to the BIPM, no process has been validated.

Presently, 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.

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.

Some numbers

Furthermore, with the redundant time transfer equipment (see Table 1) in many contributing laboratories, and the variety of methods used at the BIPM (all-in-view GPS SC/MC, GPS P3, GPS PPP, GLONASS common-views, and combined links GPS/GLONASS and TW GPSPPP) the number of time links processed and checked at the execution of *Circular T* is not far from 200, while the number of non-redundant links for *Circular T* is 71 (as in March 2013). Some of these links are used in the calculation of the weekly rapid UTC, UTCr.

Table 1: Number of participating laboratories and GNSS equipment for each RMO.

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	-

[1] The notation u_B adopted until 2015 is to be replaced following the convention described in section A.3.5 of this document.

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 establishes a prioritized programme for calibrations of equipment in the international system of time links.

A.3) Outline of the proposed 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.

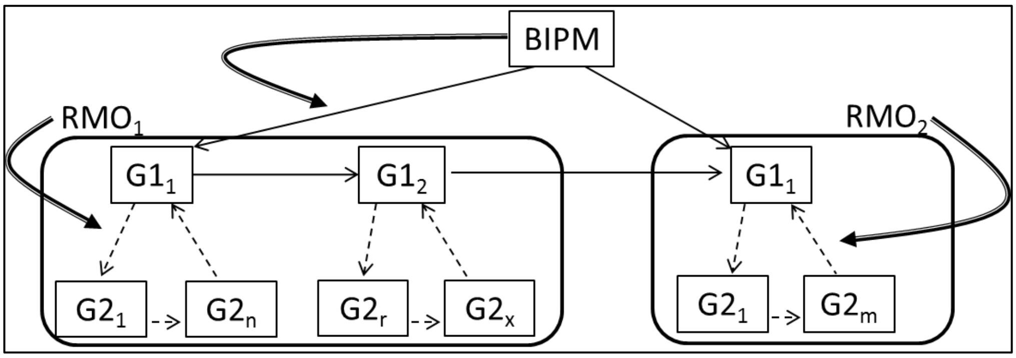

Figure 1: Schema of the GNSS calibration organization for the UTC generation. G1 and G2 refer to Group 1 and Group 2 laboratory, the curved arrows shows the organization responsibility. Solid arrows represent Group 1 trips and dashed arrows represent Group 2 trips.

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).

While "differential calibration with closure" trips should provide the core of the BIPM calibrations, it should still be possible to use "golden system calibration" visits when a trip is not practicable. In practice, a system to be calibrated could visit a calibrated Group 1 system (at a Group 1 lab or the BIPM), or a calibrated Group 1 system could be sent to one laboratory, for side-by-side operation. However time links involving systems so calibrated will be assigned a higher u_B uncertainty due to the absence of verification by a closure measurement. The Cal_Id will accommodate such a procedure.

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

Group 1: Those that operate all techniques (including 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 (two if possible) to be included in Group 1: SIM, EURAMET, APMP and COOMET.

> AFRIMETS has, at the moment of the preparation of the Guidelines, a small number of laboratories in TAI (KEBS, ZA, NIS), GULFMET has two (INPL, MTC), but it is under organization. We do not expect that these RMOs could provide calibration support, and unless other RMOs propose to cover the calibrations of equipment in these regions, they will be provided by the BIPM.

Group 2: other contributing laboratories not in Group 1. Their GNSS equipment will be calibrated in visits organized by the RMOs. 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 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:

- 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 techniques, namely as of this writing:

- GPS C1 , acronym GPSC1
- GPS P1-P2 , acronym GPSP3

It is planned that trips planned for GPSP3 can also be used for GPSC1, and this will be the case for the Group 1 trips organized by the BIPM. For Group 2, specific GPSC1 trips should be organized for laboratories not equipped with geodetic systems.

The list of GNSS codes covered 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 will be maintained by the BIPM to link the Cal_Id to the participating laboratories and systems, 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, not only GNSS as 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 (typically a sequential number within a year);
- 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.

z = 2: For GNSS calibrations with other techniques (e.g. manufacturer calibration, absolute calibration, transfer using a calibrated link, ..).

Past calibrations are also referenced by a Cal_Id. Examples can be seen at http://www.bipm.org/jsp/en/TimeCalibrations.jsp under “Current files”. A new display of calibration information will be provided in section 6 of the Circular T, see an example in “Documentation”.

When a system which has been calibrated under Cal_Id=znnn-YYYY has to be replaced by a new system, a laboratory can provisionally perform an alignment of the new system to the calibrated one, if the two systems have been operated in common-clock. In this case, the new system will be assigned an extended Cal_Id of the form znnn-YYYY-LLmn where LLmn is the 4-character BIPM code of the calibrated system. Procedures to perform the alignment will be defined by the BIPM.

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. There are several possible implementations: e.g. 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.

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.

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*)] 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[2]. Below we develop how u_{CAL} values will be assigned. In addition, the u_{CAL} uncertainty of a link will be expanded to reflect the age of the calibration of the systems, following the methodology proposed in [Jiang et al. 2011].

A calibration uncertainty value u_{CAL0} will be associated to each calibration trip. This value u_{CAL0} (Cal_Id) will be assigned by the BIPM after the submission of the report as part of the validation process. This assumes that all measurements during a trip have been of equivalent quality and that a single number can be used as the calibration uncertainty of any link between two systems participating to the trip. However the possibility will be kept to assign a larger uncertainty to individual systems for which measurements were not of the same quality.

When treating a link [*UTC*(*k*)-*UTC*(*s*)] the BIPM will, from the Cal_Id of the two systems in the laboratory *k* and *s*, determine how the calibrations of the two systems can be related. There could be just one leg when *k* and *s* happen to have the same Cal_Id, up to three legs for two Group 2 systems not in the same Group 2 trip. In principle the calibration uncertainty of the link could then be determined by propagating the uncertainties of the different legs. However, doing so in the present structure of time links for TAI (with one pivot laboratory), laboratories in the region of the pivot laboratory could be directly linked to it in one single trip and would automatically receive a lower u_B uncertainty than laboratories in other regions. In order to avoid this situation, the calibration uncertainty of a link to any Group 2 system will be assigned a conventional value depending only on the technique. Based on typical uncertainties of order 1-2 ns achievable in a “differential calibration with closure” trip (Esteban et al., 2012; Jiang et al., 2013, see also Annex 4), it is proposed u_{CAL0} (GPS P3) = 2.5 ns when the two linked systems had recent calibration trips. In addition, a link could receive an u_{CAL} uncertainty value larger than the conventional value if one of the involved calibration trips or one of the involved systems had been assigned a larger uncertainty in the calibration report, or in case of alignment (see section A.3.3).

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

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

[2] 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.

where, for Group 1, u_{CAL0} is as estimated in the analysis report (typically 1.7 ns) and, for Group 2, u_{CAL0} is a default value (2.5 ns). Optional values Δu_{CAL} concern poor behavior during a calibration trip and Δu_{ALIGN} concern the alignment of a new receiver to a calibrated one. Finally the conventional uncertainty will evolve with the age of the oldest calibration trip, as proposed in Table 2.

While this procedure is being put into operation, all GNSS UTC links will retain the value u_{CAL} = 5 ns (or 7 ns for manufacturer calibration). After the first "Group 1" trip has been conducted, the system will be progressively put into operation and the new (lower) values u_{CAL} will be set to the concerned links. Links with one uncalibrated system will remain with the value u_{CAL} = 20 ns. Links with one system calibrated by "golden system calibration" visits will retain u_{CAL} = 5 ns, as in the present scheme.

Table 2: Evolution of the conventional uncertainty u_{CAL} (in ns) of a link with the age of the calibration trip

Link	u_{CAL} (To)	u_{CAL} (2-3yr)	u_{CAL} (3-5yr)	u_{CAL} (5-10yr)	u_{CAL} (>10yr)
GPSP3	u_{CAL0}	3.0	4.0	6.0	10.0
GPSC1	3.0	3.0	4.0	6.0	10.0

B. Characterization of the travelling systems.

B.1) BIPM systems

The long term characterization of BIPM reference systems (considering both traveling systems and systems remaining in the laboratory) is presented in TM 204 (Petit, 2011). Information on the stability of the traveling systems is also provided by the repeated measurements taken in the Group 1 trips, available in the trips reports. All information may be accessed through the web page http://www.bipm.org/jsp/en/TimeCalibrations.jsp.

B.2) RMOs traveling systems

Before a trip, the stability of the system to be used as travelling reference should be evaluated over duration 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 used as a traveling reference, closure of past trips may also be used to assess the stability.

At the proposal of a calibration campaign, the relevant RMO or laboratory will present documented assessment of the stability of the system to be used as a travelling reference, following the general indications above.

C. Organization of a calibration trip

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 (as of April 2015) is in Table 3. Note that there are no G1 laboratories in AFRIMETS and GULFMET. The list of Group 2 laboratories in Table 4 also indicates the age of calibration of the GNSS equipment typically used for UTC.

When the system reaches operational state (in the future), it is recommended to maintain a homogeneous age of calibration. In the meantime, priorities should be established in collaboration between RMOs and the BIPM.

Table 3: List of Group 1 laboratories (as of April 2015)

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

Table 4: List of Group 2 laboratories (as of April 2015) including the age of calibration (in years) of the GNSS equipment typically used for UTC (A0: 0 to 5; A5: 5 to 10; A10: older than 10; ic: indirect calibration / calibration via systems no longer in operation / incomplete documentation ; nc: not calibrated)

EURAMET		SIM		APMP		COOMET		AFRIMETS		GULFMET	
AOS	A5	APL	A10	AUS	A0	BY	A5	DFNT	nc	INPL	A5
BEV	ic	CNM	A5	BIRM	nc	KZ	ic	KEBS	nc	MTC	A0
BIM	A5	CNMP	A10	HKO	A10	UA	A0	NIS	nc	SASO	A0
CAO	nc	IGNA	A10	KIM	nc			ZA	nc		
CH	A10	INTI	nc	KRIS	A10						
DLR	A5	INXE	nc	MASM	nc						
DMDM	A5	NRC	A10	MSL	nc						
DTAG	ic	NRL	nc	NAO	nc						
EIM	A5	ONBA	A10	NIMT	nc						
ESTC	A0	ONRJ	A0	NMIJ	A0						
IFAG	A5			NMLS	nc						
IPQ	ic			NPLI	nc						
IT	A10			NTSC	A10						
JV	nc			SCL	A10						
LT	A5			SG	A5						
MIKE	ic			VMI	nc						
MKEH	nc										
NIMB	nc										
NPL	ic										
ORB	A0										
PL	A5										
SIQ	ic										
SMD	A0										
SMU	nc										
SP	ic										
TP	A5										
UME	A5										
VSL	A0										

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, it 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).

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 GPS P1, GPS P2, GPS C1 and (if available if both systems) GPS C2 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 calibration is not covered in this version of the Guidelines

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 timing data. Use of the calibration identifier in the header of the data files will ensure that there is no ambiguity in identifying which calibration results were used to generate timing data.

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

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

Jiang Z, Petit G, Tisserand L, Uhrich P, Rovera D and Lin S Y, 2013 Progress in the link calibration for UTC time transfer, *Proc. Joint Meeting of the 2013 IEEE FCS and of the 27th EFTF (Prag)*

Jiang Z., Arias F., Lewandowski W., Petit G., BIPM Calibration Scheme for UTC Time Links, *Proc. EFTF 2011*, pp 1064-1069

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.

Petit G., "Differential calibration of BIPM P3 systems: Long term study", BIPM TM.204, Update April 2013.

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