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Federal Department of Justice and Police FDJP

Federal Office of Metrology METAS

Measurement Report No 119-00209

Object	**GPS receiver type Septentrio PolaRx2eTR serial 3205** **Antenna type Aero AT-2775 serial 5577** **Cable type Andrew Heliax FSJ1RN-50B (ID CERN 3205)**
Order	Differential calibration of matched GPS receiver, antenna and cable against reference GPS link METAS WAB2 CH01 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. Restrictions are indicated where necessary.
Date of Measurement	15.05.2008
Marking	Not applicable.

CH-3003 Bern-Wabern, 26 May 2008

For the Measurements

Dr BERNIER Laurent-Guy
Section Length Optics and Time

Measurement Report No 119-00209

Extent of Measurement

The matched GPS receiver, antenna and cable were differentially calibrated against the reference GPS link METAS WAB2 CH01 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±1) °C

Outdoors ambient temperature (DUT antenna): min -5 °C max +25 °C

For the purpose of calibration GPS observations were collected from 2008-03-18 to 2008-05-15.

Reference data DUT link

ID:	WABT CHTT
Receiver:	type Septentrio PolaRx2eTR serial 3205
Antenna:	type Aero AT-2775 serial 5577
Antenna cable ID:	CERN 3205 (delay 202.8 ns)
Cable type:	Andrew type Heliax FSJ1RN-50B (length 50 m)

REF clock cesium CLK 1360413

Antenna phase coordinates	LAT(N)	46° 55’ 25.305996”
	LON(E)	07° 27’ 51.204390”
	ALT	611.601 m

Reference data REF link

ID:	WAB2 CH01
Receiver:	type Ashtech Z12-T, serial RT919993201
Antenna:	type Ashtech 700936F serial CR1998390144
Antenna cable ID:	KA-KR#12 (delay 208.9 ns)
Cable type:	Andrew type Heliax FSJ1RN-50B (length 50 m)

REF clock hydrogen maser CLK 1405701

Antenna phase coordinates	LAT(N)	46° 55’ 25.428228”
	LON(E)	07° 27’ 51.302700”
	ALT	612.587 m

Measurement Report No 119-00209

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.

$CAB\,DLY = D_4$ = (202.8±0.5) ns

Measurement result: internal delays

$INT\,DLY\,P_1 = D_3(P_1) + D_5(P_1)$ = (217.6±2) ns

$INT\,DLY\,P_2 = D_3(P_2) + D_5(P_2)$ = (225.7±2) 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 = 244.4 ns

$D_2 = D_i + 8.7\,\mathrm{ns}$ = 253.1 ns

D_1 = -6.3 ns

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Measurement Report No 119-00209

$REF\ DLY = D_1 + D_2$ = 246.8 ns

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

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 delay means that the physical 1-PPS signal from the reference CLK 1360413 distribution amplifier leads/lags the calibrated CLK 1360413 – UTC(CH) time scale.

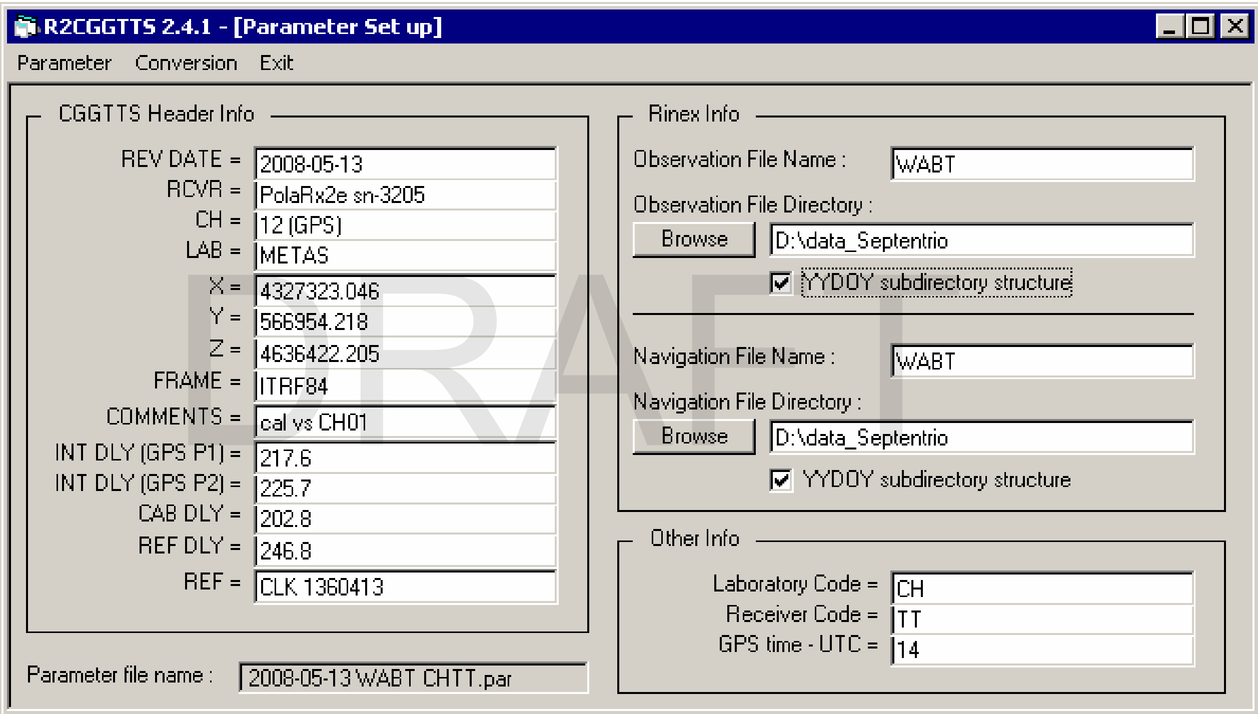


Figure 1 CGGTTS parameters of DUT link

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* ± *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.

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

Measurement Report No 119-00209

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 WAB2 CH01 P3 receiver which itself was differentially calibrated by the BIPM in 2007 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.

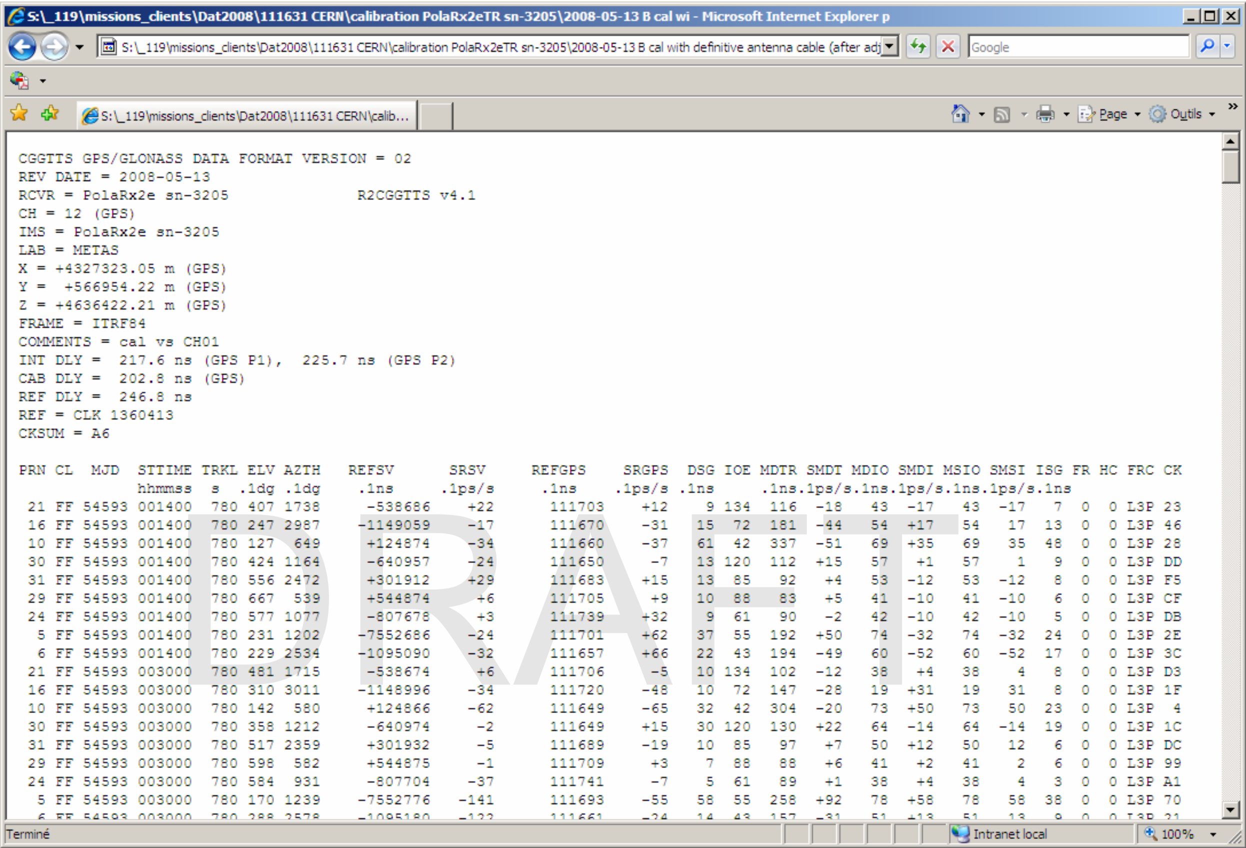
CGGTTS delays /ns
INT DLY P1
INT DLY P2
CAB DLY
REF DLY

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.

Measurement Report No 119-00209

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.



```
CGGTTS GPS/GLONASS DATA FORMAT VERSION = 02
REV DATE = 2008-05-13
RCVR = PolaRx2e sn-3205              R2CGGTTS v4.1
CH = 12 (GPS)
IMS = PolaRx2e sn-3205
LAB = METAS
X = +4327323.05 m (GPS)
Y =  +566954.22 m (GPS)
Z = +4636422.21 m (GPS)
FRAME = ITRF84
COMMENTS = cal vs CH01
INT DLY =  217.6 ns (GPS P1),  225.7 ns (GPS P2)
CAB DLY =  202.8 ns (GPS)
REF DLY =  246.8 ns
REF = CLK 1360413
CKSUM = A6

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
 21 FF 54593 001400  780 407 1738   -538686     +22     111703     +12    9 134  116  -18   43  -17   43  -17    7  0  0 L3P 23
 16 FF 54593 001400  780 247 2987  -1149059     -17     111670     -31   15  72  181  -44   54  +17   54   17   13  0  0 L3P 46
 10 FF 54593 001400  780 127  649   +124874     -34     111660     -37   61  42  337  -51   69  +35   69   35   48  0  0 L3P 28
 30 FF 54593 001400  780 424 1164   -640957     -24     111650      -7   13 120  112  +15   57   +1   57    1    9  0  0 L3P DD
 31 FF 54593 001400  780 556 2472   +301912     +29     111683     +15   13  85   92   +4   53  -12   53  -12    8  0  0 L3P F5
 29 FF 54593 001400  780 667  539   +544874      +6     111705      +9   10  88   83   +5   41  -10   41  -10    6  0  0 L3P CF
 24 FF 54593 001400  780 577 1077   -807678      +3     111739     +32    9  61   90   -2   42  -10   42  -10    5  0  0 L3P DB
  5 FF 54593 001400  780 231 1202  -7552686     -24     111701     +62   37  55  192  +50   74  -32   74  -32   24  0  0 L3P 2E
  6 FF 54593 001400  780 229 2534  -1095090     -32     111657     +66   22  43  194  -49   60  -52   60  -52   17  0  0 L3P 3C
 21 FF 54593 003000  780 481 1715   -538674      +6     111706      -5   10 134  102  -12   38   +4   38    4    8  0  0 L3P D3
 16 FF 54593 003000  780 310 3011  -1148996     -34     111720     -48   10  72  147  -28   19  +31   19   31    8  0  0 L3P 1F
 10 FF 54593 003000  780 142  580   +124866     -62     111649     -65   32  42  304  -20   73  +50   73   50   23  0  0 L3P  4
 30 FF 54593 003000  780 358 1212   -640974      -2     111649     +15   30 120  130  +22   64  -14   64  -14   19  0  0 L3P 1C
 31 FF 54593 003000  780 517 2359   +301932      -5     111689     -19   10  85   97   +7   50  +12   50   12    6  0  0 L3P DC
 29 FF 54593 003000  780 598  582   +544875      -1     111709      +3    7  88   88   +6   41   +2   41    2    6  0  0 L3P 99
 24 FF 54593 003000  780 584  931   -807704     -37     111741      -7    5  61   89   +1   38   +4   38    4    3  0  0 L3P A1
  5 FF 54593 003000  780 170 1239  -7552776    -141     111693     -55   58  55  258  +92   78  +58   78   58   38  0  0 L3P 70
```

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 difference node inside the geodetic receiver.

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

Measurement Report No 119-00209

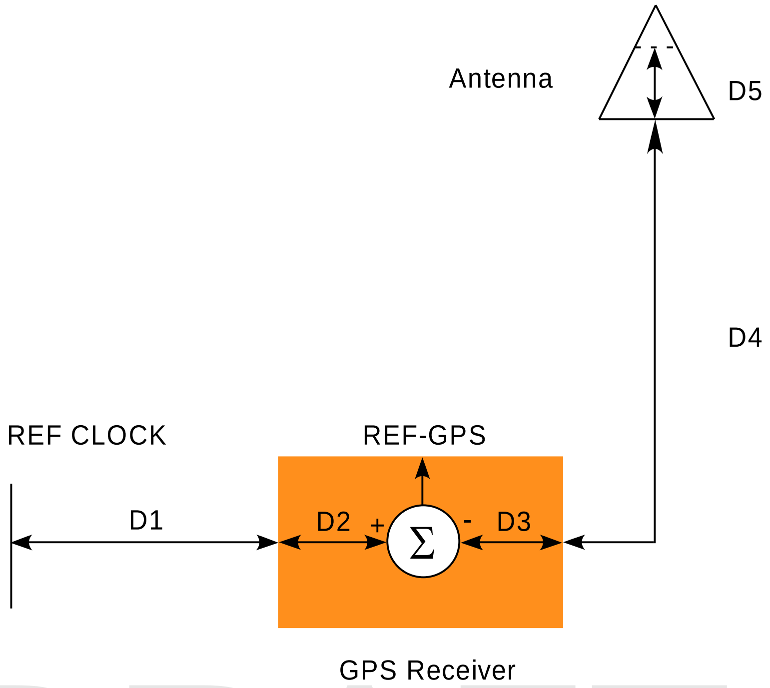


Figure 3 Timing Diagram

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 PolaRx2eTR receiver we have

$$D_2 = D_i + 8.7\,\text{ns} \qquad (2)$$

where

D_i is the insertion delay of the Septentrio PolaRx2eTR receiver, i.e. the delay between the 1-PPS input signal and the 1-PPS output signal.

Note that the Septentrio user's manual [7] specifies in section 2.18 that the 1-PPS output pulse can be be synchronised to the *measurement latching event*, i.e. to what we call here the time comparison node, by means of the command **`SetPPSParameters 1 0 local <cr>`**.

Once synchronisation is achieved, the 1-PPS output pulse occurs 8.7 ns before the *measure-ment latching event* for firmware versions 2.3 and higher. Hence the constant 8.7 ns in equation (2).

Measurement Report No 119-00209

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 [1] specifies that D_2 is a constant for a given PolaRx2eTR receiver. However D_2 can vary between 221.7 ns and 255.0 ns from unit to unit. Hence it is necessary to calibrate this delay.

The Septentrio manual [1] specifies in section 2.16 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 PolaRx2eTR 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 PolaRx2eTR 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 tinitialization, 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 synchronisation 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.

Measurement Report No 119-00209

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

$$REFGPS = X(CLK) - X(GST) \quad (6)$$

in units of 0.1 ns where $X(CLK)$ is the time of the local REF clock and $X(GST)$ 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.

$$REFGPS(P_1) = REFGPS(P_3) + MSIO \quad (7)$$

$$REFGPS(P_2) = REFGPS(P_3) + 0.647 \times MSIO \quad (8)$$

Equations (7) and (8) are actually the inverse function of the linear combination that was used by the RINEX to CGGTTS translation software to built 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.

In a zero baseline P3 common-view experiment the observations from the P3 CGGTTS files

Measurement Report No 119-00209

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,

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

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.

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

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

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

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

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

where $REFGPS_{\mathrm{raw}}$ represents the raw P_1 or P_2 observations made by the uncalibrated receiver while $REFGPS_{\mathrm{CGGTTS}}$ 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 refered 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 refered 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

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

then (11) becomes

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

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

Measurement Report No 119-00209

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 15th 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 15th 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 Polarx2/2e User Manual*, version 3.2.0, January 2007.