

CALIBRATING GPS WITH TWSTFT FOR ACCURATE TIME TRANSFER

Z. Jiang¹ and A. Niessner²

¹ Bureau International des Poids et Mesures (BIPM)
Pavillon de Breteuil F-92312 Sèvres Cedex, France zjiang@bipm.org

² Bundesamt für Eich-und Vermessungswesen, Vienna, Austria

Abstract

The uncertainty of the UTC generation is based on accurate metrological calibration. Organizing and maintaining the calibration of the time transfer facilities contributing to UTC is among the responsibilities of the BIPM. At present, the primary time transfer techniques are GPS and TWSTFT (Two-Way Satellite Time and Frequency Transfer, TW for short). 83% of UTC time links are obtained via GPS observations. The u_B (calibration uncertainty) is 1 ns for TW, 5 ns for GPS P3 code, and 5 ~ 7 ns for GPS C/A code equipment. The u_B of the time links dominates the total uncertainty of [UTC – UTC (k)]. For a UTC participating laboratory linked by GPS P3, 98% of the uncertainty budget comes from the calibration. Reducing the calibration uncertainty in a GPS time link results is a direct improvement in the related [UTC – UTC (k)].

The traditional GPS equipment calibration by the BIPM consists in circulating a master receiver among the UTC laboratories to carry out a side-by-side differential calibration with the local receivers. All the TW laboratories are backed up with GPS facilities; however, the calibrations of TW and GPS equipment are performed independently.

This paper proposes a new calibration procedure. Instead of travelling the BIPM master receiver to every laboratory worldwide, we simply transfer the TW calibration to GPS equipment at the laboratories that operate both TW and GPS. The advantages are: a) unifying the TW and GPS equipment calibration; b) reducing the GPS calibration uncertainty; c) lightening the organization of the calibration work; d) monitoring the long-term variation of the time link calibrations, which is one of the major uncertain factors for the instability of UTC.

To test the method, we compute the calibrations for a dozen of GPS PPP equipment. Further study in unifying the UTC time transfer calibration is next step of this study.

1. INTRODUCTION

Organizing and maintaining the calibration of the time transfer facilities in laboratories contributing to UTC is among the responsibilities of the BIPM. The goal to estimate the time transfer uncertainty is to determine the total uncertainty of the UTC – UTC (k), as published in Section 1 of the BIPM Circular T [1].

Under the pilot study of the GPS PPP (time transfer with Precise Point Positioning technique) [2], organized by BIPM and participated at present by some 20 GPS PPP receiver owner laboratories (cf. Table 3.2), the BIPM computes and publishes the PPP time transfer solutions and the comparisons

between GPS PPP and TW. These results are important for the uncertainty studies of both the u_A (measurement uncertainty) and the u_B (calibration uncertainty) for these two techniques, especially for their long-term calibration variations. To do this, the GPS PPP receivers should be calibrated. However, the traditional GPS receiver hardware calibration is labor-intensive and expensive in time and money: We first absolutely calibrate a BIPM receiver. We then make the calibration tours by sending the calibrated BIPM receiver to the UTC laboratories to perform a side-by-side differential calibration of the local receivers. The uncertainty of the calibration is $u_B = 5$ ns [1]. The calibration tours are often limited by the availability of the staff and equipment during the calibration campaigns. This is especially difficult for the calibrations in the Asia-Pacific areas.

On the other side, the u_B of time transfer dominates the u_B of UTC – UTC (k) and, therefore, the total uncertainty “u” in the final UTC product. Table 1.1 demonstrates the relation of the u_B of the time link and the total uncertainty of UTC – UTC (K):

Table 1.1. Percentage of the time link calibration uncertainty over the total uncertainty of UTC – UTC (K).

| Lab(k) (1) | Time link (2) | u_B of Time Link (3) | u_B of UTC-UTC(k) (4) | Total u of UTC-UTC(k) (5) | percentage of u_B (3)/(5) (6) |
|---------------|------------------|------------------------------|-------------------------------|-----------------------------------|---------------------------------------|
| PTB | TW | 1.0 | 1.1 | 1.1 | 91% |
| USNO | TW | 1.1 | 1.3 | 1.3 | 85% |
| ORB | P3 | 5.0 | 5.1 | 5.1 | 98% |
| CAO | MC | 7.0 | 7.1 | 7.2 | 97% |

The percentage of the u_B of the time links over the total uncertainty of UTC – UTC (k) is at least 85% for TW links and 97% for GPS links. Obviously, reducing the u_B of time links improves directly the uncertainty of the final UTC product.

This study proposes a method to calibrate the GPS receivers through TW. The principal idea is to transfer the TW *time link* calibration to the GPS *receiver* calibration. We point out beforehand that the definition of the calibration here is not the absolute receiver calibration. In fact, for the purpose of UTC – UTC (k) computation or for time transfer between any UTC laboratories UTC (k) and UTC (j), what is important is not the total absolute delays of the clock-receiver-antenna system at Lab (k) and Lab (j) separately, but the relative delay of the clock-receiver-antenna systems at Lab (k) with respect to Lab (j). For UTC time transfer, PTB is the only pivot of the TAI/UTC time transfer network. If all the GPS receivers are calibrated by the method proposed, the GPS time link between any Lab (k) and Lab (j) is calibrated and should be identical to the related TW link. The later has been already calibrated with $u_B \approx 1$ ns [3]. Note that the GPS receivers at Lab (k) and Lab (j) are calibrated separately through the TW links of Lab (k) - PTB and Lab (j) – PTB, but not the TW link Lab (k) – Lab (j), which is an independent TW measurement.

Taking the coverage factor $k=3$, the expanded uncertainty u_B of the proposed calibration is estimated to be 3 ns, vs. its original calibration uncertainty 5 ns. Improving the uncertainty of the GPS calibration is the one of the motivations of this study.

Finally, Ziang *et al.* [4] proposes a method to transfer the calibration from the UTC TW links to the non-UTC TW links. This paper is proposing the method to transfer the calibration from TW to GPS. One of the advantages of TW is that the u_B of TW is only 1 ns and is much better than that of GPS’s 5 ns. However, the disadvantage of TW calibration is fatal. As happened several times in past years, the

commercial telecommunication satellites or their frequencies used for TW time transfer change from time to time. In consequence, the TW links lost all their calibrations. The last change happened in February 2008. Fortunately, all the TW labs are backed up by the GPS PPP receivers. If the latter are calibrated by TW, we can then transfer back the TW calibration from GPS PPP to TW. Because both TW and GPS PPP are the high precision techniques, the calibration measurement uncertainty u_A is of the order of 0.02 ns. The quality of the transfer-back calibration is satisfied. By doing such, the whole UTC time link calibration is unified. To unify the calibration and guarantee its security for TAI/UTC generation is the next step of this study.

In the following sections, we first describe the method, then analyze the related uncertainty, and finally, as an example, we compute the 10 GPS PPP receivers' calibrations. They were the first available GPS PPP receivers in the BIPM TAIPPP pilot study in April 2008 [2]. The raw data concerned were not calibrated. Niessner *et al.* [5] presents an example of the GPS receiver calibration through TW at BEV, and the calibration result has been used for the UTC time transfer. Of course, the traditional GPS-GPS calibrations can be always organized when and where necessary.

2. THE PRINCIPAL IDEA

We first identify the concepts of *link* calibration and *receiver* calibration. A *link* calibration is baseline-fixed, i.e. the calibration result is used only for an individual baseline. A *receiver* calibration is used for any baselines with the two end receivers calibrated. It is easy to understand that the *link* calibration is the difference of the two end *receiver* calibrations. What we are seeking for in this paper is the *receiver* calibration.

2.1 SETUP OF DIFFERENT CALIBRATIONS

Figure 2.1 is the setup of the traditional GPS receiver calibration.

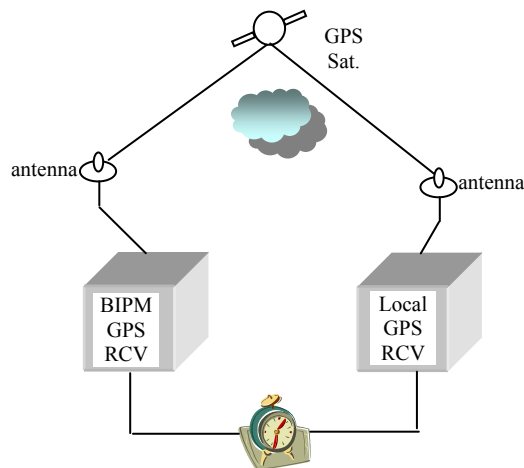


Figure 2.1. Setup of the traditional side-by-side GPS receiver calibration using common ground clock. Here, the BIPM master receiver is the travelling receiver and has been “absolutely” calibrated. The calibration uncertainty u_B is 5 ns.

Here, a common clock is used and it is cancelled by differentiating two receivers' observations. The difference of the total delay of the antenna-receiver-clock systems is the differential calibration result. The total uncertainty u_B for a P3 receiver is 5 ns, as published in Section 6 of the BIPM Circular T [6].

Now we consider another setup illustrated in Figure 2.2. Here, two clocks are used to drive separately the two receivers. The two clocks are linked each other by an internal cable (the red line in the figure), through which the clock differences are precisely measured. If ignoring the error in linking the two clocks, we obtain exactly the same calibration result as the setup of Figure 2.1.

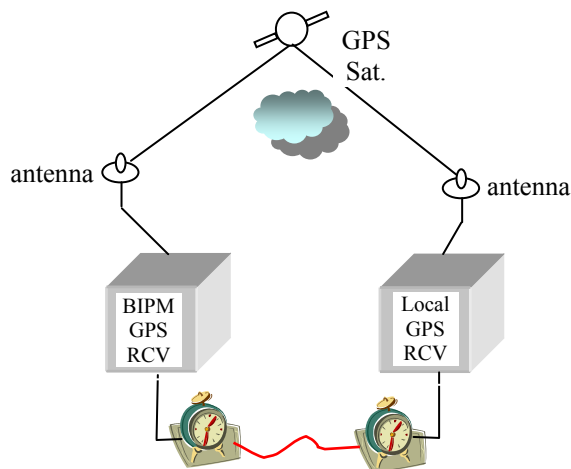


Figure 2.2. Setup of a side-by-side GPS receiver calibration using two ground clocks that are linked by an internal cable (the red line). Here, the BIPM receiver is absolutely calibrated.

Further, let us consider, in Figure 2.2, the case that one of the two clocks is at PTB and the other is at a remote UTC laboratory, say USNO, as shown in Figure 2.3. The two remote clocks are linked by a calibrated UTC TW link, of which the uncertainty is $\sqrt{(u_A^2 + u_B^2)} \approx 1.1$ ns. Note that the role of the TW link is as same as that of the cable between the two clocks in Figure 2.2. Here, the meaning of the calibration of the TW link is identical to measure the length of the internal cable between the two clocks in Figure 2.2. The difference of the two setups is that the two clocks are linked by a cable in Figure 2.2 and by a TW link in Figure 2.3. If we ignore the measurement errors in the cable and the TW link, the calibration setup in Figures 2.1, 2.2, and 2.3 are identical. This is the principal idea of this paper.

Obviously, if the GPS receiver at PTB is absolutely calibrated ($u_B = 5$ ns), the remote USNO receiver can be calibrated absolutely using the above setup. This implies that we do not need to transport a master receiver to side-by-side calibrate a local receiver if the TW link between is calibrated. The total uncertainty budget will be slightly increased, but very limited. In most cases, the increased quantity in u_B of the proposed TW-GPS calibration is $\sqrt{(5^2 + 1^2)} - 5 = 0.12$ ns.

Till now, we have been talking about the *link* calibration. In the following, we will see how to transfer the *link* calibration to the *receiver* calibration. As pointed out above, the calibration is not the absolute calibration. We are interested in the quantity which influences the UTC – UTC (k) and also in an arbitrary time link UTC (k) – UTC (j). We call the result the *receiver calibration correction (calibration for short)*, which is added to the RefGps value (the raw receiver reading in the CCTF CGGTTS GPS data files).

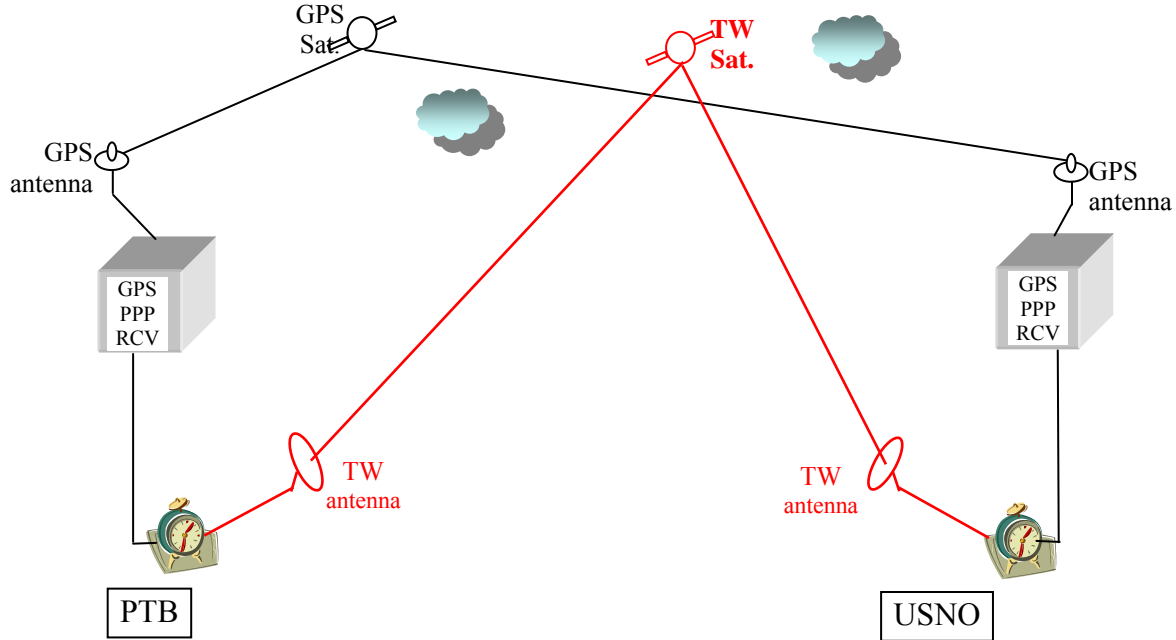


Figure 2.3. Setup of the GPS receiver calibration using two remote ground clocks that are linked by UTC TW time link (the lines, antennas, and satellite in red) between PTB and USNO.

Taking the example of the baseline USNO - PTB: suppose the traditional absolute delay of the GPS receivers is X_0 for PTB and X_u for USNO; $Link_g$ is the uncalibrated GPS link between USNO-PTB; and $Link_G$ and $Link_T$ are the calibrated GPS and TW links. We can compute the calibration value of the USNO GPS receiver as follows:

$$Link_T = Link_G = [RefGps (USNO) + X_u] - [RefGps (PTB) + X_0] \quad (1)$$

Introducing $C_u = X_u - X_0$ in above equation, we have:

$$\begin{aligned} Link_G &= [RefGps (USNO) + C_u + X_0] - [RefGps (PTB) + X_0] \\ &= RefGps (USNO) - RefGps (PTB) + C_u \\ &= Link_g + C_u \\ &= Link_T \end{aligned} \quad (2)$$

Above we used the definition of the uncalibrated GPS link:

$$Link_g = RefGps (USNO) - RefGps (PTB)$$

Therefore

$$C_u = X_u - X_0 = Link_T - Link_g \quad (3)$$

or

$$Link_G = Link_g + C_u = [RefGps (USNO) + C_u] - RefGps (PTB) \quad (4)$$

Here, C_u is namely the calibration correction for the USNO GPS receiver. As for the receiver of PTB, whether it is calibrated or not becomes meaningless for obtaining the calibrated $link_G$. To be general, we

replace the USNO by Lab (k) and Lab (j) separately and obtain the GPS receiver calibrations at Lab (k) and Lab (j):

$$C_k = X_k - X_o = \text{Link}_T(\text{Lab}_k - \text{PTB}) - \text{Link}_g(\text{Lab}_k - \text{PTB}) \quad (5)$$

and

$$C_j = X_j - X_o = \text{Link}_T(\text{Lab}_j - \text{PTB}) - \text{Link}_g(\text{Lab}_j - \text{PTB}) \quad (6)$$

Taking equation (5) minus equation (6), we have:

$$C_k - C_j = X_k - X_j = \text{Link}_T(\text{Lab}_k - \text{Lab}_j) - \text{Link}_g(\text{Lab}_k - \text{Lab}_j) \quad (7)$$

or

$$\text{Link}_T(\text{Lab}_k - \text{Lab}_j) = \text{Link}_g(\text{Lab}_k - \text{Lab}_j) + C_k - C_j \quad (8)$$

Similar as the equation (1), the calibrated GPS link equals:

$$\text{Link}_G(\text{Lab}_k - \text{Lab}_j) = [\text{RefGps}(\text{Lab}_k) + C_k] - [\text{RefGps}(\text{Lab}_j) + C_j] \quad (9)$$

In above equation (9), C_k and C_j are the GPS *receiver calibration corrections*. Introducing equations (6) and (7) into (9), we have the GPS link with the traditional absolute calibrations X_k and X_j :

$$\begin{aligned} \text{Link}_G(\text{Lab}_k - \text{Lab}_j) &= [\text{RefGps}(\text{Lab}_k) + X_k - X_o] - [\text{RefGps}(\text{Lab}_j) + X_j - X_o] \\ &= [\text{RefGps}(\text{Lab}_k) + X_k] - [\text{RefGps}(\text{Lab}_j) + X_j] \end{aligned} \quad (10)$$

Here, X_o is the absolute calibration value for PTB GPS receiver and is cancelled in any arbitrary links. Equations (9) and (10) give the same link result (within their uncertainties), but with completely different calibration setups. Equation (9) is meaningful: the GPS calibration obtained through TW links are transferred as the receiver calibration and they differ from their absolute delays by a common constant: X_o (the absolute delay of the PTB GPS receiver). However, the X_o can be determined at any lab (k). As mentioned in the introduction, the disadvantage of equation (10) is not only that it is labor-intensive and expensive in time and money, but also its u_B (5 ns). Equation (9) uses the already available TW calibration and its u_B is well reduced. In fact, equation (9) allows a *simultaneous* multi-GPS receiver calibration between N laboratories that operate both GPS and TW time transfer facilities. *Simultaneous* measurement is impossible by applying the traditional calibration (eq. 10), which requires that the BIPM master receiver be transported and occupy sequentially all the laboratories in separate periods. The possible biases due to, for example, the variations of the internal reference of GPS receiver and the geodesic hypothesis, etc., are not avoidable.

A remark on the absolute calibration: we see from relation (2) that in link_G the absolute delay of the GPS receiver at PTB X_o is cancelled and that to determine C_u the two remote clocks are cancelled. For the time transfer, the correction C_u makes the real role of the calibration. One by one, we can determine in this way the calibrations for all the GPS receivers, cf. Table 3.2. The total absolute delay at USNO is $X_u = X_o + C_u$. If the USNO GPS receiver is absolutely calibrated, we can determine the PTB absolute delay at USNO by equation (3): $X_o = X_u - C_u$. This implies it is enough to absolutely calibrate one of the GPS receivers at an arbitrary Lab_k ; we can then determine the PTB absolute delay X_o . For a third Lab_j , the absolute calibration can be obtained by $X_j = C_j + X_o$. If there is more than one receiver absolutely calibrated, the redundant calibrations will improve the calibration uncertainty. The fact that the global TW network adjustment [7] allows further improvement of the u_A of the TW links by a factor of 30% ~ 50%

means that the TW measurement errors are negligible in the total uncertainty budget of the proposed calibration.

2.2 THE UNCERTAINTY OF THE CALIBRATION

Suppose the PTB receiver is absolutely calibrated, the uncertainty of the absolute calibration for the GPS receiver of Lab_k is:

$$U^2 = u_B[TW (Lab_k - PTB)]^2 + u_A(C_k)^2 + u_B(X_0)^2 \quad (11)$$

As discussed above, the constant X₀ is cancelled for all links. In the sense of the UTC – UTC (k) and UTC (k) – UTC (j), the influence of the term u_B (X₀) is null. Therefore, the total uncertainty of the calibration is:

$$u^2 = u_B[TW (Lab_k - PTB)]^2 + u_A(C_k)^2 \quad (12)$$

From [1, 3], the first term is 1 ns and the second term is the sum of the measurement uncertainties of GPS and TW; i.e. u_A²(GPS) + u_A²(TW). The u_A(GPS) is 0.7 ns for P3 and 2.5 ns for C/A. u_A(TW) is 0.5 ns. Suppose we use UTC/TAI monthly data for the calibration and there are about 360 common points (12 points per day and 30 days per month). We have:

$$u (TW/GPS) = \sqrt{\{u_B[TW (Lab_k - PTB)]^2 + u_A(C_k)^2\}} \quad (13)$$

$$u (TW/GPS P3) = \sqrt{\{1^2 + (0.5^2 + 0.7^2)/360\}} = 1.001 \ll 3 \text{ ns} \quad (13a)$$

$$u (TW/GPS C/A) = \sqrt{\{1^2 + (0.5^2 + 2.5^2)/360\}} = 1.009 \ll 3 \text{ ns} \quad (13b)$$

Expressions 13a and 13b give the total calibration uncertainty, and here the u_B(TW) = 1 ns is applied. The influence of the measurement uncertainty (u_A) is almost negligible when a month average is used. On the other hand, the biases due to the long-term instability of the GPS receiver and the related laboratory equipment as well as the geodesic hypothesis in the IGS corrections should be also taken into account in the total uncertainty budget. It is not easy to estimate exactly all these biases. Hence, we apply a coverage factor *k* to ensure the uncertainty estimation. Taking *k* = 3, we have the expanded uncertainty u_B ≈ 3 ns.

It should be noted that, for those TW links calibrated through GPS, such as the baseline NIST-PTB, the uncertainty u_B(TW) = 5 ns. Therefore, the GPS receivers calibrated through these TW links will not be better than 5 ns (cf. Table 3.2).

3. NUMERICAL TEST

The data set used for the numerical test is the TAI 0804 (April 2008, MJD 54554-54586). Ten GPS PPP laboratories are involved. Table 3.1 is the list of the links with data not completed. The standard deviations (Std) are bigger than usual and the calibration results (the values of “Mean”) may not be as good as for the others. Table 3.2 is all the calibration result.

Table 3.1. Links used for the calibration with gaps.

| Link | N | Nim | Max | Mean | Std | Gaps |
|-------|-----|---------|---------|----------------|-------|--------------|
| ITPTB | 223 | 462.124 | 466.305 | 464.620 | 0.781 | after 54567 |
| SPPTB | 247 | 474.428 | 477.557 | 476.477 | 0.689 | before 54576 |

Table 3.2 is the calibration result. The column ‘Lab’ is the GPS PPP laboratory name; the values in column of ‘Calib.’ are the calibration corrections to be added to the RefGPS values and the values after the “±” are the standard deviations of the calibration; the column Numb. lists the number of the common epochs used for the calibration; the column ‘CalibType’ is the type of link used for the calibration; and the last column u_B is the calibration uncertainty. The total absolute delay for a receiver equals the value in the table plus the constant X_0 (the absolute delay of PTB receiver, equations 3 or 5 or 6). For example, if $X_0=0$, the values in Table 3.2 become the absolute delays of the receivers. Whatever is the value X_0 , it will not change the total uncertainty of UTC – UTC (k) or UTC (k) – UTC (j). It should be pointed out that the purpose of this paper is to introduce the method. The calibration results listed in Table 3.2 correspond to the setup of the raw data set status in 0804 (2008 April). Because it was the very beginning of the BIPM GPS PPP pilot project, the setup of the receivers might be changed since then.

Table 3.2. Calibrations of the GPS PPP receivers / ns the calibration results (Calib.) are added to the RefGPS values, which correspond to the setup of the raw data set 0804 (April 2008).

| Lab | Calib. | Std | Numb. | CalibType | u_B |
|------------|-------------------|------------|--------------|------------------|-------------------------|
| CH | 137.7±0.52 | | 344 | TW | 3 |
| IT | 464.6±0.78 | | 223 | TW | 3 |
| NIST | 418.5±0.48 | | 381 | GPS | 5 |
| OP | 146.3±0.55 | | 355 | TW | 3 |
| ROA | 523.4±0.84 | | 305 | GPS | 5 |
| SP | 476.5±0.69 | | 247 | TW | 3 |
| USNO | 517.1±0.62 | | 339 | TW | 3 |
| VSL | 449.3±0.58 | | 217 | GPS | 5 |
| NICT | 511.7±0.73 | | 696 | GPS | 5 |
| PTB | 0.0 | | | TW | 3 |

For the comparison of 0804 TW and GPS PPP links, the calibration values listed in Table 3.2 have been applied to GPS PPP receivers; the link comparison results are published on the BIPM ftp site: <ftp://tai.bipm.org/TimeLink/LkC/0804/>. An example of the perfect agreement of the traditional calibration for the non-UTC TW and GPS PPP links is SP - NIST, for which the mean value of the differences between the two techniques is 0.013 ns, with the standard deviation 0.127 ns (Figure 3.1). Table 3.3 gives more examples of the agreements of the calibrations between TW and GPS PPP. The column Mean lists the mean values of the differences over N points. They approximate zero.

Finally, as a remark: on MJD 54571, there is a GPS PPP link jump of about 2 ns due probably to the GPS receiver PTBB at PTB. Because we don’t know the exact cause, its influence on the calibration is not clear.

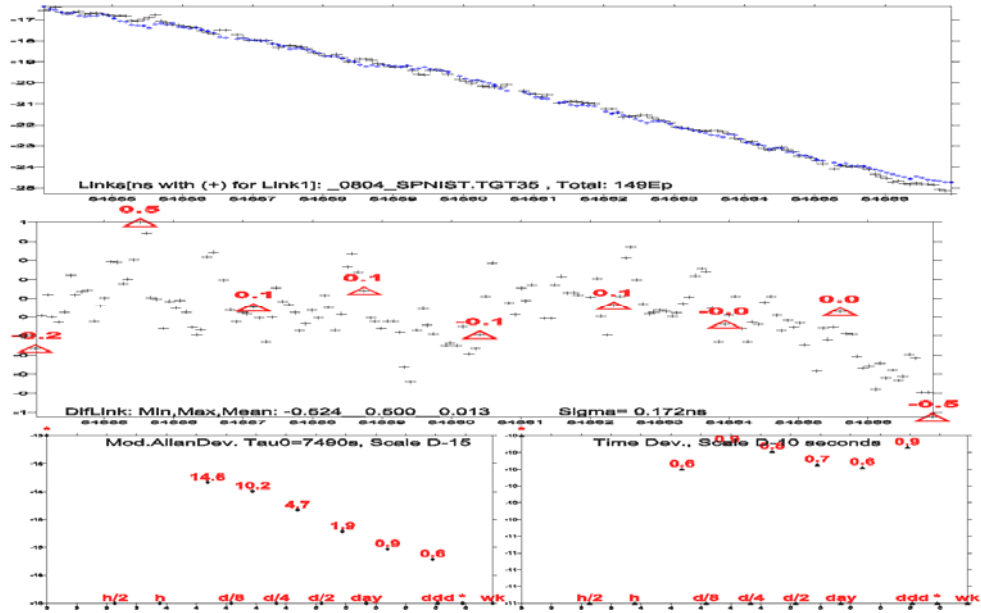


Figure 3.1. Comparison of TW and the calibrated GPS PPP time links between SP and NIST (0804, MJD 54554-54586) / ns. The top plot illustrates the two links (TW blue circles and PPP black crosses); the middle plot is the differences between the two links in ns: the mean value is 0.013 ± 0.172 ns; in the bottom plots, the left is the Mod. Allan dev. of the differences and the right is the related time deviation.

Table 3.3. Comparison between the UTC TW links and the receiver calibrated GPS PPP Links / ns.

| Link | N | Min | Max | Mean | RMS |
|----------|-----|--------|-------|--------|-------|
| CH-PTB | 344 | -1.252 | 1.410 | -0.028 | 0.515 |
| NIST-PTB | 381 | -1.117 | 1.405 | 0.012 | 0.488 |
| NICT-PTB | 696 | -1.638 | 2.578 | 0.027 | 0.730 |
| OP-PTB | 355 | -1.318 | 1.521 | -0.040 | 0.553 |
| ROA-PTB | 305 | -3.271 | 1.577 | 0.020 | 0.826 |
| USNO-PTB | 339 | -1.571 | 1.486 | -0.011 | 0.619 |
| VSL-PTB | 217 | -1.910 | 1.508 | 0.024 | 0.576 |
| IT-PTB | 223 | -2.476 | 1.705 | 0.020 | 0.781 |
| SP-PTB | 247 | -2.072 | 1.057 | -0.023 | 0.690 |

4. CONCLUSION

83% of UTC time links are obtained via GPS observations. The u_B (calibration uncertainty) is 1 ns for TW and 5 ~ 7 ns for GPS. The u_B of the time transfer dominates the total uncertainty of $[UTC - UTC(k)]$. Any improvement in u_B results directly in the uncertainty of $[UTC - UTC(k)]$.

The traditional GPS equipment calibration needs to circulate the BIPM master receiver among laboratories to carry out a side-by-side differential calibration of the local receivers. The stability of the master receiver and the GPS/IGS system is essential. Therefore, in addition to the extra cost of the travel

and manpower, the calibrations may affect by the instability of the master receiver during the travels and the possible biases in the geodesic corrections. The uncertainty of the calibration u_B is 5 ns as applied in the UTC/TAI generation.

We propose a new calibration procedure. Instead of transporting the master receiver to every laboratory worldwide, we transfer the TW calibration to GPS receivers at the laboratories that operate both TW and GPS. The advantages of the method are:

- Unifying the TW and GPS equipment calibration;
- Reducing the GPS calibration uncertainty. Considering that the u_B for TW is 1 ns, the expanded u_B for GPS calibration will be ± 3 ns with the coverage factor $k = 3$;
- Monitoring the long-term variation of the time link calibrations, which is one of the uncertain factors for the instability of UTC.

To test the method, we compute the calibrations for a dozen of GPS PPP equipment.

ACKNOWLEDGMENT

We thank the UTC laboratories for the GPS and TW data used in this study.

REFERENCES

- [1] BIPM Circular T 244, May 2008, <http://www.bipm.org>
- [2] BIPM pilot study of GPS PPP for TAI time transfer, <ftp://tai.bipm.org/TimeLink/TAIPPP>, <http://www.bipm.org>
- [3] D. Piester, A. Bauch, L. Breakiron, D. Matsakis, B. Blanzano, and O. Koudelka, 2008, “Time transfer with nanosecond accuracy for the realization of International Atomic Time,” **Metrologia**, **45**, 185-198.
- [4] Z. Jiang, W. Lewandowski, and D. Piester, 2009, “Calibration of TWSTFT Links through the Triangle Closure Condition,” in Proceedings of the 40th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 1-4 December 2008, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 469-486.
- [5] A. Niessner, W. Mache, B. Blanzano, O. Koudelka, J. Becker, D. Piester, Z. Jiang, and F. Arias, 2009, “Calibration of the BEV GPS receiver by using TWSTFT,” in Proceedings of the 40th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 1-4 December 2008, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 545-550.
- [6] Z. Jiang and G. Petit, 2006, “Redundancy in the TAI TWSTFT time transfer network,” in Proceedings of the 20th European Frequency and Time Forum (EFTF), 27-30 March 2006, Braunschweig, Germany, pp. 468-475.
- [7] Z. Jiang, 2008, “Towards a TWSTFT Network Time Transfer,” **Metrologia**, **45**, S6-S11.