A Study on Using SDR Receivers for the Europe-Europe and Transatlantic TWSTFT Links

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ABSTRACT

The International Bureau of Weights and Measures and the Consultative Committee for Time and Frequency Working Group on Two-Way Satellite Time and Frequency Transfer (TWSTFT) have stimulated a pilot study on using software defined radio (SDR) receivers for TWSTFT in the framework of the realization of Coordinated Universal Time. The SDR receivers based on a software developed by TL have been set up at PTB, OP and NIST during the summer and fall of 2016. Continuous SDR TWSTFT measurements have been established for the OP/PTB, NIST/OP and NIST/PTB links. From the SDR TWSTFT clock comparison results (TWSTFT difference), we observed that the commonly present but undesired diurnal pattern in the OP/PTB SDR TWSTFT difference is greatly reduced compared to the diurnal pattern in the difference obtained from the regular (non-SDR) TWSTFT equipment. However, the diurnal reduction in the NIST/OP and NIST/PTB SDR TWSTFT differences is not as significant as in the OP/PTB link. This is a strong indication that the application of SDR receivers has the ability to significantly improve the stability of some TWSTFT links, but is not a solution for all links. In this paper, we will analyze the diurnal reduction using the SDR receivers for the three links and study the dominant causes for the diurnal effect in the Europe-Europe and transatlantic TWSTFT links.

Key words: TWSTFT, Software Defined Radio, SDR, time transfer, diurnal, instability.

I. INTRODUCTION

Two-Way Satellite Time and Frequency Transfer (TWSTFT) is one of the precise time and frequency transfer techniques used in comparisons of remote clocks and in the generation of Coordinated Universal Time (UTC). Its stability is reduced by a daily variation pattern (diurnal) as observed in the TWSTFT clock comparison results (refer to as TWSTFT differences hereafter). The diurnal exists in most of the Asia-Asia, Asia-Europe, Europe-Europe and Europe-US (transatlantic) TWSTFT links. The magnitude of the diurnal in TWSTFT differences varies from 0.5 ns to almost 2 ns, peak-to-peak, for different links and at different times. Several studies have investigated the origins of the diurnal [1-5]. The studies showed that some of the diurnal contributors, such as the ionospheric delay variation and the time of arrival variation due to the Sagnac effect that have a solar day periodicity, were not the dominant cause of the diurnal. There were also other studies and developments aimed at the reduction of diurnal in some TWSTFT links [6-8].

With the software defined radio (SDR) receiver system developed by the National Standard Time and Frequency Laboratory, Telecommunication Laboratories (TL), the diurnal in several TWSTFT links in the Asia-Pacific region [7] [9] was significantly reduced. Based on these results, the International Bureau of Weights and Measures (BIPM) and the Consultative Committee for Time and Frequency (CCTF) Working Group on TWSTFT stimulated a pilot study on using the SDR technology for TWSTFT in February, 2016 [10]. Under the framework of the realization of UTC, the pilot study is to investigate the impact of using SDR for the TWSTFT links in other regions, such as Asia-Europe, Europe-Europe, and Europe-US. Eighteen TWSTFT timing laboratories that contribute to UTC expressed their interest to participate in the pilot study. Nine laboratories, including the National Institute of Standards and Technology (NIST), the LNE-SYRTE/Observatoire de Paris (OP), and the Physikalisch-Technische Bundesanstalt (PTB), have installed the SDR receiver system in the summer and fall of 2016. The SDR TWSTFT measurements have been continuously made for more than three months at NIST, OP and PTB.

In this paper, we study the SDR TWSTFT differences for the OP/PTB, NIST/OP and NIST/PTB links. Section II contains a brief description of the three links, the SDR system setups and the TWSTFT measurements used in study. We present our analysis of the SDR TWSTFT results in Section III and conclude the study in Section IV.

II. DESCRIPTIONS OF THE TWSTFT LINKS AND THE SDR MEASUREMENTS

The TelStar 11N (T-11N) satellite† is used by both of the Europe-Europe (including OP/PTB) and transatlantic (including NIST/OP and NIST/PTB) TWSTFT. The Europe-Europe TWSTFT uses 1.7 MHz bandwidth on a Ku-band transponder of the T-11N satellite. The transatlantic TWSTFT uses 1.6 MHz bandwidth on each of the two Ku-band transponders of the T-11N satellite, one for the east-west direction and one for the west-east direction. The OP/PTB, NIST/OP and NIST/PTB links are illustrated in Fig. 1.

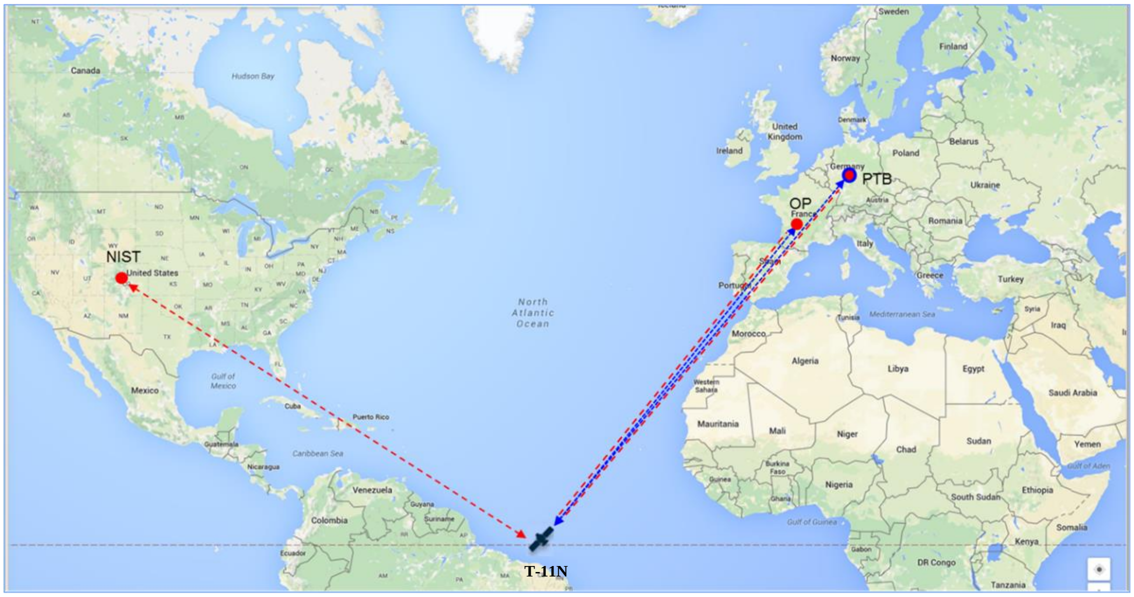

Fig. 1 The OP/PTB, NIST/OP and NIST/PTB TWSTFT links. The blue dash lines indicate the Europe-Europe link. The red dash lines show the transatlantic links.

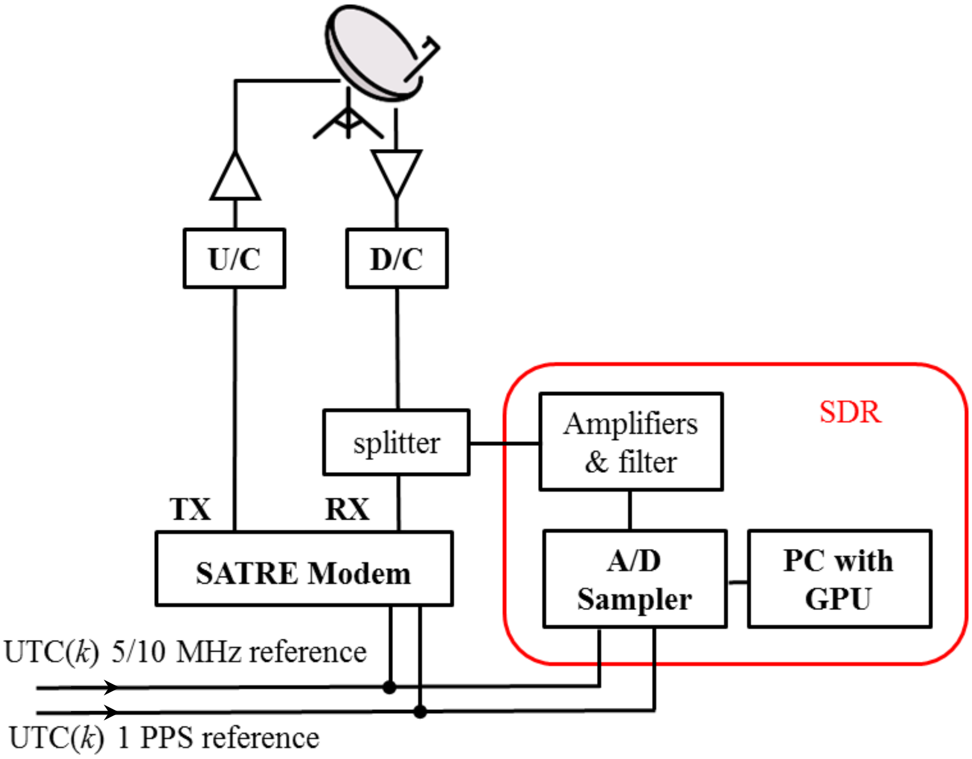

Fig. 2 Block diagram of generic SDR measurement set up at NIST, OP and PTB.

The Europe-Europe and transatlantic TWSTFT use the 1 MChip/s pseudo-random noise (PRN) codes generated by SATRE† modems. The measurements are scheduled in every even UTC hour, 12 times a day. About 15 European timing laboratories participate in the regular Europe-Europe TWSTFT. Most of these laboratories also participate in the transatlantic TWSTFT. The measurements between each pair of the remote earth stations are made in a 2-minute session with a 1-minute locking period before the measurements. During the 2-minute session, the measurements are made every second. The 120 one-second measurements are saved and reduced to a single data point according to the International Telecommunication Union Radiocommunication Sector (ITU-R) recommendation [11]. The ITU format data files are shared among the participants and reported to the BIPM for UTC computation.

The SDR receiver system is used to receive the TWSTFT coded signals generated by SATRE modems. The key components of the SDR consist of an analog to digital (A/D) sampler for making the TWSTFT measurements, a graphic processing unit (GPU) card installed in a computer for processing the TWSTFT measurements with dedicated software developed by TL. In addition, one or two amplifiers and a bandpass filter are used to optimize the input signal to the A/D sampler. The received TWSTFT 1 MChip/s PRN signal at the 70 MHz intermediate frequency (IF) are fed to both the SATRE modem and the SDR receiver. A generic SDR measurement setup is depicted in Fig. 2. With the GPU card and the computer used by NIST, OP and PTB, the SDR receiver is capable of simultaneously processing the one-second measurements of six PRN codes. The one-second SDR measurements are saved and converted to the ITU format data for every two minutes. This results in denser data with respect to the operational SATRE data, which are limited by switching a single receiving channel between up to 16 stations during each measurement hour. During the even hours, OP and PTB transmit signals (generated by SATRE modems) for either the Europe-Europe or the transatlantic TWSTFT while NIST only transmits signal (generated by SATRE modem) for transatlantic TWSTFT according to the Europe-Europe and transatlantic TWSTFT schedule. Table 1 shows the availability of NIST, OP and PTB TWSTFT signals on the Europe-Europe and transatlantic transponders during even UTC hours.

Therefore, the SDR TWSTFT can have up to seventeen 2-minute OP/PTB measurement sessions and three 2-minute measurement sessions for each of the NIST/OP and NIST/PTB links in every even UTC hour. On the other hand, there is only one 2-minute session for each of the OP/PTB, NIST/OP and NIST/PTB links from SATRE measurements.

Table 1. TWSTFT signals availability on T-11N transponders during even UTC hours

Time in UTC even hour (eh)	Signals available for Europe-Europe TWSTFT	Signal available for transatlantic TWSTFT
eh:07:00 – eh:28:59	OP, PTB	
eh:33:00 – eh:38:59		NIST, OP
eh:39:00 – eh:44:59	OP, PTB	
eh:45:00 – eh:50:59		NIST, PTB
eh:51:00 – eh:56:59	OP, PTB	

III. IMPACT OF SDR TWSTFT ON THE OP/PTB, NIST/OP AND NIST/PTB LINKS

In this section, we analyze the SDR measurements during Modified Julian Dates (MJDs) 57643 to 57742 (September 12, 2016 – December 20, 2016) for the OP/PTB, NIST/OP and NIST/PTB links. During the 100-day period, there were no changes in the OP and PTB SDR systems. However, the NIST SDR measurements were affected by two events. During MJDs 57718 to 57722, the cooling for the TWSTFT room failed and that resulted in the changes of the timing for the NIST SATRE transmit signal (reference delay) and a delay variation in the SDR bandpass filter. On MJD 57734, the bandpass filter was replaced and the signal power level to SDR system was adjusted that resulted in time steps in the NIST SDR measurements. The NIST SDR measurements during these events were corrected for the analysis. Because the SDR systems at NIST, OP and PTB are not calibrated, we remove a constant from the SDR difference on MJD 57643 to align it with the SATRE difference for each of the three links.

Figures 3 to 5 show a 10-day segment of the TWSTFT differences with the ITU format data for the three links. In these figures, we present the SDR differences for each of the 2-minute SDR measurements (up to 17 points for the OP/PTB link and three points for the transatlantic links in one hour), for the hourly averages and for the measurements taken at the same time as the SATRE measurements. The differences from the SATRE measurements are included for a comparison. For the OP/PTB link, the diurnal in the SDR differences is significantly reduced. However, the NIST/OP and NIST/PTB SDR differences show no obvious improvement in the diurnal.

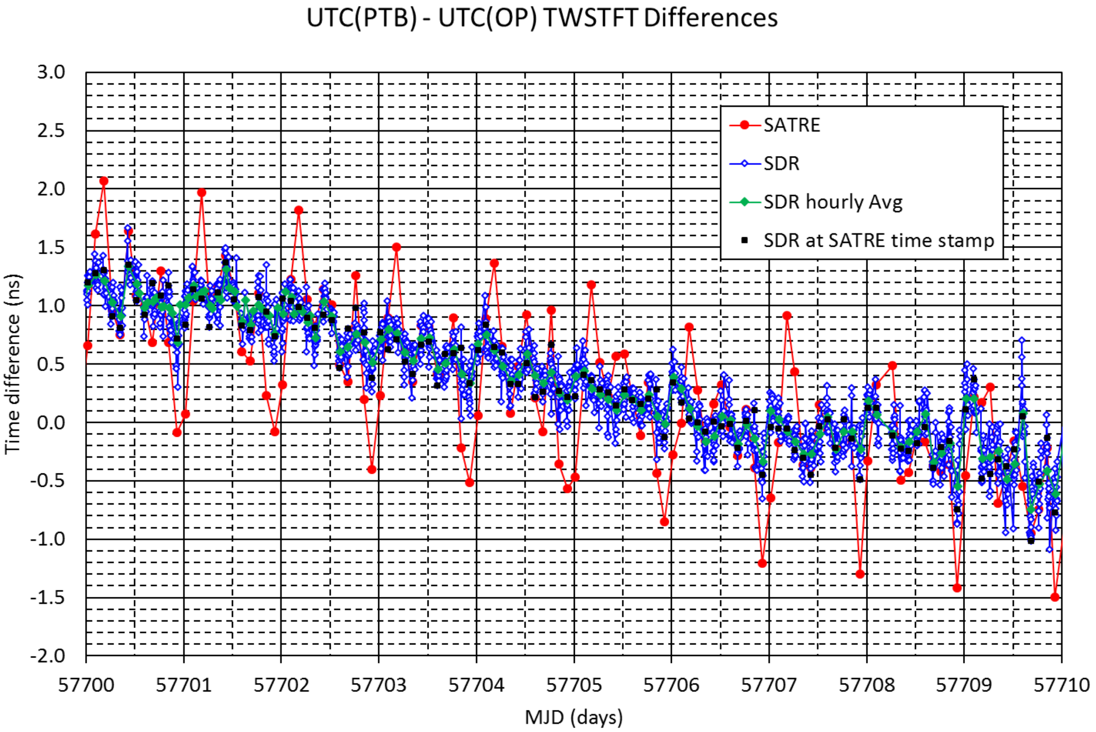

Fig. 3 TWSTFT differences obtained from SATRE and SDR measurements of the OP/PTB link during MJDs 57700 to 57709 (November 8, 2016 to November 17, 2016).

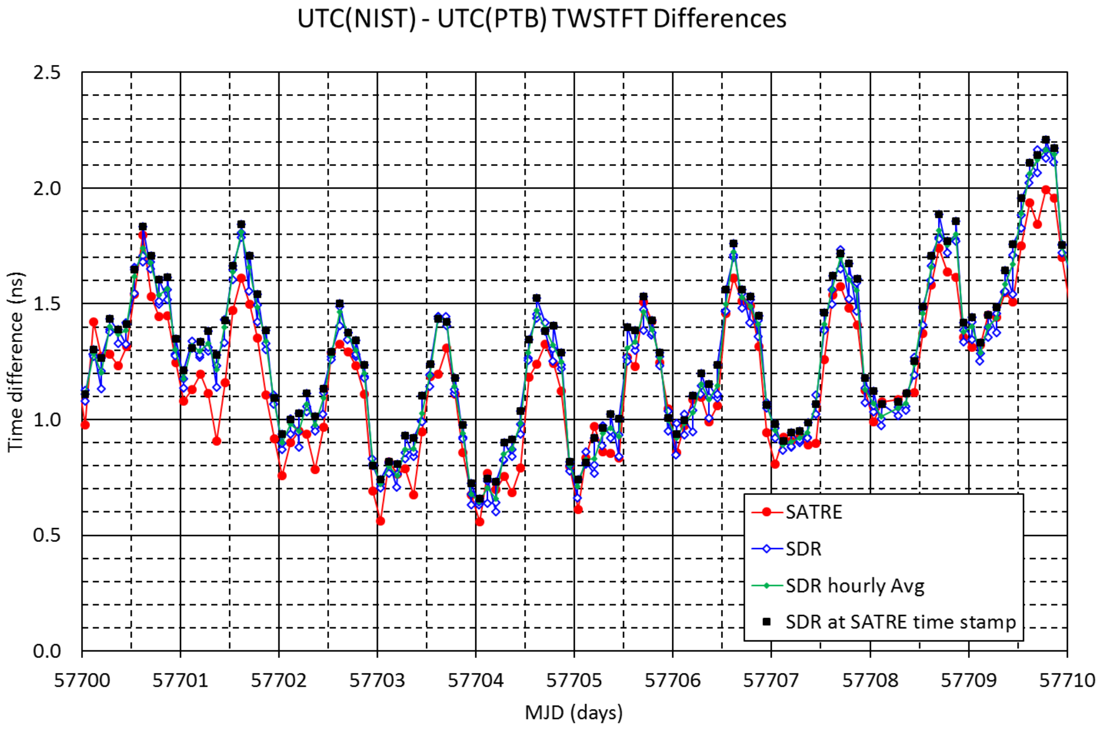

Fig. 4 TWSTFT differences obtained from SATRE and SDR measurements of the NIST/PTB link during MJDs 57700 to 57709 (November 8, 2016 to November 17, 2016).

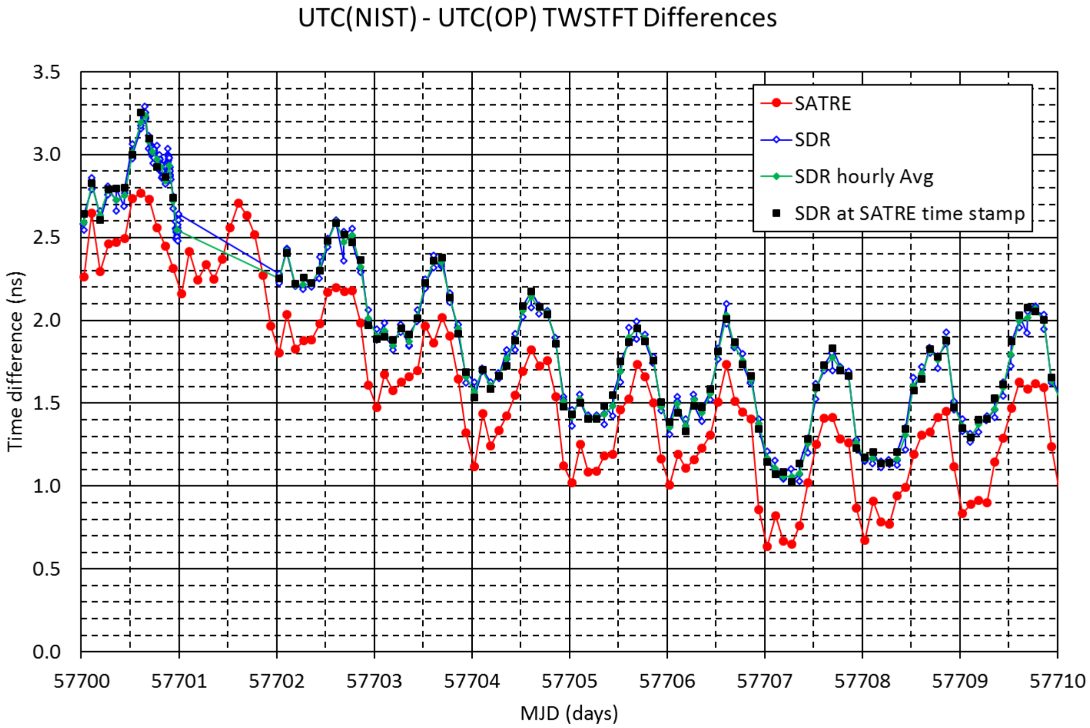

Fig. 5 TWSTFT differences obtained from SATRE and SDR measurements of the NIST/OP link during MJDs 57700 to 57709 (November 8, 2016 to November 17, 2016). The SDR differences deviated from the initial alignment to the SATRE difference on MJD 57643 by about 400 ps over this 10-day period. The cause of the deviation is unknown.

To take a closer look at the diurnal reduction, we use the Fast Fourier Transform (FFT) for a spectral analysis of the TWSTFT differences obtained from SATRE measurements, SDR hourly averaged measurements and the SDR measurements taken at the same time of the SATRE measurements. Figures 6 to 9 show the amplitude of Fourier elements (in arbitrary units) of the diurnal (day component) and other components in the TWSTFT differences of the three links computed from the 100-day measurements. The components are presented with an arbitrary unit because we are only interested in the comparison of the diurnal reduction. We use the diurnal component of the SATRE difference as the reference and divide it by the diurnal component of the SDR difference to obtain the SDR diurnal reduction factor. The results of the three links are shown in Table 2. From these results, we see the diurnal reduction factor is approximately seven for the OP/PTB link, while there is very little reduction for the NIST/OP and NIST/PTB links. We consider the diurnal reduction factors for the SDR hourly averaged difference and the SDR difference at SATRE measurement time as statistically equivalent. However, we will see in the Time deviation analysis that using the hourly averaged SDR difference can reduce time transfer noise.

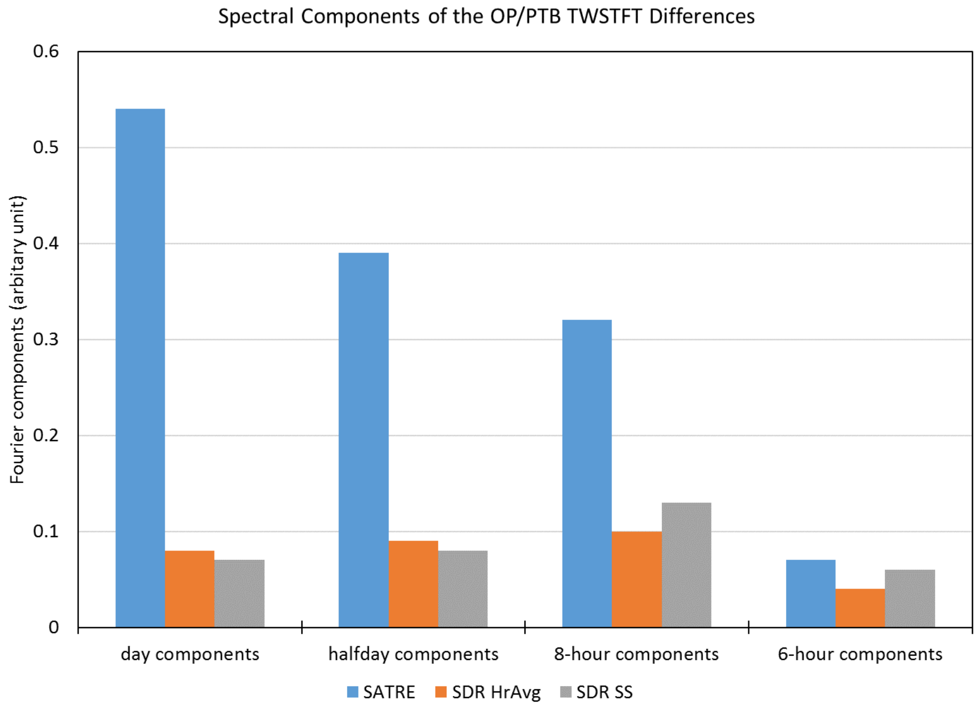

Fig. 6 Spectral analysis of diurnal and other components in (PTB – OP) TWSTFT differences obtained from SATRE data, SDR hourly averaged data (SDR HrAvg), and SDR data at SATRE time slot (SDR SS).

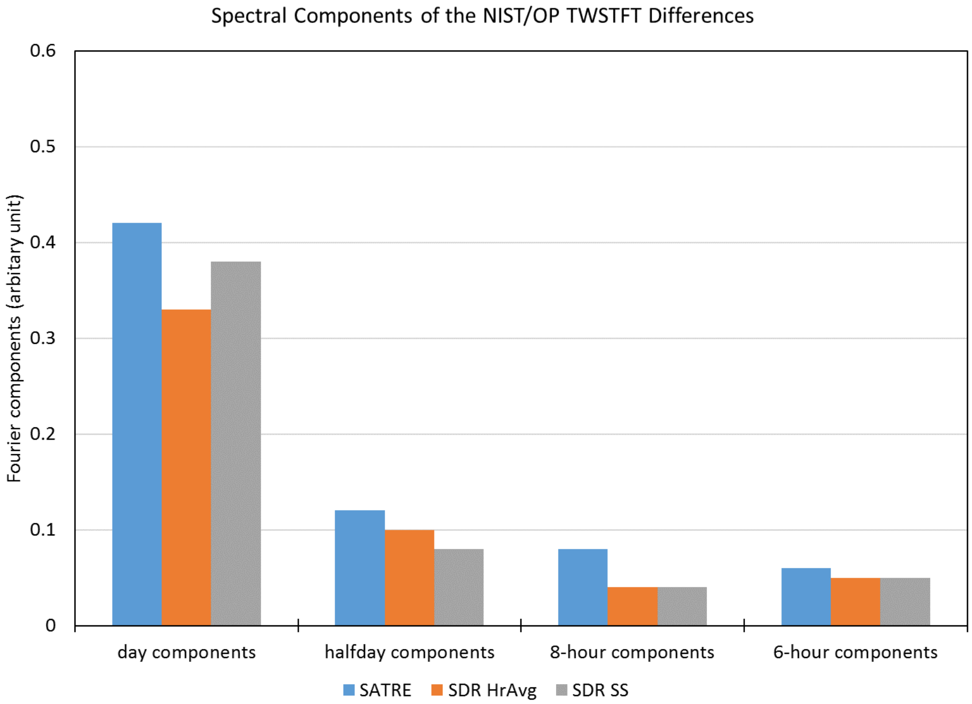

Fig. 7 Spectral analysis of diurnal and other components in (NIST – OP) TWSTFT differences obtained from SATRE data, SDR hourly averaged data (SDR HrAvg), and SDR data at SATRE time slot (SDR SS).

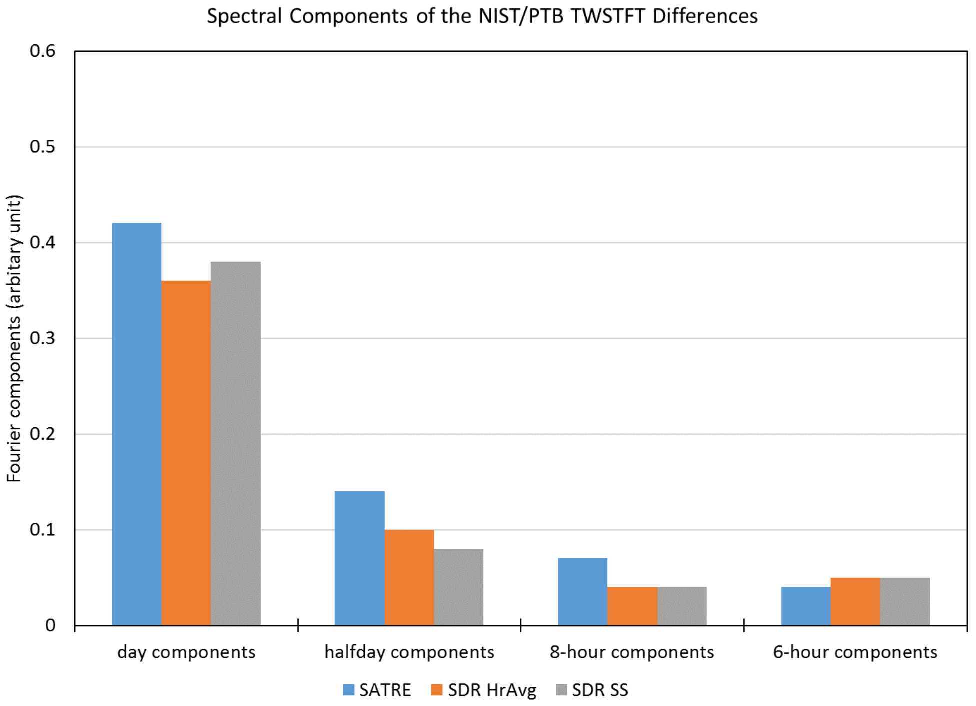

Fig.8 Spectral analysis of diurnal and other components in (NIST – PTB) TWSTFT differences obtained from SATRE data, SDR hourly averaged data (SDR HrAvg), and SDR data at SATRE time slot (SDR SS).

Table 2. Diurnal reduction factor of SDR TWSTFT differences

SDR differences	OP/PTB link	NIST/OP link	NIST/PTB
hourly average	6.8	1.3	1.2
at SATRE measurement time	7.7	1.1	1.1

The SDR TWSTFT differences also improve the time transfer stability for all of the three links, as shown by the Time deviation (TDEV) plots in Figures 9 to 11. For the OP/PTB link, the TDEVs of the SDR differences contain no diurnal pattern and the time transfer instability is decreased for averaging times from 7200 s (two hours) to about 300000 s (3.5 days). The TDEVs reach about 50 ps at averaging times of one day. For averaging times from 7200 s to 100000 s, the OP/PTB TDEV for the hourly averaged SDR difference shows improvement over the OP/PTB TDEV for the SDR difference at the SATRE measurement time due to the averaging of seventeen measurements in one hour. The improvement of the SDR differences for the NIST/OP and NIST/PTB links can only be seen at averaging times of 7200 s. Averaging over the three SDR measurements in one hour makes no difference in the TDEVs for the NIST/OP and NIST/PTB links.

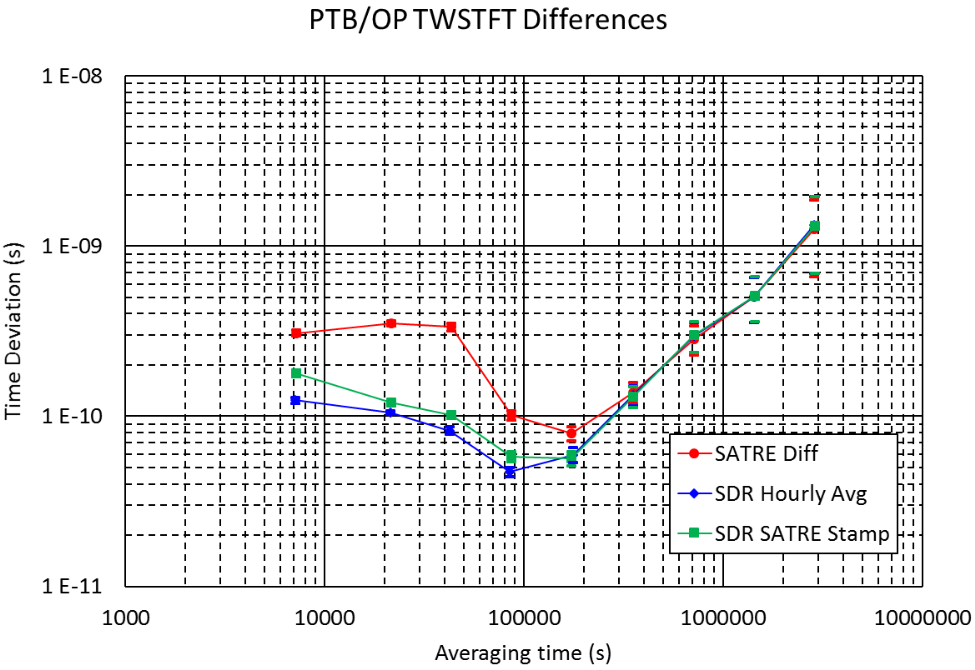

Fig. 9 Time deviation of the (PTB – OP) TWSTFT differences for MJDs 57643 to 57742.

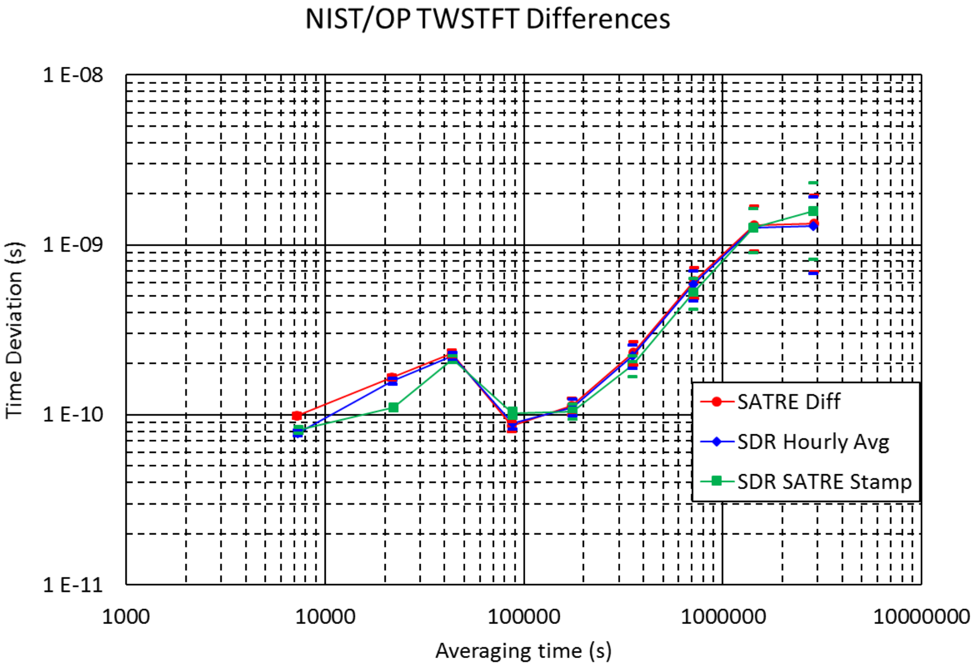

Fig. 10 Time deviation of the (NIST – OP) TWSTFT differences for MJDs 57643 to 57742.

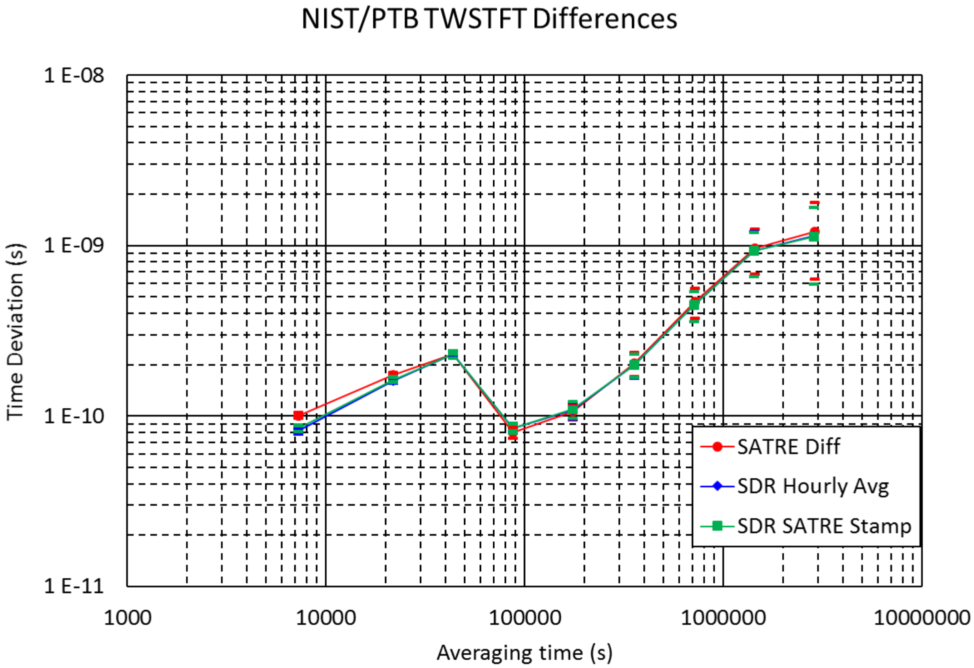

Fig. 11 Time deviation of the (NIST – PTB) TWSTFT differences for MJDs 57643 to 57742.

To analyze the short-term time transfer noise in SDR TWSTFT, NIST and OP conducted an odd-hour experiment from 17:00 UTC on MJD 57700 (November 8, 2016) to 18:00 UTC on MJD 57701 (November 9, 2016). During the experiment, continuous one-second measurements were made by both SDR receivers and SATRE modems from minute 10 to 30 and from minute 33 to 57, a total of 2640 one-second measurements in every odd hour. We use TDEV of the one-second TWSTFT differences to evaluate the time transfer noise. The 180 seconds data gap (from 30 minute to 33 minute of an odd hour) does not change the characteristics of the TDEV, so we concatenate the one-second difference in computing the TDEV for every odd hour. A typical TDEV of the SDR one-second odd-hour TWSTFT differences is shown in Fig. 12. The TDEV of the SATRE one-second TWSTFT difference of the same odd-hour is included in Fig. 12 for comparison. The TDEV of the SATRE one-second TWSTFT difference starts at averaging time of 2 s, because a software used to extract the SATRE one-second measurements introduced a 60 s data gap between each of the 120 s one-second data. The TDEVs for all of the 13 odd-hour SDR differences are dominated by white phase noise for averaging times from one second to about 100 seconds. The TDEVs are less than 200 ps at averaging times of one second and averaged down to about 20 ps at averaging times of 100 seconds. Most of the TDEVs show flicker phase noise at about 20 ps after averaging times of 100 seconds but a few TDEVs still show white phase noise for averaging times up to 1000 seconds and reach 6 to 7 ps. This means the time transfer instability can be significantly reduced by averaging 600 s or so one-second differences to extend averaging times to 100 s, and the observation could be a motivation to extend the measurement time of a TWSTFT session over the currently used 120 s to further reduce the measurement noise. The TDEVs for the SATRE odd-hour one-second TWSTFT differences have the similar characteristics as that for the SDR. However, the SATRE TDEVs are about three times larger. We want to point out that these characteristics are obtained from the odd-hour measurements. The time transfer noise is very likely different for the even-hour measurements due to two TWSTFT PRN coded signals traveling simultaneously through each of the two transatlantic transponders.

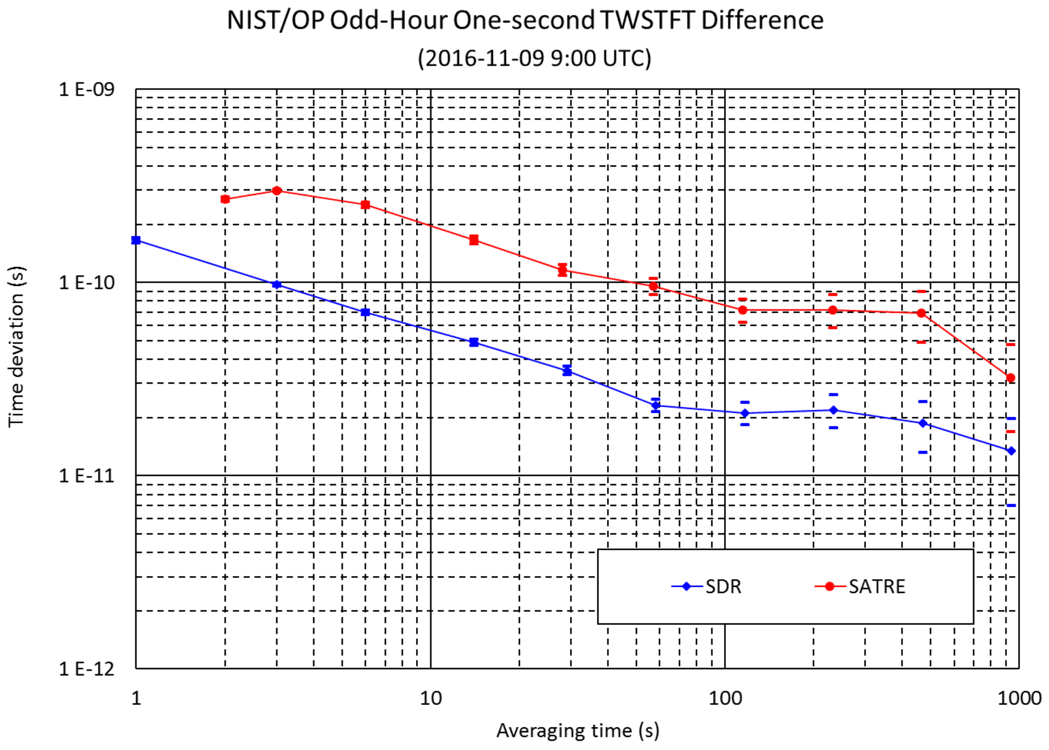

Fig. 12 Typical time deviations of the NIST/OP odd-hour one-second TWSTFT difference.

The diurnal in TWSTFT differences apparently comes from different sources. Some of the sources are related to the daily variation of the propagation delay, such as the time of arrival variation due to the satellite motion, the ionospheric delay change from nighttime to daytime, and the variation of the delay through the TWSTFT equipment caused by temperature fluctuations in combination with the temperature coefficients of the equipment's internal delays. Other sources are associated with interference in receiving the TWSTFT PRN codes, such as the in-band interference from other TWSTFT PRN codes transmitted at the same time, and out-of-band interference from the signals next to our TWSTFT frequency bands. The results presented in this section indicate the dominant cause of the diurnal in the OP/PTB difference is different than that in the NIST/OP and NIST/PTB differences. The SDR TWSTFT effectively eliminates the diurnal in the OP/PTB link but makes only a minor improvement in the NIST/OP and NIST/PTB links. The study in [8] pointed out that the in-band and/or out-of-band interference are very likely the major contributors to the diurnal in the Europe-Europe TWSTFT. Using SDR TWSTFT for the OP/PTB link has the same effect as using the triangle TWSTFT via the transatlantic link (indirect link computed from the PTB – OP = [(NIST - OP) – (NIST - PTB)]). This means the SDR TWSTFT is capable of reducing the diurnal contributed by the in-band and/or out-of-band interference. Figures 13 and 14 show a comparison of the direct SATRE TWSTFT, direct SDR TWSTFT and the triangle TWSTFT (via NIST) for the OP/PTB link. However, SDR TWSTFT cannot overcome the diurnal in the transatlantic TWSTFT differences. Because the transatlantic TWSTFT signals go through two transponders on the T-11N satellite, it is very likely that the dominant cause of the transatlantic TWSTFT diurnal is the propagation delay variation of the two transponders which may have different temperature coefficients of their internal delays and/or see different amounts of solar radiation. This inference of why the SDR TWSTFT cannot reduce the diurnal in transatlantic links is for the use of the 1 MChip/s codes on the T-11N satellite. We have seen the diurnal in a transatlantic TWSTFT link vanished in odd hours when using 2.5 MChip/s codes on a different satellite [5].

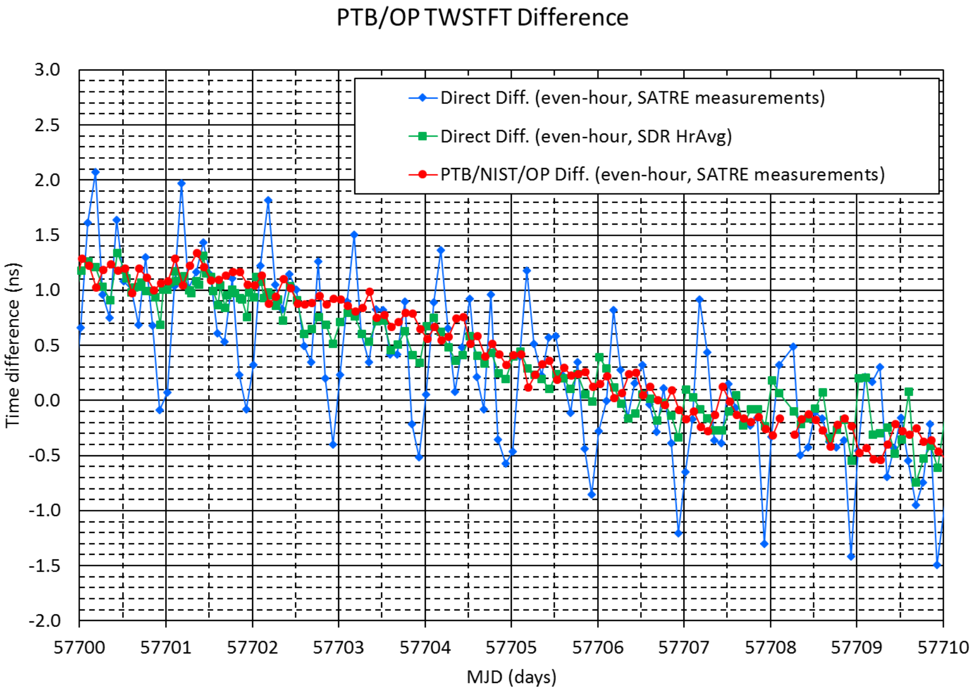

Fig. 13 PTB - OP TWSTFT differences with the [(NIST – OP) – (NIST – PTB)] triangle SATRE difference, and direct SATRE and SDR differences during MJDs 57700 to 57710 (November 8, 2016 to November 17, 2016).

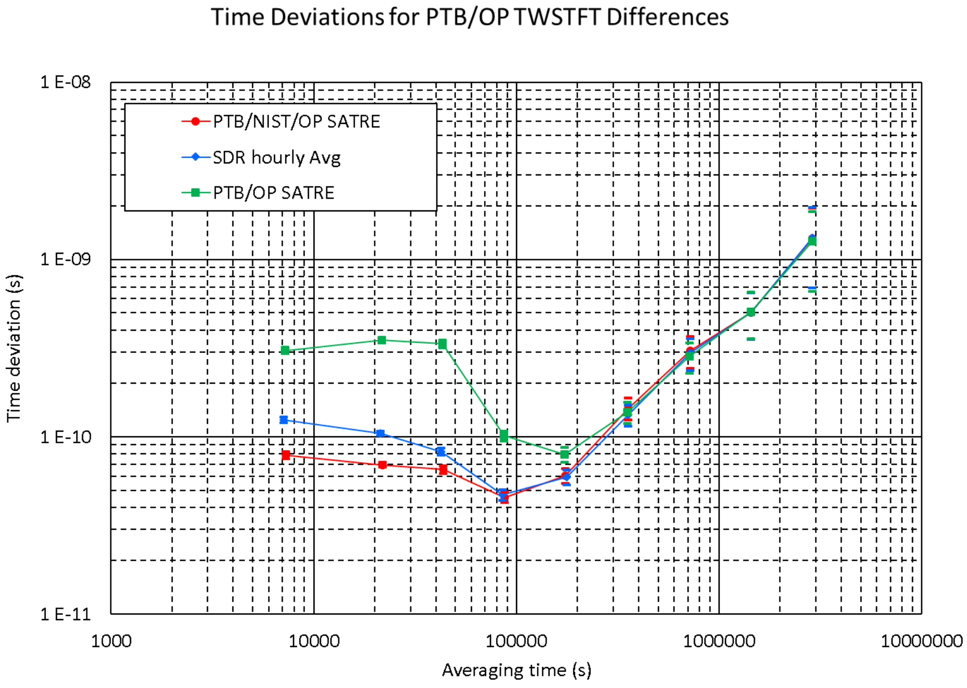

Fig. 14 Time deviations of PTB - OP TWSTFT using the [(NIST – OP) – (NIST – PTB)] triangle SATRE difference, and direct SATRE and SDR differences over MJDs 57643 to 57742 (September 12, 2016 to December 20, 2016).

IV. CONCLUSIONS

Our study has shown the use of the SDR TWSTFT effectively reduces the diurnal in the OP/PTB link, but does very little to reduce the diurnal in the NIST/OP and NIST/PTB links. The results indicate the dominant cause of the diurnal for the OP/PTB link is different than that for the NIST/OP and NIST/PTB links. The comparison of the SDR TWSTFT to the triangle SATRE TWSTFT via NIST for the OP/PTB link strongly suggests that the in-band and/or out-of-band interference is the dominant cause of the diurnal for the OP/PTB link. Our study also shows the time transfer noise can be reduced by averaging the one-second SDR measurements over a longer than 2-minute interval as used currently by the SATRE measurements. This is possible because the SDR system can simultaneously receive six TWSTFT PRN codes at the same time. Doing so will require an update of the TWSTFT schedule and data processing procedures.

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†**DISCLAIMER**: Commercial products are identified for technical completeness only, and no endorsement by BIPM, NIST, OP PTB and TL is implied.

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