# Report of Two Way Satellite Time and Frequency Transfer (TWSTFT) Working Group

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## 1. Introduction

Since the last CCTF Meeting, much has happened in the area of TWSTFT. As in many areas of science and technology, there has been expansion, development, modification and transformation. After the last meeting of the CCTF, TWSTFT operations were impacted by a change in the policy of Intelsat General with regard to scientific programs using their satellites. The new policy was to charge for time as capacity was dwindling due to increase use of satellite communications systems. After gaining the cooperation of the Participating Stations, NIST and PTB were able to work out a plan for undertaking a contract with Intelsat General. This major upheaval to operations was followed by an equally significant impact to operations. TWSTFT operations were going to have to temporarily change from satellite IS-707 to satellite IS-3R until a new satellite TS-11N was to be launched in 2009. IS-707 was suffering from equipment malfunctions and the move to IS-3R was not going to be permanent as it was running out of fuel to maintain its position in space. The move to IS-3R occurred in February 2008. We are now engaged in undertaking a new contract for use of TS-11N as soon as it is declared operational as will be mentioned in Section 2 of this report.

A very important concern with the move to TS-11N is its cost and how it will impact operations. Cost of a satellite is solely a function of the amount of bandwidth that a customer uses. We have been looking at the effect on precision and accuracy that a change in the bandwidth that we currently use will have on our timing data. Section 5 will report on the studies that are being done.

As the role of TWSTFT is important to the BIPM in the acquisition of clock data, many laboratories are interested in preserving, maintaining and improving the services that are provided by TWSTFT. Consequently, we have seen a growth in the use of TWSTFT within the Asia/Pacific Rim and the development of connectivity between Europe and the Asia/Pacific Rim as will be seen in Sections 3 and 4 of this report. Around the world connectivity of TWSTFT is the ultimate goal.

Along with an improvement of operations expanding the TWSTFT area of coverage and use, we have also seen an improvement in TWSTFT techniques and analyses as shown in the area of calibration of TWSTFT operations both directly through Portable Station visits to labs (see Section 6) and through indirect calibration through a new sophisticated analysis as developed at the BIPM (see Section 7).

## 2. Status of the EU/US TWSTFT Network (Tom Parker, NIST)

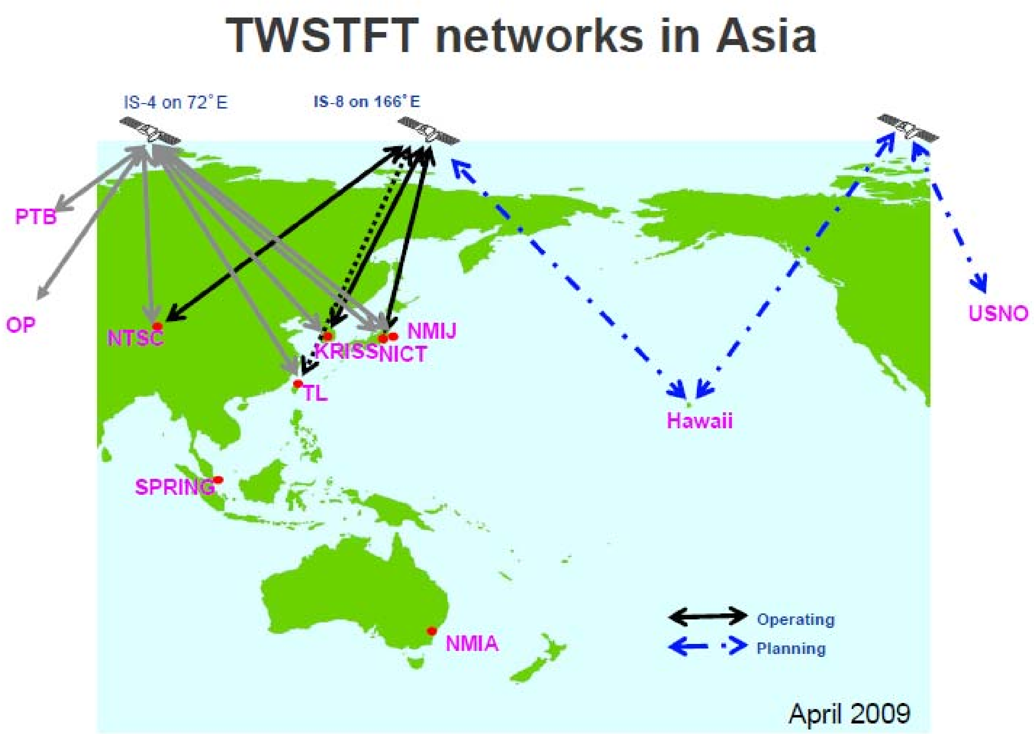
In September of 2009 the current satellite, IS-3R, is expected to reach the end of its useful life. The only known other satellite that can provide the necessary coverage is the recently launched Telstar 11-N, owned by Telesat. Intelsat General, our current service provider, quoted a price for 3.5 MHz of bandwidth on Telstar 11-N which is twice the price we are paying on IS-3R. The Telesat Company quoted a price which is 25% higher than the current price. Either price increase was beyond what could be afforded the TWSTFT Participating Stations. Therefore, we have been investigating the use of a lower chip rate (1 MChip/s versus 2.5 MChip/s) in order to reduce the bandwidth which we currently use. The price scales linearly with bandwidth. Tests (see Section 5) have shown that there is only a modest degradation in performance for most links by using the lower chip rate.

Therefore we have decided to purchase a bandwidth of only 2.5 MHz which will be adequate for the 1 MChip/s codes and will also allow some testing with 2.5 MChip/s codes with RF band-pass filters. The total cost for this non-preemptable capacity will be about US$350,000 per year. This cost will be split evenly between the European and US stations. NIST is handling the purchase order and the process is underway. The purchase is being made in an open bid process so we don't know which company will be awarded the contract, but there is a good chance it will be Telesat Co. We expect to have a contract in place by July or August.

## 3. Status of the Asia/Pacific Rim TWSTFT Network (Miho Fujieda, NICT)

The Asia/Pacific Rim link had been established using the satellite JCSAT-1B (150°). This satellite was in use until the end of March, 2009. Due to the end of the lifetime of JCSAT-1B, we switched to IS-8 (166°) on April 1, in 2009. Unfortunately, Singapore is not covered by this satellite and therefore we had to terminate the time transfer operation with SPRING. Thus, the current participants of the link are KRISS, NTSC and NICT. TL will join soon. Time transfers are done once every hour, 24 times per day. Its time stability at 1 hour is about 500 ps.

NICT and USNO have a plan to establish a link using a relay station in Hawaii. The Hawaii – Asia link also will also be connected by IS-8. The USNO-Hawaii-Asia link will be used for monitoring the time difference between GPS time and QZSS (quasi-zenith satellite system) time as well as contribution to TAI.




## 4. Status of Asia/EU TWSTFT Network (Miho Fujieda, NICT & Dirk Piester, PTB)

The Asia/EU TWSTFT link has been established by using IS-4 (72°) satellite. From April 2009, the link-fee share program has started with all participants. The current participants are PTB and OP in EU, KRISS, NMIJ, NTSC, TL and NICT in Asia. NIM and VSL will join the link in the near future. Currently the PTB-NICT link is only used as one of the TAI links. Time transfers are performed once every one hour, 24 times per day. The time stability at 1 hour is about 600 ps. A diurnal variation at the 1 ns level has been observed and efforts are being made to understand and solve the problem, but the attempts have not been successful so far. Nevertheless the direct comparisons between Cs atomic fountains have been successfully performed twice between PTB and NICT. The results proved that this link has a frequency uncertainty below $10^{-15}$ [1].

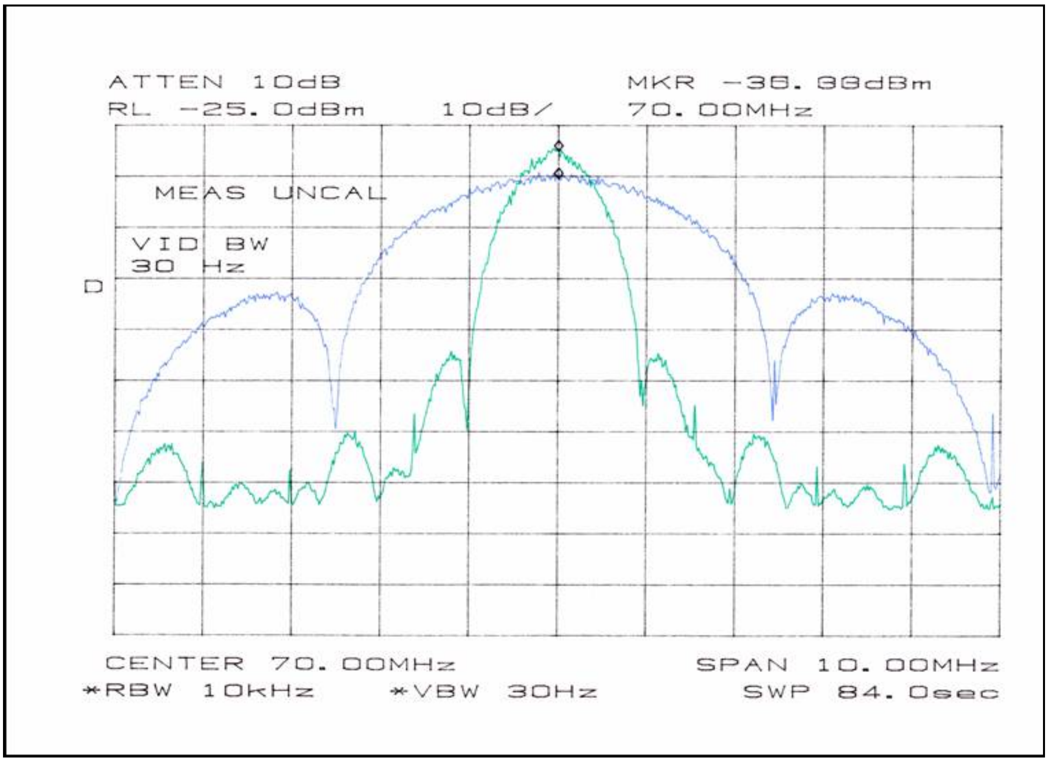
Intelsat announced that the lifetime of IS-4 would end in summer 2010 and its successor would not have a beam to connect EU and Asia. We have begun investigating the availability of alternative satellites.

[1] M. Fujieda et al., Proceedings of EFTF 2007, pp. 937-941, 2007.

## 5. 1 MHz Chipping Rate Tests (Victor Zhang, NIST)

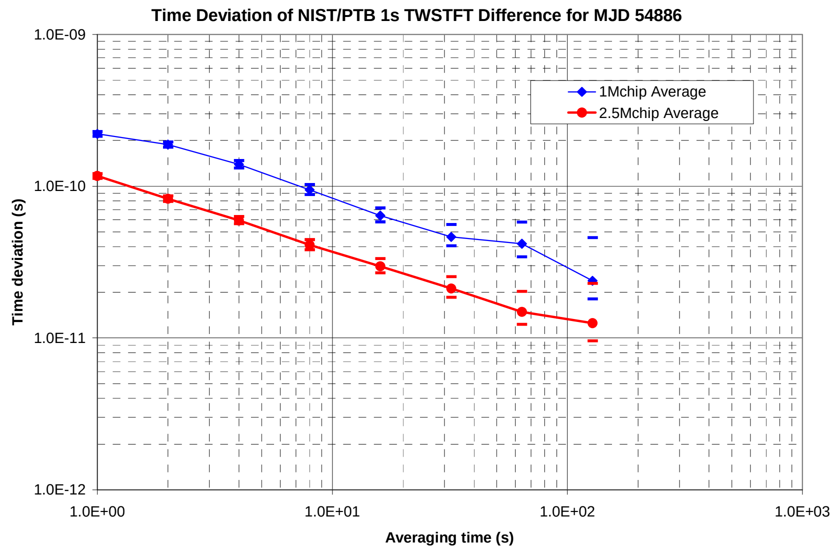
Using the 1 MChip/s codes for the transatlantic and Europe to Europe TWSTFT was proposed as an alternative to continuing TWSTFT with 2.5 MHz bandwidth on the new satellite in order to reduce operational costs. To investigate the performance of using a 1 MChip/s chipping rate for TWSTFT, NIST coordinated a 1 MChip/s TWSTFT test. The test started on February 23, 2009 and the test is still on- going as of May 1, 2009. The 1 MChip/s test runs during odd-hours, using the same earth stations' settings as used by the 2.5 MChip/s TWSTFT during the even-hours, on the same transponders of the IS-3R satellite. Seven European laboratories (AOS, CH, IT, OP, PTB, ROA, and SP) and two North American laboratories (NIST and USNO) have participated in the test. The spectrum of the spread spectrum signals generated by a 1 MHz and a 2.5 MHz chipping rate are shown below.

**Spectrum of 1 MHz and a 2.5 MHz Chipping Rate Transmitted Signal**




In our studies of the 1 MChip/s chipping rate TWSTFT performance, we compared the instability of the 1 MChip/s TWSTFT and 2.5 MChip/s TWSTFT. Our analysis shows the following results:

- 1 MChip/s TWSTFT increases the short term instability (as measured by Time Deviation, TDEV, for averaging times from 1 second to 128 seconds).
- For averaging times of 2 hours and longer, the TDEVs of the 2-minute, 4-minuteand 10-minute 1 MChip/s measurements are almost the same.
- 1 MChip/s TWSTFT contains a strong diurnal for most of the links (for some stations as much as 2 ns.), the level of diurnal varies from link to link.
- For most of the links, 1 MChip/s TWSTFT appears to degrade the stability for averaging times from 2 hours to less than 1 day, the level of degradation varies from link to link.
- For most of the links, 1 MChip/s and 2.5 MChip/s TWSTFT have the same TDEV for the averaging times from 1 day and longer.




## 6. Direct Calibration Activities (Andreas Bauch, PTB)

In order to perform true time comparisons, it is necessary to determine the differential signal delays in the TWSTFT stations involved. This is possible in different ways. The practice developed in recent years in Europe includes co-location of a portable earth station with the ground stations involved in the link [1]. It has been demonstrated that this method can provide a calibration uncertainty on the order of 1 ns.

Three calibration exercises of Ku-band links connecting European stations were performed since the last CCTF, involving the following institutes:

| No. | Year | Participating Institutes | Reference |
|---|---|---|---|
| 1 | 2006 | TUG-PTB-METAS-TUG | [2] |
| 2 | 2007 | TUG-BEV-PTB-TUG | [3] |
| 3 | 2008 | TUG-PTB-NPL-OP-INRiM-VSL-METAS-TUG | [4] |

Calibration constants with estimated uncertainties down to 0.9 ns were achieved in these campaigns. The reproducibility of TWSTFT calibrations could be tested on some of the links during campaign No. 3. The mean deviation between the actual and previously determined calibration values for links to PTB was < 0.5 ns. The CALR values and their uncertainties to be used in TAI calculations by BIPM since 1 April 2009 are given in Table 1.

*Table 1. CALR values and their uncertainties for use in TWSTFT data files for report to BIPM obtained in campaign 3.*

| Link | | | | |
|---|---|---|---|---|
| k | l | CALR(k) | CALR(l) | U (ns) |
| CH01 | IT02 | 110.6 | -110.6 | 1.0 |
| CH01 | NPL01 | -703.8 | 703.8 | 1.0 |
| CH01 | OP01 | 7110.3 | -7110.3 | 0.9 |
| CH01 | PTB04 | -205.6 | 205.6 | 1.0 |
| CH01 | TUG01 | 125.9 | -125.9 | 0.8 |
| IT02 | NPL01 | -814.4 | 814.4 | 1.2 |
| IT02 | OP01 | 6999.7 | -6999.7 | 1.1 |
| IT02 | PTB04 | -316.2 | 316.2 | 1.2 |
| IT02 | TUG01 | 15.2 | -15.2 | 1.0 |
| NPL01 | OP01 | 7814.1 | -7814.1 | 1.0 |
| NPL01 | PTB04 | 498.2 | -498.2 | 1.2 |
| NPL01 | TUG01 | 829.6 | -829.6 | 1.0 |
| OP01 | PTB04 | -7315.9 | 7315.9 | 1.1 |
| OP01 | TUG01 | -6984.5 | 6984.5 | 0.9 |
| PTB04 | TUG01 | 331.5 | -331.5 | 1.0 |

In campaign No. 2 the GPS time link between BEV and PTB was calibrated by means of TWSTFT. The type-B uncertainty of this link could be reduced by nearly a factor of 2 [5].

Following the same approach as done in Europe, NICT provided a transportable TWSTFT station and calibrated the links between NICT and TL and NICT and KRISS in March and October 2006, respectively. The achieved combined uncertainties for the CALR values were 0.6 ns and 1.3 ns, respectively.

USNO and PTB perform TWSTFT on two independent links, one in Ku-band (jointly with partners in Europe and NIST) and one in X-band. The X-band satellite has a wide-angle antenna, covering central Europe and the US East Coast, so that calibration using a portable station becomes technically feasible. One such calibration of the links was carried out by USNO in March 2007. The calibration values valid for the Ku-band and also for the X-band were found different from previously determined values by 2.2 ns. Currently (early May 2009), another calibration is being performed whose results are not yet available.

References

[1] D. Piester, A. Bauch, L. Breakiron, D. Matsakis, B. Blanzano, O. Koudelka,

Metrologia **45**, 85-198 (2008)

[2] C. Schlunegger, G. Dudle, L.-G. Bernier, D. Piester, J. Becker, B. Blanzano,

Proc. IEEE International Frequency Control Symposium Jointly with the 21st European Frequency and Time Forum, Geneva, Switzerland, 29 May – 1 Jun 2007, pp. 918-922 (2007)

[3] A. Niessner, W. Mache, B. Blanzano, O. Koudelka, J. Becker, D. Piester, Z. Jiang, F. Arias, Proccedings 40th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 1-4 Dec 2008, Reston, Virginia, USA, pp. 543 - 548

[4] A. Bauch, D. Piester, B. Blanzano, O. Koudelka, E. Kroon, E. Dierikx, P. Whibberley, J. Achkar, D. Rovera, L. Lorini, F. Cordara, C. Schlunegger, to be published in Proc. IEEE International Frequency Control Symposium Jointly with the 23rd European Frequency and Time Forum, Beancon, France, 21-24 April 2009

[5] Z. Jiang and F. Arias, *"Improving the calibration of the BEV GPS receiver calibrated by using TWSTFT,"* BIPM TM 155 (2008).

## 7. Indirect Calibration Activities [BIPM TM 151] (Zhiheng Jiang and W. Lewandowski, BIPM)

*Calibration of Europe-America redundant TW Links through the Triangle Closure Condition (TCC)*

**Summary:**

All the TW links used for UTC have been calibrated using one of the two methods :

- Aligning a TW link to a GPS link with the uncertainty type B: $u_B$(GPS) 5 ns
- Using a portable TW ground station with the uncertainty type B: $u_B$(TW) ≈ 1 ns [3]

However, 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 are the redundant (or non-UTC) links. In this network, only a limited number of links were calibrated to enable the UTC time transfer or other scientific applications. Most of the redundant links have never been calibrated and therefore not used.

[1,2, c.f. Annex 1] presents a strategy to calibrate the whole TW network by transferring the existing TW calibrations to the non-calibrated links using the so called TCC method (triangle-closure condition, Figure 1).

Applying the TCC method, we calibrated the Europe-America TW network comprised of 10 national timing laboratories (Figure 2). The UTC data set 0804 (April 2008) were used for the calibration computation (Annex 2).

**The estimated uncertainty of $u_B$(TCC)**

Depending on the original calibration uncertainties with TW or GPS, the uncertainties of the TCC are estimated to be 2 ns or 6 ns respectively (Table 1). This is satisfying for most of the metrological and scientific applications.

**Table 1** The TCC uncertainty $u_B$(TCC)/ns (c.f. Annex 2)

| **Labs/Links** | **Labs/Links** | $u_B$(TCC) |
|---|---|---|
| $u_B$ (GPS/GPS or TW/GPS)<br><br>TCC composed with the links calibrated with GPS and TW | AOS, NIST, ROA concerned links<br><br>with PTB, USNO, OP, IT, VSL, CH, SP | 6 ns |
| $u_B$ (TW)<br><br>TCC composed with the links calibrated with TW | all the other links in<br><br>Tables 2a and 2b | 2 ns |

The calibration values have been implemented into the standard ITU TW data files by the 10 laboratories since MJD 54677, 30 July 2008 (Table 2a and 2b). For the first time in the TW history, all the links in the network were calibrated.

See [1] and [2] for details.

## REFERENCES

[1] Z Jiang and W Lewandowski, 2008, "*TWSTFT Calibration Transfer from UTC Links to Non UTC Links using Triangle Geometric Condition*", BIPM TM 151, ftp://tai.bipm.org/TimeLink/LkC/TM151_TwCalib.doc

[2] Z. Jiang[1], W. Lewandowski and D. Piester: Calibration of TWSTFT Links through the Triangle Closure Condition, Proc. PTTI 2008

[3] D Piester., A. Bauch, L. Breakiron, D. Matsakis, B. Blanzano, O. Koudelka, 2008, "*Time transfer with nanosecond accuracy for the realization of International Atomic Time*", Metrologia, vol. 45, 185 – 198, 2008

## *Annex 1: The method of the TCC*

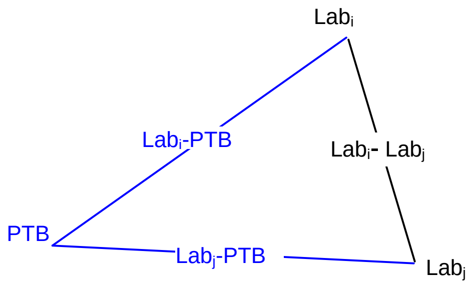



**Figure 1** Redundant (Non-UTC) TW link calibration using TCC (triangle closure condition)

The principle of the TCC is as follows: 1) all UTC links, i.e. the links with the UTC pivot laboratory PTB, are calibrated; 2) from Figures 2, any redundant link $Lab_i$-$Lab_j$ can be used to compose a TCC with the two adjacent UTC links $Lab_i$-PTB and $Lab_j$-PTB. Because all time scales UTC(Lab), i.e. all the clocks are cancelled in TCC, the sum of the three links in the triangle should be zero if link measurement errors and noise are neglected.

Based on the TCC and by some mathematical developments [1,2], we can obtain the calibration value CALR:

$$CALR(i,j)= -CALR(j,i)= TW(Lab_i–PTB) –TW(Lab_j–PTB) –TW(Lab_i–Lab_j) \qquad (1)$$

Equation (1) is used for the computation of the CALR which is based on the European practice to reset ESDVAR=N.A. (not available). For the laboratories i and j keeping its non-zero ESDVAR(i,j) and/or ESDVAR(j,i) values for the link $TW(Lab_i – Lab_j)$, the ESDVAR values should be removed from equation (1), i.e., American practices, we have then:

$$CALR(i,j)= –CALR(j,i)=$$

$$=TW(Lab_i–PTB) –TW(Lab_j-PTB) –TW(Lab_i–Lab_j) – [ESDVAR(i,j) – ESDVAR(j,i)]/2 \qquad (2)$$

## *Annex 2: The Europe-America TW network and the link calibrations*

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 2 displays the status of the TW links. Except for the link between NIST and USNO, all the links are available: 9 UTC links of which 6 are calibrated with TW equipment (blue lines) and 3 are calibrated with an alignment to GPS (red lines). The number of the redundant links to be calibrated is 35.

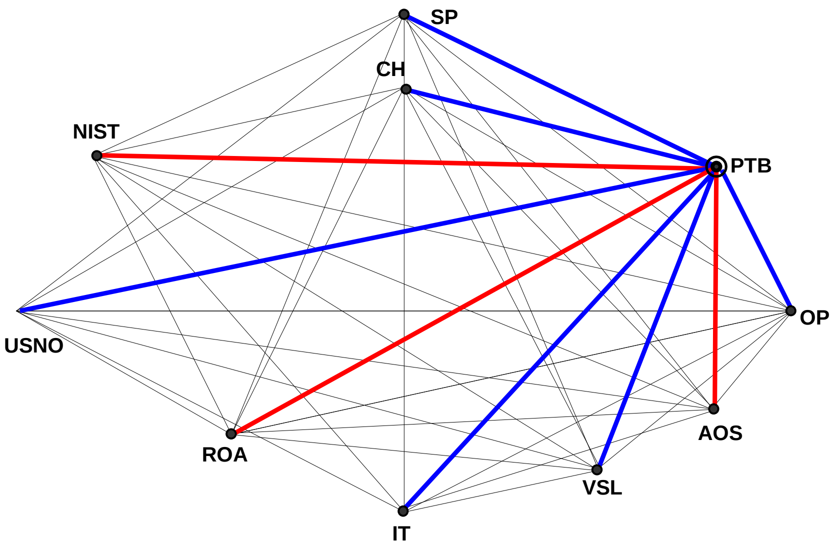



**Figure 2** Status of the TW network of Apr. 2008, Mjd 54554-54584 (TW0804). There are 10 UTC laboratories: AOS, CH, IT, NIST, OP, PTB, ROA, SP, USNO and VSL. The 9 color lines are UTC links: 6 blue are TW calibrations and 3 red are GPS calibrations. The 35 black lines are the redundant links to be TCC-calibrated

## *Annex 3: The calibration results*

The CALR values (Table 2a and 2b) were implemented by all the TW laboratories since UTC 0 h of Mjd 54677, the 30 July 2008.

**Table 2a** Calibrated CALR Values for redundant links / ns  (for the Laboratories their ESDVAR values are stated as 99999.999 i.e. N.A.)

| Labi | Labj | S | CALR | Std | ESDVAR | N | ε | $u_B$ |
|---|---|---|---|---|---|---|---|---|
| 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 |
| 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 | 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 |

**Table 2b** The Calibrated CALR Values for redundant links / ns

(For the Laboratories their ESDVAR values are available)

| Labi | Labj | S | CALR | 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 |