A Study of the Diurnal in the Transatlantic TWSTFT Difference

Victor Zhang and Thomas E. Parker

Time and Frequency Division of the National Institute of Standards and Technology
325 Broadway, Boulder, Colorado, U.S.A.
vzhang@boulder.nist.gov

Abstract—The daily variation (diurnal) in two-way satellite time and frequency transfer (TWSTFT) difference is one of the most significant instabilities of the TWSTFT technique. The diurnal comes from the daily delay change of the TWSTFT signal paths. In recent years, there is a persistent diurnal, at the 1 ns to 2 ns level, in the transatlantic and the Europe-to-Europe TWSTFT links. In this paper, we study the diurnal in the transatlantic TWSTFT differences. We will show that a small part of the diurnal is due to the path non-reciprocity between two earth stations and a satellite; the diurnal can come from multiple TWSTFT signals transmitted at the same time; TWSTFT using different satellites and frequencies results in different diurnal levels; and the environmental effects on the earth stations and the satellite transponders also contribute to the daily delay variation of the TWSFTF difference.

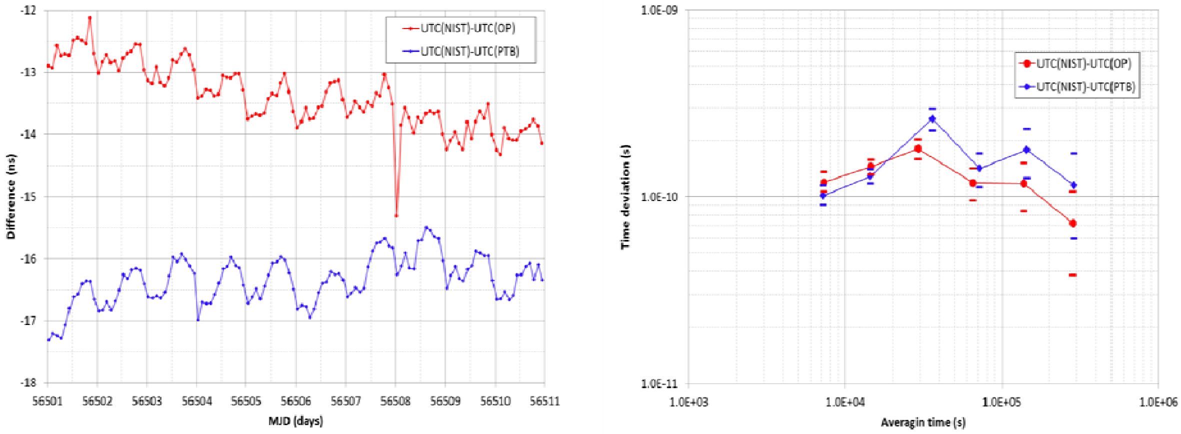
Key words: time and frequency transfer; two-way satellite time and frequency transfer

I. INTRODUCTION

Two-way satellite time and frequency transfer (TWSTFT) is accomplished by two remote earth stations that transmit and receive pseudo-random noise (PRN) codes. The PRN codes carry the timing information of the reference clock for each station. Each station simultaneously transmits a PRN code to a geostationary satellite and receives the PRN code of the remote station from the satellite, while measuring the time difference between the transmit (TX) and its receive (RX) signals (TX – RX). The TX signal carries the timing of the local reference clock and the RX signal carries the timing of the remote reference clock plus the delays in the signal path. The signal path in each direction is highly reciprocal. Thus, by differencing the two TX – RX measurements made by each station at the same time, most of the path delays are canceled in the difference and we obtain the time difference of two remote clocks. We use two transponders on a satellite for the transatlantic TWSTFT; one transponder points to the United States and the other points to Europe. In principle, the non-reciprocal path delays of a TWSTFT link can be calibrated using a portable earth station or with other time transfer methods. However, the change of path delays is more difficult to correct, and that directly impacts TWSTFT instability.

The transatlantic Ku-band TWSTFT operation was established in the late 1990s. In recent years, the National Institute of Standards and Technology (NIST) and the US Naval Observatory (USNO) in the United States and up to 14 European timing laboratories, including the LNE-SYRTE, Observatoire de Paris (OP) in France and the Physikalisch-Technische Bundesanstalt (PTB) in Germany participate in the TWSTFT for comparing the time and frequency of remote clocks over transatlantic distances. The lowest time transfer instability, as measured by the Time Deviation (TDEV), is about 100 ps or less for averaging times at 1 day over the transatlantic baseline. The TWSTFT operation is coordinated by the CCTF TWSTFT working group. To schedule all of the TWSTFT measurements in a 60-minute interval, the European stations take turns to transmit their assigned PRN codes in a three-minute interval, two stations at the same time, while NIST and USNO transmit their assigned codes continuously during regular daily operation. Each pair of remote stations makes the TX - RX measurements every second for two minutes in a designated time slot. The measurements are repeated in every even hour, 12 times a day.

Since 2007, the transatlantic TWSTFT has gone through several satellite changes. Bandwidth for the TWSTFT signals and chip-rate of PRN codes have also been reduced due to the significant increase of satellite cost. Starting from July of 2011, the TWSTFT operation has been using 1 MChip/s PRN codes with 1.6 MHz bandwidth on the Telestar -11N(1) (T-11N) geostationary satellite. The TWSTFT differences contain up to a 2 ns peak-to-peak diurnal for all of the transatlantic links. Examples of the UTC(NIST) – UTC(OP) and UTC(NIST) – UTC(PTB) TWSTFT differences and their TDEVs are shown in Figure 1, where UTC(k) is local realization of the Coordinated Universal Time (UTC) by a timing laboratory k. The peaks around averaging times of 40,000 s in Figure 1 (b) are due to the diurnal. Without the diurnal, the TDEVs at averaging times of one day would be much lower. The diurnal becomes a significant contributor to the transatlantic TWSTFT instability.



(a) Time differences (b) Time deviation of the time differences

Figure 1. Diurnal in the UTC(NIST) – UTC(OP) and UTC(NIST) – UTC(PTB) TWSTFT differences. The differences were obtained from the TWSTFT by use of 1 MChip/s PRN codes with 1.6 MHz bandwith on the T-11N satellite.

Several studies [1], [2], [3], [4], have discussed the origins of the TWSTFT instability and their impact on the diurnal in the TWSTFT difference. In this paper, we focus on the diurnal elements and their contribution to the Ku-band transatlantic TWSTFT. We study the diurnals for the TWSTFT links between NIST, USNO in the United States and OP, PTB in Europe. In Section II, we analyze the diurnal contributions due to path non-reciprocity, the Sagnac effect, and ionospheric delay when using the T-11N satellite with 1 MChip/s codes and 1.6 MHz bandwidth. Section III shows the diurnal is related to the satellite and the TWSTFT parameters, such as the uplink and downlink frequencies. In Section IV, we illustrate that the diurnal sometimes can come from multiple PRN codes transmitted at the same time, and the diurnal might be from the satellite transponders. In Section V, we examine the correlation between the earth station environment and the diurnal. Section VI summarizes our study.

II. VARIATIONS OF PATH NON-RECIPROCITY, SAGNAC EFFECT AND IONOSPHERIC DELAY

In general, the times of arrival (TOA) of simultaneous transmitted signals at a satellite are different because of the different distances between a geostationary satellite and different earth stations. The TOA is equivalent to the uplink (station to satellite) path delay. If there were no satellite motion, the difference in the two uplink delays would be canceled in the TWSTFT difference because the delay from station A to the satellite (uplink$_{A\text{-}S}$ delay) is equal to the delay from the satellite to station A (downlink$_{S\text{-}A}$ delay) and vice versa. However, a geostationary satellite moves relative to the Earth surface. As a result, the TOA changes based on the range of the satellite motion and satellite velocity, producing a sinusoidal variation as shown in Figure 2. The difference in the two TOAs cannot be completely canceled in the TWSTFT difference because the change in an uplink delay from one station is not equal to the change in a downlink delay from the other station. Assume the satellite motion is in the radial direction, the path non-reciprocity due to the satellite motion can be estimated by

$$d_{SAT} = \frac{TOA\ difference\ of\ a\ TWSTFT\ link\ \times satellite\ velocity}{speed\ of\ light}\ . \quad (1)$$

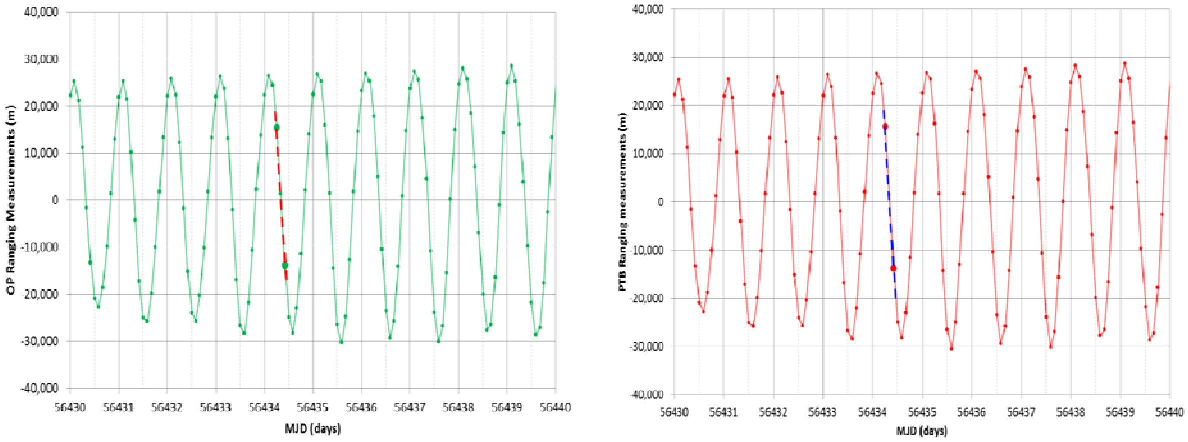


Figure 2. Examples of the T-11N satellite daily motion as obtained from ranging measurements made by OP (left) and PTB (right). The Ranging measurements are twice the distance to the satellite. The maximum distance variation between T-11N and OP or PTB is within ±15 km. The maximum satellite velocity as estimated by the tangent lines is about 2 m/s.

Assuming the latitude and longitude of the T-11N satellite vary within ±0.1 º of the nominal position every day, we estimated the corresponding TOA for the NIST/OP, NIST/PTB, USNO/OP, and USNO/PTB links using the coordinates of the four earth stations. The maximum distance change between the T-11N satellite and the earth stations at NIST and USNO is within ±15 km, which is in good agreement with the OP and PTB ranging measurements as shown in Figure 2.The largest TOA difference is around 5 ms for the NIST/OP TWSTFT link. With the 2 m/s maximum satellite velocity as shown in Figure 2, the maximum path non-reciprocity due to the T-11N motion is for the NIST/OP TWSTFT link at about 33 ps. Table I shows the results for the four links.

TABLE I. Peak-to-peak path non-reciprocity and delay change due to Sagnac effect for T-11N satellite's 30 km motion.

Links	**NIST/OP**	**NIST/PTB**	**USNO/OP**	**USNO/PTB**
$\boldsymbol{d_{SAT}}$ (ps)	33	19	-19	-27
$\boldsymbol{d_{Sagnac}}$ (ps)	176	181	143	148

The Sagnac effect introduces a propagation delay (d_{Sagnac}) in the TWSTFT signal path. The d_{Sagnac} is a function of the coordinates of the satellite and the earth station. Therefore, the satellite daily motion causes the d_{Sagnac} to fluctuate accordingly. We have seen from the ranging measurements and computation that the T-11N satellite can move up to 30 km/day peak-to-peak with respect to the earth. Using the method described in [4] and [5], we obtained the d_{Sagnac} corresponding to the 30 km motion of the T-11N satellite as shown in Table I.

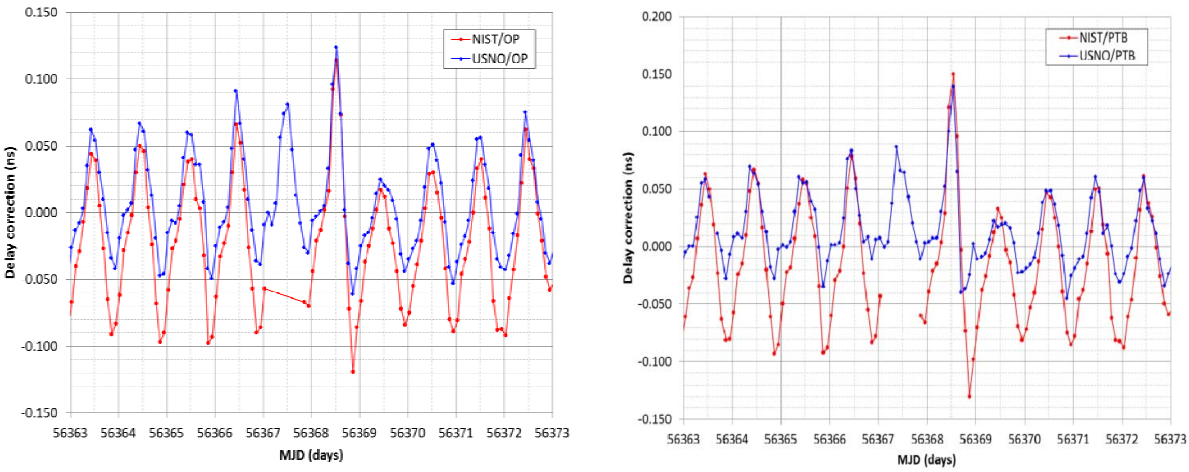


Figure 3. Examples of the ionosphere delay corrections. The delay is subtracted from the TWSTFT difference to make the ionosphere delay correction. The maximum variation of the ionosphere delay correction is about ±150 ps.

The Ku-band uplink and downlink frequencies are around 14 GHz and 12 GHz, respectively. Because the TWSTFT signals go through the dispersive ionosphere, the uplink and downlink signals have different delays due to the frequency difference. The ionosphere delay varies with the solar activity, i.e., the daytime delay and nighttime delay are different. Using the measured Total Electron Content (TEC) in the IONosphere EXchange (IONEX) map format from the International Global Navigation Satellite Systems Service (IGS), Figure 3 shows the ionosphere delay corrections for the NIST/OP, NIST/PTB, USNO/OP and USNO/PTB links using the T-11N satellite. The ionosphere delay peaks during the midday of the UTC, which is the early morning in the US and around early afternoon in Europe. The maixumum ionospheric delay correction is typically about 150 ps. Assume as a worst case that the contributions from the path non-reciprocity, Sagnac effect and ionosphere delay are in phase with each other, their maximum combined diurnal (33 + 181 + 150) would be 364 ps. This means the contributions from these three elements cannot account for all of the diurnals in the TWSTFT differences for using the 1 MChip/s PRN codes with 1.6 MHz bandwidth on the T-11N satellite.

III. CHANGES OF SATELLITE AND TWSTFT PARAMETERS

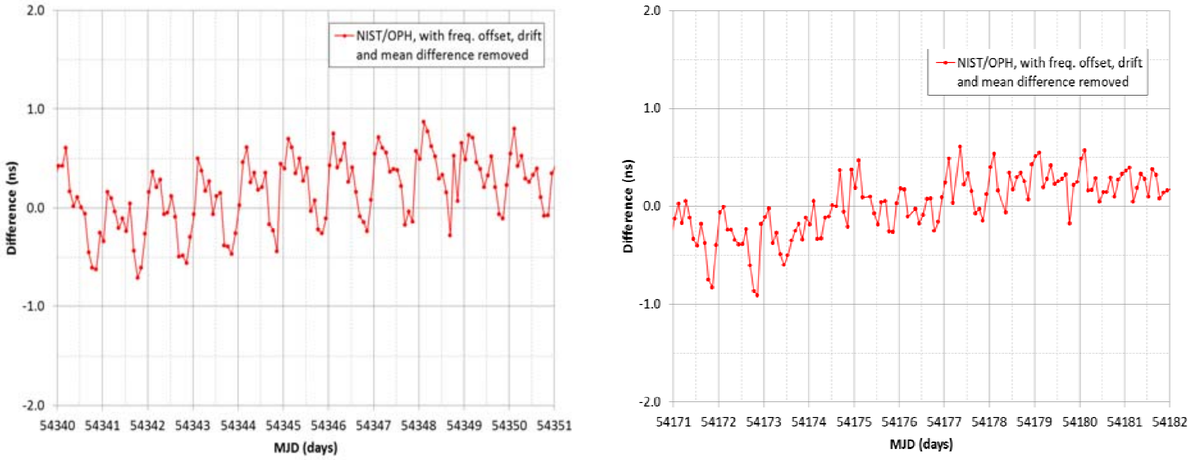
Because of satellite availability, the transatlantic TWSTFT operation has gone through three satellite changes since 2007. Each satellite change was accompanied by a change of the uplink and downlink frequencies. The chip-rate of the PRN codes was reduced from 2.5 MChip/s to 1 MChip/s and the bandwidth used for TWSTFT was reduced from 3.7 MHz to 2.5 MHz in July 2009 to lower the cost of satellite time. The bandwidth was further reduced from 2.5 MHz to 1.6 MHz in July 2011. Table II summarizes the changes since 2007.

During the TWSTFT operations using the 2.5MChip/s PRN codes with 3.7 MHz bandwidth on the IS-707[(1)] satellite, we see consistent diurnals at the level of 1 to 1.5 ns peak-to-peak most of the time. There were some periods of time when the diurnal was reduced or disappeared for one or two days for no apparent reason. Figure 4 shows examples of the diurnal in the NIST/OP TWSTFT when doing TWSTFT on the IS-707 satellite.

When the satellite was switched to the IS-3R[(1)], we see an immediate diurnal reduction in the NIST/PTB difference, as shown in Figure 5 (a). There was no change in temperature and humidity diurnal at the earth stations (see Section V for more details). Figure 5 (b) shows there were diurnal flare ups. Overall, the diurnal in the NIST/OP difference was less than 0.5 ns, and the diurnal in the NIST/PTB difference was about 1 ns or less. Because no earth station equipment was changed and because the only parameters that did change were the uplink and downlink frequencies for the satellite change from IS-707 to IS-3R, the diurnal reduction is certainly related to satellite in use and the uplink/downlink frequency. The two transponders on the IS-3R satellite might have similar temperature coefficients such that the delay variations in each direction were partially canceled in the TWSTFT differences. We will study the satellite transponder contribution in the next section. The uplink and downlink frequencies could also play a role. It has been shown that reflections (multi-path) of the TWSTFT spread spectrum signal can introduce time errors in the TWSTFT results [6]. These reflections can be caused by impedance mismatches in transmission lines in the TWSTFT equipment or even on the satellite. The group delay (timing) error is very sensitive to the power level of the reflected signal, the carrier frequency (Ku band in this case), and the delay of the transmission line. As a result, the effective temperature coefficient of group delay can be either greatly amplified or reduced, or even change sign relative to the inherent temperature coefficient of phase delay of the transmission line as the carrier frequency is changed. The IS-3R frequencies could be in the region such that the effective temperature coefficients were small for our Ku-band equipment. Another possible uplink and downlink frequencies related source of the diurnal is the interference from the out-of-band signals adjacent to our TWSTFT signals, which we will not study in this paper.

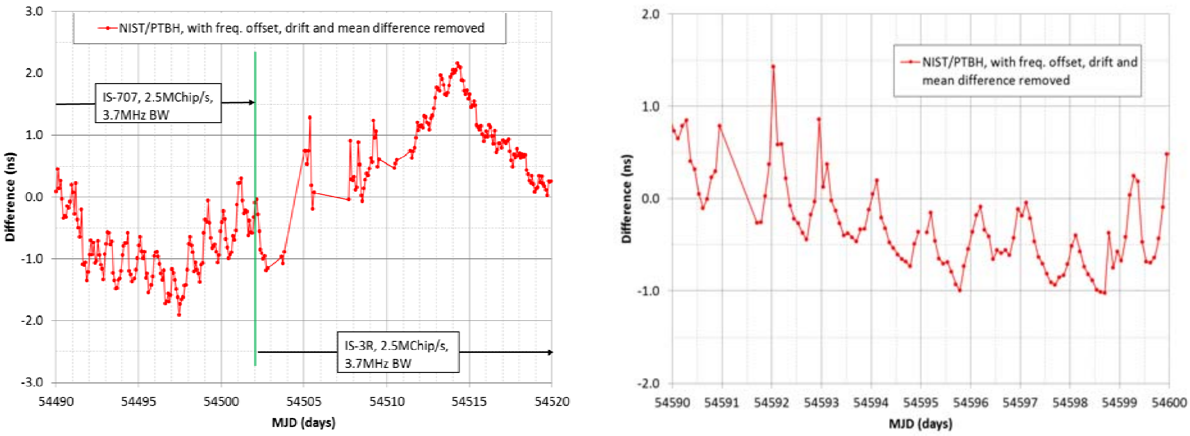
Table II. Changes in transatlantic TWSTFT since 2007.

Satellite	Chip-rate (MChip/s)	BW (MHz)	US		Europe		Date of Operation
			f_{uplink} (MHz)	$f_{downlink}$ (MHz)	f_{uplink} (MHz)	$f_{downlink}$ (MHz)	
IS-707	2.5	3.7	14211.750	11916.750	14211.750	12716.750	10/25/2006 - 2/5/2008 (54033 - 54501)
IS-3R	2.5	3.7	14375.050	12030.750	14330.750	12627.050	2/6/2008 - 7/30/2009 (54502 - 55042)
T-11N	1	2.5	14285.550	11726.550	14026.550	11485.550	8/1/2009 - 7/26/2011 (55043 - 55768)
T-11N	1	1.6	14298.430	11746.590	14046.590	11498.430	7/27/2011 - 8/2/2011 (55769 - 55775)
T-11N	1	1.6	14289.060	11746.590	14046.590	11489.060	Since 8/3/2011 (55775)



(a) diurnal was about 1 ns most of the time (b) diurnal reduced on MJDs 54176, 54180 and 54181

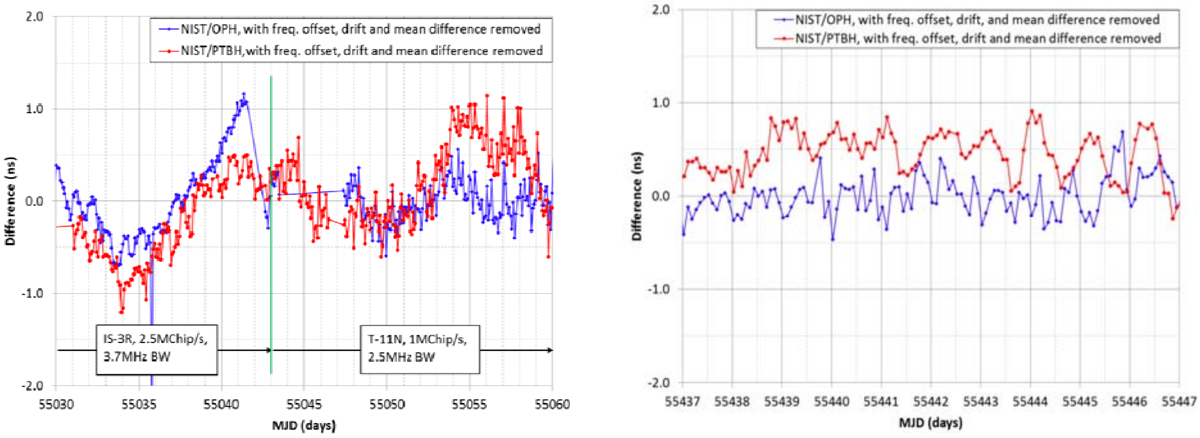
Figure 4. Examples of the diurnal in the NIST/OP TWSTFT difference while using 2.5 MChip/s PRN codes with 3.7 MHz bandwidth on the IS-707 satellite. The diurnal minimum occurs in the second half of each day.



(a) diurnal reduced when switched to the IS-3R satellite (b) there were diurnal flare ups

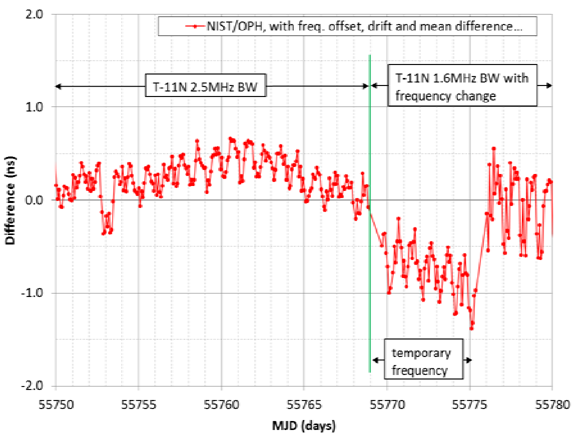
Figure 5. Examples of the diurnal in the NIST/PTB TWSTFT difference while using 2.5 MChip/s PRN codes with 3.7 MHz bandwidth on the IS-3R satellite. The diurnal minimum occurs in the second half of each day.

When the transatlantic TWSTFT was switched to the T-11N satellite in July 2009, not only were the uplink and downlink frequencies changed, but also the chip-rate of the PRN codes and the bandwidth were reduced to 1 MChip/s and 2.5 MHz, respectively. The 1 MChip/s codes need only 1.6 MHz bandwidth [7] such that the TWSTFT spread spectrum signal won't be distorted. The 2.5 MHz bandwidth was intended to study the performance of TWSTFT with 2.5 MHz Surface Acoustic Wave filters using 2.5 MChip/s codes [8]. Figure 6 (a) shows that noise in the TWSTFT differences increased when using the T-11N satellite with the reduced chip-rate and bandwidth. The chip-rate reduction decreases the resolution of the TWSTFT measurements, and that can increase noise in the TWSTFT difference. Figure 6 (b) shows that the diurnals vary from day to day, and that the NIST/OP and NIST/PTB TWSTFT differences contain different levels and patterns of diurnals. It is not shown here that the maximum peak-to-peak diurnal is about 1 ns in the NIST/OP TWSTFT difference and is about 3 ns in the NIST/PTB TWSTFT difference during the use of T-11N satellite with 1 MChip/s codes and 2.5 MHz bandwidth.

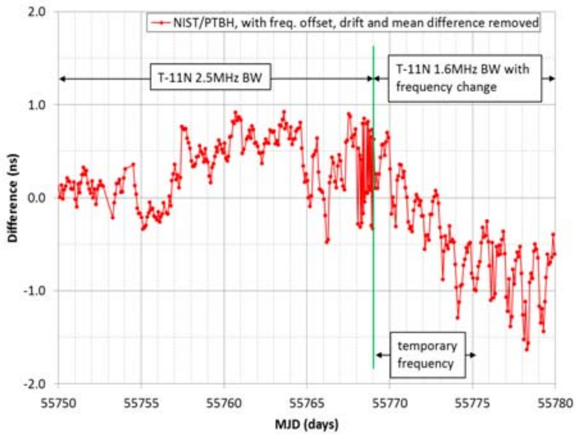


(a) noise increased when switched to the T-11N satellite (b) NIST/OP and NIST/PTB have different diurnal

Figure 6. Examples of the diurnal in the NIST/OP and NIST/PTB TWSTFT differences while using 1 MChip/s PRN codes with 2.5 MHz bandwidth on the T-11N satellite.



(a) NIST/OP TWSTFT difference

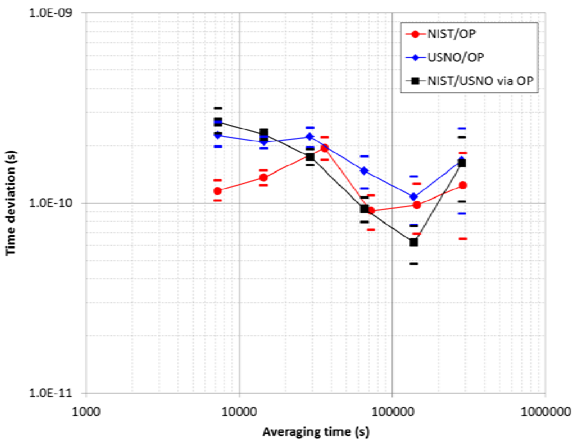


b) NIST/PTB TWSTFT differene

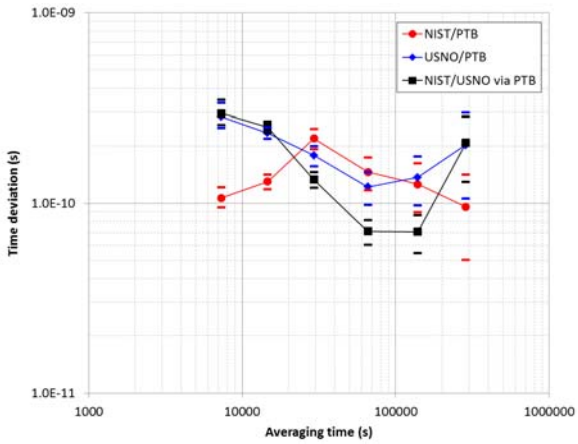
Figure 7. The diurnal level increased in both the NIST/OP and NIST/PTB TWSTFT difference after bandwidth reduction as well as uplink and downlink frequency change.

The bandwidth for the transatlantic TWSTFT on the T-11N satellite was reduced from 2.5 MHz to 1.6 MHz at the end of July 2011. As shown in Figure 7, the diurnal increased in both the NIST/OP and NIST/PTB TWSTFT differences. Other than the bandwidth reduction and the uplink/downlink frequency change, nothing else was changed in each TWSTFT link. The bandwidth reduction alone should not change the diurnal. However, when combined with the uplink and downlink frequencies change, our TWSTFT signals are closer to adjacent signals and therefore could be more susceptible to interference from out-of-band signals. The level of diurnal in the NIST/OP and NIST/PTB TWSTFT differences ranges from 0.5 to 1.5 ns, and is mostly about 1 ns. The diurnal maximum occurs at the second half of the UTC day, as shown in Figure 1 and Figure 7.

IV. TRANSPONDER DELAY VARIATIONS AND INTERFERENCE FROM IN-BAND SIGNALS



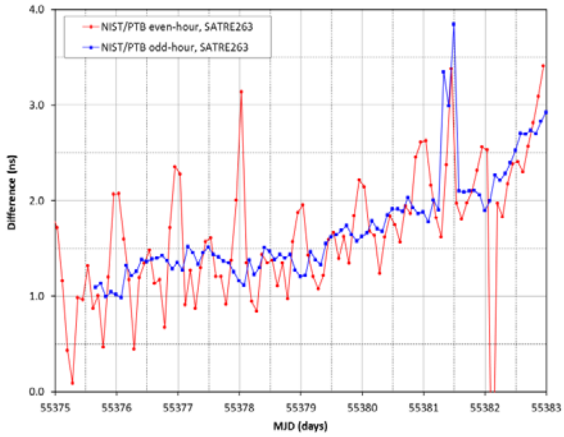
(a) Time deviations of the NIST/OP, USNO/OP and NIST/USNO TWSTFT differences



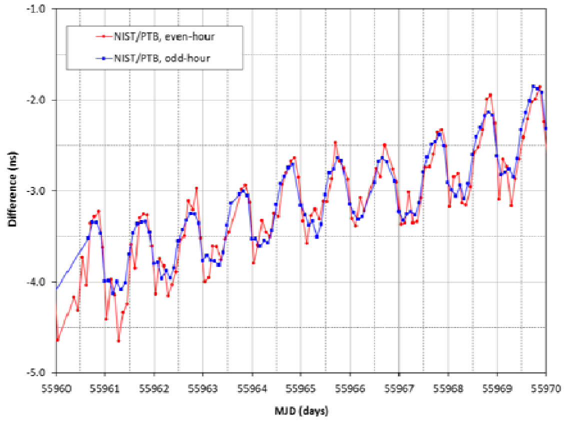
(b) Time deviations of the NIST/PTB, USNO/PTB and NIST/USNO TWSTFT differences

Figure 8. Time deviations computed from the TWSTFT differences for MJDs 56509 – 56518. The NIST/USNO TWSTFT differences are computed from the NIST/OP - USNO/OP and the NIST/PTB - USNO/PTB differences.

The transatlantic TWSTFT signals go through two transponders on a satellite. The difference in the two transponders' delay variation will show up in the transatlantic TWSTFT difference. The delay variation can come from the transponders' daily temperature variation or due to the power consumption of the payload which could introduce a diurnal in the transatlantic TWSTFT difference. In Figure 8, we show the TDEVs of a 10-day NIST/USNO TWSTFT differences when using the T-11N satellite with 1 MChip/s codes and 1.6 MHz bandwidth. The NIST/USNO TWSTFT differences are obtained by NIST/OP - USNO/OP and NIST/PTB - USNO/PTB. While the TDEVs of the NIST/OP and NIST/PTB differences show an obvious diurnal, the diurnal in the USNO/OP and USNO/PTB TDEVs is obscured by high measurement noise at averaging times from 2 to 8 hours. The TDEVs of the NIST/USNO differences for averaging times from 2 to 4 hours are about the same level as that for the USNO/OP and USNO/PTB differences. However, the TDEVs for averaging times longer than 4 hours are reduced. This means part of the diurnals in the NIST/OP and USNO/OP differences as well as in the NIST/PTB and USNO/PTB differences are canceled in the NIST/USNO differences. Although it is not shown here, we see the same diurnal reduction in NIST/USNO difference obtained from all of the NIST and USNO to Europe links. It is unlikely the NIST and USNO earth stations equipment have similar daily delay variation. We suspect the diurnal reduction is gained from the cancelation of the difference in the two T-11N transponders' delay variation. However, we do not have the temperature coefficient information on the two transponders on T-11N.



(a) NIST/PTB odd-hour difference showed no diurnal, while the even-hour difference showed a diurnal when using T-11N with 1 MChip/s codes and 2.5 MHz bandwidth.



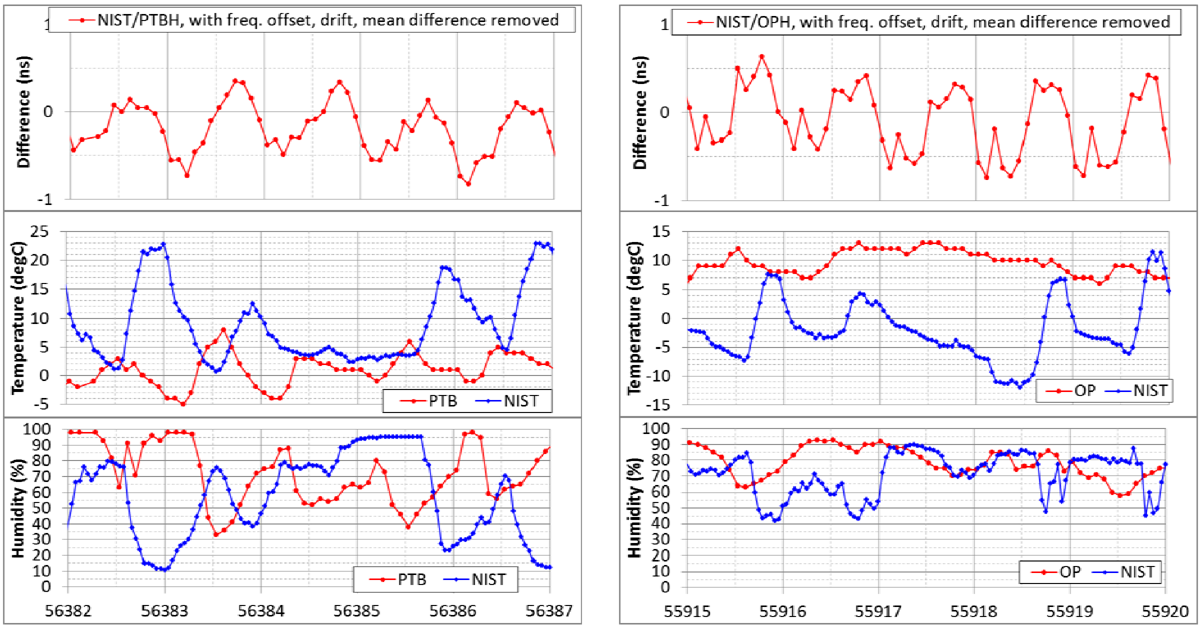
(b) NIST/PTB odd-hour and even-hour differences both contain diurnals when using T-11N with 1MChip/s codes and 1.6 MHz bandwidth. The NIST and PTB signals were transmitted with 7.123 kHz offsets.

Figure 9. NIST/PTB TWSTFT differences from odd-hour (experiment) and even-hour (regular operation) measurements.

During an experiment between NIST and PTB using the T-11N satellite with 1 MChip/s codes and 2.5 MHz bandwidth in August 2010, we noticed there was no diurnal in the difference obtained during odd hours as shown in Figure 9 (a). Both NIST and PTB used the exact same equipment and parameters in the even-hour and the odd-hour TWSTFT. The only difference is there was no other TWSTFT signal transmitted during the NIST/PTB odd-hour TWSTFT, but USNO and a European station were doing TWSTFT during the NIST/PTB even-hour TWSTFT. This observation indicates the diurnal in the NIST/PTB even-hour TWSTFT came from the TWSTFT signals transmitted at the same time, or the interference of the in-band signals. To counteract the in-band signal interference, NIST and PTB introduced a 7.123 kHz offset at the 70 MHz intermediate TX and RX frequencies since MJD 55412 (August 4, 2010). However, the frequency offset has made no big difference in diurnal reduction. Figure 9 (b) shows the NIST/PTB even-hour and odd-hour differences in February 2012 using the T-11N satellite with 1 MChip/s codes and 1.6 MHz bandwidth. This time, the diurnal is present in both even-hour and odd-hour differences. In comparing the TWSTFT settings of the two even-hour/odd-hour experiments, the uplink and downlink frequencies were different and the bandwidth was reduced, but no earth station equipment was changed. A recent USNO/PTB even-hour and odd-hour experiment showed the diurnal is also present in both even-hour and odd-hour differences. This means the interference from the in-band signals was the dominant source of the even-hour diurnal during the 2010 experiment, but other elements became the dominant source of diurnal after the uplink and downlink frequencies changed as well as the bandwidth reduction in July 2011. One possible dominant source of the diurnal could be interference from out-of-band signals because there is not much separation between our TWSTFT signals and the neighboring signals after the bandwidth reduction. The other possible source is signal reflection as discussed in Section III. The reflection is both frequency and temperature dependent.

V. CORRELATION WITH EARTH STATION ENVIRONMENTAL MEASUREMENTS

The delay change of the TWSTFT equipment, especially those used out-doors, due to the daily temperature and humidity variation contributes to the diurnal in the TWSTFT difference. After analyzing the environmental measurements reported in the TWSTFT data files since 2007, we find no causal relationship between the diurnal in the TWSTFT difference and the earth station environmental data.



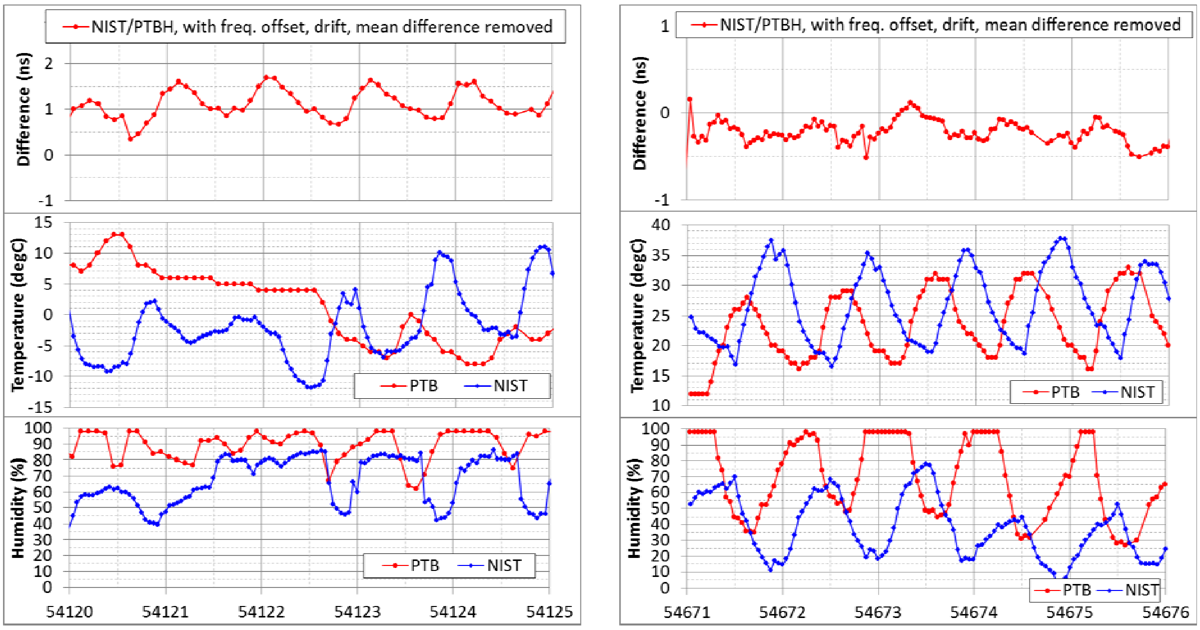
(a) NIST/PTB: no environmental diurnal for MJD 56384 but diurnal is shown in TWSTFT over the data period.

(b) NIST/OP: no environmental diurnal for MJD 55917 but diurnal is shown in TWSTFT over the data period.

Figure 10. Correlation of diurnal in TWSTFT difference and earth station environmental measurements when using the T-11N satellite with 1 MChip/s codes and 1.6 MHz bandwidth.

In Figure 10, it seemed the diurnal in both the NIST/PTB and NIST/OP TWSTFT is somewhat correlated to the NIST earth station temperature over the data periods. However, the change of temperature at NIST and PTB was small on MJD 56384 (Figure 10 (a)) and there was no temperature diurnal at NIST and OP on MJD 55917 (Figure 10 (b)), but the diurnal in TWSTFT differences remained the same on those days. We see the same situation in Figure 11 (a) for the NIST/PTB TWSTFT using the IS-707 satellite with 2.5 MChip/s codes and 3.7 MHz bandwidth. In Figure 11 (b), we see the NIST/PTB TWSTFT using the IS-3R satellite with 2.5 MChip/s codes and 3.7 MHz bandwidth contains small diurnal in that data period, while the temperature and humidity showed very large daily variations.

Notice that the maximum diurnal of the TWSTFT difference in Figure 10 occurs in the second half of the day (in UTC), whereas the diurnal maximum in Figure 11 occurs in the first half of the day. Because the differences are obtained using different satellites with different uplink and downlink frequencies, the diurnal pattern change could indicate that the delay variation due to earth station or satellite environment is related to the reflection of the TWSTFT signal in the transmission lines of the TWSTFT or satellite equipment which is both temperature and frequency sensitive.



(a) IS-707: small environmental diurnal for MJD 54121, but diurnal is shown in TWSTFT over the data period.

(b) IS-3R: large environmental diurnal but small diurnal is shown in TWSTFT over the data period.

Figure 11. Correlation of diurnal in NIST/PTB TWSTFT difference and earth station environmental measurements when using the IS-707 and IS-3R satellites with 2.5 MChip/s codes and 3.7 MHz bandwidth.

VI. CONCLUSIONS

With 1 MChip/s PRN codes and 1.6 MHz bandwidth on the T-11N satellite, there is a 1 to 2 ns peak-to-peak diurnal in all of the transatlantic TWSTFT links. In the presence of the diurnal, the best TDEV can only reach 100 ps at averaging times of 1 day (see Figure 8 (a)). With the ranging measurements from OP and PTB to the T-11N satellite and the IGS TEC map, we estimate the maximum combined diurnal contribution from path non-reciprocity, Sagnac effect and ionosphere delay is about 364 ps in a worst case. We have shown the magnitude and pattern of the diurnal changed when the transatlantic TWSTFT went through the satellite and parameter changes, which indicates the diurnal is dependent on satellite and TWSTFT parameters, including the uplink and downlink frequencies, chip-rate and bandwidth. The diurnal is reduced in the NIST/USNO TWSTFT differences as obtained from the NIST and USNO direct transatlantic TWSTFT measurements. This indicates the difference in delay variation of the two T-11N transponders used in transatlantic TWSTFT have a significant contribution to the diurnal. The diurnal can sometimes come from other TWSTFT signals transmitted at the same time. This in-band signal interference might be related to uplink and downlink frequencies, and it could be obscured by other diurnal contributors. Finally, we found no causal relationship between the 1 to 2 ns diurnal and the earth station's temperature and humidity variation.

With the 1.6 MHz bandwidth, there is very little or no separation between our signals and the neighboring signals. We plan to investigate the impact of interference from out-of-band signals on the diurnal in the TWSTFT difference in our upcoming study.

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(1) Commercial products and companies are identified for technical completeness only, and no endorsement by authors and organizations is implied.

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