TWSTFT Calibration Guidelines for UTC Time Links (V2016)

Acronyms

BIPM:	Bureau International des Poids et Mesures
CCD:	Common Clock Difference
DCD:	Double Clock Difference, i.e., difference between two time link techniques
CCTF:	Consultative Committee for Time and Frequency
CI:	Calibration Identification
GPS:	Global Positioning System
GPSPPP:	GPS Precise Point Positioning
ITU:	International Telecommunication Union
TCC:	Triangle Closure Calibration
TWSTFT:	Two-Way Satellite Time and Frequency Transfer
UTC:	Coordinated Universal Time
UTC(*k*):	Coordinated Universal Time as realized by laboratory Acronyms for laboratory *k*[1]

I. General

Two-Way Satellite Time and Frequency Transfer (TWSTFT) has been a primary technique contributing to the comparison of clocks and primary frequency standards in UTC generation for over one and a half decades. It has been proven that TWSTFT is the most accurate technique for time transfer measurements based on the exchange of radio frequency signals via satellites. The measurement technique and data format have been described in dedicated publications [1, 14, 15]. The current version of the ITU-R recommendations [1] is applicable for the data computation. TWSTFT is independent from and complementary to GPS time transfer and the long-term stability of its calibration has been demonstrated in many cases. In addition, quasi-real time data exchange and computations are currently operational.

The importance of TWSTFT has grown over the past few years, with the introduction into UTC computations of time links based on a combination of TWSTFT and GPS Precise Point Positioning (GPSPPP). This strategy combines the accuracy of TWSTFT with the precision of GPS carrier phase solutions while also minimizing the effect of diurnal variations seen in time transfer results in some TWSTFT links. The use of TWSTFT in UTC computation also brings greater importance to the need for systematic calibration and recalibration of TWSTFT links. Wider application is nevertheless recommended whenever possible.

[1] Refer to "Acronyms and locations of the timing centres which maintain a local approximation of UTC, UTC(k) and/or an independent local time scale TA(k)" at ftp://ftp2.bipm.org/pub/tai/publication/acronyms/acronyms.pdf.

This document provides guidelines for the calibration of TWSTFT links. A link is referred to as the time and frequency comparisons between two time laboratories using a specific technique, such as TWSTFT or GPS. Each TWSTFT link calibration determines the combined delays of the TWSTFT link as described in [1]. The members of the CCTF Working Group on TWSTFT and the BIPM are authors of the Guidelines and are responsible for keeping it up to date. Proposals for updating the Guidelines will be discussed at the annual TWSTFT meetings and will be based on calibration experiences.

Calibration of a TWSTFT link can be achieved by using either a TWSTFT mobile station or a GPS travelling calibrator. In some cases, the use of a GPS travelling calibrator is the only practical means available, this is the case with all links in the Asia-Europe network and in the Europe-USA network. The Type B uncertainty (u_B) of the GPS link calibration has been reduced to 1.5 ns as reported by the PTB, ROA, NIM, INRIM, TL and BIPM [2-7], and the BIPM's GPS-based calibration system (METODE) [7, 8] has been applied successfully to the calibration of the UTC TWSTFT links NICT-PTB, NIM-PTB and TL-PTB. It is suggested, that GPS calibrations be undertaken as a complementary part of TWSTFT calibrations. Simultaneous calibrations, if agreed by participants, would serve as a check against large errors and also help to improve both techniques.

II. Performance of a TWSTFT link calibration

A TWSTFT link calibration campaign is carried out using a TWSTFT mobile station and/or a GPS travelling system that is circulated among several time laboratories contributing to UTC, referred to as the "participants" in this document. The provider of the travelling calibration device can also be considered as a participant.

2.1 Using a TWSTFT mobile station

This is the primary technique used for a UTC TWSTFT time link calibration.

The technical specifications for the participating and the mobile stations are not mandated by this document. As a demonstration and for reference, Annex I provides a TWSTFT calibration experience containing the uncertainty budgets for the Type A and Type B uncertainties [11, 12].

For each calibration campaign, and as agreed by all the participants, one coordinator is appointed. The coordinator must be a member of the CCTF WG on TWSTFT, representing a laboratory contributing to UTC which operates a TWSTFT station.

The coordinator will interact with the participants to reach agreement on the planning, the provider, the costs and the procedure/schedule of a calibration campaign, more specifically:

1. Establishing a list of participants;
2. Deciding on the TWSTFT station which will be used for the closure measurements of the campaign;
3. If the "pivot" station of the TWSTFT network (at present PTB) is not a participant in the campaign, selecting the station that will serve as intermediate station to calculate the calibration result (CALR values) via triangulation (TCC);
4. Establishing, with the support of the provider, the measurement schedule for the campaign;
5. Reporting to the BIPM on the campaign under preparation, providing information on the list of participants and the closure station of the calibration campaign (items 1 and 2 above), and the dates for the calibration campaign (item 1 below);
6. Collecting the technical specifications and the raw data from each visited station;
7. Processing the data and computing the calibration results using the measurement data that was processed and submitted by each participant;
8. Preparing the draft report and submitting it to participants for approval;
9. Preparing the final report in agreement with participants and submitting it to the BIPM.

In agreement between the coordinator and the participants, one provider is appointed. The provider will interact with the coordinator and the participants to reach an agreement on the following points:

1. Discussing the contractual conditions and dates for the calibration campaign with the participants;
2. Establishing the measurement schedule with the support of the coordinator;
3. Agreeing the technical protocol with the participants;
4. Planning visits to different sites with the support of the coordinator and according to the schedule;

5. Operating the mobile station at each site according to the protocol.

2.2 Using GPS travelling calibration equipment

Calibration via GPS can be used as a supplement or an alternative when calibration via the mobile TWSTFT station is not applicable.

Unlike differential GPS receiver calibration, which uses the CCD of the two GPS receivers (the travelling and the local receivers), the DCD is used in this case. It is obtained from the differences between the TWSTFT and GPS time links. The local GPS receiver of Lab(*k*) is not involved. Based on [2-7], a combined calibration uncertainty of 1.5 ns is attainable.

The coordinator of a TW link calibration by means of a GPS calibrator is responsible for organizing and conducting the measurement campaign, and usually provides the GPS calibration equipment. He/she must be a member of the CCTF WG on TWSTFT, representing a laboratory that contributes to UTC and which operates a TWSTFT station, or the BIPM. The technical specifications for the participants and the travelling calibration equipment are not mandated by this document. As a demonstration and for reference, Annex II describes a TWSTFT calibration campaign with GPS calibration equipment.

Usually, each participant in a calibration campaign covers the total cost of the door-to-door shipping of the travelling equipment to the next laboratory, including the related custom fees and insurance when necessary.

III. The calibration report

The coordinator is charged with preparing the report, based on the input supplied by the participants. For this purpose, the participants will provide the raw data and any other technical information relevant to the measurement. Sections 3.1 and 3.2 specify what the report must contain, and examples are provided in the annexes.

3.1 Calibration using a TWSTFT mobile station

1. A description of the calibration campaign;
2. The technical protocol;
3. A technical description of the common clock difference or link difference measurements performed at each of the stations visited;
4. Report of the results and their corresponding uncertainties;
5. The measurement data processing for the computation of the CALibration Result (CALR), Earth Station Delay VARiation (ESDVAR) and their related uncertainties;
6. The complete evaluation of the uncertainty budget;
7. In cases where the pivot of the TWSTFT network does not participate in the campaign, the report must include uncertainty of the link between the selected intermediate station for the calibration and the pivot;
8. In the case of calibration by the TCC technique, a description of the method for evaluating the uncertainties is required.

The calibration report must be approved by all participating laboratories, and will be published on the BIPM website after approval.

Annex I is an example of the TWSTFT calibration campaign and the calibration report. The exact style is not mandated by these guidelines, but the annex is provided as a reference to carry out the calibration and prepare the report.

3.2 Calibration using GPS calibration equipment

Using GPS to calibrate a TWSTFT link is a simple alternative. Nevertheless, reporting the results is essential and all key points listed in subsection 3.1 should be addressed in an adequate way. Annex II is an example of the GPS time link calibration campaign and the calibration report. It is not mandated by the guidelines but is a reference to carry out a calibration and to prepare the report.

Notes that apply for 3.1 and 3.2:

1. Any of the following stations can be used as the starting-closing station for a calibration campaign:
   a. The pivot laboratory in the UTC time links network (PTB at present);
   b. A UTC(*k*), i.e. any UTC TWSTFT station that is part of the calibration trip;
   c. Other stations as decided by the TWSTFT working group.
2. As a reference, Annex I gives an example of the uncertainty of the closure measurement at the pivot or intermediate stations. If the calibration design only uses data between the mobile station and its common-clock laboratory with CCD, then an extra term of 0.5 ns is needed in the uncertainty budget to allow for closure variations between: the mobile station; the laboratory that has been calibrated; and the participating remote sites whose data are not used to calibrate the site in question.
3. The stability of the intermediate station needs to be guaranteed over the period of the calibration campaign. This could be achieved by performing repeated common clock measurements, by the use of a satellite simulator, and/or by comparison with the corresponding GPS measurements.
4. TCC can be used, cf. [13] for the method and related uncertainty;
5. If applicable, the TWSTFT link calibration result is suggested to be compared to the latest GPS calibration results. Considering the independence of the two techniques, the difference should be in agreement with the combined uncertainty of the two techniques: $U \leq \sqrt{[u^2(\mathrm{TW})+u^2(\mathrm{GPS})]}$. If not, a discussion over the causes is recommended;
6. The implementation of the calibration results will be decided between the participants and the BIPM. For post-processing applications the calibration report would ideally include an estimate of the epoch for the onset of the new calibration value.

IV. The role of the BIPM

The role of the BIPM is:

1. To verify that the report respects the Guidelines for UTC time links, to ask for clarifications if necessary, and to approve it.
2. To assign a Calibration Identification (CI) number to each accepted Result (CALR).
3. To review the calibration report, and publish it on the BIPM website.
4. To propose the date of implementation of the calibration results in the ITU data files in agreement with the participants.
5. To monitor the stability of UTC time link calibrations through the monthly comparisons between the TWSTFT and GPS time transfer links. The comparison results are regularly published at ftp://tai.bipm.org/TimeLink/LkC/. As a supplement to the laboratories' monitoring their systems and links, the BIPM will contact the relevant laboratories if anomalous behaviour is apparent. When necessary, the BIPM will perform the global network calibration through the TCC technique.
6. For post-processing purposes, to maintain a computer-readable file that would indicate the epochs over which the calibrations indicated in the operational data files should be adjusted to take into account new calibration values.
7. To report to the CCTF Working Group on TWSTFT on the status of the time link calibrations.

V. Implementation of the calibrations

It is preferable, but not mandatory, that all of the links implement the calibrations on the same date. However, the two participants in a link must implement the calibration at the same time to avoid unnecessary time steps. Implementation of the calibration results should be made, ideally, within two months following the assignment of the CI numbers. To facilitate the calculation of *Circular T*, the date of implementation of calibration results should be fixed between two periods of calculation of *Circular T*, on a MJD date not ending in 4 or 9.

References

[1] Recommendation ITU-R TF.1153-4 (2015) The operational use of Two-Way Satellite Time and Frequency Transfer employing pseudorange noise codes, http://www.itu.int/rec/R-REC-TF.1153-4-201508-I/en.

[2] Esteban H., Galindo F. J., Bauch A., Polewka T., Cerretto G., Costa R., Whibberley P., Uhrich P., Chupin B., and Jiang Z. (2015) GPS Time Link Calibrations in the Frame of EURAMET Project 1156, *Proc. IFCS-EFTF2015*, April 2015, Denver, USA.

[3] Feldmann T., Bauch A., Piester D., Rost M., Goldberg E., Mitchell S., and Fonville B. (2011), "Advanced GPS-Based Time Link Calibration with PTB's new GPS Calibration Setup", *Proc. 42nd Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting Meeting*, Reston, USA, 2010, (CD-ROM).
[4] Cerretto G., Esteban H., Pallavicini M., Pettiti Va., Plantard C., and Razeto A. (2012) Measurement of CNGS Muon Neutrinos Speed with Borexino: INRIM and ROA Contribution. *Proc. 44th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting*, Reston, Virginia, USA, pp. 133 - 140, 2012.
[5] Liang K., Feldmann T., Bauch A., Piester D., Zhang A., and Gao X. (2011) Summary of the Link Calibration between NIM and PTB Using a Traveling GPS Receiver, *Proc. 2011 Joint Conference of the IEEE International Frequency Control Symposium & European Frequency and Time Forum* : Hyatt Regency, San Francisco, May 2 - 5, 2011, San Francisco, California (2011), [CD-ROM], 280 – 285.
[6] Lin Calvin S.Y., Huang Y.J., and Tseng W.H. (2014) Upper Limit Uncertainty Estimation of TL METODE Calibration Tour Using Moving Cs Clock Method, *Proc. ION PTTI 2014*.
[7] Jiang Z., Czubla A., Nawrocki J., Lewandowski W., and Arias F. (2015), Comparing a GPS time link calibration to an optical fibre self-calibration with 200 ps accuracy, 2015 *Metrologia* **52** 384 doi:10.1088/0026-1394/52/2/384.
[8] Jiang Z., Arias F., Lewandowski W., and Petit G. (2011) BIPM Calibration Scheme for UTC Time Links, *Proc. 2011 Joint Conference of the IEEE International Frequency Control Symposium & European Frequency and Time Forum*, Hyatt Regency, San Francisco, May 2 - 5, 2011, San Francisco, California (2011), [CD-ROM], pp 1064-1069.
[9] Piester D., Bumgarner R., and McKinley A. (2014) The June (2014) calibration of the link UTC(USNO) – UTC(PTB) by means of the USNO portable X-band TWSTFT station, presented to the 22nd CCTF Working Group on TWSTFT, VNIIFTRI, 15-16 Sept. 2014, Mendeleevo, Russia (available at the BIPM WGTWSTFT members' area/WG_22nd_Meeting/WGTWSTFT/22-03-03).
[10] Galindo F. J., Bauch A., Piester D., Esteban H., Sesia I., Achkar J., and Jaldehag K. (2014) European TWSTFT Calibration Campaign 2014, Calibration report approved by BIPM, March 2015 (available at the BIPM WGTWSTFT members' area/Calibrations).
[11] JCGM 106:2012 Evaluation of measurement data – The role of measurement uncertainty in conformity assessment.
[12] JCGM 200:2012 International vocabulary of metrology – Basic and general concepts and associated terms (VIM) 3rd edition.
[13] Jiang Z., Piester D., and Liang K. (2010) Restoring a TWSTFT Calibration with a GPS Bridge, *Proc. EFTF2010*.
[14] Bauch A. Piester D., Fujieda M., and Lewandowski W. (2011) Directive for operational use and data handling in two-way satellite time and frequency transfer (TWSTFT), *Rapport BIPM 2011/01*, BIPM, 2011.
[15] Kirchner D. (1999) Two Way Satellite Time and Frequency Transfer (TWSTFT): Principle, Implementation, and Current Performance, *Review of Radio Science 1996-1999*, pp. 27-44.

Annexes

Annex I Report of TWSTFT calibration using TWSTFT mobile station
Proc. PTTI2016, pp 243-257

Annex II Report of TWSTFT time link calibration using GPS
Proc. PTTI2016, pp 231-242

Version History

V2015 – Approved by the CCTF WG TWSTFT in September 2015 at BIPM.
V2016 – Editorial corrections based on the version 2015 and the updated reference [1]. Approved by the CCTF WG TWSTFT in September 2016 at NIST.