LONG-TERM STABILITY OF REMOTE CLOCK COMPARISONS WITH IGS CLOCK PRODUCTS

Victor Zhang, Thomas E. Parker, and Marc A. Weiss
Time and Frequency Division
National Institute of Standards and Technology
Boulder, CO 80305, USA
E-mail: ***vzhang@boulder.nist.gov***

Abstract

The International GNSS Service (IGS) clock products contain clock information about the local reference for the IGS tracking receivers with respect to the IGS time. The clock information is obtained from GPS carrier-phase measurements. Many timing laboratories now operate IGS tracking receivers using high-quality clocks as the local reference. The IGS clock products allow timing laboratories to use the GPS carrier-phase measurements for comparing these clocks without significant postprocessing by the user. In this paper, we study the stability of remote clock comparisons performed with the IGS clock products during the past 2 years. We compare the remote clock differences obtained with the IGS clock products to the remote clock comparisons with two-way satellite time and frequency transfer and GPS common view. We focus on the long-term differential performance of these transfer systems, on the order of many months.

I. INTRODUCTION

The GPS common-view (CV), all-in-view (AV) time and frequency transfer and the two-way satellite time and frequency transfer (TWSTFT) techniques are used in the daily operations of remote clock comparison. The international timing laboratories also use these techniques to contribute their clock data to the formation of International Atomic Time (TAI) and Coordinated Universal Time (UTC). GPS CV and AV time and frequency transfer **[1,2]** are based exclusively on the C/A code pseudo-range measurements between the received GPS signal and the local reference clock. With the aid of the International GNSS Service (IGS) products **[3]**, the AV improves the CV time and frequency transfer over a very long baseline. For a transatlantic link, the time transfer stability of multichannel CV and AV can reach subnanosecond at 1 day as measured by the time deviation (TDEV). TWSTFT uses communication satellites for simultaneously exchanging timing signals among the pairs of timing laboratories **[4]**. TWSTFT regularly delivers time transfer stability at a few hundreds of picoseconds (ps) at 1 day for the transatlantic links. Occasionally, 1-day stabilities at, or below, 100 ps are observed **[5]** (also see Section III). Because it requires the use of a communication satellite and both transmit and receive equipment at the timing laboratories, TWSTFT is more expensive than GPS CV and AV.

The GPS carrier-phase time and frequency transfer technique **[6]** uses both carrier-phase and pseudo-range measurements of geodetic receivers to compare remote clocks. Because the GPS carrier frequencies are at least 1000 times higher than the rate of C/A code, the GPS carrier-phase measurements are potentially more precise than those of GPS CV and AV. Many studies have shown that the time transfer stability of GPS carrier-phase is better than that of the TWSTFT for averaging times of less than 1 day, and is comparable to that of the TWSTFT for averaging times ranging from 1 day to a few tens of days. However, the GPS carrier-phase technique requires a significant amount of postprocessing to achieve the comparison results.

As a result of the International GNSS Service/Bureau International des Poids et Mesures (IGS/BIPM) Pilot Project **[7]**, the IGS has produced its clock products since November, 2000. The IGS clock products are based on the carrier-phase and code measurements made by the receivers in the IGS worldwide tracking network. The products contain the clock information of each GPS satellite and the local reference for a subset of IGS stations with respect to the IGS time (IGST). The clock information, (REF – IGST), is reported at 5-minute intervals. Many timing laboratories now participate in the IGS tracking network using high-quality clocks as the reference for the IGS receivers. With the IGS state-of-the-art data analysis groups, methods, and products, we can use the IGS clock products for GPS carrier-phase comparison without the burden of processing the carrier-phase measurements ourselves.

Table 1.

Link (Distance)	NIST/USNO (2400 km)	NIST/PTB (7530 km)	NIST/CH (7730 km)
Data Period	53519 – 54372	53519 – 54372	54213 – 54372
Reference Clock	UTC (NIST), UTC (USNO)	UTC (NIST), UTC (PTB)	UTC (NIST), CH H-maser
TWSTFT Comparison	Ku-band (NIST-PTB) – (USNO-PTB)	Ku-band NIST – PTB	Ku-band NIST - CH
IGS Receiver	NISU, USN3	NISU, PTBB	NISU, WAB2
Common-view Receiver	NISU, USNOTTS2	NISU, PTBTTS2	NISU, WAB2

NIST: National Institute of Standards and Technology in Boulder, Colorado, USA
USNO: United States Naval Observatory in Washington, DC, USA
PTB: Physikalisch-Technische Bundesanstalt in Braunschweig, Germany
CH: Swiss Federal Office of Metrology (METAS), Bern-Wabern, Switzerland.

In this paper, we study the long-term stability of using the IGS final clock products for remote clock comparisons of the three links shown in Table 1. We difference the (REF_A – IGST) and (REF_B – IGST) with the same time tag to compare the two reference clocks. For the NIST/USNO and NIST/PTB links, we compare the performance of using IGS clock products for remote clock comparison (IGSCLK) to that of the TWSTFT and CV over 854 days. For the NIST/CH link, we limit the comparisons of IGSCLK, TWSTFT, and CV to 160 days, because there is a large gap in the NIST/CH TWSTFT data. Because there is no direct TWSTFT link between NIST and USNO at this time, the NIST/USNO TWSTFT result is obtained from the difference of (NIST – PTB) and (USNO – PTB) TWSTFT results. The reference clock at CH is a hydrogen maser instead of UTC (CH). The CH CV data are generated from the CH IGS receiver with the ionosphere-free code (P3) method. USNO and PTB use geodetic receivers for the IGS tracking network and timing receivers for CV. This introduces some error and noise in the comparison result between the IGSCLK method and CV. In Section II, we look at some of the anomalies that we found in the IGS final clock products data. In Section III, we study the long-term stability of remote clock comparison with IGS final clock products. Because the time transfer stability is dominated by the clock noise for averaging times longer than a few days, we use the double-differences among the IGSCLK, TWSTFT, and CV to estimate the long-term stability of the IGSCLK method. Section IV summarizes our study.

II. THE ANOMALIES IN THE IGS CLOCK PRODUCTS DATA

The (REF – IGST) data contain data outages, time steps, anomalous excursions, and day-boundary discontinuities. Some of the time steps and excursions were caused by local factors at the IGS stations, such as a reference clock change and receiver problem. The IGS Station Mail is used to log the IGS station problems. However, not all of the anomalies were recorded in the IGS Station Mail.

Table 2 summarizes the data outage for the IGS clock products data used in our study. The longest continuous stretch of data outage is 6 days and 7 days for the (REF_{USNO} – IGST) and (REF_{PTB} – IGST), respectively. Sometimes a big time step in the IGS clock products data occurred after a data gap of 1 or more days. Figure 1 shows an example of such a time step in the (REF_{PTB} – IGST) data. There are no data for MJD 54263. When data came back on MJD 54264, there was a time step of about 6 ns between the data on MJD 54262 and MJD 54264. We do not know the cause of the time step, but the size of the time step is too big to have been introduced by UTC (PTB) or the IGST in only 1 day.

Table 2.

Laboratory	CH	NIST	PTB	USNO
Data Period	53519 – 54372	53519 – 54372	54213 – 54372	54213 – 54372
Total number of days of no data	17	16	38	16
Total missing data	12 %	3.4 %	5 %	1.9 %

Figure 2 shows a portion of the (REF_{NIST} – IGST) data. In addition to several excursions of the size as large as 12 ns, there are two 25-ns time steps occurring on MJD 54251 and on MJD 54360. The 25-ns time steps were caused by the NIST IGS receiver. According to our measurements, the receiver clock locked to a different cycle of the frequency multiplied up from the reference 5 MHz on those days.

The excursions were very likely caused by the local factors at the IGS stations. Most of the excursions in the IGS clock products data lasted about 1 day or less. However, several excursions lasted for a long period of time. Figure 3 shows two excursions in the (REF_{USNO} – IGST). The short excursion between MJD 53959 and MJD 53960 lasted a little over 1 day. A long excursion started on MJD 53924 and lasted until MJD 53954, a total of 31 days. The excursion subsided after the data gap on MJD 53955.

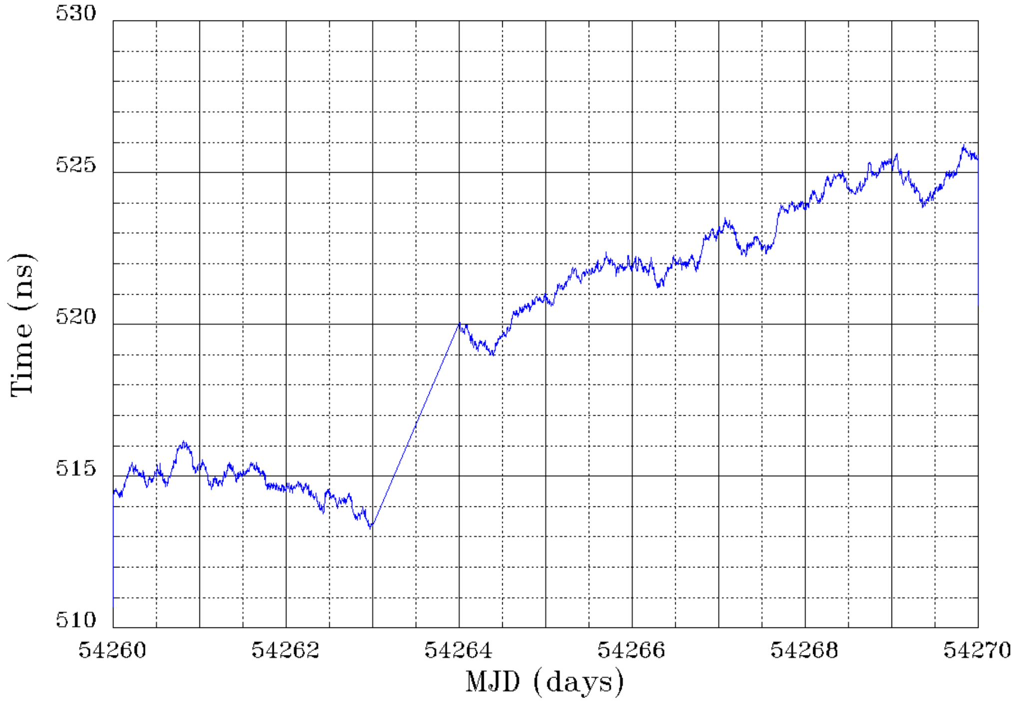

Figure 1. Time step in (REF_{PTB} – IGST) after a 1-day data gap.

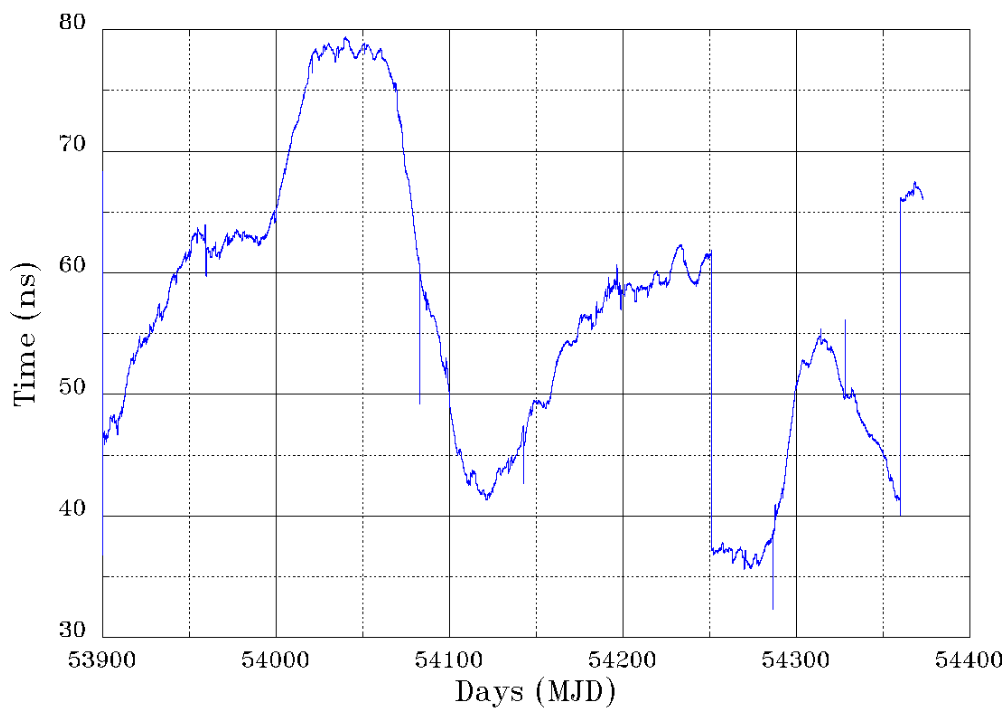

Figure 2. Example of time steps and excursions in the (REF_{NIST} – IGST) data.

There are day-boundary discontinuities that come from the carrier-phase analysis method. Most of the day-boundary discontinuities in the IGS clock products data are less than 1 ns.

The data outages, time steps, excursions and day-boundary discontinuities degrade the accuracy and stability of remote clock comparison using the IGS clock products. To study the long-term stability of time and frequency transfer using the IGS clock products, we corrected the time steps and excursions caused by the local factors of IGS stations based on events reported in the IGS Station Mail. All the day-boundary discontinuities are untouched, because they are a characteristics of the IGS clock products. For the (REF_{NIST} – IGST) data, we only corrected the excursion caused by the change of the NIST reference clock and the two 25-ns time steps caused by the receiver clock. There are no anomalies for the USNO and CH IGS stations recorded in the IGS Station Mail over the data period of our study. We did not correct the (REF_{CH} – IGST) data. For the purpose of studying its impact on the long-term stability, we removed the steps of 4.3 ns on MJD 53924 and 4.1 ns on MJD 53954 to correct the 31-day excursion in the (REF_{USNO} – IGST). The correction was estimated based on the (NIST – USNO) CV difference on these days, as shown by the red trace in Figure 3. The (REF_{PTB} – IGST) data came from two different receivers. Data from the primary receiver started showing frequent big time steps in late June of 2006. A temporary receiver was used in the PTB IGS station from late July to mid-November of 2006 (MJD 53942 to MJD 54052). To be able to study the long-term stability of the IGSCLK for the NIST/PTB link, we corrected the time steps and excursions due to the receiver problem and receiver change. The corrections were estimated based on the (NIST – PTB) TWSTFT differences. We also deleted the excursion that occurred between MJD 53847 and MJD 53848 caused by the PTB reference clock.

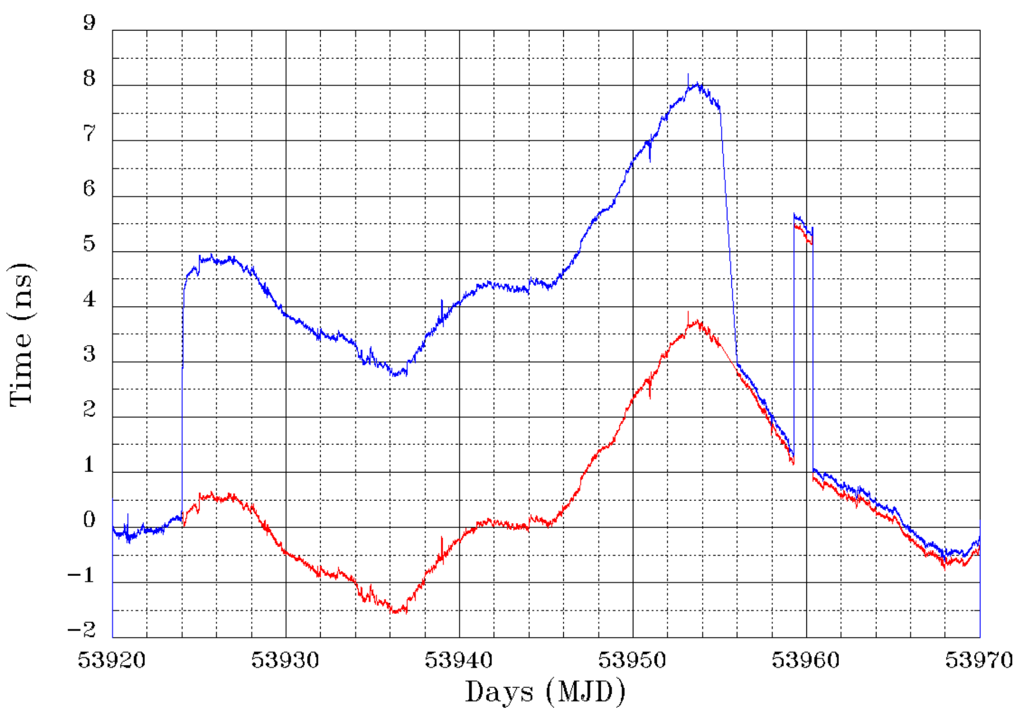

Figure 3. Excursions in (REF_{USNO} – IGST). The trace in blue is from the original IGS clock products data. The trace in red is the correction estimated from the (NIST-USNO) CV difference.

III. LONG-TERM STABILITY OF THE REMOTE CLOCK COMPARISON USING THE IGS CLOCK PRODUCTS

NIST, USNO, PTB, and CH all use multichannel receivers for CV. The multichannel receivers produce the 13-minute (REF – GPS) data for all satellites being tracked every 16 minutes. We applied the IGS measured ionosphere delay correction to the CV data before computing the NIST/USNO and NIST/PTB CV differences. The NIST/CH CV differences were computed from the data generated with the P3 method. The transatlantic TWSTFT operation is carried out with the Ku-band signals every 2 hours. The TWSTFT data used in computing the remote clock difference are the mid-point of a linear least-squares quadratic fit to the 2-minute measurements. We differenced the results of TWSTFT, CV, and IGSCLK at the closest matching times of a few minutes to obtain the double-difference for each link. The double-differences are used to study the long-term stability of the IGSCLK method.

The NIST/USNO comparison results are shown in Figure 4 through Figure 6. Figure 4 compares the time transfer stability of IGSCLK, TWSTFT, and CV. The TDEV for the IGSCLK starts at 40 ps at a 5-minute averaging time and reaches 300 ps at one day. The TDEV for the TWSTFT is about 200 ps for averaging times of less than 1 day and shows a diurnal. The TDEV for the CV averages down to about 300 ps at 1 day. The time transfer stability of each of the three methods is obscured by the clock noise for averaging times longer than 4 days.

.

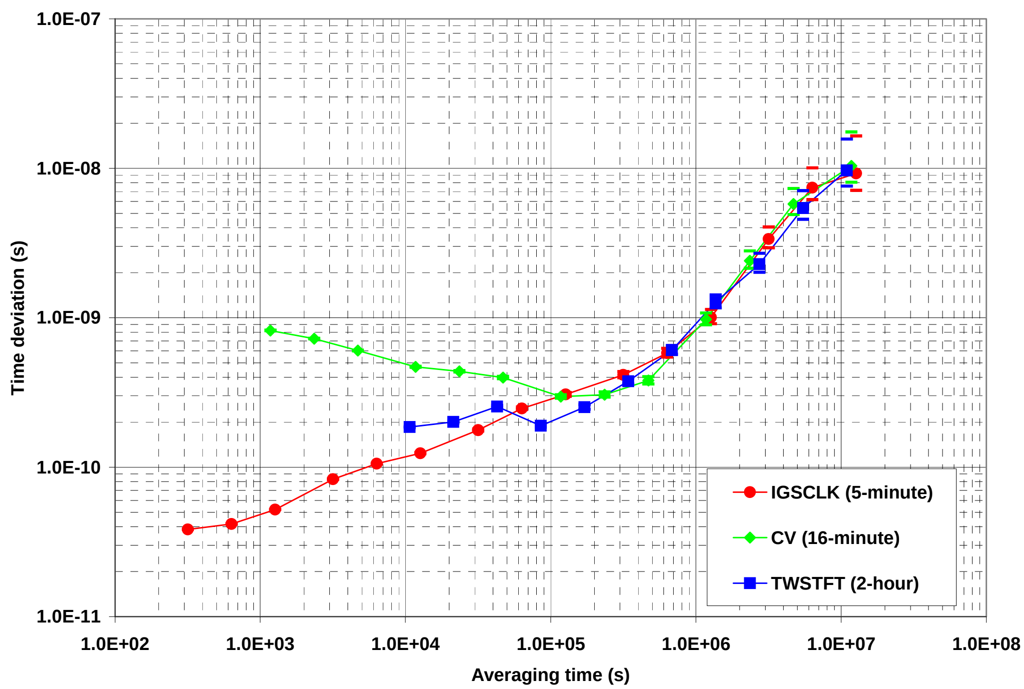

Figure 4. Stability of different time transfer methods for the NIST/USNO link.

With the clock difference removed by the double-difference, Figure 5 shows the combined time transfer stability of the (TWSTFT – IGSCLK), (TWSTFT – CV), and (IGSCLK – CV). The TDEV for (TWSTFT – IGSCLK) and (IGSCLK – CV) are computed with the 31-day excursion remaining in the (REF_{USNO} – IGST) data. The TDEV for the (TWSTFT – CV) is under 400 ps for averaging times ranging from 1 day to 45 days. The TDEV increases after 45 days, which could be caused by an annual cycle in the instability of the two systems. The (TWSTFT – IGSCLK) and (IGSCLK – CV) have about the same performance, indicating the combined stability of both comparisons may be dominated by the instability from the IGSCLK method. Figure 6 reveals the impact of the 31-day excursion to the time transfer stability. With the excursion corrected based on the CV difference results, the TDEV of the (TWSTFT – IGSCLK) is under 400 ps for averaging times from 1 day to 45 days. The possible annual cycle instability between the TWSTFT and IGSCLK is also more obvious. One can conclude from the data in Figure 5 and 6 that all three techniques have similar levels of instabilities in the range of 1 day to 45 days.

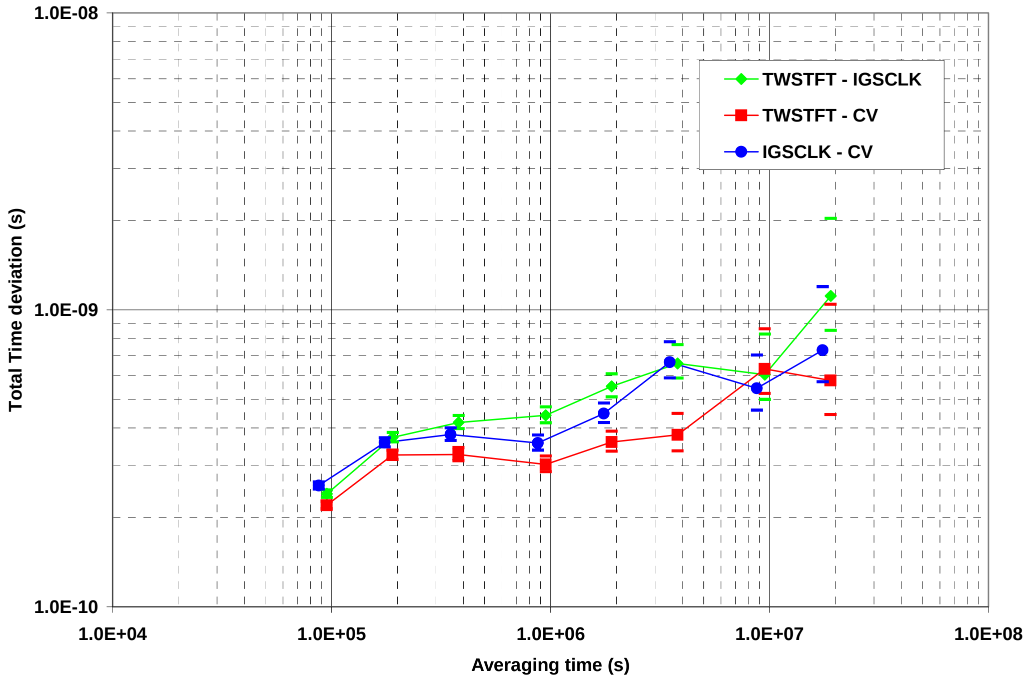

Figure 5. Combined stability of the double-differences for the NIST/USNO link.

The NIST/PTB comparison results are shown in Figure 7 and Figure 8. From Figure 7, we see the TDEVs of the three time transfer methods have relationships similar to those from the NIST/USNO link. For averaging times of less than 5 days, the TDEV is at a higher level than that of the corresponding method for the NIST/USNO link. Because UTC (PTB) is based on a cesium frequency standard, which is less stable than a hydrogen maser in the short term, the TDEV contains more clock noise than that of the NIST/USNO link. The TDEV at 1 day for IGSCLK and TWSTFT is dominated by the clock noise. Besides the clock noise, the longer baseline and fewer common-view satellites between NIST and PTB add more transfer noise to the NIST/PTB CV result. By canceling the clock contribution in the double-differences, the combined time transfer stability of the (TWSTFT – IGSCLK) is around 300 ps from 1 day to 45 days, as shown in Figure 8. This is about the same level as that for the 31-day excursion corrected NIST/USNO (TWSTFT – IGSCLK) result. The combined time transfer stabilities for the (TWSTFT – CV) and (IGSCLK – CV) follow each other closely and are less than 600 ps from 1 day to 45 days. This means both combined time transfer stabilities are dominated by the CV transfer noise.

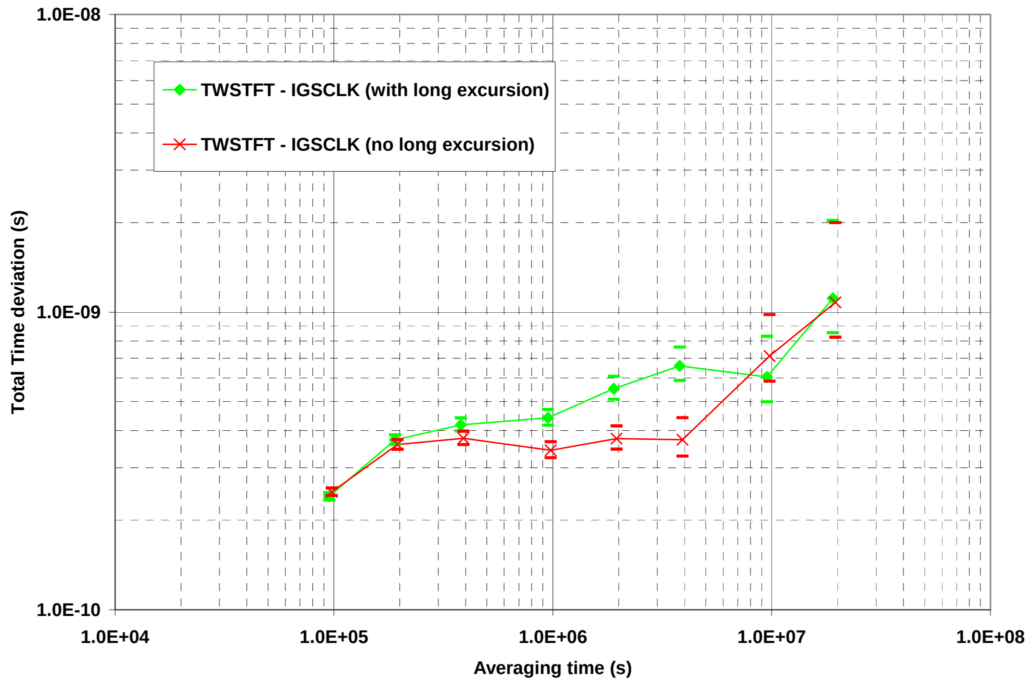

Figure 6. Impact of the 31-day excursion in the (REF_{USNO} – IGST) to the time stability.

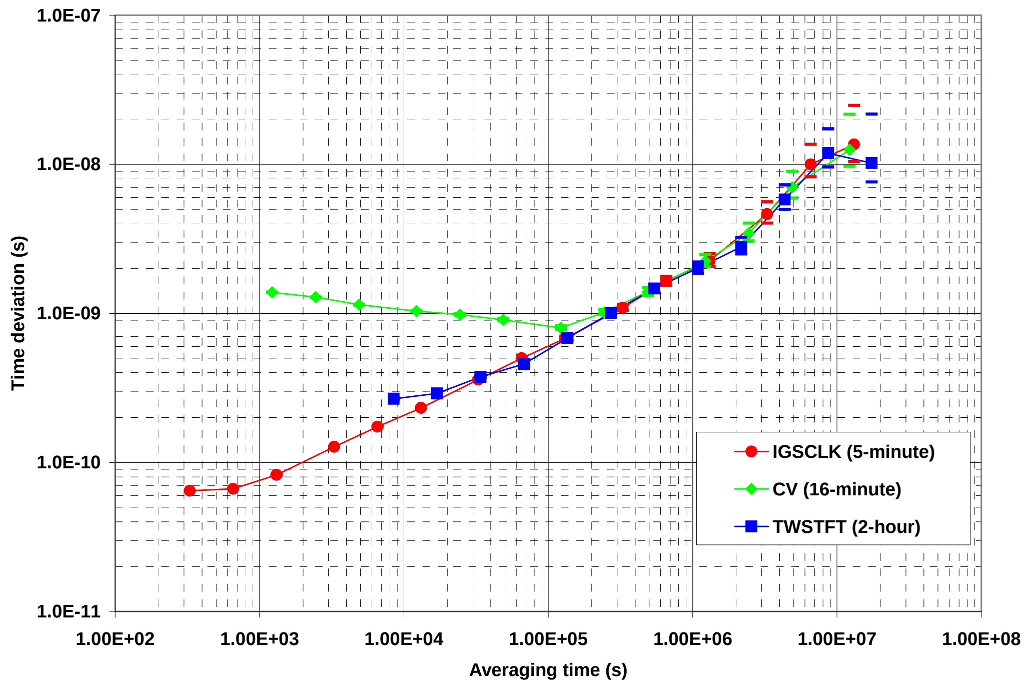

Figure 7. Stability of different time transfer systems for the NIST/PTB link.

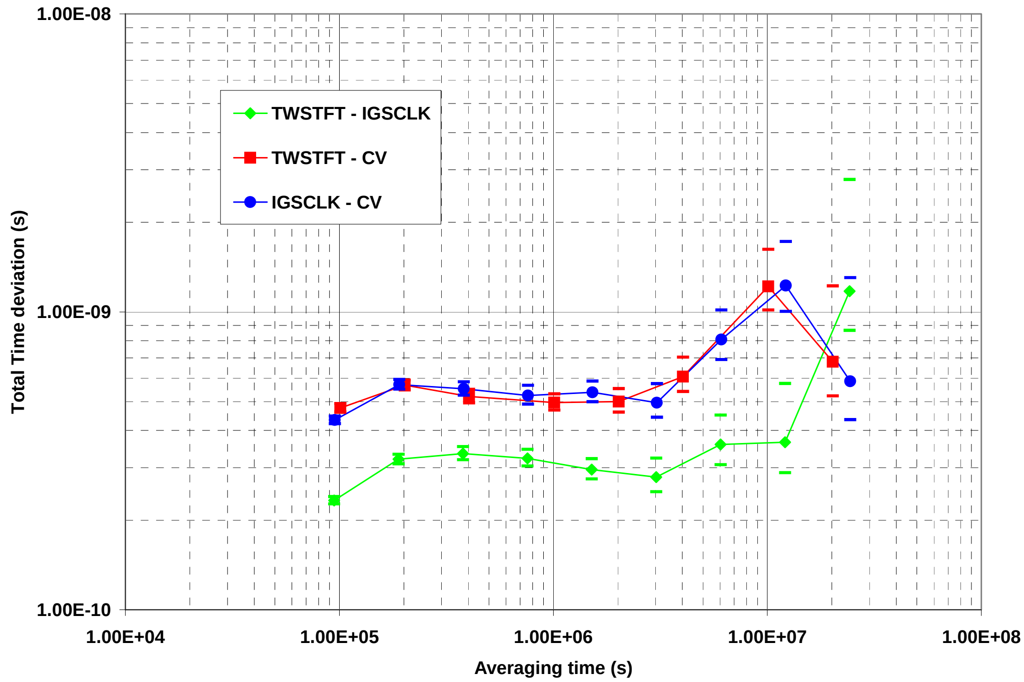

Figure 8. Combined stability of the double-differences for the NIST/PTB link.

The UTC (NIST), CH hydrogen maser comparison results are shown in Figure 9 and Figure 10. The time transfer noise for P3 CV averages down from 2 ns at 16-minute to 700 ps at 1 day. The TDEV at 1 day is about 400 ps higher than that of the NIST/USNO CV results. The TDEV for the IGSCLK is below 200 ps at 1 day, which is about the same as the NIST/USNO IGSCLK result. The baseline between NIST and CH is more than 5000 km longer than the baseline between NIST and USNO.

This means, that unlike the CV, the performance of the IGSCLK method is independent of the distance between the remote clocks. The TDEV of the TWSTFT is very good. Even with the diurnal, the TDEV at 1 day is below 100 ps. The combined time transfer stability for the (TWSTFT – IGSCLK) is less than 300 ps from 1 day to 45 days. The combined time transfer stability for the (TWSTFT – P3 CV) and (IGSCLK – P3 CV) is around 500 ps, dominated by the transfer noise from the P3 CV.

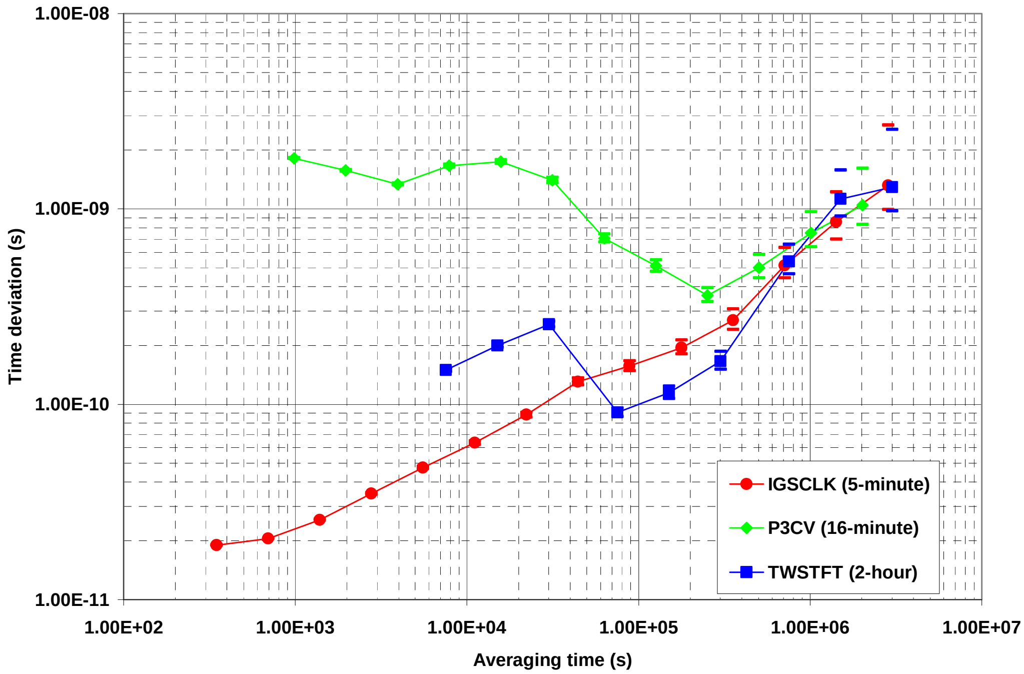

Figure 9. Stability of different time transfer methods for the NIST/CH link.

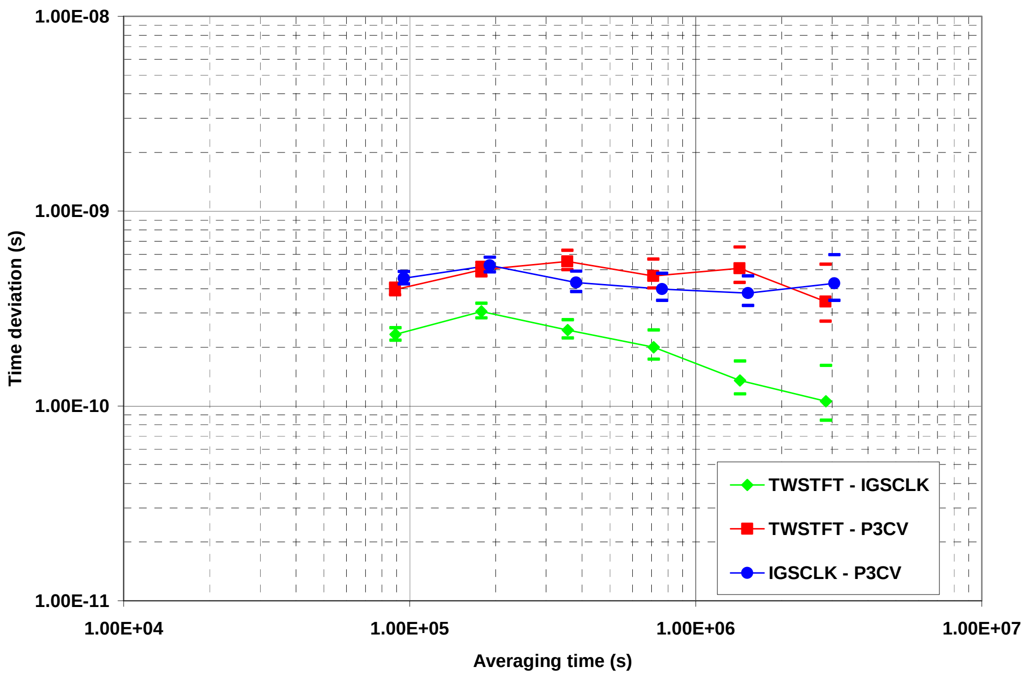

Figure 10. Combined stability of the double-differences for the NIST/CH link.

IV. CONCLUSIONS

Our study shows that the time transfer stability of the IGSCLK method is, not surprisingly, better than that of the TWSTFT and CV for averaging times up to half a day. The long-term time transfer stability of the IGSCLK is comparable to that of the TWSTFT for the NIST/USNO, NIST/PTB, and NIST/CH links. The NIST/USNO combined IGSCLK and TWSTFT time transfer stability is less than 700 ps for averaging times from 1 day to about 45 days. The combined time transfer stability can be around 400 ps with the 31-day excursion removed. The combined time transfer stability is less than 300 ps for the NIST/PTB and NIST/CH links for averaging times from 1 day to about 45 days. Without a third independent time transfer system (other than the TWSTFT and GPS), we are unable to estimate the time transfer stability of the IGSCLK method. The combined time transfer stability shows an increasing trend after the averaging time over 45 days. The increase could be caused by an instability in the difference of the two systems due to an annual cycle. The long-term stability of the IGSCLK method is comparable to that of the CV for the NIST/USNO link, and is better than that of the CV for the NIST/PTB and NIST/CH links. We see that the stability of the IGSCLK method is not affected by the distance between remote clocks.

Some data processing is needed to deal with time steps and excursions caused by local factors of the IGS Stations. However, not all anomalies are reported. These unreported anomalies complicate the data process and degrade the performance of the IGSCLK method.

ACKNOWLEDGMENTS

We thank CH, PTB, and USNO for the use of their data in our study, as well as our colleagues Laurent-Guy Bernier and Christian Schlunegger of the CH, Dirk Piester of the PTB, and Demetrios Matsakis of the USNO for providing the information about their time transfer systems and for discussions of the technical issues. We also thank all components of the IGS. Without their accomplishments, this study would not be possible.

REFERENCE

[1] D. W. Allan and M. A. Weiss, 1980, *"Accurate Time and Frequency Transfer during Common-view of a GPS Satellite,"* in Proceedings of the 34th Annual Frequency Control Symposium, 28-30 May 1980, Philadelphia, Pennsylvania, USA (IEEE, Piscataway, New Jersey), pp. 334-356.

[2] Z. Jiang and G. Petit, 2004, *"Time Transfer with GPS All in View,"* in Proceedings of the 2004 Asia-Pacific Workshop on Time and Frequency, 18-19 October 2004, Beijing, China, pp. 236-243.

[3] J.M. Dow, R.E. Neilan, and G. Gendt, 2005, "*The International GPS Service (IGS): Celebrating the 10th Anniversary and Looking to the Next Decade*," **Advances in Space Research, 36,** 320-326.

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

[5] A. Bauch, J. Achkar, R.Dach, R. Hlavac, L. Lorini, T. Parker, G. Petit, and P. Uhrich, 2005, "*Time and Frequency Comparisons Between Four European Timing Institutes and NIST using Multiple*

Techniques," in Proceedings of the 19th European Frequency and Time Forum (EFTF), 21-24 March 2005, Besançon, France, pp. 101-109.

[6] K. M. Larson, J. Levine, L. M. Nelson, and T. E. Parker, 2000, *"Assessment of GPS Carrier-Phase Stability for Time-Transfer Applications,"* **IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, UFFC-47,** 484-494.

[7] J. Ray and K. Senior, 2003, *"IGS/BIPM Pilot Project: GPS Carrier Phase for Time/Frequency Transfer and Timescale Formation,"* **Metrologia, 40,** 270-288.