A Study on Reducing the Diurnal in the Europe-to-Europe TWSTFT Links

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Abstract—Most of the Two-Way Satellite Time and Frequency Transfer (TWSTFT or TW) links exhibit a daily variation (diurnal) on the order of 1 ns in the differences. The stability of TW is degraded by the diurnal. Many studies on the sources of diurnal have been carried out, but no dominating cause of the diurnal has been found.

In this study, we examine the diurnal in several Europe-to-Europe TW links and report that the diurnal and the short-term transfer noise can be reduced by using the triangle difference of the transatlantic TW. We will also analyze where the improvement comes from.

Keywords—Two-Way Satellite Time and Frequency Transfer (TWSTFT or TW), time and frequency transfer stability, TW diurnal, triangle TW difference, Triangle Closure Calibration

I. INTRODUCTION

Two-Way Satellite Time and Frequency Transfer (TWSTFT or TW) is used by many international timing laboratories to compare their clocks and to contribute their timescale data to the generation of International Atomic Time (TAI) and Coordinated Universal Time (UTC). Currently, 15 European timing laboratories participate in the Europe-to-Europe Two-Way Satellite Time and Frequency Transfer (TW hereafter) network. These European timing laboratories also participate in the transatlantic TW network with two timing laboratories in the U.S. The Europe-to-Europe and transatlantic TW networks use three Ku-band transponders on a geostationary satellite. One transponder with 1.7 MHz bandwidth is used by the Europe-to-Europe TW. The other two transponders, each with 1.6 MHz bandwidth, are used for the transatlantic TW. The TW measurements between each pair of timing laboratories are made during a two-minute interval of a scheduled time slot in every even UTC hour. The timing information is carried by the 1 MChip/s pseudo-random noise (PRN) codes. Among all of the TW links, the TW links to the Physikalisch-Technische Bundesanstalt (PTB) in Germany are referred to as UTC links because these TW data are used by the International Bureau of Weights and Measures (BIPM) in the generation of TAI and UTC.

In recent years, various successful TW link calibrations using a TW mobile station reported a calibration uncertainty of 1 ns. However, most of the TW links exhibit a daily variation (diurnal) on the order of 1 ns in the TW differences. The diurnal degrades the stability of TW links and therefore increases the combined uncertainty of TW links. It can also increase the TW link calibration uncertainty when a TW mobile station is used to calibrate a TW link and when the calibration measurements are made in less than one day.

There have been several studies searching for the origin or origins of the diurnal in the TW differences. These studies have investigated environmental effects in the TW indoor and outdoor equipment, the daily propagation delay variation due to the ionospheric delay change, the impact of satellite motion on the signal time of arrival, the Sagnac and the Doppler effects on the TW measurements [1-3]. Nevertheless, none of these studies found the dominant cause of the diurnal. A recent study [4] showed the diurnal in the Asian-Pacific region TW links was minimized by using a software defined receiver (SDR) technique. A pilot study on using the SDR technique will be launched this year to verify if the technique can also minimize the diurnal for the Asia-to-Europe, Europe-to-Europe, and transatlantic TW links.

In this paper, we present our analysis on reducing the diurnal in the Europe-to-Europe TW links with the transatlantic triangle TW differences. In Section II, we examine the diurnal in TW difference for five Europe-to-Europe links and report that the diurnal and the short-term transfer noise can be reduced by using the triangle difference of the transatlantic TW differences. We will analyze where the improvement comes from in Section III and conclude the study in Section IV.

II. USING TRANSATLANTIC TRIANGLE TW DIFFERENCES FOR THE EUROPE-TO EUROPE TW

In our study, we examine the diurnal in five Europe-to-Europe TW UTC links for the data period from January 1, 2013 to December 31, 2015 (MJDs 56293 to 57387). The five UTC links are listed in Table I. The magnitude of the diurnal in these links varies from link to link and from time to time. Fig. 1 shows an example of the five links' direct TW difference over a 5-day period. On average, the peak-to-peak diurnal of the Europe-to-Europe direct TW links is about 1 ns.

TABLE I. FIVE EUROPE-TO-EUROPE TW UTC LINKS

Pivot station	Remote station
PTB	Federal Institute of Metrology (METAS), Bern-Wabern, Switzerland (CH)
PTB	Istituto Nazionale di Ricerca Metrologica (INRIM), Torino, Italy (IT)
PTB	Laboratoire national de métrologie et d'essais – Systèmes de références space-temps, Observatoire de Paris (LNE-SYRTE), Paris, France (OP)
PTB	Real Instituto y Observatorio de la Armada, San Fernando, Spain (ROA)
PTB	Sveriges Provnings-och Forskningsinstitut (Swedish National Testing and Research Institute), Borås, Sweden (SP)

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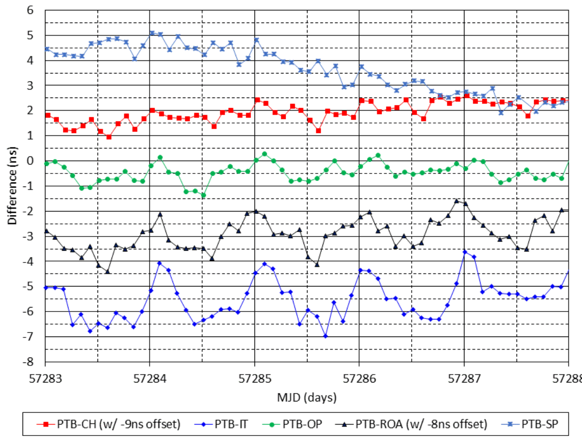

Fig. 1. Example of the direct Europe-to-Europe TW differences. The differences are offset for illustration purpose.

The transatlantic TW differences between the six European stations and the National Institute of Standards and Technology (NIST) are used to compute the triangle differences for the Europe-to-Europe TW links. For example, the triangle difference for the (PTB – OP) link is computed with the transatlantic TW differences of (NIST – OP) – (NIST – PTB). Because the two transatlantic TW measurements are made at different times during the even UTC hours, we use the Time Deviation (TDev) to verify if the triangle difference with a matching approach introduces error or noise compared to that of an interpolation approach. In the matching approach, we treat the two transatlantic TW differences of the same hour as if they were made at the same epoch. In the interpolation approach, the two transatlantic TW differences are interpolated to the beginning of the hour. Fig. 2 shows the comparison for the (PTB – OP) link via the transatlantic TW with NIST. For averaging times less than eight hours, the TDevs for the matching approach are a little higher than that of the interpolation approach. The improvement of the interpolation approach is due to the average between the two adjacent data points. With this result, we will use the matching approach for computing the transatlantic triangle TW differences, because it is simpler.

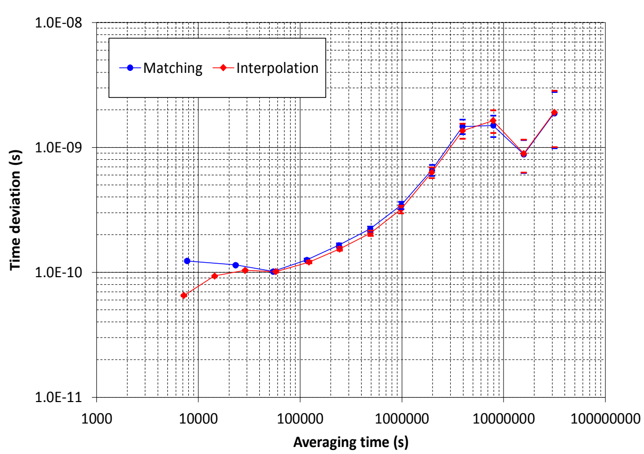

Fig. 2. Time deviations of triangle differences of the (PTB – OP) link using the transatlantic TW with NIST.

The spectral analysis of the diurnal (day component) and other components in the direct and triangle TW differences for the (PTB – OP) link are shown in Fig. 3. The results are obtained from the Fast Fourier Transform (FFT). The diurnal in the triangle difference is noticeably reduced. The other components are also reduced, except for the half-day component (pattern occurs twice a day) which is slightly increased. We use the diurnal component of the direct TW differences as the reference and divide it by the diurnal component of the triangle difference to obtain the diurnal reduction factor. Table II shows the results for the five Europe-to-Europe UTC TW links. The results show that the transatlantic triangle TW difference indeed reduces diurnals in the Europe-to-Europe direct TW difference for all of the five links studied. The diurnal in the triangle difference is at least 2.7 times smaller than that in the direct difference. To check if the diurnal reduction is transatlantic link dependent, we computed the transatlantic TW differences among the U.S. Naval Observatory (USNO), PTB and CH. The FFT result of triangle difference of (USNO – CH) – (USNO – PTB) also shows the diurnal of the triangle difference is 7.1 times smaller than that of the direct (PTB – CH) difference. A 5-day TW difference plot for the (PTB – CH) link is shown in Fig. 4, which shows that both of the transatlantic links with NIST and USNO reduce the diurnal.

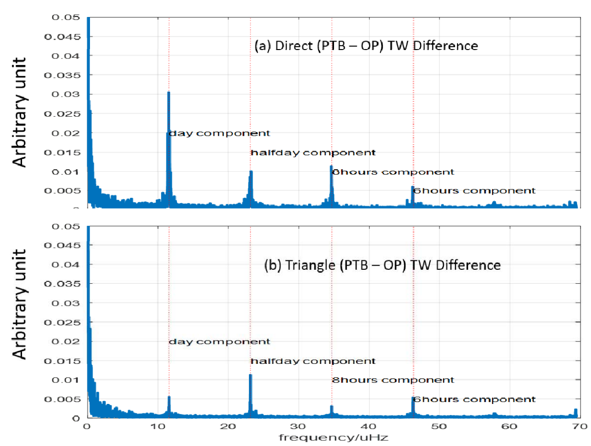

Fig. 3. Spectral analysis of diurnal and other components in (PTB – OP) TW difference. The components of the TW differences are presented with an arbitrary unit because we are only interested in the comparison of the diurnal reduction of the triangle difference relative to the direct difference.

TABLE II. DIURNAL REDUCTION USING THE TRANSATLANTIC TRIANGLE DIFFERENCES.

Link	PTB-CH	PTB-IT	PTB-OP	PTB-ROA	PTB-SP
Diurnal Reduction	11.0	2.7	5.5	3.4	3.0

Figures 5 to 9 show the TDev of the direct and triangle differences for the five links. The diurnal in each of the five links is reduced by using the triangle difference approach. As shown in Fig. 5, both of the (USNO – CH) – (USNO – PTB) and the (NIST – CH) – (NIST – PTB) triangle differences reduce the diurnal and the TW transfer noise for averaging times less than eight hours, but the transatlantic TW differences via USNO contain higher TW transfer noise. The TDevs at averaging times around 12 hours are shown in Table III for a quick overview.

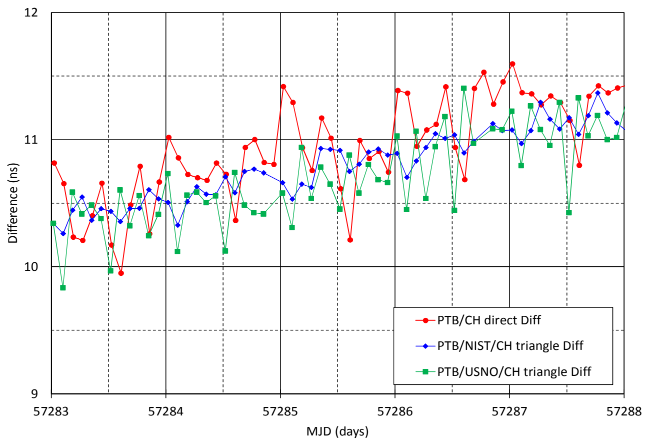

Fig. 4. (PTB – CH) direct and triangle TW differences.

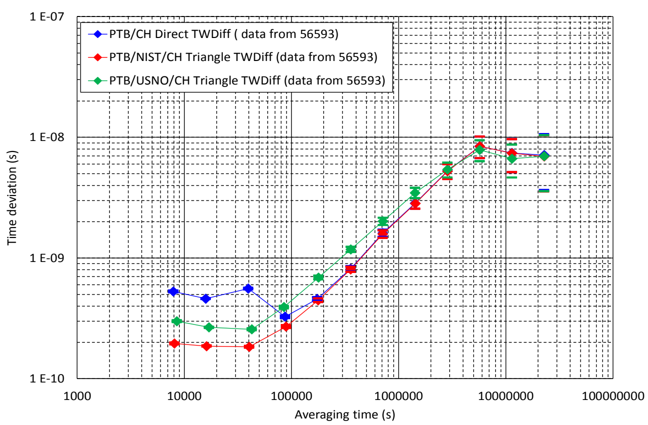

Fig. 5. Time deviations of the (PTB – CH) TW differences.

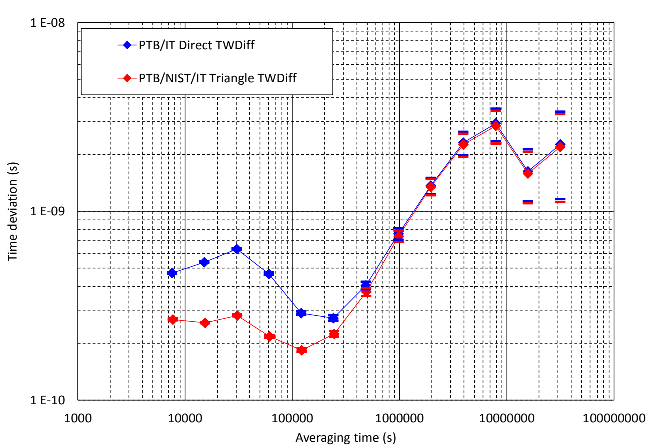

Fig. 6. Time deviations of the (PTB – IT) TW differences.

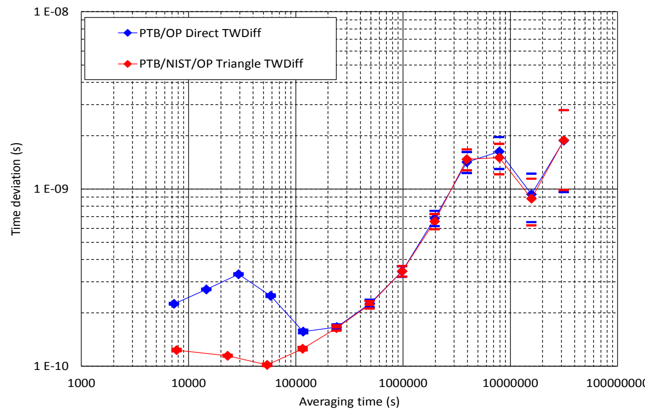

Fig. 7. Time deviations of the (PTB – OP) TW differences.

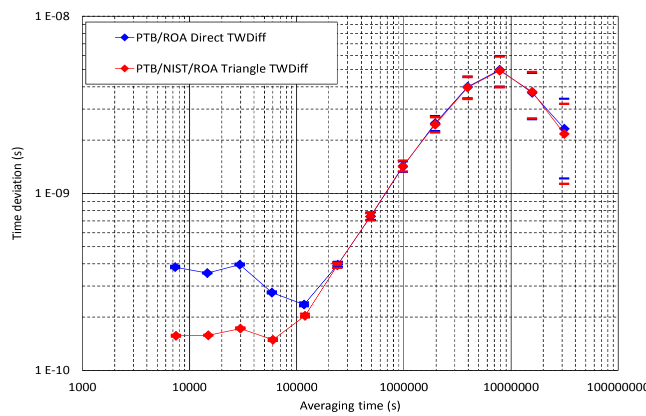

Fig. 8. Time deviations of the (PTB – ROA) TW differences.

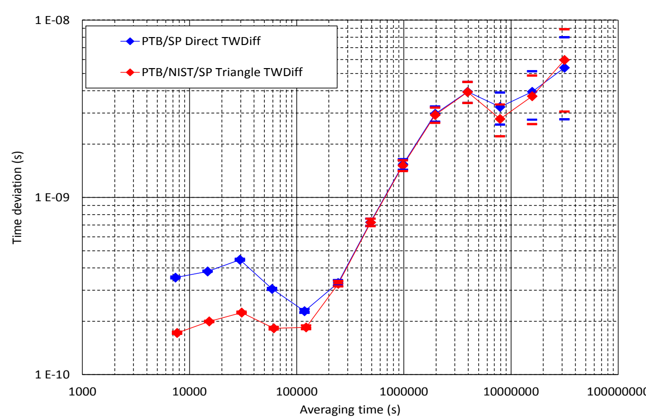

Fig. 9. Time deviations of the (PTB – SP) TW differences.

TABLE III. TIME DEVIATIONS FOR AVERAGING TIME AROUND 12 HOURS.

Link	PTB-CH	PTB-IT	PTB-OP	PTB-ROA	PTB-SP
TDev of Direct difference (ns)	0.557	0.631	0.331	0.395	0.445
TDev of Triangle difference (ns)	0.184	0.281	0.102	0.172	0.224

III. SOURCES OF DIURNAL IN THE EUROPE-TO-EUROPE TW LINKS

Section II shows that the diurnal in the Europe-to-Europe TW links is reduced by using the transatlantic triangle TW differences. Although the triangle difference results do not directly show the source of the diurnals in the Europe-to-Europe TW links, they do strongly suggest some possible causes and also some things that are not causes.

One can visualize the situation by dividing the link geometry into two parts. One is the part east of the satellite (i.e. Europe) and the other part is west of the satellite (i.e. North America) as shown in Fig. 10. In the direct Europe-to-Europe links only the area east of the satellite is relevant. In the triangle links the geometry in the east is identical to that of the Europe-to-Europe links, but now the western area is added. However, the geometry of the western area will be essentially identical for the two European stations in the triangle links. The only reason the two parts are not identical for the direct and triangle links is that the up and down link frequencies are not exactly the same and the times at which the TW sessions take place are not identical. The uplink carrier frequencies differ by only 1.7 % at most, while the downlink carrier frequencies differ by a maximum of 7.1 %. The average times between direct and triangle links range from about 3 to 38 minutes. The times between the sessions of the two relevant station pairs at the NIST end range from 3 to 21 minutes. None of these factors should make a significant contribution to the diurnals.

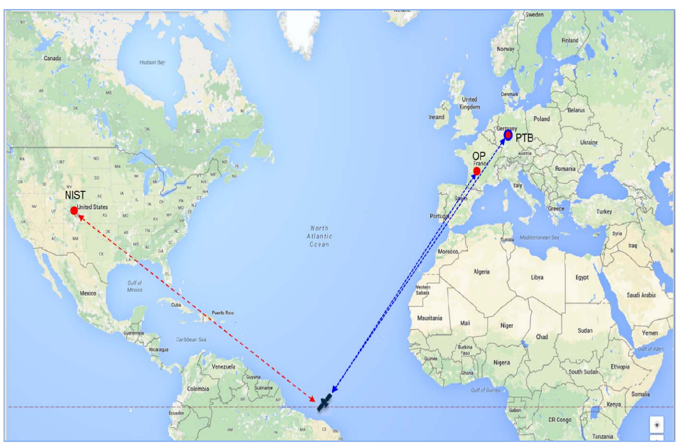

Fig. 10. The geometry example of the Europe-to-Europe and transatlantic TW links among NIST, OP and PTB.

Because the eastern geometry and station equipment are virtually identical for the direct and triangle links, the sources of the diurnal due to environment (temperature and humidity), modems, ionosphere, and satellite motion (Sagnac, Doppler and time of arrival) must also be nearly identical and therefore small. Of course, in the triangle links there is the addition of the western part where all the same issues come into play. However, these contributors will nearly cancel because both European stations will see virtually the same contributors. Taking these conditions into account, the only major differences between the direct and triangle links are the transponders (hardware and traffic) on the satellite. The only caveats are the small differences in carrier frequencies and session times. For the direct Europe-to-Europe links, the same transponder is used for both directions. For the transatlantic links, two transponders are used, one for the east to west direction and one for the west to east direction. Thus it appears that something related to the transponder for Europe is a dominant source of the diurnal in the direct Europe-to-Europe links. Since the two station to station signals pass through the same transponder at virtually the same time it is unlikely that a transponder hardware issue such as a temperature coefficient could cause the diurnal. About the only possibility remaining is some code dependent in-band or out-of-band interference issue.

The Europe-to-Europe links are crowded. Up to five links are making TW measurements at the same time. In addition, there are strong signals on both sides of the TW frequency band. On the other hand, there are only up to two transatlantic TW measurements at the same time and there is only one neighboring signal next to the Europe-to-US TW signal. In general, the diurnal in the transatlantic links is smaller than that of the Europe-to-Europe links. Thus, we suspect that in-band and/or out-of-band interference are major contributors to the diurnal in the Europe-to-Europe TW.

IV. CONCLUSIONS

Our study has shown that the diurnal in the Europe-to-Europe TW can be reduced analytically with the transatlantic triangle differences. The triangle difference approach cuts down the diurnal component in the direct Europe-to-Europe TW differences by a minimum of 2.7 times. Compared to that of the direct TW difference, the TDev of the triangle differences is decreased by more than 200 ps for averaging times less than 12 hours. It is not clear what the rationale is behind the diurnal reduction using the triangle difference, although we think the in-band and out-of-band interferences are major contributors of the diurnal in the Europe-to-Europe TW.

If the non-UTC transatlantic TW links are calibrated with the Triangle Closure Calibration described in the newly approved TW calibration guidelines [5], the transatlantic triangle TW links can be used as the Europe-to-Europe TW UTC links with improved link uncertainty in the TAI and UTC computation.

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