Comparison of Two Continuous GPS Carrier-Phase Time Transfer Techniques

Jian Yao[1], Ivan Skakun[2], Zhiheng Jiang[3], and Judah Levine[1]

[1] Time and Frequency Division and JILA, National Institute of Standards and Technology and University of Colorado, Boulder, CO, USA

[2] PNT Information and Analysis Center, Central Research Institute of Machine Building, Korolyov City, Russia

[3] Bureau International des Poids et Mesures, Pavillon de Breteuil, F-92312 Sèvres Cedex, France

E-mail: jian.yao@nist.gov

***Abstract*—Global Positioning System (GPS) carrier-phase (CP) time transfer, as a widely accepted high-precision time transfer method, frequently shows a data-batch boundary discontinuity of up to 1 ns, because of the inconsistency of the phase ambiguities between two consecutive data batches. To eliminate the data-batch boundary discontinuity, several techniques have been proposed in recent years. The question is how large the solutions of these techniques differ from each other and how well the solutions are faithful to clocks. To answer these questions, this paper chooses two techniques to study: Revised RINEX-Shift (RRS) technique [1-2], and Phase Common-View (Phase-CV) technique [3-4]. This paper shows that the time deviation of the difference between the two techniques is below 100 ps, for an averaging time of less than 10 days. Especially, for an averaging time of less than 1 day, the time deviation is less than 30 ps. We also find that both RRS and Phase-CV match TWSTFT (two-way satellite time and frequency transfer) and TWOTFT (two-way optical-fiber time and frequency transfer) quite well. The difference is typically within ±0.3 ns for more than 20 days. The above results are all based on a short-distance links (less than 2500 km). A long-distance comparison between these two techniques, such as a transatlantic link, has not yet been investigated.**

Keywords: GPS, Carrrier-phase time transfer, boundary discontinuity, Revised RINEX-Shift, Phase common-view, two-way satellite time transfer, two-way optical-fiber time transfer

I. Introduction

Global Positioning System (GPS) carrier-phase (CP) time transfer is a widely accepted high-precision time transfer method. This method provides much lower short-term noise than other time transfer methods, such as TWSTFT (two-way satellite time and frequency transfer) and GPS common-view (CV) time transfer. TWOTFT (two-way optical-fiber time and frequency transfer), as an emerging time transfer method, can potentially be more precise than GPS CP. However, a long-distance performance of TWOTFT, such as a transatlantic link, is unknown. Besides, it requires a lot of infrastructure work and is also expensive to maintain. Thus, GPS CP is and will continue to be one of the mainstream time transfer methods.

Along with the development of GPS CP time transfer method, the problem of data-batch boundary discontinuity attracts a lot of attention. The boundary discontinuity can quite seriously affect the long-term (e.g., > 1 day) time-transfer result. Studies show that the boundary discontinuity comes from the uncertainty in the phase-ambiguity estimation for each data batch. Fundamentally, this uncertainty further comes from the code noise, because the code measurements are used to estimate the phase ambiguity [5].

To solve the boundary-discontinuity problem, several techniques have been proposed in recent years [1-4, 6-7]. Each technique looks perfect on paper. However, there is little study on the comparison between these techniques. Thus, we have no idea of how large the results of these techniques differ from each other and how well the results are faithful to clocks. This paper focuses on answering these questions. Here, two techniques are chosen for comparison: Revised RINEX-Shift (RRS) technique [1-2], and Phase Common-View (Phase-CV) technique [3-4]. Section II provides the basic principles of these two techniques. The advantages and disadvantages of each technique are also discussed in this section. Section III compares their performance for baselines of 600 km – 2500 km, with TWSTFT as a reference. A three-station closure of Phase-CV is also done, to check its self-consistency. Section IV compares the results of these two techniques with a TWOTFT result for a baseline of ~268 km. These comparisons make us conclude that both techniques work well for a baseline of no longer than 2500 km.

II. Principles of RRS and Phase-CV

The RRS is actually an updated version of PPP (precise point positioning). It runs PPP for a data batch of multi-days (here, we choose 10 days) and extracts the middle epoch. Then it shifts the data batch by a small time step (here, we choose 10 min), runs PPP, and extracts the new middle epoch. It does the data-batch shift by 10 min again and again. The solutions at all middle epochs form the RRS result [2]. Here, we should mention, if there is a GPS data anomaly, a program is run to repair the anomaly and the RRS program uses the repaired GPS data [8]. Previous study has shown that the RRS technique can achieve the 10^{-17} level of instability for an

978-1-4799-8866-2/15/$31.00 ©2015 IEEE

averaging time of 20 days with TWSTFT as a reference, while the conventional 30-days PPP processing is still ~2×10^{-16} for the same averaging time [2].

Phase-CV is similar to the traditional GPS CV time transfer, but using the phase data rather than the code data. Phase-CV is achieved by two steps. First, it uses PPP to estimate the absolute station coordinates and tropospheric zenith delays (TZD). Second, it does the single-difference of phase measurements between two stations, for the same GPS satellite. The single-difference recovers the integer property of the phase ambiguities. By using the coordinates and TZDs in the first step, we can resolve the integer ambiguities and clock difference between the two stations [3].

Before we study the technical performance of each technique in the later sections, we here want to address the advantages and disadvantages of each technique. These issues are often ignored, but they can sometimes be even more important than the pure technical performance.

First, RRS requires only a single station, while Phase-CV requires two stations. So RRS is still a type of PPP, while Phase-CV is not.

Second, RRS works for any baseline, short or long, since RRS does a time comparison between local time and the IGS time. The long-baseline performance of RRS (between NIST and PTB), with respect to TWSTFT, has been shown by Figure 11 of [2]. Phase-CV typically works worse as the baseline increases, because of few common-view GPS satellites and no common path. The network processing of Phase-CV, which is still under development, may help the long-baseline performance of Phase-CV.

Third, the solution of RRS is unique, no matter what the start date and the end date are. However, the solution of Phase-CV is not unique. First, it depends on the absolute station position, which can vary by ~1 cm when different GPS data batches are used. Thus, different people may use slightly different positions for Phase-CV. A slightly incorrect absolute position can lead to a small slope in the Phase-CV solution. The absolute position may also change as time passes. Second, Phase-CV is for frequency transfer. In order to achieve time transfer, we need to align the Phase-CV solution with the PPP solution on a long time interval (e.g., > 10 days). However, the choice of a long time interval is arbitrary. Different long time intervals (e.g., MJD 56000 – 56010, or MJD 56001 – 56015) in PPP can lead to different absolute times in Phase-CV. This can make Phase-CV ambiguous in time transfer.

Fourth, RRS can be affected by the errors from the GPS satellite orbit and clock. Even though IGS has provided precise satellite orbit and clock information, there could still be small errors, e.g., a few millimeters. Phase-CV works well in this aspect, because it cancels out the common errors from satellites and path. Besides, Phase-CV is more likely to be insensitive to small noise because of the integer property of the phase ambiguity. For a short baseline (< 100 km), broadcast ephemeris can even be used for Phase-CV without too much performance degrading.

Fifth, RRS increases the computation burden quite significantly, although it can be parallelized easily (e.g., one microprocessor core is used to compute MJD 56000.0-56000.25, and another core is used to compute MJD 56000.25-56000.50). Phase-CV requires more computation than PPP, but the increase is not big. Phase-CV is a sequential process.

Sixth, Phase-CV can work in real time or near real time, while RRS cannot. RRS has a latency of 5 days.

Lastly, Phase-CV sometimes cannot keep the integer ambiguity property, which leads to a re-initialization of the processing settings, while RRS does not have this problem.

III. Comparison between RRS and Phase-CV

In this section, we compare RRS and Phase-CV, for baselines of 600 – 2500 km. We will see that they agree fairly well.

PTBB is a GPS receiver at PTB (Physikalisch-Technische Bundesanstalt), Germany. The coordinates of this receiver are X = 3844060.1 m, Y = 709661.2 m, and Z = 5023129.5 m, in the ITRF (international terrestrial reference system) coordinate system. The reference time of PTBB is UTC(PTB) with a constant delay. OPMT is a GPS receiver at OP (Paris Observatory), France, with the coordinates of X = 4202777.4 m, Y = 171368.0 m, and Z = 4778660.2 m. The reference time of OPMT comes from a hydrogen maser, which usually has a non-zero slope. We should mention that the TWSTFT facilities at both PTB and OP share the same reference times as the GPS receivers. The baseline of the link of "OPMT-PTBB" is ~692 km.

We do the time comparison between OPMT and PTBB using RRS, Phase-CV, and TWSTFT, for MJD (Modified Julian Date) 56881.0 – 56905.0 (Figure 1). Note, the slope from the hydrogen maser at OP has already been removed and some constant offsets are added to the three curves to overlap each other. Here, we should emphasize that we use exactly the same GPS data of OPMT and PTBB for both RRS and Phase-CV. From Figure 1, we can see that both RRS and Phase-CV provide continuous solutions. They match each other very well. They also match the TWSTFT result quite well, although there is an approximately 0.5 ns discrepancy during MJD 56887-56895. This discrepancy could come from either GPS time transfer or TWSTFT or both [9].

To investigate the agreement between RRS and Phase-CV, we do double-difference between RRS and Phase-CV for the link of "OPMT – PTBB" (Figure 2). The difference is within ±200 ps. This indicates a good match between the two techniques. Modified total deviation (Figure 3) and time total deviation (Figure 4) reveal the frequency stability of the double difference between RRS and Phase-CV. From Figure 3, we can see that the two techniques match with a fractional uncertainty of ~5×10^{-16} for an averaging time of 1 day, and ~2×10^{-16} for an averaging time of 10 days. Figure 4 shows that the time deviation of the double difference is below 100 ps for an averaging time of less than 10 days. Especially, the time deviation is less than 30 ps within 1 day. This indicates that even though we process the GPS code and phase data using two different techniques, the time-transfer results are consistent with each other. This validates both techniques.

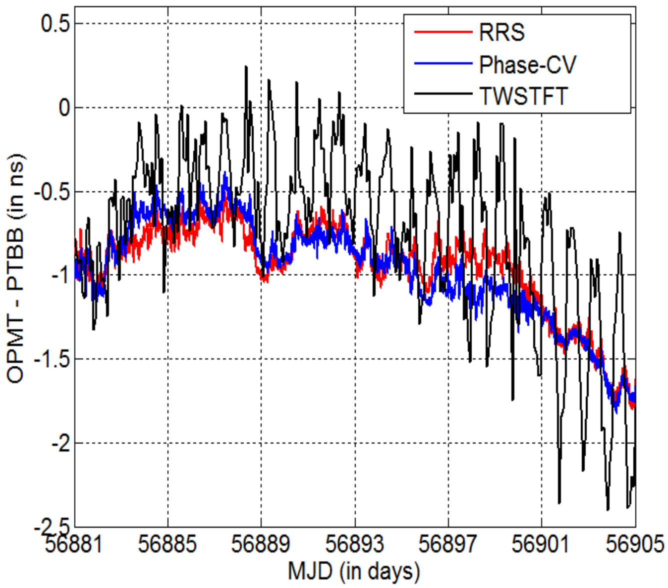

Figure 1. Time comparison between OPMT and PTBB, using RRS, Phase-CV, and TWSTFT. Note, TWSTFT facilities at both OP and PTB share the same reference times as GPS receivers. Slope from the hydrogen maser at OPMT has been removed, and some constant offsets are added to the three curves to overlap each other.

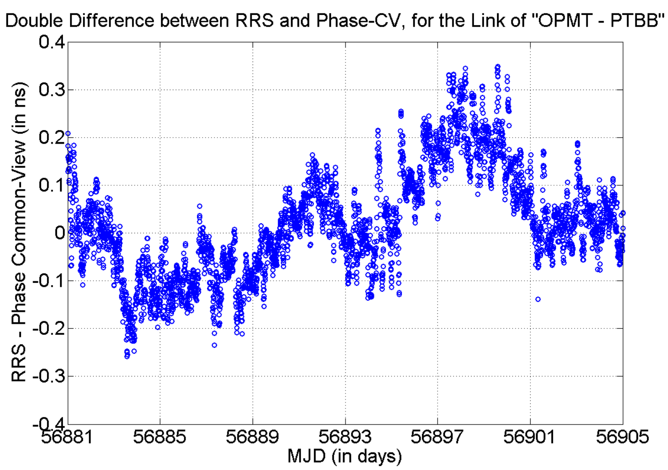

Figure 2. Double difference between RRS and Phase-CV during 56881.0 – 56905.0, for the link of "OPMT-PTBB."

To further verify the above conclusion that both techniques match each other very well, we also compute the double difference between the two techniques for other baselines.

MDVJ is a GPS receiver in Mendeleevo, Russia, with the coordinates of X = 2845456.3 m, Y = 2160954.3 m, and Z = 5265993.4 m. The baseline between PTBB and MDVJ is approximately 1778 km. And the baseline between OPMT and MDVJ is approximately 2457 km. The double differences between RRS and Phase-CV for these two baselines are shown in Figure 5 and Figure 6, respectively. Again, we can see that RRS is within approximately ±200 ps of Phase-CV. Here, we should mention that the Phase-CV has an average offset of about +0.35 ns for the link of "OPMT-MDVJ". This constant offset leads to the curve in Figure 6 shifting down by 0.35 ns. The reason for the offset comes from the ambiguity of the absolute time in Phase-CV. Phase-CV itself can only provide the frequency transfer result. To provide the time transfer result, it requires the assistance of the conventional PPP solution. However, the boundary discontinuity in the conventional PPP can lead to a slightly biased time transfer result. That is why Phase-CV is 0.35 ns biased from RRS in Figure 6.

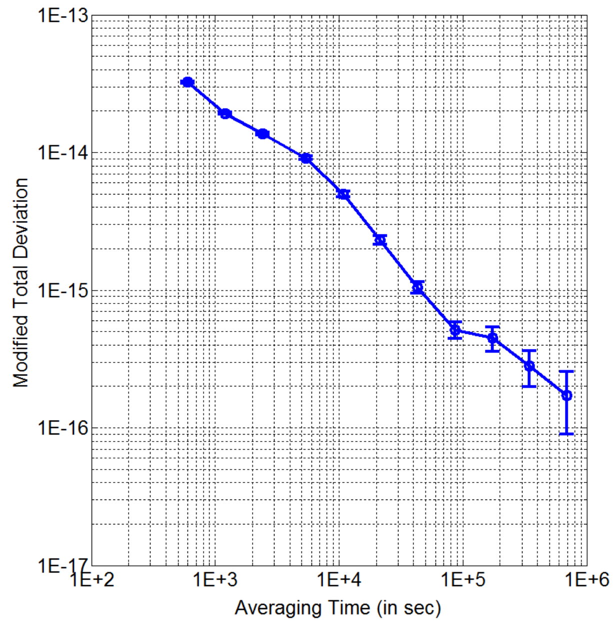

Figure 3. Modified total deviation for the double difference between RRS and Phase-CV, for the link of "OPMT-PTBB."

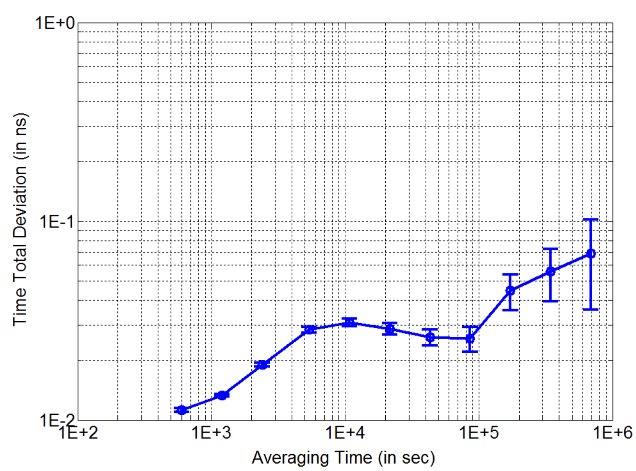

Figure 4. Time total deviation for the double difference between RRS and Phase-CV, for the link of "OPMT-PTBB."

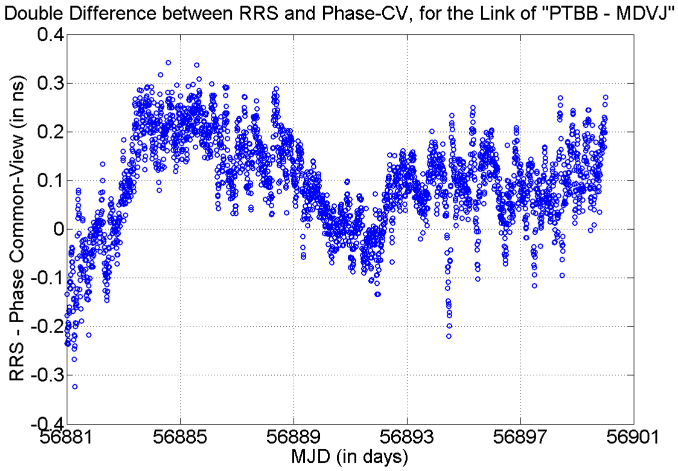

Figure 5. Double difference between RRS and Phase-CV during 56881.0 – 56900.0, for the link of "PTBB-MDVJ."

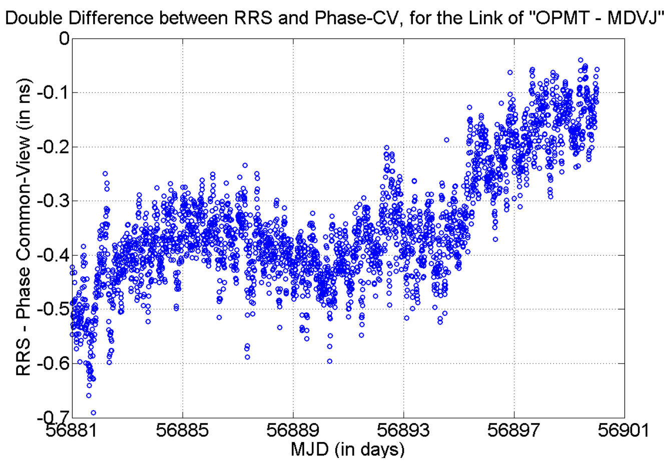

Figure 6. Double difference between RRS and Phase-CV during 56881.0 – 56900.0, for the link of "OPMT-MDVJ."

From the above discussion, we know that RRS and Phase-CV agree within ±200 ps. Now that we have done the time transfer between each two of the three stations, a three-station closure may tell us the self-consistency of a time transfer technique. Since RRS is a type of single-point technique, the time difference between two stations is achieved by introducing a common reference time. Often, we choose the IGS (international GNSS service) time (IGST) as the common reference time. Then, the three-station closure of RRS becomes

$$\begin{aligned} Closure &= (PTBB - MDVJ) + (MDVJ - OPMT) + (OPMT - PTBB) \\ &= [(PTBB - IGST) - (MDVJ - IGST)] + \\ &\quad [(MDVJ - IGST) - (OPMT - IGST)] + \\ &\quad [(OPMT - IGST) - (PTBB - IGST)] \\ &= [(PTBB - IGST) - (PTBB - IGST)] + \\ &\quad [(MDVJ - IGST) - (MDVJ - IGST)] + \\ &\quad [(OPMT - IGST) - (OPMT - IGST)] \\ &= 0 + 0 + 0 = 0. \end{aligned} \quad (1)$$

Equation (1) indicates that the three-station closure of RRS is always exactly 0. The red curve in Figure 7 further confirms this conclusion. However, the Phase-CV is a type of common-view technique. It provides the time difference between two stations directly and no common reference time needs to be introduced in the Phase-CV. Thus, the three-station closure of Phase-CV is

$$Closure = (PTBB - MDVJ) + (MDVJ - OPMT) + (OPMT - PTBB). \quad (2)$$

Equation (2) cannot be further simplified. Thus, the closure of Phase-CV is not necessary to be exactly 0. The closure test for Phase-CV can show how well it is self-consistent. The black curve in Figure 7 shows the result of the Phase-CV three-station closure test. We can see that the closure is not around 0 ns. Instead, it is shifted by approximately -0.37 ns. As mentioned before, this offset comes from the ambiguity of the absolute time in Phase-CV. From Figure 7, we know that the peak-to-peak value of the closure is as small as ~60 ps. Besides, the closure does not change over time. These indicate that the Phase-CV processing is self-consistent for frequency transfer.

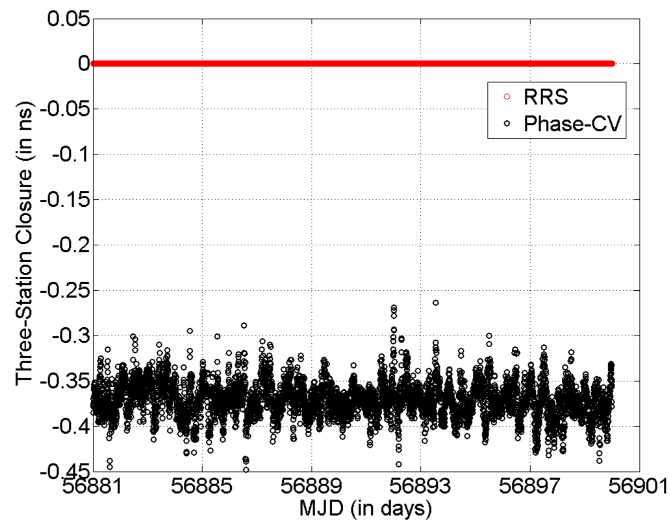

Figure 7. Three-station closure of RRS (red) and Phase-CV (black). The closure is achieved by adding together the links of "PTBB-MDVJ," "MDVJ-OPMT," and "OPMT-PTBB."

IV. Comparison of RRS and Phase-CV with TWOTFT

TWOTFT is a fast-emerging time transfer technique. Many people have demonstrated its ultra-precise time transfer capability [10-12]. Thus, a comparison between GPS and TWOTFT can provide the instability of GPS time transfer, because the instability of TWOTFT is typically smaller or even negligible when compared to GPS.

There is an optical fiber link between AOS (Astrogeodynamical Observatory) and PL (Polish Atomic Time Scale) in Poland [13]. The length of the optical fiber is ~ 420 km. There are also two GPS receivers, i.e., AO_4 and GUM4, at AOS and PL, respectively. The coordinates of AO_4 are X = 3738358.4 m, Y = 1148173.7 m, and Z = 5021815.8 m. The coordinates of GUM4 are X = 3653847.0 m, Y = 1402629.2 m, and Z = 5019465.1 m. Thus, the baseline between these two stations is approximately 268 km. The time references for the optical fiber link and the GPS receivers are the same at each station.

Figure 8 shows the time difference between AOS and PL using TWOTFT, RRS, and Phase-CV, for MJD 56902.0 – 56928.0. We make the three curves match at MJD 56928.0 for a better comparison. The TWOTFT result (blue curve) is hard to see in Figure 8, because it is almost completely covered by the red/black curve. This indicates that both RRS and Phase-CV agree with TWOTFT well over the entire 26 days.

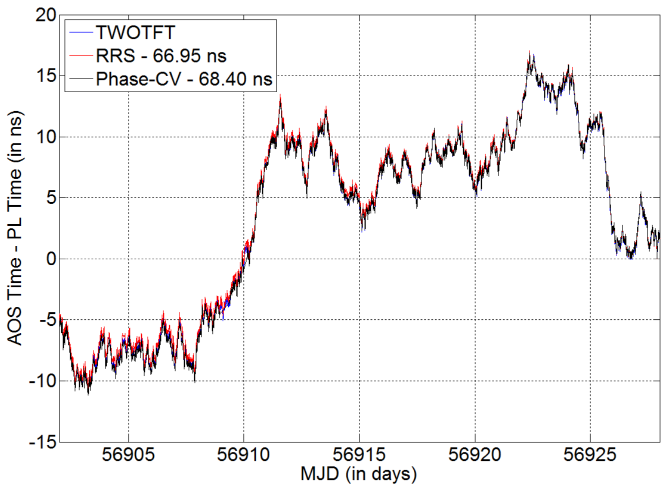

Figure 8. Time difference between AOS and PL using TWOTFT (blue), RRS (red), and Phase-CV (black). The red and black curves are shifted by 66.95 ns and 68.40 ns, respectively, in order to match the blue curve at MJD 56928.0. The blue curve is almost completely covered by the red/black curve. This indicates that RRS and Phase-CV match TWOTFT very well.

To show the difference between GPS time transfer and TWOTFT, we do double difference between RRS/Phase-CV and TWOTFT (Figure 9). The BIPM 35-days PPP (i.e., TAIPPP 35 days) result [14] is also provided in Figure 9, as a reference. There are two anomaly points at 56909.35 and 56921.81. The BIPM TAIPPP shows two jumps at both anomaly points. The jumps are 0.7 ns and 0.4 ns, respectively. Because of the jumps, the trend is changed significantly. For example, the time change from 56909 to 56922 is approximately 0.9 ns, which significantly affects the time-comparison result. In contrast, the RRS technique (red curve) performs very well at both anomaly points. It remains flat (within ± 100 ps) compared to TWOTFT, during 56903 – 56915. There is also no significant change around the second anomaly point (i.e., during 56921.5 – 56922.5). Over the whole 26 days, the difference between RRS and TWOTFT is less than ±250 ps. This indicates the correctness of RRS. The Phase-CV (black curve) does not do well at the first anomaly point. It reinitializes the filter and thus is very noisy during the whole day of MJD 56909. Actually, there was also a jump of about −1 ns on MJD 56909 in the original Phase-CV result, because we need to re-estimate the absolute time using PPP when a re-initialization occurs. We have already removed this jump in Figure 9. There was also a jump at the second anomaly point in the original Phase-CV result. We again removed the jump by a simple concatenation. From the black curve, we can see that the difference between Phase-CV and TWOTFT is also less than ±250 ps. Its slope is pretty small and is not affected by the jumps and the anomaly points. Especially, it keeps flat during 56917 – 56920, while there is a small dent in RRS. The reason why Phase-CV is so flat probably comes from the fact that Phase-CV uses phase only and thus the noise in code is well excluded. From the above analysis, Phase-CV is good for the frequency transfer. For the time-transfer purpose, a careful calibration or adjustment at each re-initialization point is required in Phase-CV. Next, let's consider the long-term trend of the three curves in Figure 9. We can see that RRS and BIPM TAIPPP goes down by ~100 ps during the 26 days, while Phase-CV goes up by ~300 ps. The increase in Phase-CV is probably because station coordinates were not estimated in the same filter and was fixed for the whole 26 days. Note that the three GPS carrier-phase techniques use the same GPS data, but, unfortunately, the long-term trends are different. This indicates that different GPS CP techniques introduce different long-term trends. And it is hard to tell which technique is more correct. In this case, the long-term difference between RRS and Phase-CV is ~ 400 ps for 26 days, which matches our conclusion in Section III that the difference between RRS and Phase-CV is within ± 200 ps.

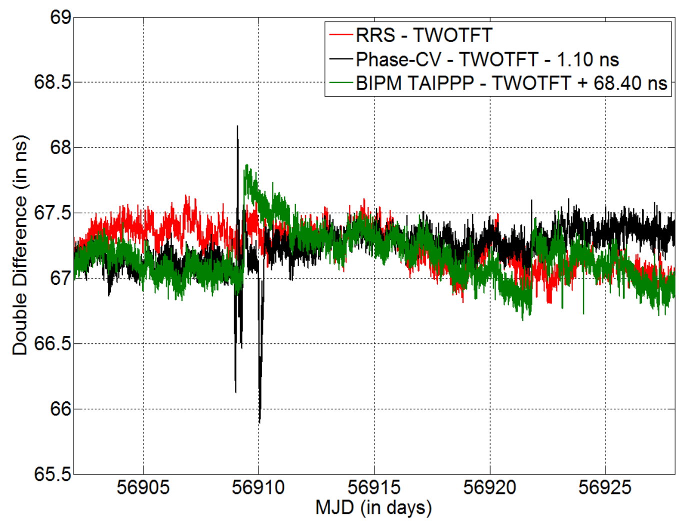

Figure 9. Double differences of "RRS – TWOTFT" (red), "Phase-CV – TWOTFT" (black), and "BIPM TAIPPP – TWOTFT" (green), for the link between AOS and PL. (Note, the black curve is shift by -1.1 ns for a better comparison. And the black curve is shifted by +68.40 ns, because the BIPM TAIPPP result has already included the delay calibration corrections.)

To study the frequency stabilities of RRS, Phase-CV, and BIPM TAIPPP, with respect to TWOTFT, we compute the modified total deviation of the double difference (Figure 10). Note, we have already removed the bad data of Phase-CV on MJD 56909. We can see that Phase-CV provides the smallest instability. RRS is better than BIPM TAIPPP after ~ 6 hours. Both RRS and Phase-CV provide ~1×10^{-16} level of instability after 5 days. The above results are only based on the fact that the baseline is ~268 km. For a transatlantic link, the RRS performance has little change (see Figure 4.16 in [15]). However, the Phase-CV performance typically gets worse, if three bridge stations are introduced. We add the four short baselines (< 2000 km) together to achieve the transatlantic time transfer. Thus, the Phase-CV instability for the transatlantic link is increased to double of the instability for a short baseline ($\sqrt{1^2+1^2+1^2+1^2}=2$). This theoretical frequency instability for a long-distance link is shown by the blue dotted curve in Figure 10. We can see that RRS becomes the best among RRS, Phase-CV, and BIPM TAIPPP for the case of a transatlantic link.

The three curves in Figure 10 can also be used to set the upper limit of the frequency instability of the time transfer techniques. For example, the upper limit of the RRS instability is 5×10^{-15} at 3 hours, 9×10^{-16} at 1 day, and 2×10^{-16} at 5 days. The upper limit of Phase-CV instability (for ~268 km baseline) is similar to RRS instability, but with a significant improvement at 1 day (i.e., 6×10^{-16}).

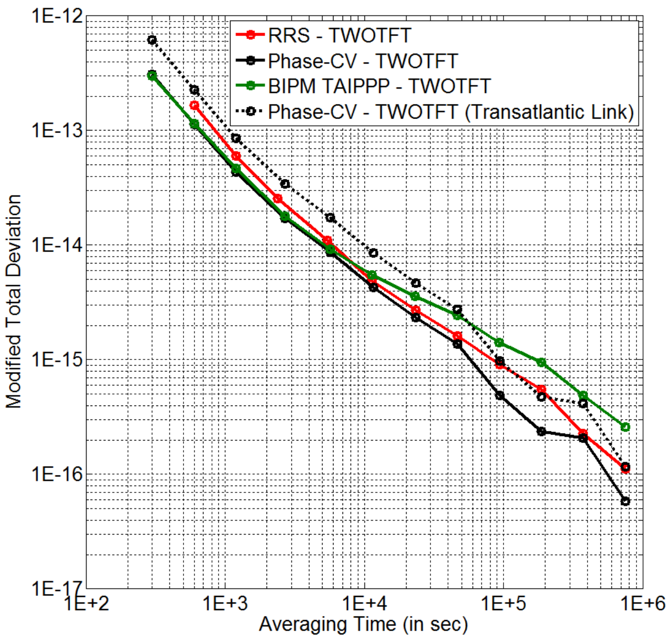

Figure 10. Frequency instability of "RRS – TWOTFT" (red solid), "Phase-CV – TWOTFT" (black solid), and "BIPM TAIPPP – TWOTFT" (green solid), for the link between AOS and PL. For a transatlantic link, the theoretical frequency instability of "Phase-CV – TWOTFT" is shown by the black dotted curve. Note, bad data in Phase-CV were already removed for the black solid curve.

In order to improve the performance of RRS, we adjust the weights of code and phase in RRS. The RRS is actually a phase time transfer technique with a long-term steering (e.g., > 1 day) to the code data. Since the code data are noisier than the phase data, we decrease the weight of code in RRS so that the long-term steering is not overreacting. For example, we change the weight ratio of code to phase from the default 1:10000 to 1:40000. We find that this change makes the dent during 56917 – 56920 and also other oscillations in the red curve in Figure 9 become smaller. Figure 11 shows the RRS result with the improvement of code&phase weights. In terms of frequency stability, there is an obvious improvement for the averaging time of ~1 day (see Figure 12). Now, the upper limit of the RRS instability becomes 7×10^{-16} at 1 day.

Admittedly, both RRS and Phase-CV are still under development and they can be further improved. Nevertheless, even without any further improvement, both techniques are already better than the BIPM TAIPPP, based on the above comparison with TWOTFT.

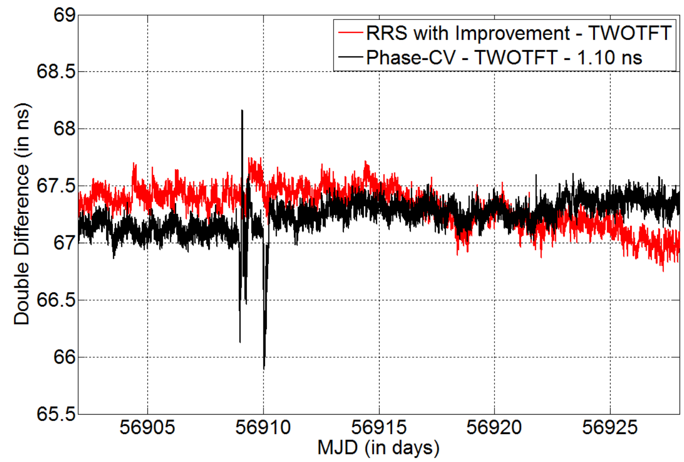

Figure 11. Double differences of "RRS with Improvement – TWOTFT" (red), for the link between AOS and PL. The black curve is the same as Figure 9. It is plotted in this figure as a reference.

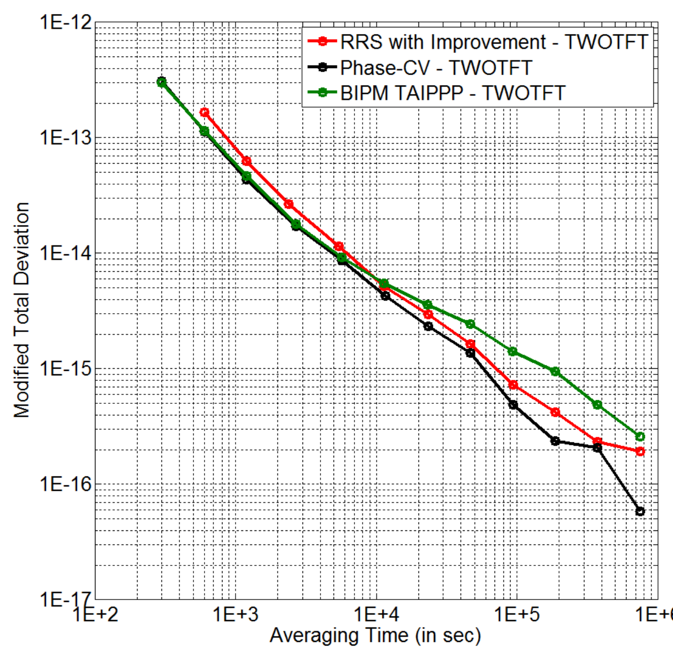

Figure 12. Performance of RRS with improvement in code and phase weights (red curve), for the link between AOS and PL. The black and green curves are the same as Figure 10. They are plotted in this figure as a reference.

V. CONCLUSIONS

In this paper, we compare two continuous GPS carrier-phase time transfer techniques: Revised RINEX-Shift (RRS) technique, and Phase Common-View (Phase-CV) technique. The time difference between these two techniques is typically within ±200 ps for baselines of less than 2500 km. This indicates a good agreement between the two techniques.

The double difference between these two techniques and other independent time transfer techniques, such as TWSTFT and TWOTFT, can reveal how well the two continuous solutions are faithful to clocks. We find that both RRS and Phase-CV match the long-term trend of TWSTFT quite well. However, RRS and Phase-CV can sometimes walk ~ 0.5 ns away from TWSTFT. This can come from either TWSTFT or GPS, or even both. Compared with a two-way optical fiber link with a ~268 km baseline, both RRS and Phase-CV vary less than ±250 ps during 26 days. This comparison confirms the correctness of both techniques. We find that Phase-CV can provide a slightly better frequency transfer result than RRS for the averaging time of around 1 day. However, this is only for the case of baseline = 268 km. Its long-distance (e.g., a transatlantic link) performance is unknown (typically worse with bridge stations introduced) and hard to verify, because of no such fiber link. However, a network processing of Phase-CV, which is still under development, may help the long-distance performance. The ambiguity of the absolute time and the problem of re-initialization in the Phase-CV solution also need to be solved, if the time transfer, instead of the frequency transfer, is our main concern. Our study also shows that the conventional BIPM TAIPPP can have an incorrect time-transfer slope due to the data-batch boundary discontinuity. With the advent of RRS and Phase-CV, the GPS time transfer becomes more faithful to clocks and thus can observe a remote clock behavior better.

ACKNOWLEDGEMENTS

The authors thank Francois Lahaye for sharing the NRCan PPP software. Jerzy Nawrocki at AOS, Poland and Albin Czubla at PL, Poland are specially thanked for providing the optical-fiber-link data and the GPS data. We also thank those people who maintain the GPS receivers of PTBB, OPMT, MDVJ, AO_4, and GUM4. IGS is gratefully acknowledged for providing GPS tracking data, station coordinates, and satellite ephemerides.

REFERENCES

[1] J. Yao and J. Levine, “A new algorithm to eliminate GPS carrier-phase time transfer boundary discontinuity,” Proc. 45th ION PTTI Meeting, pp. 292–303, 2013.

[2] J. Yao, and J. Levine, “An improvement of RINEX-Shift algorithm for continuous GPS carrier-phase time transfer,” Proc. 27th ION GNSS+ 2014 Conference, pp. 1253–1260, 2014.

[3] J. Delporte, F. Mercier, D. Laurichesse, and O. Galy, “GPS carrier-phase time transfer using single-difference integer ambiguity resolution,” International Journal of Navigation and Observation, 2008.

[4] G. Petit, A. Kanj, S. Loyer, J. Delporte, F. Mercier, and F. Perosanz, “1×10^{-16} frequency transfer by GPS PPP with integer ambiguity resolution,” Metrologia, 52, pp. 301-309, 2015.

[5] J. Yao and J. Levine, “GPS carrier-phase time transfer boundary discontinuity investigation,” Proc. 44th PTTI Meeting, pp. 317–326, 2012.

[6] R. Dach, T. Schildknecht, U. Hugentobler, L.-G. Bernier, and G. Dudle, “Continuous geodetic time transfer analysis method,” IEEE Trans. Ultrason., Ferroe-lect., Freq. Contr., vol. 53, no. 7, pp. 1250–1259, 2006.

[7] P. Defraigne, C. Bruyninx, and N. Guyennon, “PPP and phase-only GPS time and frequency transfer,” Proc. 2007 IEEE IFCS/EFTF Meeting, pp. 904-908, 2007.

[8] J. Yao, and J. Levine, “GPS measurements anomaly and continuous GPS carrier-phase time transfer,” Proc. 46th ION PTTI Meeting, 2014.

[9] V. Zhang, T. Parker, and J. Yao, “Long-term uncertainty in time transfer using GPS and TWSTFT techniques,” To be published in Proc. 2015 IEEE IFCS/EFTF Meeting, 2015.

[10] J. Ye, *et al*, “Delivery of high-stability optical and microwave frequency standards over an optical fiber network,” J. Opt. Soc. Am. B, vol. 20, pp. 1459-1467, 2003.

[11] K. Predehl, *et al*, “A 920-kilometer optical fiber link for frequency metrology at the 19th decimal place,” Science, vol. 336, pp. 441-444, 2012.

[12] L. Hu, G. Wu, H. Zhang, and J. Chen, “A 300-kilometer optical fiber time transfer using bidirectional TDM dissemination,” Proc. 46th ION PTTI Meeting, pp. 41-44, 2014.

[13] Ł. Śliwczyński, P. Krehlik, A. Czubla, Ł. Buczek, and M. Lipiński , “Dissemination of time and RF frequency via a stabilized fibre optic link over a distance of 420 km,” Metrologia, vol. 50, pp. 133–145, 2013.

[14] G. Petit and F. Mercier, “The time stability of PPP links for TAI,” Proc. 2011 IEEE IFCS/EFTF Meeting, pp. 1041- 1045, 2011.

[15] J. Yao, “Continuous GPS carrier-phase time transfer,” Ph.D. thesis, University of Colorado at Boulder, 2014.