Implementation of SDR TWSTFT in UTC Computation

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5 PTB: Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
6 NTSC: National Time Service Center, Lintong, Xian, China
7 SU: Main Metrological Center for State Service of Time and Frequency, FGUP VNIIFTRI, Russia
8 KRISS Korea Research Institute of Standards and Science
9 AOS: AOS: Astrogeodynamic Observatory of Space Research Center, Borowiec, Poland
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BIOGRAPHIES

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ABSTRACT

Two-Way Satellite Time and Frequency Transfer (TWSTFT or TW for short) is one of the primary techniques for the realization of Coordinated Universal Time (UTC), which is computed by the International Bureau of Weights and Measures (BIPM). TWSTFT is carried out continuously by about 20 timing laboratories around the world. One limiting factor of the TWSTFT performance is the daily pattern (diurnals) in the TWSTFT data. Their peak-to-peak variations were observed as up to 2 ns in some extreme cases. They must be attributed to the equipment on ground or the satellite transponder, but no clear understanding has been achieved for some years. In 2014 and 2015, it was demonstrated inlinks between Asian stations that the use of Software-Defined Radio (SDR) receivers for TWSTFT could considerably reduce the diurnals and also the TWSTFT measurement noise.

In 2016, BIPM and the Consultative Committee for Time and Frequency (CCTF) working group (WG) on TWSTFT launched a pilot study on the application of SDR receivers in the Asia to Asia, Asia to Europe, Europe to Europe and Europe to USA TWSTFT networks.

The very first results of the pilot study have been reported to the PTTI 2017. The results show, 1) for continental (short) links: SDR TWSTFT demonstrates a significant gain in reducing the diurnals by a factor of two to three; 2) for inter-continental (very-long) links: SDR TWSTFT displays a small gain of measurement noise at short averaging times; 3) SDR receivers show superior or at least similar performance compared with SATRE[†] measurements for all links.

The CCTF WG on TWSTFT prepared a recommendation "On Improving the uncertainty of Two-Way Satellite Time and Frequency Transfer (TWSTFT) in UTC Generation" for the 21st CCTF meeting. One of the recommended items is to introduce the use of SDR TWSTFT in UTC generation. The recommendation was approved by CCTF during the meeting in June 2017.

In the current setups, a SDR receiver and the collocated SATRE modem receive the signals transmitted by remote SATRE modems, and the two devices independently determine the arrival time of the received signal. Thus, a few setup changes are necessary to implement SDR receivers into operational TWSTFT ground stations. On the other hand, the data computation, e.g. for calibrated time transfer, needs some caution in the data processing and provision, which are not trivial. Thus, an Ad hoc Group has been established to work out a procedure for the use of the SDR TWSTFT in UTC computation.

This paper reports on the progress of the work for using SDR TWSTFT in UTC computation. Section 1 introduces SDR TWSTFT and the pilot study. Section 2 presents the considerations for using SDR TWSTFT in UTC generation. Section 3 and 4 show the methods for analysing SDR TWSTFT and the analysis results. Sections 5 and 6 discusses the further improvement of SDR TWSTFT and summarizes the work towards using SDR TWSTFT in UTC generation.

1. INTRODUCTION

Two-Way Satellite Time and Frequency Transfer (TWSTFT or TW for short) is a primary technique for the generation of Coordinated Universal Time (UTC) [1,2]. Its dominant source of statistical uncertainty is the daily variation (diurnals) observed in the link data, whose peak-to-peak amplitude can be up to 2 ns in extreme cases.

SDR TWSTFT stands for the application of Software-Defined Radio receivers in TWSTFT. A SDR receiver (SDR for short) works in parallel with the Satellite Time and Ranging Equipment (SATRE modem or SATRE for short) which has been used by the international timing community since 2003 in the UTC generation. In fact, the SDR receives the down converted signal (Rx) and then determines the arrival time of the signal independent of the SATRE [3], cf. the Figure 1.1. With the application of SDR in TWSTFT, a reduction of the diurnals and thus the measurement noise in Asian TWSTFT links was observed [3,4]. Because of the encouraging results and after a first validation by the International Bureau of Weights and Measures (BIPM) [4], the BIPM and the Consultative Committee for Time and Frequency (CCTF) working group (WG) on TWSTFT launched a pilot study during the TWSTFT participating stations meeting at the Precise Time and Time Interval (PTTI) conference in Monterey, California in February 2016. The goal of the pilot study has been to investigate the impact of using SDR TWSTFT in Asia to Asia, Asia to Europe, Europe to Europe and Europe to USA links with different satellites, c.f. the Figure 1.2.

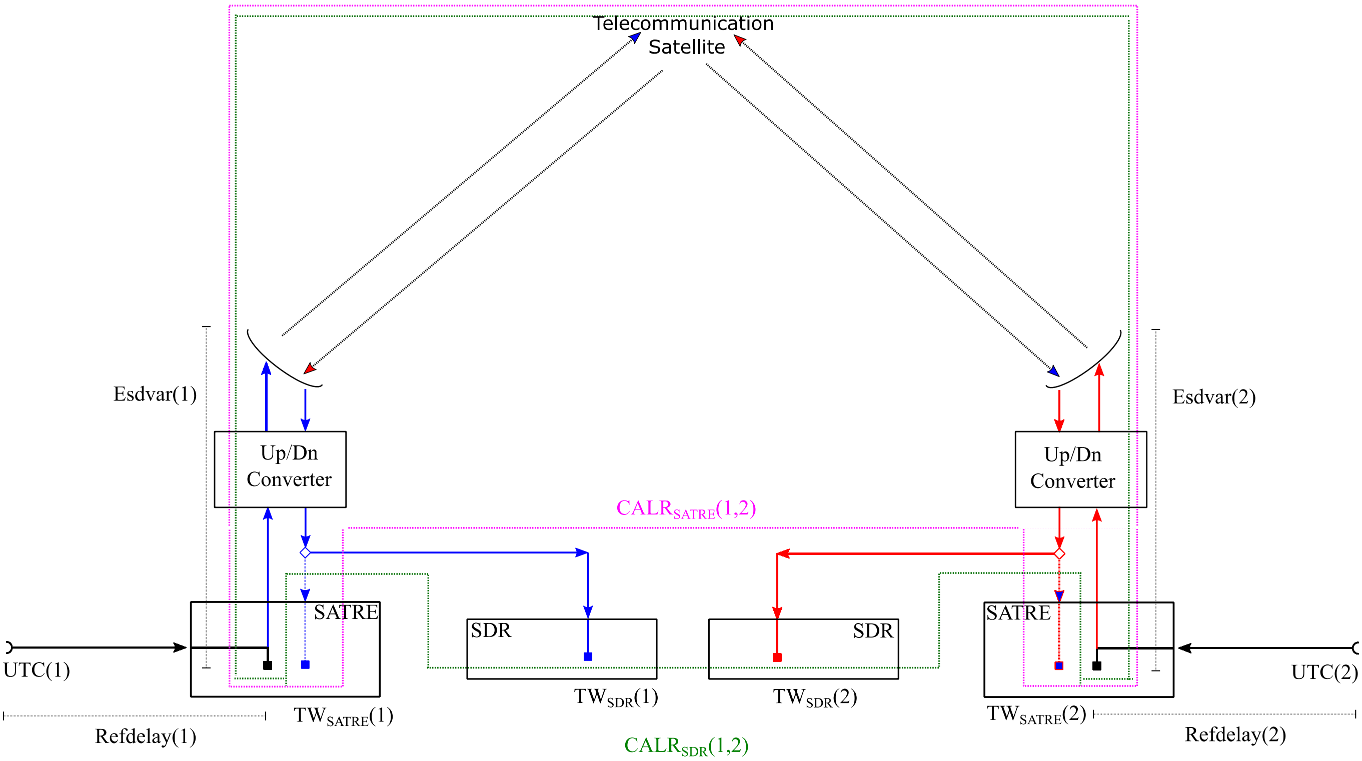


Figure 1.1 Illustration of the main paths of a TWSTFT link based on SATRE modems and on SDR receivers for comparison of two remote clocks

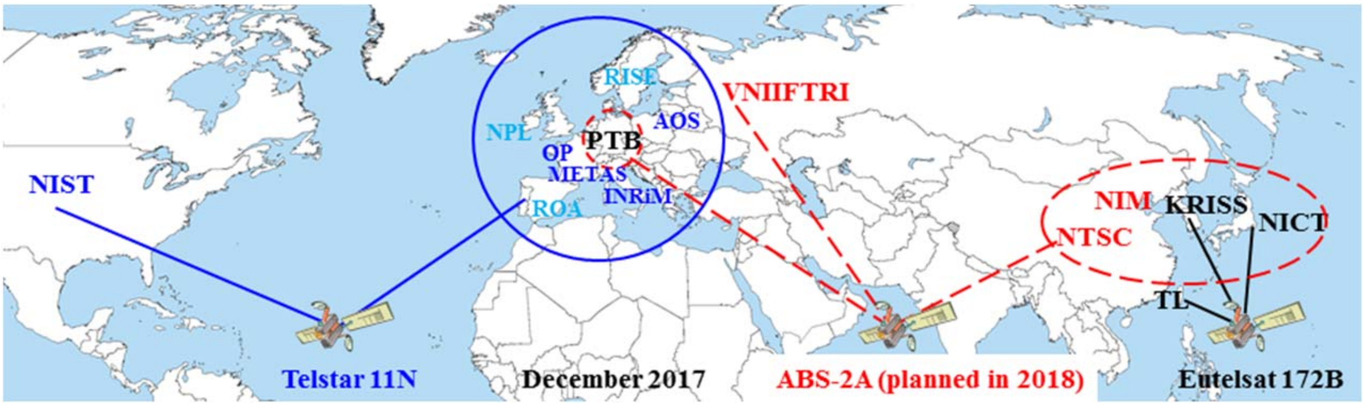


Figure 1.2 Participating stations in the SDR pilot project (status of December 2017). The links in blue are for the Europe-Europe and Europe-USA SDR TWSTFT. The links in red are for the Asia-Europe SDR TWSTFT. The links in black are for the Asia-Asia SDR TWSTFT. Until June 2017, the AM22 was used in the place of ABS-2A.

So far, 15 timing laboratories have installed SDR receivers and participate in daily SDR TWSTFT. The participants include: TL, NICT, KRISS (KRIS), NTSC and NIM in Asia; PTB, OP, VNIIFTRI (SU), INRIM (IT), METAS (CH), AOS (PL), RISE (ex SP, Sweden), ROA (ES) and NPL (UK) in Europe; and NIST in USA. Three satellite links in the Ku band have been used in the pilot study, they were routed through the satellites Eutelsat 172B for the Asia to Asia links, Express AM22 for the Asia to Europe links until June 2017, and Telstar 11N for the Europe to Europe and the Europe to USA links. At the time of this writing, the successor of AM22 satellite has been selected as ABS-2A and the Asia to Europe TWSTFT links will soon be reinstalled.

Continental (in Asia and in Europe), and also transcontinental (Asia-Europe, Europe-USA) SDR TWSTFT time links have been established. The SDR TWSTFT pilot study has been a global experiment involving leading laboratories. During the 25th annual meeting of the CCTF WG on TWSTFT held at NTSC in May 2017, the participating laboratories reported their results and analysis of the SDR pilot study [5]. The BIPM presented its validation [6].

The major conclusions were:

- for continental links: SDR TWSTFT demonstrates significant gain in reducing the diurnals by a factor of two to three;
- for inter-continental (very-long) links: SDR TWSTFT displays little gain of measurement noise at short averaging times;
- SDR receivers show superior or at least similar performance compared with SATRE measurements for all links.

Based on these findings, the WG on TWSTFT prepared the recommendation “On Improving the uncertainty of Two-Way Satellite Time and Frequency Transfer (TWSTFT) for UTC Generation” [13] for the 21st CCTF meeting held on 9-10 June 2017 at BIPM. At the meeting, the recommendation was submitted to the CCTF and the latter approved the recommendation. This means, that the process of implementation of SDR TWSTFT into UTC generation can start.

Aiming at a routine computation of using SDR TWSTFT for UTC, there were still some open points to address. An Ad hoc Group composed of 5 experts from BIPM, NIST, OP, PTB and TL was setup to resolve these issues, comprising of data collection, treating discontinuities, calibration of SDR TWSTFT links, data format and computation programs, etc. Its attention was focussed on the practical issues towards its use in the UTC computation. The BIPM should perform a final evaluation using at least six months’ continuous data. One of the tasks of the Ad hoc Group has been to prepare a report on implementing the recommendation and request approval of the implementation of the SDR TWSTFT used in the UTC generation. In this paper, the main results of the report are presented to the scientific community.

2. BASIC CONSIDERATIONS

2.1 Calibration of SDR TWSTFT links

The use of SDR TWSTFT links in UTC generation requires that the signal delays along the full propagation path have been determined. According to the TWSTFT calibration guidelines [2], a SDR link calibration can be made using a ‘2-step procedure’ as described below. The calibration results are going to be computed and issued by BIPM coordinated with the SDR TWSTFT participants.

The two-step procedure:

1. For UTC links:
   a) if the SATRE link is calibrated, the SDR link should be aligned to it;
   b) if the SATRE link is not calibrated, both links – the SATRE and the corresponding SDR link – should be calibrated together by using a TWSTFT mobile station or GPS calibrator with the ‘link’ method [2];
2. The non-UTC link delay should be calibrated by the triangle closure calibration (TCC) method [2];

A Calibration Identifier (CI) number is issued to each SDR link calibration. The TWSTFT calibration guideline is to be accordingly updated.

2.2 Conventional uncertainty u_A and u_B

For the UTC SATRE links, the *conventional* values of u_A and u_B are 0.5 ns and 1.0 ns (using TWSTFT mobile station calibration) or 1.5 ns (with GPS Calibrator) respectively. These values are assigned to time differences UTC-UTC(k), reported in the BIPM Circular T (Section 1) at a five-day grid, and are derived from a detailed report on the used link data in Section 5 of Circular T. The conventional uncertainty as assigned by BIPM is usually higher than the individually estimated one. For example, the reported u_B of the USNO-PTB SATRE link calibration is 0.6 ns while the conventional value is 1.0 ns [1].

The corresponding values of u_A and u_B for SDR links are 0.2 ns and 1.0 to 1.5 ns, respectively. In fact, as reported in [3,5,6] and in this paper, for short baselines, such as OP-PTB, a gain factor of two or three is obtained in the stabilities (SDR vs. SATRE). For long baselines, such as NIST-PTB with much smaller diurnal comparing to most of other links, e.g. the link of OP-PTB. The stability of the SATRE link is already below to 0.2 ns, see [6] and the discussion in the section below. As for u_B, the same conventional value is valid for both the SATRE and the SDR links because, as mentioned above, the conventional u_B of the SATRE link is often higher than the measured one. Hence, the combined u_B of the SDR link is usually within the conventional u_B of the SATRE link.

The conventional value of the u_B for the SDR TCC calibration is 2 ns, the same as that when using SATRE data [2,17].The u_B of SDR links may be improved if a direct SDR link calibration is performed. This study is ongoing.

2.3 Reporting the SDR TWSTFT data

1) We focus on the data files in the format of the International Telecommunication Union Recommendation ITU-R TF.1153-4 [7] (ITU format or ITU for short) used in the UTC computation. It is recommended that the 1-s data files should be archived in local computers but not submitted to BIPM;
2) The SDR data in ITU format should be submitted to the BIPM ftp site in the dedicated SDR folder, in the same way as the SATRE TWSTFT data;
3) The conventional ITU data format and file name [7] for the SATRE modem should be used for the SDR data. The differences between a SATRE data file and a SDR data file are as the followings:
   - In the header of a SDR file, there is an identification comment line, such as:
     `* MODEM     SATRE 076, Software-Defined Radio Receiver`
   - The identification number for the SDR receivers should equal the SATRE earth station number plus 50, usually to be between 51 and 59. For example, for the SDR link of NIST-OP, we have the SDR Local Station ID and Remote Station ID as 'NIST**51** OP**51'** in comparison to the SATRE Local Station ID and Remote Station ID 'NIST**01** OP**01'.**
4) For reporting the SDR data in ITU format for the UTC computation, a 300 s-interval is to be used. One of the advantages of this interval is that the SDR TWSTFT data can be compared exactly to the measurement of other time and frequency transfer data on the same epoch, such as the BIPM GPS PPP (GPS Precise Point Positioning) solution.

2.4 Further improvement on SDR TWSTFT for UTC

Without touching the hardware, we can still improve the stability of a SDR link by the following methods:

1) Combination of SDR TWSTFT and GPS PPP. The same kind of combination of SATRE TWSTFT and GPS PPP has been used in UTC time transfer since 2009 [14];
2) Complete or partial network time transfer to fully use the redundant data [8-12,15]. Previous studies [10,11] suggest a simplified version, the so-called indirect link.

The related programs of the two methods are almost available in the BIPM UTC/TAI software package Tsoft, c.f., Section 5.

2.5 Operational Procedures

The procedures listed below were defined in order to make the automatic computation of a SDR link becoming equal to that of the SATRE link in the standard BIPM Circular T monthly computation, as well as in the complete computations such as the link comparison and the publication in the BIPM web site.

1) Elimination of phase steps in the SDR measurements when a SDR receiver is restarted has to happen. The new release of the SDR software V2018.1 [25] guaranties that the measurements continue without steps when restarting the device;
2) The value and the definition of the REFDELAY (reference delay) for SDR are identical to that of the SATRE;
3) The SDR ITU format data interval is to be a fixed value, at present, 300 s. This is realised by the software obs2ITU which converts the SDR raw measurement data to the standard ITU data format;
4) CALR (link calibration) and ESDVAR (earth station delay variation) values are defined as Figure 1.1 shows. CALR and/or ESDVAR parameters may be adjusted to align SDR and SATRE links.

2.6 Schedule of the implementation of SDR TWSTFT in UTC

1) The SDR TWSTFT participants were requested to update their procedures as listed in Section 2.5 and to make the equipment operational for routine measurements before July 2017;

2) During July-December 2017, measurements were carried out among the SDR TWSTFT participants and the test computations/calibrations were made at BIPM;
3) BIPM made a final data analysis using the 6-month data of 1707-1712 (July 2017 to December 2017) and reports the results to the SDR ad hoc Group, and informs the WG on TWSTFT. The Ad hoc Group should prepare the final validation report to the WG and to the BIPM;
4) From October 2017 onwards, BIPM has used the SDR data as the *backup* UTC links in the monthly Circular T computation. The BIPM publishes monthly on the BIPM web the results of the SDR link and its comparison to other techniques;
5) SDR TWSTFT is going to be introduced for UTC computation in BIPM Circular T on an earliest possible date in 2018. The decision will be made jointly by the BIPM and the WG on TWSTFT, represented by the Ad hoc group, in a link by link approval;
6) In June 2018, a final report of the SDR TWSTFT Pilot Study will be presented to the 26th TWSTFT WG meeting in Poland (2018).

3. THE METHOD AND THE EARLIER STUDY

The SDR TWSTFT measurement data were collected from TL, KRISS, NICT since October 2014, and from NTSC, PTB, OP, NIST, AOS, CH(METAS), IT(INRIM), SP(RISE) and SU(VNIIFTRI) since July 2016. The SDR links discussed in Section 4 were calibrated with an alignment to the corresponding SATRE links.

In the following sections, we first make a quick review of the precedent studies and results (Section 3). We then focus on the results of the latest 6-month analysis (Section 4). In Section 5, we study and validate the methods to further improve the quality of SDR. Section 6 is a summary.

In this section, we give an outline of the analysis method and the earlier study results. Details can be found in the [5,6,17,22].The study is based on the analysis of the double clock difference (DCD) over a baseline between (a) the SATRE and the SDR links, and (b) the SATRE or SDR and GPS PPP/IPPP (Integer Ambiguity GPS PPP solution [21]) links. The DCD is very helpful for the uncertainty analysis.

Methods of the BIPM validation:

- We analyse the $\boldsymbol{\sigma}$ (standard deviation) and the Time Deviation (TDev) $\boldsymbol{\sigma}_X$ of DCD;
- The data used are mainly: SATRE TWSTFT, SDR TWSTFT, GPS PPP and GPS IPPP;
- The 4 indicators of the assessment of the quality and the level of the improvement are the following:
  1. σ_X for evaluation of the instabilities at different averaging times (τ)
  2. σ (DCD) for revealing the agreement with GPS PPP/IPPP: the smaller the better
  3. σ of the triangle closures for indication of the uncertainty and the noise level of the links: the smaller the better
  4. σ of discrepancies to GPS PPP or to BIPM Circular T for the long-term stability: the smaller the better
- Gain factors: $\boldsymbol{\sigma}_{\mathrm{SATRE}}/\boldsymbol{\sigma}_{\mathrm{SDR}}$, $\boldsymbol{\sigma}_{\mathrm{X\text{-}SATRE}}/\boldsymbol{\sigma}_{\mathrm{X\text{-}SDR}}$: the larger the better

In the future, we will have TWOTFT (Two-Way Optical-fibre Time and Frequency Transfer) as a new tool for the analysis, whose stability and accuracy are both in order of 100 ps, thanks to the links of TWSTFT and TWOTFT established between AOS and GUM (PL) [19].

Example (1) The gain in SDR link vs. the SATRE link over the baseline OP-PTB

The left plot in Figure 3.1 depicts the TWSTFT differences of SATRE and SDR links, respectively. Obviously, the SATRE link suffers considerable diurnal variations. The right plot is the TDev of the two sets of link data which shows more clearly how the diurnal and the noise level affect the SATRE TWSTFT from 2 hour to about one day. Table 3.1 gives the gain factor in TDev, 3.7 on average.

Table 3.1 Gain factors in TDev of the SDR versus SATRE link at different averaging time (τ)

τ /h	Gain
2	3.3
8	5.2
16	3.9
mean	**3.7**

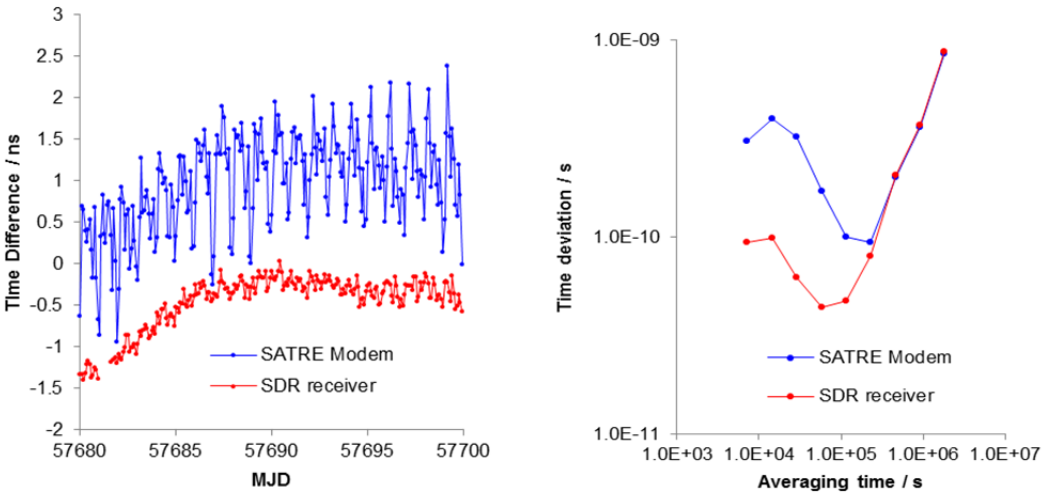


Figure 3.1 The SDR and the SATRE links and the corresponding TDev over the baseline OP-PTB

Example (2) Comparing the GPS PPP link to the TW SATRE and TW SDR links to study the gains

In the following we will compare GPS PPP links to TW SATRE and TW SDR links over the baselines TL-NICT and OP-PTB in Asia and in Europe using different satellites.

Unlike to example (1) where the TW SATRE solution was used as reference, we use the GPS PPP as the reference. Being independent from TWSTFT, the GPS PPP solution seems suitable to validate the improvement in the SDR method. Its statistical measurement uncertainty is small (u_A=0.3 ns [1]) and it is almost not affected by diurnal variations. Making a choice between TW SATRE or TW SDR link data, those which agree better with GPS PPP are considered to better represent the clock differences. Comparing TWSTFT to GPS PPP allows for also investigating the stability of SDR in view of the calibration, a key issue in the UTC time transfer. We emphasize that SDR TWSTFT and GPS PPP are independent and therefore the standard deviation and the TDev of the DCD give a conservative estimation than the truth.

Table 3.2 Gain factor in TDev in the DCD of SATRE versus SDR links against the PPP link over the baseline TL-NICT

τ /h	SATRE-PPP σ_X /ps	SDR-PPP σ_X /ps	Gain $\sigma_{X/SATRE-PPP}/\sigma_{X/SDR-PPP}$
1	140	40	3.5
2	90	45	2.0
6	125	38	3.3
12	79	48	1.6
24	68	59	1.2
Mean			**2.3**

Table 3.3 Gain factor in TDev in the DCD of SATRE versus SDR link against the PPP link over the baseline OP-PTB

τ /h	SATRE-PPP σ_X /ps	SDR-PPP σ_X /ps	Gain $\sigma_{X/SATRE-PPP}/\sigma_{X/SDR-PPP}$
2	210	160	1.3
4	340	160	2.1
8	330	110	3.0
16	170	80	2.1
Mean			**2.1**

Tables 3.2 and 3.3 contain the gain factors in TDev in the DCD of SATRE versus SDR links against the PPP link on different averaging times ranging from 2 hours to one day. The average gain is 2.3 for the baseline TL-NICT and 2.1 for OP-PTB, considering that PPP is not errorless.

Example (3) Comparison of the triangle closures given by the SATRE and SDR measurements

In theory, the triangle closure of (A-B) + (B-C) - (A-C) should be zero. A non-zero closure is hence a 'real' error, the larger the worse, the smaller the better. The gain factor is here the ratio of the standard deviation of closures. Table 3.4 gives the result of three triangles. The gain factor is 4.5 on average. It is important to point out that the deviation of the closure results constitutes a real error, therefore the gain factor here indicates potentially a significant improvement of the systematic uncertainties in TWSTFT links. C.f. the Section 4.3 of TM267 [6] for detailed information on the data used.

Table 3.4 Gain factor of the SDR vs. the SATRE links given by the triangle closure analysis

Triangles	Gain factor= σ(SATRE)/σ(SDR)
OP-NIST-PTB	4.3
NICT-KRIS-TL	4.8
PTB-NTSC-SU	4.5
Mean	**4.5**

Example (4) Long-term stability of the SDR TWSTFT links

Then long-term stability of SDR links is no doubt one of the most important issues. Once a SDR link is calibrated, it should be kept stable. A comparison between the SDR TWSTFT and the GPS PPP over the baseline TL-KRIS for about 400 days was made and the σ of the DCD is 1.1 ns, which is the usual long-term variation or even better between the TWSTFT and GPS. The long-term stability of the SDR link is satisfactory for use as UTC time transfer. C.f. the Section 4.4 of [6] for detailed information on the data used.

Example (5) Test calibration of the SDR Europe-USA network

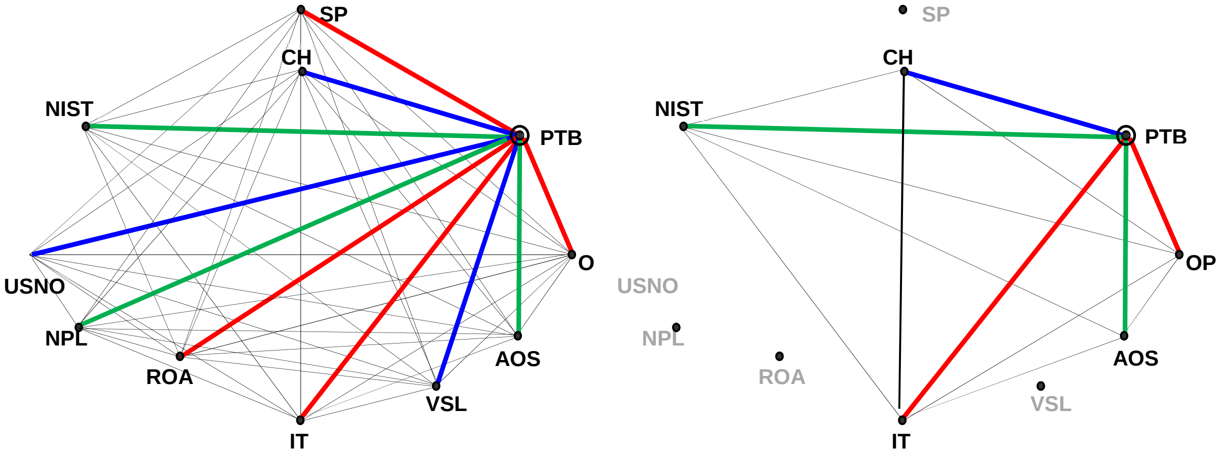


Figure 3.2 The Europe-USA TW SATRE (left) and TW SDR (right) networks

The test calibration result is given in Table 3.5 of the TM273 [23]. The data set used was the UTC 1704 (April 2017). This is just a numerical experience and the CI is assigned 999 for all the links.

Example (6) Further improve the quality of the SDR TWSTFT

Further improving the stability of the SDR is possible. Practically, we have immediately two numerical tools: the combination of SDR TWSTFT and GPS carrier phase [14] and the indirect links [8,10,11]. Figure 3.3 shows the TDev of the PTB-OP TWSTFT differences computed with the SATRE, SDR and the *indirect*-SDR via NIST. The numerical tests show that the latter is the most stable, cf. the next section for the improvement with the combination of SDR TWSTFT and GPS PPP.

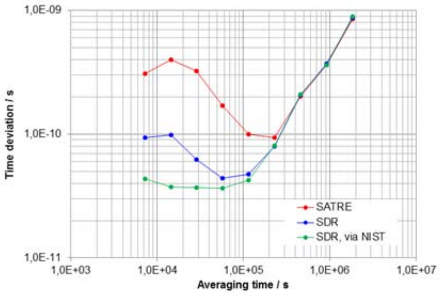


Figure 3.3 TDev of the TWSTFT link PTB-OP computed with the SATRE, SDR and the *indirect*-SDR methods

4. LATEST ANALYSIS USING 6-MONTH DATA OF JULY-DECEMBER 2017

Required by the CCTF WG on TWSTFT, the BIPM performed a final analysis aimed at verifying that the procedures discussed in Section 2 are adequate for using the SDR links in UTC generation. 183 days of data from the latest 6 months (July to December 2017, MJD 57935-58118) were used in the analysis. Because the Asia-Europe TW links were not operational during this period due to the AM22 satellite being out of service, only the available Europe-Europe, Europe-America and Asia-Asia links have been analysed in this report, c.f. the Figure 1.2.

In addition to the SDR TWSTFT data, the other data analysed were collected from the UTC data sets. A total of four types of the measurements are collected and carefully analysed, that include SATRE TWSTFT, SDR TWSTFT, GPS PPP and GPS IPPP. At this moment, only the OP-PTB GPS IPPP link was available.

4.1 Calibration

The SDR links analysed here were relatively calibrated by alignment to the related SATRE links using the data set 1709 (September 2017). Table 4.1.1 below lists the SDR TWSTFT calibration corrections for the UTC links in Europe and a non-UTC link in Asia. The calibration of the TL-KRIS SDR link was made by the alignment to the GPS PPP link. Here σ is the standard deviation of the alignment, that is, the fitting to the measurements that gives the scatter level of the measurements containing the noises from both the SATRE and SDR. It is not the standard deviation of the mean values (the correction) which can be computed by the σ over the root of *N*-1. The 'alignment' uncertainty is in fact very small and negligible in the 2-step calibration procedure using SDR and the SATRE links.

Note here that, the calibration corrections given in Table 4.1.1 are of the new setups and the latest values used for the UTC backup computation. Here yymm stands for year and month. The same is in the following discussion.

Table 4.1.1 The TW SDR link calibration corrections

Link	Correction /ns	N-Point	σ /ns	CI of SATRE link	Data set used /yymm
AOS-PTB	-54.449	329	0.659	449	1709
CH-PTB	-128.909	356	0.454	284	1709
IT-PTB	-188.926	376	0.519	434	1709
NIST-PTB	-113.862	245	0.108	393	1709
OP-PTB	2263.247	305	0.428	437	1709
TL-KRIS	-2441.649	4101	0.241	GPS PPP	1710

4.2 One-month data analysis

UTC is computed and published monthly. The monthly data set is therefore the base of the analysis. In this section, we investigate all the SDR links for UTC backup computation. The data were collected from the latest data sets 1712 (December 2017). The GPS IPPP links are not calibrated.

Below, we will discuss the time links, the link comparisons, that is the DCD, between SDR, SATRE, GPS PPP and GPS IPPP, as well as the related statistics. We discuss the daily and monthly stabilities and the biases between techniques. Special attention is paid to the reduction of the diurnals which may be the most important advantage of the SDR technique.

The analyses of 1-month data and 6-month data (Section 4.3) reveal the major issue of the SDR TWSTFT at this time: the discontinuity (missing data and time step) due to the changes in hardware, software and reference signals. These issues can be mitigated by improvement of the SDR TWSTFT system and carefully monitoring the SDR TWSTFT operation.

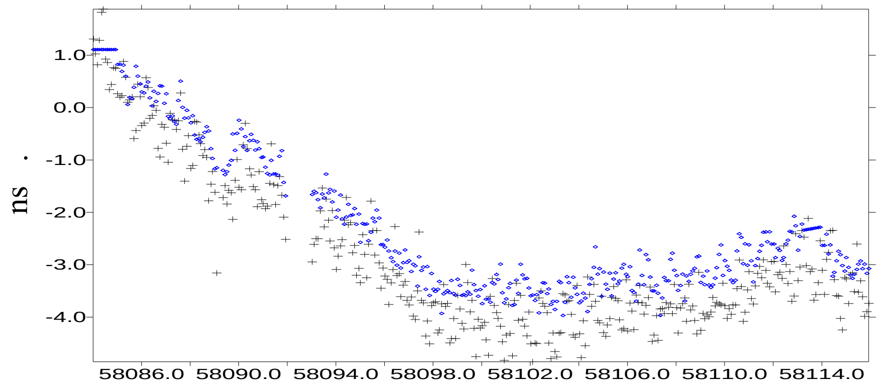
In the following, we will not show all the results but some typical examples.

4.2.1 The OP-PTB baseline

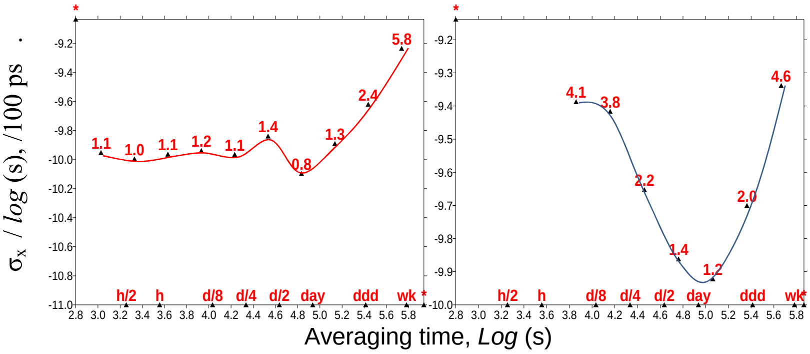
In Figure 4.2.1x, DCD is obtained by differentiating two time link data sets. The TDev plots show the log σ_x (in seconds) versus log averaging time (in seconds). "-10" on the vertical represents thus 100 ps. The numbers in the plots represent σ_x-values in picoseconds.

We first compare the SDR link to the SATRE link and the results are given in Figure 4.2.1a. Then we compare the TW SDR link to the GPS IPPP link. The IPPP solution is the GPS PPP solution obtained by solving the inter ambiguity. It is more precise than the PPP solution. The results are given in Figures 4.2.1b-1 to 4.2.1b-3. Because the IPPP solution is more precise than the PPP one, GPS PPP is not used for the analysis over the baseline OP-PTB when IPPP is available.

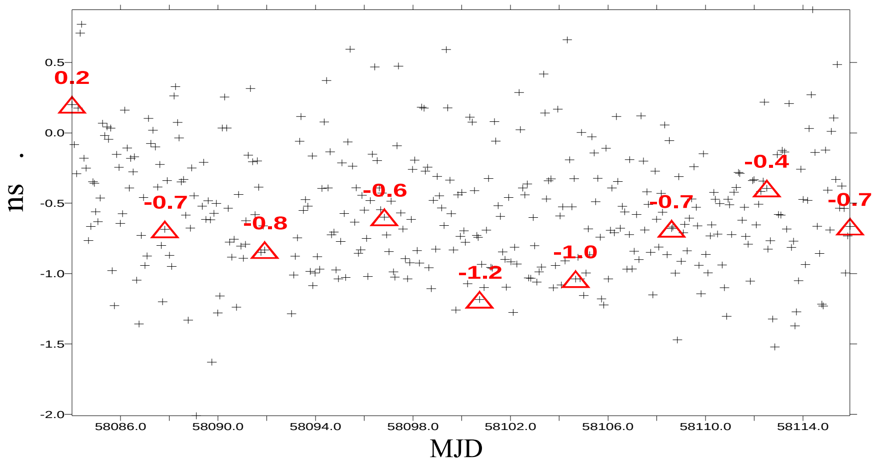
A) Comparing the SDR TWSTFT to SATRE TWSTFT



(a) SDR TWSTFT (blue) and SATRE TWSTFT (black) / MJD



(b) Time Deviations of the SDR (left) and SATRE (right) TWSTFT links



(c) DCD of SDR link and SATRE link with σ(DCD)=0.517 ns

Figure 4.2.1a Comparison between TW SDR and TW SATRE time links over the baseline OP-PTB

B) Comparing the SDR TWSTFT to GPS IPPP

The best and most accurate reference to validate the SDR technique should be the TWOTFT (Two-Way Optical-fibre Time and Frequency Transfer), which has the stability and accuracy of about 100 ps [19]. Unfortunately, such a baseline where the two techniques of SDR TWSTFT and the TWOTFT are available does not exist at this time. The next most precise technique for time transfer at present is the IPPP, i.e. the GPS PPP with integer ambiguity [21]. Both the TWOTFT and the IPPP are believed free of the disturbances seen as diurnal variations.

As well known, the phase ambiguities of GPS carrier frequencies are physically integer number but the usual PPP solves the ambiguities as real values. Associated errors may sum up as Random Walk instability. The IPPP may eliminate this bias. When required, the BIPM produces the IPPP solution using the CNES/GRGS specific satellite products and software GINS.

Experience shows that at averaging times of 4 to 5 hours, 2×10^{-15} in frequency stability may be reached. Comparison with the TWOTFT link indicates an accuracy of frequency transfer of 1×10^{-16} may be reached in 3 to 5 days. The frequency transfer of the 10^{-16} level has been reported by comparing with two-way carrier phase [24].

We have a 10-day of IPPP solution for MJDs from 57935 to 57944 in the beginning of July. Here after we show the link and link comparison results.

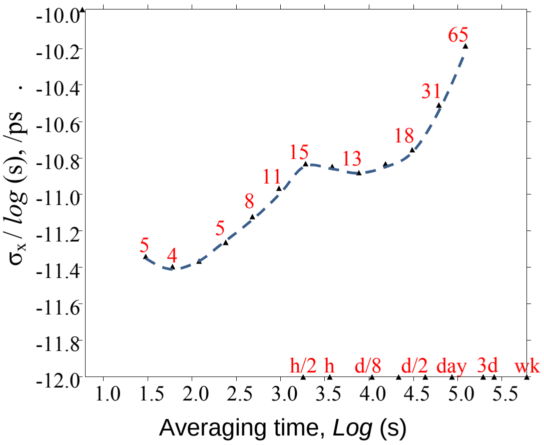


Figure 4.2.1b-1 The TDev of the IPPP time link over the baseline OP-PTB

A comparison between GPS PPP and GPS IPPP time links over the baseline OP-PTB gives that the σ(DCD)=0.088 ns. The PPP and IPPP solutions are considered to be correlated. The latter is more precise.

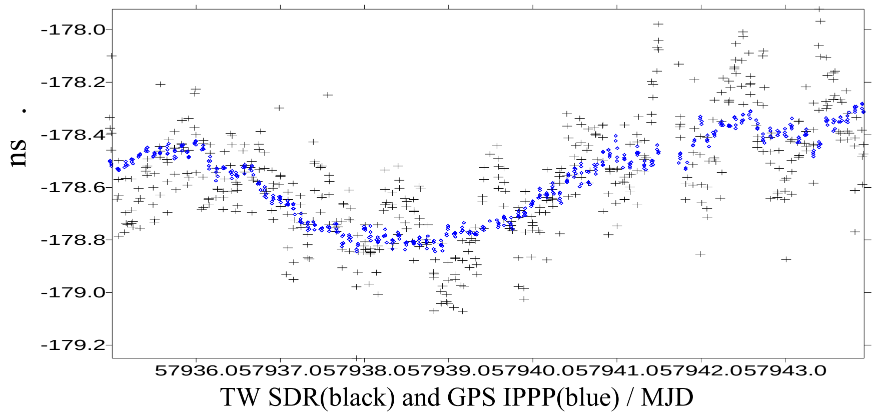


Figure 4.2.1b-2 Comparison between TW SDR and GPS IPPP time links over the baseline OP-PTB with σ(DCD)=0.158 ns

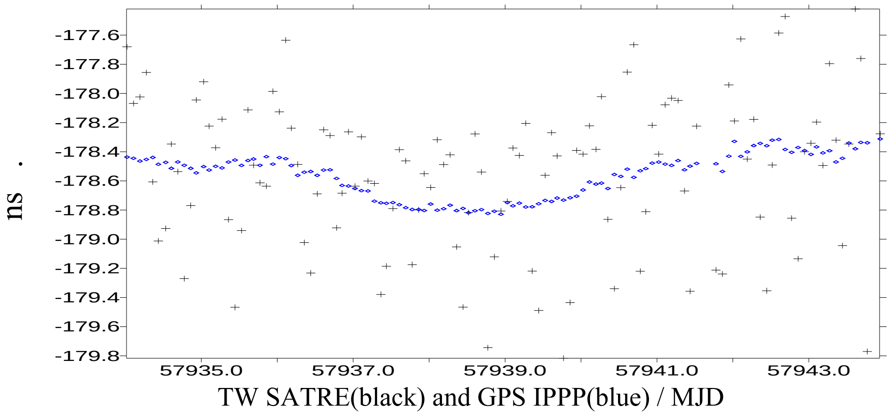


Figure 4.2.1b-3 Comparison between SATRE and IPPP time links over the baseline OP-PTB with σ(DCD)=0.516 ns

4.2.2 The TL-KRIS baseline

Similar to the discussion in the last section, we show the SDR time link and the TDev over the baseline TL-KRIS in the following figure. As can be seen, the instability of the SDR link reaches 45 ps in less than 60 minutes of averaging time.

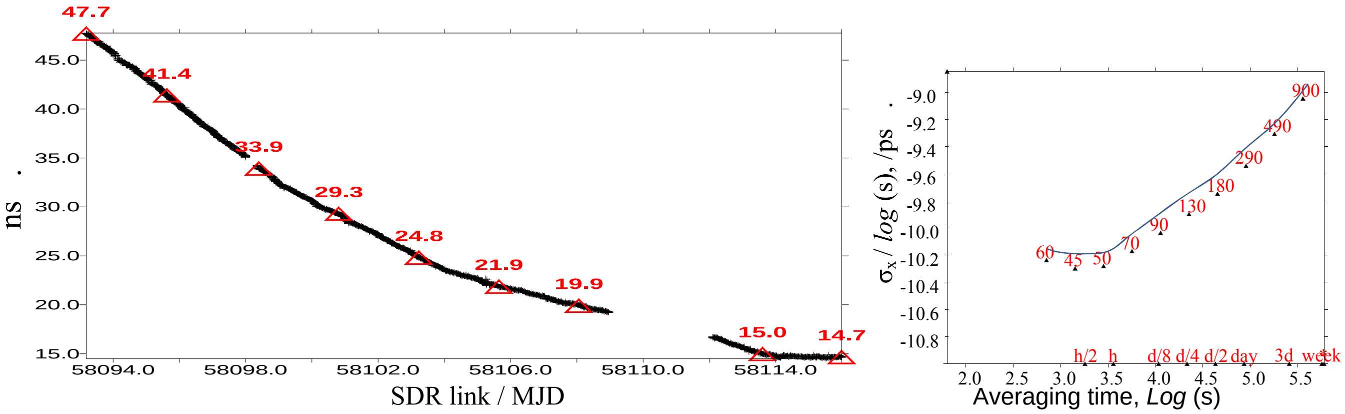


Figure 4.2.2 SDR link and the TDev over the baseline TL-KRIS

The SDR link can be further improved by the methods of the indirect linking and the combination of the SDR and GPS PPP. See details in the Section 5 below.

4.2.3 The AOS-PTB baseline

Figure 4.2.3 shows the SDR and SATRE time links and the link comparison. The σ(DCD)=0.727 ns. As can be seen obviously, the instability comes mainly from the noise in the SATRE measurements.

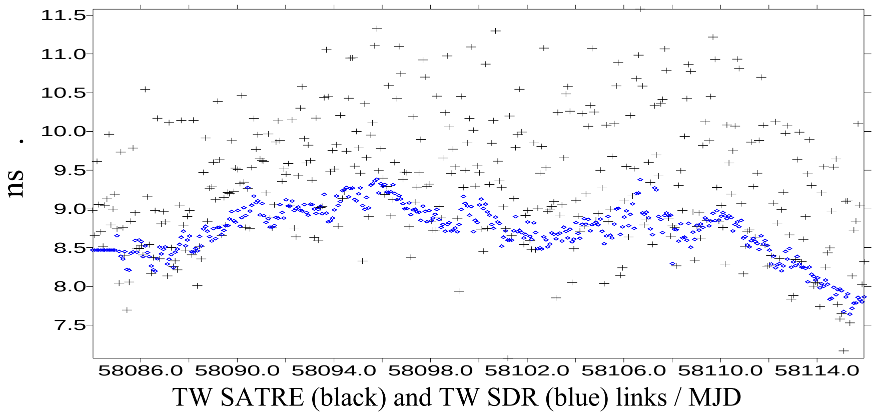
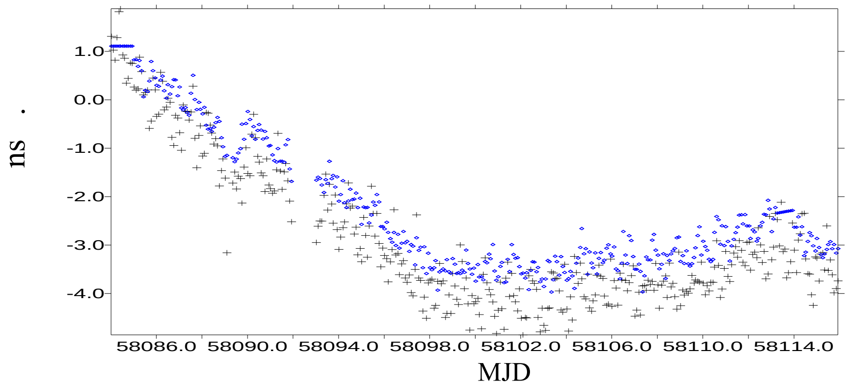


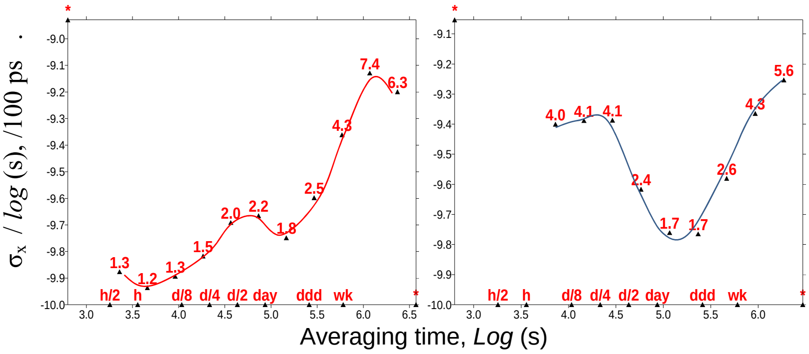
Figure 4.2.3 Comparison between SDR and SATRE time links over the baseline AOS-PTB with σ(DCD)=0.727 ns.

4.2.4 The IT-PTB baseline

The same as above, we show the SDR vs. the SATRE time links and the TDev over the IT-PTB baseline. As can be seen in the TDev plots the stability in the SDR is largely better than that of the SATRE at any averaging time.



(a) SATRE (black) and SDR (blue) links with the σ(DCD)=0.443 ns



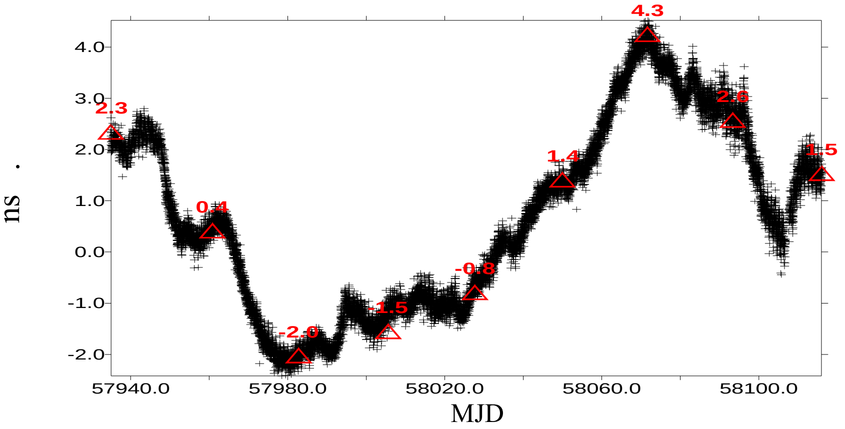
(b) TDev of SDR (left) and SATRE (right) links

Figure 4.2.4 Comparison between TW SDR and TW SATRE time links over the baseline IT-PTB

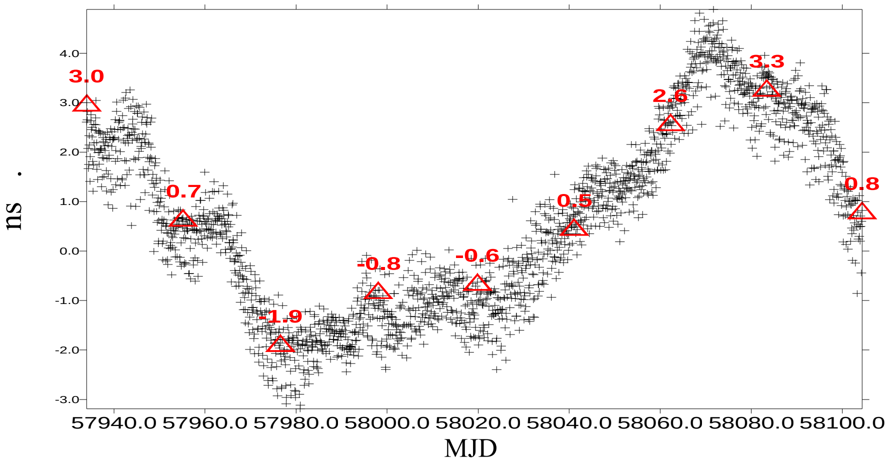
4.3 Six-months data analysis

Obviously, the long-term stability in UTC time links is very important. In [20] we discussed the long-term stability of the SDR linkhere only one example of the Asian link of TL-NICT was analysed and the standard deviation of the DCD between the SDR TWSTFT and GPS PPP links was 1.09 ns. This suggests the SDR link is at least as stable as the GPS PPP link. To complete the study and to have a more general conclusion, we give here other examples of the Europe-Europe-US UTC links over 6 months.

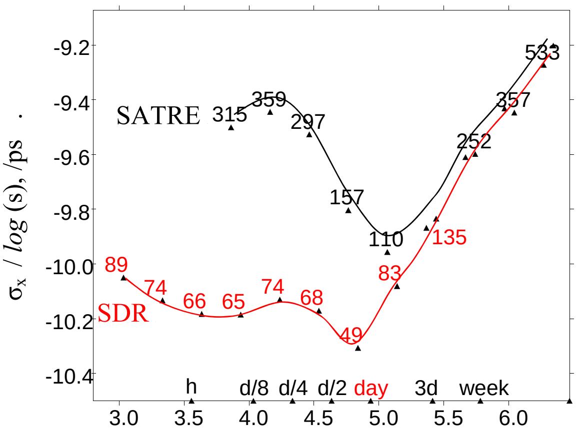
4.3.1 The OP-PTB baseline



(a) SDR TWSTFT difference

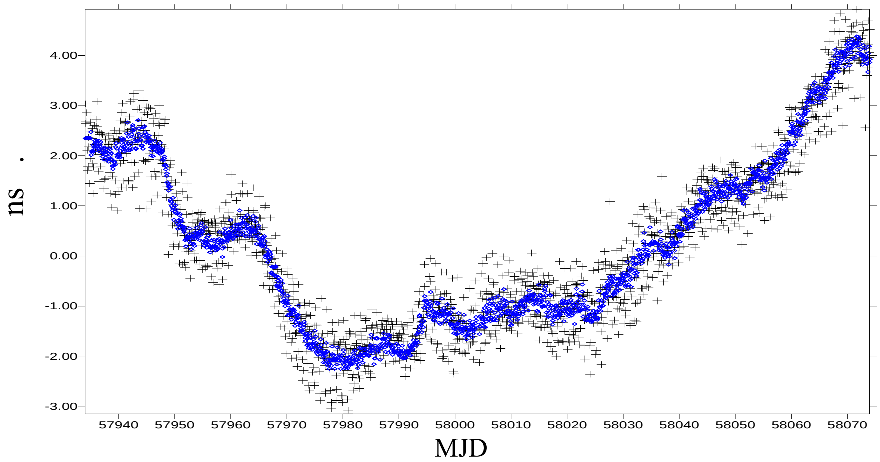


(b) SATRE TWSTFT difference

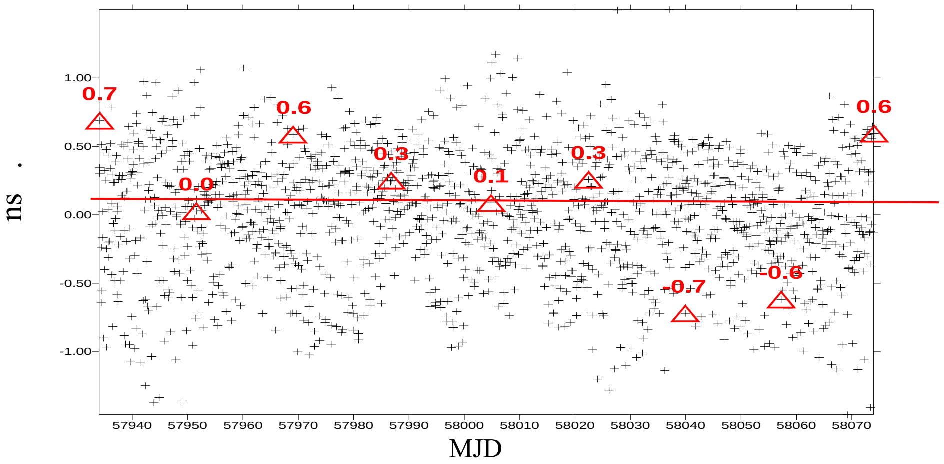


(c) TDev of SDR and SATRE TWSTFT differences

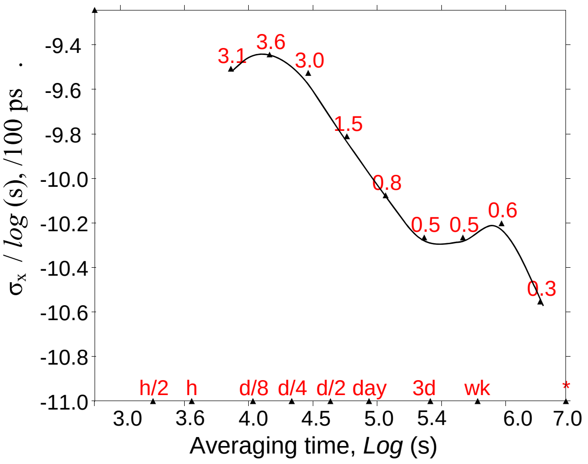
Figure 4.3.1-1 TW SDR and TW SATRE links over the baseline OP-PTB



(a) TWSTFT differences of SDR (blue) vs. SATRE (black) links

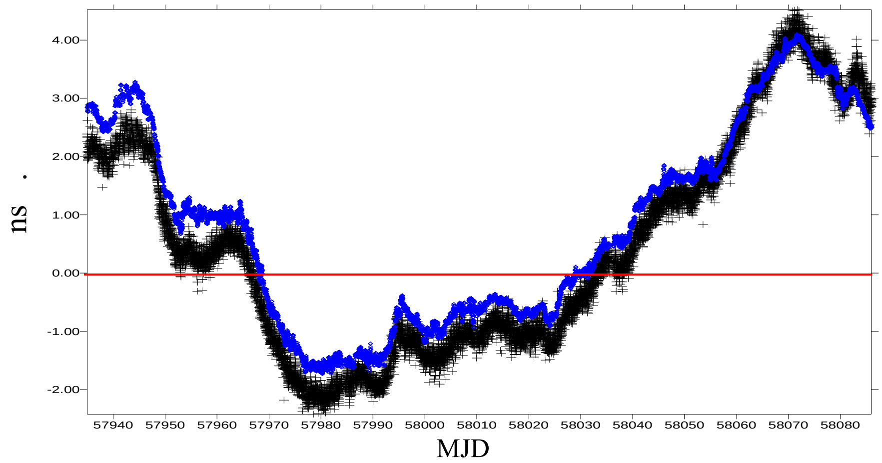


(b) DCD of SDR and SATRE links with the σ(DCD)=0.445 ns with no slope observed

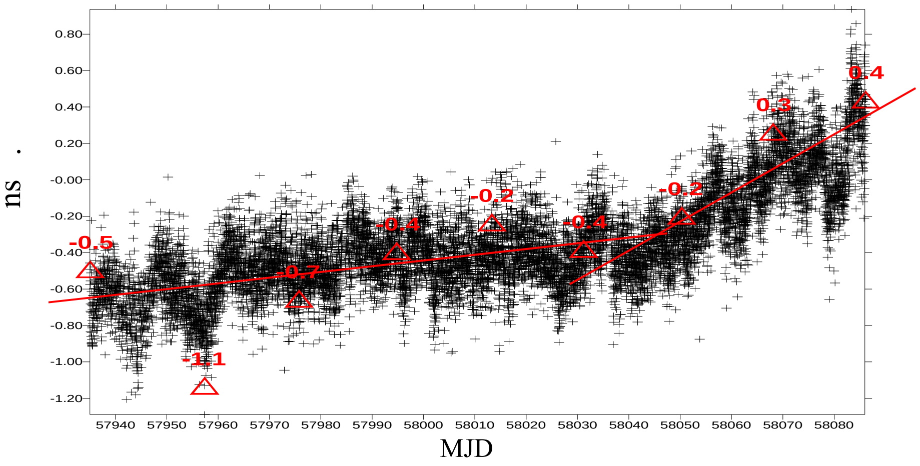


(c) TDev of the DCD of which the instability comes mainly from the noise and diurnal in SATRE measurements

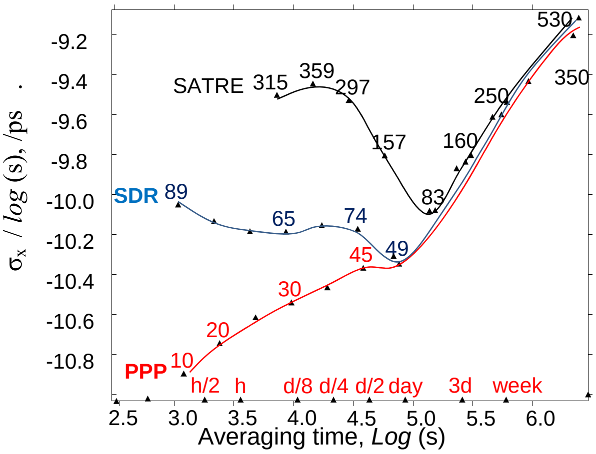
Figure 4.3.1-2 Comparisons of TW SDR and TW SATRE time links over the baseline OP-PTB



(a) Time transfer difference of SDR (black) and. GPS PPP (blue) links



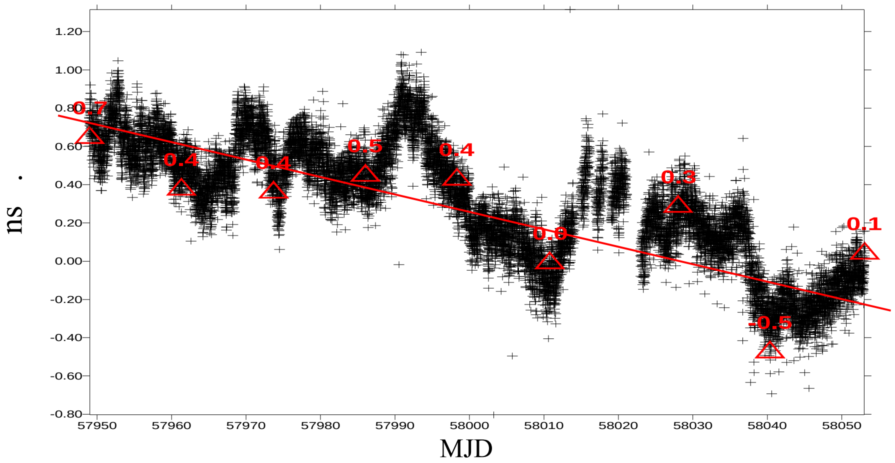
(b) DCD of SDR and GPS PPP links with the σ(DCD)=0.283 ns and two slopes



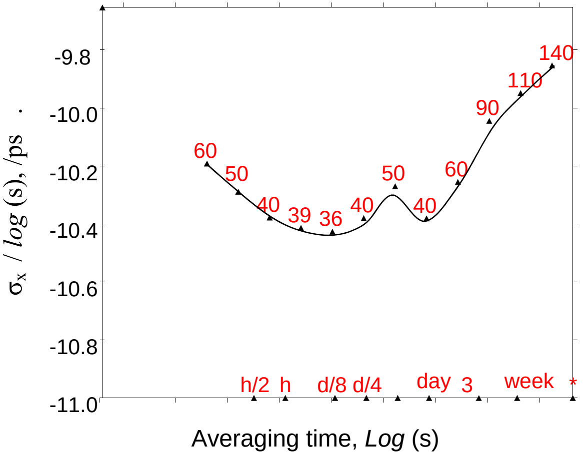
(c) Time deviation of the DCD

Figure 4.3.1-3 The TDev of TW SDR, TW SATRE and GPS PPP over the baseline OP-PTB

4.3.2 The baseline TL-KRIS



(a) DCD of SDT and GPS PPP links with the σ(DCD)=0.314 ns and a slope



(b) Time deviation of the DCD

Figure 4.3.2-1 Comparison between SDR and GPS PPP time links over the baseline TL-KRIS

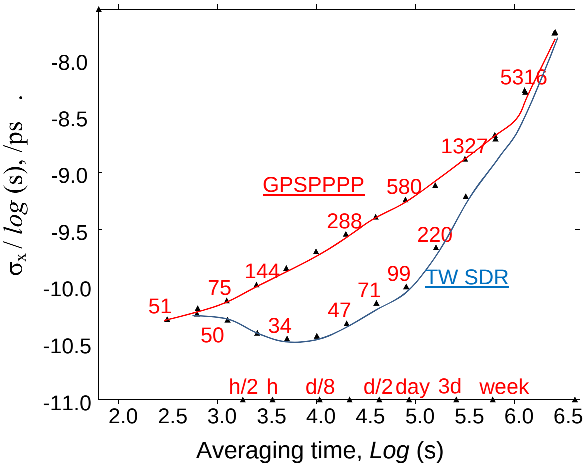


Figure 4.3.2-2 Comparison of the TDev of the SDR (blue) and GPS PPP (red) time links over the baseline TL-KRIS

As given in the plot, the TDev reaches to 34 ps on two hours averaging time. The SDR link is more stable than that of the GPS PPP in both short and long-terms.

4.3.3 The baseline CH-PTB

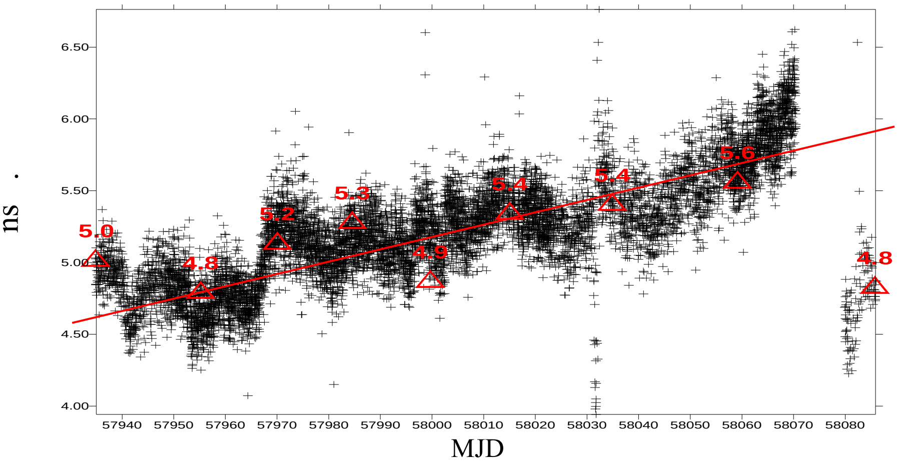


Figure 4.3.3-1 DCD of TW SDR and GPS PPP time links over the baseline CH-PTB with the σ(DCD)=0.389 ns and a slope plus a step in the DCD

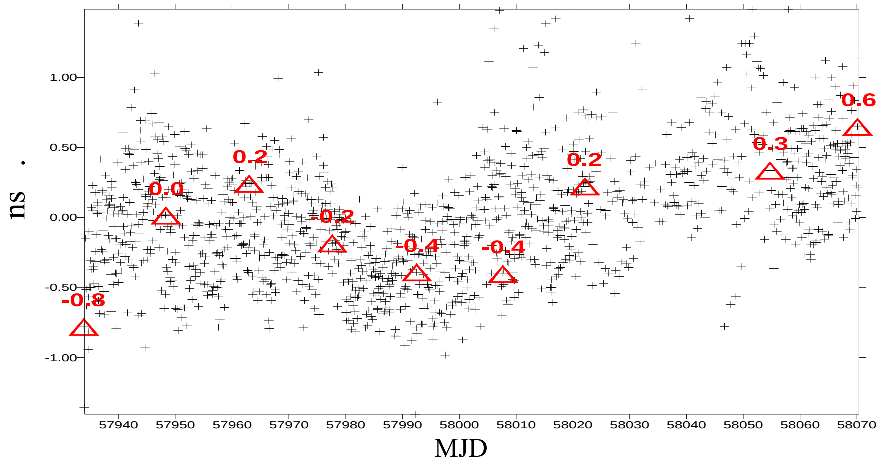


Figure 4.3.3-2 DCD of TW SDR and TW SATRE time links over the baseline CH-PTB with the σ(DCD)=0.441 ns without slop observed

4.3.4 The baseline IT-PTB

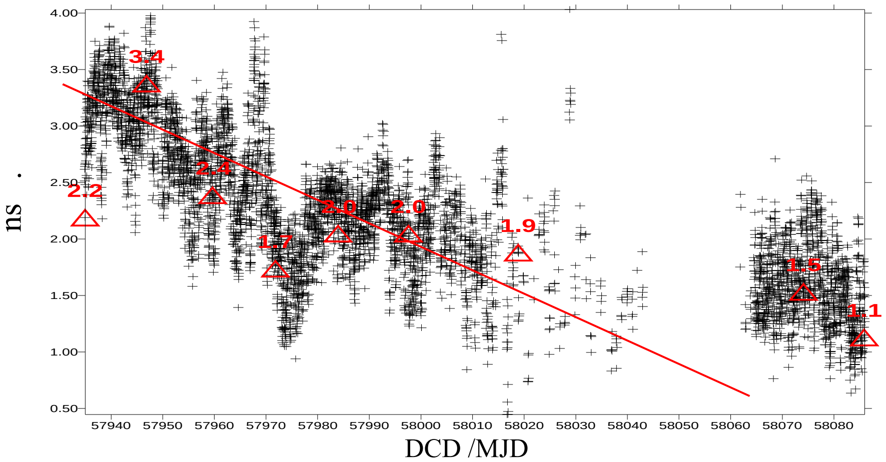
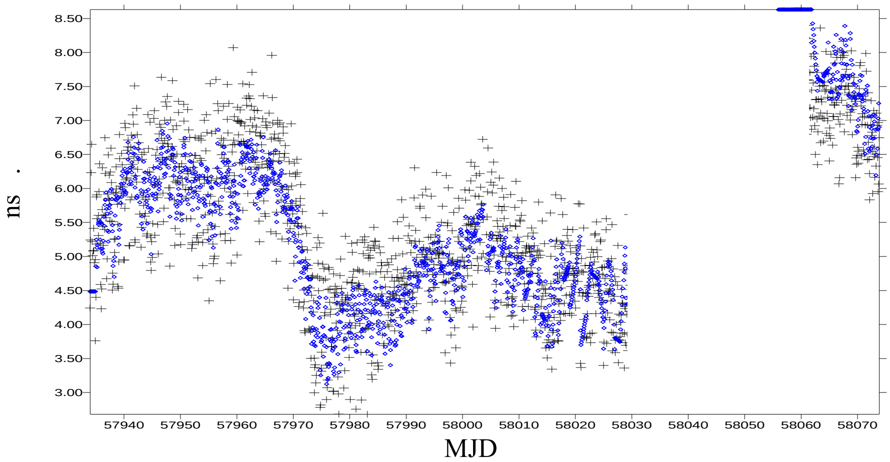
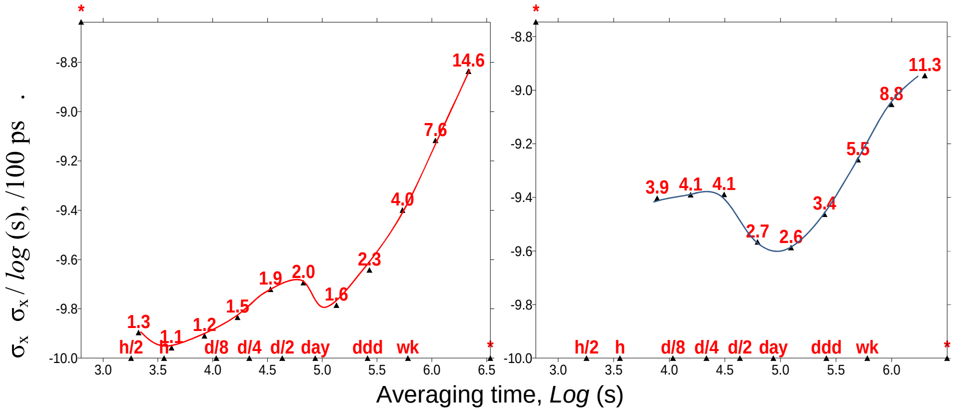


Figure 4.3.4-1 DCD of SDR and GPS PPP time links over the baseline IT-PTB with the σ(DCD)=0.653 ns and a slop



(a) TWSTFT differences of SDR (blue) and SATRE (black) links



(b) TDev of SDR (left) and SATRE (right)TWSTFT differences

Figure 4.3.4-2 Comparison between TW SDR and SATRE time links over the baseline IT-PTB

Here, the up plot is the DCD of the two links with the σ(DCD)=0.708 ns without slope. The down plot is the TDev of the two links. Again, as shown in the Figure, the stability of SDR reaches 110 ps in about one hour and is much more stable than that of the SATRE. Between the 58030 and 58060, both the TW SDR and SATRE data were disturbed and not shown here.

4.4 Summary of the 6-month analysis

Based on the analysis above, we have the following observations:

- There are time steps and gaps, in particular, in the links of IT-PTB, AOS-PTB and NIST-PTB. The results of AOS-PTB and NIST-PTB can be found in TM273 [23];
- IT-PTB link is a little nosier than normal;
- Similar conclusions as given in the earlier study, c.f. the TM267 [6] can be made:
  - For the inner-continental links, the TDev of the SDR links is greatly improved as compared to that of the SATRE links in both the measurement noise and the diurnal;
  - For the link NIST-PTB, the measurement noise is improved but the diurnal, which is already very small and in fact the smallest of all the UTC links, is not considerably improved. In fact, the SATRE TWSTFT link NIST-PTB is the most stable one in the TW network. The short term TDev or u_A is about 100 ps, much smaller than the conventional u_A of 200 ps, see section 2.2. That is, 200 ps is almost the uncertainty limit of SDR (for the satellite T11N). It is hence difficult to further improve the uncertainty in an order of 100 ps. In Asia, it seems the links with the satellite 172B are more stable;
  - The best operated and the most stable SDR link is of OP-PTB which can be readily used as a UTC link
- At present, not all the SDR ITU data are as reliable (in terms of data gaps and time steps) as that of SATRE. The data quality will be improved with more experiences in operating and monitoring SDR TWSTFT. A coordinator is to be named to monitor the SDR measurement quality and find a trouble-shooting solution when necessary.

We make here a summary of the 1-month and 6-month analyses:

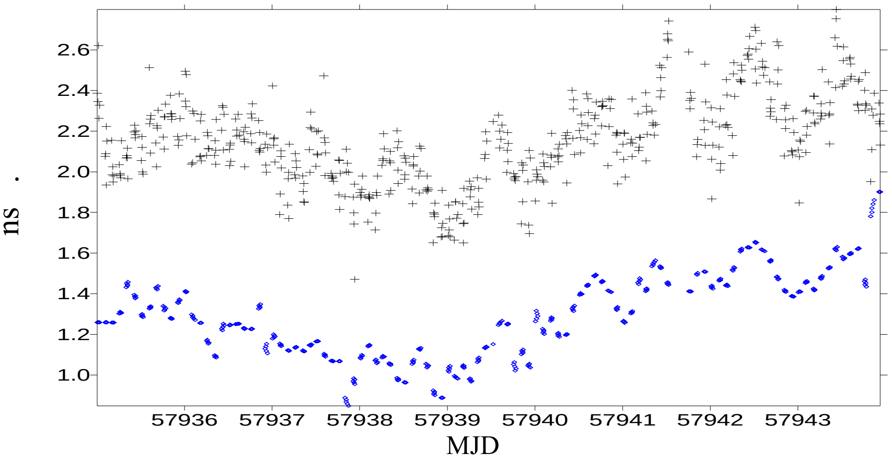
- We confirm the earlier conclusions: the diurnals are considerably reduced, in particular for the inner-Europe links. In consequence, the statistical uncertainty is decreased by a factor of 2 or 3 in most cases;
- In long-term and in normal case (without steps due to the changes in hardware and the software), the SDR links are consistent with GPS PPP links, e.g., for the period of 183 day, $\sigma(DCD_{SDR\text{-}GPSPPP})=0.283$ ns for the baseline of OP-PTB; $\sigma(DCD_{SDR\text{-}GPSPPP})=0.314$ ns for the baseline of TL-KRIS; $\sigma(DCD_{SDR\text{-}GPSPPP})=0.389$ ns for the baseline of CH-PTB and $\sigma(DCD_{SDR\text{-}GPS\ PPP})=0.653$ ns for the baseline of IT-PTB. AOS and NIST suffered several huge steps and we could not make the long-term comparisons;
- In long-term the SDR and SATRE links are well consistent with each other;
- However, we observe a kind of slope between the SDR and GPS PPP links, which seems in the same order as that between SATRE and GPS PPP links. Further studies will be made in this direction;
- The major issue is the steps in the SDR measurement data. The operators of the SDR TWSTFT should pay more attention to the SDR operation at least at the beginning of the SDR TWSTFT operation.

5. STEPS TO FURTHER IMPROVE THE SDR QUALITY

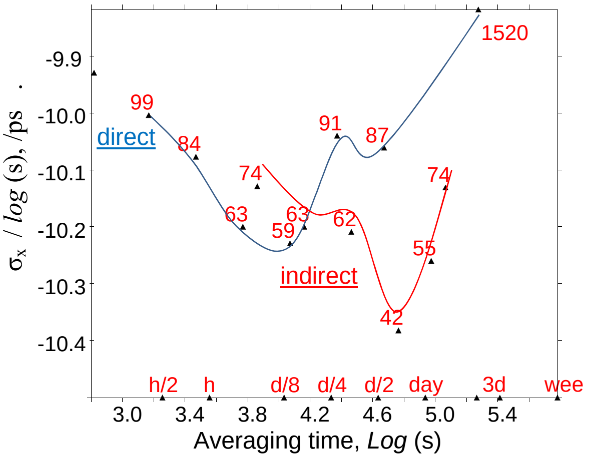
We have pointed out that the uncertainty of the SDR link may be further improved by:

- The indirect link method [10,11] as a simplified application of the TW network time transfer [8];
- The combination of the TW SDR and the GPS PPP which contains the carrier phase information, namely SDR+PPP [14].

As we also know, the GPS IPPP is at present the most precise link available [21] among the techniques used in the practice of the clock comparison. We may therefore use the IPPP to investigate the gains of the improved results obtained by the above two methods. In the followings, we show examples of indirect SDR link, SDR+PPP link and comparing them to IPPP link over the OP-PTB baseline.



(a) TWSTFT differences of Indirect SDR (blue) vs. direct SDR (black) links with the σ(DCD)=0.159 ns



(b) TDev of the TWSTFT differences for direct and indirect SDR links

Figure 5.1 Comparison between direct and indirect (via NIST) TW SDR links over the baseline OP-PTB

The time stability curves show clearly that the TDev of the indirect link is much more stable than that of the direct link. Further investigation beyond the physical reasons may refer to [10, 11] and also [18].

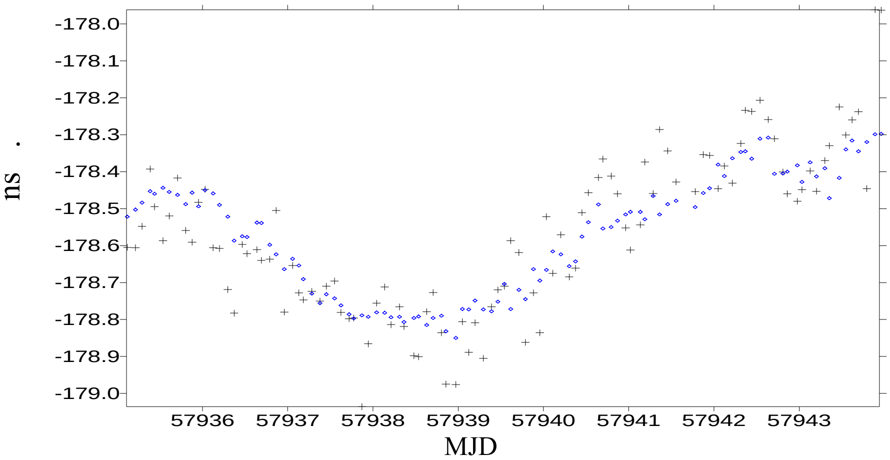
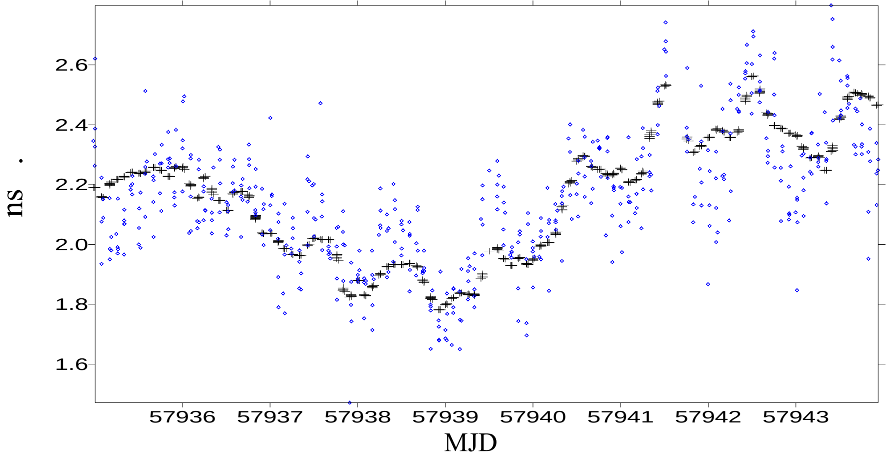
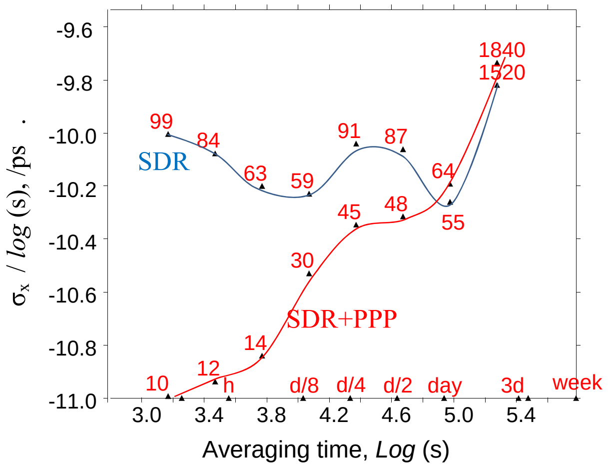


Figure 5.2 Comparison between GPS IPPP (blue) and TW SDR indirect (black, via NIST) links over the baseline OP-PTB with the σ(DCD)=0.104 ns

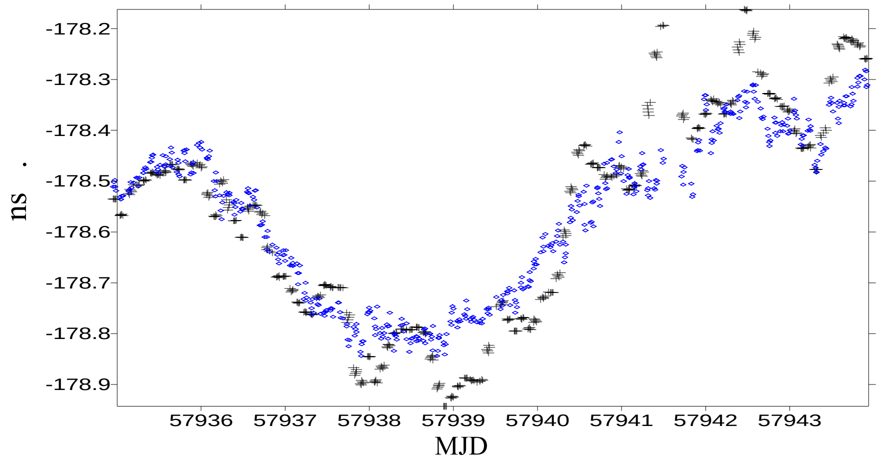


(a) Time transfer differences of SDR+PPP (black) vs. SDR(blue) links with the σ(DCD)=0.143 ns

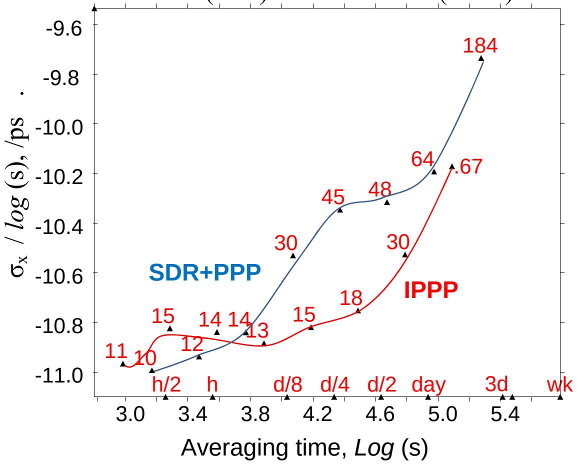


(b) TDev of the SDR+PPP (red) and SDR (blue) links

Figure 5.3 Comparison between the combined TW SDR+GPS PPP and the TW SDR links over the baseline OP-PTB. An excellent stability in the combined SDR+PPP link can be observed



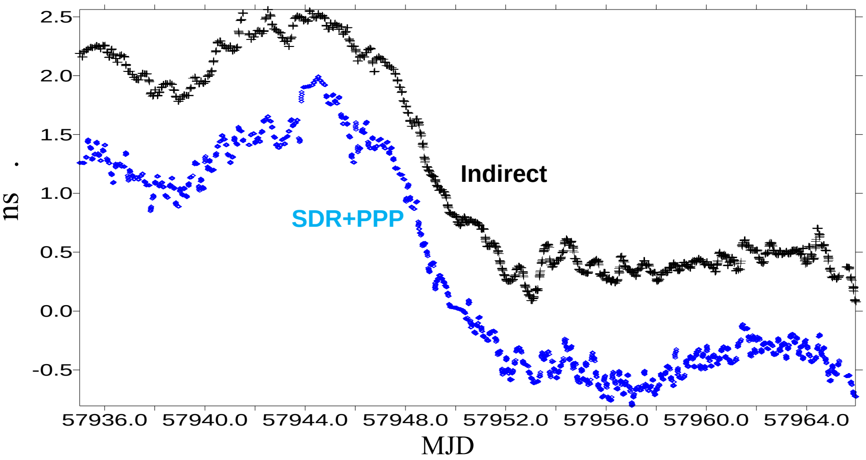
(a) Time transfer differences of IPPP (blue) and SDR+PPP (black) links with the σ(DCD)=0.078 ns



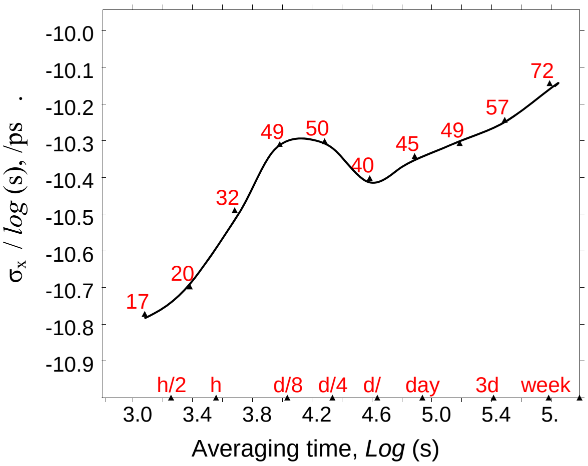
(b) TDev of IPPP (red) and SDR+PPP (blue) links

Figure 5.4 Comparison between IPPP and SDR+PPP links over the baseline OP-PTB

In Figure 5.4, we see both IPPP and SDR+PPP links have excellent stability. However, a detailed look shows that the IPPP solution is more stable than the PPP solution in averaging time of 4-5 hours which is about the duration of a passage of a GPS satellite visible by a receiver on the Earth.



(a) Time transfer differences of SDR indirect (blue, via NIST) and SDR+PPP (black) links with σ(DCD)=0.112 ns



(b) TDev of the DCD($SDR_{INDIRECT}$-SDR+PPP)

Figure 5.5 Comparison between the TW SDR indirect (via NIST) link and the combined SDR+PPP link over OP-PTB

In the Figure 5.5, it seems that the indirect SDR link is a little noisier than that of the SDR+PPP link. However, it is important to underline that the indirect link is a TWSTFT technique, completely independent from the GPS.

As a summary, table 4.4 takes the IPPP as the reference to compare the other linking techniques: GPS PPP, SDR, SATRE, SDR indirect link via NIST ($SDR_{ind/NIST}$) and the combination (SDR+PPP), cf. the Section 4.2.1 in [23] for the computation details and the plots etc.

Table 4.4 Comparing IPPP to PPP, SATRE, SDR, $SDR_{ind/NIST}$, and the combined link (SDR+PPP) over the baseline OP-PTB

DCD	No	Min/ns	Max/ns	Mean/ns	σ/ns	Gain factor vs. SATRE-IPPP
PPP-IPPP	2880	1.175	1.703	1.378	0.088	-
SDR-IPPP	524	0.198	1.247	0.721	0.158	**3.3**
SATRE-IPPP	118	-1.183	1.638	0.679	0.516	**1.0**
$SDR_{ind/NIST}$-IPPP	105	-0.383	0.201	-0.136	0.104	**5.0**
(SDR+PPP)-IPPP	524	0.547	1.004	0.725	0.078	**6.6***

* Note here that, the solutions (SDR+PPP) and IPPP may not be independent.

In the table, the DCD (double clock differences) is obtained by comparing two links. “Min” and “Max” are the minimum and maximum values of the DCD during the analysed time. Mean and σ are the mean value and standard deviation, respectively. Because the IPPP is the most precise and taken as the reference, the smaller the σ, the more precise the link. The Gain factor in the table is the ratio of the σ of the biggest DCD of SATRE-IPPP 0.516 ns over another link. As can be seen, the most precise link is the combination of SDR and PPP, the gain factor is 6.6. However, SDR+PPP and IPPP are correlated and thus the gain factor should be judged with caution. The second is the indirect SDR link with the gain factor 5.0 and then is 3.3 for the SDR link, that confirms the earlier study. Here we did not compute the Gain factor for PPP-IPPP because they are the same type of measurement using the same raw data set for the computations and therefore strongly correlated.

Noting that the gain factor of the indirect SDR link $\mathrm{SDR}_{\mathrm{ind/NIST}}$ vs. the IPPP is 5.0 and the techniques are completely independent from each other. The $\mathrm{SDR}_{\mathrm{ind/NIST}}$ considerably improves the stability of the SDR, hence it is the most precise TWSTFT technique. Here the NIST in USA is used as the relay station. Because the redundant links, here NIST-OP and NIST-PTB, are always available with the direct link OP-PTB, composing the indirect link does not need to have extra equipment investment or make any extra measurements. Although the indirect TW signals travel distances much longer than the direct ones, the quality is significantly improved, due to the fact that the common affections in NIST-OP and NIST-PTB are mostly cancelled or at least greatly reduced. Not all stations can be used as the relay station of an indirect link, e.g., for the inner-Europe links, none of the European stations can be used as an ideal relay station. They usually increase the instability. The indirect link method works not only for the SDR links but also for the indirect SATRE [10,11]. Further investigations are ongoing.

6. DISCUSSION AND CONCLUSION

In this paper, we discussed the background of the SDR TWSTFT. We quickly reviewed the results of earlier studies and gave the solutions for final open points, including the SDR device setups and the Tsoft software preparation towards this new technique to be used for UTC computation. Technically and practically, the SDR TWSTFT is now ready being accepted for UTC time links. From October 2017, Circular T 359, the SDR link has been used as the backup UTC time link.

The results have been and will continue to be published monthly on the BIPM web site:

ftp://ftp2.bipm.org/pub/tai/timelinks/lkc/1711/opptb/lnk/opptb.tttts.gif for the SDR link;
ftp://ftp2.bipm.org/pub/tai/timelinks/lkc/1711/opptb/dlk/opptb.ttts5.gif for the comparison of SDR-SATRE:
ftp://ftp2.bipm.org/pub/tai/timelinks/lkc/1711/opptb/dlk/opptb.t3sa5.gif for the comparison of SDR-GPS PPP.

As required by the CCTF WG on TWSTFT, the BIPM made the final evaluation using the latest 6-month data from July to December 2017 to better understand the characteristics of the SDR TWSTFT, such as the long-term stability, consistency with existing accurate UTC time transfer links, and find the potential problems in the hardware and the software and fix them.

From the analysis, we summarise our results about the SDR TWSTFT as below:

- We confirm the earlier conclusions, mainly that the diurnals are considerably reduced, in particular for the inner-Europe links. In consequence, the uncertainty is decreased by a factor of 2 or 3 in most cases;
- In long-term and in regular operation (without steps due to the changes in hardware and the software), the SDR links are consistent with the corresponding GPS PPP links, e.g., for the baseline OP-PTB with σ=0.283 ns; TL-KRIS σ=0.314 ns; CH-PTB σ=0.389 ns and IT-PTB σ=0.653 ns. The AOS and NIST SDR links suffered several huge steps and we could not make the long-term comparisons;
- On long-term the SDR and SATRE links are suitably consistent with each other;
- However, we observed a slope in the DCD between the SDR and GPS PPP links, which seems of the same order as that between SATRE and GPS PPP links. If we take into account the slope (the long-term variations between SATRE and GPS PPP links), the σ(DCD) of the SDR and GPS links given above will be much smaller. Further study is to be made in this direction;
- BIPM has made SDR TWSTFT a backup UTC link. It computes the SDR links monthly, makes the link comparisons between the SDR and the other links of SATRE, GPS PPP, GPS IPPP and in the coming future the TWOTFT when possible, thanks to the participations in TWSTFT measurements of AOS and GUM (PL) recently;
- BIPM and the WG on TWSTFT will co-ordinately make decision link by link to introduce the SDR TWSTFT in the UTC computation;
- The major issue is the data gap and time steps in the SDR measurement data, caused mainly by the SDR device maintain and operation. The operators of the SDR TWSTFT operation should pay more attention at least at the beginning of the SDR TWSTFT;

Finally, the conclusion:

The uncertainty of the current (SATRE) TWSTFT is limited by the instabilities (diurnal) of the signal arrival time. The SDR receiver implemented in the TWSTFT earth stations allows a more precise measurement of the arrival time of the coded signal and reduces the diurnal significantly. SDR receiver has been successfully installed at the 15 laboratories AOS, CH, KRIS, IT, NICT, NIM, NIST, NPL, NTSC, OP, PTB, SP, SU, ROA and TL since 2015. Experiments have been carried out continually.

In Jan 2016, a pilot project was launched jointly by BIPM and the CCTF WG on TWSTFT aiming at validating SDR TWSTFT used by laboratories in Asia, Europe and USA with different satellites. The goal of the pilot project is to apply the SDR TWSTFT in UTC generation.

During the last two years, extensive tests and analysis have been made to test the SDR devices, the operational setups, the method and the related software, such as the software packages "Obs2Itu" and the BIPM UTC computation program "Tsoft".

The gain factors obtained vary from 1.03 to 3.7, and 2 on average, depending on the satellite covering regions and link situations. We can conclude that compared with the SATRE TWSTFT solution, the SDR TWSTFT may improve the time stability by a factor of 2 to 3 on the short-term (in 1-2 hours) and its long-term stability is consistent with the major existing UTC time links such as the TW SATRE and GPS PPP links.

For the Circular T computation, the suggested conventional uncertainties of the TW SDR are:

- u_B equals to the corresponding uncertainty of SATRE link;
- u_A to be 0.2 ns.

Further studies may focus on how to improve the accuracy of the SDR technique by combining it to GPS carrier phase and by fully use of the redundancy in the TWSTFT network, that is, forming the so called 'indirect' time links. Encouraging results have been obtained. Another important issue is the TW SDR link calibration, of which the procedure is agreed upon by the WG on TWSTFT and BIPM.

The SDR is an open platform for the operators of the TWSTFT ground stations. People may make deeper studies, for example, by taking out the carrier phase information for various applications.

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[†] **Disclaimer:** Commercial products are identified for the sake of technical clarity. No endorsement by the BIPM or a pilot project participant is implied. We further caution the readers that none of the described equipment's apparent strengths or weaknesses may be characteristic of items currently marketed.

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