

Accurate TWSTFT time transfer with indirect links

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BIOGRAPHIES

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ABSTRACT

The conventional wisdom suggests that a direct Two-Way Satellite Time and Frequency Transfer (TWSTFT or TW) time link should result in a smaller uncertainty than that of an indirect TW link over the same baseline [12]. This is why all Coordinated Universal Time (UTC) TW links are direct and therefore assumed to be the most precise. This paper shows an exception to this logic.

Following the use of the Global Positioning System (GPS) all-in-view [1], the UTC links, including Global Navigation Satellite Systems (GNSS) and TWSTFT, became the direct links between Lab(k) and the PTB (Physikalisch-Technische Bundesanstalt, Germany), which is the single pivot laboratory of the international UTC network. Currently, the daily variation (diurnal) in TW differences is the dominant source of instability in TWSTFT. This, at least in the case of the inner-European network, may be significantly reduced by an indirect link through a third intermediate laboratory in the USA, acting as a relaying laboratory [2, 3]. In this study, we examined the direct and indirect Europe-Europe TW links with data collected by SATRE modems and using the NIST (National Institute of Standards and Technology) or the USNO (US Naval Observatory) laboratory as an intermediate laboratory. We applied the Time deviation (Tdev), triangle closures, and the gains obtained by comparing with the results of the GPS Precise Point Positioning (GPSPPP) [4] and the TW software-defined radio (SDR) receiver [5, 6, 7] as indicators to verify the improvements in the indirect links versus the direct links. Considerable improvements were obtained by a factor of two or three. On the same TW baselines, we further investigated the TW SDR indirect links and gains continued to be observed.

In addition, the rapidly developing new time and frequency transfer techniques, such as optical fibres, are often not linked directly with the present pivot laboratory, the PTB. Therefore, indirect links or the multi-pivot UTC time transfer network configuration for future UTC generation is meaningful and has to be reconsidered.

Finally, one of the most important characteristics of the indirect link is that it does not require new equipment or additional measurements. Only minor modifications were required to the software and this has already been carried out in the BIPM UTC/TAI computation software package, Tsoft.

Keywords: TWSTFT or TW, GPSPPP, SDR, Diurnal, Time deviation, Stability, Closures, Direct link and Indirect links

1. INTRODUCTION

Let A - B denote a direct link of the baseline between laboratories A and B as shown in Figure 1.1, where the baseline is between PTB (Physikalisch-Technische Bundesanstalt, Germany) and Lab(k). An indirect link between A and B is the link involving an intermediate laboratory C (Lab(i) in Figure 1.1): $(A - B)^C = A - C + (C - B)$. For example, using NIST (National Institute of Standards and Technology) as an intermediate laboratory, we can obtain the indirect link between PTB and OP (Laboratoire National de Métrologie et d'Essais – Systèmes de références space-temps, Observatoire de Paris (LNE-SYRTE), France), i.e. $(PTB - OP)^{NIST} = PTB - NIST + (NIST - OP)$.

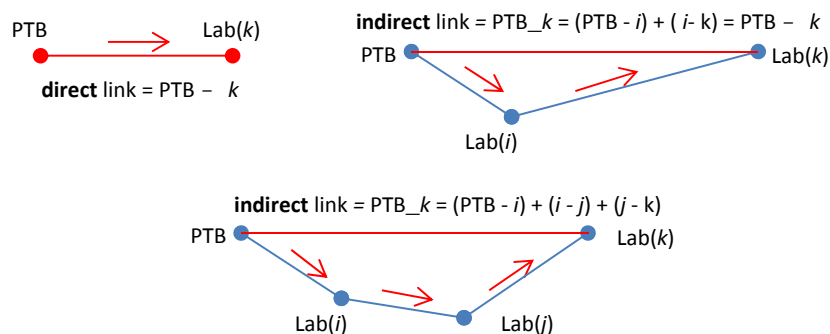


Figure 1.1 The direct and indirect links between PTB and lab(k). To date, all the UTC links are direct and therefore the shortest. These are traditionally believed to be the most accurate. But is this always true?

The conventional wisdom suggests that a direct Two-Way Satellite Time and Frequency Transfer (TWSTFT or TW for short) time link should result in a smaller uncertainty than that of the indirect TW link with intermediate connection(s) [12], i.e., the uncertainty of $(A - B)^C$ is larger than that of $A - B$. That is why all the UTC links are direct ones to PTB. However, our study shows an indirect Europe-Europe TW link, by using an intermediate laboratory located in the USA, can have a considerable smaller uncertainty than that of the direct link.

To date all UTC links have been direct links between Lab(k) and the PTB for both the Global Navigation Satellite Systems (GNSS) and the TW techniques. In past decades, the daily variation in TW differences (diurnal) has been the dominant error source in TW time transfer. The only operational way to cancel or reduce the diurnal effects, at least in the present UTC computation, is to combine the TW and GPSPPP (GPS Precise Point Positioning) measurements (termed in BIPM *Circular T* TWGPPP), because the magnitude of diurnal is much smaller or negligible in GPSPPP. TWGPPP has been used for UTC time transfer since 2009 [8].

In 2007, Jiang and Petit [2] defined the concept of an indirect time transfer link and determined that an indirect TW link combined with a GPSPPP link may be as advantageous as the direct link. An indirect link is a link made via a third laboratory as an intermediary. Multi-relaying indirect system is possible.

Later studies [3,9] found, for the Europe-Europe TW, an indirect link can greatly improve the uncertainty compared to that of the related direct link, which is a standard UTC computation link. These works prove that, for the inner-European UTC TW links, the corresponding indirect links via NIST or USNO (US Naval Observatory) are more stable than direct links due to the significantly reduced diurnal and noise levels. The authors investigated the cause of the diurnal and suggested that it might be related to signal interference caused by density of traffic on the satellite transponder. They used the frequency spectral technique to numerically compare the gains of the indirect links versus the direct links. The indirect links reduce the diurnal components by a factor of two or three in many cases. In the worst case, the reduction is about 20 %. In conclusion, the authors note that by reducing the diurnal and increasing the stability with the indirect link via a laboratory in the USA, the inner-European TW links can be significantly improved.

Based on these ideas, we study the Europe-Europe indirect links using the European laboratory SP (Swedish National Testing and Research Institute, Sweden) and the USA laboratories NIST and USNO as the intermediate laboratories. We applied the Time deviation (Tdev), triangle closures, the GPSPPP and Software Defined Radio (SDR) TW receiver as indicators as well as the spectral analysis to numerate the gains achieved by indirect links. We test our hypothesis by using different methods listed below. In this paper, only the case of a single relay laboratory is discussed.

- We first implement the calibration results [10,11] in the TW data files so that all the UTC and non-UTC links, i.e. all the direct and indirect links are calibrated;
- We compare the direct and indirect links to each other to study if there are any calibration discrepancies. As discussed in [2], the combination of TW and GPSPPP will retain the exact calibration of the TW link. This is the same for the indirect links;
- We know that the GPSPPP time link solution is more stable in the short term (hours or shorter) and is not affected by the diurnal. So, in addition to the traditional Tdev, the GPSPPP link is also taken as a good reference to estimate the improvement in the reductions of both noise and diurnal. As an indicator of the assessment gain, its limit is its precision, Type A uncertainty $u_A \leq 0.3$ ns;
- The newly developed SDR TW receivers can eliminate the diurnal in the differences obtained by SATRE measurements of some of the direct links. For these direct SDR TW links, the precision is $u_A \leq 0.2$ ns [5, 6]. The SDR is used as the same way as the GPSPPP as an indicator;
- The spectral power analyses may indicate also the gains of the indirect links in the frequency field;
- We study the role of the intermediate laboratories: one in Europe (SP) and two in the USA (NIST and USNO).

In the following discussions, we use the symbols ‘-’ and ‘_’ to indicate the direct and indirect links, e.g., Lab2 – Lab1 is a direct link and Lab2_Lab1 = (Lab2 - Lab1)^j is an indirect link via laboratory j. The term ‘indirect link’ was first used in [2] in 2007 then carefully reviewed in 2016 [9] encouraged by the study [3]. The fact that the new TWSTFT calibration guideline authorizes the TCC (triangle closure calibration) [11], the indirect link is theoretically authorized for UTC time transfer.

2. THE EUROPE-EUROPE-USA TW NETWORK AND THE CALIBRATIONS

TWSTFT is the primary technique for UTC time transfer.

2.1 The Configuration of Europe–Europe-USA TWSTFT network

The nine available TW laboratories in Europe and the USA are investigated in this study: CH (Federal Institute of Metrology (METAS), Switzerland), IT (Istituto Nazionale di Ricerca Metrologica (INRIM), Italy), OP, PTB, ROA (Real Instituto y Observatorio de la Armada, Spain), SP, VSL (Dutch Metrology Institute, the Netherlands), NIST and USNO, see Figure 2.1.1, which also gives basic information about UTC TW operations.

There are eight direct UTC links: CH–PTB, IT–PTB, OP–PTB, ROA–PTB, SP–PTB, VSL–PTB, NIST–PTB and USNO–PTB.

In 2015, the BIPM gathered all the available results from the extensive calibration campaigns for both TW and GPS. Starting on the Modified Julian date (MJD) 57357 or 1 December 2015 at 0 h UTC [10], most of the laboratories in UTC TW network implemented the TW link calibration results in the TW International Telecommunication Union (ITU) data files (NIST officially implemented the calibration on MJD 57506). The result is that all the TW data used in this study are calibrated.

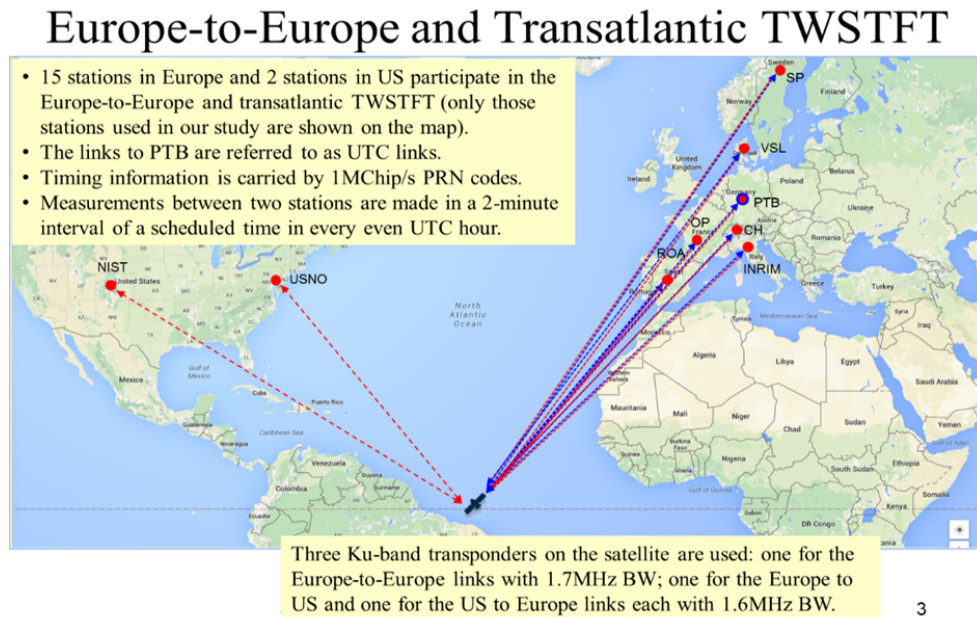


Figure 2.1.1 Configuration of the Europe–Europe–USA TW network based on Zhang *et al.* [3]

2.2 The TWSTFT direct and indirect links

Corresponding to the six direct inner-European links, there are six indirect TW links via each of the three relay laboratories: NIST and USNO in USA and SP in Europe, for example: via NIST, we have: $(CH-PTB)^{NIST}$, $(IT-PTB)^{NIST}$, $(OP-PTB)^{NIST}$, $(ROA-PTB)^{NIST}$, $(SP-PTB)^{NIST}$, and $(VSL-PTB)^{NIST}$.

An indirect link is the sum of two direct links to an intermediate laboratory, e.g., the indirect links via NIST and USNO are correspondingly: $(CH-PTB)^{NIST} = (CH-NIST)-(PTB-NIST)$ and $(CH-PTB)^{USNO} = (CH-USNO)-(PTB-USNO)$. An indirect link numerically is the point-to-point differences of the two direct links with the intermediate laboratory, NIST/USNO here, being cancelled. The same is found for all the other links. The data interval is two hours for the Europe-Europe and transatlantic TW. Because the two direct measurements to the intermediate laboratory are made at different times, interpolation is made using Tsoft to bring the second link within the first link's measurement time frames.

Below, we take the baseline between OP and PTB as an example. Figure 2.2.1a is the TW difference of direct link and Figure 2.2.1b is the TW difference of indirect link via NIST: $(OP-PTB)^{NIST} = (OP-NIST)-(PTB-NIST)$; see Figure 2.2.1c for the two components of the indirect links. The February 2016 (1602) data set is incomplete but this does not alter the results.

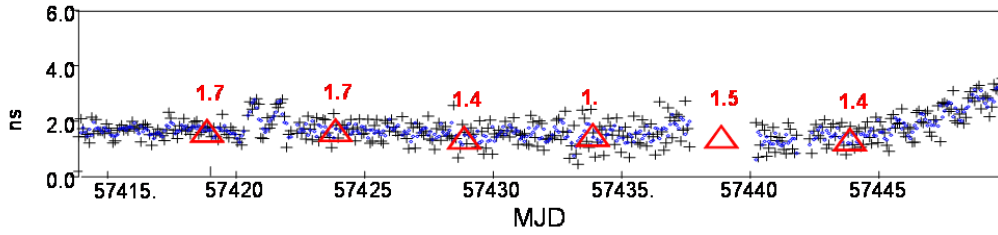


Figure 2.2.1a The direct UTC TW link OP-PTB (black crosses are TW and blue symbols are the smoothed measures)

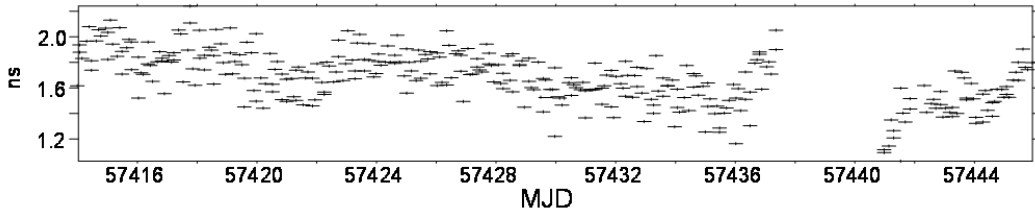


Figure 2.2.1b The indirect UTC TW link $(OP-PTB)^{NIST}$ (the difference of the two links is shown in Figure 2.2.1c)

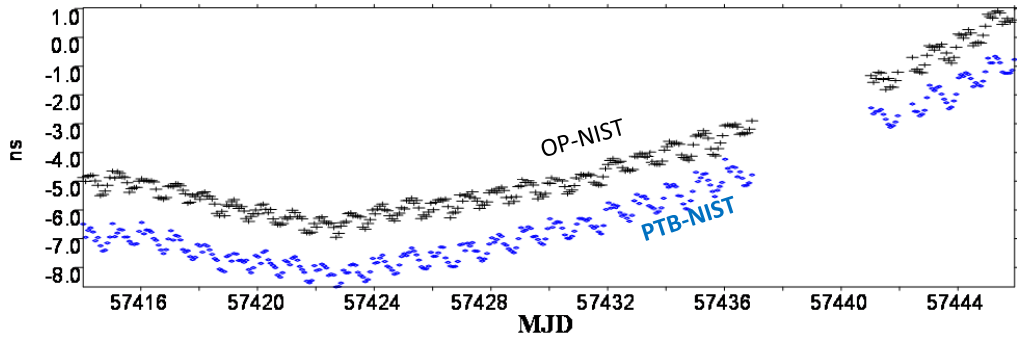


Figure 2.2.1c The two direct TW links OP-NIST and PTB-NIST; highly correlated diurnals present

2.3 Consistency in the TWSTFT calibrations of the direct and indirect links

The aim of this study is to reduce the diurnal and the instability of UTC TW links in order to improve them for use in the computation of UTC. With the calibrations of UTC and non-UTC links, the time transfer results between PTB and Lab(*k*) should therefore be the same for direct and indirect links. We expect the difference in the two types of link is within the Type A uncertainty ($u_A = 0.5$ ns) and, on average, for all links, the differences should be as small as possible. The consistency can be verified by comparing the direct and indirect links.

Figure 2.3.1a shows a comparison of the calibration consistency for the OP-PTB and $(OP-PTB)^{NIST}$. The indirect link TW difference (blue circles) is shown to be more stable with less noise. Figure 2.3.1b is the double clock difference (DCD) between the direct and indirect links, which is a measure of the discrepancy in the calibrations of the two links. The mean value of the DCD should be statistically close to zero. The scatter is dominated by the diurnal and the measurement noises in the direct link (black crosses). In the case of baseline between OP and PTB, the mean value of the DCD and its standard deviation σ of the DCD are -0.062 ± 0.451 ns.

Table 2.3.1 gives the differences of all the six pairs of links. The maximum discrepancy is 0.462 ns (VSL-PTB) below the TW link measurement uncertainty $u_A = 0.5$ ns. The mean value of all the links are statistically zero. This confirms that calibrations of the direct and indirect links are fully consistent.

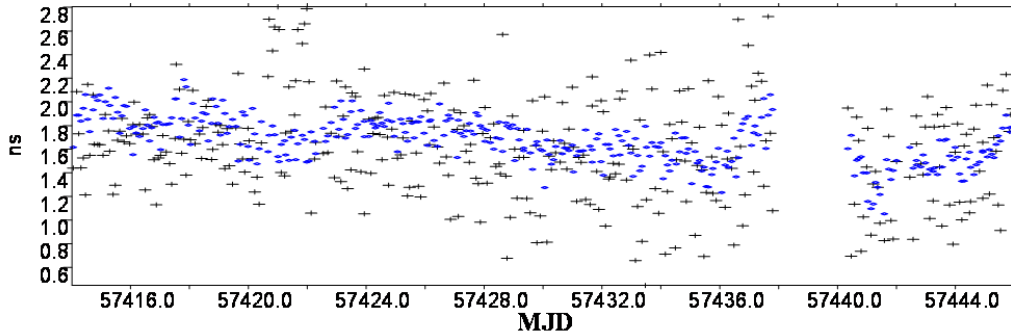


Figure 2.3.1a The direct (Fig. 2.2.1a, black crosses) and indirect (blue circles, Fig. 2.2.1b via NIST) TW differences. The difference of direct link (crosses) scatters much more than that of the indirect link (blue circles)

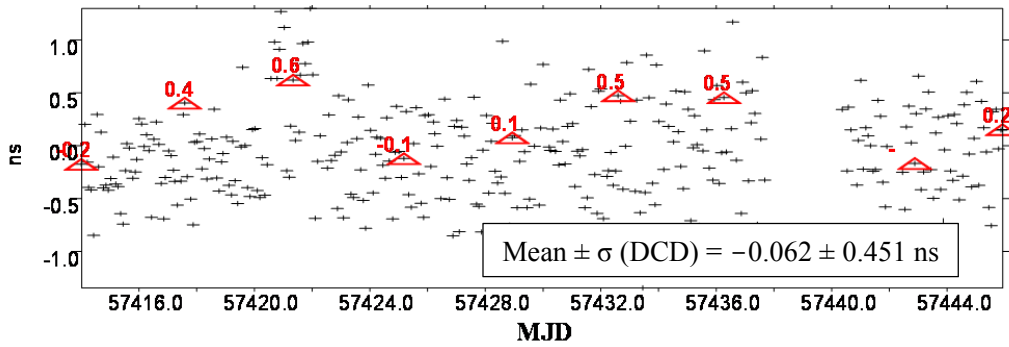


Figure 2.3.1b The differences (DCD) of the direct and indirect links in Figure 2.3.1a

Table 2.3.1 Differences between the direct link and the indirect links via USNO and NIST

baseline	N	(Direct-Indirect) $\pm \sigma_N$ via NIST /ns	(Direct-Indirect) $\pm \sigma_U$ via USNO /ns
CHPTB	335	0.305 \pm 0.586	0.228 \pm 0.608
ITPTB	365	-0.163 \pm 0.835	0.054 \pm 0.822
OPPTB	355	-0.062 \pm 0.451	-0.069 \pm 0.553
ROAPT	335	0.268 \pm 0.811	0.250 \pm 0.793
SPPTB	360	0.249 \pm 0.453	0.188 \pm 0.523
VSLPTB	370	-0.462 \pm 0.567	-0.455 \pm 0.785
Mean		0.022	0.033

3. IMPROVEMENT IN REDUCING THE INSTABILITY AND THE DIURNALS

In this section, we quantify the improvement of the indirect links with respect to the direct links. We use mainly the following five indicators to assess the gains achieved:

1. Comparison of the TW links to the GPSPPP, that is, to compute the double clock difference (DCD). GPSPPP is a completely independent measurement and is almost unaffected by the diurnal. In addition, the measurement noise is much less than TW in short-term of a few hours or less. It follows that the smaller the standard deviation (σ) of the DCD the better. We call this the 'faithfulness' to the clock behaviour. Noting that conventional value of the Type A uncertainty (u_A) for GPSPPP is 0.3 ns. Therefore, the limit of this indicator is of the order of ~ 0.2 to ~ 0.3 ns, according to the experience of the authors;
2. Comparison of the TW SATRE difference to the TW SDR difference of the same link, similarly to GPSPPP, the TW SDR difference for Europe-Europe links is also much more stable with a u_A of about 0.2 ns and without significant diurnal;
3. Spectral analysis of the diurnal and other components [3]. It is evident that the smaller the diurnal component the better. Here we investigate the relative gains between the direct and indirect links;

4. The Time deviation. Here we investigate the time stability, the diurnal and other terms on different averaging times;
5. The triangle closures. Again, smaller of the closure is better.

All the computation results are given in the Annexes of [9]. Interested readers can refer to them. Hereinafter, we summarize our conclusions by discussing a few typical examples, mainly the baselines between OP and PTB and between CH and PTB, which is illustrated using plots and tables.

3.1 Comparison to GPSPPP

We take the baseline between OP and PTB with the February 2016(1602) data set as an example. Figures 3.1.1a through 3.1.1c are the comparisons of time transfer results between GPSPPP and the direct and indirect TW links (via NIST). We obtained the DCDs; the mean values of the two DCDs are -1.619 ns and -1.559 ns respectively and the difference is 0.06 ns. Hence, the two calibrations of (OP-PTB) and (OP-PTB)^{NIST} are in perfect agreement. The standard deviations are 0.427 ns (direct-PPP) and 0.196 ns (indirect-PPP). The gain factor is 2.2 , or a gain of 54% (via NIST), as given in Table 3.1.1.

The table also lists the gains (or improvements) of the six inner-European indirect links versus the direct links for the corresponding intermediate laboratories SP, NIST and USNO. The gains are -16% , 48.7% and 42.0% respectively. The gain of the indirect link via SP is negative. This implies that the diurnal in the Europe-Europe TW cannot be reduced by the indirect links via a European laboratory. As a consequence, indirect link via a European laboratory will not be discussed in the remainder of this paper. The gains achieved for using indirect links via the USA laboratories are clear: NIST is better than USNO, with gains of 48.7% compared to 42.0% . As GPSPPP is limited by its u_A (0.3 ns); the real gains should be greater than those given in Table 3.1.1.

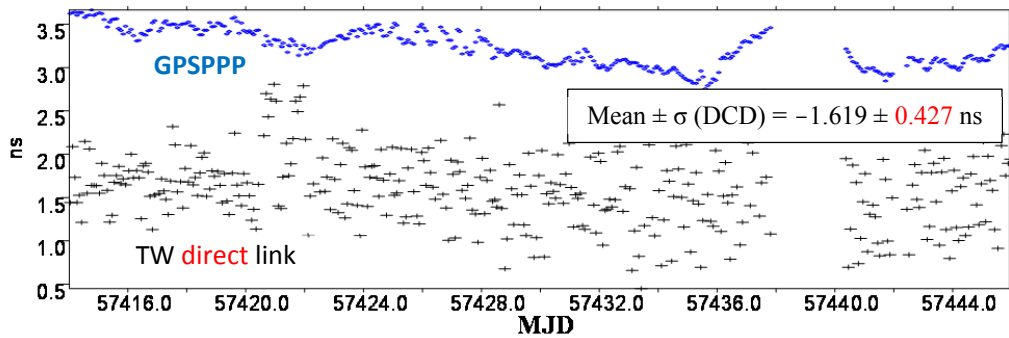


Figure 3.1.1a The direct OP-PTB link (black crosses) versus the GPSPPP link (blue circles)

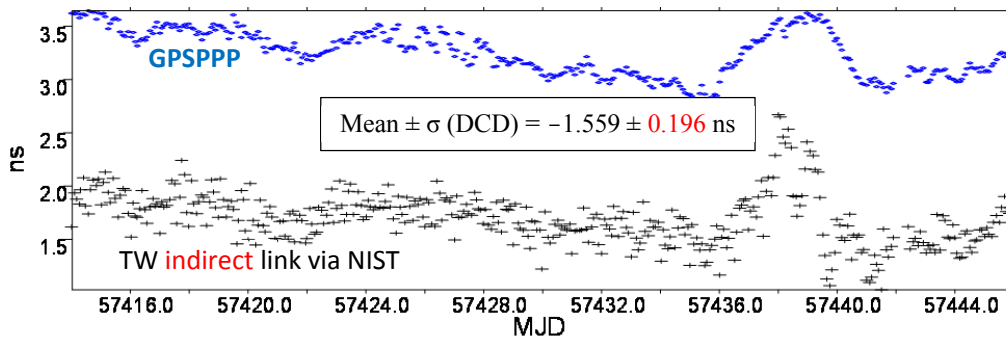


Figure 3.1.1b The indirect (OP-PTB)^{NIST} link (black crosses) versus the GPSPPP link (blue circles)

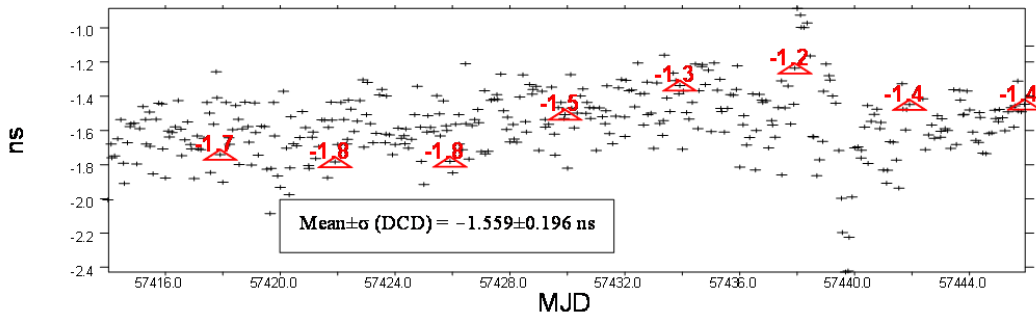


Figure 3.1.1c Double clock difference (DCD) of Figure 3.1.1b (the Mean $\pm \sigma = -1.559 \pm 0.196$)

Table 3.1.1 Comparing GPSPPP to the TW direct link and the indirect links via SP, NIST or USNO

link	N	Direct $\pm \sigma$ /ns	Indirect $\pm \sigma_S$ via SP /ns	Indirect $\pm \sigma_N$ via NIST/ns	Indirect $\pm \sigma_U$ via USNO/ns	Gain = $(\sigma - \sigma_S)/\sigma$ via SP %	Gain = $(\sigma - \sigma_N)/\sigma$ via NIST %	Gain = $(\sigma - \sigma_U)/\sigma$ via USNO %
CHPTB	335	1.785 \pm 0.610	1.801 \pm 0.741	1.476 \pm 0.227	1.549 \pm 0.238	-21 %	63 %	61 %
ITPTB	365	-4.720 \pm 0.812	-5.739 \pm 0.945	-4.515 \pm 0.425	-4.714 \pm 0.528	-16 %	48 %	35 %
OPPTB	355	-1.619 \pm 0.427	-1.492 \pm 0.534	-1.559 \pm 0.196	-1.519 \pm 0.351	-25 %	54 %	18 %
ROAPT	335	2.111 \pm 0.831	1.759 \pm 0.820	1.832 \pm 0.412	1.883 \pm 0.392	1 %	50 %	54 %
SPPTB	360	2.047 \pm 0.536		1.811 \pm 0.251	1.862 \pm 0.286		53 %	47 %
VSLPTB	370	0.431 \pm 0.558	0.551 \pm 0.668	0.862 \pm 0.425	0.879 \pm 0.349	-20 %	24 %	37 %
Mean						-16 %	48.7 %	42.0 %

3.2 Spectral analysis

This section is based on [3]. Spectral analysis of the diurnal (day component) and other components in the direct and indirect links (referred to as *triangle difference* in Figure 3.2.1) are obtained using fast Fourier transform (FFT). Three years (2013–2015) of data were analyzed. Figure 3.2.1 shows an example of the results for the baselines between CH and PTB and between OP and PTB. The diurnal in the direct link is noticeably reduced in the indirect link. The other components are also reduced, except for the half-day component, which is slightly increased in the (OP–PTB)^{NIST} indirect link. We use the diurnal component of the direct link as the reference and divide it by the diurnal component of the indirect link to obtain the diurnal reduction factor.

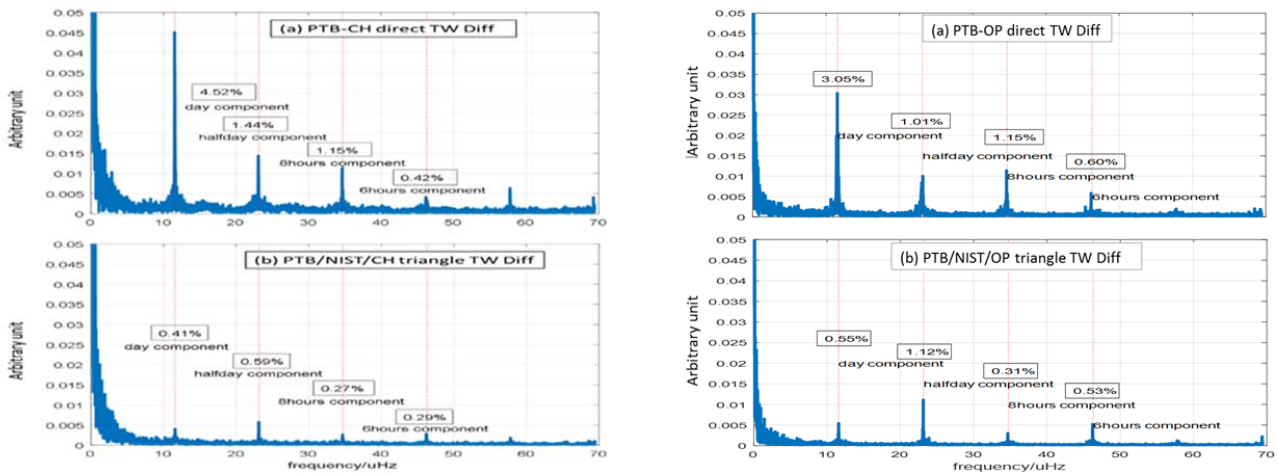


Fig. 3.2.1 Spectral analysis of diurnals and other components in the direct and indirect links over the baselines between CH and PTB (left) and between OP and PTB (right). Here triangle difference stands for the indirect link

The components of the TW differences are presented with an arbitrary unit because we are only interested in the comparison of the relative diurnal reduction in the indirect links relatively to the direct links.

Table 3.2.1 shows the results for the five inner-European UTC TW links via NIST. The results show that the indirect link indeed

reduces diurnals in the direct links by a minimum of 2.7 times. To check if the diurnal reduction is transatlantic link dependent, we computed the transatlantic TW differences among the USNO, PTB and CH. The FFT result of the link of (CH - PTB)^{USNO} also shows that the diurnal in the indirect link is 7.1 times smaller than that of the direct CH – PTB difference.

Table 3.2.1 The gain factor of the diurnal reduction in the indirect links versus the direct links

Link	PTB_CH	PTB_IT	PTB_OP	PTB_ROA	PTB_SP
Gain factor of the diurnal reduction	11.0	2.7	5.5	3.4	3.0

3.3 Time deviation analysis

In this section, we use Time deviation (Tdev) to study the gains in reducing the diurnal and the instability on different averaging times.

Figure 3.3.1 is the Tdev of the direct (blue) and indirect (red) links for the baseline between OP and PTB. The Tdevs are obtained by using 3 years of continuous data [3]. We observe that the diurnal is greatly reduced and stability is significantly improved.

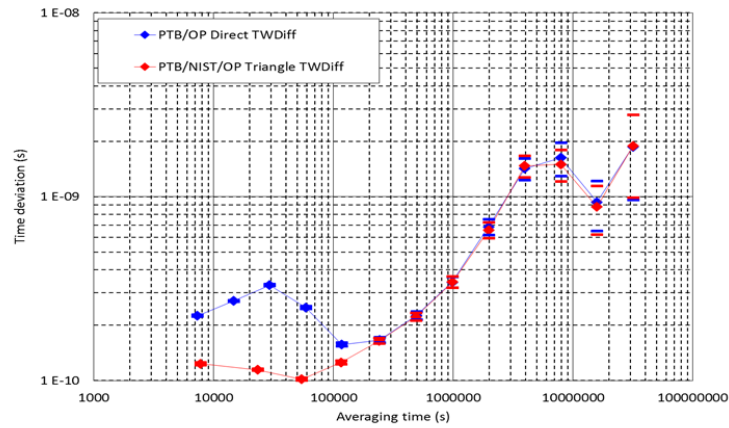


Figure 3.3.1 Tdevs of the direct (blue) and indirect (red) links for the baseline between OP and PTB, based on 3-year data, Zhang *et al.* [3]

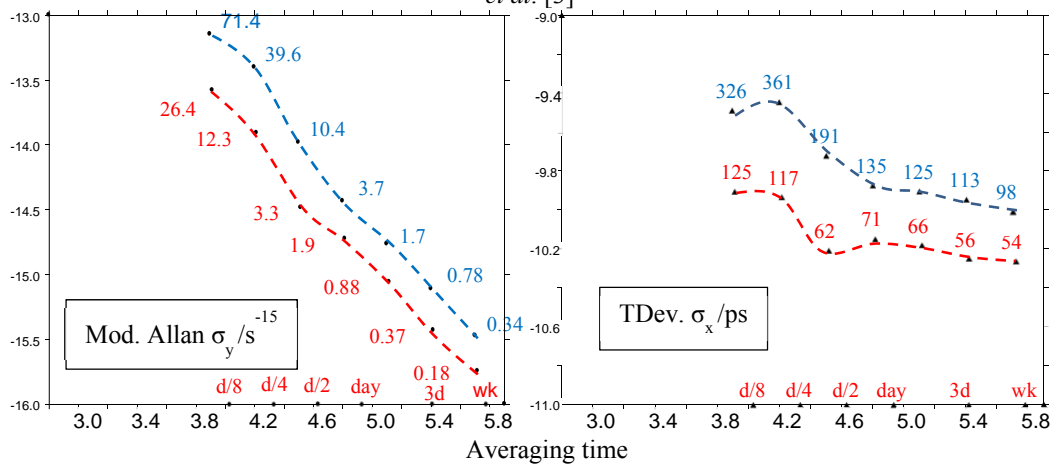


Figure 3.3.2 The Modified Allan Deviation and Time deviation of the OP – PTB direct (blue) and indirect (red) links for the baseline between OP and PTB based on the one-month data set 1602 (shown in Figure 2.3.1a). The values of the Modified Allan Deviation (in 1×10^{-15}) and the Time deviation (in ps) are shown in the plots together with the corresponding averaging times (in s).

Figure 3.3.2 shows the Modified Allan Deviation and Time deviation of the direct and indirect links for the baseline between OP and PTB based on the one-month data set 1602. (see Figure 2.3.1a). We reached the same conclusion as for the 3-year data set above.

Tables 3.3.1a and 3.3.1b are based on the same data sets 1602 for the baselines between CH and PTB and between OP and PTB. Here the gains on each averaging time of 2, 4, 6, 8, 16 and 32 hours are given. As shown in the table, the gains on the baseline between CH and PTB are correspondingly 55 % and 39 % for the indirect links via NIST and USNO. For the baseline between OP and PTB, the gains are 58 % and 60 % for the indirect link via NIST and USNO. On average, the gains are respectively 57 % for NIST and 50 % for USNO. The gain via NIST is observed to be slightly larger than that for the USNO.

Table 3.3.1a Gain in Tdev of the TW direct link (**CH – PTB**) versus the indirect links via NIST or USNO

Averaging Time	Direct $\pm \sigma$ /ns	Indirect $\pm \sigma_{X_n}$ via NIST/ns	Indirect $\pm \sigma_{X_u}$ via USNO/ns	Gain = $(\sigma - \sigma_{X_n})/\sigma$ via NIST %	Gain = $(\sigma - \sigma_{X_u})/\sigma$ via USNO %
2 hours	0.39	0.14	0.21	64 %	46 %
4 hours	0.34	0.13	0.14	62 %	59 %
8 hours	0.52	0.09	0.11	83 %	79 %
16 hours	0.23	0.11	0.14	52 %	39 %
32 hours	0.21	0.18	0.21	14 %	0 %
Mean				55 %	39 %

Table 3.3.1b Gain in Tdev of the TW direct link (**OP – PTB**) versus the indirect links via NIST or USNO

Averaging Time	Direct $\pm \sigma$ /ns	Indirect $\pm \sigma_{X_n}$ via NIST/ns	Indirect $\pm \sigma_{X_u}$ Via USNO/ns	Gain = $(\sigma - \sigma_{X_n})/\sigma$ via NIST %	Gain = $(\sigma - \sigma_{X_u})/\sigma$ via USNO %
2 hours	0.326	0.125	0.120	62 %	63 %
4 hours	0.361	0.117	0.110	68 %	70 %
8 hours	0.191	0.062	0.060	68 %	69 %
16 hours	0.135	0.071	0.070	47 %	48 %
32 hours	0.125	0.066	0.060	47 %	52 %
Mean				58 %	60 %

3.4 Comparison to SDR

The Software-Defined Radio (SDR) Receiver for TWSTFT is a newly developed technique, characterized by a significant reduction in the diurnal and the measurement noise in some of the Asia-Asia and Europe-Europe direct TW links. The first is the major error source in TWSTFT. Compared to the results using SATRE modem, the SDR can TW improve the stability of the TW transfer by a factor two or three for some of the inner-European and inner-Asian links. Detailed information can be found in [5,6,7]. In this section, we use the SDR TW as a precise reference to evaluate the improvement in the indirect link with respect to the direct link for the baseline between OP and PTB.

In this section, we make a detailed discussion on a longer period of data set of 100 days.

Figure 3.4.1 shows the comparison of the direct and indirect (via NIST) links over the baseline between OP and PTB. Here the time transfer results are obtained separately from the SATRE modem and the SDR measurements. As can be seen, with both the SATRE modem and the SDR results, the indirect links are more precise than the direct links. For example, between the MJD 57710 and 57730, the SDR direct link result (blue/top) is disturbed, even though it is much more stable than the SATRE direct link result (red/below). The noises and the diurnal are stronger than in the earlier period. These disturbances disappear completely in the indirect links when using both the SATRE modem (violet/below) and the SDR (green/top).

Figure 3.4.2 is the comparison of the Time deviations of the direct and indirect (via NIST) links for the baseline between OP and PTB. The Tdevs are computed from the data collected during MJD 57645 and MJD 57745 with the SATRE and SDR measurements. In the order of the stability from the most stable to the most instable, we have the SDR indirect (green), the SATRE indirect, the SDR direct and the SATRE direct. It is interesting and important to notice that the indirect link SATRE link is more stable than the SDR direct link and that the performance of SDR direct link can be improved further with the corresponding indirect link.

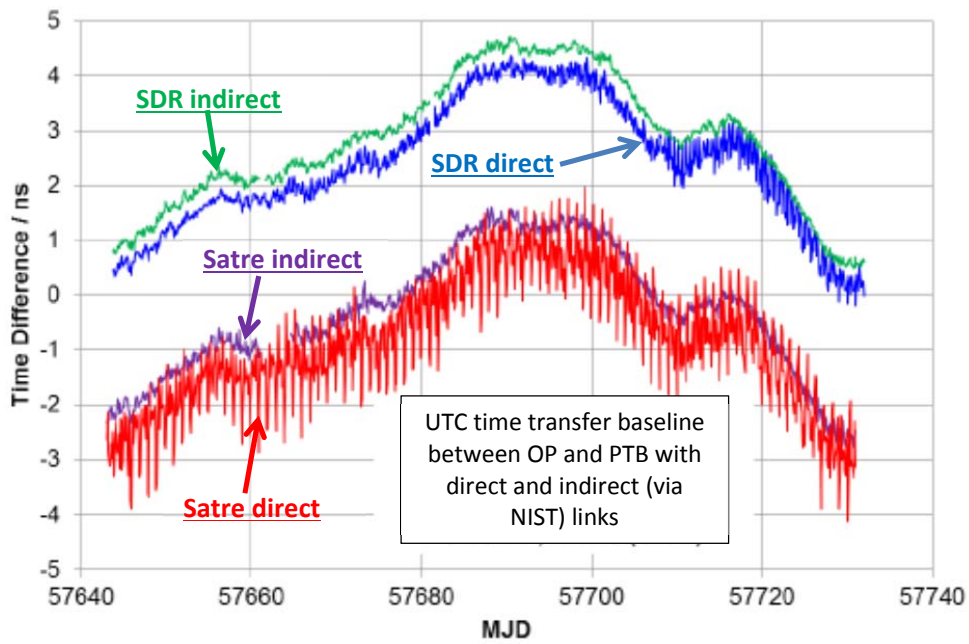


Figure 3.4.1 Comparisons of the direct and indirect links over the baseline between OP and PTB. The time transfer results are obtained separately from the SATRE modem and the SDR measurements. The SDR curves are shifted upwards to better illustrate the difference.

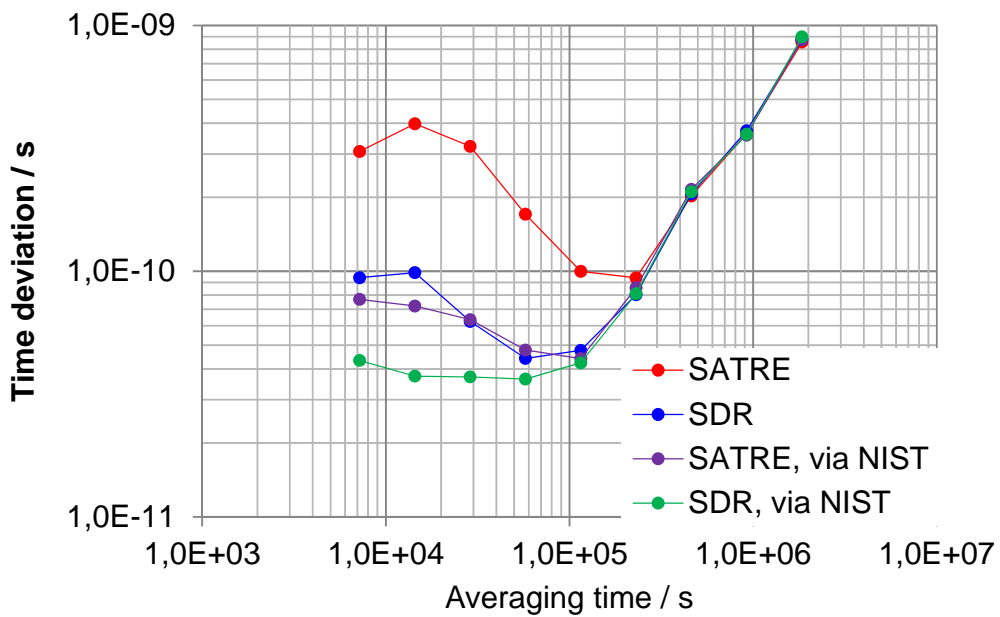


Figure 3.4.2 Comparison of the Time deviations of direct and indirect links for the baseline between OP and PTB. The Tdevs are computed from the data collected during MJD 57645 and MJD 57745 with the SATRE and SDR measurements

Table 3.4.1 Gain in Tdev of the TW direct link (OP-PTB) vs. the indirect links via NIST of SATRE and SDR

Average time	Indirect $\pm \sigma_{Xn}$ SATRE/ns	Direct $\pm \sigma$ SDR/ns	Indirect $\pm \sigma_{Xn}$ SDR/ns	Gain = $(\sigma - \sigma_{Xn})/\sigma$ = [(2) - (3)]/(3) /%	Gain = $(\sigma - \sigma_{Xn})/\sigma$ = [(4) - (3)]/(3) /%
(1)	(2)	(3)	(4)	(5) %	(6)
2 hours	0.077	0.094	0.043	18.1 %	54.2 %
4 hours	0.072	0.099	0.037	27.2 %	62.6 %
8 hours	0.064	0.063	0.037	0.0 %	41.2 %
16 hours	0.048	0.044	0.036	-9.1 %	18.2 %
32 hours	0.044	0.048	0.042	8.3 %	12.5 %
Mean				8.9 %	40.2 %

Table 3.4.1 gives the gains in Tdev of the TW direct link (OP-PTB) vs. the indirect links via NIST using SATRE and SDR for different averaging times of 2, 4, 6, 8, 16 and 32 hours, as shown in the column (1). Columns (2), (3) and (4) are correspondingly the Tdev on different averaging time for the indirect SATRE, direct SDR and indirect SDR. As given in the Figure 3.4.2, the indirect SATRE link (2) is more stable than the SDR direct link (3) with a gain of 8.9 % on average. The most stable is the indirect SDR link with a gain of 40.2 % on average vs. the direct SDR link.

3.5 Triangle closure analysis

Triangle closure is not completely independent from the DCD of the direct and indirect links. It gives however the gains in SDR from another point of view.

Figure 3.5.1 shows the comparisons of triangle closures composed of the direct and indirect links (double clock differences between SDR and SATRE measurements) over the triangle of OP-NIST-PTB, where the triangle closure of the direct links is computed with $(PTB - OP)_{SDR} - (PTB - OP)_{SATRE}$ and the triangle closure of the indirect links is computed with $(PTB - OP)_{SDR}^{NIST} - (PTB - OP)_{SATRE}^{NIST}$. The indirect curve is shifted up by 2.5 ns to better show the difference between them. The scatter of the direct link triangle difference is up to 2 ns, while that of the indirect link is about 0.3 ns.

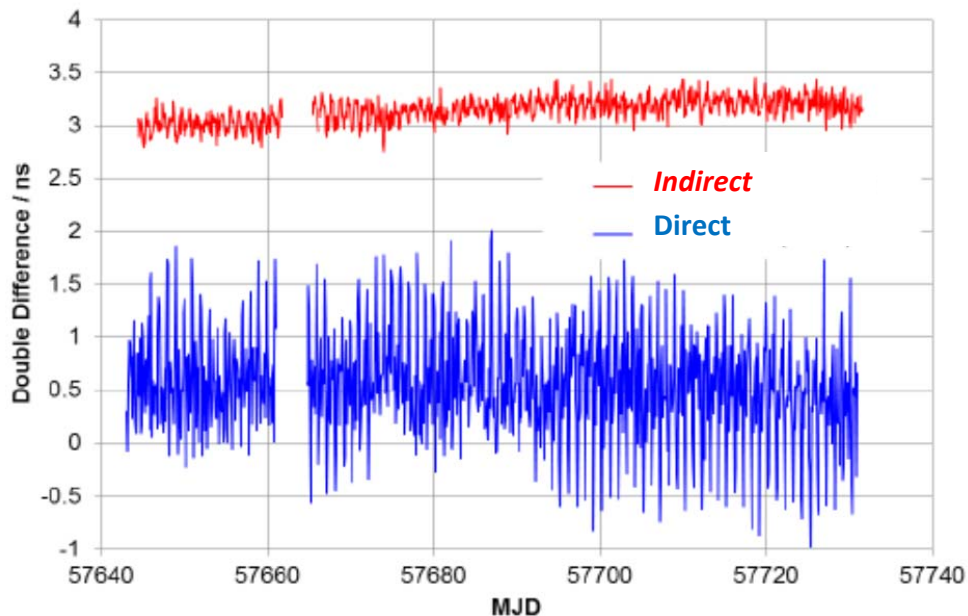


Figure 3.5.1 Comparisons of triangle closures comprising the direct and indirect links over the triangle OP_NIST_PT B. The indirect curve is shifted upwards to better illustrate the two differences

4. CONCLUSION

Conventionally, we consider that a direct measurement is always better than an indirect measurement, because there is one more uncertainty source(s) in the latter. This is true when the uncertainty of the measurands is of normal distribution. When a dominant instability is more important than the measurement noise, such as the diurnal, a well-designed measurement schedule to cancel the bias is helpful to reduce the total uncertainty, even if it appears that geometrically, the time transfer signals detour much more indirectly. The inner-European indirect link via the USA is such a case, and it has been proven by different authors using different methods.

The diurnal, which is the major and the dominant error source in the precise TW links, can be reduced by a factor of two or three times in the indirect Europe-Europe links via transatlantic links to NIST and USNO. Its calibration however will be kept the same as the direct links. The indirect SATRE link is more stable than the corresponding SDR direct link, of which the stability can be furtherly improved by its indirect link.

However, not all laboratories can serve as an intermediate laboratory to compose an indirect link, which can gain with respect to the direct link. In the Europe-Europe case, using SP as the intermediate laboratory, all the indirect links showed a worse uncertainty. We observed that both the diurnal and instability increased.

The indirect link may be considered for the UTC TW time transfer computation. No hardware investment is needed for the TW indirect time transfers. No extra operational procedure or additional measurements are required; just a minor change to the routes of the signal propagation by composing an indirect link with the ‘right’ relaying laboratory. This new function has been updated in the BIPM UTC/TAI computation software package, Tsoft.

[†]**Disclaimer:** Commercial products are identified for technical completeness only, and no endorsement is implied. This Paper includes contributions from the U.S. Government and is not subject to copyright.

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