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Doppler sensitivity and its effect on transatlantic TWSTFT links[3]

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Abstract

Some investigations have concluded that the diurnal pattern in the time comparison results of present two way satellite time and frequency transfer (TWSTFT) links may come mainly from Doppler dependent errors in the time of arrival (TOA) measurements made by the receivers of the TWSTFT modems. In this paper, several experiments were carried out to test if there is a Doppler dependent error in the 'delay' measurements of the receivers currently used. By simulating quantitative Doppler effects in the time transfer signal both on the carrier and the code, a type of Doppler sensitivity on the code was observed in the receivers, which has about -0.49 ns offset in 'delay' measurement for a 1×10^{-9} fractional Doppler shift. This sensitivity is basically the same for modems with different serial numbers from the same manufacture. We calculated this Doppler caused diurnal pattern in the time comparison results of the transatlantic TWSTFT link between NIST and PTB and found that it is very small and negligible, because the Doppler dependent error is almost identical in the NIST and PTB measurements and therefore it is nearly canceled in the TWSTFT difference.

Keywords: two way satellite time and frequency transfer (TWSTFT), Doppler effects, the diurnal pattern

(Some figures may appear in colour only in the online journal)

1. Introduction

Two way satellite time and frequency transfer (TWSTFT or TW) is a commonly used technique to precisely compare the time and frequency standards operated by laboratories in America, Europe and Asia. Its high precision and independence from the Global Navigation Satellite System (GNSS) make it very important for the generation of International Atomic Time (TAI) [1, 2]. However, a daily variation pattern, or diurnal, is observed in the time difference results in almost all of the TWSTFT links around the world, which significantly degrades the performance of the present TWSTFT links [3–5]. A number of studies have been carried out to understand the causes of the diurnal. Zhang and Parker [6] calculated the daily variation of the ionosphere effect on TWSTFT and the daily variation of the Sagnac effect due to the satellite movement, and concluded that neither of them is the main reason for the diurnal. For a longtime, the Doppler effects due to satellite motion has been considered as a potential contributor to the diurnal. Recently, Huang *et al* [7] proposed that the delay-locked loop (DLL) used in current TWSTFT modems may have a delay measurement error which is dependent on the daily satellite Doppler pattern, or some other factors, which could cause the observed diurnal. In this paper, we investigated the Doppler sensitivity of current TWSTFT modems and estimated its effect on the transatlantic TWSTFT links.

In section 2, we investigate the Doppler response of the DLL in the SATRE modem's receiver module. SATRE modems are manufactured by TimeTech GmbH∗ and used by all of the TWSTFT links for TAI. By simulating Doppler effects on the carrier and code of the time transfer signal, we

[3] Commercial products are identified for technical completeness only, and no endorsement by NIST is implied.

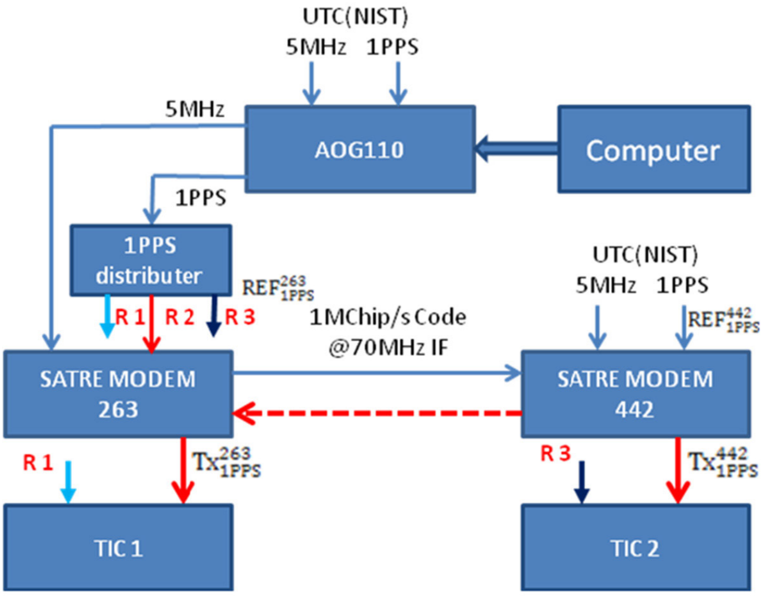

Figure 1. Diagram of the 'IF' experiment for the Doppler response measurement. The 10 MHz from UTC(NIST) is used as the time-base reference for the TICs.

find a type of Doppler sensitivity in the modem. We observe that it has about a -0.49 ns offset in the 'delay' measurements for a $+1 \times 10^{-9}$ fractional Doppler shift. We also find that the value of this Doppler sensitivity is almost the same among three different SATRE modems. By calculating the TWSTFT link geometry and the Doppler characteristic of the transatlantic link between NIST and PTB in section 3, we deduce that this Doppler sensitivity can only cause a very small amount of the diurnal in the TWSTFT difference and is not the main reason for it. We summarize our study in section 4.

2. Doppler response of SATRE modem

In this section, we discuss a series of bench experiments that were carried out to evaluate the Doppler response characteristics of the receiver module in SATRE modems.

2.1. Doppler response experiment at the intermediate frequency

The diagram of the Doppler experiment setup is shown in figure 1. In the experiment, two modems (identified as modem 263 and 442) are used to make intermediate frequency ('IF') two-way measurements, that is to say the 70 MHz 'IF' transmit (TX) signal of modem 263 is sent directly to the receive (RX) 'IF' input port of modem 442 by a coaxial cable, and vice versa. The reference frequency and 1 PPS (pulse per second) for modem 442 are UTC(NIST). However, the reference frequency and 1 PPS for modem 263 come from an auxiliary output generator (AOG). The reference frequency for the AOG is from UTC(NIST) and the 1 PPS from the AOG is initially referenced to the 1 PPS from UTC(NIST). We use a computer to control the AOG and adjust its output frequency by small frequency steps. The AOG 1 PPS output is also affected by the frequency steps. By doing this, Doppler effects are simulated in both the carrier and code signals transmitted by modem 263 as compared to modem 442. Modem 442 receives the simulated time transfer signal, and makes the measurement. We express it by

$$\Delta T_{442} = Tx^{442}_{1\,\mathrm{PPS}} - Rx^{442}_{1\,\mathrm{PPS}}. \tag{1}$$

where ΔT_{442} is the 'delay' or ($TX - RX$) measurement of modem 442, $Tx^{442}_{1\,\mathrm{PPS}}$ is the transmitted 1 PPS which represents the timing of the modem 442's reference clock and $Rx^{442}_{1\,\mathrm{PPS}}$ is the received 1 PPS of modem 442. We know that $Rx^{442}_{1\,\mathrm{PPS}}$ is restored from the transmitted signal of modem 263 through the transmitting path. If the path delay is a constant, then $Rx^{442}_{1\,\mathrm{PPS}}$ can be expressed as $Tx^{263}_{1\,\mathrm{PPS}} + C_1$. Thus,

$$\Delta T_{442} = Tx^{442}_{1\,\mathrm{PPS}} - Tx^{263}_{1\,\mathrm{PPS}} - C_1. \tag{2}$$

where $Tx^{263}_{1\,\mathrm{PPS}}$ is the transmitted 1 PPS of modem 263 and C_1 is the fixed path delay. Theoretically, the transmitted 1 PPS is always synchronized to $\mathrm{REF}^{263}_{1\,\mathrm{PPS}}$ with a fixed delay which we refer to as the transmitted delay. Here $\mathrm{REF}^{263}_{1\,\mathrm{PPS}}$ ($R1$, $R2$ and $R3$ in figure 1) is the 1 PPS reference split from the AOG 1 PPS output by a pulse distribution amplifier, with $R2$ used as the 1 PPS reference for modem 263. Then the measurement of modem 442 can be expressed as

$$\Delta T_{442} = Tx^{442}_{1\,\mathrm{PPS}} - \mathrm{REF}^{263}_{1\,\mathrm{PPS}} - C_1 - C_2. \tag{3}$$

where C_2 is the transmitted delay of modem 263.In order to check if there is any measurement offset in ΔT_{442}, a commercial time interval counter (TIC2 in figure 1) is used to measure the time interval of $\mathrm{REF}^{263}_{1\,\mathrm{PPS}}$ and $Tx^{442}_{1\,\mathrm{PPS}}$ directly, which can be expressed as

$$\Delta T_{\mathrm{TIC2}} = \mathrm{REF}^{263}_{1\,\mathrm{PPS}} - Tx^{442}_{1\,\mathrm{PPS}} = -\Delta T_{442} - (C_1 + C_2). \tag{4}$$

This quantity is opposite in sign to ΔT_{442} with a fixed offset. Herein the TIC2 measurement is used as the 'true value' to check the measurement of modem 442.

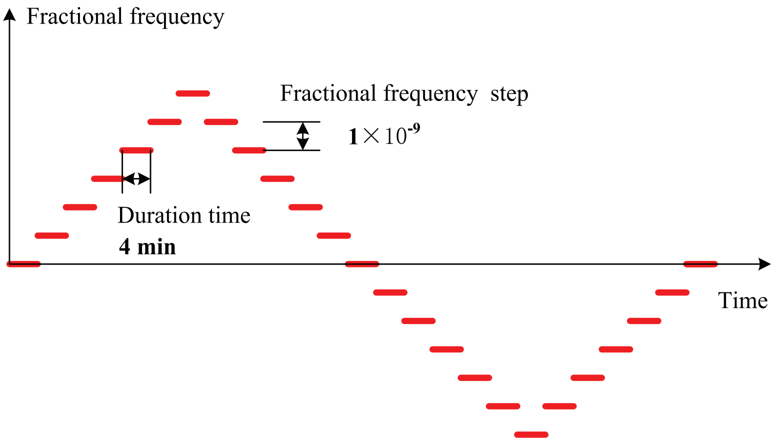

Figure 2. The relative frequency pattern designed to control the AOG to simulate the Doppler shift.

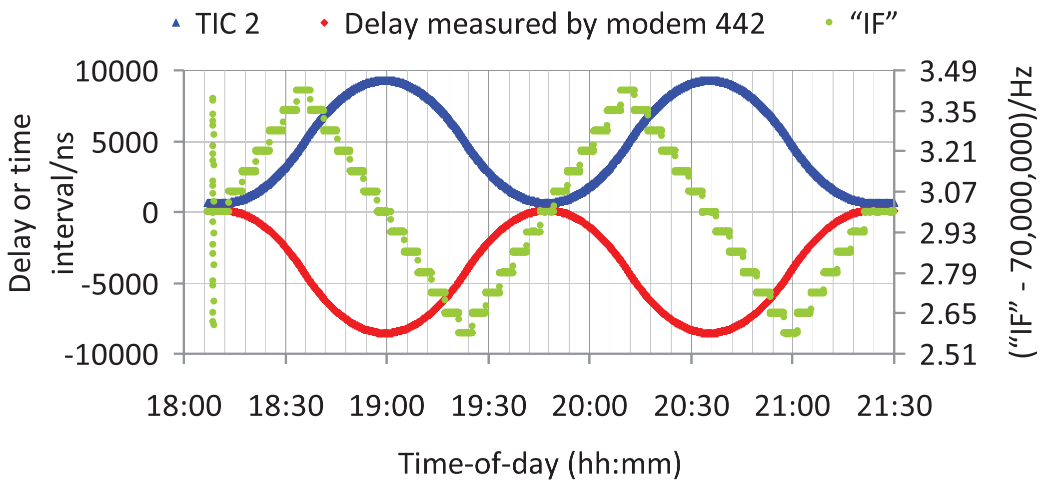

Figure 3. Curves of the 'delay' measured by modem 442, time interval measured by TIC2 and the intermediate frequency ('IF') measured by modem 442 during the time the Doppler shifts is simulated.

During the experiment, we set the code rate of the time transfer signal to 1 MChip s^{-1} which is the same as used in the transatlantic TWSTFT links. The 'IF' is 70.000 003 MHz. We program a relative frequency variation pattern (see figure 2) and control the output frequency of the AOG. The output frequency of the AOG is varied over a range from a fractional frequency of -6×10^{-9} to $+6 \times 10^{-9}$ with a step size of 1×10^{-9}. The duration for each step is 4 min. By adjusting the reference of modem 263, we effectively simulate a Doppler shift added to both carrier and code in the transmitted signal from the point of view of modem 442. The range of this fractional frequency variation at 'IF' is about the same level as the fractional Doppler variation in operational TWSTFT links.

The total duration of the test is about four hours. We then analyzed the received 'IF' (received intermediate frequency with simulated Doppler shift) and 'delay' measurements from modem 442 together with the time interval measurements from TIC2. The curves of those quantities are illustrated in figure 3. The 'IF' measured by modem 442 is almost identical to the pattern we programmed, which means the carrier loop in the modem's receiver module tracks the carrier frequency's Doppler shift very well. The measurements by TIC2 and the 'delay' measurements by modem 442 appear highly symmetrical, which agrees with equation (4).

However, when we add the two groups of measurements together, we get a new pattern as shown in figure 4. The pattern illustrates clearly that there is an offset between the TIC2 measurements and the modem's 'delay' measurements. Because TIC2 makes a direct 1 PPS measurement, its measurement is more reliable. However, the modem measurements are more complex, and it is logical that we attribute this pattern of offset to the modem. There are two possibilities that the modem could cause this pattern. One is a measurement error made by the receiver module of modem 442 in receiving the Doppler shifted signal. The other possibility is that the transmitted delay of modem 263, or C_2, may change with the frequency adjustment. In order to detect if the transmitted delay is fixed or not during the experiment, another TIC (TIC1) is used to measure the interval between $Tx^{263}_{1\,\mathrm{PPS}}$ and $\mathrm{REF}^{263}_{1\,\mathrm{PPS}}$ (see figure 1).We find the TIC1 measurements are basically flat, although the measurement noise is larger when the AOG is being adjusted. Therefore, the offset pattern must come from the receiver module of modem 442. Figure 5 illustrates the correlation between the fractional Doppler shift and the measurement offset of modem 442. They are highly correlated with a linear slope equal to -0.49. Here we call this slope the Doppler sensitivity coefficient of the modem and represent it as s.

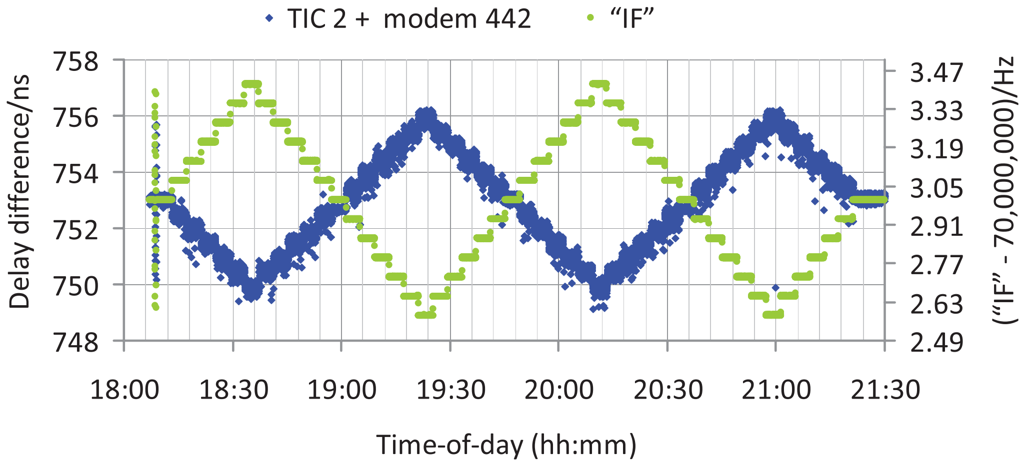

Figure 4. Delay offset between modem 442 measurements and the TIC2 measurements. The blue dots are the differences of measurements made by modem 442 and TIC2 (representing the true value). The green dots are the 'IF' measured by modem 442.

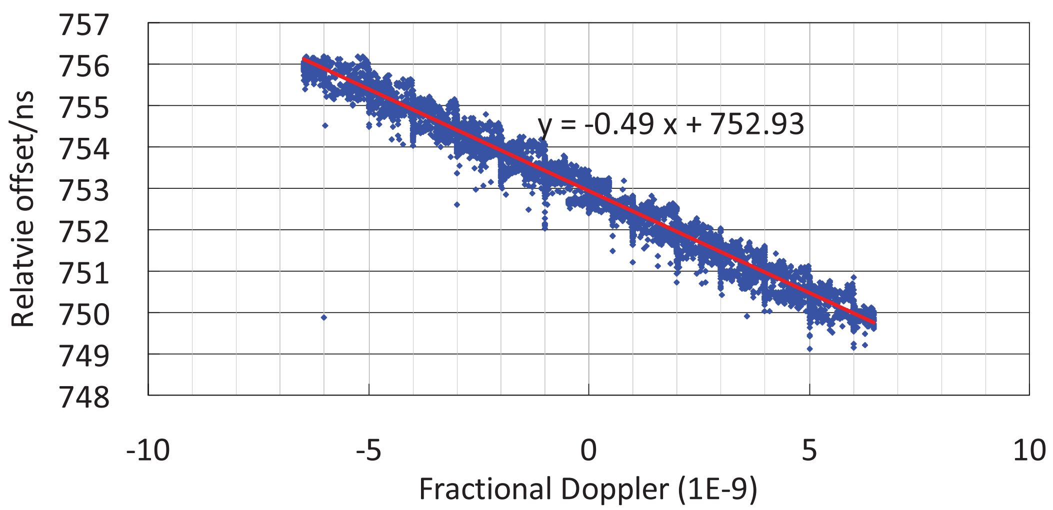

Figure 5. Correlation between fractional Doppler shift and the measurement offset of modem 442.

In operational TWSTFT links, there is Doppler shift in the received timing signal due to the geostationary (GEO) satellite motion. Typically, the fractional Doppler shift is in the range of -6×10^{-9} to $+6 \times 10^{-9}$ in one day, which means the rate of the range change from one earth station to the satellite and then to the other station spans from about -3 ns s^{-1} to $+3$ ns s^{-1}. That is to say, this kind of Doppler sensitivity will produce about a 6 ns daily peak-to-peak variation in the 'delay' measurements of one direction.

2.2. Consistency of Doppler response among different modems

From the above analysis, we reach the conclusion that the 'delay' measurement of modem 442 is linearly correlated to the fractional Doppler shift with a coefficient equals to about -0.49 ns/1 $\times$ 10^{-9}. This Doppler sensitivity may be the cause of the diurnal in operational TWSTFT links. To test this hypothesis, we have to answer the following questions: Does this Doppler sensitivity exist in other modems? Do they have the same coefficients?

In the previous experiment, modem 263 also receives the time transfer signal from modem 442. So modem 263 also responds to an effective Doppler shift in making 'delay' measurements for the signal transmitted from modem 442. However, the Doppler value that modem 263 observes is opposite in sign from what modem 442 sees. During the experiment, we collected the data measured by modem 263 and modem 442 simultaneously. Using a similar analysis as previously, we find that TIC2 and modem 263 are measuring two quantities that have a fixed offset relative to each other. Subtracting the measurements of modem 263 from the measurements of TIC2, we get an offset pattern which has almost the same features as figure 4. To get a closer look at the offset discrepancy of modem 442 and modem 263, we subtract the offset values of modem 263 from the offset values of modem 442 and obtain figure 6. It's clear that the two modems have essentially the same Doppler sensitivity.

To further verify the consistency of the Doppler sensitivity, a third SATRE modem (modem 706) was chosen to replace modem 263. The same experimental procedures and analyses were carried out again and the same results were obtained.

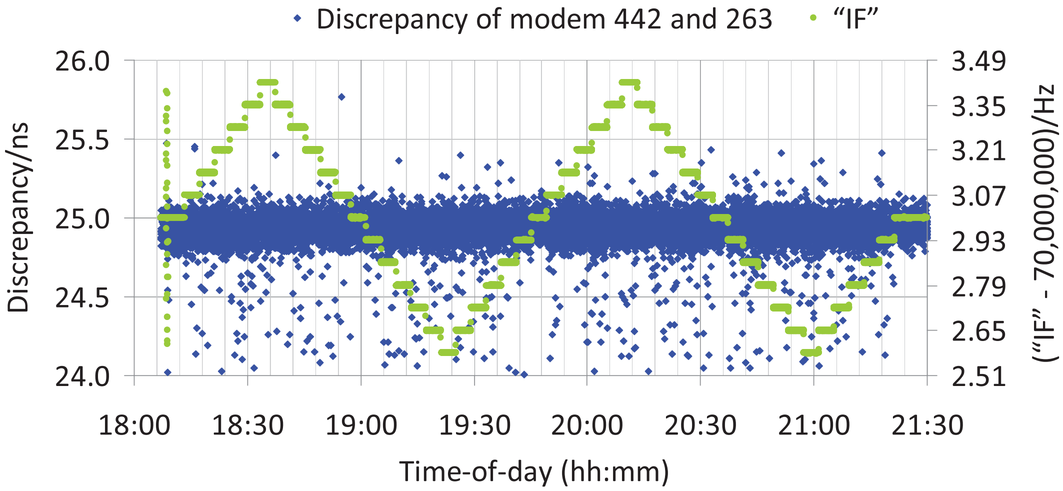

Figure 6. Difference of the delay offsets obtained by modem 263 and modem 442.

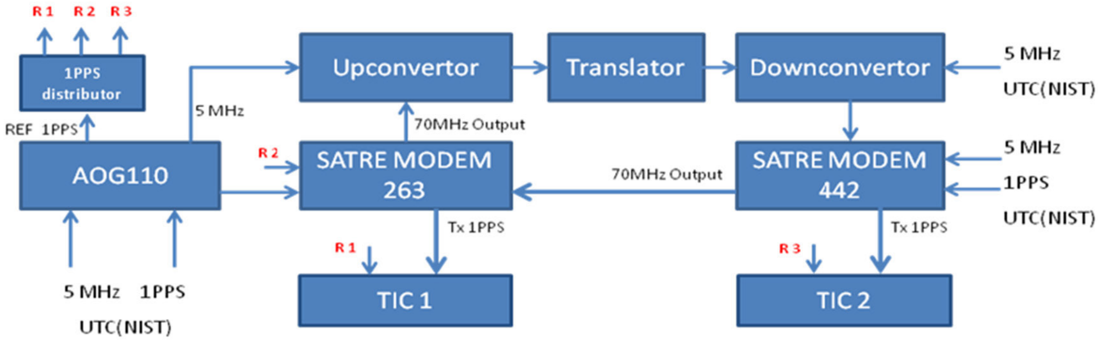

Figure 7. Diagram of the Doppler response experiment with Doppler introduced at Ku-band frequencies and the 'IF'. UTC(NIST) 10 MHz is used as the reference for the TIC1 and TIC2 time-base.

Since the device serial numbers of the three modems are significantly different from each other and they should be produced indifferent batches, it is very likely that all of the SATRE modems may have the same value of Doppler sensitivity.

2.3. Doppler response experiment at Ku-band and intermediate frequencies

In operational TWSTFT links, the absolute carrier frequency's Doppler shift, in Hz, at Ku-band is much larger than that simulated in the 'IF' bench experiment. To determine if the Doppler shift on the Ku-band carrier frequency has any additional effects on the 'delay' measurements, an asymmetrical Ku-band and 'IF' two-way experiment was designed. The diagram of the experiment setup is shown in figure 7. Here the 'IF' signal from modem 263 is up-converted to the uplink Ku-band frequency, translated to the downlink Ku-band frequency by a translator, and then down-converted back to the 'IF'. However, the signal from modem 442 to 263 is still the direct 'IF' signal. The local oscillator of the up-convertor is referenced to the output of the AOG. When the AOG is adjusted, the carrier frequency of the signal from modem 263 to 442 changes, while the 'IF' signal in the opposite direction does not. Figure 8 shows the delay offset between modem 442 and TIC2 measurements together with its measured 'IF'. The delay offset is same as the previous result. The received 'IF' is noisier than before, and has an obvious drift in it. This noise and drift come from the free running crystal oscillator in the translator. We calculate the difference of the delay offset measurements made by modems 442 and 263, and find that the delay offset of the modem is not affected by the Doppler shift in the Ku-band carrier frequency.

From these experiments, we reach the following conclusions:

(1) There are offsets in 'delay' measurements in SATRE modems which are only sensitive to the fractional Doppler shift in the code. The sensitivity coefficient is about -0.49 ns/1×10^{-9} (where 1×10^{-9} is the fractional Doppler shift in the code).
(2) Three SATRE modems exhibited essentially the same Doppler sensitivity. Therefore, it is likely that all SATRE modems are the same.

3. The effects of Doppler sensitivity on transatlantic TWSTFT links

Basically, the code Doppler shifts for the paths from East to West and from West to East due to the motion of the geostationary satellite should be the same in a typical transatlantic link. Thus the Doppler induced delay offset seen by modems on each side will nearly be cancelled if the modems have the same sensitivity, which they appear to have. However, if

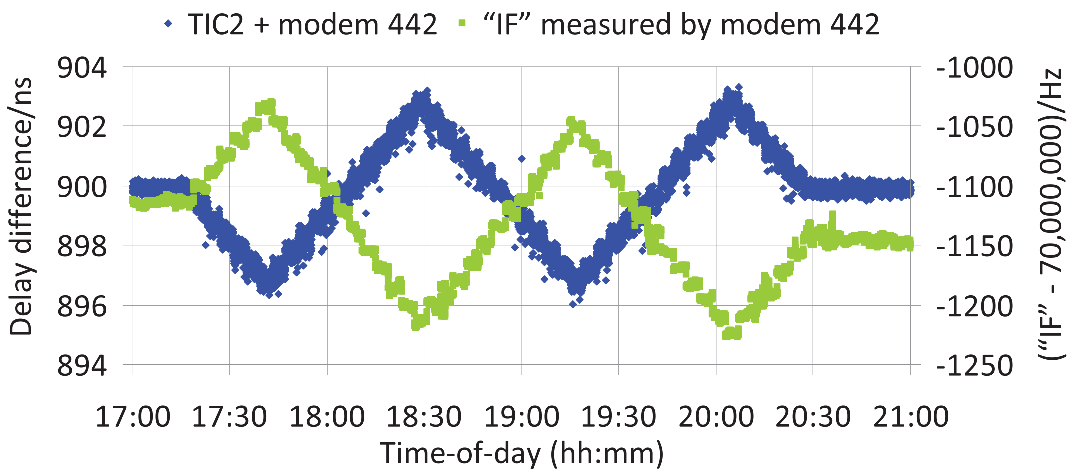

Figure 8. Delay offset between modem 442 and TIC2 measurements with Doppler introduced at Ku-band frequencies and the 'IF'.

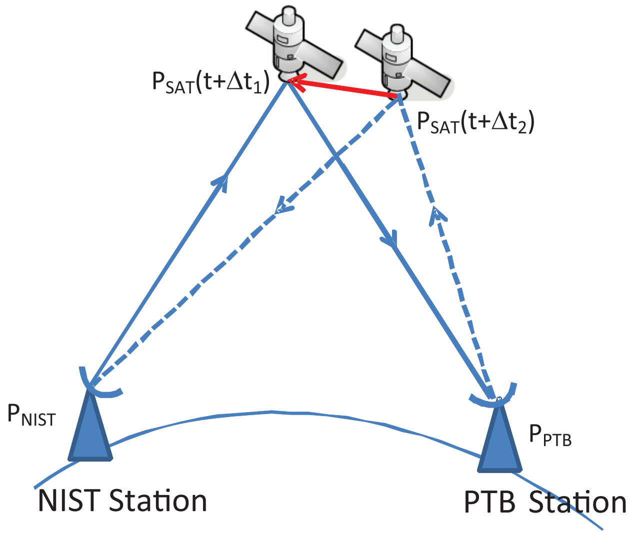

Figure 9. Geometry of the NIST and PTB TWSTFT link.

Table 1. Osculating elements of Telstar 11N.

Osculating elements	Value
Epoch	2013:075:07:35:34:365 UTC
Semi-major axis	42 166.138 046 km
Eccentricity	0.000 201 838 89
Inclination	0.021 938°
Mean anomaly	281.228 577°
Augment of perigee	154.532 491°
Right ascension of ascending node	174.648 549°

we examine the situation carefully, we will find the time of arrival (TOA) of the two signals at the satellite is not exactly the same, which means the observed Doppler shifts will not be identical and may have differences. Due to the fact that the motion of the satellite is a diurnal pattern, the Doppler differences between the two directions in TWSTFT are also a diurnal pattern. In this section we will examine the magnitude of this Doppler induced diurnal pattern in transatlantic TWSTFT links.

For this investigation, the TWSTFT link between NIST (National Institute of Standards and Technology) in Boulder, Colorado and PTB (Physikalisch-Technische Bundesanstalt) in Germany is used as an example, which is a typical transatlantic link. Telstar 11N$*$ is the satellite for the link. We have estimated the code Doppler differences in this link based on the geometry of the earth stations and the satellite (see figure 9).

Assuming $\boldsymbol{p}_{\text{NIST}}$, $\boldsymbol{p}_{\text{SAT}}$, $\boldsymbol{p}_{\text{PTB}}$ are the positions of the NIST earth station, satellite and PTB earth station, respectively, in the earth-centered, earth-fixed (ECEF) reference system, the range that the signal propagates at time t from NIST to the satellite and then to PTB is

$$R_{\text{NIST-PTB}} = \left|\boldsymbol{p}_{\text{NIST}}(t) - \boldsymbol{p}_{\text{SAT}}(t+\Delta t_1)\right| + \left|\boldsymbol{p}_{\text{SAT}}(t+\Delta t_1) - \boldsymbol{p}_{\text{PTB}}(t+\Delta t_1+\Delta t_2')\right|. \tag{5}$$

The signal is simultaneously transmitted from PTB to the satellite and then to NIST, and the range is,

$$R_{\text{PTB-NIST}} = \left|\boldsymbol{p}_{\text{PTB}}(t) - \boldsymbol{p}_{\text{SAT}}(t+\Delta t_2)\right| + \left|\boldsymbol{p}_{\text{SAT}}(t+\Delta t_2) - \boldsymbol{p}_{\text{NIST}}(t+\Delta t_1'+\Delta t_2)\right|. \tag{6}$$

Here, Δt_1 is the signal travel time at t from NIST to the satellite. Δt_2 is the travel time at t from PTB to the satellite. $\Delta t_1'$ is the signal travel time at $t+\Delta t_2$ from satellite to NIST. $\Delta t_2'$ is the signal travel time at $t+\Delta t_1$ from satellite to PTB.Here the group delay of the satellite transponder is neglected.

According to the Doppler equation, the fractional code Doppler can be expressed as

$$D(t) = \frac{1}{c}\cdot\frac{\mathrm{d}R(t)}{\mathrm{d}t}. \tag{7}$$

Where c is the velocity of light. Thus, the fractional code Doppler difference is

$$\Delta D(t) = \frac{1}{c}\cdot\frac{\mathrm{d}[R_{\text{NIST-PTB}} - R_{\text{PTB-NIST}}]}{\mathrm{d}t} \approx \frac{\mathrm{d}v_{\text{NIST-SAT-PTB}}(t)}{c\cdot\mathrm{d}t}\cdot(\Delta t_1 - \Delta t_2). \tag{8}$$

Where $v_{\text{NIST-SAT-PTB}}(t)$ is the range variation rate from NIST to satellite to PTB, and $\Delta t_1 - \Delta t_2$ is the TOA difference of the signal from NIST to the satellite and from PTB to the satellite. Then the diurnal caused by the code Doppler difference is $s\cdot\Delta D(t)$, where s is the Doppler sensitivity.

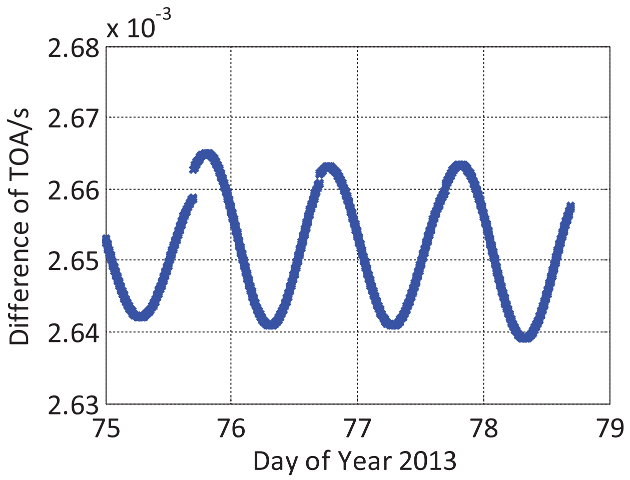

Figure 10. TOA difference between NIST to satellite and PTB to satellite.

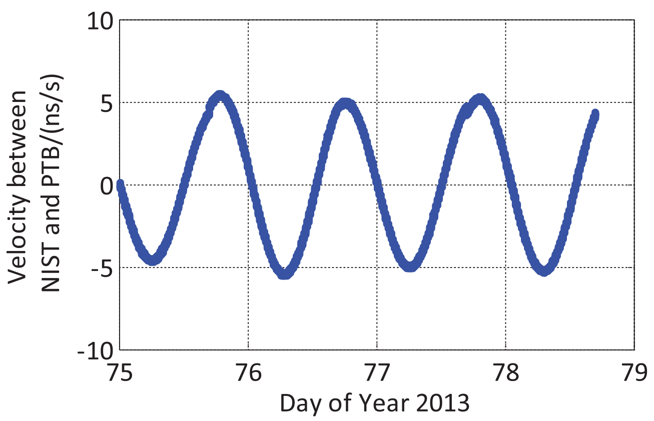

Figure 11. Range variation rate (the velocity) from NIST to satellite to PTB.

Since the precise position coordinates of the satellite are not accessible, the orbit osculating elements are used to give an approximate calculation of the satellite position and velocity. Reference [8] gives the definition of the osculating elements and the algorithms for satellite position calculation according to those elements. Table 1 lists the osculating elements of the Telstar 11N satellite for a certain epoch (the data was provided by Telesat, the owner and operator of the satellite).

Four groups of osculating elements from epoch 2013: 075–2013:078 at one point each day are used to calculate the positions of the satellite during the time. Considering the position coordinates of station NIST and PTB, the TOA differences between NIST—Satellite and PTB—Satellite are shown in figure 10. There are four segments of data computed from the four groups of elements. Discontinuities exist at the boundary of each segment due to the calculation errors of positions using the osculating elements.

To give an approximate estimation of the fractional Doppler difference in the code, a sin function is used to fit the curve of $v_{\mathrm{NIST-SAT-PTB}}(t)$ in figure 11, that is

$$v_{\mathrm{NIST-SAT-PTB}}(t) = A \cdot \sin(2\pi {}^{t}\!/_{T} + \varphi). \tag{9}$$

The amplitude $A \approx 1.74\,\mathrm{m\,s^{-1}}$, and $T = 86\,400$ is the variation period of the velocity. Therefore, the diurnal due to the Doppler difference in code is

$$s \cdot D(t) = s \cdot \frac{2\pi A}{T} \cdot (\Delta t_1 - \Delta t_2) \cdot \cos(2\pi {}^{t}\!/_{T} + \varphi)$$
$$\leqslant 5.4 \times 10^{-7}\,\mathrm{ns}.$$

From the above calculation, the Doppler asymmetry in code of the transatlantic link is so small that the Doppler caused diurnal is negligible.

4. Conclusions

The Doppler shift caused by satellite motion is suspected as a possible source of the observed diurnal in TWSTFT time comparisons. From several bench experiments, a Doppler sensitivity in the modem's receiver module is observed, which is linearly dependent on the fractional Doppler shift in the code. This sensitivity causes a -0.49 ns offset in the 'delay' measurement when the fractional Doppler is $+1 \times 10^{-9}$. This sensitivity is only related to the Doppler in the code and not in the carrier. The delay error is most likely caused by the DLL in the SATRE modem. For SATRE modems with different serial numbers, the sensitivity coefficient is essentially the same. This may not be the case if modems from different manufactures are used.

In transatlantic TWSTFT links, the Doppler shift seen by modems on each side is nearly the same except for slight differences in the TOA at the satellite. The magnitude of the diurnal caused by this TOA induced Doppler differences in the NIST and PTB TWSTFT link has been estimated. Our analysis shows that the Doppler differences in the code in both directions are mostly cancelled, and therefore the Doppler induced diurnal pattern is so small that it is negligible compared to the observed diurnal in the operational TWSTFT measurements.

Disclaimer

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