Transatlantic 2.5 MChip/s Two-Way Satellite Time and Frequency Transfer with Surface Acoustic Wave Filters

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***Abstract*—From August 2010 to April 2011, NIST and OP conducted an experiment of using surface acoustic wave (SAW) filters in transatlantic two-way satellite time and frequency transfer (TWSTFT) with 2.5 MChip/s pseudo-random noise (PRN) codes. The SAW filters used in the experiment are 2.5 MHz band-pass filters with a center frequency of 70 MHz. Instead of using 3.5 MHz bandwidth required for the 2.5 MChip/s signal, the use of SAW filters allows the 2.5 MChip/s TWSTFT to use only 2.5 MHz bandwidth on a satellite transponder. We evaluated the SAW filters. We compared the time transfer instability of the filtered 2.5 MChip/s TWSTFT to the 1 MChip/s TWSTFT with and without the SAW filters. This paper presents the experiment results**.

I. Introduction

The timing information of TWSTFT signals is carried by PRN codes [1]. The resolution of TWSTFT measurements is proportional to the chip-rate of the PRN code being used. The minimum bandwidth required for a TWSTFT signal is approximately 1.4 times the chip-rate of the PRN codes [2].

The transatlantic TWSTFT network used 2.5 MChip/s PRN codes with 3.5 MHz bandwidth, in Ku-band, from the early 1990s, when the network was established, until a satellite change in July 2009. The TWSTFT operation was then changed to use 1 MChip/s PRN codes with 2.5 MHz bandwidth. The chip-rate reduction was made because of the significant increase in satellite subscription cost, and our previous study [3] showed the time transfer instability, as measured by the Time deviation (TDEV), of the 1 MChip/s TWSTFT was about the same as the TDEV of the 2.5 MChip/s TWSTFT for averaging times of one day and longer. The SAW filters were not available at the time of our previous study. We acquired 2.5 MHz bandwidth on the new satellite so we could do experiments on the 2.5 MChip/s TWSTFT with SAW filters after the filters were made available in early 2010.

The concept of 2.5 MChip/s TWSTFT with SAW filters was proposed by colleagues at the National Institute of Information and Communication Technology (NICT) in Japan. Previous experiments were conducted in the Asian-Pacific TWSTFT network. The scheme takes advantage of the high measurement resolution of the 2.5 MChip/s codes, but limits the TWSTFT signal to 2.5 MHz bandwidth with SAW filters. To study the performance of the filtered 2.5 MChip/s TWSTFT with SAW filters across a transatlantic link, NIST and OP conducted an experiment from August 2010 to April 2011with the SAW filters kindly loaned to us by TimeTech GmbH* of Germany. We show characteristics of the SAW filters used in our experiment and the experiment configuration in Sections II and III. Analysis of the 2.5 MChip/s TWSTFT with SAW filters is presented in Section IV. Section V summarizes the experiment results.

II. Characteristics of the 2.5MHz Band-Pass SAW Filter

Figure 1 shows the spectrum of the 1 MChip/s code (in red), main lobe of the 2.5 MChip/s code (in green) and the

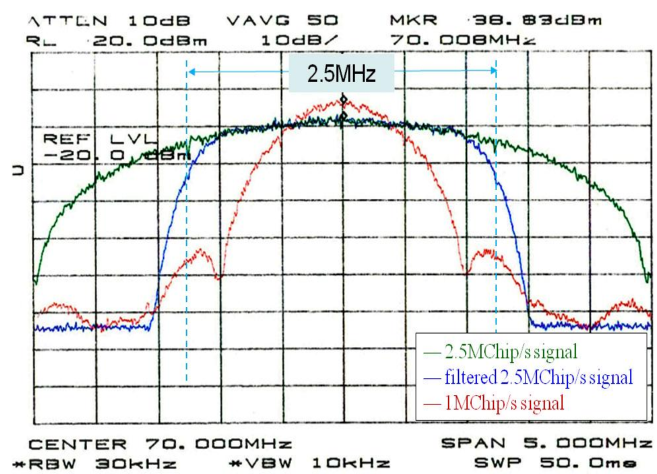

Figure 1. Spectrum of the 1 MChip/s (in red), main lobe of the 2.5 MChip/s (in green) and the filtered 2.5 MChip/s (in blue) TWSTFT signals.

*Commercial products and companies are identified for technical completeness only, and no endorsement by authors and organizations is implied filtered 2.5 MChip/s code (in blue). When comparing the filtered 2.5 MChip/s signal to the 2.5 MChip/s signal, we see that the SAW filter provides unity gain to the 2.5 MChip/s signal in a range of about 2 MHz centered at 70 MHz. The 2.5 MChip/s signal is attenuated about 15 dB at the 2.5 MHz boundaries. Because the main lobe of the 1 MChip/s signal is bounded by 2 MHz, passing a 1 MChip/s signal through the SAW filter does not distort the main lobe.

We evaluated the SAW filter's characteristics by a loop test using a SATRE* modem manufactured by TimeTech and the SAW filter unit at NIST. The peak-to-peak variation of the one-second measurements increases by about 50 ps for each SAW filter added in the loop [4]. The use of the SAW filter inserts a large signal path delay of about 5.2 µs. This delay is sensitive to temperature variations, with a temperature coefficient estimated to be 200 ps/°C. However, the delay sensitivity to temperature can be compensated by use of SAW filters in both the transmit (TX) and receive (RX) paths. Figure 2 shows the SAW filter's delay response to frequency change. The measurements were made with SAW filters in both TX and RX paths. We shifted TX and RX frequencies from -10 kHz to +10 kHz in 2 kHz steps with respect to 70 MHz. The delay dependence on frequency varies between 184 ps/2 kHz and 289 ps/2 kHz.

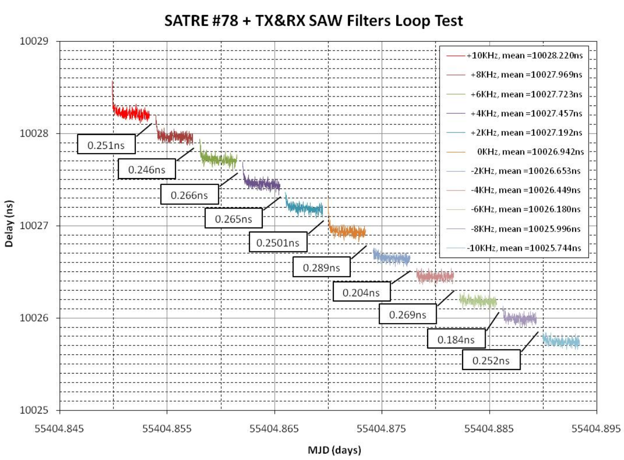

Figure 2. SAW filter's delay response to frequency change of ±10 kHz with respect to 70 MHz. Each step corresponds to the delay for a 2 kHz frequency change.

The SAW unit at OP was also evaluated by use of a vector analyzer. Figure 3 shows the measurement results of return loss (Trace 1, in yellow), insertion loss (Trace 2, in blue) and delay response to frequency change (Trace 3, in red). These characteristics were evaluated for frequencies from 68.9 MHz to 71.1 MHz. After correcting for the delays and for the losses from the cables and adaptors used in the measurements, the return loss is about 30 dB, which means the SAW filters have a very good impedance match. The insertion loss is about 0.4 dB for 70 ± 1 MHz. The delay through a SAW filter is 4.842 µs at 70 MHz, which is about 360 ns different than the SAW filter unit at NIST. Figure 3 also shows the SAW filters' delay response to frequency change is not linear.

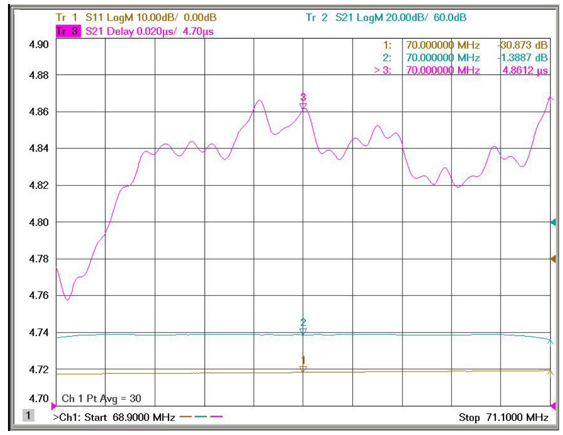

Figure 3. SAW filter's return loss (Trace 1, in yellow), insertion loss (Trace 2, in blue) and delay response to frequency change (Trace 3, in red) measured by a vector analyzer

Although the large constant delay introduced by SAW filters will be mostly canceled in the TWSTFT difference, TWSTFT links using SAW filters should be recalibrated to correct for the residual of delay difference of the two directions. The frequency of the received TWSTFT signal varies due to the daily satellite motion, or due to free running internal oscillators in some transceivers. The SAW filter's delay response to frequency change will increase the uncertainty of TWSTFT.

III. EXPERIMENT CONFIGURATION

The regular NIST/OP 1MChip/s TWSTFT measurements are made in a 2-minute session during even hours of Coordinated Universal Time (UTC), 12 times a day. The experiment measurements were made in three 2-minute sessions during odd hours of UTC. Table 1 shows the measurement schedule. The measurement of odd-hour 1 MChip/s TWSTFT without SAW filters was added in March 2011 to study the effect of SAW filters on the 1 MChip/s TWSTFT. No other station, but NIST and OP, transmitted signals during the three odd-hour sessions.

TABLE 1 TWSTFT measurement schedule

Measurements	Measurement sessions	Measurement period
1 MChip/s without SAW filter (regular transatlantic link)	2-minute in even hours, 12 times a day	August 18, 2010 to April 11, 2011 (MJDs 55426 to 55662)
1 MChip/s without SAW filter	2-minute in odd hours, 12 times a day	March 25, 2011 to April 11, 2011 (MJDs 55645 to 55662)
1 MChip/s with SAW filter	2-minute in odd hours, 12 times a day	August 18, 2010 to April 11, 2011 (MJDs 55426 to 55662)
2.5 MChip/s with SAW filters	2-minute in odd hours, 12 times a day	August 18, 2010 to April 11, 2011 (MJDs 55426 to 55662)

Figure 4 shows a block diagram of the experiment configurations at NIST and OP. Both NIST and OP used

SATRE modems for all the TWSTFT measurements. A TimeTech SAW filter unit contains two SAW filters, one for the TX path and one for the RX path. The signals for the TWSTFT with SAW filters went through the TX and RX SAW filters at both NIST and OP.

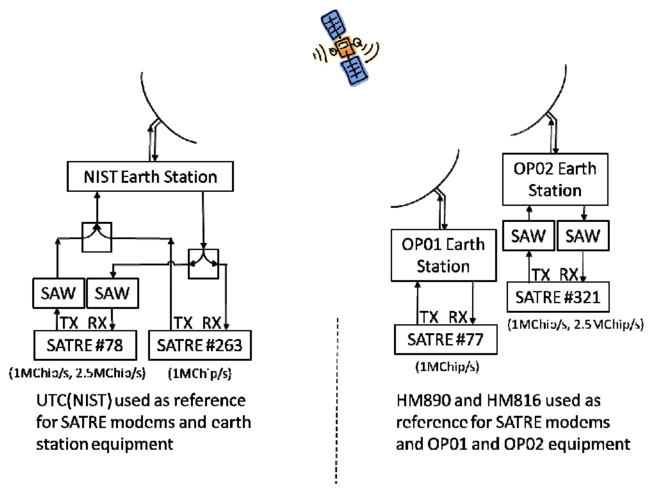

Figure 4. Block Diagram of NIST/OP TWSTFT with and without SAW filters.

At NIST, the same earth station and same radio-frequency (RF) equipment were used for both TWSTFT with and without SAW filters. A pair of power combiner and power splitter was used to channel the TWSTFT signals between the earth station equipment and the two modems. At OP, earth station OP01 was used for TWSTFT without SAW filter, and earth station OP02 was used for the TWSTFT with SAW filters.

Reference signals for the NIST TWSTFT were derived from the NIST time scale, UTC(NIST). During the experiment, reference signals for the OP TWSTFT were derived from two hydrogen MASERs, HM890 and HM816. The HM816 was used for MJDs 55496 to 55593 (October 27, 2010 to February 1, 2011) during the maintenance of HM890. The corrections for converting the OP reference signals to UTC(OP) are available, but were not used in our analysis.

IV. RESULTS OF THE 2.5 MCHIP/S TWSTFT USING SAW FILTERS

We compared the 2.5 MChip/s TWSTFT using SAW filters to the 1 MChip/s TWSTFT with and without SAW filters. We also investigated the effect of SAW filters on the 1 MChip/s PRN codes by comparing the 1 MChip/s TWSTFT with and without SAW filters. Because the NIST/OP link with SAW filters is not calibrated with respect to the NIST/OP link without SAW filters, we are not able to estimate the delay change from use of SAW filters. We will focus our analysis on the time transfer instability of the TWSTFT using SAW filters. The experiment results are shown in Figures 5 through 7.

Figure 5 shows the three TWSTFT differences between UTC(NIST) and OPH (hydrogen MASER) for MJDs from 55433 to 55662. The three differences are for the even-hour 1 MChip/s TWSTFT without SAW filters (in red), the odd-hour 1 MChip/s TWSTFT with SAW filters (in blue) and the odd-hour 2.5 MChip/s TWSTFT with SAW filters (in green). The frequency offset, drift and mean time difference are removed from the direct NIST/OPH differences. The even-hour 1 MChip/s TWSTFT without SAW filter contains larger short-term variations than the odd-hour 1 MChip/s and 2.5 MChip/s TWSTFT with SAW filters until around MJD 55610. The larger short-term variation might be introduced by interference from other TWSTFT signals transmitted at the same time with about the same frequency during even hours [4]. The reduction of short-term variation after MJD 55610 is partially attributed to a frequency offset in the NIST TX signal introduced to mitigate the multi-signal interference. Figure 5 also shows a big difference fluctuation when the HM816 was used as the reference clock at OP.

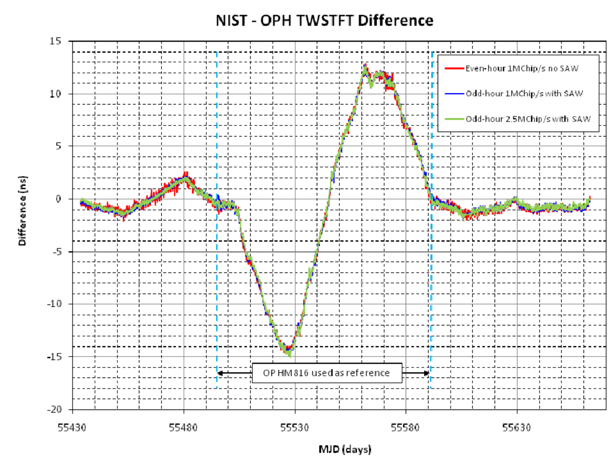

Figure 5. NIST/OPH TWSTFT differences for even-hour 1 MChip/s without SAW filters (in red), odd-hour 1 MChip/s with SAW filters (in blue), and 2.5 MChip/s with SAW filters (in green). Frequency offset, drift and mean time difference are removed from the differences.

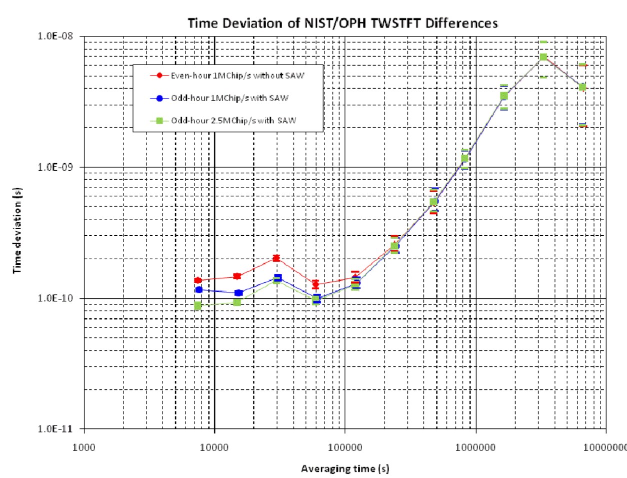

Figure 6. Time transfer instability of the NIST/OPH TWSTFT for MJDs 55433 to 55662.

TDEVs for the three differences are shown in Figure 6. All of the TDEVs are 200 ps or less for averaging times less than 32 hours. The TDEVs are dominated by clock noise after averaging times longer than 32 hours. For averaging times of 32 hours and less, the TDEVs of the odd-hour TWSTFT with SAW filters contains less transfer noise than the even-hour TWSTFT without SAW filter which reflects the larger short-term variations in Figure 5. For averaging times from 2 hours to about 16 hours, the time transfer instability of the filtered 2.5 MChip/s TWSTFT shows a small improvement when compared to the filtered 1 MChip/s TWSTFT. This means the change of measurement noise due to chip-rate change between 2.5 MChip/s and 1 MChip/s is only a small contributor to the short-term instability. The dominant short-term instability for the transatlantic TWSTFT comes from the sources described in a 2005 study [5].

The frequency instability, as measured by the Allan Deviation (ADEV) for the three differences are shown in Figure 7. At averaging times of 1 day, the ADEVs are about 6 × 10^{-15} for the even-hour 1 MChip/s TWSTFT, and about 4 × 10^{-15} for the odd-hour 1 Mchip/s and 2.5 Mchip/s TWSTFT with SAW filters. The ADEVs are continuously averaged down to about 2 × 10^{-15} at averaging times of about 2.5 days. After that, the ADEVs demonstrate frequency instability mainly from the OP HM816 clock, visible in Figure 5.

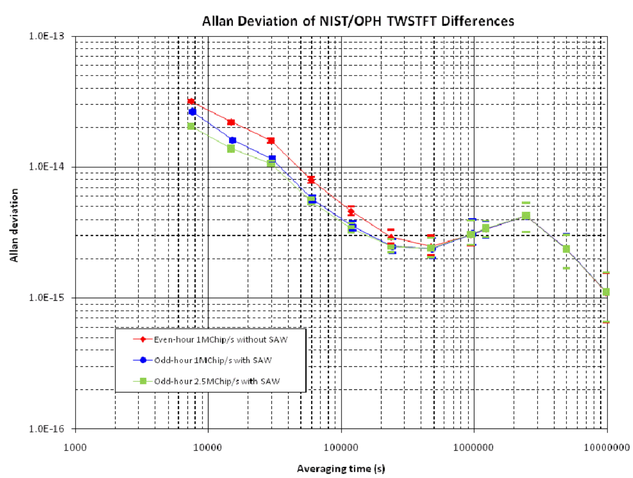

Figure 7 Frequency instability of the NIST/OPH TWSTFT for MJDs 55433 to 55662.

The comparison of time transfer instability for the 1 MChip/s TWSTFT with and without SAW filters is shown in Figure 8. Data used in computing the TDEVs were obtained from the two 2-minute measurement sessions in odd hours from MJD 55645 to MJD 55662. The measurements were made in odd-hours to minimize the interference from other TWSTFT signals transmitted at the same time with about the same frequency. The measurements of 1 MChip/s TWSTFT without SAW filters were obtained from the NIST_SATRE #263/OP01_SATRE #77 link. The measurements of 1 MChip/s TWSTFT with SAW filters were obtained from the NIST_SATRE #78/OP02_SATRE #321 link. The two measurement sessions were seven minutes apart. The TDEV for the 1 MChip/s TWSTFT with SAW filters is about 100 ps, and it is higher than that of the 1 MChip/s TWSTFT without SAW filters for averaging times of two hours and four hours. Based on our loop test results, the high level of TDEV at averaging times of two hours and four hours for the 1 MChip/s TWSTFT with SAW filters might come from the noise contributed by SAW filters. The TDEV for the 1 MChip/s TWSTFT without SAW filter increases after averaging longer than one day. That could come from the instability of the NIST_SATRE #263/OP01_SATRE #77 link.

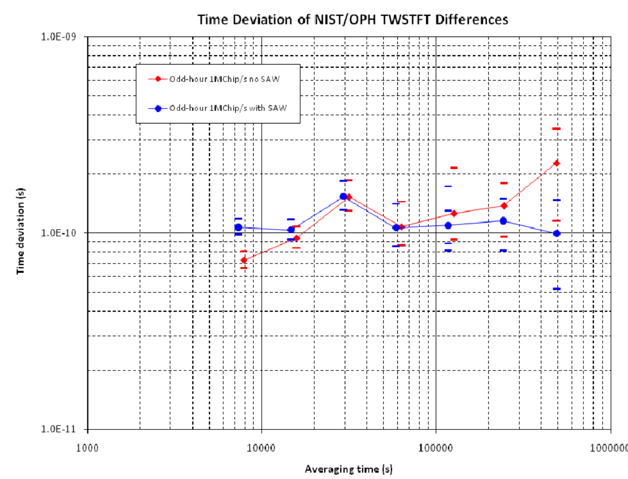

Figure 8 Comparison of 1 MChip/s TWSTFT with and without SAW filters. The TDEVs are computed with TWSTFT difference for MJDs 55645 to 55662.

All the TDEVs in Figures 6 and 8 show a diurnal at and below 200 ps. The diurnal is not from the use of SAW filters because it is also visible in the TWSTFT without SAW filters.

V. CONCLUSIONS

Our study shows the SAW filters can be used for 2.5 MChip/s TWSTFT with only 2.5 MHz bandwidth. The noise from SAW filters contributes to the short-term time transfer instability. The SAW filter's frequency dependent delay can increase the uncertainty of the TWSTFT. The 2.5 MChip/s TWSTFT with SAW filters provides a small improvement, about 10 to 20 ps in TDEV, over the 1 MChip/s TWSTFT without SAW filter for averaging times from two hours to 16 hours. The TDEV and ADEV for the filtered 2.5 MChip/s TWSTFT with SAW filters are about 100 ps and 4 × 10^{-15} at averaging times of one day. The TDEV and ADEV could be a little better if the TWSTFT differences had no diurnal. Because of the noise introduced by SAW filters, the 1 MChip/s TWSTFT works better without the SAW filters.

ACKNOWLEDGMENT

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REFERENCES

[1] D. Kirchner, "Two-Way Satellite Time and Frequency Transfer (TWSTFT): Principle, Implementation, and Current Performance," Review of Radio Science 1996-1999, Oxford University Press, New York, NY USA, pp. 27-44, 1999.

[2] L. B. Veenstra, "International Two-Way Satellite Time Transfers Using INTELSAT Space Segments and Small Earth Stations," in Proceedings of the 22nd Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 4-6 December, 1990, Vienna, Virginia, USA, pp. 383-398.

[3] V. Zhang, T. E. Parker, J. Achkar, A. Bauch, L. Lorini, D. Matsakis, D. Piester, and D. G. Rovera, "Two-way Satellite Time and Frequency Transfer Using 1 MChip/s Codes," in Proceedings of the 41st Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 16-19 November, 2009, Santa Ana Pueblo, New Mexico, USA, pp. 371-382.

[4] V. Zhang, T. E. Parker, J. Lowe, NIST Report to the 18th CCTF TWSTFT Working Group Meeting, 16-17 September, 2010, Beijing, China.

[5] T. E. Parker and Victor Zhang, "Sources of Instability in Two-Way Satellite Time Transfer," in Proceedings of 2005 Joint IEEE International Frequency Symposium and the 37th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 29-31 August 2005, Vancouver, Canada, pp. 745-751.