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Certificate of Calibration No 117-00612

Object	**GPS rcvr type Septentrio PolaRx4TR PRO serial 3001325** **Antenna type Aero AT-1675 serial 5100** **Cable type Andrew Heliax FSJ1RN-50B (ID 3001318-5100)**
Order	Differential calibration of matched GPS receiver, antenna and cable against reference GPS link METAS WAB1 CH00 for P3 common-view time transfer.
Applicant	CERN, CH-1211, Genève 23, Switzerland
Traceability	The reported measurement values are traceable to national standards and thus to internationally supported realizations of the SI-units.
Date of Calibration	17.02.2012
Marking	Calibration label METAS 02.2012

CH-3003 Bern-Wabern, 02 March 2012

For the Measurements   Sector Length, Optics and Time

Dr Laurent-Guy Bernier   Dr. Rudolf Thalmann, Head of sector

Mutual recognition

This certificate is consistent with Calibration and Measurement Capabilities (CMCs) that are included in Appendix C of the Mutual Recognition Arrangement (MRA) drawn up by the International Committee for Weights and Measures. Under the MRA, all participating institutes recognize the validity of each other's calibration certificates and measurement reports for the quantities, ranges and measurement uncertainties specified in Appendix C (for details see www.bipm.org).

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Extent of the Calibration

The matched GPS receiver, antenna and cable were differentially calibrated against the reference GPS link METAS WAB1 CH00 for the purpose of P3 common-view time transfer.

Measurement Procedure

The BIPM differential calibration procedure was used (see Appendix).

Measurement Conditions

Laboratory ambient temperature (DUT receiver):   (21.0±1.0) °C

Outdoors ambient temperature (DUT antenna):   min -15 °C max -04 °C

For the purpose of calibration GPS observations were collected from 2012-02-12 to 2012-02-13.

Reference data DUT link

ID:	CERA
Receiver:	type Septentrio PolaRx4TR PRO serial 3001325
Antenna:	type Aero AT-1675 serial 5100
Antenna cable ID:	CERN 3001325-5100 (delay 200.0 ns)
Cable type:	Andrew type Heliax FSJ1RN-50B (length 48 m)

REF clock   UTC(CH)

Antenna phase coordinates   LAT(N)   46° 55' 25.4159"
                                   LON(E)   07° 27' 51.3403"
                                   ALT   612.650 m

Reference data REF link

ID:	WAB1 CH00
Receiver:	type Septentrio PolaRx2eTR serial 3289
Antenna:	type Ashtech 700936F serial CR14349
Antenna cable ID:	KA-KR#11 (delay 221.7 ns)
Cable type:	Andrew type Heliax FSJ1RN-50B (length 50 m)

REF clock   UTC(CH)

Antenna phase coordinates   LAT(N)   46° 55' 25.5455"
                                   LON(E)   07° 27' 51.1217"
                                   ALT   612.555 m

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Measurement result: delay of antenna cable

Counter: Stanford Research type SR620 serial 2895
Method: Start: input A, internal ECL reference (1 kHz)
                 Stop: input B, trigger -1.4 V, DC coupling, 50Ω impedance
                 SR620 ECL reference signal connected to one cable connector
                 Counter input B connected to other cable connector
                 Measure time interval once with test cables only and once with DUT cable inserted.

$$CAB\,DLY = D_4 = \quad (200.0 \pm 0.5) \text{ ns}$$

Measurement result: internal delays

$$INT\,DLY\,P_1 = D_3(P_1) + D_5(P_1) = (55.2 \pm 2.0) \text{ ns}$$

$$INT\,DLY\,P_2 = D_3(P_2) + D_5(P_2) = (53.7 \pm 2.0) \text{ ns}$$

Note that the specified uncertainty covers only the zero-baseline differential calibration of the DUT link versus the REF link. The uncertainty is dominated by the calibration of D_i which is very sensitive to the trigger level because the rise time of the 1-PPS output is large.

The stated uncertainty does not include the calibration offset of the REF link versus UTC. An estimated of that offset is given in the Appendix.

The stated uncertainty does not include the uncompensated propagation effects that occur when the baseline is not zero. An estimate of that effect is given in the appendix.

CGGTTS parameters of DUT link

The CGGTTS parameters of Figure 1 applicable to the DUT link are based on the following parameters.

$$D_i = 145.2 \text{ ns}$$

$$D_2 = D_i = 145.2 \text{ ns}$$

$$D_1 = 25.4 \text{ ns}$$

$$REF\,DLY = D_1 + D_2 = 170.6 \text{ ns}$$

Note that D_i was calibrated according to the procedure described in the Appendix.

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Note that the delay D_1 depends on a calibration of the 1-PPS signal from the reference clock.

A negative/positive value of the REF DLY means that the physical 1-PPS signal from the reference UTC(CH) distribution amplifier which is connected to the 1-PPS input of the DUT leads/lags the UTC(CH) time scale.

Figure 1 CGGTTS parameters of DUT link

Uncertainty of Measurement

The reported uncertainty of measurement is stated as the combined standard uncertainty multiplied by a coverage factor $k = 2$. The measured value (y) and the associated expanded uncertainty (U) represent the interval ($y \pm U$) which contains the value of the measured quantity with a probability of approximately 95 %. The uncertainty was estimated following the guidelines of the ISO (GUM:1995).

The measurement uncertainty contains contributions originating from the measurement standard, from the calibration method, from the environmental conditions and from the object being calibrated. The long-term characteristic of the object being calibrated is not included.

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Appendix: Definitions and Methods

1.1 Introduction

The differential calibration was performed according to the standard procedure that the BIPM uses for the differential calibration of the P3 GPS receivers used in National Metrology Institutes (NMI) for the generation of TAI (Temps Atomique International) [1], [2], [3].

However, when the BIPM organises differential calibration trips, the travelling reference receiver provided by the BIPM is absolutely calibrated using a satellite simulator. The P3 GPS receivers of the NMI's are then differentially calibrated against the absolutely calibrated reference receiver.

On the other hand, the present calibration is differential to the second degree. The DUT (Device Under test) GPS receiver was calibrated against the reference WAB1 CH00 P3 receiver which itself was differentially calibrated by the BIPM in 2009 against an absolutely calibrated reference receiver. Hence the absolute DUT calibration uncertainty cumulates the uncertainty of the internal delay parameters of the BIPM reference receiver and of the METAS reference receiver.

1.2 Definitions of internal delays

There is no need to calibrate the internal delays of a geodetic receiver used for standard geodetic applications. In normal operation the pseudo-range and the carrier phase measurements are collected and the observation data are processed and solved for the position and local time as defined at the location of the phase reference plane of the antenna.

This is why the headers of RINEX observation and navigation data files do not contain any parameter related to the internal delays. RINEX is the standard file format used by the international geodetic community for geodetic surveying [6].

On the other hand when the RINEX data is translated into CGGTTS data [4] [5] for the purpose of GPS P3 common-view time transfer, a number of calibrated delay parameters are used to translate the time comparison node from the antenna reference plane down to a conventional reference location which allows absolute time comparison between the local reference clock and the satellite reference clock.

CGGTTS delays /ns
INT DLY P1
INT DLY P2
CAB DLY
REF DLY

Table 1 CGGTTS Calibrated Delays

The CGGTTS (CCTF Group on GNSS Time Transfer Standards) is the standard data file format used by the BIPM and by the NMI's for Common-View time transfer. CCTF is the Consultative Committee for Time and Frequency.

Figure 2 below is an example of CGGTTS data file generated with the DUT geodetic GPS receiver. Table 1 lists the calibrated delays that appear in the CGGTTS header.

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```
GZCERA55.972 - Bloc-notes
Fichier  Edition  Format  Affichage  ?
CGGTTS GPS/GLONASS DATA FORMAT VERSION = 02
REV DATE = 2012-02-10
RCVR = PolaRx4TR 3001325           R2CGGTTS v4.3
CH = 12 (GPS)
IMS = PolaRx4TR 3001325
LAB = CERN
X = +4327320.92 m (GPS)
Y =  +566956.84 m (GPS)
Z = +4636425.29 m (GPS)
FRAME = ITRF88
COMMENTS = cal 2012-02-10-B CERA
INT DLY =    55.2 ns (GPS P1),    53.7 ns (GPS P2)
CAB DLY =   200.0 ns (GPS)
REF DLY =   170.6 ns
REF = UTC(CH)
CKSUM = 40

PRN CL  MJD  STTIME TRKL ELV AZTH  REFSV     SRSV   REFGPS    SRGPS  DSG IOE MDTR SMDT MDIO SMDI MSIO SMSI ISG FR HC FRC CK
              hhmmss  s  .1dg .1dg  .1ns     .1ps/s  .1ns     .1ps/s .1ns    .1ns.1ps/s.1ns.1ps/s.1ns.1ps/s.1ns
29 FF 55972 000200 780 557 2131 -2847383   -26     126     +10    7  21  92  -9   72  -14   72  -14   5  0  0 L3P CB
25 FF 55972 000200 780 788 3600  -316401    +6     103      +9    5  57  77  +0   63   -5   63   -5   3  0  0 L3P 67
 9 FF 55972 000200 780 151 1460 -1385545   -84     142     -58   25 105 289 +127  95  +55   95   55  17  0  0 L3P 31
31 FF 55972 000200 780 319 3104 -2082274   -53      99      -6   14  30 143  -27   78   +5   78    5  10  0  0 L3P BB
12 FF 55972 000200 780 485  789  -524739   -34     136     -12    8  57 101  +10   71  +11   71   11   5  0  0 L3P B3
14 FF 55972 000200 780 329 2522 -1938682   -19     134      -6   13  18 139  +17   82  +25   82   25  10  0  0 L3P F5
 4 FF 55972 000200 780 137  395  -942253   -16     122     +99   39  60 315  +89   71  -92   71  -92  26  0  0 L3P F3
 2 FF 55972 000200 780 331  711 -3789924   -28     141     -12   10  23 138   +3   68   -7   68   -7   8  0  0 L3P AA
24 FF 55972 001800 780 161 2824 +2549922   +26     110     +28   23 118 271  -95  210  -40  210  -40  17  0  0 L3P 37
29 FF 55972 001800 780 635 2164 -2847413   -41     131      -4    6  21  85   -6   64   -3   64   -3   4  0  0 L3P 98
25 FF 55972 001800 780 777  382  -316405    -2     102      +0    3  57  78   +1   63   -3   63   -3   2  0  0 L3P 53
31 FF 55972 001800 780 383 3085 -2082306   -33     112     +14    7  30 122  -18   70  -15   70  -15   5  0  0 L3P D8
12 FF 55972 001800 780 426  851  -524763   -20     133      +1    7  57 112  +13   75   +8   75    8   5  0  0 L3P 84
14 FF 55972 001800 780 281 2454 -1938691   -19     137      -5   13  18 161  +28   90  +20   90   20   8  0  0 L3P E7
 2 FF 55972 001800 780 318  633 -3789937    -3     143     +13   11  23 144   +8   56  -21   56  -21   7  0  0 L3P BB
24 FF 55972 003400 780 219 2865 +2549922    -3     113      -1   16 118 203  -53  197  -10  197  -10  11  0  0 L3P 1E
29 FF 55972 003400 780 714 2204 -2847445   -30     134      +7    5  21  80   -4   59   -5   59   -5   4  0  0 L3P 9A
25 FF 55972 003400 780 737  647  -316404    -5     103      -3    4  57  79   +2   63   +7   63    7   2  0  0 L3P 57
31 FF 55972 003400 780 446 3048 -2082358   -47     105      -1    7  30 108  -12   75   +1   75    1   5  0  0 L3P A0
12 FF 55972 003400 780 366  908  -524779   -70     137     -48    9  57 127  +18   83  +56   83   56   7  0  0 L3P E8
14 FF 55972 003400 780 227 2396 -1938704   -39     138     -25   19  18 196  +47   93  +26   93   26  12  0  0 L3P 26
```

Figure 2 Example of CGGTTS Data File Including Header

$INT\ DLY\ P_1$ and $INT\ DLY\ P_2$ are the internal delays of the GPS geodetic receiver. There are two internal delay parameters because the P_1 and P_2 observations are based on two different carrier frequencies, so the propagation delay might be different.
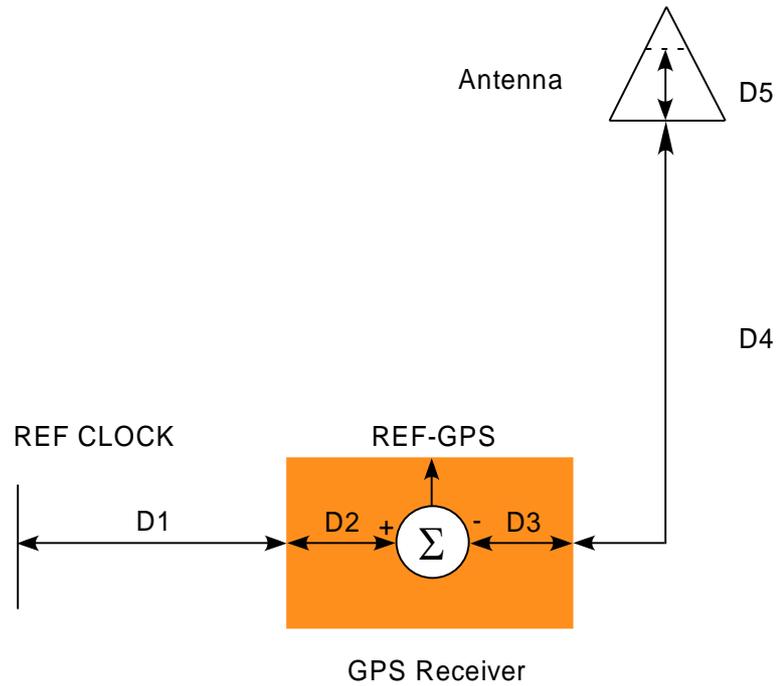
$CAB\ DLY$ is the delay of the coaxial cable that connects the antenna to the receiver.

$REF\ DLY$ is the delay between the local REF clock 1-PPS signal and the reference time differ-ence node inside the geodetic receiver.

The delay parameters can be defined by referring to the timing diagram of Figure 3

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Figure 3 Timing Diagram

The *REF DLY* is defined as

$$REF\ DLY = D_1 + D_2 \qquad (1)$$

where D_1 is the external part of the REF DLY, i.e. the delay between the laboratory reference node of the REF clock and the 1-PPS input connector of the GPS receiver.

D_2 is the internal part of the REF DLY, In the particular case of the Septentrio PolaRx4TR PRO receiver we have

$$D_2 = D_i + 0.0\,\text{ns} \qquad (2)$$

where

D_i is the insertion delay of the Septentrio PolaRx4TR receiver, i.e. the delay between the 1-PPS input signal and the 1-PPS output signal.

Note that the Septentrio manual [7] page 8 specifies that the 1-PPS output pulse can be synchronized to the *measurement latching event*, i.e. to what we call here the time comparison node, by means of the command `setPPSParameters,sec1,Low2High,0,RxClock <cr>`.

Once synchronization is achieved, the 1-PPS output pulse is synchronous with the *measurement latching event*. Hence the constant 0.0 ns in equation (2).

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The BIPM procedure [1] specifies a DC trigger level of +0.5 V with 50 Ω matched impedance loading for the measurement the 1-PPS input to 1-PPS output delay D_i.

The Septentrio manual [7] specifies that D_2 is a constant that depends on the phase relationship between the 10 MHz signal and the 1-PPS input. D_2 can vary between 130.3 ns and 150.3 ns. Hence it is necessary to calibrate this delay.

The Septentrio manual [7] specifies that the amplitude of the 10 MHz reference input p-p amplitude in a 50 Ω matched impedance must be in a range of [0.5 V, 2.0 V] for correct internal timing of the PolaRx4TR receiver.

Note that the zero crossings of the 10 MHz REF input must have a constant synchronization delay versus the 1-PPS REF input signal (i.e. the 1-PPS and the 10 MHz must be generated from the same frequency standard). The value of D_2 actually depends on the value of the synchronization delay. Hence D_2 must be calibrated only after an unspecified but constant synchronization delay has been achieved.

Note, finally, that the internal timing of the PolaRx4TR is based exclusively on the 10 MHz REF signal. After a hardware reset, the internal clock is calibrated only once versus the 1-PPS REF signal. Hence, after initialization, the 1-PPS REF signal becomes irrelevant and can even be disconnected without any impact on the internal timing. As a consequence, a hardware reset and a calibration of D_i are compulsory after each modification of the system configuration that might affect the synchronization delay of the REF 10 MHz versus the REF 1-PPS.

Regarding the antenna cable delay, we have

$$CAB\,DLY = D_4 \tag{3}$$

which means that $CAB\,DLY$ covers exclusively the delay of the coaxial cable that connects the antenna to the receiver. The antenna cable can be replaced without losing the calibration of the matched set of receiver and antenna, provided that the parameter $CAB\,DLY$ is set to the actual calibrated value of the cable delay.

The $INT\,DLY\,P_1$ and $INT\,DLY\,P_2$ parameters reflect the internal delays of the DUT receiver and of the DUT antenna at the P_1 and P_2 carrier frequencies.

$$INT\,DLY\,P_1 = D_3(P_1) + D_5(P_1) \tag{4}$$

$$INT\,DLY\,P_2 = D_3(P_2) + D_5(P_2) \tag{5}$$

In principle, it would be possible, but more difficult, to calibrate independently the receiver internal delay D_3 and the antenna internal delay D_5. This would allow to match and mix different receivers and antennas without losing the calibration. However in the present calibration we chose to calibrate a matched set of DUT receiver and antenna.

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In the CGGTTS output file, the result $REFGPS$ is the measured time difference

$$REFGPS = X\left(CLK\right) - X\left(GST\right) \tag{6}$$

in units of 0.1 ns where $X\left(CLK\right)$ is the time of the local REF clock and $X\left(GST\right)$ is the estimation of GPS system time broadcasted by the GPS satellite PRN for a given track of duration $TRKL$ started on Modified Julian Day MJD at epoch $STTIME$.

In the case of a P3 CGGTTS file [4] the $REFGPS$ time differences are based on the *ionosphere-free* code P_3 which is actually a linear combination of the P_1 and P_2 codes.

Since the propagation delay through the ionosphere is different at the P_1 and P_2 carrier frequencies, due to the dispersion of the ionosphere, it is possible to construct a linear combination P_3 that compensates for the ionospheric delay variations, hence the name *ionosphere-free* code.

In order to calibrate independently the $INT\ DLY\ P_1$ and $INT\ DLY\ P_2$ internal delay parameters, it is necessary to first reconstruct the P_1 and P_2 comparisons from the *ionosphere-free* P_3 observations. This is done as follows.

$$REFGPS\left(P_1\right) = REFGPS\left(P_3\right) + MSIO \tag{7}$$

$$REFGPS\left(P_2\right) = REFGPS\left(P_3\right) + 0.647 \times MSIO \tag{8}$$

Equations (7) and (8) are actually the inverse function of the linear combination that was used by the RINEX to CGGTTS translation software to build the P_3 *ionosphere-free* observations from the P_1 and P_2 observations.

The field $MSIO$ in the P3 CGGTTS format [4] contains the difference between the P_1 and the P_3 observations for each satellite and for each track.

1.3 Zero baseline differential calibration procedure

To calibrate the DUT P3 link (matched set of receiver, antenna and antenna cable) against a REF P3 link, it is necessary to setup a zero-base line P3 common-view experiment.

The first step is to calibrate the antenna cable delay D_4.

Then the DUT link is connected to the 1-PPS and to the 10 MHz signals of a REF clock that is the same or that can be related to the REF clock that drives the REF link. The components D_1 and D_2 of $REF\ DLY$ are calibrated.

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In a zero baseline P3 common-view experiment the observations from the P3 CGGTTS files generated by the DUT and REF link are processed in a common-view mode, i.e. the differences are taken track by track and satellite by satellite,

$$REFGPS(DUT) - REFGPS(REF) = [X(CLK_{DUT}) - X(GST)] - [X(CLK_{REF}) - X(GST)] \quad (9)$$

and since the broadcasted value of the estimated GPS system time $X(GST)$ is a common term, the system time cancels out yielding the difference between the local clocks.

$$REFGPS(DUT) - REFGPS(REF) = X(CLK_{DUT}) - X(CLK_{REF}) \quad (10)$$

If the two links refer to the same local clock, then we should have

$$REFGPS(DUT) - REFGPS(REF) = X(CLK_{DUT}) - X(CLK_{REF}) = 0 \quad (11)$$

provided that the delay parameters in the P3 CGGTTS file header are correctly calibrated.

Indeed we have for each link and for each carrier frequency

$$REFGPS_{CGGTTS} = REFGPS_{raw} - CAB\,DLY - INT\,DLY + REF\,DLY \, , \quad (12)$$

where $REFGPS_{raw}$ represents the raw P_1 or P_2 observations made by the uncalibrated receiver while $REFGPS_{CGGTTS}$ represents the calibrated observations as found in the P3 CGGTTS output files after translation by the RINEX to CGGTTS translation software.

Hence, once $CAB\,DLY$ and $REF\,DLY$ are independently calibrated, the zero baseline P3 common-view experiment is used to determine the $INT\,DLY\,P_1$ and $INT\,DLY\,P_2$ internal delay parameters of the DUT link.

As a matter of fact, if the DUT link and the REF link are referred to the same physical clock and if the internal delay parameters of the REF link are assumed to be correctly calibrated, then adjusting the internal delay parameters of the DUT link to cancel equation (11) will yield the correct internal delay parameters for the DUT link. This is what the differential calibration is all about.

In the particular case where the DUT link and the REF link and not referred to the same physical clock, then it is necessary to refer the physical clocks to each other via the UTC(CH) local time scale.

If we define

$$CLK\,OFFSET = [CLK_{DUT} - UTC(CH)] - [CLK_{REF} - UTC(CH)], \quad (13)$$

then (11) becomes

$$[X(CLK_{DUT}) - X(CLK_{REF})] - CLK\,OFFSET = 0 . \quad (14)$$

As a matter of fact, in (14) $[X(CLK_{DUT}) - X(CLK_{REF})]$ is the clock difference as measured via

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the zero baseline P3 common-view experiment, while $CLK\ OFFSET$ is the actual clock difference independently measured against UTC(CH). If the DUT link is properly calibrated, then the double difference (14) should be zero.

Note, finally, that the $INT\ DLY\ P_1$ and $INT\ DLY\ P_2$ internal delay parameters are actually adjusted in two steps.

In the first step the P_1 and P_2 observations are reconstructed from the *ionosphere-free* P_3 observations using (7) and (8). During that first step, the constants $INT\ DLY\ P_1$ and $INT\ DLY\ P_2$ are independently adjusted to yields the same offset in the P_1 based version of (14) and in the P_2 based version of (14) which is not necessarily zero. This first step determines the correct *difference* between the delays $INT\ DLY\ P_1$ and $INT\ DLY\ P_2$.

Then, in a second step, the $INT\ DLY\ P_1$ and $INT\ DLY\ P_2$ internal delay parameters are adjusted *together*, maintaining the correct difference determined in the previous step, to adjust the P_3 based offset (14) to zero.

1.4 Discussion of uncertainties

The differential calibration is performed by means of a zero baseline P3 common-view experiment. The zero baseline statement means that the antennas of the DUT and of the REF links are located a few meters apart, which implies that the propagation paths from a GPS satellite to the antennas are identical. Hence hypothetical systematic errors associated with propagation are common mode and cancel out in the measurement.

On the other hand, in an actual P3 common-view time transfer experiment, the propagation paths are not identical and the larger the baseline, the larger the uncompensated propagation effects.

Another source of uncertainty is the temperature dependence of the delays. Both the geodetic receiver, the antenna cable and the antenna itself, which contains active electronics, are temperature dependent. Hence the calibrated delays may change if the operating temperatures are very different from the calibration temperature. With the DUT link we have observed environmental changes of the order of ± 1 ns. The temperature dependence of the DUT link was not calibrated.

According to BIPM [2] the absolute uncertainty (i.e. including both the uncertainty of the differential calibration of the DUT receiver and the uncertainty on the absolute delays of the REF receiver) of a calibrated P3 link based on an Ashtech Z12-T receiver is ± 3 ns.

The uncertainty that BIPM specifies in the monthly publication Circular T for calibrated P3 TAI links operated in NMI's is ± 5 ns. This uncertainty includes the uncompensated propagation effects.

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1.5   Reference documents

[1]   *Calibration of Geodetic-Type Receivers Using the Traveling BIPM PolaRx2 Receiver, Guidelines and Operational Procedures*, BIPM procedure calibgeo-V41.pdf.

[2]   *Estimation of the Values and Uncertainties of the BIPM Z12-T Receiver and Antenna delays, for Use in Differential Calibration Exercices*, by G. Petit, BIPM Time Section Technical Memorandum TM.116, July 2002.

[3]   *Progresses in the Calibration of Geodetic Like GPS Receivers for Accurate Time Comparisons*, by G. Petit, Z. Jiang, P. Moussay, J. White, E. Powers, G. Dudle, P. Uhrich, in Proceedings 15[th] EFTF, Neuchâtel, Switzerland, 2001.

[4]   *Proposal to Use Geodetic-Type Receivers for Time Transfer Using the CGGTTS Format*, by P. Defraigne, G. Petit, BIPM Time Section Technical Memorandum TM.110, November 2001.

[5]   *Time Transfer to TAI Using Geodetic Receivers*, by P. Defraigne, C. Bruyninx, J. Clarke, J. Ray, K. Senior, Proceedings 15[th] EFTF, Neuchâtel, Switzerland 2001, pp. 164-166.

[6]   *RINEX , the Receiver Independent Exchange Format*, version 3.00, by Werner Gurtner, Astronomical Institute, University of Bern, and Lou Estey, UNAVCO, Boulder CO, November 2007.

[7]   *Septentrio PolaRx4 Product Family Hardware Manual* v1.4.08.