# CALIBRATION OF TWSTFT LINKS THROUGH THE TRIANGLE CLOSURE CONDITION

**Z. Jiang, W. Lewandowski**
**Bureau International des Poids et Mesures (BIPM)**
**Pavillon de Breteuil F-92312 Sèvres Cedex, France**
**E-mail:** ***zjiang@bipm.org***

**D. Piester**
**Physikalisch-Technische Bundesanstalt (PTB)**
**Bundesallee 100, D-38116 Braunschweig, Germany**

**Abstract**

***Nanosecond uncertainty TWSTFT (Two-Way Satellite Time and Frequency Transfer, TW for short) is, together with GPS time transfer, the primary technique used for UTC generation. The high accuracy of TW with a potential sub-nanosecond uncertainty is based on a metrological calibration which is, however, not only labor- and cost-intensive, but also limited by the complexity of the organization and the availability of equipment.***

***TW is operated in a network of which every link is measured independently. For an N-point network, there are N(N-1)/2 independent links, of which N-1 are UTC links and ($N^2$-3N+2)/2 redundant links. In this network, only a limited number of links were calibrated to enable true time transfer for UTC or other scientific applications.***

***In this paper, we present a strategy to calibrate the whole TW network by transferring the existing TW calibrations to the uncalibrated links using the so called triangle-closure condition. The uncertainty of a TW calibration is typical $u_B$=1 ns. The uncertainty of the triangle calibration is increased by a factor of about √2, corresponding to an effective uncertainty of about 2 ns for the redundant links, which is satisfactory at present for the metrological time transfer necessities.***

***Applying the triangle-closure condition, we computed all the non-UTC link calibrations and the results have been implemented in the European-American TW network since MJD 54677 (30 July 2008).***

## 1. INTRODUCTION

Acronyms used in this paper:

| | |
|---|---|
| AOS | Astrogeodynamical Observatory in Borowiec, Poland |
| BIPM | Bureau International des Poids et Mesures in Sèvres, France |
| CH | Federal Office of Metrology (METAS) in Bern-Wabern, Switzerland |
| IT | Istituto Nazionale di Ricerca Metrologica (INRIM) in Torino, Italy |
| NIST | National Institute of Standards and Technology in Boulder, Colorado, USA |

| | |
|---|---|
| OP | Laboratoire National de Metrologie et d'Essais–Observatoire de Paris, France |
| PTB | Physikalisch-Technische Bundesanstalt in Braunschweig, Germany |
| ROA | Real Instituto y Observatorio de la Armada, San Fernando, Spain |
| SP | Swedish National Testing and Research Institute in Borås, Sweden |
| USNO | US Naval Observatory in Washington, DC, USA |
| VSL | NMi Van Swinden Laboratorium BV in Delft, the Netherlands |
| GPS | Global Positioning System |
| TW | TWSTFT (Two-Way Satellite Time and Frequency Transfer) |
| CALR (i, j) | Calibration value in the TW data file **[1]**, CALR (i, j) = − CALR (j, i) |
| ESDVAR (i, j) | Earth station i delay variation vs. the station j in the ITU data file |
| TCC | Triangle closure calibration |
| $u_B$(*) | Calibration uncertainty of technique *, for example TW, GPS, or TCC |
| $u_A$(*) | Measurement uncertainty of technique * |
| UTC | Coordinated Universal Time. |

Organizing and maintaining the metrological calibration of the time transfer facilities contributing to UTC is among the responsibilities of the national timing laboratories and the BIPM. TW is, together with GPS, the primary time transfer technique for UTC generation. All the TW links used for UTC have been calibrated using one of the two methods **[2]**:

1) Aligning a TW link to a GPS link
2) Using a portable TW ground station.
3)

The total calibration uncertainty $u_B$ depends on the method employed:

1) $u_B$(GPS) is 5 ~ 7 ns. From TW and GPS inter-technique comparisons, the standard deviation of the residuals of TW-GPS alignment is on the order of 1 ns (cf. *ftp://tai.bipm.org/TimeLink/LkC*). Assuming a Gaussian distribution, the precision of the alignment is then $1/\sqrt{N}$ = 0.05 ns. N is the number of the common points used and is 360 for a complete month's data set. Compared to $u_B$(GPS), the alignment error is ignorable. We take usually $u_B$(GPS) as the total uncertainty of this method.

2) Various studies **[3-6]** prove that the measurement uncertainty $u_A$, the calibration uncertainty $u_B$, and the reproducibility are at the nanosecond level or below. So the total uncertainty for an operational link is U (TW) ≈ 1 ns. To illustrate the data base, the history of the TW calibrations organized for Europe-Europe and Europe-America time links between 1997 and 2007 is listed in Table 1.1.

Table 1.1. European and transatlantic TW calibrations using the portable stations (after **[4]**).

| Year | Participating institutes |
|---|---|
| 1997 | TUG, DTAG, PTB |
| 2002 | USNO, PTB |
| 2003 | USNO, PTB |
| 2003 | INRIM, PTB |
| 2004 | PTB, VSL, OP, NPL |
| 2004 | USNO, PTB |
| 2004 | USNO, PTB |
| 2005 | USNO, PTB |
| 2005 | PTB, SP, VSL, NPL, OP, IT |
| 2006 | USNO, PTB |
| 2006 | TUG, PTB, CH |
| 2007 | USNO, PTB |
| 2007 | USNO, PTB |

As mentioned, $u_B$(TW) is five times smaller than $u_B$(GPS). One reason is that unexplainable jumps at the nanosecond level occurred in the GPS time links **[7]**. This implies that the long-term stability or the reproducibility of the GPS calibrations is not always ensured at the nanosecond level. In view of the accuracy of the UTC time transfer, TW operation is more advantageous. However, until now (as shown in Table 1), only a part of the existing TW links has been calibrated so far, because a TW calibration is laborious and costly and limited by the availability of equipment and trained staff for the calibration campaigns.

The last pan-European calibration campaign was performed in 2006 **[5]**. Since then, due to the changes of telecommunication satellites or the transmit frequencies, many of the redundant link calibrations available at that time have been lost. In this paper, we present a calibration strategy by transferring the existing TW calibrations to the uncalibrated links using the so called triangle closure condition. Assuming $u_B$(TW) = 1 ns, the uncertainty of the triangle calibration is on the order of $\sqrt{2} \sim 2$ ns, satisfying at present for the metrological or most other scientific time transfer necessities. Note that recently a TW campaign was conducted to calibrate the links between TUG, PTB, NPL, OP, INRIM, METAS, and VSL. Once the results are available, it would be an independent test of the long-term stability of the TW as well as the TCC.

On the other hand, as a part of the pilot study of the GPS PPP links (time transfer using the GPS Precise Point Positioning technique) **[8]**, the BIPM computes and, since April 2008, publishes on its ftp site (*ftp://tai.bipm.org/TimeLink/LkC*) the inter-link comparison results between GPS PPP and TW time transfers. These results are important for the studies of $u_A$ and $u_B$. Because the TW and GPS links are independently measured, the comparison between TW and GPS PPP is helpful to study their short- and long-term behaviors. Calibrated links would be more useful than uncelebrated links for these studies, which is an additional motivation to carry out this calibration of the whole TW network.

## 2. PRINCIPLE OF THE TRIANGLE CLOSURE CALIBRATION (TCC)

Time scale differences between two laboratories can be computed according to Ref. **[1]** using

$$\begin{aligned} \mathrm{UTC}\,(\mathrm{Lab}_i) - \mathrm{UTC}\,(\mathrm{Lab}_j) = {} & \tfrac{1}{2}\,[\mathrm{TW}\,(\mathrm{Lab}_i) - \mathrm{TW}\,(\mathrm{Lab}_j)] \\ & + \tfrac{1}{2}\,[\mathrm{ESDVAR}\,(\mathrm{Lab}_i) - \mathrm{ESDVAR}\,(\mathrm{Lab}_i)] \\ & + \mathrm{REFDELAY}\,(\mathrm{Lab}_i) - \mathrm{REFDELAY}\,(\mathrm{Lab}_i) \\ & + \mathrm{CALR}\,(i,j) \end{aligned} \tag{2.0}$$

where TW is the counter reading in the TWSTFT station; ESDVAR the Earth station delay variation used to report known the changes in the setup of a TWSTFT ground station; REFDELAY the reference delay, the time difference between the local time scale, and the modem 1-pps output synchronous with its transmission signal; and CALR the calibration value, which has to be added to yield the true time difference between the two representations of UTC. For more details, see **[1]**. In the following we abbreviate ½ [TW($\mathrm{Lab}_i$) - TW($\mathrm{Lab}_j$)] = TW($\mathrm{Lab}_i$-$\mathrm{Lab}_j$) and neglect the REFDELAY. In a triangle closure it is justified if all measurements for the following data computation are recorded quasi at the same epoch. To perform a calibration is to determine the value of CALR (i,j) **[1]**. The sum of the CALR (i,j) and the TW (i,j) represents the modem clock difference between i and j (equation 2.2). Sometimes due to a change of the hardware setup, a modification of the calibration value is made and the corresponding correction is listed in the column ESDVAR. The value of the ESDVAR value is not a part of the link calibration exercise, but a monitor of the history of station delay changes. In European practice **[5]**, ESDVAR is reset to zero after each CALR calibration. In American practice **[9]**, keeping the original ESDVAR values is preferred. To simplify the explanation and computation, we first give the equations to compute the CALR value with the condition of ESDVAR = 0 (valid for the European stations) and then remove the non-zero ESDVAR values from the CALR determined as required by the American practice. This is, however, only a convention without any physical basis.

## 2.1 The Method of the TCC

The principle of the TCC is as follows: In a first step, all UTC links, i.e. the links with the UTC pivot laboratory PTB, are calibrated. In a second step, as one can see from Figures 2.1 and 3.1, any non-UTC link $Lab_i - Lab_j$ can be composed with the two adjacent UTC links $Lab_i - PTB$ and $Lab_j - PTB$. Because

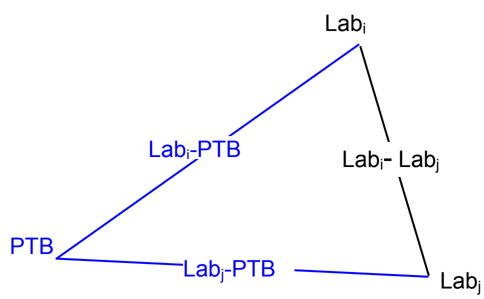


Figure 2.1. Non-UTC TW link calibration using the triangle closure condition.

all time scales UTC (Lab), i.e. all the clocks, are cancelled (equation 2.1), the sum of the three vectors in the triangle should be zero if link measurement errors and noise are neglected. This is the so-called ***triangle closure condition*** for TW redundant link calibration, i.e. TCC:

$$[\mathrm{UTC}\ (\mathrm{Lab}_i) - \mathrm{UTC}\ (\mathrm{PTB})] - [\mathrm{UTC}\ (\mathrm{Lab}_j) - \mathrm{UTC}\ (\mathrm{PTB})] + [\mathrm{UTC}\ (\mathrm{Lab}_j) - \mathrm{UTC}\ (\mathrm{Lab}_i)] = \mathbf{Closure} \Rightarrow \mathbf{0} \qquad (2.1)$$

Assuming the TW measurement is TW ($Lab_j - Lab_i$) and ESDVAR = 0, by the definition of CALR (i,j), we have:

$$\mathrm{UTC}\ (\mathrm{Lab}_j) - \mathrm{UTC}\ (\mathrm{Lab}_i) = \mathrm{TW}\ (\mathrm{Lab}_j - \mathrm{Lab}_i) + \mathrm{CALR}\ (j,i) = -\ [\mathrm{TW}\ (\mathrm{Lab}_i - \mathrm{Lab}_j) + \mathrm{CALR}(i,j)] \qquad (2.2)$$

Introducing equation (2.2) into (2.1)

$$[\mathrm{UTC}\ (\mathrm{Lab}_i) - \mathrm{UTC}\ (\mathrm{PTB})] - [\mathrm{UTC}\ (\mathrm{Lab}_j) - \mathrm{UTC}\ (\mathrm{PTB})] + [\mathrm{TW}\ (\mathrm{Lab}_j - \mathrm{Lab}_i) + \mathrm{CALR}\ (j,i)] = 0 \qquad (2.3)$$

Keeping the CALR and moving the other terms to the right:

$$\mathrm{CALR}\ (j,i) = [\mathrm{UTC}\ (\mathrm{Lab}_j) - \mathrm{UTC}\ (\mathrm{PTB})] - [\mathrm{UTC}\ (\mathrm{Lab}_i) - \mathrm{UTC}\ (\mathrm{PTB})] - \mathrm{TW}\ (\mathrm{Lab}_j\text{-}\mathrm{Lab}_i) \qquad (2.4)$$

Replacing the terms UTC with the calibrated TW links:

$$\mathrm{CALR}\ (i,j) = -\ \mathrm{CALR}\ (j,i) = \mathrm{TW}\ (\mathrm{Lab}_i - \mathrm{PTB}) - \mathrm{TW}\ (\mathrm{Lab}_j - \mathrm{PTB}) - \mathrm{TW}\ (\mathrm{Lab}_i - \mathrm{Lab}_j) \qquad (2.5a)$$

Equation (2.5a) is used for the computation of the CALR. This is based on the European practice of resetting ESDVAR = 0. The laboratories i and j keeping their non-zero ESDVAR (i,j) and/or ESDVAR (j,i) values for the link TW ($Lab_i - Lab_j$) should be removed from equation 2.5a (c.f. also eq. 2.0):

$$\text{CALR (i,j)} = -\text{CALR (j,i)} = \\ = \text{TW} (Lab_i - \text{PTB}) - \text{TW} (Lab_j - \text{PTB}) - \text{TW} (Lab_i - Lab_j) - [\text{ESDVAR (i,j)} - \text{ESDVAR (j,i)}]/2 \quad (2.5b)$$

## 2.2 THE UNCERTAINTY: $u_B$(TCC)

First, according to the definition of ESDVAR, it does not contribute to the $u_B$(TCC) budget. After the calibration, the non-zero closure is nothing but the TW link measurement errors which can be characterized by the statistics of the triangle closures. Obviously, in order to reduce the influence of the TCC error, the number of the triangles used should be big enough so as to average out the measurement noises and the short-term periodic variation, such as the diurnals. The typical UTC month (30 days) is used for the TCC computation. For a complete TW schedule, there are 12 measurements per day and totally about 360 measurements per month. For each triangle, there is a TCC calibration given by equation (2.5a). Suppose ε is the uncertainty of the mean value; we have the total uncertainty of the TCC:

$$u_B(\text{TCC}) = \sqrt{\{u_{Bi}^2 + u_{Bj}^2 + \varepsilon^2\}} \quad (2.6)$$

Here, $u_i$ and $u_j$ are respectively the calibration uncertainties of the related UTC links:

$$u_{Bi} = u_B\,[\text{UTC} (Lab_i) - \text{UTC (PTB)}] \quad (2.7a)$$
$$u_{Bj} = u_B\,[\text{UTC} (Lab_j) - \text{UTC (PTB)}] \quad (2.7b)$$

ε can be determined by the standard deviation of the mean of the CALR, supposing the closures to obey the normal (Gaussian) distribution for a large number of data. In the following histograms (Figures 2.2.1 to 2.2.6), there are some examples of the closures. From them, it appears that the closures caused by the measurement noises are of Gaussian distribution in the UTC monthly data sample. An approximate estimation is $u_A/\sqrt{N}$. Here, we estimate $u_A$= 0.5 ns as the typical TW measurement uncertainty **[2]** and N ≈ 360 is the number of the closures. We obtain ε ≈ 0.02 ns, which is negligibly small. We analyzed all the closures produced by the 360 × 35 triangles and find that the closures can be assumed to be Gaussian distributed.

Figures 2.2.1 to 2.2.6 depict the histograms of triangle closures. There are triangles of intra-Europe as well as transatlantic. These data were used for the TCC computation as described in Section 3. The mean values are approximately zero. The standard deviations vary from 0.24 ns to 0.51 ns. Table 3.1 in the next section displays the statistical results of all 35 triangles. However, some of the histograms are not characterized as a typical normal distribution; an example is shown in Figure 2.2.3 for the triangle PTB – SP − USNO. It seems that some deviations of 100 ~ 200 ps exist due to unknown reasons.

```
PicoSec|No.|
   -875|  1| +
   -750|  1| +
   -625|  7| +++++++
   -500| 22| ++++++++++++++++++++++
   -375| 17| +++++++++++++++++
   -250| 41| +++++++++++++++++++++++++++++++++++++++++
   -125| 54| ++++++++++++++++++++++++++++++++++++++++++++++++++++++
      0| 60| ++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
    125| 52| ++++++++++++++++++++++++++++++++++++++++++++++++++++
    250| 36| ++++++++++++++++++++++++++++++++++++
    375| 32| ++++++++++++++++++++++++++++++++
    500| 18| ++++++++++++++++++
    625|  2| ++
    750|  6| ++++++
    875|  1| +
   1000|  0|
   1125|  1| +
```

Figure 2.2.1. Histogram of triangle closures Δ PTB – CH – IT; N = 351, Std = 484 ps. The vertical axes: PicoSec is the interval in picoseconds and No. is the number of the closures fall in an interval. N and Std are the total number and the standard deviation of the closures respectively. The same legend is applied in the following figures.

```
PicoSec|No.|
  -1125|  1| +
  -1000|  1| +
   -875|  1| +
   -750|  5| +++++
   -625|  8| ++++++++
   -500| 21| +++++++++++++++++++++
   -375| 25| +++++++++++++++++++++++++
   -250| 33| +++++++++++++++++++++++++++++++++
   -125| 53| +++++++++++++++++++++++++++++++++++++++++++++++++++++
      0| 59| +++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
    125| 55| +++++++++++++++++++++++++++++++++++++++++++++++++++++++
    250| 36| ++++++++++++++++++++++++++++++++++++
    375| 19| +++++++++++++++++++
    500| 15| +++++++++++++++
    625| 10| ++++++++++
    750|  5| +++++
    875|  2| ++
   1000|  2| ++
```

Figure 2.2.2. Histogram of triangle closures Δ PTB – IT – USNO; N = 351, Std = 336 ps.

```
PicoSec|No.|
  -1750|  1| +
  -1625|  1| +
  -1500|  2| ++
  -1375|  1| +
  -1250|  5| +++++
  -1125|  5| +++++
  -1000|  7| +++++++
   -875| 11| +++++++++++
   -750| 15| +++++++++++++++
   -625|  7| +++++++
   -500| 12| ++++++++++++
   -375| 22| ++++++++++++++++++++++
   -250| 22| ++++++++++++++++++++++
   -125| 42| ++++++++++++++++++++++++++++++++++++++++++
      0| 31| +++++++++++++++++++++++++++++++
    125| 38| ++++++++++++++++++++++++++++++++++++++
    250| 34| ++++++++++++++++++++++++++++++++++
    375| 40| ++++++++++++++++++++++++++++++++++++++++
    500| 33| +++++++++++++++++++++++++++++++++
    625| 29| +++++++++++++++++++++++++++++
    750|  9| +++++++++
    875|  6| ++++++
   1000|  1| +
```

Figure 2.2.3. Histogram of triangle closures Δ PTB – SP − USNO; N = 374, Std = 515 ps. It is not a typical normal distribution. Biases exist due to unknown reasons.

```
PicoSec|No.|
   -875|  1| +
   -750|  4| ++++
   -625| 10| ++++++++++
   -500| 12| ++++++++++++
   -375| 23| +++++++++++++++++++++++
   -250| 55| +++++++++++++++++++++++++++++++++++++++++++++++++++++++
   -125| 48| ++++++++++++++++++++++++++++++++++++++++++++++++
      0| 53| +++++++++++++++++++++++++++++++++++++++++++++++++++++
    125| 43| +++++++++++++++++++++++++++++++++++++++++++
    250| 49| +++++++++++++++++++++++++++++++++++++++++++++++++
    375| 34| ++++++++++++++++++++++++++++++++++
    500| 15| +++++++++++++++
    625|  6| ++++++
    750|  1| +
    875|  2| ++
   1000|  1| +
```

Figure 2.2.4. Histogram of triangle closures Δ PTB – OP – USNO; N = 357, Std = 311 ps.

```
PicoSec|No.|
  -1250|  2| ++
  -1125|  1| +
  -1000|  1| +
   -875|  6| ++++++
   -750|  6| ++++++
   -625| 12| ++++++++++++
   -500| 19| +++++++++++++++++++
   -375| 27| +++++++++++++++++++++++++++
   -250| 32| ++++++++++++++++++++++++++++++++
   -125| 50| ++++++++++++++++++++++++++++++++++++++++++++++++++
      0| 45| +++++++++++++++++++++++++++++++++++++++++++++
    125| 43| +++++++++++++++++++++++++++++++++++++++++++
    250| 40| ++++++++++++++++++++++++++++++++++++++++
    375| 28| ++++++++++++++++++++++++++++
    500| 19| +++++++++++++++++++
    625| 14| ++++++++++++++
    750|  7| +++++++
    875|  4| ++++
   1000|  2| ++
   1125|  0|
   1250|  1| +
```

Figure 2.2.5. Histogram of triangle closures Δ PTB – IT – NIST; N = 359, Std = 398 ps.

```
PicoSec|No.|
   -625|  5| +++++
   -500|  9| +++++++++
   -375| 19| +++++++++++++++++++
   -250| 52| ++++++++++++++++++++++++++++++++++++++++++++++++++++
   -125| 57| +++++++++++++++++++++++++++++++++++++++++++++++++++++++++
      0| 79| +++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
    125| 72| ++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
    250| 35| +++++++++++++++++++++++++++++++++++
    375| 19| +++++++++++++++++++
    500| 12| ++++++++++++
    625|  3| +++
    750|  2| ++
```

Figure 2.2.6. Histogram of triangle closures Δ PTB – OP – SP; N = 364, Std = 245 ps.

Table 2.2.1. Uncertainties estimated for the normal and worst cases / ns.

| Term | normal case | worst case |
|---|---|---|
| $u_B(GPS)$ | 5 | 5 |
| $u_B(TW)$ | 1 | 1.2 |
| ε | 0.02 | 1.2 |

Now let us fill in the values in the uncertainty estimation equation (2.6). From Section 6 of BIPM Circular T 244 **[2]** and **[4]**, we take the calibration uncertainty as $u_B(TW)$ = 1 ns and $u_B(GPS)$ = 5 ns. ε is estimated to be about 0.02 ns, as mentioned above. Taking into account the worst cases, for example the closures are not white, etc., we list in Table 2.2.1 the estimated uncertainties for the normal and the worst cases (in a conservative approach) and fill the values in equations (2.6). It turns out, for the TW-GPS mixed triangles:

$$u_{B1}(TCC)_{normal} = \sqrt{\{5^2+1^2+0.02^2\}} = 5.10\text{ ns} < u_{B1}(TCC)_{worst} = \sqrt{\{5^2+1.2^2+1^2\}} = 5.24\text{ ns} < \mathbf{6\ ns} \qquad (2.8)$$

and for the TW triangles:

$$u_{B2}(TCC)_{normal} = \sqrt{\{1^2+1^2+0.02^2\}} = 1.41\text{ ns} < u_{B2}(TCC)_{worst} = \sqrt{\{1.2^2+1.2^2+1^2\}} = 1.97\text{ ns} < \mathbf{2\ ns} \qquad (2.9)$$

The values on the right-hand of equation (2.8) and (2.9) give the rounded TCC uncertainty estimations. It should be pointed out that there are GPS − GPS calibration triangles; for example, the link NIST − ROA (Figure 3.1). By imposing the TCC condition, the pivot GPS receiver at PTB is cancelled. Its influence to the calibration is negligible. The TCC becomes similar to that of the GPS alignment. In practice, we assign the $u_B(GPS) = 5$ ns to the GPS alignment calibration. Therefore, the $u_B$ of GPS − GPS triangle is grouped into the GPS − TW mixed calibration; that is, 6 ns. Thus, we have the TCC uncertainties:

Table 2.2.2. The TCC uncertainty $u_B(TCC)$*/ ns

| Labs/Links | $u_B(TCC)$ |
|---|---|
| AOS, NIST, ROA concerned links with PTB, USNO, OP, IT, VSL, CH, SP | 6 |
| all the other links in Table 4a and 4b | 2 |

* See Tables 4a and 4b below for the $u_B(TCC)$ of all the links.

## 3. THE DATA SET

We use the data of April 2008 (MJD 54554-54584, BIPM designation: TW0804). There are N = 10 TW laboratories involved: AOS, CH, IT, NIST, OP, PTB, ROA, SP, USNO and VSL. Figure 3.1 displays the status of the TW links. Except for the link between NIST and USNO, all the links are available: nine UTC links of which six are calibrated with TW equipment (blue lines) and three are calibrated with an alignment to GPS (red lines). The number of the redundant links to be calibrated is 35.

To compose the triangles, we have to form the triples of TW measurements at common epochs. This was done by interpolating the measured values to the nearest TW scheduling epochs. The maximum interpolation interval is 3 hours. The NIST − PTB schedule was used for this purpose. A triangle is composed only when all the three epochs, i.e. all the three links, are available. For AOS, the TW0804 was the first month to be used as a UTC time link and the data of the first days were missing.

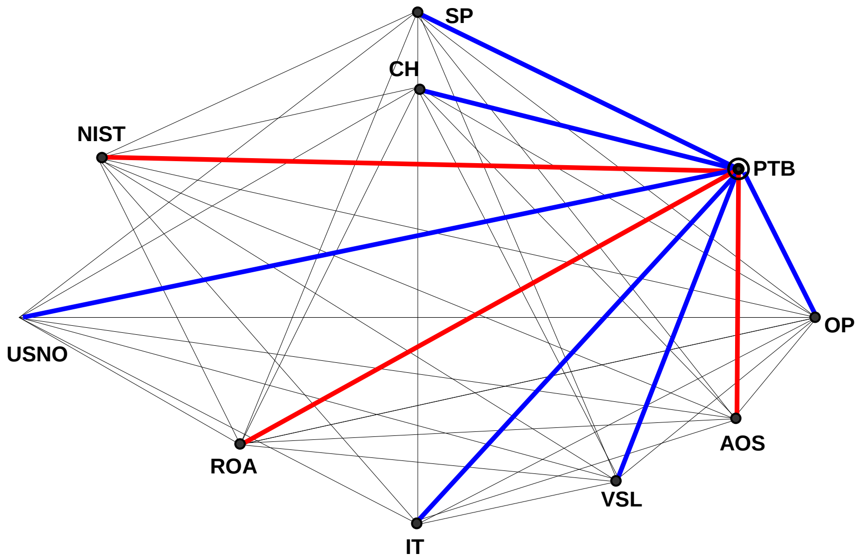


Figure 3.1. Status of the TW network of Apr. 2008, MJD 54554-54584. There are 10 UTC laboratories. The nine color lines are UTC links: the six blue are TW calibrations and the three red are GPS calibrations. The 35 black lines are to be TCC-calibrated.

Table 3.1 shows the statistics of the 35 independent triangle closures after the calibration. Here, N is the number of the triangles, varying from 172 to 384 and giving an idea of the data base of each TCC. RMS is the root mean square and Std is the standard deviation. The mean values are almost zero, except a few non-zero values due to rounding errors in the computation. The RMS and Std are equal to each other at the 10-ps level. The RMS varies from about 0.18 to 0.63 ns except for the seven VSL-involved triangles, whose RMS values are bigger than 1 ns (the worst case estimation in equations 2.8 and 2.9). The numbers of the VSL-related triangles are only about 230, compared with the nominal number of 360. A closer look at these links shows that they appear less accurate than usual. As shown in Table 3.1, big outliers up to 7 ns exist in the columns Min (minimum) and Max (Maximum). The smallest is 0.18 ns for the triangle number 17: PTB – IT − OP. As a summary, the inner-Europe triangles (accompanied with short baselines) have slightly smaller closures than the transatlantic triangles.

Table 3.1. Statistics of the triangle closures after TCC / ns (**N** is the number of the triangles, **RMS** is the root mean squares, **Std** is the standard deviation).

| | Triangles | | N | Min | Max | Mean | RMS | Std |
|---|---|---|---|---|---|---|---|---|
| 1 | T PTB AOS CH | : | 288 | -0.95 | 0.62 | 0.00 | 0.23 | 0.23 |
| 2 | T PTB AOS IT | : | 344 | -0.97 | 1.00 | 0.00 | 0.31 | 0.31 |
| 3 | T PTB AOS NIST | : | 326 | -0.82 | 1.53 | 0.00 | 0.33 | 0.33 |
| 4 | T PTB AOS OP | : | 329 | -0.92 | 0.98 | 0.00 | 0.32 | 0.32 |
| 5 | T PTB AOS ROA | : | 241 | -1.18 | 1.99 | 0.00 | 0.40 | 0.40 |
| 6 | T PTB AOS SP | : | 348 | -1.52 | 1.57 | 0.00 | 0.53 | 0.53 |
| 7 | T PTB AOS USNO | : | 277 | -0.83 | 1.02 | 0.00 | 0.29 | 0.29 |
| 8 | T PTB AOS VSL | : | 231 | -1.24 | 1.53 | 0.00 | 0.48 | 0.48 |
| 9 | T PTB CH IT | : | 357 | -7.12 | 1.07 | -0.01 | 0.48 | 0.48 |
| 10 | T PTB CH NIST | : | 384 | -6.09 | 1.08 | -0.02 | 0.42 | 0.42 |
| 11 | T PTB CH OP | : | 367 | -7.63 | 1.35 | -0.06 | 0.52 | 0.51 |
| 12 | T PTB CH ROA | : | 172 | -1.87 | 3.62 | 0.01 | 0.58 | 0.58 |
| 13 | T PTB CH SP | : | 377 | -7.37 | 1.51 | 0.02 | 0.63 | 0.63 |
| 14 | T PTB CH USNO | : | 375 | -5.68 | 1.00 | 0.00 | 0.43 | 0.43 |
| 15 | T PTB CH VSL | : | 245 | -4.99 | 5.38 | 0.13 | 1.14 | 1.13 |
| 16 | T PTB IT NIST | : | 360 | -1.25 | 1.26 | 0.00 | 0.40 | 0.40 |
| 17 | T PTB IT OP | : | 343 | -1.08 | 0.82 | 0.00 | 0.18 | 0.18 |
| 18 | T PTB IT ROA | : | 292 | -0.80 | 1.74 | 0.00 | 0.25 | 0.25 |
| 19 | T PTB IT SP | : | 359 | -1.02 | 0.68 | 0.00 | 0.23 | 0.23 |
| 20 | T PTB IT USNO | : | 351 | -1.07 | 1.00 | 0.00 | 0.34 | 0.34 |
| 21 | T PTB IT VSL | : | 236 | -1.71 | 5.76 | 0.00 | 1.00 | 1.00 |
| 22 | T PTB NIST OP | : | 367 | -0.78 | 0.92 | 0.00 | 0.29 | 0.29 |
| 23 | T PTB NIST ROA | : | 316 | -1.08 | 1.65 | 0.00 | 0.44 | 0.44 |
| 24 | T PTB NIST SP | : | 384 | -0.83 | 1.68 | 0.00 | 0.49 | 0.49 |
| 25 | T PTB NIST VSL | : | 246 | -4.64 | 7.19 | 0.00 | 1.57 | 1.57 |
| 26 | T PTB OP ROA | : | 297 | -0.59 | 1.69 | 0.00 | 0.27 | 0.27 |
| 27 | T PTB OP SP | : | 365 | -0.66 | 0.73 | 0.00 | 0.25 | 0.25 |
| 28 | T PTB OP USNO | : | 358 | -0.89 | 0.96 | 0.00 | 0.31 | 0.31 |
| 29 | T PTB OP VSL | : | 232 | -2.05 | 5.34 | 0.00 | 1.24 | 1.24 |
| 30 | T PTB ROA SP | : | 314 | -1.02 | 1.23 | 0.00 | 0.31 | 0.31 |
| 31 | T PTB ROA USNO | : | 306 | -1.76 | 1.03 | 0.00 | 0.44 | 0.44 |
| 32 | T PTB ROA VSL | : | 217 | -2.10 | 5.36 | 0.00 | 1.31 | 1.31 |
| 33 | T PTB SP USNO | : | 374 | -1.72 | 0.96 | 0.00 | 0.52 | 0.52 |
| 34 | T PTB SP VSL | : | 245 | -2.45 | 6.02 | 0.00 | 1.36 | 1.36 |
| 35 | T PTB USNO VSL | : | 235 | -1.80 | 7.03 | 0.00 | 1.55 | 1.55 |

## 4. THE TCC CALIBRATION RESULTS: CALR

Now we determine the calibration results, i.e. the CALR to be reported in the TW data files (see **[1]**). As discussed in Section 2.1, there are two cases:

1) Use equation 2.5a to determine the CALR with ESDVAR = 0 (Table 4a)
2) Use equation 2.5b to determine the CALR keeping the original ESDVAR value (Table 4b).

In the first case, when an ESDVAR value is not measured or not available, it should be filled up with 9999.999. The CALR and ESDVAR values are listed respectively in Table 4a and 4b. The column S is

Table 4a. Calibrated CALR Values for non-UTC links / ns (for the Laboratories, their ESDVAR values are stated as 99999.999).

| Labi | Labj | S | CARL | Std | ESDVAR | N | ε | $u_B$ |
|---|---|---|---|---|---|---|---|---|
| AOS | CH | 1 | 21.039 | 0.227 | 99999.999 | 288 | 0.013 | 6 |
| CH | AOS | 1 | -21.039 | 0.227 | 99999.999 | 288 | 0.013 | 6 |
| AOS | IT | 1 | 132.777 | 0.313 | 99999.999 | 344 | 0.017 | 6 |
| IT | AOS | 1 | -132.777 | 0.313 | 99999.999 | 344 | 0.017 | 6 |
| AOS | OP | 1 | 7133.267 | 0.320 | 99999.999 | 329 | 0.018 | 6 |
| OP | AOS | 1 | -7133.267 | 0.320 | 99999.999 | 329 | 0.018 | 6 |
| AOS | ROA | 1 | 105.365 | 0.400 | 99999.999 | 241 | 0.026 | 6 |
| ROA | AOS | 1 | -105.365 | 0.400 | 99999.999 | 241 | 0.026 | 6 |
| AOS | SP | 1 | 4.478 | 0.533 | 99999.999 | 348 | 0.029 | 6 |
| SP | AOS | 1 | -4.478 | 0.533 | 99999.999 | 348 | 0.029 | 6 |
| AOS | VSL | 1 | 117.862 | 0.478 | 99999.999 | 231 | 0.031 | 6 |
| VSL | AOS | 1 | -117.862 | 0.478 | 99999.999 | 231 | 0.031 | 6 |
| CH | IT | 1 | 110.859 | 0.484 | 99999.999 | 357 | 0.026 | 2 |
| IT | CH | 1 | -110.859 | 0.484 | 99999.999 | 357 | 0.026 | 2 |
| CH | OP | 1 | 7112.132 | 0.513 | 99999.999 | 367 | 0.027 | 2 |
| OP | CH | 1 | -7112.132 | 0.513 | 99999.999 | 367 | 0.027 | 2 |
| CH | ROA | 1 | 83.825 | 0.585 | 99999.999 | 172 | 0.045 | 6 |
| ROA | CH | 1 | -83.825 | 0.585 | 99999.999 | 172 | 0.045 | 6 |
| CH | SP | 1 | -16.414 | 0.625 | 99999.999 | 377 | 0.032 | 2 |
| SP | CH | 1 | 16.414 | 0.625 | 99999.999 | 377 | 0.032 | 2 |
| CH | VSL | 1 | 96.498 | 1.130 | 99999.999 | 245 | 0.072 | 2 |
| VSL | CH | 1 | -96.498 | 1.130 | 99999.999 | 245 | 0.072 | 2 |
| IT | OP | 1 | 7000.408 | 0.185 | 99999.999 | 343 | 0.010 | 2 |
| OP | IT | 1 | -7000.408 | 0.185 | 99999.999 | 343 | 0.010 | 2 |
| IT | ROA | 1 | -27.984 | 0.246 | 99999.999 | 292 | 0.014 | 6 |
| ROA | IT | 1 | 27.984 | 0.246 | 99999.999 | 292 | 0.014 | 6 |
| IT | SP | 1 | -128.372 | 0.232 | 99999.999 | 359 | 0.012 | 2 |
| SP | IT | 1 | 128.372 | 0.232 | 99999.999 | 359 | 0.012 | 2 |
| IT | VSL | 1 | -14.696 | 0.998 | 99999.999 | 236 | 0.065 | 2 |
| VSL | IT | 1 | 14.696 | 0.998 | 99999.999 | 236 | 0.065 | 2 |
| OP | ROA | 1 | -7028.065 | 0.271 | 99999.999 | 297 | 0.016 | 6 |
| ROA | OP | 1 | 7028.065 | 0.271 | 99999.999 | 297 | 0.016 | 6 |
| OP | SP | 1 | -7128.663 | 0.245 | 99999.999 | 365 | 0.013 | 2 |
| SP | OP | 1 | 7128.663 | 0.245 | 99999.999 | 365 | 0.013 | 2 |
| OP | VSL | 1 | -7015.433 | 1.245 | 99999.999 | 232 | 0.082 | 2 |
| VSL | OP | 1 | 7015.433 | 1.245 | 99999.999 | 232 | 0.082 | 2 |
| ROA | SP | 1 | -100.440 | 0.307 | 99999.999 | 314 | 0.017 | 6 |
| SP | ROA | 1 | 100.440 | 0.307 | 99999.999 | 314 | 0.017 | 6 |
| ROA | VSL | 1 | 12.746 | 1.305 | 99999.999 | 217 | 0.089 | 6 |
| VSL | ROA | 1 | -12.746 | 1.305 | 99999.999 | 217 | 0.089 | 6 |
| SP | VSL | 1 | 113.117 | 1.361 | 99999.999 | 245 | 0.087 | 2 |
| VSL | SP | 1 | -113.117 | 1.361 | 99999.999 | 245 | 0.087 | 2 |

the calibration identifier. S = 1 means that equation (2.0) can be used. Alternatives are described in Ref. **[1]**. Std is the standard deviation of the closures. As defined in Section 2.2, ε is the standard deviation of the TCC given in the tables. N is the number of triangles used. $u_B$ is the total uncertainty of the TCC CALR value (c.f. Table 2.2.2). The CALR values were implemented by all the TW laboratories since UTC 0 h of MJD 54677, 30 July 2008 (see **[10]** for the operational details).

Table 4b. The calibrated CALR values for non-UTC links / ns (for the Laboratories whose ESDVAR values are available).

| Labi | Labj | S | CARL | Std | ESDVAR | N | ε | $u_B$ |
|---|---|---|---|---|---|---|---|---|
| NIST | AOS | 1 | 154.480 | 0.335 | 224.040 | 326 | 0.019 | 6 |
| AOS | NIST | 1 | -154.480 | 0.335 | 99999.999 | 326 | 0.019 | 6 |
| USNO | AOS | 1 | 403.432 | 0.286 | -387.250 | 277 | 0.017 | 6 |
| AOS | USNO | 1 | -403.432 | 0.286 | 99999.999 | 277 | 0.017 | 6 |
| NIST | CH | 1 | 176.060 | 0.420 | 224.040 | 384 | 0.021 | 6 |
| CH | NIST | 1 | -176.060 | 0.420 | 99999.999 | 384 | 0.021 | 6 |
| USNO | CH | 1 | 425.057 | 0.426 | -387.250 | 375 | 0.022 | 2 |
| CH | USNO | 1 | -425.057 | 0.426 | 99999.999 | 375 | 0.022 | 2 |
| NIST | IT | 1 | 285.833 | 0.398 | 224.040 | 360 | 0.021 | 6 |
| IT | NIST | 1 | -285.833 | 0.398 | 99999.999 | 360 | 0.021 | 6 |
| USNO | IT | 1 | 534.735 | 0.336 | -387.250 | 351 | 0.018 | 2 |
| IT | USNO | 1 | -534.735 | 0.336 | 99999.999 | 351 | 0.018 | 2 |
| NIST | OP | 1 | 7287.687 | 0.292 | 224.040 | 367 | 0.015 | 6 |
| OP | NIST | 1 | -7287.687 | 0.292 | 99999.999 | 367 | 0.015 | 6 |
| NIST | ROA | 1 | 258.436 | 0.437 | 224.040 | 316 | 0.025 | 6 |
| ROA | NIST | 1 | -258.436 | 0.437 | 99999.999 | 316 | 0.025 | 6 |
| NIST | SP | 1 | 159.322 | 0.495 | 224.040 | 384 | 0.025 | 6 |
| SP | NIST | 1 | -159.322 | 0.495 | 99999.999 | 384 | 0.025 | 6 |
| NIST | VSL | 1 | 273.323 | 1.569 | 224.040 | 246 | 0.100 | 6 |
| VSL | NIST | 1 | -273.323 | 1.569 | 99999.999 | 246 | 0.100 | 6 |
| USNO | OP | 1 | 7536.583 | 0.311 | -387.250 | 358 | 0.016 | 2 |
| OP | USNO | 1 | -7536.583 | 0.311 | 99999.999 | 358 | 0.016 | 2 |
| USNO | ROA | 1 | 507.564 | 0.440 | -387.250 | 306 | 0.025 | 6 |
| ROA | USNO | 1 | -507.564 | 0.440 | 99999.999 | 306 | 0.025 | 6 |
| USNO | SP | 1 | 408.247 | 0.515 | -387.250 | 374 | 0.027 | 2 |
| SP | USNO | 1 | -408.247 | 0.515 | 99999.999 | 374 | 0.027 | 2 |
| USNO | VSL | 1 | 522.444 | 1.547 | -387.250 | 235 | 0.101 | 2 |
| VSL | USNO | 1 | -522.444 | 1.547 | 99999.999 | 235 | 0.101 | 2 |

# 5. EVALUATION OF THE NEW CALIBRATION AND DISCUSSIONS

## 5.1 EVALUATION

After the last satellite change happened in February 2008, most of the non-UTC link calibrations were lost. From cooperation of the BIPM and the related TW laboratories, some of them were successfully recovered using the GPS carrier-phase bridges **[9]**. Table 5 is a comparison of the three CALR values in Table 4a and that obtained by the bridging computation. The uncertainty of the bridged CALR values is estimated as about 1.5 ns and that in Table 4a as 2 ns. Then the tolerance of the difference is $[(1.5 \text{ ns})^2 + (2 \text{ ns})^2]^{1/2} = 2.5$ ns (1−σ).

Table 5. Differences between the TW calibration and the TCC / ns.

| Link | CALR Bridged | CALR in Tab.4a | Difference | Tolerance |
|---|---|---|---|---|
| SP-OP | 7127.8 ±1.5 | 7128.7 ±2 | -1.1 | ± 2.5 |
| VSL-OP | 2014.5 ±1.5 | 2015.4 ±2 | -0.9 | ± 2.5 |
| IT-OP | -1.0 ±1.5 | 0.4 ±2 | -1.4 | ± 2.5 |

The differences are −1.1, −0.9 and −1.4 and thus well below 2.5 ns. If taking a closer look, the differences are all negative with a mean of −1.1 ns. This implies that these discrepancies come from rather a systematic bias whose amplitude is about 1 ns. The bias may be due to the calibration variations or the bridging errors or other causes. Anyway, the differences are probably not caused by the triangle closure errors, which are dominated by measurement uncertainty and are random.

## 5.2 Discussion

### 5.2.1 Tendency and Correlation in the Closures

In Section 2.2, we analyzed the statistic characteristics of the triangle closures based on the large samples. The figures in this section illustrate the time-dependent behavior of the closures. Below is only a general view on this topic. The goal is to find the size of the data sample, which should be big enough to average out the noises and possible biases existing in the triangle closures.

Figure 5.2.1a displays the closures of a time series of 30 days. They are of the same closures depicted in the histogram in Figure 2.2.5 from the transatlantic triangle PTB – IT − NIST. The arbitrarily chosen high-order polynomial fit gives the tendency of variation in the closures (the blue curve). The variation has an amplitude of about 200 ps and suggests a periodicity of about 25 days. Figure 5.2.1b enlarges the part between MJD 54560-54570. The red curve is a two-term periodic approximation. In addition to the 25-days periodic tendency, the adjacent points seem correlated and present a diurnal-like variation, of which the amplitude is about 200 ps.

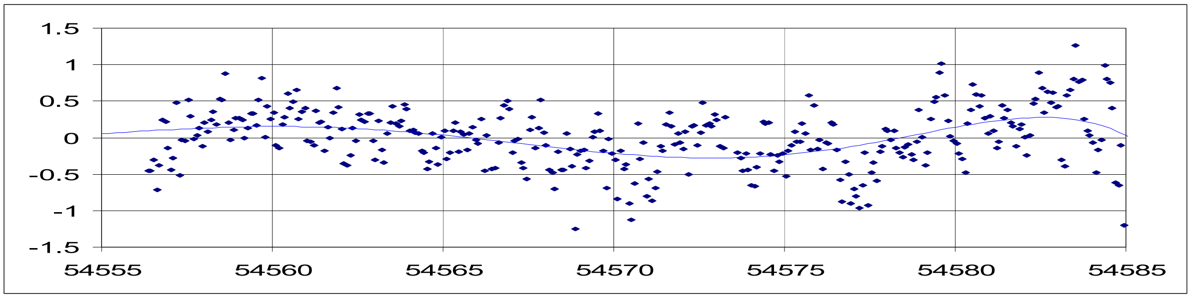


Figure 5.2.1a. Triangle closure of Δ PTB – IT − NIST in the data set UTC 0804 (MJD 54556-54585) corresponding to Figure 2.2.5; N = 359, Std = 398 ps. The blue curve is a 6th-order polynomial fit.

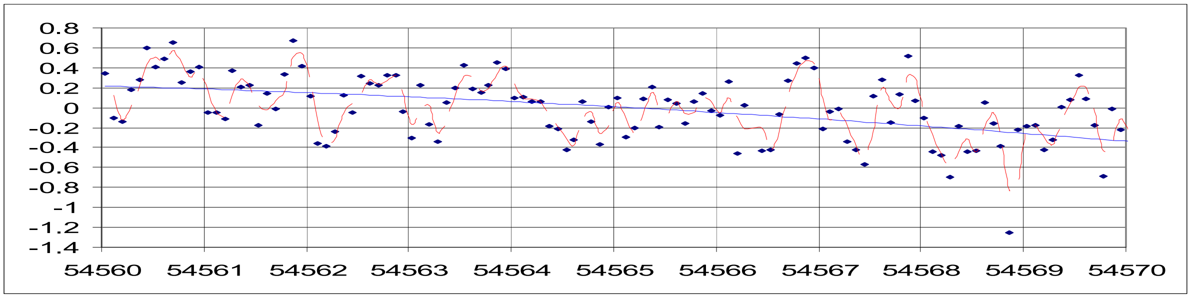


Figure 5.2.1b. Enlarged part of Figure 5.2.1a: Triangle closure of Δ PTB – IT − NIST of MJD 54560-54570. The blue curve is the polynomial fit. The red curve is a two-term periodic approximation.

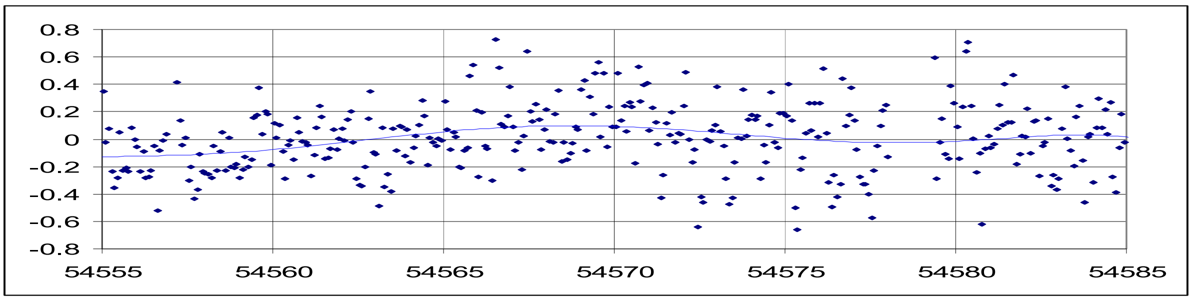


Figure 5.2.2a. Triangle closure Δ PTB – OP − SP in the data set UTC 0804 (MJD 54555-54585) corresponding to Figure 2.2.6; N = 364, Std = 245 ps. The blue curve is a 6$^{th}$-order polynomial fit.

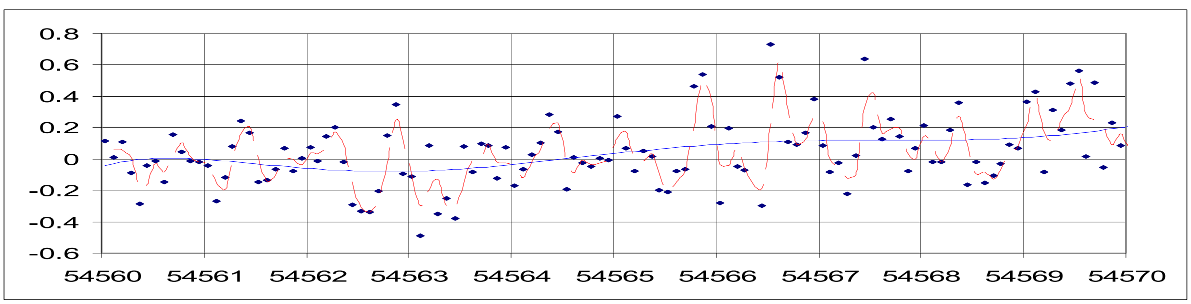


Figure 5.2.2b. Enlarged part of Figure 5.2.2a: Triangle closure Δ PTB – OP − SP of MJD 54560-54570. The blue curve is the polynomial fit. The red curve is a two-term periodic approximation.

Similar remarks can be made by looking at the Figure 5.2.2a and b. They correspond to the histogram in Figure 2.2.6 for Δ PTB – OP − SP. In this intra-Europe triangle, again a 25-day periodic term and the diurnal-like variations appear with similar amplitude. The baseline lengths of the triangles correlate with the measurement noises, the standard deviation for the Δ PTB – IT − NIST is 398 ps, and that of Δ PTB – OP − SP is 245 ps. But it seems that the periodic signal characters do not depend strongly on the distance.

From equation (2.1), the definition of the closure, the periodic tendencies of different wavelengths could be anything but the clocks. The goal of this paper is not to investigate the closures' behavior. More detailed studies can be found **[11-13,4]**. Our question is whether these tendencies have an influence on the TCC result. We conclude that the tendencies can be averaged out in one month's data. Although the closures do not show a typical Gaussian distribution, the mean values are good enough for the CALR determination, because the sample is big enough.

### 5.2.2 Future Calibration and Recalibration

A procedure for the GPS-TW time link calibration was developed at BIPM and installed in the UTC calculation software Tsoft. BIPM is ready to supply the calibration services in the following cases:

1. Supporting the change of satellites or frequencies, as happened in February 2008. Because all the TW laboratories are backed up by GPS PPP (except for AOS at present), it is suggested that GPS PPP solutions be used to bridge the TW UTC links and then transfer the UTC link calibration to the non-UTC links by employing the TCC;
2. Recalibration of TW links;
3. Implementation of new TW ground stations;
4. Transferring the procedure to the Asian-Pacific TW network;
5. Calibration GPS with TW **[14]** and, if necessary, recover the TW calibration with GPS.

## 6. SUMMARY

We have proposed a strategy to transfer the calibrated time links to the rest of the links in the UTC TW network using the method TCC (triangle closure calibration). We such calibrated the Europe-America TW network, comprised of 10 national timing laboratories. The UTC data set 0804 (April 2008) was used for the computation. Depending on the original calibration uncertainties of TW or GPS, the uncertainties of the TCC are 2 ns or 6 ns respectively. This is satisfactory for most of the metrological and scientific applications. The calibration values have been implemented into the standard ITU TW data files by the 10 laboratories. For the first time in TW history, all the links in the network are calibrated.

The next step is to calibrate the Asia-Pacific TW network using the TCC procedure. The BIPM intends to maintain this calibration service for the ceaselessly increasing scale of the UTC TW network. Further study is being undertaken to transfer the TW calibration to GPS so as to improve its calibration uncertainty, which is actually 5 ~ 7 ns, and to unify the calibration for UTC generation.

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