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Values and uncertainties of the hardware delays of BIPM geodetic systems and estimation of the type B uncertainty of P3/PPP link calibrations

G. Petit

This memorandum presents results and uncertainties for the calibration of hardware delays of the BIPM geodetic receiver and associated antennas. These systems are used for differential calibration of similar systems, and the typical type B uncertainty of P3/PPP links between such receivers is also derived in two cases (so-called “equipment calibration” and “link calibration by traveling equipment”).

After recalling some definitions in section 1, section 2 presents the results of long-term differential calibration of different systems at the BIPM and section 3 gives the conventional values chosen for the hardware delays of these systems (see Table 1).

System	**P1**	**P2**	P1-P2
BP0C Z12-T	**305.6 ns**	**321.9 ns**	-16.3 ns
BP0M Z12-T	**304.5 ns**	**323.0 ns**	-18.5 ns
BP0R PolaRx2	**222.5 ns**	**224.5 ns**	-2.0 ns
BP0T GTR50 (1)	**-3.0 ns**	**-3.0 ns**	0.0 ns
BP0U GTR50 (1)	**-3.0 ns**	**-3.0 ns**	0.0 ns

Table 1: Conventional values of hardware delays of the BIPM reference systems.

The BIPM systems are to be used for differential calibration. Section 4 presents two types of differential calibration (equipment calibration and link calibration by traveling equipment) and estimates the associated type B uncertainties (see Table 2).

Typical value of ..	P3
Equipment calibration (EC) uncertainty (one system)	3.8 ns
u_B for a time link calibrated as EC-EC	5.4 ns
u_B for a time link calibrated by traveling equipment	2.3 ns

Table 2: Type B uncertainty of different types of P3 calibrations

1. Definitions

As presented in [Petit et al., 2001a] for the Z12-T, the calibration of a geodetic system is divided in (up to) 6 different parts (Figure 1), here listed from the laboratory reference to the antenna:

- X_P = Delay of the 1PPS-in to the laboratory reference
- X_O = Delay of the “internal reference” to the 1PPS-in
- X_R = receiver internal delay, measured from the “internal reference”

- [X_D = short cable + splitter delay] This term is relevant for “common antenna” operation but is not present in normal operation where two systems are in parallel operation, and will hereafter be skipped.

- X_C = antenna cable delay

- X_S = antenna delay

In practice X_D is not used and (X_R + X_S) are considered together as the hardware delay of the system, therefore only four quantities are considered.

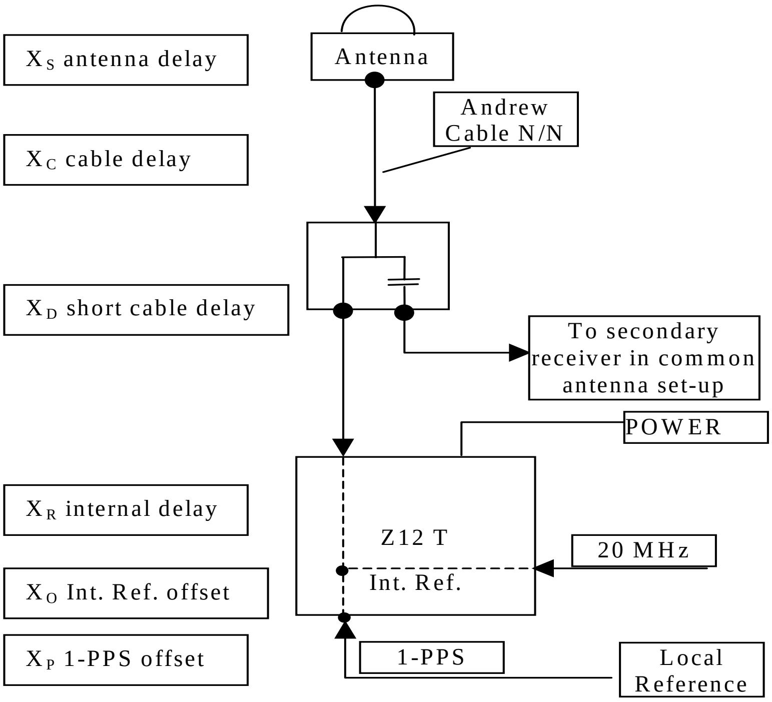

Figure 1: Definition of the different delays used in the most general set-up of a geodetic system (here shown for a Z12-T) from [Petit et al, 2001a].

The precise definition the “internal reference”, to which the GPS measurements are referred, depends on the type of geodetic receiver. In some cases, e.g. for the GTR50 receiver, X_O is measured in real time by the receiver and is included in the measurement values, so that it need not be taken into account.
During a calibration exercise where two systems are set-up in parallel operation with the same reference clock, the values of X_P and X_C (and if necessary, depending on the set-up, X_O) are to be measured at each new set-up. The value of (X_R + X_S) for the system under study is the result of the calibration exercise.

2. Long term comparisons of several systems

Several systems have been successively installed at the BIPM and have been inter-compared.

BP0C (Ashtech Z12-T) since 2000
BP0M (Ashtech Z12-T) since 2004
BP0O (Septentrio PolaRx2) between 2004 and 2007 (not considered below)
BP0R (Septentrio PolaRx2) since 2006

BP0T (Dicom GTR50) since 2007
BP0U (Dicom GTR50) since 2008

The two BIPM Z12-T systems have been differentially calibrated (i.e. all measurements have been carried out like in a calibration exercise) at 14 occasions over close to 6 years (see Figure 2). Similarly, results of differential calibrations for the other receivers are available for about 2 years (see Figures 2 and 3).

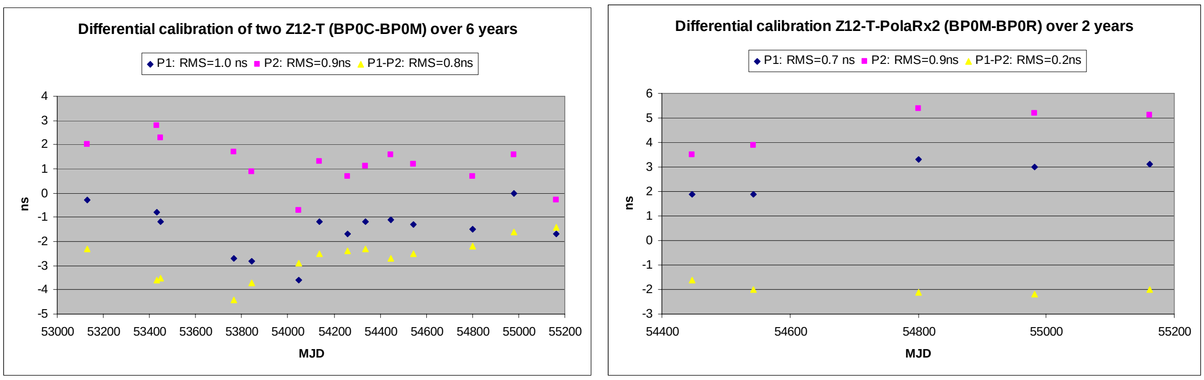

Figure 2: Long term comparison of differential calibration of the BP0M Z12-T system with the BP0C Z12-T (left) and the BP0R PolaRx2 (right).

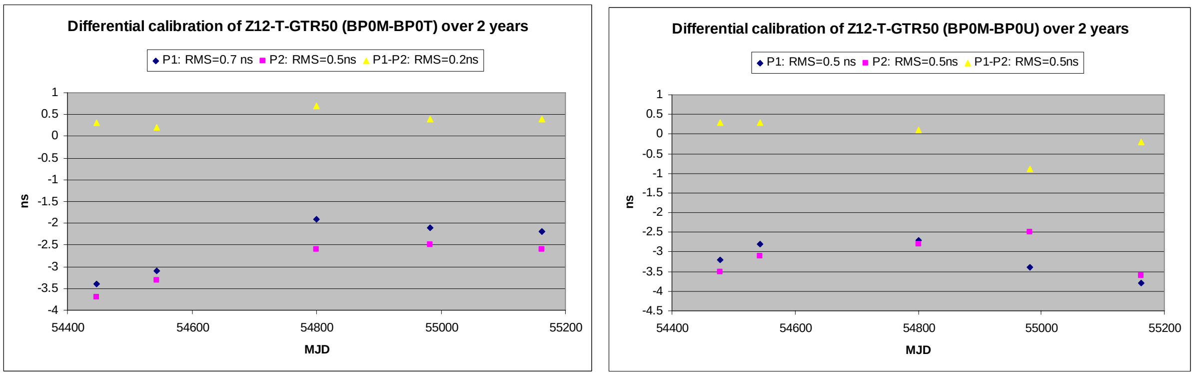

Figure 3: Long term comparison of differential calibration of the BP0M Z12-T system with two GTR50 (left: BP0T, right: BP0U).

We see that the long-term repeatability of a differential calibration exercise using this kind of systems is at a level of about 1 ns RMS for both P1 and P2. Because the differential calibration instability is caused both by the intrinsic instability of hardware delays and by the uncertainty in the manual measurements associated with the calibration (mostly that of the quantity X_O), the actual long term instability of hardware delays is necessarily slightly lower than that of the calibration results. We infer that the level of long-term instability may be at a level of order 0.7 ns RMS.

3. Conventional values for the hardware delays of BIPM systems

Originally, the Z12-T BP0C system was absolutely calibrated at the Naval Research laboratory [Petit et al., 2001b] and conventional values of (X_R + X_S) for this system were derived (see [Petit, 2002]). From the BP0C (X_R + X_S) values, we derive conventional values for all other BIPM systems.

After several years of parallel operation (see preceding section) we observe that the hardware delays of several geodetic receivers installed at the BIPM are stable at a level close to or below 1 ns RMS for all delays (P1, P2, P1-P2). We therefore use the average of all differential calibrations to derive conventional ($X_R + X_S$) values for all systems, shown in Table 1 (first page).

4. Uncertainties associated to the results of a differential calibration

We consider two cases:

1. Determination of the absolute value of ($X_{Ri} + X_{Si}$) for a system “S” by local comparison to the reference system “Ref”. This is named “equipment calibration” (EC). A time link between any two systems that have been calibrated by EC is also considered calibrated by “equipment calibration” EC-EC.
2. Determination of the differential value of ($X_{Ri} + X_{Si}$) for two systems “S1” and “S2” by comparison to the reference system “Ref” traveling from “S1” to “S2”. The time link S1-S2 is considered calibrated by “link calibration by traveling equipment” LC(TE).

In both cases, we compare a system “S” to a reference system “Ref” set-up with the same reference clock, by computing

$$(X_{Ri} + X_{Si})(S) = \Delta Pi + (X_{Ri} + X_{Si} + X_C - X_O - X_P)(Ref) - (X_C - X_O - X_P)(S) \qquad (1)$$

where ΔPi is the average difference of the pseudo-ranges at frequency Li, taking into account the different positions of the antenna phase centers.

The values of X_P (cable), X_C (cable) and, if necessary, X_O (additional measurement) are to be measured at each new set-up. Typical uncertainties are of order 0.3 ns for X_P or X_C, and 0.5 ns for X_O.

4.1 Equipment calibration

The values of ($X_R + X_S$) are typically presented as one result per frequency. Because the useful measurement are generally not the pseudo-ranges P1 and P2 at the two frequencies, but rather the ionosphere free pseudo-range P3 = 2.545xP1 – 1.545xP2 = P1 + 1.545x(P1-P2), it may be useful to express the results of calibration (values and uncertainties) as P1 and P1-P2. Particularly X_P, X_O and X_C should have similar effect on P1 and P2 so have a negligible contribution to the P1-P2 uncertainty.

We can estimate the uncertainty in the results of the differential calibration from the uncertainties of the different parts, as follows (see [Petit, 2002] for details):

	L1 or L2	L1-L2
ΔPi	0.1 ns	0.1 ns
($X_{Ri} + X_{Si}$)(Ref)	2.1 ns	2.0 ns
($X_C - X_O - X_P$)(Ref)	0.7 ns	0.0 ns
($X_C - X_O - X_P$)(Study)	0.7 ns	0.0 ns

We infer the following uncertainties for an equipment calibration:

($X_{Ri} + X_{Si}$)(Study)	2.3 ns	2.0 ns

From the P1 and (P1-P2) uncertainties, the uncertainty in a P3 equipment calibration is 3.8 ns.

If we consider a link between two systems with such an equipment calibration, assuming that the two results are completely independent, the u_B value of the link is 5.4 ns. In TAI computation, a conventional value of 5.0 ns is taken for such links.

4.2 Link calibration by traveling equipment

Equation (1) is written for both systems “S1” and “S2”. The difference yields:

$$(X_{\mathrm{Ri}} + X_{\mathrm{Si}})(\mathrm{S1{-}S2}) = \Delta \mathrm{Pi1} - \Delta \mathrm{Pi2} + (X_{\mathrm{C}} - X_{\mathrm{O}} - X_{\mathrm{P}})(\mathrm{Ref1}) - (X_{\mathrm{C}} - X_{\mathrm{O}} - X_{\mathrm{P}})(\mathrm{S1})$$
$$- (X_{\mathrm{C}} - X_{\mathrm{O}} - X_{\mathrm{P}})(\mathrm{Ref2}) + (X_{\mathrm{C}} - X_{\mathrm{O}} - X_{\mathrm{P}})(\mathrm{S2}) + \delta(X_{\mathrm{Ri}} + X_{\mathrm{Si}}) \qquad (2)$$

where Ref1/2 refers to the measurements of “Ref” at location 1/2 and where $\delta(X_{\mathrm{Ri}} + X_{\mathrm{Si}})$ represents possible variations of $(X_{\mathrm{Ri}} + X_{\mathrm{Si}})$ between the two measurements.

Similarly we estimate:

	L1 or L2	L1-L2
ΔPi (1/2)	0.1 ns	0.1 ns
$\delta(X_{\mathrm{Ri}} + X_{\mathrm{Si}})$(Ref)	1.0 ns	1.0 ns
$(X_{\mathrm{C}} - X_{\mathrm{O}} - X_{\mathrm{P}})$(Refi) (1/2)	0.7 ns	0.0 ns
$(X_{\mathrm{C}} - X_{\mathrm{O}} - X_{\mathrm{P}})$(Si (1/2)	0.7 ns	0.0 ns

We infer the following uncertainties for a link calibration:

$(X_{\mathrm{Ri}} + X_{\mathrm{Si}})$(S1-S2)	1.7 ns	1.0 ns

Here we take $\delta(X_{\mathrm{Ri}} + X_{\mathrm{Si}})(\mathrm{Ref}) = 1.0$ ns, from the long term instability obtained in section 2. Note that, in such link calibrations, the interval between the visits to the two systems is typically a few weeks, so that this uncertainty may be somewhat pessimistic.

From the P1 and (P1-P2) uncertainties, the uncertainty in the link calibration LC(TE) of the P3 link between the two systems is 2.3 ns.

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References

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