TWO-WAY SATELLITE TIME AND FREQUENCY TRANSFER USING 1 MCHIP/S CODES

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Abstract

The Ku-band transatlantic and Europe-to-Europe two-way satellite time and frequency transfer (TWSTFT) operations used 2.5 MChip/s pseudo-random codes with 3.5 MHz bandwidth until the end of July 2009. The cost of TWSTFT operation is associated with the bandwidth used on a geostationary satellite. The transatlantic and Europe-to-Europe TWSTFT operations faced a significant increase in cost for using 3.5 MHz bandwidth on a new satellite. The use of 1 MChip/s pseudo-random codes with 2.5 MHz bandwidth was one of the alternatives for continuing the TWSTFT operations without the increase in cost. Two timing laboratories in the US and eight timing laboratories in Europe participated in an experiment from February to July of 2009 to study the 1 MChip/s TWSTFT performance. Based on the study results, the transatlantic and Europe-to-Europe TWSTFT operations switched to a new satellite using 1 MChip/s codes with 2.5 MHz bandwidth since 1 August 2009. In this paper, we report the performance of 1 MChip/s TWSTFT for the transatlantic and Europe-to-Europe links.

I. INTRODUCTION

Two-way satellite time and frequency transfer (TWSTFT) **[1]** has become an important technique used internationally for comparing time and frequency standards over long distances. The data from the transatlantic and Europe-to-Europe TWSTFT links to the *Physikalisch-Technische Bundesanstalt* (PTB) are also used by the *Bureau International des Poids et Mesures* (BIPM) in the computations of the International Atomic Time (TAI) and the Coordinated Universal Time (UTC).

Most of the transatlantic and all of the Europe-to-Europe TWSTFT comparisons have used 2.5 MChip/s pseudo-random codes with 3.5 MHz bandwidth at Ku-band microwave frequencies for many years. The Consultative Committee for Time and Frequency (CCTF) Working Group on TWSTFT establishes a code assignment for each participating laboratory and a schedule of 2-minute measurement segments between each pair of remote laboratories. Nominally, the TWSTFT measurements are made between each pair of laboratories during even hours, 12 times a day. The 1 s measurements taken during 2 minutes are then reduced according to the Recommendation TF.1153-2 of the International Telecommunication Union, Radiocommunication Sector (ITU-R) **[2]**. The accuracy of a TWSTFT link is about 1 ns if the link is calibrated by a portable two-way earth station **[3]**. The best stability of a TWSTFT link, as measured by the Time Deviation (TDEV), is less than 100 ps at averaging times around 1 day **[4]**. From February 2008 to July 2009, the TWSTFT operations were carried out on three transponders of the Intelsat* IS-3R satellite. It was announced in 2008 that the IS-3R satellite could reach its end of life in the fall of 2009. The Ku-band transatlantic and Europe-to-Europe TWSTFT operations faced a significant increase in cost to continue using the 3.5 MHz bandwidth on a new satellite. The use of 1 MChip/s pseudo-random codes with 2.5 MHz bandwidth was one of the alternatives for continuing the TWSTFT operations without increase in cost. The question was what level of stability degradation the 1 MChip/s TWSTFT would bring. Two timing laboratories in the US and eight timing laboratories in Europe participated in an experiment from February to July of 2009 to study the 1 MChip/s TWSTFT performance. Based on the study results, the Ku-band transatlantic and Europe-to-Europe TWSTFT operations have switched to use 1 MChip/s codes with 2.5 MHz bandwidth on three transponders of the TeleSat* T-11N satellite since 1 August 2009.

In this paper, we report the performance of 1 MChip/s TWSTFT for the transatlantic and Europe-to-Europe links. The 1 MChip/s experiment is described in Section II. Section III shows the spectrum of the 1 MChip/s signals. We present the short-term and long-term stabilities of the 1 MChip/s TWSTFT in Section IV and V.

II. THE 1 MCHIP/S TWSTFT EXPERIMENT

The 1 MChip/s experiment was conducted on the IS-3R satellite during odd hours from 23 February to 10 July of 2009. Table 1 lists the participating laboratories and their earth station ID. The experiment was divided into three phases.

Table 1. Participants in the 1 MChip/s TWSTFT experiment.

AOS	Astrogeodynamical Observatory, Space Research Centre P.A.S., Borowiec, Poland
CH	Swiss Federal Office of Metrology, Switzerland (METAS)
IT	Istituto Nazionale di Ricerca Metrologica (INRiM), Italy
NIST	National Institute of Standards and Technology, Boulder, Colorado, U.S.A.
NPL	National Physical Laboratory, Teddington, United Kingdom
OP	Observatoire de Paris/LNE-SYRTE, Paris, France
PTB	Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
ROA	Real Instituto y Observatorio de la Armada, San Fernando, Spain
SP	Sveriges Provnings- och Forskningsinstitut (Technical Research Institute of Sweden)
USNO	U.S. Naval Observatory, Washington D.C., USA

During the first phase of experiment, from 23 February to 2 March (MJD from 54885 to 54892), NIST and PTB made 10 minutes of 1 s measurements using each of the 1 Mchip/s and the 2.5 MChip/s codes in the same odd hour to compare the short-term (averaging times from 1 s to 128 s) stability of the two chip rates.

For the second phase of experiment, from 2 to 16 March (MJD from 54892 to 54906), NIST, OP, PTB, and USNO made 10 minutes of 1 s measurements by use of the 1 MChip/s codes to study the short-term stability and the effect of multi-signal transmission on the 1 MChip/s TWSTFT. The measurement sessions were scheduled such that there was no overlap among the NIST/OP, NIST/PTB, OP/PTB, OP/USNO, and PTB/USNO measurement sessions. From 2 to 9 March (MJD from 54892 to 54899), each earth station transmitted its signal only during its own allocated measurement session to simulate a single-signal transmission mode. From 9 to 16 March (MJD from 54899 to 54906), all of the four earth stations transmitted signals during the whole hour to create a multi-signal transmission environment. We used the TDEV of the 10-minute TWSTFT differences of the single-signal and multi-signal transmission modes to assess the effect of the multi-signal transmission on the 1 MChip/s TWSTFT. Unfortunately, the analysis did not provide conclusive results, because the effect of multi-signal transmission was masked by other strong noise processes and diurnal fluctuations during the second phase of the experiment.

In the third phase of experiment, from 16 March to 10 July (MJD from 54906 to 55022), we returned to the 2-minute measurement schedule for each pair of links among all the participating laboratories. From these 2-minute 1 MChip/s measurements, we studied the long-term (averaging times from 2 hours) stability of the 1 MChip/s TWSTFT. Because all the participating laboratories were also doing the 2.5 MChip/s TWSTFT during even hours on the IS-3R satellite, we were able to compare the long-term stability between the 1 MChip/s and the 2.5 MChip/s TWSTFT.

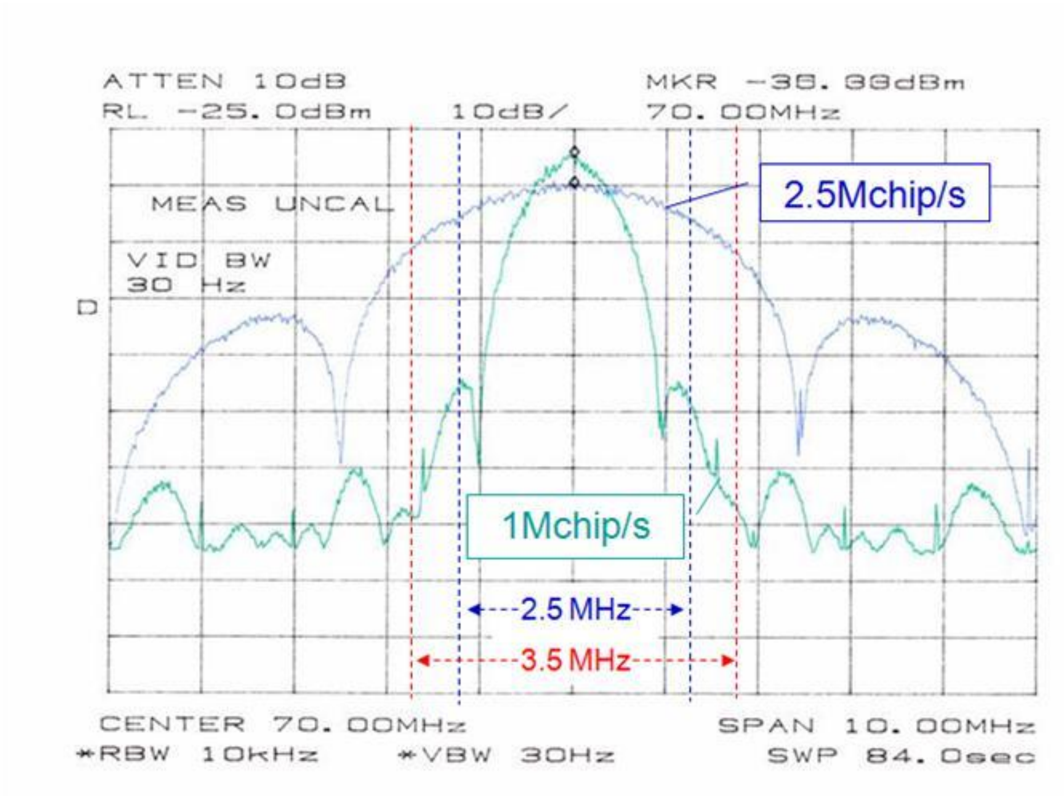

Figure 1. 1 MChip/s and 2.5 MChip/s TX IF spectrum signals.

III. THE 1 MCHIP/S SIGNAL

Figure 1 and 2 show the transmit (TX) and receive (RX) spread-spectrum signals for both the 1 MChip/s and the 2.5 MChip/s codes at the 70 MHz intermediate frequency (IF). These TX and RX signals were obtained from a NIST SATRE* modem. The SATRE modem applies a digital filter in generation of the 1 MChip/s codes, so the side lobe of the 1 MChip/s signal has a structure different from that of the 2.5 MChip/s signal. The main lobe of the 1 MChip/s TX signal is bounded by 2 MHz. The 2.5 MHz bandwidth contains the peak of the first side lobes. The peak of the first side lobes is about 40 dB down from the peak of the main lobe. With the estimate that two TX signals transmitting at the same time will increase the total signal power by 3 dB, it takes more than 10,000 TX signals transmitting at the same time to bring up the TX signal power by 40 dB at the 2.5 MHz boundaries. With two earth stations in the US and up to 12 earth stations in Europe, there is no risk of leaking our signals to the adjacent frequency band. This frequency safety margin can be seen clearly in the RX IF spectrum. In theory, we need only 1.4 MHz bandwidth for the 1 MChip/s TWSTFT operation. The 2.5 MHz bandwidth allows us to experiment with other approaches, such as filtering the 2.5 MChip/s signal with a 2.5 MHz bandpass filter, to optimize the quality of the Ku-band transatlantic and Europe-to-Europe TWSTFT links with the same cost.

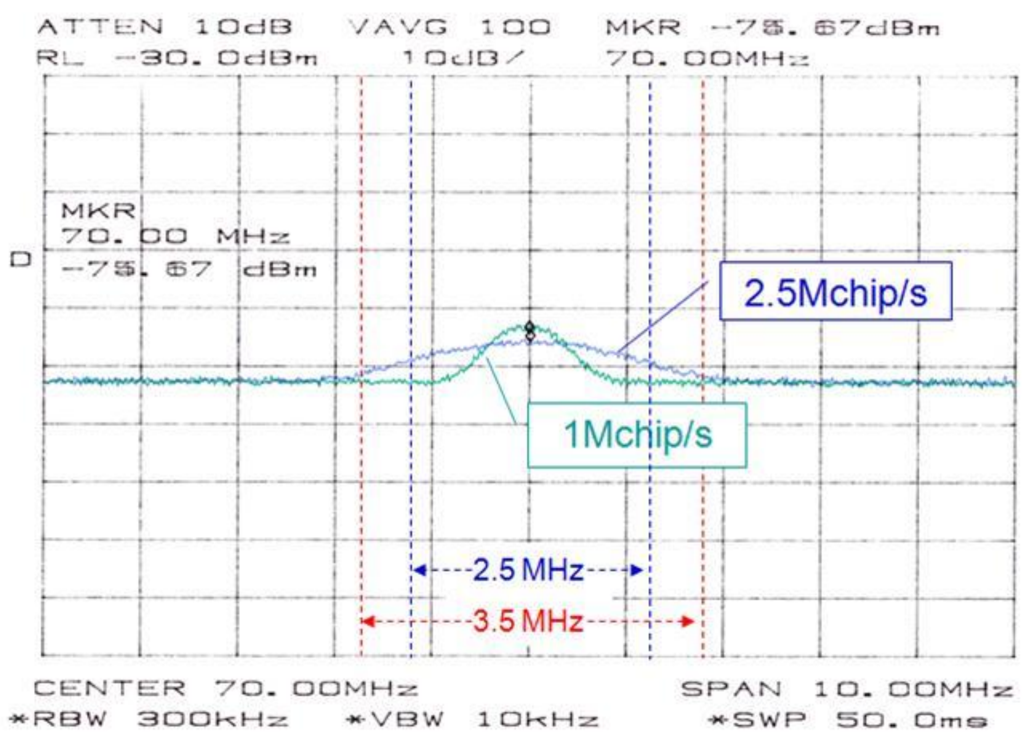

Figure 2. 1 MChip/s and 2.5 MChip/s RX IF spectrum signals.

IV. THE SHORT-TERM STABILITY

We use TDEV in analyzing the short-term stability. Figure 3 shows an example of the TDEV for the NIST/PTB link on 24 February (MJD 54886). The TDEV for each chip rate is an average of the 12 TDEVs of the 10-minute 1 s TWSTFT differences during the day. For averaging times from 1 s to 128 s, the TDEV for both chip rates are dominated by white phase noise, which is introduced mainly by transfer noise. However, the TDEV for the 1 MChip/s TWSTFT is about 2.5 times higher than that of the 2.5 MChip/s TWSTFT. This is expected because the reduction in processing gain is proportional to the chip-rate ratio. With the 10-minute measurements, flicker phase noise is not observed at the 10 to 20 ps level in the TDEV for each chip rate. The analysis of the NIST/PTB 10-minute 1 s differences from 23 February to 2 March (MJD from 54885 to 54892) shows the similar results.

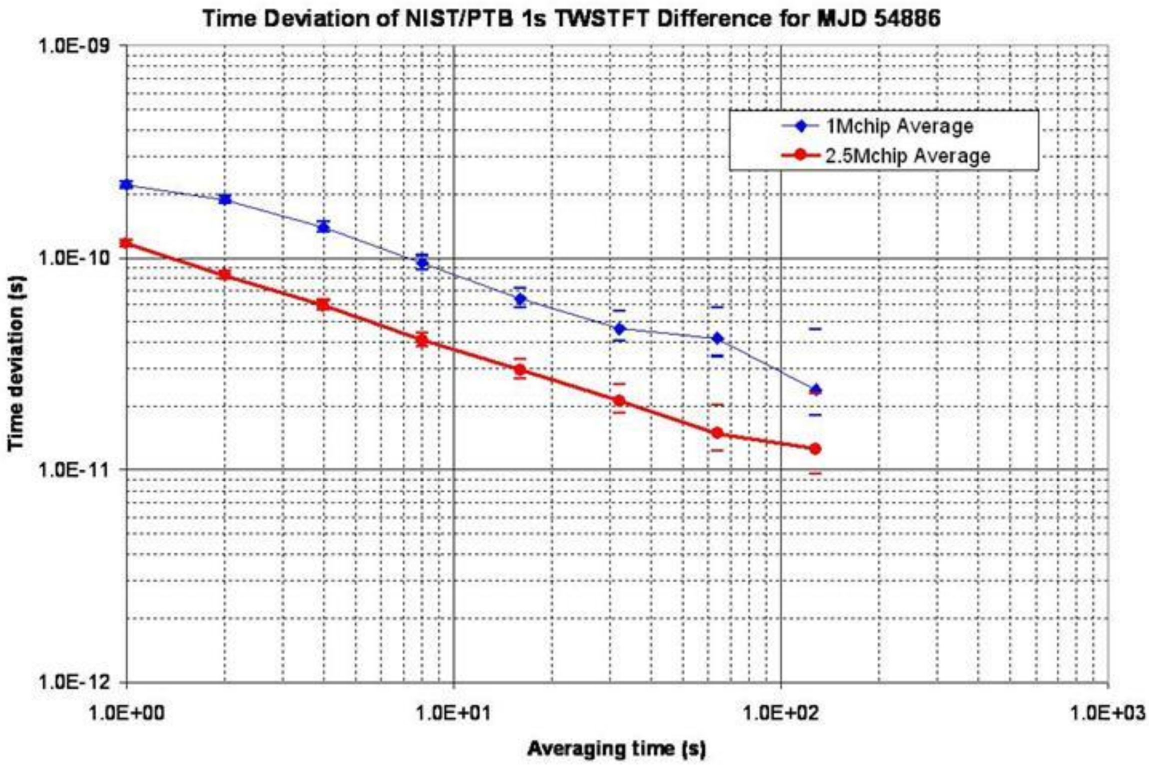

Figure 3. Short-term stability of the NIST/PTB TWSTFT.

Figure 4 shows an example of the TDEV for the NIST/PTB, NIST/OP, PTB/OP, USNO/OP, and USNO/PTB 1 MChip/s TWSTFT differences on 4 March (MJD 54894). The TDEV for each link is an average of the 12 TDEVs of the 10-minute 1 s TWSTFT differences during the day. The short-term stability for each of the four transatlantic links is similar. The TDEVs start around 200 to 300 ps at an averaging time of 1 s and reach 20 to 40 ps when averaged over 128 s. Each TDEV is dominated by white phase noise. The short-term stability for the PTB/OP link is also dominated by white phase noise. However, it is about 2.5 times higher than that of the transatlantic links. Analysis of the transatlantic and PTB/OP 10-minute 1 s differences from 2 to 16 March (MJD from 54892 to 54906) shows similar results. Because there is no PTB/OP 10-minute 2.5 MChip/s measurement during the second phase of experiment, we could not compare short-term stability between the 1 MChip/s and 2.5 MChip/s TWSTFT. Figure 5 shows the PTB/OP TWSTFT differences during the second phase of the experiment. The 1 MChip/s differences are computed from the odd-hour 10-minute measurements. The 2.5 MChip/s differences are obtained from the even-hour 2-minute measurements. The 1 MChip/s TWSTFT difference shows a larger variation between the adjacent points and the difference shows a diurnal variation. This could mean the PTB/OP 1 MChip/s TWSTFT was affected by some strong noise and diurnal fluctuation in both the short term and the long term.

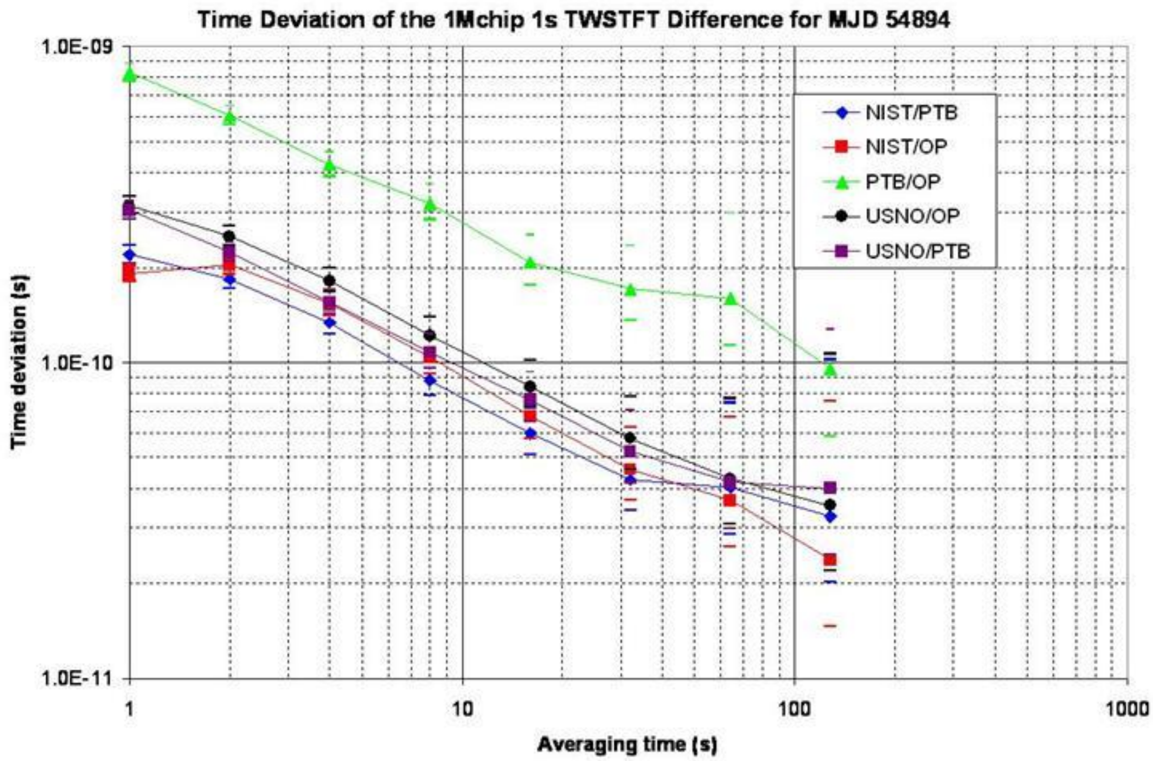

Figure 4. Short-term stability of the transatlantic and Europe-to-Europe 1 MChip/s TWSTFT

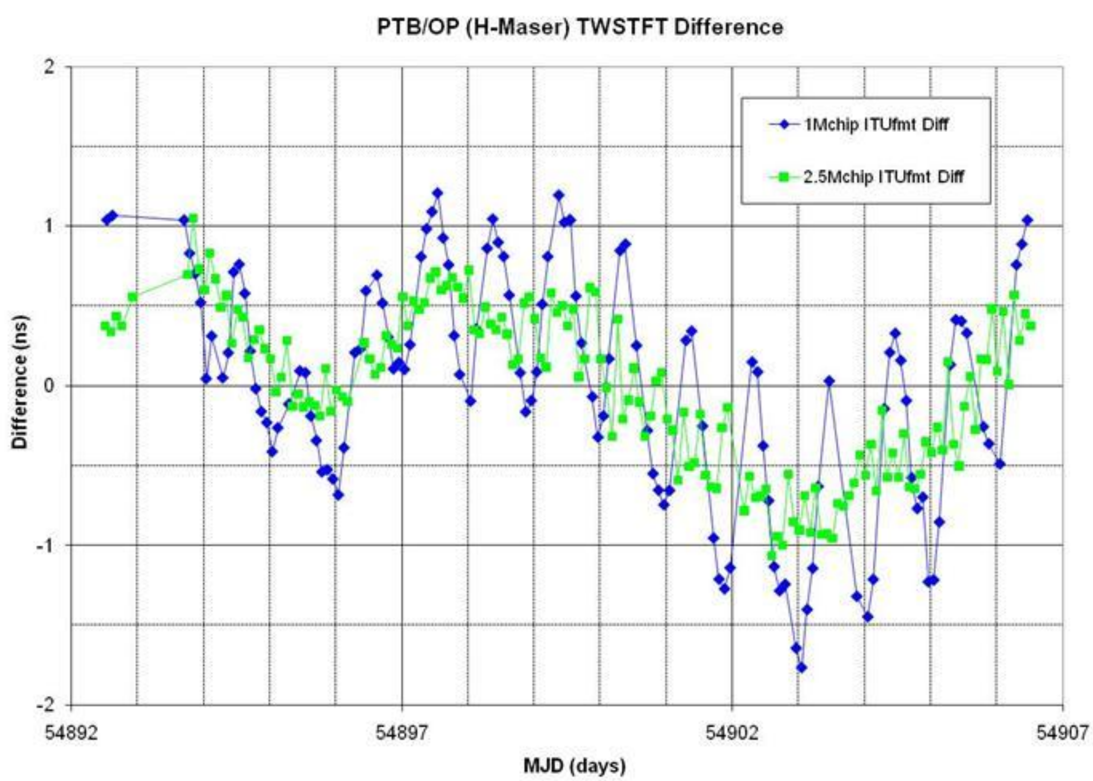

Figure 5. TWSTFT differences of the PTB/OP link.

V. THE LONG-TERM STABILITY

With the NIST/PTB 10-minute 1 s measurements made during the first phase of experiment, we estimate the effect of measurement length on the long-term stability. Figure 6 shows the TDEVs computed with the measurements made from 24 to 28 February (MJD from 54886 to 54890). For averaging times of 2 and 4 hours, the TDEVs of the 2, 4, and 10-minute 1 MChip/s measurements are almost identical. The TDEVs are all dominated by flicker phase noise at the 100 ps level. For averaging times longer than 4 hours, the TDEVs are dominated by the instability of the two reference clocks being compared. For averaging times from 2 hours, we see no noticeable difference between the 2-minute 1 MChip/s TDEV and the 2-minute 2.5 MChip/s TDEV. Therefore, increasing the 1 MChip/s measurement length has no effect on improving long-term stability. The 1 MChip/s short-term stability degradation, as shown in Figure 3, is masked by a flicker noise process that dominates at 2 hours and longer.

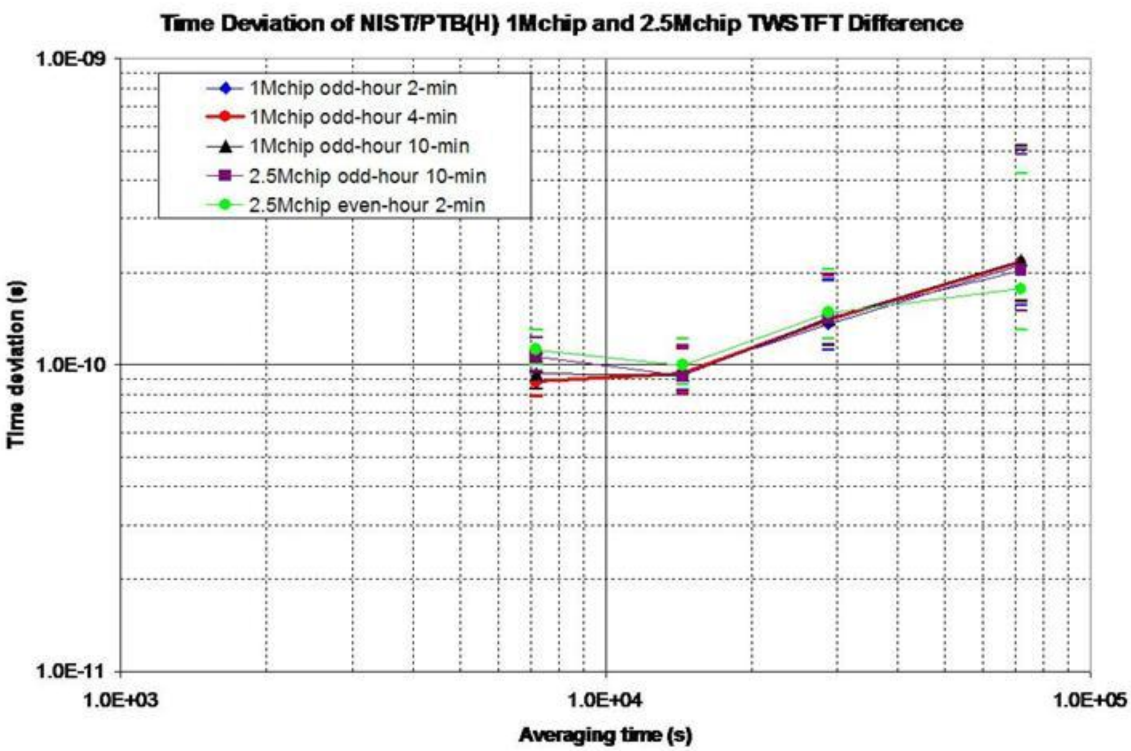

Figure 6. Time deviation of NIST/PTB TWSTFT with different measurement lengths.

Figure 7 compares the long-term stability of the 1 MChip/s and 2.5 MChip/s maser-to-maser TWSTFT between NIST and OP. The 2-minute data from 19 March to 10 July (MJD from 54909 to 55022) are used in the TDEV computation. The 1 MChip/s measurements were made during odd hours and the 2.5 MChip/s measurements were made at even hours on the IS-3R satellite. Because the reference signals at NIST and OP are both generated based on hydrogen maser clocks, and the stability of a hydrogen maser clock is much lower than the TWSTFT transfer noise for averaging times less than 1 day, it is desirable to compute the TDEV for the maser-to-maser TWSTFT difference in order to see the transfer noise for averaging times at one day and less. From Figure 7, we see the TDEVs for both chip rates are almost identical. The TDEVs are dominated by flicker phase noise for averaging times from 2 hours to 32 hours at the 70 ps level, except for a diurnal for both chip rates. The frequency stability, as measured by the

Allan deviations (ADEV), of the NIST/OP maser-to-maser 1 MChip/s and 2.5 MChip/s TWSTFT are shown in Figure 8. The ADEVs are computed with the same data as used in computing the TDEVs shown in Figure 7. From Figure 8, we see the ADEV for the 1 MChip/s and for the 2.5 MChip/s TWSTFT are almost identical. Both ADEVs represent flicker phase noise for averaging times less than 1 day. The ADEVs reach about 3×10^{-15} at an averaging time of 1 day.

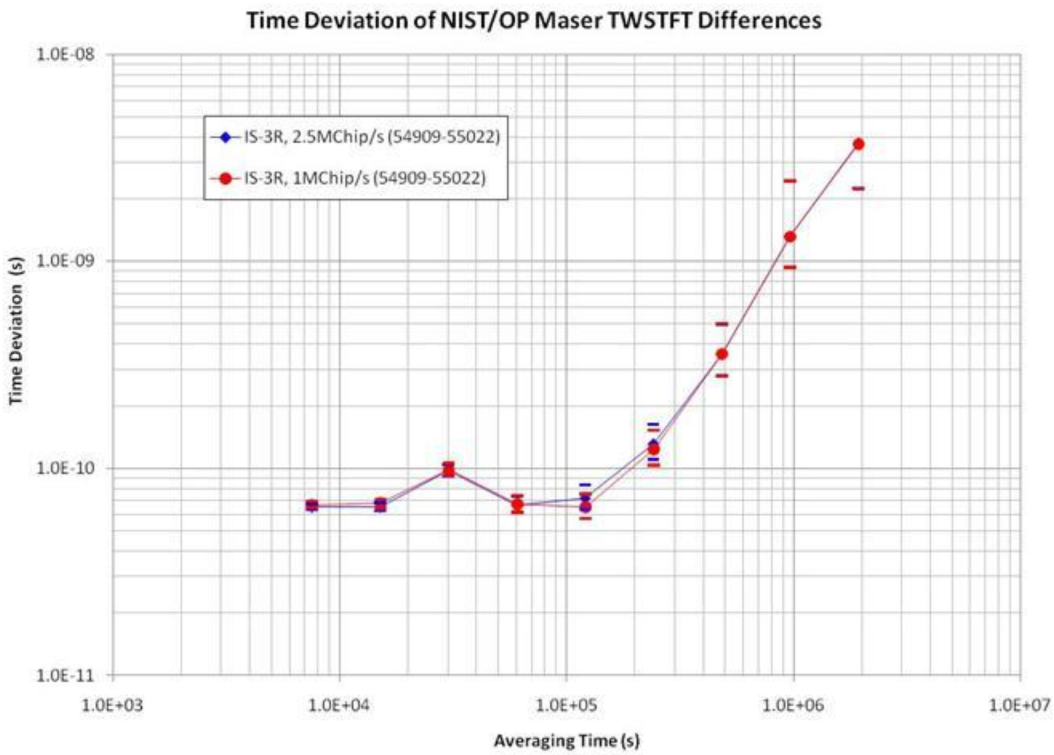

Figure 7. NIST/OP 1 MChip/s and 2.5 MChip/s long-term stability using the IS-3R satellite.

Figure 9 and Figure 10 show the TDEVs and ADEVs for the NIST/OP, NIST/PTB, PTB/OP, and USNO/PTB 1 MChip/s TWSTFT using the T-11N satellite. The TDEVs and ADEVs are computed with maser-to-maser TWSTFT differences from 31 July to 14 October (MJD from 55043 to 55118). The TDEV is below 100 ps for the NIST/OP TWSTFT when averaged over about 1 day, which is about the same as that for the 2.5 MChip/s TWSTFT (see Figure 7). However, all four of the TDEVs show some white phase noise component for averaging times from 2 hours to about 1 day. The 1 MChip/s TWSTFT measurements on the T-11N satellite contain more transfer noise than the 1 MChip/s and the 2.5 MChip/s TWSTFT on the IS-3R satellite. All links on the T-11N satellite contain significantly higher noise. As indicated by the ADEV plots in Figure 10, there are dominant white phase and flicker phase noise contributions. The NIST/OP ADEV is a little higher than the ADEV obtained when using the IS-3R satellite (see Figure 8). The change in the TDEV and ADEV could come from the combination of the satellite change, chip-rate reduction, and ground-station equipment changes. The noise process in TDEV and the frequency stability in ADEV are also related to the data quality of the two reference clocks being compared. For example, the PTB maser did not behave regularly for well known reasons during the interval under study. An attempt was made to clean up the disturbances, but the NIST/PTB TWSTFT results, as shown in Figure 9 and Figure 10, may reflect the PTB maser performance.

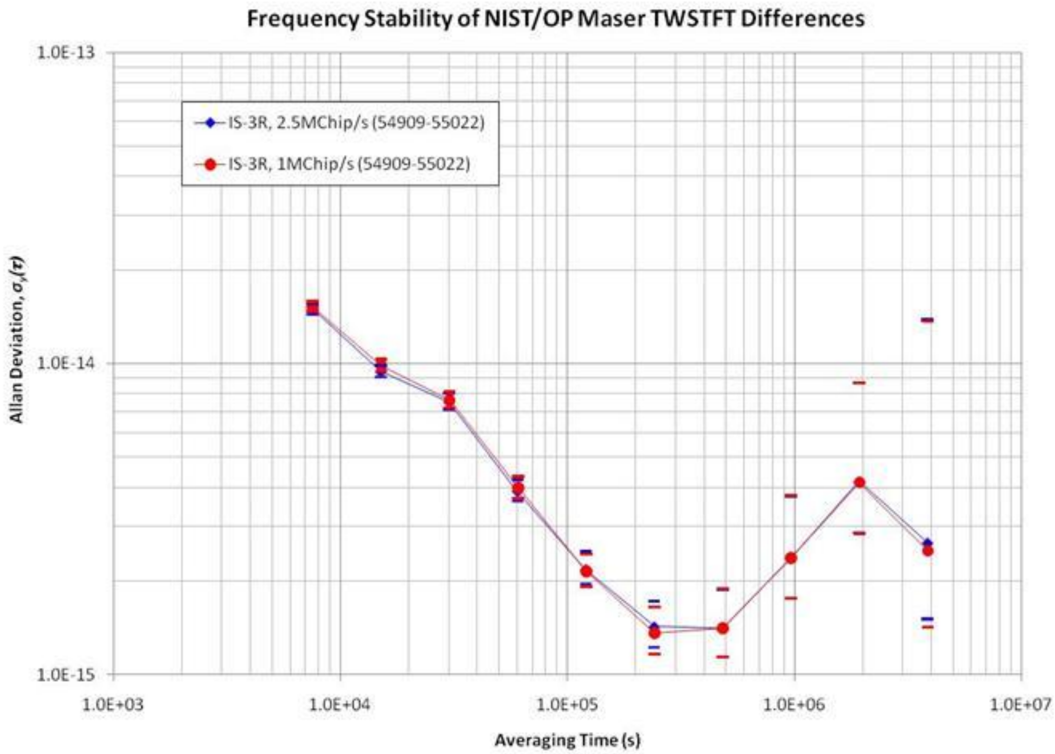

Figure 8. Frequency stability of the NIST/OP maser-to-maser 1 MChip/s and 2.5 MChip/s TWSTFT.

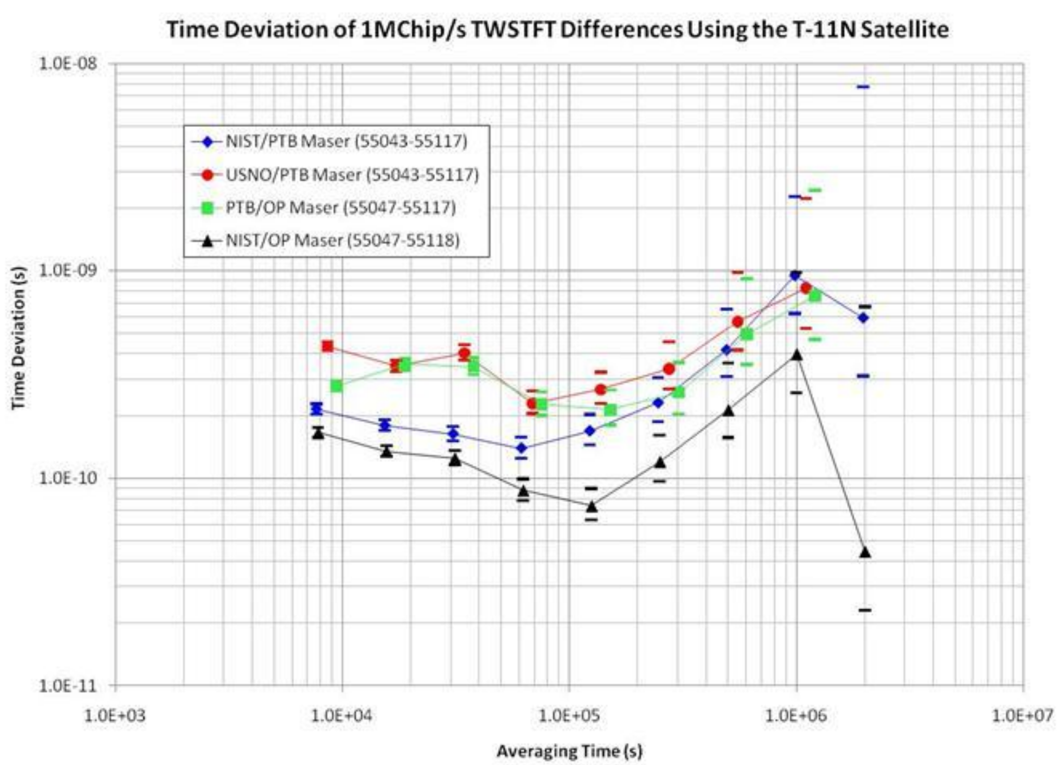

Figure 9. Long-term stability of the 1 MChip/s TWSTFT using the T-11N satellite.

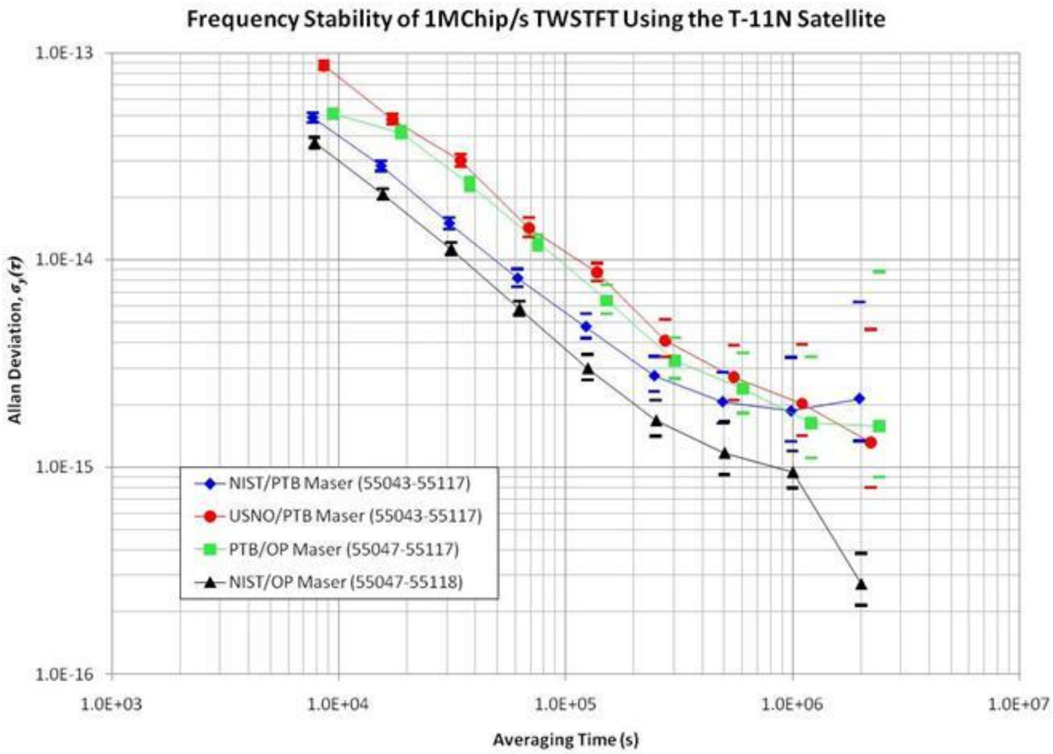

Figure 10. Frequency stability of the 1 MChip/s maser-to-maser TWSTFT using the T-11N Satellite.

VI. CONCLUSIONS

The Ku-band transatlantic and the Europe-to-Europe TWSTFT operations have been changed to 1 MChip/s codes with a 2.5 MHz bandwidth on the T-11N satellite since August of 2009. From the 1 MChip/s TWSTFT experiment on the IS-3R satellite, our analysis shows the short-term instability of the 1 MChip/s TWSTFT is increased by 2.5 times as compared to that of the 2.5 MChip/s TWSTFT. For averaging times of 2 hours and longer, there is no noticeable difference in the TDEV for the 2-minute, 4-minute, and 10-minute 1 MChip/s measurements. The 1 MChip/s short-term stability degradation is masked by a different noise process at 2 hours. It has been reported that the 2.5 MChip/s multi-signal transmission increases the instability of the TWSTFT measurements by a factor of 1.4 **[5]**. However, our study on the effect of 1 MChip/s multi-signal transmission gave us no conclusive answer with the method used. From the analysis of the TWSTFT results on the T-11N satellite, the TDEV for the 1 MChip/s TWSTFT shows a component of white phase noise for averaging times from 2 hours to about 1 day. Whereas, the 1MChip/s TWSTFT for most of the links has similar levels of TDEV as that of the 2.5 MChip/s TWSTFT for the averaging times from 1 day and longer. The best TDEV of the 1 MChip/s TWSTFT can reach below 100 ps, and the best frequency stability is about 4×10^{-15} at an averaging time around 1 day.

** The identification of commercial products is done for technical completeness only, and implies no endorsement by any of the authors and organizations.*

VII. ACKNOWLEDGMENTS

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