# GNSS G1/G2 Calibration Report

## 2016 GPS CV
## Relative Calibration Campaign
## in SP and INRIM

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Content

## 1. Introduction.

This report is aiming at providing the results of the Group 1 / Group 2 GPS receiver relative calibration campaign organised by LNE-SYRTE in Observatoire de Paris (OP). We have tried to align this report on the BIPM guidelines for GNSS calibration [RD5] which were discussed inside the CCTF Working Group on GNSS in 2015, and which are going to become the standard to follow for such activities.

The campaign took place from February 22 to June 22, 2016, in the following sites, consecutively:

- Start of the campaign in OP, France.
- SP, Borås, Sweden.
- PTB, Braunschweig, Germany.
- INRIM, Torino, Italy.
- End of the campaign in OP, France.

In SP, PTB and INRIM, the traveling equipment implementation and the delay measurements were carried out by local staff according to a Calibration Procedure [RD2] prepared by LNE-SYRTE, and this work is warmly acknowledged.

A summary of the calibration results is provided in Section 2 next page for SP and INRIM receivers. All the obtained results are in line with the uncertainty target for a Group 1 / Group 2 calibration.

***<u>Important note.</u>***

Because we also obtained for the PTB reference receiver PTBB a significant discrepancy between OP calibration results and BIPM Group 1 ones, we investigated a potentially undetected change of the delays of the reference receiver for this campaign: OPMT. By comparing results from BIPM G1 1001-2014 [RD7, RD11] and from BIPM G1 1001-2016 [RD9, RD10] on the link OP-PTB, we indeed saw a significant ΔP3 offset, attributed to OPMT delays for the largest part of it. This is analysed in the Annex D of this report. Therefore, even if the computations inside the rest of the report are based on 1001-2014 OPMT delays, we computed updated delays based on 1001-2016 OPMT delays, this being detailed in the Annex D. ***The Table 1 in the Summary next page is providing updated delays based on OPMT delays issued from BIPM G1 1001-2016 report [RD9, RD10]***. In the document, only Section 10.4 and Table 8 are also partly referring to the 1001-2016 OPMT delays. Note that for the updated computations, all other parameters remained unchanged.

## 2. Summary of the calibration results.

Site by site and receiver by receiver, Table 1 provides the relative calibration results of this campaign. Note that all delays and uncertainties are computed for links between a given receiver and the OP reference receiver for this campaign OPMT. The delays provided here are to be used as INTDLY(P1) and INTDLY(P2) parameters, either inside the usual parameter files which are at the input of the BIPM standard TAIP3 processing which transforms RINEX files into CGGTTS files [RD3], or for the proper linear combination insuring the alignment of the PPP processing phase origin on the local reference. In some cases, the reference delays (REFDLY) and the antenna cable delays (CABDLY) being unknown, they are included in the INTDLY provided. Note that, despite the fact that the misclosure remains the most important part of the uncertainty budgets, this might lead to a slightly lower uncertainty compared to other sites. This might appear as a positive result. But the drawback is that in the case of change or failure in the reference signal distribution or in the antenna cable, the station calibration would be lost until a new calibration campaign would take place again.

As indicated in the Introduction, and contrary to the rest of the report, we used for this Table an updated computation based on OPMT delays provided by BIPM G1 1001-2016 calibration results. See Annex D for more details.

***Table 1. Results of the 2016 GPS calibration campaign against OPMT (delays from 1001-2016) with uncertainties computed according to EURAMET standards (all values in ns).***

| Station | Receiver name | INTDLY(P1) | u(P1) [$k = 2$] | INTDLY(P2) | u(P2) [$k = 2$] | u(P3) [$k = 2$] |
|---|---|---|---|---|---|---|
| **SP** | SP01 | 234.1 * | 2.0 | 246.0 * | 2.2 | 2.3 |
| | SP02 | 235.7 * | 2.0 | 244.6 * | 2.2 | 2.3 |
| **INRiM** | IENG/IT1Z | 308.6 | 2.4 | 318.9 | 2.5 | 2.5 |
| | GTRB/IT__ | - 34.8 | 2.3 | - 20.8 | 2.4 | 2.5 |
| | GTRI/IT2_ | - 143.7 | 2.3 | - 131.4 | 2.4 | 2.5 |
| | INR7 | 229.8 ** | 2.3 | 231.1 ** | 2.4 | 2.5 |

*Reference delay and antenna cable delay included: REFDLY = 0.0 ns, CABDLY = 0.0 ns.

**Antenna cable delay included: CABDLY = 0.0 ns.

## 3. Acronym list.

| | |
|---|---|
| ADEV: | Allan Standard Deviation. |
| BIPM: | Bureau International des Poids et Mesures, Sèvres, France. |
| CABDLY: | Antenna cable delay. |
| CCTF: | Consultative Committee on Time and Frequency. |
| CGGTTS: | CCTF GPS GLONASS Time Transfer Standard format. |
| CIPM: | Comité International des Poids et Mesures. |
| DI: | Designated Institute. |
| DUT: | Device under test. |
| EURAMET: | European regional metrology area. |
| GLONASS: | Russian GNSS. |
| GNSS: | Global Navigation Satellite System. |
| GPS: | American GNSS. |
| IGS: | International GNSS Service. |
| IGSR: | IGS time scale obtained from the use of IGS Rapid Products. |
| INRiM: | Istituto Nazionale de la Riserca Metrologica, Italy. |
| INTDLY: | GPS receiver internal delay for P1 or P2 GPS code. |
| L1P: | CGGTTS data obtained from GPS P code pseudo-ranges on L1 GPS carrier. |
| L2P: | CGGTTS data obtained from GPS P code pseudo-ranges on L2 GPS carrier. |
| L3P: | Ionosphere-free linear combination obtained form CGGTTS files L1P and L2P. |
| LNE: | Laboratoire National de Métrologie et d'Essais, France. |
| LNE-SYRTE: | French NML in charge of Time and Frequency units, located in OP. |
| NA: | Not available. |
| nan: | Not available number. |
| NIST: | National Institute of Standards and Technology, USA. |
| NMI: | National Metrology Institute. |
| NML: | National Metrology Laboratory. |
| NRCan: | National Resources Canada. |
| OP: | Observatoire de Paris, France. |
| ORB: | Observatoire Royal de Belgique, Belgium. |
| P1: | GPS P code transmitted on L1 carrier. |
| P2: | GPS P code transmitted on L2 carrier. |
| P3: | Ionosphere-free linear combination obtained from P1 and P2 in RINEX files. |
| PPP: | Geodetic Precise Point Positioning. |
| PPS: | Pulse per second. |
| PSC: | Power splitter combiner. |
| PTB: | Physikalisch-Technische Bundesanstalt, Germany. |

REFDLY: Delay parameter for the connection to the local time scale reference point.

RINEX: Geodetic GPS receiver international exchange data format.

RMS: Root Mean Square.

SP: Technical Research Institute of Sweden.

SYRTE: Systèmes de Référence Temps-Espace, laboratory in OP.

TAIP3: Ionosphere-free linear combination by using ORB software.

TDEV: Allan Time Standard Deviation.

TIC: Time Interval Counter.

TVF: Time Validation Facility.

TWSTFT: Two-Way Satellite Time and Frequency Transfer.

## 4. Reference documents.

[RD1] P. Uhrich and D. Valat, "*GPS receiver relative calibration campaign preparation for Galileo In-Orbit Validation*", Proc. of the 24th European Frequency and Time Forum (EFTF), Noordwijk, The Netherlands, April 2010 (CD-Rom).

[RD2] LNE-SYRTE _ Calibration Procedure, "*2016 Galileo TVF relative calibration campaign: GPS receiver calibration procedure for visited laboratories*", P. Uhrich, G.D. Rovera, LNE-SYRTE, Observatoire de Paris, Issue 2.0, March 4, 2016.

[RD3] P. Defraigne and G. Petit, "*Time transfer to TAI using geodetic receivers*", Metrologia, 2003, 40, n°4, 184-188.

[RD4] M. Weiss, V. Zhang, J. White, K. Senior, D. Matsakis, S. Mitchell, P. Uhrich, D. Valat, W. Lewandowski, G. Petit, A. Bauch, T. Feldman, A. Proia, "*Coordinating GPS Calibrations Among NIST, NRL, USNO, PTB, and OP*", Proc. of the 25th EFTF and the 2008 IEEE Frequency Control Symposium (IFCS) Joint Meeting, San Francisco, USA, April 2011 (CD-Rom).

[RD5] BIPM guidelines for GNSS calibration, V3.2, 15/02/2016.

[RD6] P. Uhrich, G.D. Rovera, B. Chupin, J. Galindo, H. Esteban, K. Jaldehag, C. Rieck, A. Bauch, T. Polewka, G. Cerretto, G. Fantino and R. Piriz, "*Use of two traveling GPS receivers for a relative calibration campaign among European laboratories*", Proc. of the he 29th EFTF and the 2015 IEEE Frequency Control Symposium (IFCS) Joint Meeting, Boulder, USA, April 2015.

[RD7] BIPM TM243, "*Determination of reference GPS "INTDLY" values of Group 1 geodetic receivers in the initial Group 1 trip (Cal_Id = 1001-2014)*", v7, 24 August 2016.

[RD8] G.D. Rovera, B. Chupin, M. Abgrall and P. Uhrich, "*A simple computation technique for improving the short-term stability and the robustness of GPS TAIP3 Common-Views*", Proc. of the 27th EFTF and the 2013 IFCS Joint Meeting, Prague, Czech Republic, 2013.

[RD9] BIPM, "*Group 1 calibration trip (Cal_Id 1001-2016)*", Draft Phase 2, V1.0 / 20161226.

[RD10] BIPM GP/TM266, "*Continuity of GPS "INTDLY" values of Group 1 geodetic receivers in successive Group 1 trips*", Draft v0, 16 December 2016.

[RD11] BIPM, "*Initial Group1 calibration trip (Cal_Id 1001-2014)*", v1.9 / 20160713, Final Version.

## 5. List of Figures.

## 6. List of Tables.

## 7. Description of equipment and operations.

The basis of this Group 1 / Group 2 relative calibration campaign was a round-trip of a traveling equipment starting and ending in OP. The reference receiver for this campaign was OPMT, an Ashtech ZXII-T multichannel two-frequencies GPS receiver located in OP, which is also the basis of the IGS station OPMT. This receiver was relatively calibrated by BIPM since 1998 on a regular basis, exhibiting since 2004 a consistency over time of its internal delays at the ns level despite numerous changes of reference clock signals. Following the first BIPM Group 1 relative calibration published in summer 2015, the OPMT internal delays were updated in August 2015. This lead to offsets of about - 1.1 ns for INTDLY(P1) and about - 1.7 ns for INTDLY(P2) with respect to former values. But the resulting deviation on the P3 linear combination is about - 0.17 ns only, hence an almost negligible effect when compared to the conventional uncertainty of 1.7 ns of the link OP-PTB for TAI. This is allowing for a consistent comparison of the new results to former calibrated delays.

The OP traveling equipment was made of two Septentrio PolaRx4 multichannel multi-frequencies multi-GNSS receivers called OPM3 and OPM7, together with a Choke-Ring Ashtech antenna and a 50 m antenna cable, plus a Time Interval Counter (TIC) Stanford SR620. In all locations, it was checked that the relationship between PPS_OUT and PPS_IN was in agreement with the Septentrio requirements, depending on the PolaRx type. In the visited laboratories, the local equipment to be calibrated are detailed in the Annex A, which contains all the “BIPM Information Sheets” according to [RD5]. Note that delays and antenna coordinates in Annex A are issued from the calibration computations.

The summary of the GPS relative calibration campaign is described in Table 2 as required in [RD5]. Thanks to the flexibility of the laboratories, there was no significant deviation from the originally planned schedule. The name of the traveling equipment and of the fixed receiver(s) in each site is also provided in Table 2. The equipment transport was organised by OP separately from one site to the other only a few days in advance, by trying to stay in line with the original schedule. This is the most convenient way to proceed, because it is flexible enough in case of an unexpected issue in one given site.

***Table 2. Summary information on the calibration trip.***

| Institute | Status of equipment | Dates of measurement | Receiver type | BIPM code | RINEX name |
|---|---|---|---|---|---|
| OP | Traveling | | Septentrio PolaRx4TR | OPM7 | OPM7 |
| OP | Traveling | | Septentrio PolaRx4TR | OPM3 | OPM3 |
| OP | Goup 1 Reference | 57429 – 57447 | Ashtech Z-XII3T | OPMT | OPMT |
| OP | Goup 1 Reference | 57549 – 57567 | Ashtech Z-XII3T | OPMT | OPMT |
| SP | Goup 2 | 57452 – 57457 | Javad E_GGD | SP01 | SP01 |
| SP | Goup 2 | 57452 – 57457 | Javad E GGD | SP02 | SP02 |
| PTB | Goup 2 | 57479 – 57489 | ASHTECH Z-XII3T | PTBB | PTBB |
| PTB | Goup 2 | 57479 – 57488 | DICOM GTR50 | PT07 | PT07 |
| PTB | Goup 2 | 57479 – 57488 | DICOM GTR51 | PT10 | PT10 |
| INRIM | Goup 2 | 57519 – 57525 | ASHTECH Z-XII3T | IENG | IENG |
| INRIM | Goup 2 | 57519 – 57525 | DICOM GTR50 | GTRI | GTRI |
| INRIM | Goup 2 | 57519 – 57525 | DICOM GTR50 | GTRB | GTRB |
| INRIM | Goup 2 | 57519 – 57525 | PolaRx4-TR | INR7 | INR7 |

Note that in the frame of this campaign we call “Group 2” the PTB equipment because we computed all PTB receiver delays as if this laboratory was included in EURAMET Group 2. But, of course, this does not change the PTB position among Group 1 laboratories.

## 8. Data and processing.

The OPMT collected raw data are transformed into RINEX 2.1 format by using the UNAVCO TEQC software. The proprietary software SBFtoRIN is used to convert the raw data binary files of the Septentrio traveling receivers into hourly RINEX format, with TEQC again for getting daily RINEX 2.1 files. Local visited receivers RINEX 2.1 data are provided by the visited laboratories. The calibration is consisting in building differential pseudo-ranges for each code P1 and P2 separately between pairs of receivers in common-clock set-up, these differences being corrected by the know reference delay (REFDLY) and antenna cable delay (CABDLY) when available. For each location, the coordinates of the antenna phase centres were especially computed for the calibration period from RINEX files by using the NRCan PPP software. The geometric correction between pairs of antenna phase centres for receivers in common-clock set-up is computed by using the satellite ephemeris BRDC files provided by IGS. From the known delays of the reference receiver OPMT, and from an average of the traveling receiver delays between the start and the end of the campaign, we can obtain INTDLY(P1) and INTDLY (P2) for the receivers in the visited sites.

Note that DICOM receivers are already including all the implemented delays in the RINEX data. Therefore, we are first providing the raw computation results, and then compute additionally the actual INTDLY to be implemented according to the following equation:

$$\text{INTDLY(Px)\_New} = \text{INTDLY(Px)\_Old} + \text{CABDLY} - \text{REFDLY} + \text{INDLY(Px)\_Cal} \quad (1)$$

where Px is either P1 or P2, INTDLY(Px)_Old are the INTDLY which are currently implemented in the DICOM receiver and INTDLY(Px)_Cal are the results of the raw processing as obtained by LNE-SYRTE during this campaign. The INTDLY(Px)_Old, CABDLY and REFDLY are taken from the headers of the related CGGTTS files collected according to the campaign schedule.

As a conservative estimate, the noise of the P1 and P2 differences is obtained from the highest value of the one-sigma statistical uncertainty of the TDEV at an averaging period close to 1 d. In the case there is not enough data to compute a TDEV at 1 d, the TDEV of the largest possible averaging period is computed to provide the required noise value.

REFDLY values are measured against the local UTC(k) physical reference point according either to a technique used in the visited laboratory or to the technique described in Annex D. In the case no REFDLY is provided or measured, this parameter is set to 0.0 ns, and the related delay is thus included in the INTDLY values. CABDLY is provided by operators in the visited sites. When no value is available for this parameter, the CABDLY value is set to 0.0 ns in the parameter file, and the related delay is thus included in the INTDLY values.

For validation purposes, P3 CGGTTS files are computed by using the R2CGGTTS software provided by P. Defraigne (ORB), and Common-Views (CV) are built between pairs of receivers. This is more especially the case between the two traveling receivers in each location, in order to better assess the stability of the traveling ensemble all over the calibration campaign. We have decided to consider as conservative value for the traveling equipment stability during the campaign the maximum value between the highest misclosure between the start and the end of the campaign on one side and the highest CV mean offset between the two traveling receivers on the other side. The noise of the P3 CV data is issued from a TDEV analysis similar as above.

## 9. Results of raw data processing.

Table 3 is providing the RAWDIF values as required by [RD5]. In addition, Table 4 provides a summary of the INTDLY(P1) and INTDLY(P2) delays computed from the raw differences between RINEX files, together with the REFDLY and CABDLY used for these computations when available. Table 4 also contains the P1 and P2 internal delays of the traveling equipment computed against OPMT, averaged between the start and the end of the campaign, with the related REFDLY when located in remote stations. From our point of view, this Table 4 is the most comprehensive summary of the calibration campaign, outside the uncertainty budget computations.

All the plots of the P1 and P2 computed delays and of the related TDEV analysis are provided in Annex B. The related P3 CV between the traveling equipment and the local ones, computed by using the results of the calibration, and the related TDEV are also made available in Annex B for each site.

***Table 3. Summary information on raw calibration results (all values in ns).***

| Pair | Dates of measurement | Rawdiff P1 | Unc | Rawdiff P2 | Unc |
|---|---|---|---|---|---|
| OPM7-OPMT | 57429 – 57447 | 280.26 | 0.051 | 288.45 | 0.051 |
| OPM3-OPMT | 57429 – 57447 | 295.76 | 0.050 | 303.65 | 0.058 |
| OPM7-OPMT | 57549 – 57567 | 280.36 | 0.075 | 288.45 | 0.075 |
| OPM3-OPMT | 57549 – 57567 | 282.86 | 0.083 | 290.65 | 0.083 |
| SP01-OPM7 | 57452 – 57457 | 142.65 | 0.061 | 150.9 | 0.231 |
| SP01-OPM3 | 57452 – 57457 | 141.7 | 0.074 | 149.55 | 0.237 |
| SP02-OPM7 | 57452 – 57457 | 144.25 | 0.052 | 149.4 | 0.229 |
| SP02-OPM3 | 57452 – 57457 | 143.2 | 0.067 | 148.05 | 0.230 |
| PTBB-OPM7 | 57479 – 57489 | 428.15 | 0.034 | 440 | 0.051 |
| PTBB-OPM3 | 57479 – 57489 | 428.7 | 0.035 | 440.15 | 0.053 |
| PT07-OPM7 | 57479 – 57488 | -103.45 | 0.044 | -106.7 | 0.050 |
| PT07-OPM3 | 57479 – 57488 | -102.9 | 0.046 | -106.55 | 0.054 |
| PT10-OPM7 | 57479 – 57488 | -103.85 | 0.050 | -107.5 | 0.071 |
| PT10-OPM3 | 57479 – 57488 | -103.3 | 0.058 | -107.25 | 0.073 |
| IENG-OPM7 | 57519 – 57525 | 15.35 | 0.034 | 22 | 0.044 |
| IENG-OPM3 | 57519 – 57525 | 15.4 | 0.040 | 21.75 | 0.049 |
| GTRI-OPM7 | 57519 – 57525 | -45.65 | 0.053 | -49.1 | 0.052 |
| GTRI-OPM3 | 57519 – 57525 | -45.5 | 0.047 | -49.35 | 0.049 |
| GTRB-OPM7 | 57519 – 57525 | -45.75 | 0.039 | -48.9 | 0.052 |
| GTRB-OPM3 | 57519 – 57525 | -45.7 | 0.037 | -49.15 | 0.051 |
| INR7-OPM7 | 57519 – 57525 | -341.45 | 0.034 | -343.9 | 0.042 |
| INR7-OPM3 | 57519 – 57525 | -341.4 | 0.043 | -344.15 | 0.042 |

## *Table 4. Summary information on receiver delays (all values in ns).*

| Receiver | Reference | Dates of measurement | REFDLY | CABDLY | P1_DLY | Unc | P2_DLY | Unc |
|---|---|---|---|---|---|---|---|---|
| OPMT | Ref | 57429 – 57447 | 155.95 | 156.5 | 310.21 | | 321.60 | |
| OPM7 | OPMT | 57429 – 57447 | 238.5 | 218.6 | 50.4 | 0.051 | 53.6 | 0.057 |
| OPM3 | OPMT | 57429 – 57447 | 254.1 | 218.6 | 50.5 | 0.050 | 54.0 | 0.058 |
| OPMT | Ref | 57549 – 57567 | 155.95 | 156.5 | 310.21 | | 321.60 | |
| OPM7 | OPMT | 57549 – 57567 | 239.3 | 218.6 | 51.1 | 0.075 | 54.4 | 0.081 |
| OPM3 | OPMT | 57549 – 57567 | 241.4 | 218.6 | 50.7 | 0.083 | 54.3 | 0.083 |
| OPM7 | Ref | 57452 – 57457 | 176.9 | 218.6 | 50.75 | | 54.00 | |
| OPM3 | Ref | 57452 – 57457 | 175.5 | 218.6 | 50.60 | | 54.15 | |
| SP01 | OPM7 | 57452 – 57457 | 0.0 | 0.0 | 235.1 | 0.061 | 246.6 | 0.231 |
| SP01 | OPM3 | 57452 – 57457 | 0.0 | 0.0 | 235.4 | 0.074 | 246.8 | 0.237 |
| SP02 | OPM7 | 57452 – 57457 | 0.0 | 0.0 | 236.7 | 0.052 | 245.1 | 0.229 |
| SP02 | OPM3 | 57452 – 57457 | 0.0 | 0.0 | 236.9 | 0.067 | 245.3 | 0.230 |
| OPM7 | Ref | 57479 – 57489 | 164.3 | 218.6 | 50.75 | | 54.00 | |
| OPM3 | Ref | 57479 – 57489 | 164.6 | 218.6 | 50.60 | | 54.15 | |
| PTBB | OPM7 | 57479 – 57489 | 74.0 | 301.7 | 305.5 | 0.034 | 320.6 | 0.051 |
| PTBB | OPM3 | 57479 – 57489 | 74.0 | 301.7 | 305.6 | 0.035 | 320.6 | 0.053 |
| PT07 | OPM7 | 57479 – 57488 | 43.6 | 245.8 | -200.6 | 0.044 | -200.6 | 0.050 |
| PT07 | OPM3 | 57479 – 57488 | 43.6 | 245.8 | -200.5 | 0.046 | -200.6 | 0.054 |
| PT10 | OPM7 | 57479 – 57488 | 52.3 | 250.0 | -196.5 | 0.050 | -196.9 | 0.071 |
| PT10 | OPM3 | 57479 – 57488 | 52.3 | 250.0 | -196.4 | 0.058 | -196.8 | 0.073 |
| OPM7 | Ref | 57519 – 57525 | 222.9 | 218.6 | 50.75 | | 54.00 | |
| OPM3 | Ref | 57519 – 57525 | 222.5 | 218.6 | 50.60 | | 54.15 | |
| IENG | OPM7 | 57519 – 57525 | 384.3 | 136.6 | 309.5 | 0.034 | 319.4 | 0.044 |
| IENG | OPM3 | 57519 – 57525 | 384.3 | 136.6 | 309.8 | 0.040 | 319.7 | 0.049 |
| GTRI | OPM7 | 57519 – 57525 | 19.4 | 210.9 | -190.7 | 0.053 | -190.9 | 0.052 |
| GTRI | OPM3 | 57519 – 57525 | 19.4 | 210.9 | -190.3 | 0.047 | -190.6 | 0.049 |
| GTRB | OPM7 | 57519 – 57525 | 22.8 | 131.0 | -107.5 | 0.039 | -107.4 | 0.052 |
| GTRB | OPM3 | 57519 – 57525 | 22.8 | 131.0 | -107.2 | 0.037 | -107.1 | 0.051 |
| INR7 | OPM7 | 57519 – 57525 | 525.8 | 0.0 | 230.8 | 0.034 | 231.6 | 0.042 |
| INR7 | OPM3 | 57519 – 57525 | 525.8 | 0.0 | 231.1 | 0.043 | 231.9 | 0.042 |

# 10. Calibration results.

## 10.1 Traveling system against reference system.

According to [RD5], Table 5 is providing the computed internal delays INTDLY(P1) and INTDLY(P2) for both traveling receivers OPM3 and OPM7 against the reference receiver OPMT at the start and at the end of the campaign. The mean values are the ones used for the computations of the visited equipment delays against each of the traveling receiver.

***Table 5. Traveling vs. reference system (all values in ns).***

| Pair | Dates of measurement | INTDLY P1 | INTDLY P2 | P1 -P2 |
|---|---|---|---|---|
| OPM7-OPMT | 57429 – 57447 | 50.4 | 53.6 | -3.2 |
| OPM7-OPMT | 57549 – 57567 | 51.1 | 54.4 | -3.6 |
| misclosure | | 0.7 | 0.8 | 0.1 |
| mean | | 50.75 | 54 | -3.25 |
| OPM3-OPMT | 57429 – 57447 | 50.5 | 54.0 | -3.5 |
| OPM3-OPMT | 57549 – 57567 | 50.7 | 54.3 | -3.6 |
| misclosure | | 0.2 | 0.3 | 0.1 |
| mean | | 50.6 | 54.15 | -3.55 |

The misclosure values of INTDLY(P1) and INTDLY(P2) appearing in Table 5 here between the start and the end of the campaign for OPM7 against OPMT are the largest observed during the whole campaign. They are therefore the ones used for the conservative uncertainty budget computations in Section 13, that is 0.7 ns for P1 and 0.8 ns for P2.

## 10.2. Traveling system against visited systems.

According to [RD5], Table 6 is providing the computed internal delays INTDLY(P1) and INTDLY(P2) for the visited systems by using OPM3 and OPM7 as reference systems, by using the available RINEX files. In addition, Table 6 also provides the computed differences between both traveling receivers, allowing for a monitoring of the consistency of the traveling equipment during the whole campaign, which stayed within 0.6 ns. This is below the other limits computed above for estimating the misclosure of P1 and P2 delays, and it is therefore disregarded afterwards.

***Table 6. Traveling vs. visited systems (all values in ns).***

| Pair | Dates of measurement | INTDLY P1 | INTDLY P2 | P1 -P2 |
|---|---|---|---|---|
| OPM7-SP01 | 57452 – 57457 | 235.1 | 246.6 | -11.5 |
| OPM3-SP01 | 57452 – 57457 | 235.4 | 246.8 | -11.4 |
| OPM7 to OPM3 | 57452 – 57457 | 0.3 | 0.2 | 0.1 |
| mean | | 235.25 | 246.70 | -11.45 |
| OPM7-SP02 | 57452 – 57457 | 236.7 | 245.1 | -8.4 |
| OPM3-SP02 | 57452 – 57457 | 236.9 | 245.3 | -8.4 |
| OPM7 to OPM3 | 57452 – 57457 | 0.2 | 0.2 | 0 |
| mean | | 236.80 | 245.20 | -8.4 |
| OPM7-PTBB | 57479 – 57489 | 305.5 | 320.6 | -15.1 |
| OPM3-PTBB | 57479 – 57489 | 305.6 | 320.6 | -15 |
| OPM7 to OPM3 | 57479 – 57489 | 0.1 | 0 | 0.1 |
| mean | | 305.55 | 320.60 | -15.05 |
| OPM7-PT07 | 57479 – 57488 | -201.1 | -201.1 | 0 |
| OPM3-PT07 | 57479 – 57488 | -201.0 | -201.1 | 0.1 |
| OPM7 to OPM3 | 57479 – 57488 | 0.1 | 0 | 0.1 |
| mean | | -201.05 | -201.10 | 0.05 |
| OPM7-PT10 | 57479 – 57488 | -196.4 | -196.8 | 0.4 |
| OPM3-PT10 | 57479 – 57488 | -196.3 | -196.8 | 0.5 |
| OPM7 to OPM3 | 57479 – 57488 | 0.1 | 0 | 0.1 |
| mean | | -196.35 | -196.80 | 0.45 |
| OPM7-IENG | 57519 – 57525 | 309.5 | 319.4 | -9.9 |
| OPM3-IENG | 57519 – 57525 | 309.8 | 319.7 | -9.9 |
| OPM7 to OPM3 | 57519 – 57525 | 0.3 | 0.3 | 0 |
| mean | | 309.65 | 319.55 | -9.9 |
| OPM7-GTRI | 57519 – 57525 | -190.7 | -190.9 | 0.2 |
| OPM3-GTRI | 57519 – 57525 | -190.3 | -190.6 | 0.3 |
| OPM7 to OPM3 | 57519 – 57525 | 0.4 | 0.3 | 0.1 |
| mean | | -190.50 | -190.75 | 0.25 |
| OPM7-GTRB | 57519 – 57525 | -107.5 | -107.4 | -0.1 |
| OPM3-GTRB | 57519 – 57525 | -107.2 | -107.1 | -0.1 |
| OPM7 to OPM3 | 57519 – 57525 | 0.3 | 0.3 | 0 |
| mean | | -107.35 | -107.25 | -0.1 |
| OPM7-INR7 | 57519 – 57525 | 230.8 | 231.6 | -0.8 |
| OPM3-INR7 | 57519 – 57525 | 231.1 | 231.9 | -0.8 |
| OPM7 to OPM3 | 57519 – 57525 | 0.3 | 0.3 | 0 |
| mean | | 230.95 | 231.75 | -0.8 |

### 10.3. Additional computation for DICOM receivers.

For the DICOM receivers, an additional computation has to be carried out according to equation (1). The DICOM receivers in this campaign are: PT07, PT10, GTRB and GTRI. Table 7 is providing the actual INTDLY parameters to be potentially implemented in these receivers. We have used as parameters for equation (1) the REFDLY and CABDLY parameters which are provided in Table 3 for each of these receivers, plus the “old” INTDLY which were taken from the related CGGTTS files as generated by the visited laboratories during the period the OP traveling equipment was on site, hence before application of the calibration computation which results are presented in this report.

***Table 7. Additionally computed delays for DICOM receivers (all values in ns).***

| DICOM receiver | *Old INTDLY(P1)* | New INTDLY(P1) | *Old INTDLY(P2)* | New INTDLY(P2) | *Old delays P1 - P2* | New delays P1 - P2 | CABDLY | REFDLY |
|---|---|---|---|---|---|---|---|---|
| PT07 (GTR50) | *- 36.30* | - 35.60 | *- 23.80* | - 23.20 | *- 12.50* | - 12.40 | 245.80 | 43.60 |
| PT10 (GTR51) | *- 40.30* | - 38.90 | *- 46.60* | - 45.60 | *6.30* | 6.70 | 250.00 | 52.30 |
| GTRB (GTR50) | *- 34.50* | - 33.65 | *- 21.10* | - 20.15 | *13.40* | - 13.50 | 131.00 | 22.80 |
| GTRI (GTR50) | *- 143.50* | - 142.50 | *- 131.50* | - 130.60 | *- 12.00* | - 11.90 | 210.90 | 19.40 |

We can see that the computed offset between old and new P1 – P2 differences is 0.10 ns for all three GTR50 receivers, but reaches 0.40 ns for the GTR51 one. We also note some consistency in the P1 – P2 delays inside about 2.35 ns peak to peak among the GTR50 receivers, which are clearly different from the GTR51 one.

### 10.4. P3 delay computation for SP.

SP requested that the calibration results be expressed as P3 delays for both receivers, in order to determine a potential offset against the current value to be added to the relevant data. For the P3 CV computations, we used as in [RD5]:

$$P3 = P1 + 1.545 \times (P1 - P2) \qquad (3)$$

even if a proper computation would have lead to a factor equal to 1.546. Table 8 contains different P3 delays:

- The P3 delays used for data provision to BIPM, based on a TWSTFT calibration.
- The P3 delays used for Galileo TVF data provision from the 2014 calibration.
- The P3 delays originally computed from this G1/G2 calibration campaign results based on OPMT 1001-2014 delays.
- The updated P3 delays computed from OPMT 1001-2016 delays.

As can be seen, the offset between these P3 delays for both receivers remains below 0.2 ns between the TVF 2014 and the G1/G2 calibration. But there is a significant offset of about 2 ns between this G1/G2 calibration based on OPMT 1001-2014 and the original P3 delays, hence close to the limit of the Group 2 conventional uncertainty. This offset becomes almost insignificant when using the OPMT 1001-2016 delays for the delay computations. See Annex D for more details.

***Table 8. P3 computed delays for SP receivers (all values in ns).***

| Receiver | P3 delays (TWSTFT 2005) | P3 delays (Galileo TVF 2014) | P3 delays (G1/G2 2016 OPMT 1001-2014) | Updated P3 delays (OPMT 1001-2016) | Δ[G1/G2 2016 – TVF 2014] | Δ[G1/G2 2016 – TWSTFT 2005] | Δ[Updated 2016 – TWSTFT 2005] |
|---|---|---|---|---|---|---|---|
| **SP01** | 216.0 | 217.8 | 217.6 | 215.6 | - 0.2 | + 1.6 | - 0.4 |
| **SP02** | 221.5 | 223.8 | 223.8 | 222.0 | 0.0 | + 2.3 | 0.5 |

# 11. Validation of the calibration results.

## 11.1. Internal validation.

The internal validation aims at cross-checking that there is neither software issue nor mistake in some parameter figures used for the calibration computations. Therefore, the internal validation is based on two kinds of results:

- the direct comparison between the two traveling receivers in common-clock and common-antenna setup when implemented in the different visited sites;
- the TAIP3 CV computation between the traveling receivers and the locally implemented receivers after computation of the local receiver delays.

The TAIP3 CV between OPM3 and OPM7 have been computed from data collected in each visited site, by using as internal delay parameters the mean values of the delays against OPMT between the start and the end of the campaign (provided in Table 5). This is one of the ways to estimate the reproducibility error affecting the campaign results due to the traveling equipment only. We obtain the plot in the Figure 1, and the mean values for all sites are given in Table 9.

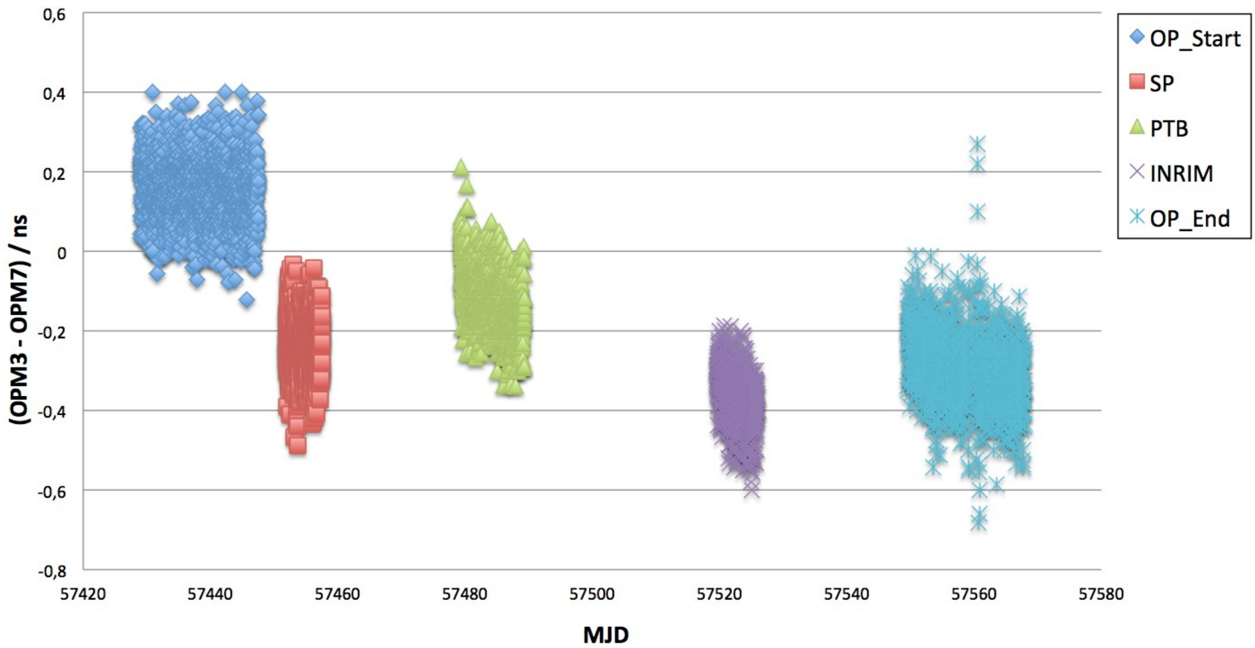


***Figure 1. Averaged TAIP3 CV between OPM3 and OPM7 in all the visited sites during the relative calibration campaign: OP at the start (blue), SP (red), PTB (green), INRiM (cyan) and back to OP at the end (light blue). OPM3 and OPM7 internal delays were computed against OPMT as the mean values between the start and the end of the campaign.***

We see that during the campaign both traveling receivers stayed close to each other within 0.524 ns peak to peak of the mean values. The largest deviation from 0 happens when OPM3 and OPM7 are implemented in INRIM. The standard deviation also stayed consistent within 90 ps in all visited sites. This is an excellent result showing how close to each other the OP traveling receivers have been staying during the campaign. This also means that in the case of deviation of this ensemble, it would be most probably due to the separate connections to the reference time scale than to the traveling equipment itself. For the conservative uncertainty budget computation of P3 CV, it was nevertheless decided to consider 0.80 ns as misclosure, which is the P2 delays discrepancy observed in Table 5 for OPM7, because it is a largest misclosure compared to the one observed here.

***Table 9. Averaged TAIP3 CV mean values between OPM3 and OPM7 in common-clock and common-antenna setup (all values in ns).***

| OPM3 – OPM7 implemented in | TAIP3 CV mean value | Standard deviation |
|---|---|---|
| **OP (start of the campaign)** | 0.154 | 0.078 |
| **SP** | - 0.232 | 0.077 |
| **PTB** | - 0.119 | 0.079 |
| **INRiM** | - 0.370 | 0.074 |
| **OP (end of the campaign)** | - 0.298 | 0.087 |

In addition, the TAIP3 CV between the traveling equipment and the local equipment have also been computed, using as parameters the calibrated delays for the local receiver. The next Table shows the mean values of such TAIP3 CV for each visited site. What we expect is mean values close to 0 together with a given standard deviation, both values small enough to consider a proper consistency of the computations. We see it is indeed the case for all sites, which provides confidence in the LNE-SYRTE data processing.

***Table 10. Averaged TAIP3 CV mean values between receivers in common-clock setup after application of calibration results (all values in ns).***

| Receiver | Receiver – OPM3 TAIP3 CV | Standard Deviation | Receiver – OPM7 TAIP3 CV | Standard Deviation |
|---|---|---|---|---|
| **OPMT** | 0.113 | 0.659 | 0.264 | 0.656 |
| **SP01** | 0.106 | 0.535 | - 0.115 | 0.536 |
| **SP02** | 0.101 | 0.535 | - 0.123 | 0.541 |
| **PTBB** | 0.063 | 0.525 | - 0.060 | 0.510 |
| **PT07** | 0.078 | 0.521 | - 0.036 | 0.509 |
| **PT10** | 0.127 | 0.576 | 0.014 | 0.571 |
| **IENG** | 0.365 | 0.441 | - 0.002 | 0.435 |
| **GTRB** | 0.059 | 0.466 | - 0.302 | 0.471 |
| **GTRI** | 0.272 | 0.554 | - 0.089 | 0.556 |
| **INR7** | 0.197 | 0.343 | - 0.167 | 0.342 |
| **OPMT** | - 0.037 | 0.604 | - 0.346 | 0.593 |

### 11.2. Comparison with older calibrated delays.

Table 11 provides a direct comparison between the delays obtained during the 2016 campaign and the ones issued from old calibrations, either obtained during one former calibration campaign [RD6] or having been changed since, either as found in the headers of CGGTTS files obtained from the laboratories or built by LNE-SYRTE on purpose.

***Table 11. Direct comparison between old calibrated delays and the results of the 2016 calibration campaign (all values in ns).***

| Station | Receiver name | INTDLY(P1) Old | INTDLY(P1) 2016 | 2016 - Old ∆P1 | INTDLY(P2) Old | INTDLY(P2) 2016 | 2016 - Old ∆P2 | 2016 – Old ∆P3 |
|---|---|---|---|---|---|---|---|---|
| **SP *** | SP01 | 235.60 * | 235.25 * | **- 0.35** | 247.10 * | 246.70 * | **- 0.40** | **- 0.27** |
| | SP02 | 237.20 * | 236.80 * | **- 0.40** | 245.85 * | 245.20 * | **- 0.65** | **- 0.01** |
| **PTB** | PTBB | 303.90 | 305.55 | **1.65** | 319.30 | 320.60 | **1.30** | **2.19** |
| | PT07 | - 36.30 | - 35.60 | **0.70** | - 23.80 | - 23.20 | **0.60** | **0.85** |
| | PT10 | - 40.30 | - 38.95 | **1.35** | - 46.60 | - 45.60 | **1.00** | **1.89** |
| **INRiM** | IENG | 305.60 | 309.65 | **4.05** | 315.60 | 319.55 | **3.95** | **4.20** |
| | GTRB | - 34.50 | - 33.65 | **0.85** | - 21.10 | - 20.15 | **0.95** | **0.70** |
| | GTRI | - 143.50 | - 142.50 | **1.00** | - 131.50 | - 130.75 | **0.75** | **1.39** |
| | INR7 | nan | 230.95 ** | | nan | 231.75 ** | | |

* Reference delay and antenna cable delay included: REFDLY = 0.0 ns, CABDLY = 0.0 ns.

** Antenna cable delay included: CABDLY = 0.0 ns.

We propose the following comments on these results.

- Results for SP receivers of this 2016 campaign are clearly in line at a consistent sub-ns level with the former 2014 results.
- Results for PTBB receiver are apparently exhibiting a discrepancy which might reach above 2 ns for P3 data.
- Results for other PTB receivers are in line with the uncertainty budgets for all types of data.
- Results for IENG receiver in INRIM are showing a clear offset with respect to the current delays for P3 data. This should be investigated by INRIM.
- Results for other INRIM receivers are in line with the uncertainty budgets for all types of data.

### 11.3. Comparison of PTBB delays with former calibrations.

We have compared the results obtained for PTBB to former calibrations achieved by OP and by BIPM during the last years. These calibration results are shown in Table 12. In this Table, we use the following names for the successive campaigns:

- Gal 1: the Galileo TVF calibration campaign having taken place in 2014 [RD6].
- BIPM G1: the first BIPM Group 1 calibration campaign (#1001-2014) having taken place in 2015 in OP and in PTB [RD7].
- N-O-P: the OP results of the calibration campaign having taken place in 2015 between three Group 1 laboratories NIST-OP-PTB (only draft report yet).
- Gal 2: the Galileo TVF calibration having taken place in 2016, which results are used for this calibration report.

***Table 12. Successive PTBB calibrations by OP and by BIPM from 2014 to 2016 (all values in ns).***

| PTBB | 2014 [Gal 1] | 2015 [BIPM G1] | 2015 [N-O-P] | 2016 [Gal 2] | 2016[Gal 2] – 2014[Gal 1] | 2016[Gal 2] – 2015[BIPM G1] | 2016 [Gal 2] – 2015 [N-O-P] |
|---|---|---|---|---|---|---|---|
| **INTDLY(P1)** | 306.85 | 303.90 | 305.95 | **305.55** | - 1.30 | 1.65 | - 0.40 |
| **INTDLY(P2)** | 322.50 | 319.30 | 320.65 | **320.60** | - 1.90 | 1.30 | - 0.05 |
| **P1 – P2** | - 15.65 | - 15.40 | - 14.7 | **- 15.05** | 0.60 | 0.35 | - 0.35 |
| **P3** | 282.67 | 280.11 | 283.24 | **282.30** | **- 0.37** | **2.19** | **- 0.94** |

What we see in this Table is that there is a clear discrepancy between BIPM results and OP results, significantly larger than the conventional BIPM uncertainty of 1.7 ns for the OP-PTB link. The resulting offsets between P3 calibrated delays from OP or from BIPM are:

- ∆P3(2014[Gal 1] – 2015 [BIPM G1]) = 2.56 ns
- ∆P3(2015[N-O-P] – 2015 [BIPM G1]) = 3.13 ns
- ∆P3(2016[Gal 2] – 2015 [BIPM G1]) = 2.19 ns

But we also note that there is a sub-ns consistency between all the OP P3 calibrated delays.

- ∆P3(2015[N-O-P] – 2014 [Gal 1]) = 0.57 ns
- ∆P3(2016[Gal 2] – 2014 [Gal 1]) = - 0.37 ns
- ∆P3(2016[Gal 2] – 2015 [N-O-P]) = - 0.94 ns

In addition, the BIPM Group 1 #1001-2014 calibrated delays have been used in both laboratories from 2015 on for both receivers OPMT (reference for all OP calibration campaigns) and PTBB. This means that these delays were implemented before the 2015 NIST-OP-PTB campaign. We remind here that the P3 offset between this BIPM #1001-2014 Group 1 campaign and the former OPMT delays was – 0.17 ns, hence negligible. Similarly, the P3 offset between this BIPM #1001-2014 Group 1 campaign and the former PTBB delays was – 0.8 ns [RD7]. Applying the BIPM Group 1 results is leading to an offset between OPMT and PTBB of about 0.6 ns on P3 data with respect to the former relative positions of both units, which does neither explain the discrepancy between BIPM results and OP ones.

Finally, we have also seen that the mean values of the offset between TAIP3 CV and TWSTFT on the OP-PTB link were about – 2.3 ns during the period of presence of the BIPM traveling equipment in OP for the first Group 1 campaign (MJD 57155-165), and about – 1,8 ns during the TVF calibration campaign (see Section 12.5 below). From analysis of OPMT position against other systems, we can detect significant changes in the P3 delays of OPMT receiving chain during given periods, before eventually going back to some continuity with previous positions. Unfortunately, we cannot plot a clear continuous comparison between different receiving chains in OP to try to better assess long term stability of OPMT. We have nevertheless analysed in more details this offsets in Annex D.

## 12. Uncertainty estimations.

This Section describes first the terms to be taken into account for the uncertainty budgets, and then provides the uncertainty budgets for each station and all the receivers involved, either for P1 and P2 delays or for TAIP3 CV against OPMT.

### 12.1. Terms to be taken into account.

The terms to be taken into account are as follows.

- A delay measured by using a Stanford SR620 Time Interval Counter (TIC) can be achieved within an uncertainty of about 0.20 ns (k = 1) by differential measurement. This is for example the uncertainty we use for a simple cable delay determination, where the noise of the measurements is typically below 10 ps. Such an uncertainty is applied for GNSS receivers requiring a 1 PPS_IN only, like DICOM GTR50, 51 or 52 receivers and JAVAD receivers: SP01, SP02, PT07, PT10, GTRB and GTRI for this campaign.
- We also use a TIC to measure the 1 PPS_OUT signal from a Septentrio receiver for getting access to the internal reference point of the main unit, provided the receiver is set to “RxClock” mode. So the uncertainty given above has to be applied, but here, the noise of the measurements is typically around 90 ps. The quadratic sum of the TIC uncertainty and of the noise of the measurements leads to a typical combined uncertainty of about 0.22 ns (k = 1). Such an uncertainty is applied for Septentrio PolaRx3 and PolaRx4 receivers: OPM3, OPM7, and INR7 for this campaign.
- For OPMT, the reference receiver of the calibration campaign, but also for PTBB and IENG, which are Ashtech Z12-T receivers, we have to consider the uncertainty on the delay between the 1 PPS local distribution system and the reference point of the GPS measurements internal to the main unit. This delay is the sum of two delays: the 1 PPS_IN cable delay, which is measured by using a TIC, hence within an uncertainty of 0.20 ns (k = 1), and the delay between this 1 PPS_IN signal and the next zero crossing of the inverted 20 Mhz_IN signal, which is measured by using an oscilloscope. We estimate the uncertainty of the measurement with an oscilloscope at about 0.30 ns (k = 1). The quadratic sum of these two terms leads to a combined uncertainty of 0.36 ns (k = 1), typical for Ashtech Z12-T reference signal.
- In addition, we also consider the TDEV at 1 d of the differences between P1- and P2-Code measurements for the P-Code delay uncertainties, and also the TDEV at 1 d of the TAIP3 CV between receivers for the P3 uncertainty budgets. We use the upper limit of the statistical uncertainty of the TDEV we can compute for an analysis period the closest possible to 1 d. This line depends of course of the statistics of the TDEV computations, which may vary from one configuration to the other.

All the terms above, plus some other terms required in [RD5], are added quadratically in the uncertainty budgets. But in addition, we have to take into account the deviation of the traveling equipment during the campaign, which is called misclosure. One of the reasons to use two main units during such a travel is also aiming at estimating the potential deviations of one unit from the other. During this calibration campaign, we were lucky to obtain very small deviations. The maximum deviation between the start and the end of the campaign on the P-Code delays of OPM3/OPM7 against OPMT is 0.7 ns for P1 and 0.8 ns for P2 (Table 5). The maximum average TAIP3 CV deviation of OPM3 against OPM7 during the campaign is below 0.6 ns peak to peak (Table 7). And the deviations of the resulting TAIP3 CV between calibrated receivers in common-clock set-up stays below 0.35 ns (Table 8). Therefore, we have decided to consider the following misclosures for all the conservative uncertainty budgets in this calibration campaign: 0.7 ns for INTDLY(P1), 0.8 ns for INTDLY(P2), and 0.8 ns for P3 CV in order to take into account the largest offset.

Because inside the Regional Metrology Organisation EURAMET the uncertainties have to be published as expanded uncertainties for k = 2 (95 %), we also provide such uncertainties obtained by a simple 2x expansion of the combined uncertainties.

Finally, “equation (2)” in the Tables below is referring to an equation in [RD5] which is about ΔSYSDLY(visited-reference):

$$\Delta SYSDLY_{V\text{-}R} = \Delta SYSDLY_{T\text{-}R} - \Delta SYSDLY_{T\text{-}V} \qquad (2)$$

where SYSDLY = INTDLY + CABDLY, and “V” for “visited”, “R” for “reference” and “T” for “traveling”.

### 12.2. Uncertainty budgets for SP receivers hardware delays.

Table 13 shows the uncertainty budgets for SP01 and Table 14 for SP02, computed according to the BIPM guidelines [RD5]. We obtain 1.2 ns for both SP01 and SP02 as P3 combined uncertainties. From the Group 1 / Group 2 relative calibration as proposed by BIPM and as agreed in the CCTF WG on GNSS, this computation proves that the agreed Group 2 uncertainty $u_{CAL0}$ = 2.5 ns can be applied to links using any of these receivers to the BIPM/TAI network.

***Table 13. SP01 uncertainty contributions (all values in ns).***

| Uncertainty | Value P1 | Value P2 | Value P1-P2 | Value P3 | Description |
|---|---|---|---|---|---|
| $u_a$ (OPM7-OPMT) | 0.063 | 0.069 | 0.093 | 0.162 | TDEV(1 d) |
| $u_a$ (OPM3-OPMT) | 0.067 | 0.071 | 0.098 | 0.167 | TDEV(1 d) |
| $u_a$ T-R | 0.065 | 0.070 | 0.096 | 0.165 | Average trav-reference |
| $u_a$ (OPM7-SP01) | 0.061 | 0.231 | 0.239 | 0.342 | TDEV(1 d) |
| $u_a$ (OPM3-SP01) | 0.067 | 0.237 | 0.248 | 0.314 | TDEV(1 d) |
| $u_a$ T-V | 0.068 | 0.234 | 0.244 | 0.328 | Average trav-visited |
| $u_a$ | 0.094 | 0.244 | 0.261 | 0.367 | Visited-reference |
| Misclosure | | | | | |
| $u_{b,1}$ | 0.7 | 0.8 | 0.1 | 0.8 | Observed Max misclosure |
| Systematic components related to RAWDIF | | | | | |
| $u_{b,11}$ | 0.05 | 0.05 | 0.05 | 0.05 | Position error at reference |
| $u_{b,12}$ | 0.05 | 0.05 | 0.05 | 0.05 | Position error at visited |
| $u_{b,13}$ | 0.05 | 0.05 | 0.05 | 0.05 | Multipaths at reference |
| $u_{b,14}$ | 0.05 | 0.05 | 0.05 | 0.05 | Multipaths at visited |
| Link of the Traveling system to the local UTC(k) | | | | | |
| $u_{b,21}$ | 0.220 | 0.220 | | 0.220 | REFDLY (at ref lab) |
| $u_{b,22}$ | 0.220 | 0.220 | | 0.220 | REFDLY (at visited lab) |
| $u_{b,TOT}$ | 0.773 | 0.864 | 0.141 | 0.864 | |
| Link of the Reference system to its local UTC(k) | | | | | |
| $u_{b,31}$ | 0.360 | 0.360 | | 0.360 | REFDLY (at ref lab) |
| Link of the Visited system to its local UTC(k) | | | | | |
| $u_{b,32}$ | 0.0 | 0.0 | | 0.0 | REFDLY (at visited lab) |
| Antenna cable delays | | | | | |
| $u_{b,41}$ | 0.5 | 0.5 | | 0.5 | CABDLY reference |
| $u_{b,42}$ | 0.0 | 0.0 | | 0.0 | CABDLY visit |
| $u_{b,SYS}$ | 0.988 | 1.061 | | 1.061 | Components of equation (2) |
| $u_{CAL0}$ | 0.992 | 1.065 | | 1.123 | Composed of ua and ub,SYS |

## *Table 14. SP02 uncertainty contributions (all values in ns).*

| Uncertainty | Value P1 | Value P2 | Value P1-P2 | Value P3 | Description |
|---|---|---|---|---|---|
| $u_a$ (OPM7-OPMT) | 0.063 | 0.069 | 0.093 | 0.162 | TDEV(1 d) |
| $u_a$ (OPM3-OPMT) | 0.067 | 0.071 | 0.098 | 0.167 | TDEV(1 d) |
| $u_a$ T-R | 0.065 | 0.070 | 0.096 | 0.165 | Average trav-reference |
| $u_a$ (OPM7-SP02) | 0.052 | 0.229 | 0.235 | 0.289 | TDEV(1 d) |
| $u_a$ (OPM3-SP02) | 0.067 | 0.230 | 0.240 | 0.349 | TDEV(1 d) |
| $u_a$ T-V | 0.059 | 0.230 | 0.237 | 0.319 | Average trav-visited |
| $u_a$ | 0.088 | 0.240 | 0.256 | 0.359 | Visited-reference |
| Misclosure | | | | | |
| $u_{b,1}$ | 0.7 | 0.8 | 0.1 | 0.8 | Observed Max misclosure |
| Systematic components related to RAWDIF | | | | | |
| $u_{b,11}$ | 0.05 | 0.05 | 0.05 | 0.05 | Position error at reference |
| $u_{b,12}$ | 0.05 | 0.05 | 0.05 | 0.05 | Position error at visited |
| $u_{b,13}$ | 0.05 | 0.05 | 0.05 | 0.05 | Multipaths at reference |
| $u_{b,14}$ | 0.05 | 0.05 | 0.05 | 0.05 | Multipaths at visited |
| Link of the Traveling system to the local UTC(k) | | | | | |
| $u_{b,21}$ | 0.220 | 0.220 | | 0.220 | REFDLY (at ref lab) |
| $u_{b,22}$ | 0.220 | 0.220 | | 0.220 | REFDLY (at visited lab) |
| $u_{b,TOT}$ | 0.773 | 0.864 | 0.141 | 0.864 | |
| Link of the Reference system to its local UTC(k) | | | | | |
| $u_{b,31}$ | 0.360 | 0.360 | | 0.360 | REFDLY (at ref lab) |
| Link of the Visited system to its local UTC(k) | | | | | |
| $u_{b,32}$ | 0.0 | 0.0 | | 0.0 | REFDLY (at visited lab) |
| Antenna cable delays | | | | | |
| $u_{b,41}$ | 0.5 | 0.5 | | 0.5 | CABDLY reference |
| $u_{b,42}$ | 0.0 | 0.0 | | 0.0 | CABDLY visit |
| $u_{b,SYS}$ | 0.988 | 1.061 | | 1.061 | Components of equation (2) |
| $u_{CAL0}$ | 0.992 | 1.065 | | 1.120 | Composed of ua and ub,SYS |

### 12.3. Uncertainty budgets for PTB receivers hardware delays.

Here follow the uncertainty budgets for PTBB, PT07 and PT10 computed according to the BIPM guidelines [RD5]. We obtain below 1.3 ns for all three receivers as P3 combined uncertainties. From the Group 1 / Group 2 relative calibration as proposed by BIPM and as agreed in the CCTF WG on GNSS, this computation might lead to the agreed Group 2 uncertainty $u_{CAL0}$ = 2.5 ns can be applied to links using any of these receivers to the BIPM/TAI network. But we also think that the final estimation should in some ways take into account the fluctuations we get from one calibration campaign to the other. However, we consider that this point should be discussed at CCTF WG on GNSS level.

***Table 15. PTBB uncertainty contributions (all values in ns).***

| Uncertainty | Value P1 | Value P2 | Value P1-P2 | Value P3 | Description |
|---|---|---|---|---|---|
| $u_a$ (OPM7-OPMT) | 0.063 | 0.069 | 0.093 | 0.162 | TDEV(1 d) |
| $u_a$ (OPM3-OPMT) | 0.067 | 0.071 | 0.098 | 0.167 | TDEV(1 d) |
| $u_a$ T-R | 0.065 | 0.070 | 0.096 | 0.165 | Average trav-reference |
| $u_a$ (OPM7-PTBB) | 0.034 | 0.051 | 0.061 | 0.126 | TDEV(1 d) |
| $u_a$ (OPM3-PTBB) | 0.067 | 0.053 | 0.064 | 0.125 | TDEV(1 d) |
| $u_a$ T-V | 0.035 | 0.052 | 0.063 | 0.126 | Average trav-visited |
| $u_a$ | 0.074 | 0.087 | 0.114 | 0.208 | Visited-reference |
| Misclosure | | | | | |
| $u_{b,1}$ | 0.7 | 0.8 | 0.1 | 0.8 | Observed Max misclosure |
| Systematic components related to RAWDIF | | | | | |
| $u_{b,11}$ | 0.05 | 0.05 | 0.05 | 0.05 | Position error at reference |
| $u_{b,12}$ | 0.05 | 0.05 | 0.05 | 0.05 | Position error at visited |
| $u_{b,13}$ | 0.05 | 0.05 | 0.05 | 0.05 | Multipaths at reference |
| $u_{b,14}$ | 0.05 | 0.05 | 0.05 | 0.05 | Multipaths at visited |
| Link of the Traveling system to the local UTC(k) | | | | | |
| $u_{b,21}$ | 0.220 | 0.220 | | 0.220 | REFDLY (at ref lab) |
| $u_{b,22}$ | 0.220 | 0.220 | | 0.220 | REFDLY (at visited lab) |
| $u_{b,TOT}$ | 0.773 | 0.864 | 0.141 | 0.864 | |
| Link of the Reference system to its local UTC(k) | | | | | |
| $u_{b,31}$ | 0.360 | 0.360 | | 0.360 | REFDLY (at ref lab) |
| Link of the Visited system to its local UTC(k) | | | | | |
| $u_{b,32}$ | 0.360 | 0.360 | | 0.360 | REFDLY (at visited lab) |
| Antenna cable delays | | | | | |
| $u_{b,41}$ | 0.5 | 0.5 | | 0.5 | CABDLY reference |
| $u_{b,42}$ | 0.5 | 0.5 | | 0.5 | CABDLY visit |
| $u_{b,SYS}$ | 1.165 | 1.227 | | 1.227 | Components of equation (2) |
| $u_{CAL0}$ | 1.167 | 1.229 | | 1.245 | Composed of ua and ub,SYS |

### *Table 16. PT07 uncertainty contributions (all values in ns).*

| Uncertainty | Value P1 | Value P2 | Value P1-P2 | Value P3 | Description |
|---|---|---|---|---|---|
| $u_a$ (OPM7-OPMT) | 0.063 | 0.069 | 0.093 | 0.162 | TDEV(1 d) |
| $u_a$ (OPM3-OPMT) | 0.067 | 0.071 | 0.098 | 0.167 | TDEV(1 d) |
| $u_a$T-R | 0.065 | 0.070 | 0.096 | 0.165 | Average trav-reference |
| $u_a$ (OPM7-PT07) | 0.044 | 0.050 | 0.067 | 0.128 | TDEV(1 d) |
| $u_a$ (OPM3-PT07) | 0.067 | 0.054 | 0.071 | 0.117 | TDEV(1 d) |
| $u_a$ T-V | 0.045 | 0.052 | 0.069 | 0.122 | Average trav-visited |
| $u_a$ | 0.079 | 0.087 | 0.118 | 0.205 | Visited-reference |
| Misclosure | | | | | |
| $u_{b,1}$ | 0.7 | 0.8 | 0.1 | 0.8 | Observed Max misclosure |
| Systematic components related to RAWDIF | | | | | |
| $u_{b,11}$ | 0.05 | 0.05 | 0.05 | 0.05 | Position error at reference |
| $u_{b,12}$ | 0.05 | 0.05 | 0.05 | 0.05 | Position error at visited |
| $u_{b,13}$ | 0.05 | 0.05 | 0.05 | 0.05 | Multipaths at reference |
| $u_{b,14}$ | 0.05 | 0.05 | 0.05 | 0.05 | Multipaths at visited |
| Link of the Traveling system to the local UTC(k) | | | | | |
| $u_{b,21}$ | 0.220 | 0.220 | | 0.220 | REFDLY (at ref lab) |
| $u_{b,22}$ | 0.220 | 0.220 | | 0.220 | REFDLY (at visited lab) |
| $u_{b,TOT}$ | 0.773 | 0.864 | 0.141 | 0.864 | |
| Link of the Reference system to its local UTC(k) | | | | | |
| $u_{b,31}$ | 0.360 | 0.360 | | 0.360 | REFDLY (at ref lab) |
| Link of the Visited system to its local UTC(k) | | | | | |
| $u_{b,32}$ | 0.200 | 0.200 | | 0.200 | REFDLY (at visited lab) |
| Antenna cable delays | | | | | |
| $u_{b,41}$ | 0.5 | 0.5 | | 0.5 | CABDLY reference |
| $u_{b,42}$ | 0.5 | 0.5 | | 0.5 | CABDLY visit |
| $u_{b,SYS}$ | 1.126 | 1.190 | | 1.190 | Components of equation (2) |
| $u_{CAL0}$ | 1.129 | 1.193 | | 1.208 | Composed of ua and ub,SYS |

## *Table 17. PT10 uncertainty contributions (all values in ns).*

| Uncertainty | Value P1 | Value P2 | Value P1-P2 | Value P3 | Description |
|---|---|---|---|---|---|
| $u_a$ (OPM7-OPMT) | 0.063 | 0.069 | 0.093 | 0.162 | TDEV(1 d) |
| $u_a$ (OPM3-OPMT) | 0.067 | 0.071 | 0.098 | 0.167 | TDEV(1 d) |
| $u_a$ T-R | 0.065 | 0.070 | 0.096 | 0.165 | Average trav-reference |
| $u_a$ (OPM7-PT10) | 0.050 | 0.071 | 0.087 | 0.198 | TDEV(1 d) |
| $u_a$ (OPM3-PT10) | 0.067 | 0.073 | 0.093 | 0.179 | TDEV(1 d) |
| $u_a$ T-V | 0.054 | 0.072 | 0.090 | 0.189 | Average trav-visited |
| $u_a$ | 0.085 | 0.100 | 0.131 | 0.251 | Visited-reference |
| Misclosure | | | | | |
| $u_{b,1}$ | 0.7 | 0.8 | 0.1 | 0.8 | Observed Max misclosure |
| Systematic components related to RAWDIF | | | | | |
| $u_{b,11}$ | 0.05 | 0.05 | 0.05 | 0.05 | Position error at reference |
| $u_{b,12}$ | 0.05 | 0.05 | 0.05 | 0.05 | Position error at visited |
| $u_{b,13}$ | 0.05 | 0.05 | 0.05 | 0.05 | Multipaths at reference |
| $u_{b,14}$ | 0.05 | 0.05 | 0.05 | 0.05 | Multipaths at visited |
| Link of the Traveling system to the local UTC(k) | | | | | |
| $u_{b,21}$ | 0.220 | 0.220 | | 0.220 | REFDLY (at ref lab) |
| $u_{b,22}$ | 0.220 | 0.220 | | 0.220 | REFDLY (at visited lab) |
| $u_{b,TOT}$ | 0.773 | 0.864 | 0.141 | 0.864 | |
| Link of the Reference system to its local UTC(k) | | | | | |
| $u_{b,31}$ | 0.360 | 0.360 | | 0.360 | REFDLY (at ref lab) |
| Link of the Visited system to its local UTC(k) | | | | | |
| $u_{b,32}$ | 0.200 | 0.200 | | 0.200 | REFDLY (at visited lab) |
| Antenna cable delays | | | | | |
| $u_{b,41}$ | 0.5 | 0.5 | | 0.5 | CABDLY reference |
| $u_{b,42}$ | 0.5 | 0.5 | | 0.5 | CABDLY visit |
| $u_{b,SYS}$ | 1.126 | 1.190 | | 1.190 | Components of equation (2) |
| $u_{CAL0}$ | 1.129 | 1.193 | | 1.216 | Composed of ua and ub,SYS |

### 12.4. Uncertainty budgets for INRIM receivers hardware delays.

Here follow the uncertainty budgets for IENG, GTRB, GTRI and INR7 computed according to the BIPM guidelines [RD5]. We obtain below 1.3 ns for all four receivers as P3 combined uncertainties. From the Group 1 / Group 2 relative calibration as proposed by BIPM and as agreed in the CCTF WG on GNSS, this computation might lead to the agreed Group 2 uncertainty $u_{CAL0}$ = 2.5 ns can be applied to links using any of these receivers to the BIPM/TAI network. But again, we also think that the final estimation should in some ways take into account the fluctuations we get from one calibration campaign to the other, such a computation remaining to be discussed at WG level.

***Table 18. IENG uncertainty contributions (all values in ns).***

| Uncertainty | Value P1 | Value P2 | Value P1-P2 | Value P3 | Description |
|---|---|---|---|---|---|
| $u_a$ (OPM7-OPMT) | 0.063 | 0.069 | 0.093 | 0.162 | TDEV(1 d) |
| $u_a$ (OPM3-OPMT) | 0.067 | 0.071 | 0.098 | 0.167 | TDEV(1 d) |
| $u_a$ T-R | 0.065 | 0.070 | 0.096 | 0.165 | Average trav-reference |
| $u_a$ (OPM7-IENG) | 0.034 | 0.044 | 0.056 | 0.154 | TDEV(1 d) |
| $u_a$ (OPM3-IENG) | 0.067 | 0.049 | 0.063 | 0.177 | TDEV(1 d) |
| $u_a$ T-V | 0.037 | 0.046 | 0.059 | 0.165 | Average trav-visited |
| $u_a$ | 0.075 | 0.084 | 0.113 | 0.233 | Visited-reference |
| Misclosure | | | | | |
| $u_{b,1}$ | 0.7 | 0.8 | 0.1 | 0.8 | Observed Max misclosure |
| Systematic components related to RAWDIF | | | | | |
| $u_{b,11}$ | 0.05 | 0.05 | 0.05 | 0.05 | Position error at reference |
| $u_{b,12}$ | 0.05 | 0.05 | 0.05 | 0.05 | Position error at visited |
| $u_{b,13}$ | 0.05 | 0.05 | 0.05 | 0.05 | Multipaths at reference |
| $u_{b,14}$ | 0.05 | 0.05 | 0.05 | 0.05 | Multipaths at visited |
| Link of the Traveling system to the local UTC(k) | | | | | |
| $u_{b,21}$ | 0.220 | 0.220 | | 0.220 | REFDLY (at ref lab) |
| $u_{b,22}$ | 0.220 | 0.220 | | 0.220 | REFDLY (at visited lab) |
| $u_{b,TOT}$ | 0.773 | 0.864 | 0.141 | 0.864 | |
| Link of the Reference system to its local UTC(k) | | | | | |
| $u_{b,31}$ | 0.360 | 0.360 | | 0.360 | REFDLY (at ref lab) |
| Link of the Visited system to its local UTC(k) | | | | | |
| $u_{b,32}$ | 0.360 | 0.360 | | 0.360 | REFDLY (at visited lab) |
| Antenna cable delays | | | | | |
| $u_{b,41}$ | 0.5 | 0.5 | | 0.5 | CABDLY reference |
| $u_{b,42}$ | 0.5 | 0.5 | | 0.5 | CABDLY visit |
| $u_{b,SYS}$ | 1.165 | 1.227 | | 1.227 | Components of equation (2) |
| $u_{CAL0}$ | 1.167 | 1.229 | | 1.249 | Composed of ua and ub,SYS |

### *Table 19. GTRB uncertainty contributions (all values in ns).*

| Uncertainty | Value P1 | Value P2 | Value P1-P2 | Value P3 | Description |
|---|---|---|---|---|---|
| $u_a$ (OPM7-OPMT) | 0.063 | 0.069 | 0.093 | 0.162 | TDEV(1 d) |
| $u_a$ (OPM3-OPMT) | 0.067 | 0.071 | 0.098 | 0.167 | TDEV(1 d) |
| $u_a$ T-R | 0.065 | 0.070 | 0.096 | 0.165 | Average trav-reference |
| $u_a$ (OPM7-GTRB) | 0.039 | 0.052 | 0.065 | 0.185 | TDEV(1 d) |
| $u_a$ (OPM3-GTRB) | 0.067 | 0.051 | 0.063 | 0.177 | TDEV(1 d) |
| $u_a$ T-V | 0.038 | 0.051 | 0.064 | 0.181 | Average trav-visited |
| $u_a$ | 0.075 | 0.087 | 0.115 | 0.245 | Visited-reference |
| Misclosure | | | | | |
| $u_{b,1}$ | 0.7 | 0.8 | 0.1 | 0.8 | Observed Max misclosure |
| Systematic components related to RAWDIF | | | | | |
| $u_{b,11}$ | 0.05 | 0.05 | 0.05 | 0.05 | Position error at reference |
| $u_{b,12}$ | 0.05 | 0.05 | 0.05 | 0.05 | Position error at visited |
| $u_{b,13}$ | 0.05 | 0.05 | 0.05 | 0.05 | Multipaths at reference |
| $u_{b,14}$ | 0.05 | 0.05 | 0.05 | 0.05 | Multipaths at visited |
| Link of the Traveling system to the local UTC(k) | | | | | |
| $u_{b,21}$ | 0.220 | 0.220 | | 0.220 | REFDLY (at ref lab) |
| $u_{b,22}$ | 0.220 | 0.220 | | 0.220 | REFDLY (at visited lab) |
| $u_{b,TOT}$ | 0.773 | 0.864 | 0.141 | 0.864 | |
| Link of the Reference system to its local UTC(k) | | | | | |
| $u_{b,31}$ | 0.360 | 0.360 | | 0.360 | REFDLY (at ref lab) |
| Link of the Visited system to its local UTC(k) | | | | | |
| $u_{b,32}$ | 0.200 | 0.200 | | 0.200 | REFDLY (at visited lab) |
| Antenna cable delays | | | | | |
| $u_{b,41}$ | 0.5 | 0.5 | | 0.5 | CABDLY reference |
| $u_{b,42}$ | 0.5 | 0.5 | | 0.5 | CABDLY visit |
| $u_{b,SYS}$ | 1.126 | 1.190 | | 1.190 | Components of equation (2) |
| $u_{CAL0}$ | 1.128 | 1.192 | | 1.215 | Composed of ua and ub,SYS |

***Table 20. GTRI uncertainty contributions (all values in ns).***

| Uncertainty | Value P1 | Value P2 | Value P1-P2 | Value P3 | Description |
|---|---|---|---|---|---|
| $u_a$ (OPM7-OPMT) | 0.063 | 0.069 | 0.093 | 0.162 | TDEV(1 d) |
| $u_a$ (OPM3-OPMT) | 0.067 | 0.071 | 0.098 | 0.167 | TDEV(1 d) |
| $u_a$ T-R | 0.065 | 0.070 | 0.096 | 0.165 | Average trav-reference |
| $u_a$ (OPM7-GTRI) | 0.053 | 0.052 | 0.074 | 0.167 | TDEV(1 d) |
| $u_a$ (OPM3-GTRI) | 0.067 | 0.049 | 0.068 | 0.176 | TDEV(1 d) |
| $u_a$ T-V | 0.050 | 0.051 | 0.071 | 0.171 | Average trav-visited |
| $u_a$ | 0.082 | 0.087 | 0.120 | 0.238 | Visited-reference |
| Misclosure | | | | | |
| $u_{b,1}$ | 0.7 | 0.8 | 0.1 | 0.8 | Observed Max misclosure |
| Systematic components related to RAWDIF | | | | | |
| $u_{b,11}$ | 0.05 | 0.05 | 0.05 | 0.05 | Position error at reference |
| $u_{b,12}$ | 0.05 | 0.05 | 0.05 | 0.05 | Position error at visited |
| $u_{b,13}$ | 0.05 | 0.05 | 0.05 | 0.05 | Multipaths at reference |
| $u_{b,14}$ | 0.05 | 0.05 | 0.05 | 0.05 | Multipaths at visited |
| Link of the Traveling system to the local UTC(k) | | | | | |
| $u_{b,21}$ | 0.220 | 0.220 | | 0.220 | REFDLY (at ref lab) |
| $u_{b,22}$ | 0.220 | 0.220 | | 0.220 | REFDLY (at visited lab) |
| $u_{b,TOT}$ | 0.773 | 0.864 | 0.141 | 0.864 | |
| Link of the Reference system to its local UTC(k) | | | | | |
| $u_{b,31}$ | 0.360 | 0.360 | | 0.360 | REFDLY (at ref lab) |
| Link of the Visited system to its local UTC(k) | | | | | |
| $u_{b,32}$ | 0.200 | 0.200 | | 0.200 | REFDLY (at visited lab) |
| Antenna cable delays | | | | | |
| $u_{b,41}$ | 0.5 | 0.5 | | 0.5 | CABDLY reference |
| $u_{b,42}$ | 0.5 | 0.5 | | 0.5 | CABDLY visit |
| $u_{b,SYS}$ | 1.126 | 1.190 | | 1.190 | Components of equation (2) |
| $u_{CAL0}$ | 1.129 | 1.193 | | 1.214 | Composed of ua and ub,SYS |

### *Table 21. INR7 uncertainty contributions (all values in ns).*

| Uncertainty | Value P1 | Value P2 | Value P1-P2 | Value P3 | Description |
|---|---|---|---|---|---|
| $u_a$ (OPM7-OPMT) | 0.063 | 0.069 | 0.093 | 0.162 | TDEV(1 d) |
| $u_a$ (OPM3-OPMT) | 0.067 | 0.071 | 0.098 | 0.167 | TDEV(1 d) |
| $u_a$ T-R | 0.065 | 0.070 | 0.096 | 0.165 | Average trav-reference |
| $u_a$ (OPM7-INR7) | 0.034 | 0.042 | 0.054 | 0.197 | TDEV(1 d) |
| $u_a$ (OPM3-INR7) | 0.067 | 0.042 | 0.060 | 0.149 | TDEV(1 d) |
| $u_a$ T-V | 0.038 | 0.042 | 0.057 | 0.173 | Average trav-visited |
| $u_a$ | 0.075 | 0.082 | 0.111 | 0.239 | Visited-reference |
| Misclosure | | | | | |
| $u_{b,1}$ | 0.7 | 0.8 | 0.1 | 0.8 | Observed Max misclosure |
| Systematic components related to RAWDIF | | | | | |
| $u_{b,11}$ | 0.05 | 0.05 | 0.05 | 0.05 | Position error at reference |
| $u_{b,12}$ | 0.05 | 0.05 | 0.05 | 0.05 | Position error at visited |
| $u_{b,13}$ | 0.05 | 0.05 | 0.05 | 0.05 | Multipaths at reference |
| $u_{b,14}$ | 0.05 | 0.05 | 0.05 | 0.05 | Multipaths at visited |
| Link of the Traveling system to the local UTC(k) | | | | | |
| $u_{b,21}$ | 0.220 | 0.220 | | 0.220 | REFDLY (at ref lab) |
| $u_{b,22}$ | 0.220 | 0.220 | | 0.220 | REFDLY (at visited lab) |
| $u_{b,TOT}$ | 0.773 | 0.864 | 0.141 | 0.864 | |
| Link of the Reference system to its local UTC(k) | | | | | |
| $u_{b,31}$ | 0.360 | 0.360 | | 0.360 | REFDLY (at ref lab) |
| Link of the Visited system to its local UTC(k) | | | | | |
| $u_{b,32}$ | 0.220 | 0.220 | | 0.220 | REFDLY (at visited lab) |
| Antenna cable delays | | | | | |
| $u_{b,41}$ | 0.5 | 0.5 | | 0.5 | CABDLY reference |
| $u_{b,42}$ | 0.5 | 0.5 | | 0.5 | CABDLY visit |
| $u_{b,SYS}$ | 1.129 | 1.194 | | 1.194 | Components of equation (2) |
| $u_{CAL0}$ | 1.131 | 1.196 | | 1.218 | Composed of ua and ub,SYS |

### 12.5. OPMT stability during the campaign.

In order to try to assess the stability of the reference receiver for this campaign, OPMT, we propose a plot of the differences between GPS CV and TWSTFT on the link between UTC(OP) and UTC(PTB) during the same period of time, based on the data files transmitted formally by both laboratories to BIPM. The GPS receivers are OPMT in OP and PTBB in PTB, respectively. Over the TVF calibration campaign period, we observe an average difference between the two techniques of about – 1.79 ns, with a standard deviation of about 0.74 ns, after suppression of 11 outliers. However, a drift of about 7 ps/d can be detected in the plot, but we cannot discriminate between the two techniques which one to blame (if any).

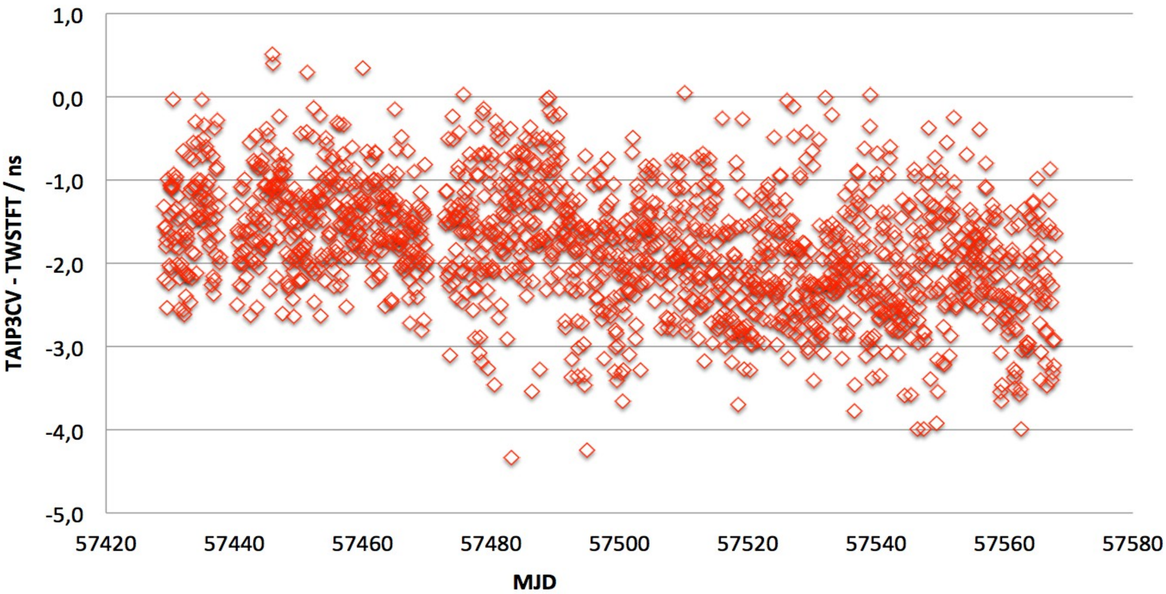


***Figure 2. Differences between UTC(PTB) and UTC(OP) as obtained from averaged TAIP3 CV by using OPMT and PTBB (as provided to BIPM), and UTC(PTB) – UTC(OP) as obtained from TWSTFT.***

The average deviation stays in line with the estimated uncertainties as published by BIPM in its Circular T and inside the CCTF Working Groups for relative calibration activities: by taking $u_{CAL}$ = 1.0 ns for the TWSTFT link between OP and PTB, plus the agreed conventional uncertainty $u_{CAL}$ = 1.7 ns for the P3 link calibration between OP and PTB as Group 1 laboratories, one obtains as quadratic sum $u_{Diff}$ = 1.97 ns. Therefore, we decided to consider no effect from OPMT in the calibration uncertainty computations, OPMT having remained stable enough during the whole TVF calibration campaign. What remains to be investigated is the offset between GPS CV and TWSTFT together with the long term drift that many laboratories are observing. But this goes far beyond this Calibration Report: this investigation was devoted since last year to a Task Group inside the CCTF WG on TWSTFT.

## 13. Final results.

Table 22 is providing the final results of this calibration campaign, following the [RD6] requirements. In addition, Table 23 is providing the computed conservative k = 2 expanded uncertainties in order to be in line with EURAMET recommendations.

***Table 22. Summary information on the calibration trip (all values in ns).***

| **Reference system** | **Cal Id** | **Date** | | **INTDLY(P1)** | **INTDLY(P2)** |
|---|---|---|---|---|---|
| OPMT | *1001-2014* | 2015.4 | | 310.2 | 321.6 |
| **Visited system** | **Cal Id** | **Date** | **$u_{CAL}$(P3)** | **INTDLY(P1)** | **INTDLY(P2)** |
| SP01 | *1013-2016* *** | 2016.2 | 1.2 | 235.2 * | 246.7 * |
| SP02 | *1013-2016* *** | 2016.2 | 1.2 | 236.8 * | 245.2 * |
| PTBB | *1013-2016* *** | 2016.3 | 1.3 | 305.6 | 320.6 |
| PT07 | *1013-2016* *** | 2016.3 | 1.3 | - 35.6 | - 23.2 |
| PT10 | *1013-2016* *** | 2016.3 | 1.3 | - 38.9 | - 45.6 |
| IENG | *1013-2016* *** | 2016.3 | 1.3 | 309.6 | 319.6 |
| GTRB | *1013-2016* *** | 2016.4 | 1.3 | - 33.7 | - 20.2 |
| GTRI | *1013-2016* *** | 2016.4 | 1.3 | - 142.5 | - 130.6 |
| INR7 | *1013-2016* *** | 2016.4 | 1.3 | 230.9 ** | 231.8 ** |

* Reference delay and antenna cable delay included: REFDLY = 0.0 ns, CABDLY = 0.0 ns.

** Antenna cable delay included: CABDLY = 0.0 ns.

*** Please see Annex D of this report for updated values of the delays appearing inside this Table.

***Table 23. Conservative k = 2 expanded uncertainties for all receivers involved with OPMT as reference following the EURAMET standards (in ns).***

| **Expanded uncertainty [k = 2]** | | **u(P1)** | **u(P2)** | **u(P3)** |
|---|---|---|---|---|
| **SP** | **SP01** | 2.0 | 2.2 | 2.3 |
| | **SP02** | 2.0 | 2.2 | 2.3 |
| **PTB** | **PTBB** | 2.4 | 2.5 | 2.5 |
| | **PT07** | 2.3 | 2.4 | 2.5 |
| | **PT10** | 2.3 | 2.4 | 2.5 |
| **INRiM** | **IENG** | 2.4 | 2.5 | 2.5 |
| | **GTRB** | 2.3 | 2.4 | 2.5 |
| | **GTRI** | 2.3 | 2.4 | 2.5 |
| | **INR7** | 2.3 | 2.4 | 2.5 |

We eventually obtain typical uncertainty values as results for this relative calibration campaign. But, again, we would suggest that the offsets seen between different campaigns should at some point be considered into such computations.

## 14. Application of the 2016 calibrated delays.

In this Section, we propose to consider what would be the consequences for the GPS CV data when applying the results of this calibration campaign. From the different periods of calibration in each laboratory site, the following Figure shows the TAIP3 CV between the CGGTTS files generated by OP after implementation of the 2016 calibrated delays and the CGGTTS files as they were provided by the laboratories with the former calibrated delays either directly to OP or to BIPM. Here, we used as "old" files the INRIM files which were provided to OP directly, which might be different from the ones provided to BIPM, the SP files provided to BIPM, and the PTB files directly provided to OP by PTB during this campaign.

Note that for the CV computations here we do not use the same basic software we developed for the calibration computations. Among other changes, the averaging out of the outliers is handled very differently [RD8]. Because we also use the newly computed antenna coordinates, and because the parameter files are built with delays expressed in 0.1 ns, we are building CGGTTS files which are slightly different from what we would get by simply adding a P3 constant offset to the "old" files built elsewhere. This is why some results below might slightly differ from the ones provided in Table 11.

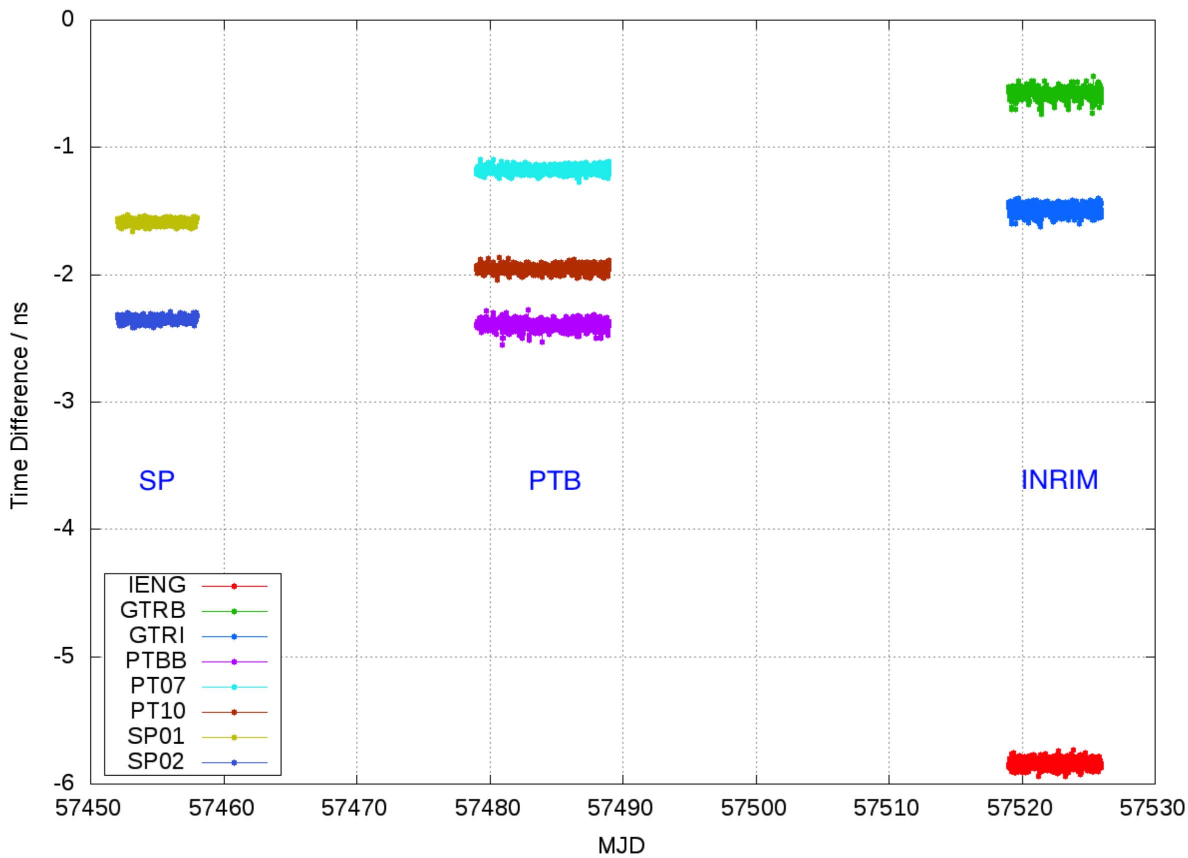


***Figure 3. TAIP3 CV between CGGTTS files computed by using the 2016 calibrated delays and CGGTTS files computed from former calibrations.***

In addition, we provide in Table 24 below the mean values and the standard deviations computed from the plotted CV. Applying the 2016 calibrated delays to the receivers located in each site would result in these TAIP3 CV average offsets for GPS time transfer inside the TAI network. We can see from Figure 3 and from Table 24 that all TAIP3 CV are within the expanded uncertainties listed in Table 23, except IENG: this receiver is clearly an outlier here. We also note from Table 24 that all standard deviations are below 41 ps. These results are showing that there is nothing unexpected in this validation computation when comparing newly generated CGGTTS files to what was obtained with some former parameters.

***Table 24. Mean values and standard deviations of the CV between CGGTTS files computed by using the 2016 calibrated delays and CGGTTS files computed from former calibrations (all values in ns).***

| TAIP3 CV | Mean values | Standard deviations | ∆P3 |
|---|---|---|---|
| SP01_2016 - SP01_BIPM | - 1.590 | 0.019 | 1.6 |
| SP02_2016 - SP02_BIPM | - 2.353 | 0.020 | 2.3 |
| PTBB_2016 - PT02_FromLab | - 2.395 | 0,033 | 2.2 |
| PT07_2016 - PT07_FromLab | - 1.177 | 0.024 | 0.9 |
| PT10_2016 - PT10_FromLab | - 1.955 | 0.026 | 1.9 |
| IENG_2016 - ITZ2_FromLab | - 5.839 | 0.032 | 4.2 |
| GTRB_2016 - GTRB_TVF | - 0.578 | 0.041 | 0.7 |
| GTRI_2016 - GTRI_TVF | - 1.495 | 0.036 | 1.4 |
| INR7_2016 - INR7_FromLab | No former data available | | |

Nevertheless, the consistency in Figure 3 of the offset positions for all receivers involved (except IENG) seems to indicate that a common part of this offset might be due to the reference receiver for this campaign OPMT. However, we assume that the OPMT position during the calibration campaign might have been staying within the GPS – TWSTFT average offset discussed in Section 12.5. This should allow for a proper consideration of the resulting calibrated delays for the receivers involved in this campaign, in order to apply some sort of a "clean start" after the implementation in 2015 of the BIPM Group1 first calibration results in OP, PTB and ROA. But because clear offsets are obtained for some local receivers, we have investigated in more details the OP-PTB link in Annex D. This eventually led to updated results for this calibration campaign.

## 15. Conclusion and perspectives.

During this relative calibration campaign, the LNE-SYRTE/OP traveling equipment behaved very well. We nevertheless recommend to empty the memory of a PolaRx4 unit before starting such a calibration trip in order to avoid instabilities we had observed formerly on some Septentrio receivers. The use of two main units for such an activity proved valuable again, because it allowed to detect some effects which would have remained undercover otherwise. The Guidelines type information sheets are provided inside Annex A for all receivers involved.

The misclosure or the reproducibility estimation, which is typically the largest term in the uncertainty budgets, remained sub-ns: the OP traveling equipment proved very stable during the campaign. We have obtained calibrated delays within uncertainties which are close to the state of the art in that matter, which is an excellent achievement. Nevertheless, there are clear offsets between the results obtained during this campaign and the current delays used by the laboratories, leading to some resulting P3 offsets significantly larger than the conventional uncertainty in the TAI network. Therefore, we would suggest first that the offsets between successive calibration campaign results be taken into account for the final estimation of the related uncertainties, and second that the visited laboratories should decide whether to implement the calibrated delays or not for their own receivers.

In particular, the resulting offsets we obtained on PTBB P3 computations are clearly questioning the uncertainty budgets. Originally, we did not think that such offsets were related to any significant changes in the campaign reference receiver OPMT during the calibration campaign since the implementation of the BIPM #1001-2014 delays. From differences against other receiving chains we have been able to build, we can see that OPMT position is significantly changing from times to times. But when looking either at the offset between GPS CV and TWSTFT on the OP-PTB link or at the offsets against other GPS receiving chains from the data available in OP, it was not so easy to conclude.

Therefore, we analysed the OP-PTB link in more details in Annex D. This eventually led to update delays for SP and INRIM receivers, which are provided in Table 1 of this report, and which are to be considered as the formal results of the LNE-SYRTE 1013-2016 G1/G2 calibration campaign. We recommend to use these updated delays for all receivers calibrated by LNE-SYRTE/OP in 2016.

## 16. Acknowledgements.

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## 17. Annexes.

## Annex A: BIPM type information sheets.

This Annex contains all the Informations sheets of the visited sites, filled in according to [RD6]. It is provided in a separate file.

Note that all hardware delays and antenna coordinates are issued from the calibration computations. In the case such parameters as they were before this calibration report would be needed, please refer to the Header of a related CGGTTS file for a MJD up to the campaign dates on each site.

## Annex B: Plots of raw data and TDEV analysis.

This Annex contains all the plots of the P1 and P2 differences for each site, together with the related TDEV, and the P3 CV after application of the calibrated delays, together with the related TDEV. It is provided in a separate file.

## Annex C: List of OP traveling equipment.

### OP TRAVELING EQUIPMENT LIST

| | | |
|---|---|---|
| Transport box | 1x | 60x60x40 cm, ≈ 40 kg |
| Distribution line 5 sockets | 1x | |
| Power cable | 1x | 10 m |
| Septentrio PolaRx4 | OPM3 | S/N 3102285 |
| Septentrio PolaRx4 | OPM7 | S/N 3001164 |
| Set of power and Ethernet Septentrio cables | 2x | |
| Septentrio power unit | 2x | |
| Stanford SR620 | 1x | S/N 4981 |
| Ethernet hub | 1x | |
| Ethernet hub power unit | 1x | |
| Ethernet cable | 1x | |
| HP Laptop | 1x | "HP640-RNT" |
| HP power unit | 1x | |
| USB key | 1x | |
| Plastic bubble protection | 1x | For laptop |
| Ashtech choke-ring antenna | 1x | S/N 6200828009 |
| Antenna metallic support | 1x | Including 1 small screw |
| Green foam pouch | 1x | For the antenna support |
| Power splitter + two short antenna cables | 1x | |
| Antenna cable HY 400 UF | 1x | 50 m long |
| BNC cables | 8x | 2x 2m, 3x 3 m, 2x 5 m, 2x 10 m long |
| BNC-BNC connectors | 4x | I |
| BNC-SMA adaptors | 3x | |
| Attenuators – 3 dB | 2x | |
| Attenuators – 6 dB | 2x | |
| Small plastic rings | many | |
| Cardboard separation | 1x | |
| Foam protection | many | |

# Annex D: Technical note about the use of OPMT 1001-2016 delays.

## 1. Introduction.

Following the G1 calibration report 1001-2016 issued by BIPM at the end of 2016 [RD9, RD10], we noted that the INTDLY(P1) and INTDLY(P2) of the reference receiver used by the LNE-SYRTE for 2016 relative calibration campaigns, OPMT, were exhibiting significant offsets against the former BIPM G1 1001-2014 campaign [RD7, RD11]. According to BIPM request, these new delays were introduced on February 2, 2017, leading to a ΔP3 offset of about – 2.0 ns for OPMT data. This issue is discussed in Section 2. We therefore decided to generate an updated delay computation for all the receivers involved in the G1/G2 campaign achieved in 2016. The results are presented in Section 3.

## 2. Offsets between BIPM 1001-2014 and BIPM 1001-2016 OPMT delays.

All LNE-SYRTE calibration campaigns achieved in 2016 were using OPMT as reference receiver. The OPMT INTDLY(P1) and INTDLY(P2) values used for all computations were issued from the BIPM first Group 1 calibration 1001-2014 released in 2015 [RD7, RD11]. But after release of the second Group 1 calibration report from BIPM 1001-2016 [RD9, RD10]. we noted that the OPMT INTDLY(P1) and INTDLY(P2) were exhibiting significant offsets against the former BIPM G1 campaign. We obtained the following offsets:

$$\Delta P1[2016 - 2014] = - 1.2 \text{ ns} \qquad \Delta P2[2016 - 2014] = - 0.7 \text{ ns}$$

According to P3 = P1 + 1.546 x (P1 – P2), such delays are leading to the following ΔP3 offset:

$$\Delta P3[2016 - 2014] = - 2.0 \text{ ns}$$

With the ΔP3 similarly computed offset of 0.7 ns for PTBB receiver, this is leading to an offset of about - 2.7 ns on the OP-PTB link potentially used for TAI computation, based on OPMT – PTBB offset. This result is clearly larger than the conventional TAI link combined uncertainty either of 1.7 ns for G1 receivers or even of 2.5 ns for G2 receivers. Therefore, we consider that the LNE-SYRTE 2016 calibrated delays for remote laboratories might lead to P3 link delay offsets which might be significantly biased.

This OPMT ΔP3 offset is also appearing consistent with the Figure 3 in Section 14 of this report, where we see that a significant number of receivers are exhibiting a ΔP3 offset close to – 2 ns when using the OPMT delays based on the BIPM G1 1001-2014 results for calibration computations.

Moreover, because different calibration campaigns have been taking place from Spring 2015 to Winter 2016, it was possible to get some additional consistency on the current G1 results on the OP-PTB link. Indeed, the OPMT – PTBB relative offset on the OP-PTB link was obtained from:

– BIPM2014: BIPM G1 1001-2014 relative calibration campaign in April-May 2015

[RD7, RD11]

- NIST2015: NIST relative calibration during a NIST-OP-PTB campaign in September-October 2015 [draft report not public yet];
- OP2015: OP relative calibration during a NIST-OP-PTB campaign in September 2015 [draft report not public yet];
- OP2016: OP relative calibration during the Galileo TVF campaign and used also for G1/G2 calibration [this report];
- BIPM2016: BIPM G1 1001-2016 relative calibration in November-December 2016 [RD9, RD10].

The Table 1 below is providing the computed offsets among these five independent campaigns for the link OP-PTB [*warning: the values are computed for PTBB – OPMT, not OPMT - PTBB*]. We clearly see that, even if the offset between BIPM consecutive G1 campaigns is larger than the TAI conventional combined uncertainty, other OP campaign results in-between are closer to the last BIPM G1 results than to the former one. We assume that the largest part of this offset between BIPM2014 and BIPM2016 is due to OPMT. We therefore think that there would be better consistency for both receivers involved on this link, OPMT and PTBB, when going backwards from the last BIPM G1 campaign and when covering the period of the G1/G2 campaign achieved by LNE-SYRTE/OP in 2016.

Table 1. PTBB - OPMT code delay offsets between all estimations from consecutive calibration campaigns. (all units in ns).

| **PTBB - OPMT** | **ΔP1** | **ΔP2** | **ΔP3** |
|---|---|---|---|
| Difference NIST 2015 – BIPM 2014 | 3.6 | 3.0 | 4.6 |
| Difference NIST 2015 – OP 2016 | 2.0 | 1.7 | 2.4 |
| Difference OP 2015 – BIPM 2014 | 2.0 | 1.3 | 3.1 |
| Difference OP 2015 – NIST 2015 | - 1.6 | - 1.6 | - 1.5 |
| **Difference OP 2016 – BIPM 2014** | **1.6** | **1.3** | **2.2** |
| Difference OP 2016 – OP 2015 | - 0.4 | 0.0 | - 0.9 |
| **Difference BIPM 2016 – BIPM 2014** | **1.8** | **1.2** | **2.7** |
| Difference BIPM 2016 – NIST 2015 | - 1.8 | - 1.7 | - 1.7 |
| Difference BIPM 2016 – OP 2015 | - 0.2 | 0.0 | - 0.2 |
| **Difference BIPM 2016 – OP 2016** | 0.2 | 0.0 | 0.7 |

Note that some apparent discrepancies might come from rounded values obtained from a first detailed computation of each delay.

## *3. Updated relative calibrated delays*.

This is why we decided to compute again the INTDLY(P1) and the INTDLY(P2) for all the LNE-SYRTE 2016 calibration campaign involved remote receivers, by updating OPMT delays from 1001-2016, no other parameter being changed. Table 2 summarizes the informations on the calibration trip according to the BIPM guidelines [RD5]. And Table 3 provides a direct comparison between the old INTDLY values, before the OP campaign took place, and the updated INTDLY values. Note that there are no data for SP receivers in this Table because the BIPM files only contain a P3 global offset. As can be seen, the updated values are generating ΔP3 offsets which differ from the former values provided by LNE-SYRTE inside this report. But, except for IENG, the ΔP3 offsets are clearly in line with the expected 1.7 ns conventional combined uncertainty.

Table 4. Updated summary information on the calibration trip (all values in ns).

| Reference system | Cal_Id | Date | | INTDLY(P1) | INTDLY(P2) |
|---|---|---|---|---|---|
| OPMT | ***1001-2016*** | 2016.9 | | 309.0 | 320.9 |
| **Visited system** | **Cal_Id** | **Date** | **u(P3)** | **INTDLY(P1)** | **INTDLY(P2)** |
| SP01 ** | *1013-2016 ** | 2016.2 | 1.2 | 234.10 | 246.05 |
| SP02 ** | *1013-2016 ** | 2016.2 | 1.2 | 235.70 | 244.55 |
| PTBB | *1013-2016 ** | 2016.3 | 1.3 | 304.40 | 320.00 |
| PT07 **** | *1013-2016 ** | 2016.3 | 1.3 | - 35.60 | - 23.30 |
| PT10 **** | *1013-2016 ** | 2016.3 | 1.3 | - 40.10 | - 46.30 |
| IENG | *1013-2016 ** | 2016.4 | 1.3 | 308.55 | 318.90 |
| GTRI **** | *1013-2016 ** | 2016.4 | 1.3 | - 143.65 | - 131.40 |
| GTRB **** | *1013-2016 ** | 2016.4 | 1.3 | - 34.80 | - 20.75 |
| INR7 *** | *1013-2016 ** | 2016.4 | 1.3 | 229.80 | 231.10 |

* All delays and parameters used for the computations in these lines are from this calibration report except for the OPMT delays which are updated from 1001-2016 BIPM G1 report.
** Reference cable delay and antenna cable delay included in hardware internal delays.
*** Antenna cable delay included in hardware internal delays.
**** DICOM GTR50/51 receiver internal delays are computed from former internal delays (see Section 10.3 of this report for details)

Table 3. Direct comparison between old calibrated delays and the updated delays provided in this Annex TN (all values in ns).

| Station | Receiver name | Old INTDLY(P1) | Updated INTDLY(P1) | Updated – Old ( P1) | Old INTDLY(P2) | Updated INTDLY(P2) | Updated – Old ( P2) | Updated – Old ( P3) |
|---|---|---|---|---|---|---|---|---|
| **PTB** | PTBB | 303.90 | 304.40 | **0.50** | 319.30 | 320.00 | **0.70** | **0.2** |
| | PT07 | - 36.30 | - 35.60 | **0.70** | - 23.80 | - 23.30 | **0.50** | **1.0** |
| | PT10 | - 40.30 | - 40.10 | **0.20** | - 46.60 | - 46.30 | **0.30** | **0.0** |
| **INRIM** | IENG | 305.60 | 308.55 | **2.95** | 315.60 | 318.90 | **3.30** | **2.4** |
| | GTRB | - 34.50 | - 34.80 | **- 0.30** | - 21.10 | - 20.75 | **0.35** | **- 1.3** |
| | GTRI | - 143.50 | - 143.65 | **- 0.15** | - 131.50 | - 131.40 | **0.10** | **- 0.5** |
| | INR7 | nan | 229.80 | | nan | 231.10 | | |

And finally, Table 4 is attempting to compare the BIPM 1001-2016 results for PTB as G1 laboratory to the updated delays computed here by LNE-SYRTE. As can be seen, there is a clear sub-ns consistency between both results when computing ∆P3 offsets for PTBB/PT02 and PT10. It is not the case for PT07, but the ∆P3 offset is almost in line with the conventional combined uncertainty for TAI network. These results are providing confidence in the LNE-SYRTE updated computations presented in this Annex TN.

Table 4. Comparison of BIPM 1001-2016 and updated LNE-SYRTE/OP computation for PTB as G1 laboratory (all values in ns).

| Station | Receiver name | BIPM INTDLY(P1) | OP INTDLY(P1) | BIPM – OP (P1) | BIPM INTDLY(P2) | OP INTDLY(P2) | BIPM – OP (P2) | ∆P3 |
|---|---|---|---|---|---|---|---|---|
| **PTB** | PTBB/PT02 | 304.5 | 304.40 | **- 0.10** | 319.8 | 320.00 | **0.20** | **- 0.6** |
| | PT07 | - 36.9 * | - 35.60 | **1.30** | - 24.3 * | - 23.30 | **1.00** | **1.8** |
| | PT10 | - 40.0 * | - 40.10 | **- 0.10** | - 46.60 * | - 46.30 | **0.30** | **- 0.7** |

* Computed from BIPM 1001-2016 offset based on “old” delays provided in Table 3 above

We do not provide any additional computations, because the report is already containing a comprehensive analysis of all other data and parameters. Note for instance that the uncertainty budgets computation does not change at all.

## *4. Conclusion*.

There is a clear sub-ns consistency between the OP 2016 campaign and the last BIPM 1001-2016 campaign results on the link OP-PTB. But it is not the case on this link between the former BIPM 1001-2014 campaign and the last one in 2016. Because the OPMT reference receiver delays were originally based on the BIPM 1001-2014 results, the delays computed form the LNE-SYRTE 2016 relative calibration campaigns might be biased. We therefore recommend to use the updated delays provided in Section 3 of this TN for all receivers calibrated by LNE-SYRTE/OP in 2016. We used the Table 4 of this TN to generate the Table 1 in Section 2 of this report.

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