The 2015 TWSTFT calibration for UTC and related time links

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Abstract

Two-Way Satellite Time and Frequency Transfer (TWSTFT or TW) is one of the primary time transfer techniques for UTC generation. In this framework the Triangle Closure Calibration (TCC) method has been used to calibrate links between certain laboratories whose links to the pivot lab are directly calibrated. TCC is based upon requiring the closure of three co-joined links to be zero. In this paper, the results of the 2015 calibration computation are presented. The uncertainties are usually below 2 ns.

Key words: TWSTFT or TW, TCC, Calibration, Uncertainty, TW Network, CALR, ESDVAR.

1. Introduction

The use of triangle closure calibration (TCC) was first proposed in 2005 [1], and the first TCC was performed in 2008 [2]. In 2014, it was highlighted by Dr. Klepczynski as one of the four most significant developments in TWSTFT history [3]. TCC was approved as a standard method for TW calibrations at the 23rd meeting of the Consultative Committee for Time and Frequency (CCTF) Working Group on TWSTFT in September, 2015, and according to the TW calibration guidelines [4] the BIPM is approved to apply TCC when necessary.

The practical need for TCC stems from the fact that a network with N labs consists of N(N-1)/2 links, of which N-1 are direct links to the pivot. Of all N(N-1)(N-2)/6 closures, $(N^2-3N+2)/2$ are independent. For example, if N=13, there are 12 pivoted links and 78 links in total. It would be difficult to calibrate all the 78 links directly with a mobile station (MS), but TCC makes it possible to do this analytically.

The principle of the TCC is quite simple:

- The closure of the three links in a triangle should be zero within the measurement noise;
- If two links are calibrated, the non-zero closure is the calibration correction for the third link.

The calibration value is specified in TW ITU-format files by the CALR and ESDVAR values of each site; typically the CALR value is changed.

As shown in Figure 1, if we have the two calibrated links (LAB_i-PTB and LAB_j-PTB), we can calibrate the link (LAB_i-LAB_j) through the closure condition:

$$\text{Closure} = [UTC(LAB_i)-UTC(PTB)]-[UTC(LAB_j) - UTC(PTB)] + [UTC(LAB_j)-UTC(LAB_i)] \equiv 0. \quad (1)$$

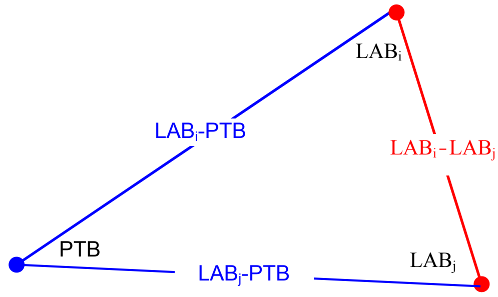

Fig. 1 The non-UTC TW link calibration via triangle closure condition (TCC)

The initially non-zero closure, using one uncalibrated link, is numerically equal to the calibration correction for that link:

$$CALR_i = -CALR_j = \text{Closure} + (ESDVAR_j - ESDVAR_i)/2. \quad (2)$$

The final calibration value is typically obtained by averaging over a month. Assuming 12 measurements per day, there are about 360 measurements. Since the observation times between links in a closure can differ by up to an hour, measured TW time differences are interpolated to the nearest common scheduled epoch, and then the closures are calculated for each epoch. The mean value and its standard deviation are computed from the individual closures. The uncertainty of the calibration can be estimated by the following equation:

$$U_{CALR(TCC)} = \sqrt{\{u_i^2 + u_j^2 + S^2\}}. \quad (3)$$

Here:

$u_i = u_B[UTC(LAB_i)-UTC(PTB)]$
$u_j = u_B[UTC(LAB_j)-UTC(PTB)]$
$S = Std/\sqrt{N}$

where Std is the Standard Deviation of the triangle closures, N is the number of triangle closures, and u_B are the calibration uncertainties of the calibrated links.

Values of S are listed in Table 5. They are of order of $u_A/\sqrt{N}$ where u_A, the RSS (square root of the summed squares) of the links' statistical uncertainties, is set to 0.5 ns. Since N is about 360 over a month, $S \sim 0.03$ ns. Inserting these very small values and the $u_B \le 1$ ns TW calibration uncertainty via MS [5-7,9,14-16], into equation 3, the link uncertainty estimate is ≤ 1.4 ns. For a TW link calibrated via GPS, we have $u_B \le 1.5$ ns [10,11], and the TCC uncertainty is ≤ 1.8 ns. The BIPM currently assigns a nominal uncertainty of 2 ns to all TCC calibrations.

2. The Data Set October, 2015 (1510)

The 1510 UTC dataset includes European and North American TW data from MJD 57292-57329. There are nine TW laboratories involved (PTB, NIST, USNO, OP, IT, ROA, VSL, CH and SP), cf. Figure 2 and Tables 1-2.

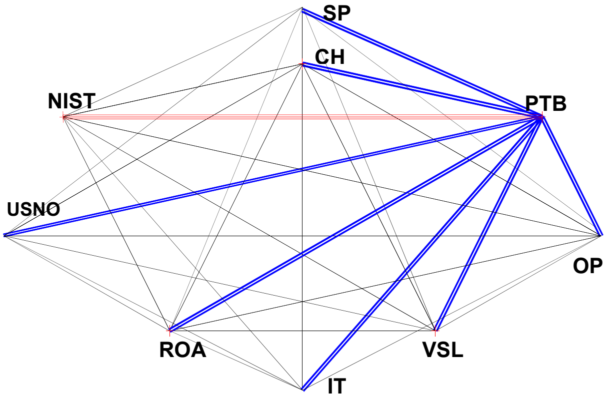

Fig. 2 The UTC time links (blue or red lines) and the redundant/non-UTC links (black lines)
The blue links are calibrated with the TW mobile station ($u_B \leq 1$ ns) and the red links with the GPS calibrator ($u_B \leq 1.5$ ns)

Table 1 All available TW links in October, 2015

No	Lab2-Lab1	No	Lab2-Lab1
1.	CH IT	19.	IT OP
2.	PTB CH	20.	VSL IT
3.	IT PTB	21.	SP IT
4.	CH NIST	22.	IT ROA
5.	NIST IT	23.	PTB NIST
6.	USNO CH	24.	NIST OP
~~7.~~	~~NIST USNO~~*	25.	SP NIST
8.	CH OP	26.	NIST ROA
9.	VSL CH	27.	PTB OP
10.	OP VSL	28.	USNO OP
11.	SP CH	29.	SP OP
12.	PTB SP	30.	USNO PTB
13.	CH ROA	31.	VSL PTB
14.	ROA OP	32.	PTB ROA
15.	SP USNO	33.	VSL ROA
16.	USNO ROA	34.	SP ROA
17.	VSL NIST	35.	VSL SP
18.	USNO IT	36.	VSL USNO

* Measurements were not available in this calculation

Table 2 Set of independent triplets
(all other triplets are linear combinations of these)

Lab1-Lab2-Lab3	Lab1-Lab2-Lab3
PTB IT USNO	PTB SP USNO
PTB IT VSL	PTB SP VSL
PTB NIST OP	PTB USNO VSL
PTB NIST ROA	PTB CH IT
PTB NIST SP	PTB CH NIST
~~PTB NIST USNO~~*	PTB CH OP
PTB NIST VSL	PTB CH ROA
PTB OP ROA	PTB CH SP
PTB OP SP	PTB CH USNO
PTB OP USNO	PTB CH VSL
PTB OP VSL	PTB IT NIST
PTB ROA SP	PTB IT OP
PTB ROA USNO	PTB IT ROA
PTB ROA VSL	PTB IT SP

* Measurements were not available in this calculation

3. The computation of the TCC calibration

Table 3 gives the changes in the closures of the 27 independent triangles composed by the 9 TW labs using the original 1510 dataset with earlier calibrations from 2011 [12] and 2014 [5].

Table 3 Deviations of some of the TCC values from their 2011 and 2014 determinations (unit in ns)

Triangle	Min	Max	Closure	StdD
PTB CH IT	-1.70	-0.90	**-1.32**	0.24
PTB CH NIST	0.10	0.70	**0.33**	0.20
PTB CH OP	0.30	0.80	**0.62**	0.17
PTB CH ROA	-5.40	-4.80	**-5.10**	0.25
PTB CH SP	-5.40	-4.80	**-5.12**	0.19
PTB CH VSL	-0.50	0.10	**-0.10**	0.22
PTB IT NIST	1.60	2.40	**2.10**	0.31
PTB IT OP	-0.30	0.70	**0.15**	0.36
PTB IT ROA	-0.60	0.10	**-0.35**	0.26
PTB IT SP	0.20	1.00	**0.50**	0.26
PTB IT USNO	-0.60	0.10	**-0.25**	0.30
PTB IT VSL	1.80	2.80	**2.13**	0.36
PTB NIST OP	0.30	0.90	**0.68**	0.21
PTB NIST ROA	-6.00	-5.40	**-5.73**	0.20
PTB NIST SP	-4.40	-4.20	**-4.33**	0.07
PTB NIST VSL	-0.50	0.40	**0.07**	0.34
PTB OP ROA	-0.90	-0.30	**-0.45**	0.21
PTB OP SP	-0.20	0.10	**-0.05**	0.11
PTB OP USNO	-0.50	-0.10	**-0.40**	0.14
PTB OP VSL	-1.00	-0.60	**-0.77**	0.14
PTB ROA SP	0.00	0.60	**0.28**	0.19
PTB ROA USNO	-1.10	-0.60	**-0.77**	0.16
PTB ROA VSL	3.90	4.50	**4.25**	0.18
PTB SP USNO	-0.80	-0.30	**-0.53**	0.21
PTB SP VSL	4.20	5.10	**4.60**	0.34

The closure mean values in column 4 of Table 3 fall into two categories. Those among mainly PTB, IT, OP, ROA, SP, and USNO [5] (cf. the **blue** lines in the table) are smaller than 0.86 ns (√3 times the Type A uncertainty 0.5 ns of an individual link) and those likely impacted by long-term variations in the closures that are discussed in Section 5. The triplets with larger changes would be due to changes in equipment, the laboratory setups, or the applied calibration values [5,12].

Figure 3 is a histogram of the closure of the PTB-OP-SP triplet. There are 291 measurements; whose quasi-normal distribution has an RMS of 119 ps and mean value close to zero. This suggests a high stability for the three links since their calibration one and a half year before, although Figure 4 (in Section 5) may indicate that the agreement is fortuitous.

```
  PS |Total 291
-500|
-400|+++++
-300|++++++++++++++++++++
-200|+++++++++++++++++++++++++++++++++++++++
-100|+++++++++++++++++++++++++++++++++++++++++++++++++++
   0|++++++++++++++++++++++++++++++++++++++++++++++++++++
 100|++++++++++++++++++++++++++++++++++++++++++++++++++
 200|++++++++++++++++++++++++++++++++++++
 300|+++++++++++++++
 400|+++++++++++++
 500|
```

Figure 3 Histogram of the closure of the triangle Δ PTB-OP-SP, after TCC calibration by the 2014 Europe campaign (unit in ps)

4. The Results of the TW Calibration: CALR and ESDVAR

In the following sections, the final calibration results are given: CALR, ESDVAR, CI, TYPE and the uncertainties. Most have been implemented in the ITU TWSTFT data files. Results involving NIST are not presented because NIST has not yet implemented the calibration.

4.1 The CALR/ESDVAR for the UTC links

Table 4 Revised CALR/ESDVAR values for implementation (unit in ns)

Labi	Labj	CALR	ESDVAR	CI	Type	uB
PTB01	CH01	+713.4	0.000	284	LC(TWSTFT)	1.0
PTB01	VSL01	+986.3	0.000	295	LC(TWSTFT)	1.0
PTB01	USNO01	+501.7	0.000	392	LC(TWSTFT)	1.0

Based on the TW calibrations via MS [6,7,9], we first revised the calibrations and uncertainties of the links to the pivot with the ESDVAR set to zero (Table 4). The USNO-PTB link calibration in July 2015 varied by only 0.4 ns from that of 2014 [5,9], less than its uncertainty.

4.2 The CALR/ESDVAR for the Non-UTC links

Table 5 lists the CALR/ESDVAR TCC calibration results for the non-UTC European-USA links.

Only the new calibrations (the red lines) concerning CH, VSL, and USNO etc. are to be implemented at this time. For those calibrations already given in [5], the same values are kept in the ITU data, as listed in the CALR′ column. N and *S* are defined in equation 3. In the Table 5, the column *Dif.*, which is the difference CALR-CALR′, compares our 2015 computation with that given in the ITU data files of 1510 (Oct. 2015), which was derived from the 2014 European calibration report [5]. The differences are small compared to the 2 ns nominal uncertainty.

Table 5 The CALR Values for the non UTC links to be implemented in the 1512 TW ITU data files (unit in ns)

CI	Type	uB	Labi	Labj	S	CALR	ESDVAR	StDev	N	*S*	No.	CALR′	*Dif.*
		2.0	IT02	OP01	1	6837.706	00000.000	±0.192	304	0.011	9	6837.3	0.4
		2.0	IT02	ROA01	1	-307.736	00000.000	±0.286	304	0.016	10	-307.7	0.0
		2.0	IT02	SP01	1	-274.671	00000.000	±0.232	304	0.013	11	-275.7	0.9
		2.0	OP01	ROA01	1	-7145.375	00000.000	±0.256	312	0.015	18	-7145.0	-0.3
		2.0	OP01	SP01	1	-7112.887	00000.000	±0.177	303	0.010	19	7112.9	0.0
		2.0	ROA01	SP01	1	32.431	00000.000	±0.278	312	0.016	22	32.1	0.3
396	TCC	2.0	CH01	IT02	1	268.748	00000.000	±0.274	295	0.016	1		
398	TCC	2.0	CH01	OP01	1	7106.790	00000.000	±0.174	303	0.010	3		
399	TCC	2.0	CH01	ROA01	1	-38.238	00000.000	±0.271	303	0.016	4		
400	TCC	2.0	CH01	SP01	1	-6.244	00000.000	±0.231	303	0.013	5		
401	TCC	2.0	CH01	USNO01	1	-212.499	00000.000	±0.156	303	0.009	6		
402	TCC	2.0	CH01	VSL01	1	271.878	00000.000	±0.437	302	0.025	7		
404	TCC	2.0	IT02	USNO01	1	-481.546	00000.000	±0.287	303	0.016	12		
405	TCC	2.0	IT02	VSL01	1	3.620	00000.000	±0.366	304	0.021	13		
410	TCC	2.0	OP01	USNO01	1	-7318.351	00000.000	±0.170	312	0.010	20		
411	TCC	2.0	OP01	VSL01	1	-6834.323	00000.000	±0.331	312	0.019	21		
412	TCC	2.0	ROA01	USNO01	1	-173.652	00000.000	±0.192	312	0.011	23		
413	TCC	2.0	ROA01	VSL01	1	310.189	00000.000	±0.298	312	0.017	24		
414	TCC	2.0	SP01	USNO01	1	-206.167	00000.000	±0.116	312	0.007	25		
415	TCC	2.0	SP01	VSL01	1	277.904	00000.000	±0.397	311	0.022	26		
416	TCC	2.0	USNO01	VSL01	1	484.234	00000.000	±0.604	287	0.036	27		

Table 6 **C**losures using the calibrated CALR and ESDVAR values for the non-UTC links

Triangle	Min	Max	Clos.	StdD
PTB CH IT	-0.50	0.30	0.00	0.25
PTB CH OP	-0.20	0.10	-0.03	0.11
PTB CH ROA	0.30	0.50	0.37	0.07
PTB CH SP	-0.50	0.10	-0.13	0.19
PTB CH USNO	-0.10	0.20	0.07	0.12
PTB CH VSL	-0.50	0.00	-0.33	0.16
PTB IT OP	-0.20	0.20	-0.02	0.13
PTB IT ROA	-0.40	0.80	0.00	0.39
PTB IT SP	-0.20	0.30	0.03	0.16
PTB IT USNO	-0.40	0.40	-0.05	0.26
PTB IT VSL	-0.40	-0.30	-0.33	0.05
PTB OP ROA	0.00	0.40	0.17	0.15
PTB OP SP	-0.20	0.10	-0.03	0.09
PTB OP USNO	-0.20	0.10	-0.03	0.09
PTB OP VSL	-0.60	-0.30	-0.47	0.11
PTB ROA SP	-0.40	0.00	-0.23	0.14
PTB ROA USNO	-0.30	0.20	-0.07	0.16
PTB ROA VSL	-0.30	0.20	-0.03	0.17
PTB SP USNO	-0.20	0.10	-0.02	0.11
PTB SP VSL	-0.60	-0.20	-0.37	0.14
PTB USNO VSL	-1.00	0.10	-0.57	0.42

Table 6 lists the statistical results of the 21 closures using only the averages over the six standard MJDs of the 1510 data set. From the table, the mean values are approximately zero, as expected. The 0.4 ns maximum standard deviation is consistent with √3 times the Type A uncertainty of u_A=0.5 ns. The implementation for these labs was made on 57357 (1 Dec. 2015) at 0h UTC [13].

5. Long-term variation of the closures

The calibrations herein are strictly applicable only at the times of calibration. Calibration variations are often assumed to be mostly due to hardware delay changes that affect all observations at a given station. We note that it is possible to obtain a lower limit of about 0.5 ns to the long-term stability of all TW links by observing the closures' variations. Figures 4-6 are plots of the 5-day averages of closures between some European lab triplets. To make this plot the CALR and ESDVAR values were ignored; if they had been consistently included, the only difference would be to make the mean zero. Where the curve is not continuous between equipment or satellite changes, the triplet's variation captures those components of delay variations that are not common to all three sites and baselines. Therefore they truly provide a lower limit to the variations. A continually updated set of closures for all European and North American triplets is made available on-line by SP [8]. The closures are the *true* errors indicating important information on the *true* Type A and Type B uncertainties and their variation. Further investigations, by different authors, are ongoing.

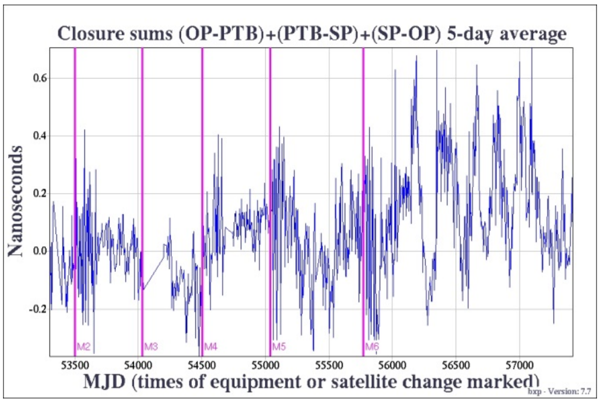

Figure 4 Closure variations between OP, PTB, and SP. Markers indicate satellite or equipment changes.

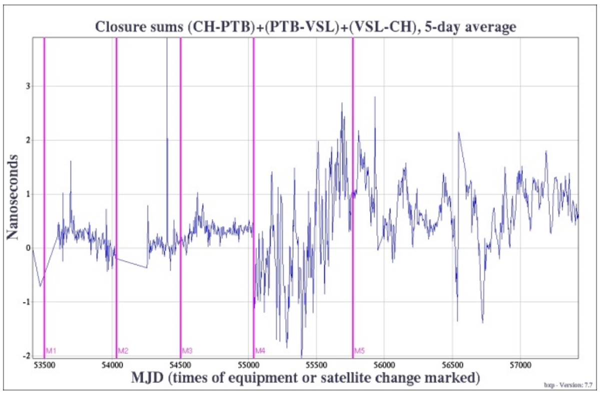

Figure 5 Closure variations between CH, PTB, and VSL. Markers indicate satellite or equipment changes.

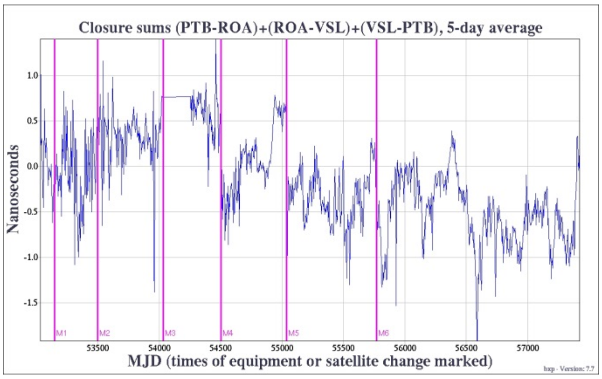

Figure 6 Closure variations between PTB, ROA, and VSL. Markers indicate satellite or equipment changes.

6. Conclusion

TCC is now an operational technique that enables any TW link to be analytically calibrated provided its two adjacent laboratories have calibrated their links to a third lab, with a slight degradation in accuracy. When measurement data are available, it will be a simple matter to carry out the similar calibrations for all European, USA and Asian laboratories in the network.

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