Summary for TL/NICT 2018 TWSTFT calibration report

G. Petit, F. Meynadier and Y.-J. Huang

The TL/NICT TWSTFT link has been calibrated during a G1 GPS calibration trip in the APMP region in 2018. By using GPS P3 measurements of fixed stations in NICT and TL, together with the data from the BIPM travelling receiver, Y.-J. Huang *et al.* (full report is appended to this summary) determined the bias of the TWSTFT link, which remained in operation throughout the campaign.

It encompassed both regular SATRE stations (NICT05 and TL03) as well as SDR links (denoted with station names NICT55 and TL53), where the receivers are SDR modules receiving the remote signal emitted by the distant SATRE modem.

Results

After this calibration, the following values should be used in calculations and ITU file, in accordance to recommendation `ITU-R TF.1153-4` :

CAL_ID	ITU file prefix	LOC	REM	REFDELAY (ns)	CALR (ns)	ESDVAR (ns)
487	twnict	NICT05	TL03	478.461	−1365.11	0.0
488	twnict	NICT55	TL53	478.461	−1837.70	0.0
487	twtl	TL03	NICT05	683.0	1365.11	0.0
488	twtl	TL53	NICT55	683.0	1837.70	0.0

Corresponding header lines in ITU files should read :

```
* CAL   487 TYPE: GPS                MJD: 58257  EST. UNCERT.:    1.700 ns
* CAL   488 TYPE: GPS                MJD: 58257  EST. UNCERT.:    1.700 ns
```

Calibration report of the TWSTFT links between NICT and TL during 2018

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Abstract

The BIPM third bi-annual G1 labs calibration campaign of APMP region (including NICT, NIM, and TL) was coordinated and finished in October 2018. While in the campaign, NICT-TL SATRE and SDR TWSTFT were continuously operated, therefore we have an opportunity to calibrate the TWSTFT links via the BIPM traveling stations which visited NICT and TL during the campaign. We used the GPS P3 solutions of NICT/TL fixed stations and BIPM traveling stations to calculate the bias of the TWSTFT links. The uncertainties of the NICT-TL TWSTFT links are evaluated by combining the uncertainty of the GPS P3 link and the disagreement between the TWSTFT and GPS P3 links.

Acronyms

APMP: Asia Pacific Metrology Programme
UTC: coordinated universal time
BIPM: International Bureau of Weights and Measures
NICT: National Institute of Information and Communications Technology
TL: Telecommunication Laboratories
TWSTFT: two-way satellite time and frequency transfer
SDR TWSTFT: software-defined radio receiver TWSTFT
GPS: global positioning system
GPS P3: GPS ionosphere-free combination of P1 and P2
GPS PPP: GPS precise point positioning
GPS IPPP: GPS integer precise point positioning
$S_{GPS\_STATION}$: system delay of the GPS_STATION
1PPSTX: A pulsed signal generated every second by the TWSTFT modem

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I. Introduction

The BIPM coordinated a GPS calibration tour for the Group 1 laboratories NICT, NIM and TL over six months in 2018. The GPS calibration system B3TS, including two traveling stations BP0U and BP1C, was prepared by the BIPM. The traveling stations were sent from the BIPM, circulated among TL, NICT and NIM, and finally back to the BIPM for closure measurement. Table 1 summarizes the time table of the tour.

Table 1 Time table of the GPS calibration tour

	BIPM	TL	NICT	NIM	BIPM
Period in MJD	58172 – 58184	58228 – 58250	58270 – 58287	58345 – 58356	58389 – 58403
Identification	A	B	C	-	D

Taking this opportunity, the TWSTFT links between NICT and TL can be calibrated using GPS P3 links [1]. A GPS P3 link can be implemented by two popular approaches. The first approach is using two fixed GPS stations. This approach requires the calibrators, which the system delays are known to us, to calibrate the system delays for two fixed stations. Instead, we use a fixed station and a traveling one to calibrate the TWSTFT links. For example, the difference between system delays of BP0U and the reference station in TL, named TLT1, was obtained in Period B. Then in Period C, BP0U was put in NICT to establish a GPS P3 link with TLT1. Finally, the TWSTFT links were calibrated by taking the GPS P3 link as the reference.

In Section II, the equipment will be described briefly. In Section III, the TWSTFT link calibration procedure will be explained. In Section IV, the GPS P3 links using a variety of stations will be taken into account. In Section V, the uncertainty budget will be evaluated. In Section VI, the calibration result will be given.

II. Description of the equipment

The GPS stations used through this report are listed in Table 2. See [2] for more details about the configuration and the information about the UTC(k) references.

Table 2 The GPS stations

Institute	Status of equipment	BIPM code	Receiver type
BIPM	Traveling	BP0U	MESIT GTR50
BIPM	Traveling	BP1C	Septentrio PolaRx3e TR
TL	Reference	TLT1	Ashtech Z-XII3T Metronome
TL	Backup	TLT2	Piktime TTS4
TL	Backup	TLT4	Septentrio PolaRx4 TR Pro

NICT	Reference	NC01	Septentrio PolaRx2 TR
NICT	Backup	NC4S	Septentrio PolaRx4 TR Pro

The TWSTFT links included two earth stations and one geostationary satellite Eutelsat 172B with 2.5 MHz bandwidth of the transponder B2. Annex I shows the configuration of each earth station. Both stations transmitted binary phase shift keying (BPSK) signals at the same uplink frequency 14040.25 MHz, and received the signals from the downlink frequency 10990.25 MHz. The code rate was 2.5 Mcps and the code identifiers were PN 0 for NICT and PN 2 for TL. The TWSTFT link was made by combining the measurements of SATRE modems, while the SDR TWSTFT link was made by the SDR receivers. These links have never been calibrated before.

III. Calibration procedure

The BIPM calibration system B3TS visited TL in May 2018, and the measurements were performed during Period B, or MJD 58228 – 58250. As depicted in Figure 1, the GPS fixed station, TLT1, and BP0U were connected to pulse per second (PPS) signals distributed by UTC(TL). The external frequency for these stations also came from UTC(TL). We use the software R2CGGTTS to convert RINEX data to the GPS P3 measurements [3]. In the configuration file, the reference cable delay is measured and given by each lab, and the internal delay as well as the antenna cable delay is set to zero. When running the software, we extract the 30-second data of REFSYS before they are fitted to 13-minute results. The GPS P3 measurement is obtained by taking median of the 30-second data over one hour. This value is time-scale difference between UTC(TL) and GPST with a bias, as shown in the Figure 2. The bias is called system delay (SYSDLY) [3]. The system delays of BP0U and TLT1 are denoted by S_{BP0U} and S_{TLT1}, respectively.

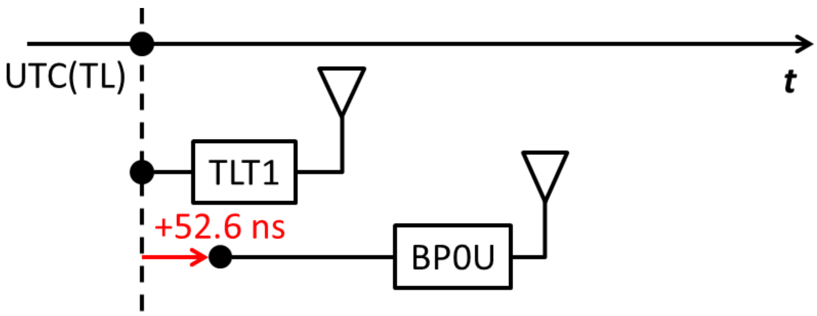


Figure 1 Common-clock configuration of the two GPS stations in TL during Period B. The reference delay values of TLT1 and BP0U were 0.0 and 52.6 ns, respectively.

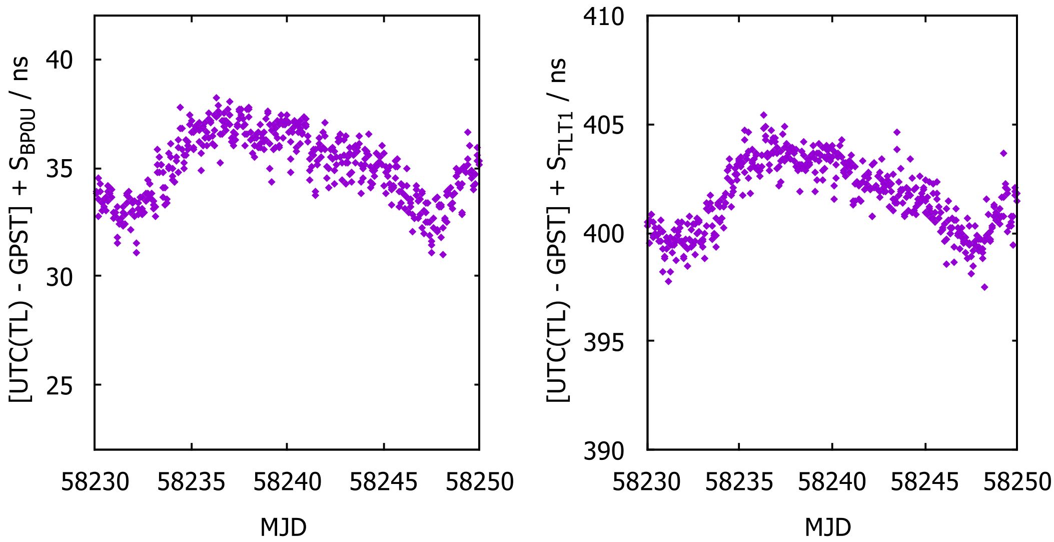


Figure 2 Time-scale difference with a bias measured by BP0U (left) and TLT1 (right)

The system delay difference, $S_{BP0U} - S_{TLT1}$, can be obtained by taking common-clock difference (CCD). The CCD is obtained by subtracting the GPS P3 hourly measurement result of TLT1 from that of BP0U. Figure 3 shows the CCD measurements. The median and the standard deviation are -366.40 ns and 0.45 ns, respectively. We use median to avoid significant outliers because sometimes the outlier is larger than expected.

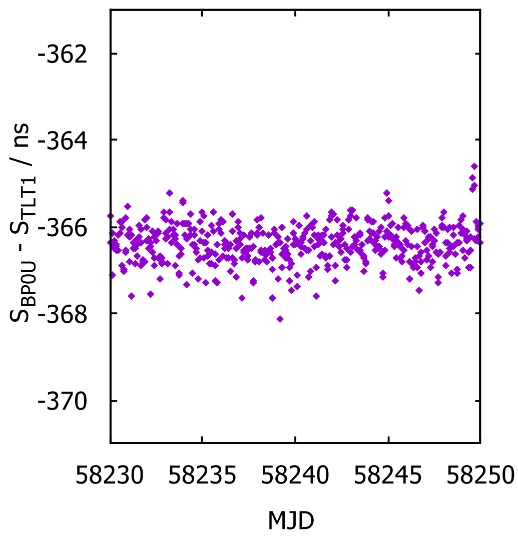


Figure 3 CCD measurements of BP0U – TLT1

Then, the traveling station BP0U visited NICT in June 2018, and the measurements were performed during Period C. As depicted in Figure 4, the reference delay value of BP0U is 252.0 ns in NICT, different from that in TL. The time-scale difference with GPST was measured in NICT and TL by BP0U and TLT1, respectively. Figure 5 shows the results.

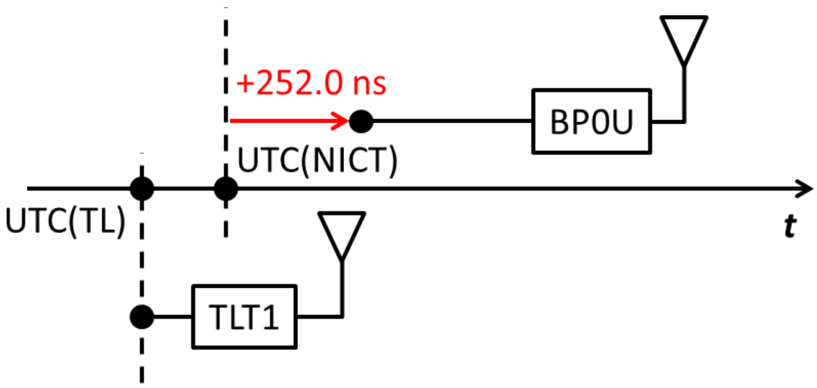


Figure 4 Configurations of the GPS P3 link with TLT1 and BP0U during Period C. The reference delay values of TLT1 and BP0U were 0.0 and 252.0 ns, respectively.

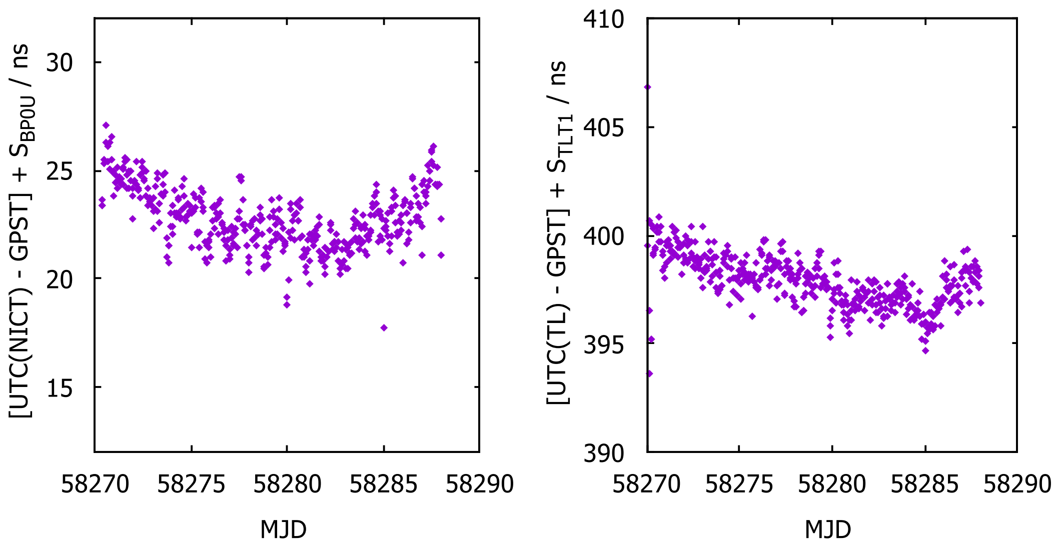


Figure 5 Time-scale difference with GPST measured by BP0U in NICT (left), and measured by TLT1 in TL (right)

The link between UTC(NICT) and UTC(TL) can be measured by subtracting the measurement result of TLT1 from that of BP0U, and then being offset by the median value of CCD. This link, called GPS P3 link, will be considered the reference for calibrating the TWSTFT link. Figure 6 shows the GPS P3 link measurements.

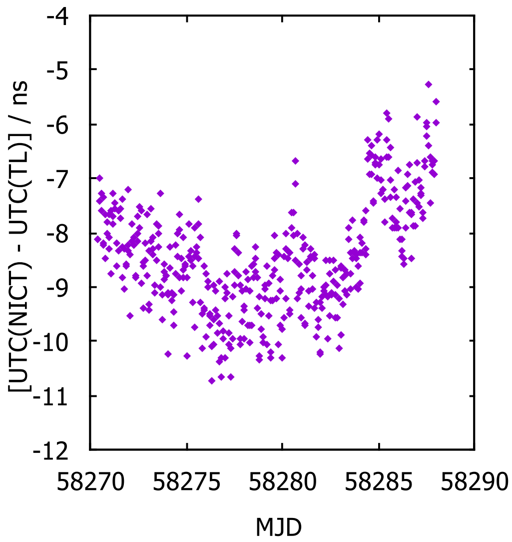


Figure 6 The GPS P3 link measurements using BP0U and TLT1

The TWSTFT link is established with two earth stations NICT05 and TL03 as Figure 7 depicted. The stations are connected to their local PPS and frequency standards. Detailed hardware configurations can be found in Annex I. From ITU-R TF. 1153-4, the time-scale difference can be expressed as a combination of the measurements in Equation (1) [4]:

$$
\begin{aligned}
&[UTC(1) - UTC(2)] \\
&= 0.5\,[TW(1) + ESDVAR(1) + CALR(1,2)] + REFDELAY(1) \qquad (1) \\
&- 0.5\,[TW(2) + ESDVAR(1) + CALR(2,1)] + REFDELAY(2)
\end{aligned}
$$

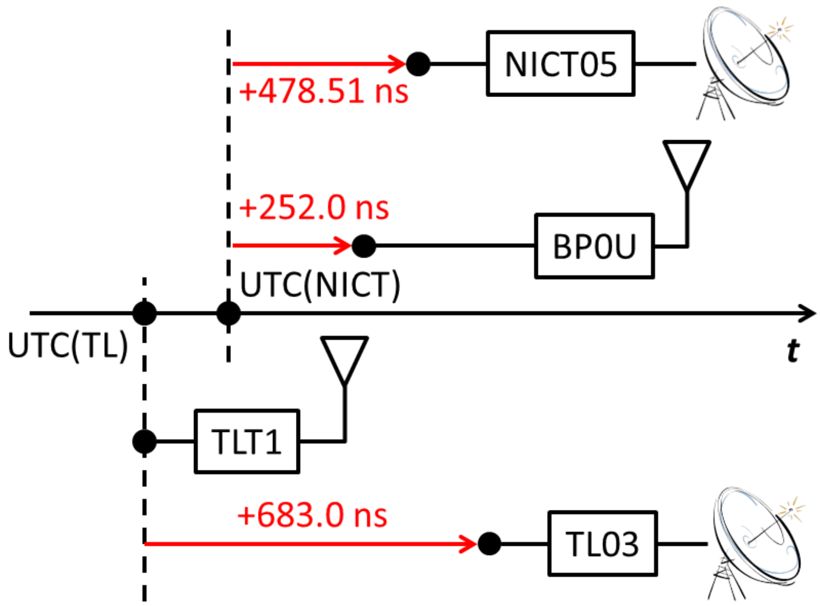


Figure 7 Configurations of the TWSTFT link with NICT05 and TL03, in parallel with the GPS P3 link during Period C. The reference delay values of NICT05 and TL03 are 478.51 ns and 683.0 ns, respectively.

Because the value of CALR(2,1) equals to the negative value of CALR(1,2), we denote CALR(2,1) as CALR and CALR(2,1) as –CALR. We set ESDVAR(k) to zero in computing the CALR. By replacing 1 and 2 with NICT05 and TL03 in Equation (1), respectively, we have:

$$[\mathrm{UTC(NICT)} - \mathrm{UTC(TL)}] + \mathrm{CALR} = 0.5\ \mathrm{TW(NICT05)} + \mathrm{REFDELAY(NICT05)} - 0.5\ \mathrm{TW(TL03)} - \mathrm{REFDELAY(TL03)} \quad (2)$$

The uncalibrated TWSTFT link is the combination of the measurements on the right-hand side of Equation (2). The REFDELAY(k) value was measured and provided by each institute. In Figure 7, the values of NICT05 and TL03 are 478.51 ns and 683.0 ns, respectively. The TW(k) value was measured during the same period as GPS P3 link by TWSTFT receivers, and it was reported in the formatted files [4]. Figure 8 shows measurements of the uncalibrated TWSTFT links.

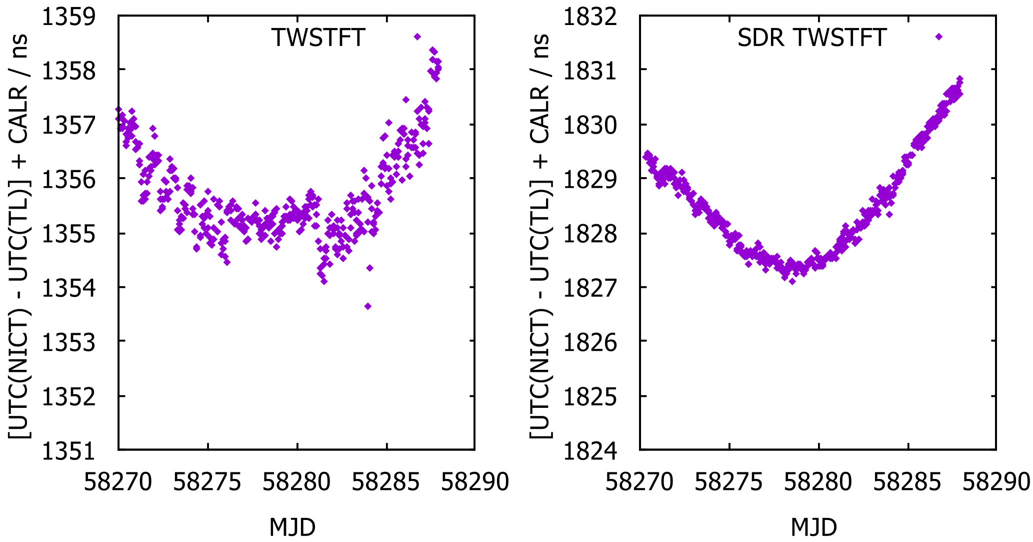


Figure 8 The measurements of the uncalibrated TWSTFT links

The CALR is assumed a constant during the calibration period. To obtain CALR, the [UTC(NICT) – UTC(TL)] in Equation (2) is replaced with the GPS P3 link shown in Figure 6. This procedure is called double-clock difference (DCD). Figure 9 shows the measurements of CALR. The measurements for TWSTFT and SDR TWSTFT have median values of 1364.14 ns and 1836.97 ns with the standard deviations 0.84 ns and 0.74 ns, respectively.

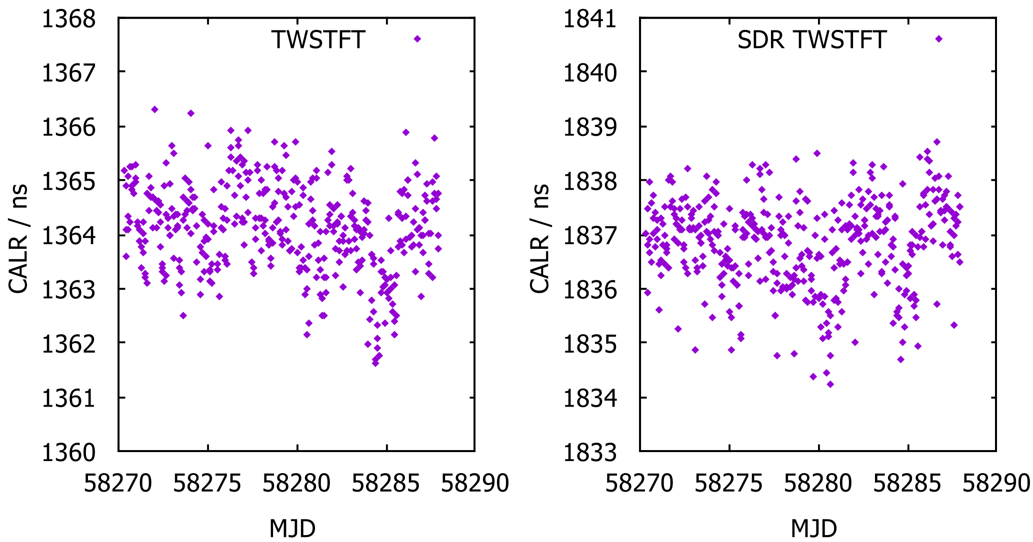


Figure 9 DCD measurements of GPS P3 – TWSTFT links

IV. GPS P3 link with a variety of GPS station pairs

The procedure in Section III can be repeated by using other GPS station pairs. We performed ten cases and summarized the DCD median value and the standard deviation in Table 3.

Table 3 DCD median value and the standard deviation using different GPS stations pairs

Case	Station in NICT	Station in TL	CCD Period	DCD period	DCD med. of TWSTFT / ns	Std. dev. / ns	DCD med. of SDR TWSTFT / ns	Std. dev. / ns
1	BP0U	TLT1	B	C	1364.14	0.84	1836.97	0.74
2	BP0U	TLT2	B	C	1364.39	0.82	1837.17	0.78
3	BP0U	TLT4	B	C	1363.93	0.72	1836.79	0.74
4	NC01	BP0U	C	B	1365.30	0.71	1837.62	0.57
5	NC4S	BP0U	C	B	1364.84	0.75	1837.09	0.73
6	BP1C	TLT1	B	C	1365.26	0.73	1838.05	0.70
7	BP1C	TLT2	B	C	1365.33	0.73	1838.07	0.65
8	BP1C	TLT4	B	C	1365.19	0.75	1837.99	0.70
9	NC01	BP1C	C	B	1366.62	0.54	1838.91	0.50
10	NC4S	BP1C	C	B	1366.07	0.61	1838.31	0.56

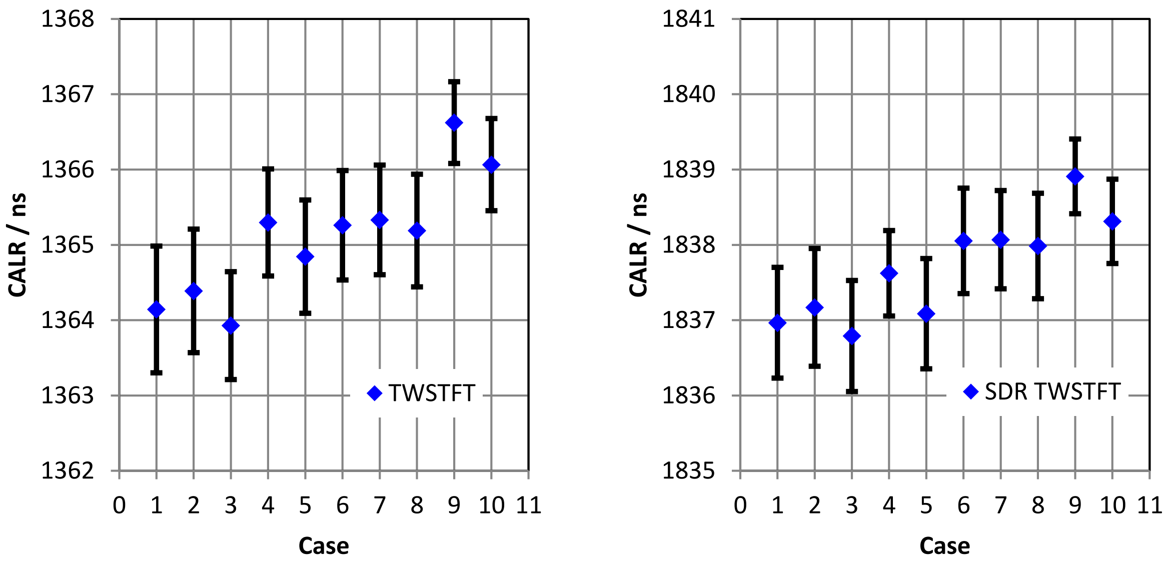


Figure 10 DCD median value and the standard deviation for each case

We noticed that between the worst cases, 3 and 9, the difference of the CALR values is 2.7 ns for TWSTFT and 2.1 ns for SDR TWSTFT. Below three possibilities may explain the difference.

1. The mismatch of $S_{BP0U} – S_{BP1C}$ is 1.03 ns between the Period B and C. See Figure 11.
2. The mismatch of $S_{NC01} – S_{NC4S}$ is 0.53 ns. See also Figure 11.

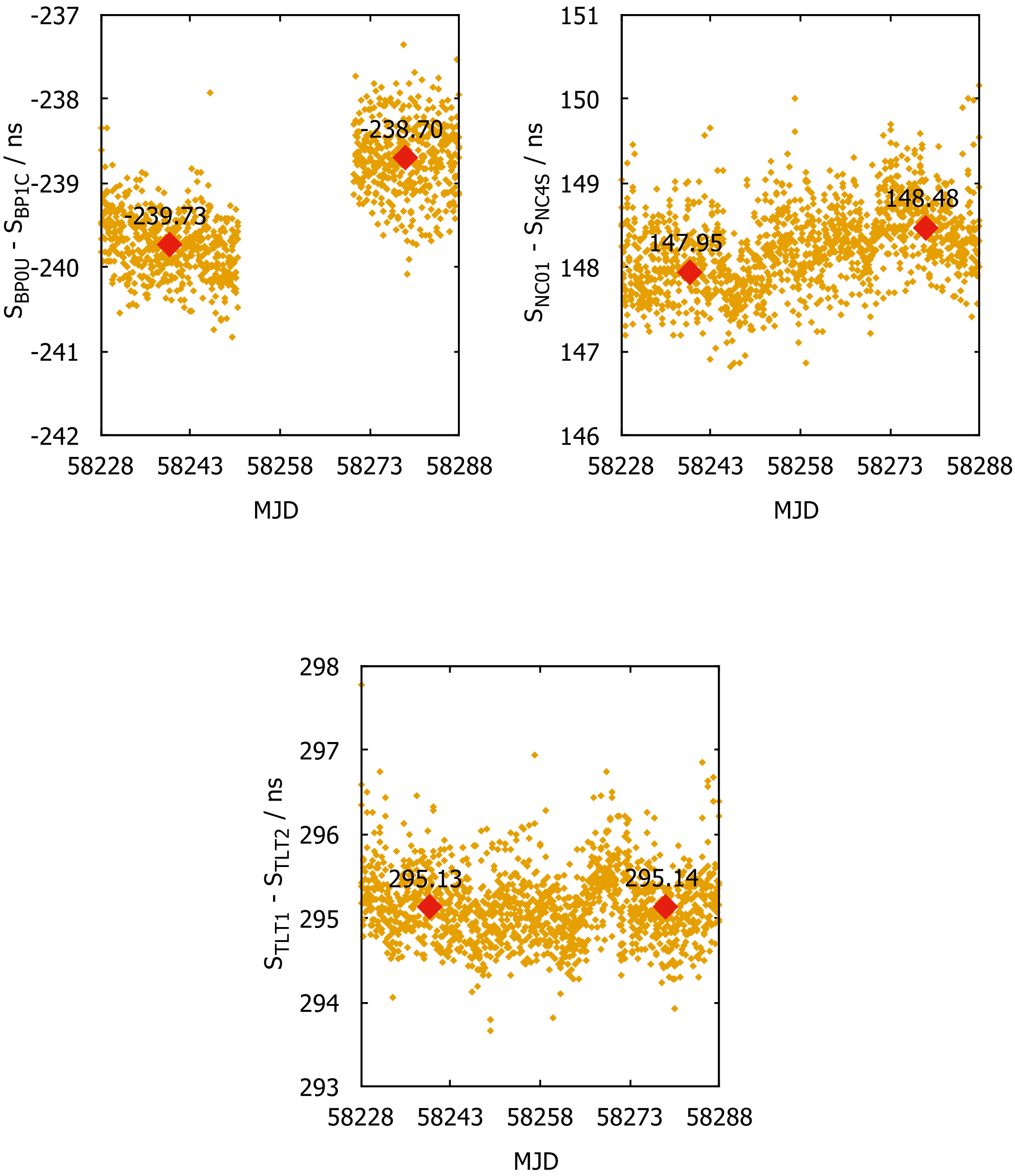


Figure 11 CCD measurements of BP0U – BP1C (top-left), NC01 – NC4S (top-right), and TLT1 – TLT2 (bottom) in Period B and C

3. The disagreement of GPS P3 and TWSTFT links between the two periods. The GPS P3 link is made by NC4S and TLT4 in which the system delays are calibrated. In Figure 12, the disagreements are 0.52 ns for TWSTFT and 0.09 ns for SDR TWSTFT.

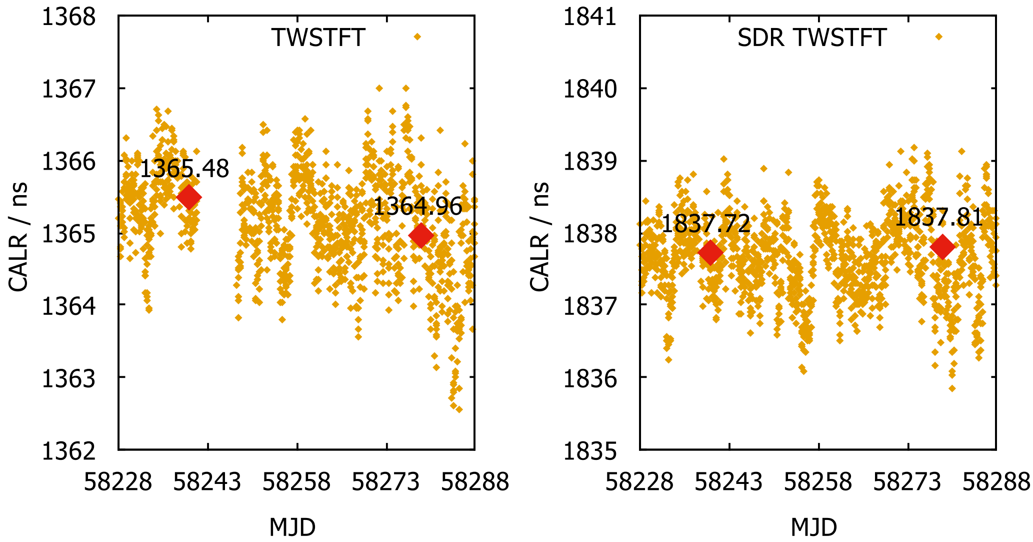


Figure 12 DCD measurements GPS P3 – TWSTFT (left) and GPS P3 – SDR TWSTFT (right). TWSTFT has no value during MJD 58241.23 to MJD 58248.

If the TWSTFT link is operated without any interruption during shipment of the traveling stations, the link will have only one CALR value. The DCD measurements in Figure 12 show something may happen around MJD 58258 but we are not sure if it comes from TWSTFT links. To be sure that, we take DCD with the GPS IPPP link made by NC01 and TLT4. The DCD shown in Figure 13 is flat except for a few GPS IPPP connection problems around MJD 58256 and between MJD 58265 and 58270. On these days, there are a few ambiguity resets and the ambiguity-fixing statistics are too weak, leading to poor connections. The comparison of TWSTFT to IPPP shows no problem between MJD 58256 and 58265 and it can be assumed that the variations seen in Figure 13 are due to IPPP connection problems. Therefore, the TWSTFT links are considered stable during this period. The final CALR value is taken as the average over the values in Table 3 since every case occurs with the same probability.

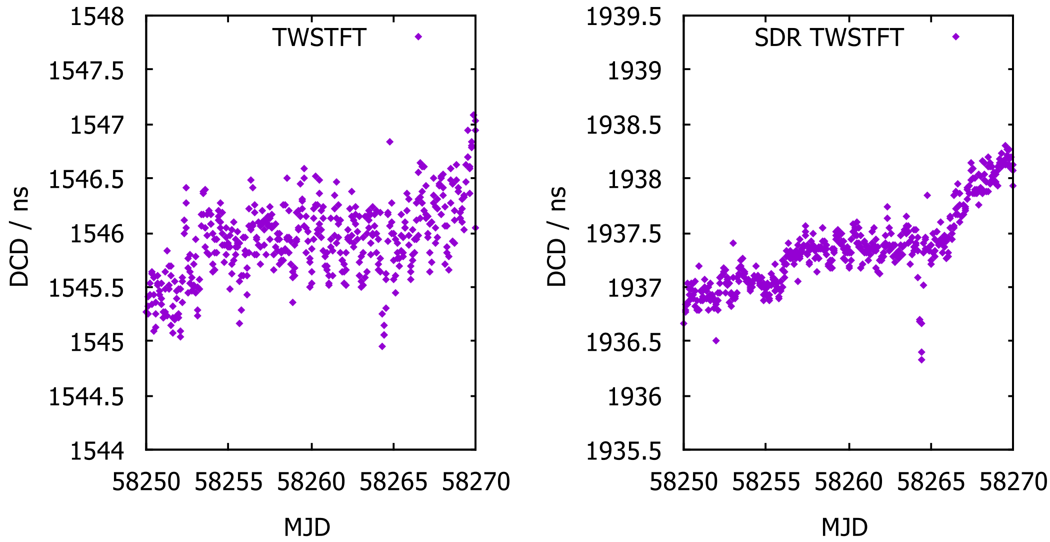


Figure 13 DCD measurements of GPS IPPP – TWSTFT (left) and GPS IPPP – SDR TWSTFT (right) during the shipment of the traveling stations

V. Uncertainty evaluation of the TWSTFT links

This section will discuss the uncertainty of the TWSTFT links. According to the guide [5], the statistical uncertainty (u_A) and the systematic uncertainty (u_B) should be evaluated.

A.1. The u_A is considered the time deviation (TDEV) of the TWSTFT link measurements at the averaging time of the measurement interval. The interval is one hour and the corresponding TDEV values are 0.22 ns and 0.08 ns for TWSTFT and SDR TWSTFT, respectively, as Figure 14 shows.

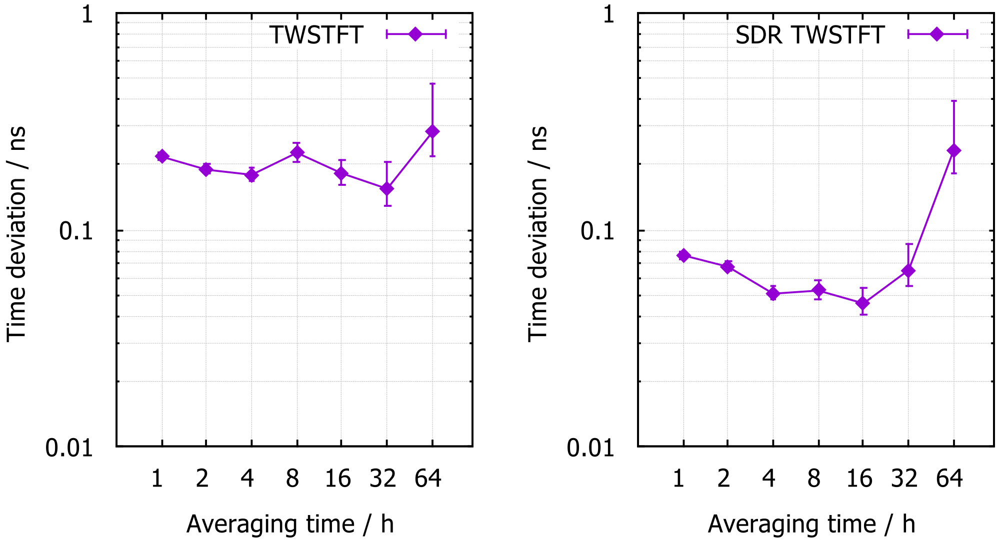


Figure 14 Time deviations of the TWSTFT links

We discuss u_B as follows. In Equation (2), the TWSTFT link on the right-hand side is a summation of the reference GPS P3 link on the left-hand side and the fixed bias, CALR. Hence, the u_B of the TWSTFT link uncertainty can be considered as a combination of the GPS P3 link uncertainty and the variation of the CALR measurements. Several studies indicate the following items should be taken into account the uncertainty of the GPS P3 link [6][7][8][9]:

B.1. The u_A of the GPS P3 link measurement: 0.41 ns. As shown in Figure 15, the value is time deviation at one hour.

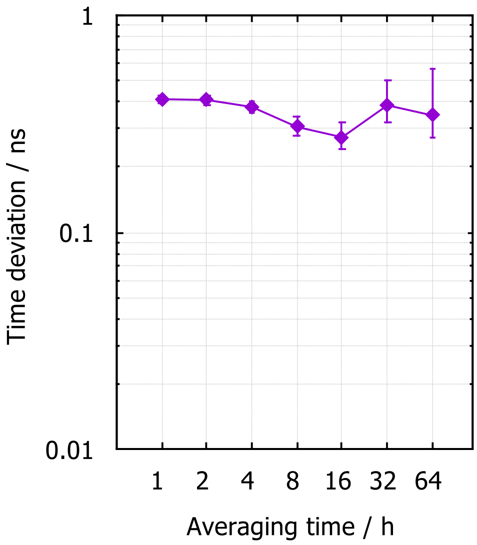


Figure 15 Time deviations of the GPS P3 link.

B.2. Uncertainty of the NICT reference used in the link: 0.8 ns in Annex I. The uncertainty between the reference used and the UTC(k) mainly comes from equipment and time-interval measurement. This uncertainty is evaluated and provided by each institute.

B.3. Uncertainty of the TL reference used in the link: 0.8 ns in Annex I.

B.4. Uncertainty of the GPS stations: 1.03 ns. The GPS P3 link assumes that the system delay of each station is a constant. The variation of system delay will be considered link uncertainty. This can be found from CCD measurements. In Figure 11, the system delay mismatch of BP0U – BP1C, NC01 – NC4S, and TLT1 – TLT2 can be found 1.03 ns, 0.53 ns and 0.01 ns, respectively and we take the largest value as the uncertainty.

B.5. The CALR value is assumed fixed, but the value may change depending on the calibration dates [10]. In Figure 12, the CALR values of TWSTFT are obtained 1365.48 ns and 1364.96 in the periods B and C, respectively. The disagreement is 0.52 ns and it should be taken into account as part of uncertainty since the GPS P3 link is the reference. To evaluate the disagreement, we select a period in which the hardware configurations of TWSTFT and GPS stations are unchanged or changed with known offset values, and then we compute the DCD over the period. Figure 16 shows the DCD between TWSTFT links and the GPS P3 link using calibrated stations TLT4 and NC4S.

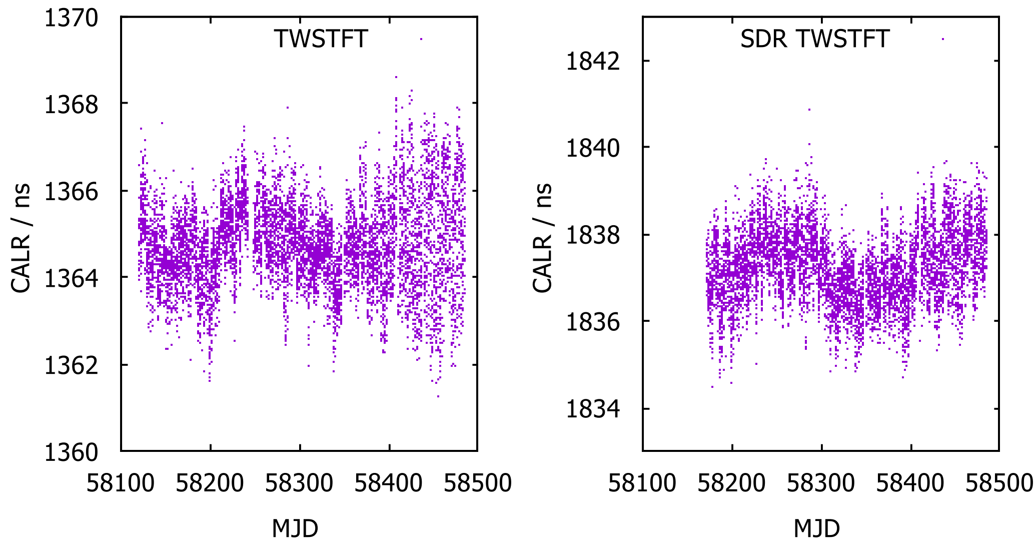


Figure 16 DCD measurements of TWSTFT (left) and SDR TWSTFT (right). The GPS P3 link contains calibrated GPS stations NC4S and TLT1.

Figure 17 shows that the TDEV of the DCD measurements have a clear bump at an averaging time of 8 h due to diurnals in TWSTFT links. We estimate this uncertainty from the TDEV values for a duration of order the time between the two measurements periods B and C, i.e. at 20-40 days. To account for the uncertainty in the TDEV values, we take a rounded value of 0.3 ns for both TWSTFT and SDR TWSTFT.

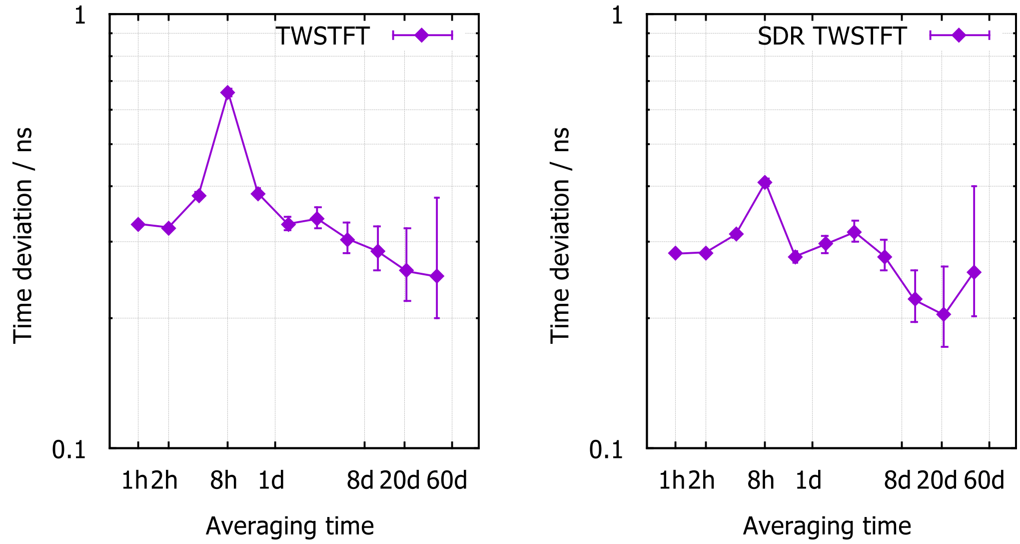


Figure 17 Time deviations of DCD measurements of TWSTFT (left) and SDR TWSTFT (right).

In summary, we list the uncertainty budget in Table 4. Combining these items in quadrature, the uncertainties of TWSTFT and SDR TWSTFT are 1.63 ns and 1.61 ns, respectively.

Table 4 Uncertainty budget of the TWSTFT links

Item	Uncertainty source	Type	Standard uncertainty / ns (TWSTFT / SDR TWSTFT)
A.1	TDEV	A	0.22 / 0.08
B.1	TDEV of GPS P3	B	0.41 / 0.41
B.2	Reference delay in NICT	B	0.80 / 0.80
B.3	Reference delay in TL	B	0.80 / 0.80
B.4	CCD mismatch	B	1.03 / 1.03
B.5	DCD disagreement	B	0.3 / 0.3
Combined uncertainty (k = 1)			1.63 / 1.61

VI. Calibration result

The final CALR value is obtained by simple mean of the values in Table 3. The values in Table 5 are suggested to be implemented in the TWSTFT ITU files. The uncertainty in Table 4 will be added in the header of the file and the calibration ID will be given by the BIPM.

Table 5 Calibration results

	Stations		Valued before the tour / ns			Values after the tour / ns		
ITU file prefix	LOC	REM	REFDELAY	CALR	ESDVAR	REFDELAY	CALR	ESDVAR
TWNICT	NICT05	TL03	478.51	0.0	171.574	478.461[1]	–1365.11	0.0
	NICT55	TL53	478.51	0.0	0.0	478.461	–1837.70	0.0
TWTL	TL03	NICT05	683.0	0.0	5.95	683.0	+1365.11	0.0
	TL53	NICT55	683.0	0.0	–3.73	683.0	+1837.70	0.0

Acknowledgement

The authors would give their appreciation to Gérard Petit, Victor Zhang, Julia Leute and Frédéric Meynadier for technical suggestions and the GPS IPPP data.

Reference

[1] The BIPM, "TWSTFT Calibration Guidelines for UTC Time Links (V1.0/2016)"

[2] The BIPM (2018), "2018 Group 1 GPS calibration trip (Cal_Id 1001-2018)"

[3] P. Defraigne and G. Petit, "CGGTTS-Version 2E: an extended standard for GNSS time transfer", *Metrologia*, **52**, 2015.

[4] International Telecommunication Union (2015) "The operational use of two-way satellite time and frequency transfer employing pseudorandom noise codes," Recommendation ITU-R TF.1153-4 (Geneva: International Telecommunication Union).

[5] The BIPM, Evaluation of measurement data – Guide to the expression of uncertainty in measurement, JCGM 100:2008

[6] Z. Jiang, D. Matsakis, V. Zhang, H. Esteban, D. Piester, S.Y. Lin and E. Dierikx, "A TWSTFT calibration guideline and the use of a GPS calibrator for UTC TWSTFT link calibrations"

[7] H. Esteban, V. Zhang, D. Piester, D., Matsakis, S.Y. Lin and Z. Jiang (2015), "TWSTFT link calibration with a GPS calibrator", BIPM TM251

[8] Z .Yang, K. Liang and Z. Jiang (2016), "UTC time link calibration report", BIPM TM264

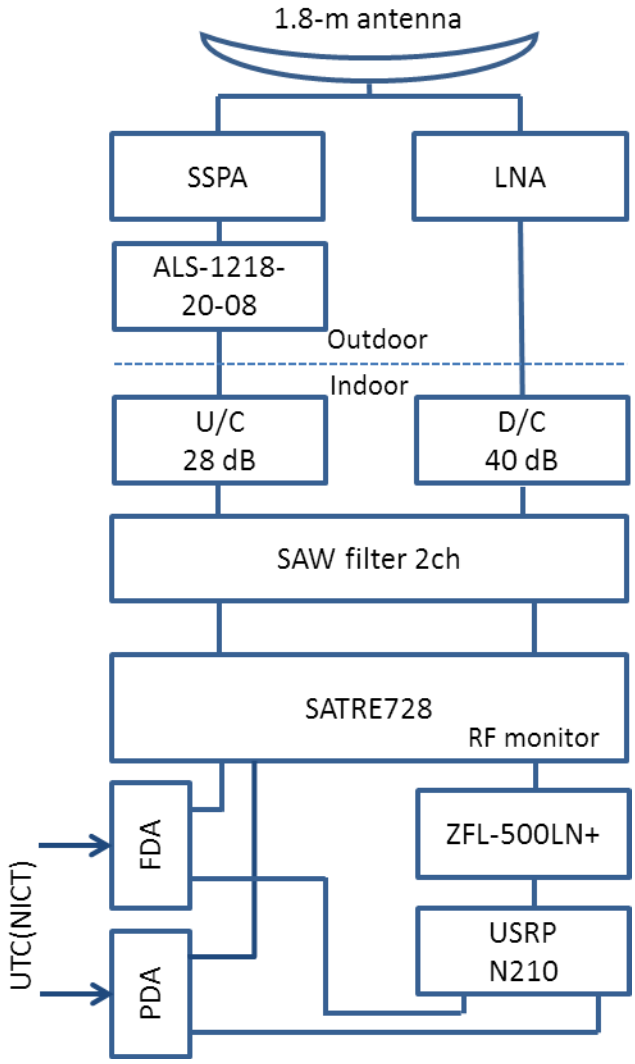
[9] W. Wu, W. Guang, J. Zhang, H. Zhang, K. Liang, Z. Yang and Z. Jiang (2016), "UTC time link calibration report", BIPM TM265

[10] S.-Y. Lin, W.-H. Tseng, H.-T. Lin, Y.-J. Huang, and K.-M. Feng (2010), "Long-term Inconsistency between TWSTFT and GPS Time Transfer Results in PTB-TL and NICT-TL Time Links", in *Proc. 24th EFTF,* Noordwijk, Netherlands, 13-16 April 2010

[1] Change of the UTC(NICT) source on MJD 58359

Annex I: Configuration of the earth stations

Station name: NICT05 (NICT55 for SDR TWSTFT)
Location: LA: N 35 42 28.194 LO: E 139 29 16.527 HT: 203.00 m
Reference delay, UTC(NICT) – 1PPSTX: +478.51 ± 0.8 ns



Station name: TL03 (TL53 for SDR TWSTFT)
Location: LA: N 24 27 12.822 LO: E 121 9 52.198 HT: +201.28 m
Reference delay, UTC(TL) – 1PPSTX: +683.0 ± 0.8 ns