Restoring a TWSTFT Calibration with a GPS Bridge

- A standard procedure for UTC time transfer

Z. Jiang[1], D. Piester[2] and K. Liang[3]

1. Bureau International des Poids et Mesures (BIPM), zjiang@bipm.org
2. Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany
3. National Institute of Metrology (NIM), P.R.China

Abstract

Two-Way Satellite Time and Frequency Transfer (TW for short) is one of the primary techniques for *UTC* (Coordinated Universal Time) time transfer. One of its advantages is its ability of accurate calibration, reflected by its low achievable Type B uncertainty, u_B(TW). Of the time links included in the calculation of *UTC*, the best u_B(TW) is about 1 ns, as compared to 5 ns for u_B(GPS). Moreover, the TW calibration is characterized by long-term stability and reproducibility within the stated calibration uncertainty.

However TW calibration is rather expensive and time consuming. It also depends on the complete configuration of the triangle Lab(1)-satellite-Lab(2). Any change in any of the segments necessitates a change in the calibration. Such a situation has occurred several times over the last years, due to exchanges of the used satellites.

After changes, a calibration can be restored by means of a bridge based on another, continued, time-transfer technique. In this paper, we discuss the restoration of TW calibrations using GPS PPP and other bridges, and estimate their uncertainties.

A standard procedure has been developed for the restoration operation. This procedure was used to restore TW calibrations following the change in satellite from IS-3R to T-11N in mid-2009, and the results were implemented in the TW links as of September 2009.

I. Introduction

Over the last decade, there has been significant development of time-transfer techniques. Both the Type A (u_A) and Type B (u_B) uncertainties have been reduced by about an order of magnitude. u_A has decreased from about 6 ns down to 0.3 ns using GPS precise point positioning (GPSPPP) time transfer technique for example, and u_B from 7 ns down to 1 ns using two-way satellite time and frequency transfer (TW) [1,2].

The u_B(TW) has been shown to be very stable with a repeatability between calibrations of about 1 ns [3]. As the u_B is the major component of the total uncertainty budget for *UTC-UTC*(k) [4], TW plays an important role in the production of *Circular T*. In addition the TW laboratories directly contribute to the generation of *UTC*. There are currently 19 laboratories operating a TW facility, including 13 (19%) of the 68 laboratories used in *UTC*. They contribute data from 253 atomic clocks (71% of the total clocks and 88% of the total clock weight forming *UTC*). In addition, they transfer data from 11 of the 12 Primary Frequency Standards used to steer the atomic time scale TAI.

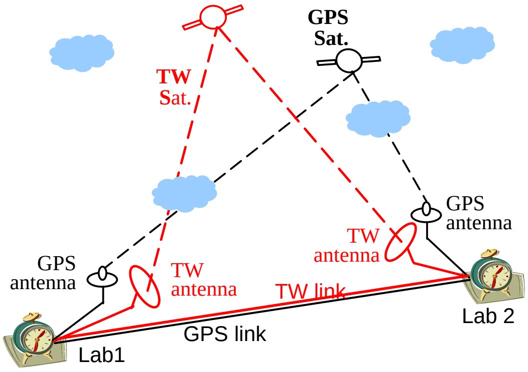

Fig. 1.1 The space triangle composed of Lab1-Sat-Lab2 and setting up of side by side GPS and TW time transfer equipment

However, TW calibrations have the drawback to be labor and time-consuming. Unlike the site-based GPS calibrations, the TW calibrations are usually done link-based. A configuration of the whole system of the satellite-baseline is illustrated in Fig. 1.1. Generally, the total differential delay of the triangle ensemble Lab1-Satellite-Lab2, of which each terminal comprises the ground-based antenna, cables, electronic equipment and satellite transponder(s), is determined in a calibration campaign and reported as a calibration value CALR following the ITU-R data format convention [5]. A change in the satellite segment, especially the frequencies or satellites as a whole, generally offset the delay along the signal paths, and necessitates either a new calibration or a restoration of the existing calibration.

Different methods exist and have been already applied for restoring a TW calibration by means of a bridge formed by continuous observations during the calibration changes. The bridge might be a clock prediction [6] or an independent TW or GPS time link [7].

A clock bridge can be used when the bridging period is very short, corresponding to a short gap in the TW data. Obviously this relies on the assumption of a constant clock rate and is not suitable for long bridges. A second TW link could also be used as a bridge, although few links (e.g. the link between USNO and PTB) have such a backup TW link available. However, all the TW laboratories are equipped with GPS carrier-phase receivers which provide backup data for *UTC* generation. A recent product of GPS carrier-phase observations is the GPS PPP links. The u_A(GPS PPP) is 0.3 ns, which is a bit lower than u_A(TW) of 0.5 ns. GPS PPP is characterized by high short-term stability and hence constitutes a suitable bridge for the restoration of TW calibrations.

In 2009 the CCTF recommended that the BIPM use the GPS PPP technique for *UTC* time transfer and GPS PPP links were accordingly introduced into the generation of *UTC* in September 2009. GPS PPP is now an operational technique and the GPS PPP bridge is an operational alternative.

II. Restoration of a *UTC* TW calibration using a GPS PPP bridge

In the ITU data format convention the TW calibration is represented by the value CALR. As described above, a CALR value is usually considered as uniquely fixed by a particular space triangle Lab1-Satellite-Lab2. A change of the TW satellite can result in a validity loss of the current CALR. To restore a CALR by means of a GPS PPP bridge requires a coexistence of TW and GPS time-transfer baselines as illustrated in Fig. 1.1, with common clocks and simultaneous observations.

As an example, Fig. 2.1 demonstrates how to use a PPP bridge to restore the CALR of USNO-PTB following the satellite switch from IS-3R to T-11N in July 2009. We first define the time-transfer differences between TW(Satellite) and PPP:

D_1 = TW(IS-3R) − PPP
D_2 = TW(T-11N) − PPP

The change of satellite requires a change in the calibration. We compute the new CALR with the PPP bridge:

CALR =[TW(IS-3R) − PPP]–[TW(T-11N) − PPP] = $D_1 - D_2$

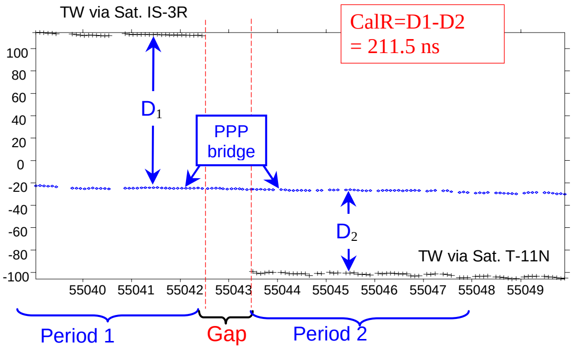

Fig. 2.1 Restoring the CALR of USNO-PTB with a PPP bridge for the satellite switch from IS-3R to T-11N. The x-axis is MJD and the y-axis is *UTC*(USNO)-*UTC*(PTB) with a vertical shift in ns

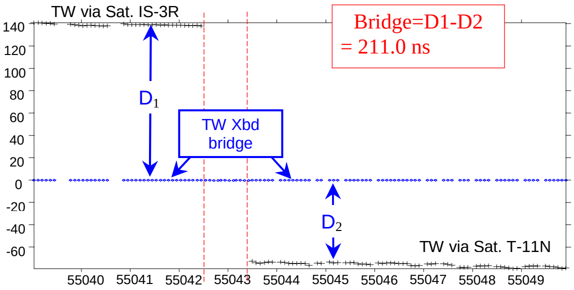

Fig. 2.2 Restoring the CALR of USNO-PTB with a TW X band bridge for the satellite switch from IS-3R to T-11N. The x-axis is MJD and the y-axis is *UTC*(USNO)-*UTC*(PTB) with a vertical shift in ns

The uncertainty of the new CALR restored by PPP can be estimated by:

$u_B(\text{new})^2 = [u_B(\text{old})^2 + u(\text{ESDVAR})^2/2 + u(\text{bridge})^2]$,

where

$u(\text{ESDVAR})^2 = u(\text{ESDVAR}_{\text{Lab}i})^2 + u(\text{ESDVAR}_{\text{Lab}j})^2$ and ESDVAR in the ITU convention represents the internal delay corrections since the last calibration for each of the two end laboratories of a link. It is determined and added only by the laboratory in question, i.e. it is a one-way operation.

Similarly, the coexisting TW X band link between USNO and PTB could also be used as the bridge. (see Fig. 2.2). The two alternatives give similar results: The PPP bridge is 211.5 ns and the X band bridge is 211.0 ns.

III. Restoration of non-*UTC* TW calibrations through the triangle closure condition

The use of the so called triangle closure condition (TCC) has been discussed in [8], and is summarized in Fig. 3.1. In a first step, the recalibration of all *UTC* links, i.e. the links with the *UTC* pivot laboratory PTB, can be made using a bridge as described above. In a second step, as can be seen in Fig. 3.1, any non-*UTC* link Lab$_i$-Lab$_j$ can be considered as a combination of two adjacent *UTC* links, Lab$_i$-PTB and Lab$_j$-PTB. TCC is defined that, in the absence of measurement errors, the closure sum of the three vectors in the triangle should be zero:

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

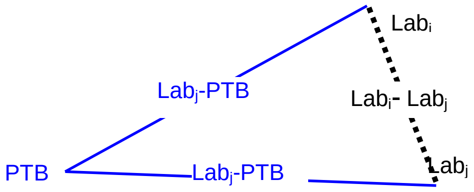

Fig. 3.1 Calibration of non-*UTC* TW link Lab$_i$-Lab$_j$ using TCC

Table 3.1 The TCC uncertainty u_B(TCC)

Labs/Links	u_B(TCC)/ns
NIST, ROA concerned links with PTB, USNO, OP, IT, VSL, CH, SP	6
all the other links in Tables 4.2 and 4.3	2

The uncertainty u_B(TCC) is discussed in detail in [9]. Two categories depending on the type of the original initial calibrations of the *UTC* links are described: a differential calibration using GPS gives u_B(TW/GPS)=5 ns (the case for links including NIST and ROA), whereas for the other links using a TW calibration gives u_B(TW/TW)=1 ns. We list the estimated uncertainties in table 3.1. These numbers are used in Section IV below.

IV. New CALR after the satellite switch

In this section, we compute the whole set of new CALR values after the satellite change from IS-3R to T-11N in mid-2009 (around MJD 55043). We first use the GPS PPP bridges to restore the CALR of the *UTC* links (LABs-PTB, cf. Tables 4.1 and 4.2a) then use TCC to compute the CALR values of the non-UTC links (LABs-LABs, Tables 4.2b and 4.2c), and then estimate the corresponding uncertainties.

In Table 4.1, D_1 is the link difference TW-GPSPPP for Period 1 MJD 55039 to MJD 55043 *before* the satellite switch; and D_2 is corresponding difference for Period 2 MJD 55043 to MJD 55054 *after* the satellite switch; the bridge result is given by CALR=D_1-D_2. Where available, Table 4.1 lists also other bridge results based on GPS MC or P3 and TW X band observations. They agree with each other within their corresponding uncertainties. N is the number of common points used in each case.

For *UTC* links the ESDVAR values were kept unchanged. For the non-*UTC* links, there are two cases: for links with NIST and USNO their original ESDVAR values were kept (Table 4.2c) as before; and for European links the vales were set to ESDVAR = 999999999 (Tables 4.2a and 4.2b) according to the ITU-R recommendations' format for a not applicable value.

The new CALR values were computed using the TW data (BIPM data set: TW0908). After implementing the new CALR in the TW0909 data (up to MJD 55095 in September 2009), we verified the closures, non-zero values being an indication of calibration errors. The results are listed in Table 4.3. Except for data missing links, new CALR/ESDVAR values are computed and listed in Tables 4.2b and 4.2c. Where N is the number of the measurements used.

The CALR/ESVAR values and the CI codes as listed in Tables 4.2 were implemented in the ITU files for the period MJD 55102 to 55108 (28 Sept - 4 Oct), and are included in the subsequent issue of *Circular T* No. 262 starting MJD 55109.

Table 4.1 Restoring the CALR of the TW *UTC* links using a GPS (MC/P3/PPP) or a TW bridge

Baseline link		**N**	**D_1±StDev/ns**	**D_2±StDev/ns**	**D_1-D_2±ε/ns**
USNO-PTB	Xband	61/56	-3.911±0.403	-214.916±0.855	+211.0±0.1
	P3	61/67	-3.396±0.656	-214.792±0.933	+211.4±0.1
	PPP	61/67	-2.614±0.372	-214.149±0.906	+211.5±0.1
NIST-PTB	MC	62/61	-0.625±1.212	197.639±1.163	-198.3±0.2
	PPP	62/61	-1.451±0.147	195.790±0.230	-197.2±0.1
CH-PTB	P3	39/101	-5.142±0.566	204.581±0.696	-209.7±0.2
	PPP	39/101	-4.352±0.168	205.094±0.408	-209.5±0.1
IT-PTB	P3	35/64	-27.626±0.539	452.311±0.717	-479.9±0.2
	PPP	35/64	-29.915±0.407	450.212±0.575	-480.1±0.1
OP-PTB	P3	51/9	1.964±0.618	7301.804±0.647	-7299.9±0.3
	PPP	51/9	1.907±0.192	7301.623±0.161	-7299.9±0.1
ROA-PTB	P3	69/68	-1.480±1.297	162.057±1.564	-298.3±0.2
	PPP	69/68	-3.614±0.339	159.746±0.972	-298.1±0.1
SP-PTB	P3	61/92	-2.039±0.907	192.406±1.533	-194.4±0.2
	PPP	61/92	-220.489±0.147	-26.135±0.749	-194.4±0.1
VSL-PTB	P3	36/98	-3.131±2.442	582.696±0.693	-585.8±0.4
	PPP	36/98	-75.481±2.490	510.378±0.550	-585.9±0.4
NPL-PTB	P3	61/0	1.216±0.691	No TW data	N.A.
	PPP	61/0	1.344±0.225	No TW data	N.A.
AOS-PTB	MC	28/0	2.597±0.916	No TW data	N.A.

Table 4.2a CALR/ESDVAR for *UTC* links. CI is the BIPM calibration identification code

CI	LAB_i	LAB_j	CALR/ns	u/ns	ESDVAR/ns
139	PTB	CH	209.500	1.0	999999999
140	PTB	USNO	-211.500	1.1	999999999
141	PTB	NIST	197.200	5.0	999999999
142	PTB	IT	480.100	1.2	999999999
143	PTB	OP	7299.900	1.1	999999999
144	PTB	ROA	298.100	5.0	999999999
145	PTB	SP	194.400	1.1	999999999
146	PTB	VSL	585.900	1.2	999999999

Table 4.2b CALR/ESDVAR for European non-*UTC* links. CI is the BIPM calibration identification code

CI	LAB_i	LAB_j	CALR/ns	u/ns	ESDVAR/ns
147	CH	IT	268.499	2.0	999999999
148	CH	OP	7091.614	2.0	999999999
149	CH	ROA	-30.460	6.0	999999999
150	CH	SP	-14.027	2.0	999999999
151	CH	VSL	262.637	2.0	999999999
152	IT	OP	6820.466	2.0	999999999
153	IT	ROA	-302.867	6.0	999999999
154	IT	SP	-284.760	2.0	999999999
155	IT	VSL	-8.265	2.0	999999999
156	OP	ROA	-7121.489	6.0	999999999
157	OP	SP	-7105.712	2.0	999999999
158	OP	VSL	-6828.525	2.0	999999999
159	ROA	SP	16.066	6.0	999999999
160	ROA	VSL	293.982	6.0	999999999
161	SP	VSL	276.616	2.0	999999999

Table 4.2c CALR/ESDVAR for European-American non-*UTC* link. CI is the BIPM calibration identification code

CI	LAB_i	LAB_j	CALR/ns	u/ns	ESDVAR/ns
162	USNO	CH	422.290	2.0	-379.910
163	USNO	IT	687.732	2.0	-379.910
164	USNO	OP	7512.354	2.0	-379.910
165	USNO	SP	406.671	2.0	-379.910
166	NIST	CH	11.859	6.0	-0.724
167	NIST	IT	280.069	6.0	-0.724
168	NIST	OP	7102.736	6.0	-0.724
169	NIST	SP	-3.680	6.0	-0.724
170	NIST	VSL	273.418	6.0	-0.724

Table 4.3 Validation of the new CALR values with the triangle closures between Mjd 55079 and MJD 55094 for the data set TW0909

Lab_i	Lab_j	Closure±STDev/ns	N
CH	IT	-0.092±0.405	194
CH	NIST	-0.413±0.256	169
CH	OP	-0.216±0.543	167
CH	SP	-0.150±0.553	168
CH	USNO	0.113±0.353	163
CH	VSL	-0.337±1.122	122
IT	NIST	-0.188±0.479	173
IT	OP	-0.267±0.466	166
IT	SP	-0.087±0.412	167
IT	USNO	-0.611±0.810	171
IT	VSL	-0.371±0.519	128
NIST	OP	0.262±0.453	170
NIST	SP	0.402±0.468	171
NIST	VSL	0.081±0.880	141
OP	SP	0.139±0.365	171
OP	USNO	0.209±0.454	167
OP	VSL	0.012±0.602	128
SP	USNO	0.251±0.503	166
SP	VSL	0.005±0.573	128

Unfortunately, there were data missing from some of the laboratories. IT, OP and SP had data gaps over 5 days, meaning that the bridge quality might be affected by possible biases in GPS, and there were no data at all for the TW links of USNO-ROA, NIST-ROA, USNO-VSL, NPL-LABs and AOS-LABs.

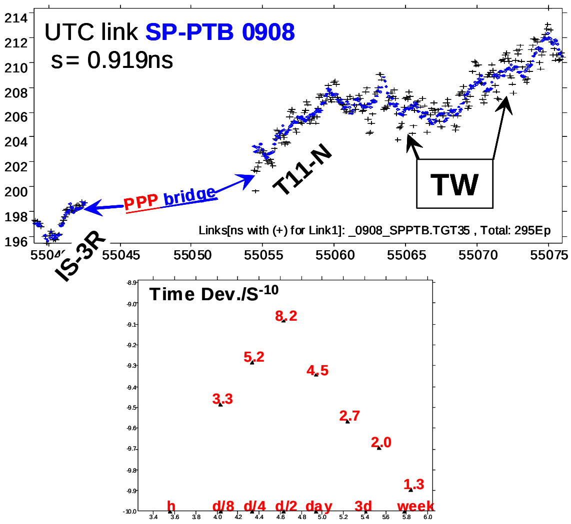

Fig. 4.1 Upper plot is the *UTC* link SP-PTB considering a GPS PPP bridge between the two satellites IS-3R and T11-N. The x-axis is MJD and the y-axis is *UTC*(SP)-*UTC*(PTB) in ns. The link by the satellite T11-N is disturbed by strong diurnals as seen in the lower plot of Time Deviation (TDev)

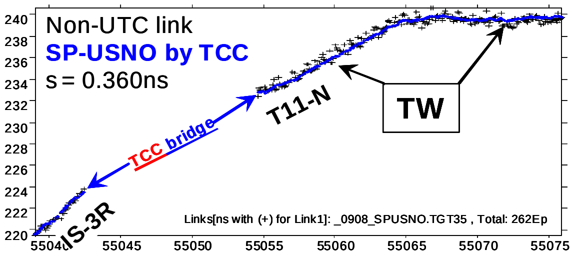

Fig. 4.2 The non-*UTC* link SP-USNO based on a GPS PPP bridge between the two satellites IS-3R and T11-N. The link by satellite T11-N is also disturbed by diurnals but less than that shown in Fig. 4.1. The x-axis is MJD and the y-axis is *UTC*(SP)-*UTC*(USNO) in ns.

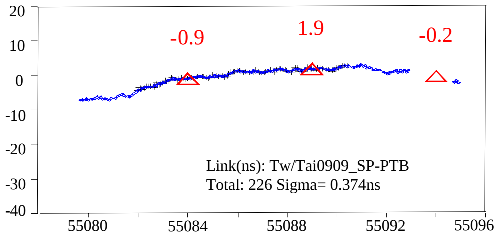

Fig. 4.3 Calibration restored time transfer SP-PTB 0909 after the satellite switch to T-11N. The x-axis is MJD and the y-axis is *UTC*(SP)-*UTC*(USNO) in ns.

Fig. 4.1 and 4.2 illustrate the TW links SP-PTB and SP-USNO realized by the two satellites IS-3R and T11-N. The passages of the two satellites are bridged by GPS PPP. Here s in the link plots is the RMS of the differences of PPP and TW by satellite T11-N. The T11-N link SP-PTB is noisier than that of IS-3R. The TDev in Fig. 4.1 shows the T11-N link is disturbed by strong diurnal variations. The calibration fits within 1 ns: 0.92 ns for SP-PTB and 0.36 ns for SP-USNO. The diurnals disappear after MJD 55080 as illustrated in Fig. 4.3.

V. A standard procedure of the calibration restoration

On several occasions over the past years, we have used a GPS bridge to restore TW calibrations. Based on these experiences, we have developed a standard procedure for the restoration computation, and this has now been incorporated in the BIPM *UTC/TAI* software package Tsoft.

To minimum the disturbance to the monthly computation of *Circular T*, the following schedule is suggested:

1. 1^{st} week after the satellite switch:
   - TW and GPS data collection
   - Computation of GPS PPP link
   - Computation of TW link for Period 1 and 2
   - Computation of CALR for *UTC* links based on the PPP bridge (Labs-PTB)
   - Computation of CALR for non-*UTC* links through the TCC (LABs-LABs)
2. 1.5-2 weeks after the switch: BIPM sends draft CALR/ ESDVAR values (with uncertainty and CI) to invited TW colleagues for checking
3. 2-2.5 weeks after the switch: BIPM sends the final CALR/ESDVAR values to all labs for confirmation
4. 3 weeks after the switch: implementation of the new calibration in ITU-formatted files and submission to the BIPM for the coming month’s *UTC/TAI* computations

It is clear that simultaneous TW and GPS PPP observations, at least 3 days before and after the satellite switch, are indispensable during the satellite changes. The GPS data, referred to the same clocks as TW, should be continuous throughout all the TW data gaps. The key to a high-quality restoration is a very short TW data gap.

VI. Summary

As several occasions in the past years, we have successfully restored TW link calibrations by means of GPS PPP bridges. Non-*UTC* TW links are re-calibrated through the TCC. A standard procedure has been developed and installed in the *UTC/TAI* computation software package Tsoft to allow facilitates:

- restoration of TW calibrations for *UTC* and non-*UTC* time transfer links
- differential calibration of TW links via calibrated GPS links.

Acknowledgement

We thank our colleagues in TW laboratories for their active cooperation.

References

[1] BIPM pilot study in GPS PPP for TAI time transfer.

[2] BIPM Circular T No. 262, Section 6, Aug. 2009.

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

[4] W. Lewandowski, D. Matsakis, G. Panfilo, P. Travella, "The evaluation of uncertainty in [UTC-UTC(k)]", *Metrologia* **43** 278–286, 2006

[5] ITU Radiocommunication Sector, "The operational use of two-way satellite time and frequency transfer employing PN codes", *Recommendation ITU-R TF.1153.2*, 2003, Geneva, Switzerland.

[6] F. Cordara, L. Lorini, V. Pettiti, P. Tavella, D. Piester, J. Becker, T. Polewka, G. de Jong, O. Koudelka, H. Ressler, B. Blanzano, C. Karel: "Calibration of the IEN-PTB TWSTFT link with a portable reference station", Proc. 18th European Frequency and Time Forum, 5-7 Apr, 2004.

[7] D. Piester, A. Bauch, J. Becker, T. Polewka, A. McKinley, L. Breakiron, A. Smith, B. Fonville, D. Matsakis, "Two-Way Satellite Time Transfer between USNO and PTB", Proc. 2005 Joint IEEE International Frequency Control Symposium and Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 29-31 Aug 2005, Vancouver, BC, Canada, pp. 316-323, 2005.

[8] Z. Jiang, W. Lewandowski, D. Piester, "Calibration of TWSTFT links through the triangle closure condition", Proc. 40th Annual Precise Time and Time Interval (PTTI), 467-483, 2008.

[9] Z. Jiang, W. Lewandowski, D. Piester, "Restoration of the TWSTFT link calibration using GPS bridging after the satellite switch from IS-3R to T-11N in July/August 2009 (around MJD 55043)", BIPM TM166, 2009.