GPS Measurements Anomaly and Continuous GPS Carrier-Phase Time Transfer

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BIOGRAPHY

Jian Yao was born in Nancheng, Jiangxi Province, China, in 1988. He received a bachelor of science degree in physics from Nanjing University, China, in 2009, and a master of science degree in physics from the University of Colorado at Boulder in 2012. He has recently received a Ph.D. degree from the University of Colorado at Boulder. He is currently a research associate at the National Institute of Standards and Technology (NIST) and the University of Colorado at Boulder, where he performs studies in GPS carrier-phase time and frequency transfer under the supervision of Dr. Judah Levine.

Judah Levine is a Fellow of the National Institute of Standards and Technology and is the leader of the Network Synchronization Project in the Time and Frequency Division, which is located in the NIST laboratories in Boulder, Colorado. He received his Ph.D. in physics from New York University in 1966. Dr. Levine is a member of the IEEE and a Fellow of the American Physical Society. He is responsible for the design and implementation of the time scales AT1 and UTC(NIST), which provide the reference signals for all of the NIST time and frequency services. In addition, he designed and built the servers that support the Automated Computer Time Service (ACTS) and the Internet Time Service, which provide time and frequency information to users in a number of different digital formats. The ACTS service is realized using a number of parallel computers that control a 12-line telephone rotary. The ACTS service receives about 4,000 requests per day. The Internet Time Service uses 24 computers which are located at several sites in the US. These computers receive about 6.5 billion requests per day for time stamps in 3 different standard formats.

ABSTRACT

The wide application of GPS carrier-phase (CP) time transfer is limited by the problem of boundary discontinuity (BD). The discontinuity has two categories. One is “day boundary discontinuity,” which has been studied extensively and can be solved by a few methods [1–5]. The other category of discontinuity, called “anomaly boundary discontinuity (anomaly-BD),” comes from a GPS-measurements data anomaly. This paper focuses on the second category of discontinuity (i.e., anomaly-BD). We first demonstrate that a few minutes of GPS-measurements data anomaly are enough to lead to a discontinuity of more than 200 picoseconds in the GPS CP time transfer. To eliminate the anomaly-BD, we propose a simple, but powerful strategy, i.e., polynomial curve-fitting for the anomaly. The fitted phase measurement is typically less than 3 cm from the original phase measurement, in terms of the root mean square (RMS). And the fitted code measurement is typically less than 80 cm from the original code measurement. If we replace the anomaly with the fitted data, we can avoid the re-estimation of the phase ambiguities after the anomaly. Thus, the anomaly-BD at the anomaly should disappear. Tests show that the curve-fitting strategy works very well for up to 20 min of GPS-measurements data anomaly.

KEY WORDS

GPS, carrier phase, time transfer, precise point positioning (PPP), boundary discontinuity, anomaly boundary discontinuity (anomaly-BD), curve fitting.

I. INTRODUCTION

Global Positioning System (GPS) carrier-phase (CP) time transfer, a widely accepted method for high-precision time transfer, provides much lower short-term noise than other time transfer methods, such as Two Way Satellite Time and Frequency Transfer (TWSTFT) and GPS Common View (CV) Time Transfer [6]. However, independent daily CP time-transfer results frequently show boundary discontinuities (BD) of up to 1 ns, because of the inconsistency of the phase ambiguities between two independent days [3, 7–8]. We call this type of boundary discontinuity “day boundary discontinuity (day-BD).” The day-BD is an obstacle for observing the short-term (< 5 days) behavior of a remote high-precision clock, such as a Cs fountain primary standard, and a Hydrogen maser [9]. Many researchers have studied the behavior and origins of day-BD in recent years [7, 10–13]. A few algorithms were proposed to eliminate the day-BD to achieve continuous GPS CP time transfer [1–5].

However, little attention was paid to another type of BD, i.e., the BD occurring at a GPS-measurements data anomaly. Similar to the day-BD, this type of BD also affects the observation of a remote high-precision clock. As for its origin, the GPS CP time-transfer processing needs to estimate a new set of phase ambiguities after the anomaly, which is typically different from the set of phase ambiguities before the anomaly. Because of the inconsistency of the phase ambiguities, we have a boundary discontinuity occurring at the anomaly. We call this type of boundary discontinuity "anomaly boundary discontinuity (anomaly-BD)."

In this paper, we focus on the anomaly-BD. In Section II, we show that a few minutes of GPS data anomaly can lead to a boundary discontinuity. Then, a polynomial curve-fitting strategy is proposed in Section III. We also test how well the curve-fitting results fit the original data. In Section IV, we apply the curve-fitting strategy to the anomaly-BD problem. We will see that this strategy can eliminate the anomaly-BD caused by up to 20 min of data anomaly.

II. THE ANOMALY AND ITS CONSEQUENCES

As many researchers in the time and frequency community have shown [3, 7–8], the boundary discontinuity comes from the uncertainty of the estimation of phase ambiguities. When the data within a data set are all good, the GPS CP time-transfer processing keeps using the same phase ambiguities. Thus, there is no discontinuity in the CP time-transfer result for the period of the data set. However, in practice, it is inevitable that a GPS receiver malfunctions (e.g., losing track), or the satellite-receiver line is blocked by an object, or the reference time for the receiver is adjusted, or even a man-made error occurs. All these problems lead to GPS-measurements data anomalies. When there is an anomaly, the CP time-transfer processing needs to re-estimate phase ambiguities for the data after the anomaly. They are typically different from the phase ambiguities for the data before the anomaly. Thus, an anomaly-BD occurs.

As an example, we record a one-day GPS-measurements data set by a geodetic GPS receiver at the National Institute of Standards and Technology (NIST). This GPS receiver is named "*NISA*." *NISA* does the GPS measurements every 30 sec. The reference time for *NISA* is UTC(NIST). The International GNSS (Global Navigation Satellite System) Service (IGS) provides the GPS satellite positions and clock offsets. The reference time for the GPS satellite clocks is the IGS time scale (IGST), which is formed by many IGS sites on the ground and steered to the GPS time in the long term. With the data set recorded by *NISA*, the GPS satellite positions, and the GPS satellite clock offsets as the inputs of the GPS CP time-transfer processing, we can compare the time difference between UTC(NIST) and the IGS time scale. To be specific, the GPS CP time-transfer processing is implemented by the NRCan Precise Point Positioning (PPP) software package [14]. Here, the date of the GPS-measurements data set is Feb. 2nd, 2013. The original data set is good and does not have any anomaly. The PPP result for the original data set is shown by the blue curve in Figure 1. We can see that the blue curve is continuous because of no data anomaly. However, if we "make" an anomaly (e.g., delete the GPS-measurements data during 8:00:00–8:09:30), then the PPP result has a discontinuity at the time of the missing data (see the black curve in Figure 1). In this example, the discontinuity is as big as ~250 ps, which is of a similar magnitude of the day-BD. Other tests show that an anomaly-BD of ~250 ps is very common. From this example, we know that a few minutes of GPS-measurements data anomaly are enough to lead to an anomaly-BD of more than 200 ps in the GPS CP time transfer.

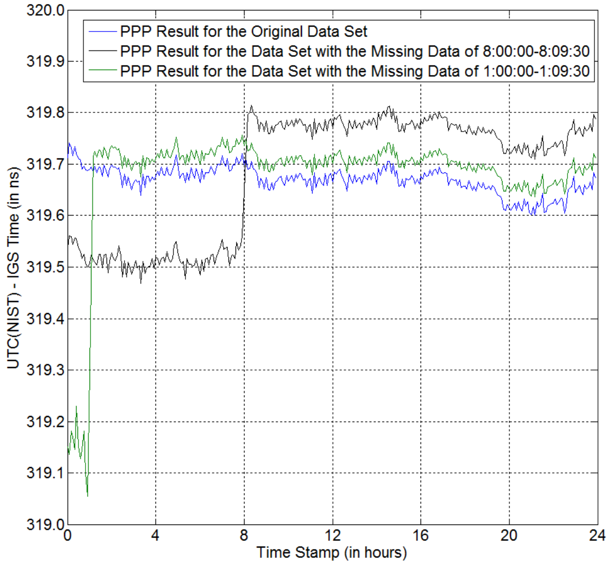

Figure 1. Illustration of the anomaly-BD. The blue curve is the PPP result for the original GPS-measurements data set, which does not have any anomaly. The black curve is the PPP result for the same data set but missing the data during 8:00:00–8:09:30. The green curve is the PPP result for the same data set but missing the data during 1:00:00–1:09:30. Note, all curves are far from 0 ns because there are cable delays for the *NISA* receiver.

However, if the anomaly occurs near the edge of a data set (i.e., either the beginning or the end), then we only have a short term of valid data between the anomaly and the edge. This results in an insufficient time for the PPP to converge when it processes this short term of data [14]. Thus, we not only have an anomaly-BD, but also have a damaged time-transfer result for this short term. The green curve in Figure 1 shows an example of an anomaly occurring near the edge of a data-arc. Here, we miss the data during 1:00:00–1:09:30. We can clearly see that the anomaly-BD is as big as ~550 ps. In addition, the green curve during 0:00:00–0:59:30 is much noisier than the blue curve. This indicates that the time-transfer result during this period is damaged because of the anomaly.

According to the above discussions, we know that a GPS data anomaly not only leads to an anomaly-BD, but also can potentially damage the time-transfer result. Thus, we want to find a strategy to deal with the anomaly. This will be discussed in the next section.

III. CURVE FITTING FOR THE ANOMALY

A straightforward strategy for dealing with the anomaly is to do curve fitting for the anomaly. We first extract the code and phase measurements for each satellite from the GPS-measurements data set. Then we detect the anomaly. If there is an anomaly, then we use polynomial regression (here, we choose the 9th order of the polynomial) to fit the good data both before and after the anomaly. Then the fitted data during the time range of the anomaly are used to replace the anomaly. Now, we run PPP with the updated GPS-measurements data set as the input. Because the anomaly has already been “repaired” in the updated data set, PPP does not need to re-estimate the phase ambiguities at the anomaly. Thus, the PPP result for the updated data set should be continuous at the anomaly. Of course, the PPP result during the time range of the anomaly should finally be disregarded, because the data at the anomaly are “made” by the polynomial regression.

To verify the above curve-fitting strategy, we keep using the same original data set as in Section II. Now, we delete 20 min of GPS-measurements data (e.g., 6:00:00–6:19:30) from this original data set. This generates an anomaly. Next, we do curve fitting for the 20 min of missing data for each satellite (e.g., PRN01), both phase-measurements data (e.g., L1) and code-measurements data (e.g., C1), by using the good data during 5:30:00–5:59:30 and 6:20:00–6:49:30 (i.e., half an hour before the anomaly and half an hour after the anomaly). Figure 2 shows the phase residual between the original data and the fitted data. We can see that the phase residual during the time range of missing data (i.e., 6:00:00–6:19:30) is tiny, only 0.03 cycle (i.e., 0.57 cm, corresponding to 19 ps), in terms of root mean square (RMS). As for the curve fitting for the code measurements, Figure 3 shows that the RMS of the code residual between the original data and the fitted data is only 0.67 m. All these demonstrate that we have a good curve fitting for PRN01.

Admittedly, PRN01, as a Block IIF GPS satellite, has a rubidium clock with an excellent short-term (< 3 hours) stability. Thus, the satellite clock noise has little impact on the curve-fitting result. Because of this, we have a very small RMS of phase residual, as shown by Figure 2. However, for the PRNs from old satellite blocks, such as Block IIA and Block IIR, the short-term (< 3 hours) clock stability is worse. Thus, the RMS of the phase residual is typically greater than that for PRN01. Nevertheless, the RMS is still quite small, compared to the carrier-wave cycle. As an example, Figure 4 shows that the RMS is only 0.25 cycle (i.e., 4.8 cm, corresponding to 160 ps), for PRN19 (note, PRN19 is a Block IIR GPS satellite). As for the code residual for other blocks of PRNs, it should be similar to PRN01 because the satellite clock noise contributes a very small part to the total code noise.

On the whole, the curve fitting for both code and phase measurements works very well. Statistically, the RMS of the code residual is typically less than 0.8 m. And, the RMS of the phase residual is typically less than 5 cm. Thus, the curve-fitting strategy can repair the GPS-measurements data anomaly very well. In other words, we can potentially “make” the GPS-measurements data good, using this strategy. Because the data are now “good”, we can avoid the re-estimation of phase ambiguities after the anomaly in the PPP processing, and thus can eliminate the anomaly-BD.

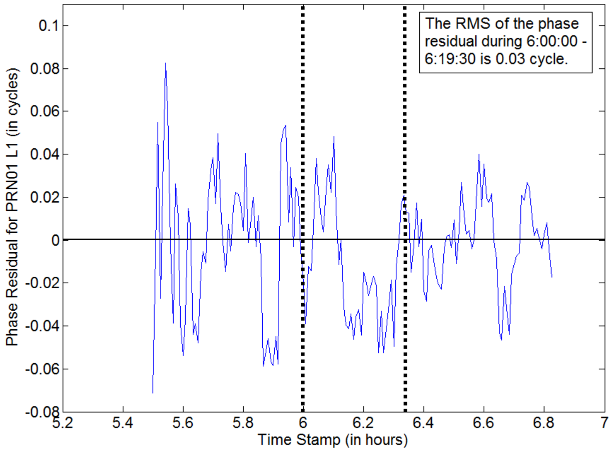

Figure 2. Phase residual, for PRN01 L1. Missing data occur during 6:00:00–6:19:30.

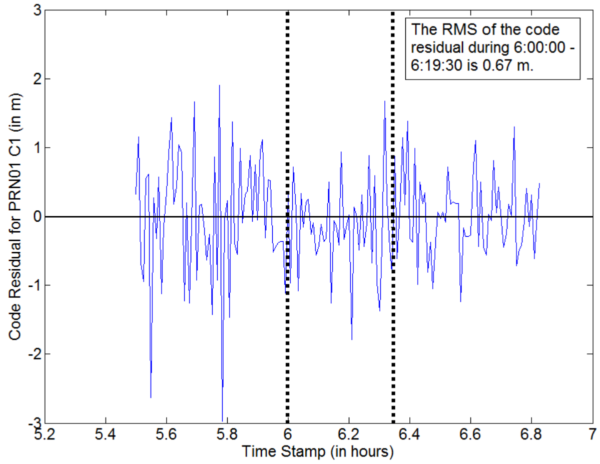

Figure 3. Code residual, for PRN01 C1. Missing data occur during 6:00:00–6:19:30.

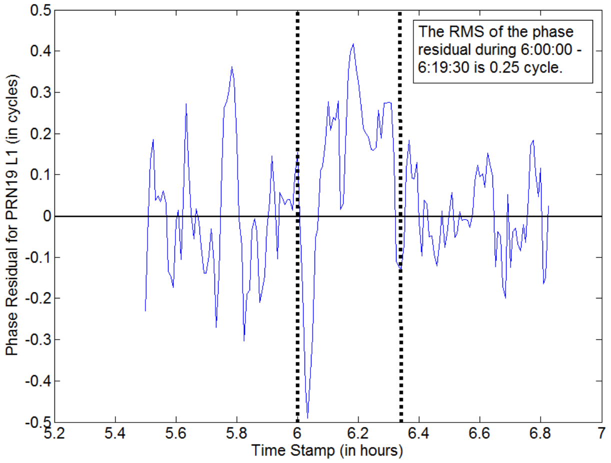

Figure 4. Phase residual, for PRN19 L1. Missing data occur during 6:00:00–6:19:30.

IV. ELIMINATING THE ANOMALY-BD BY THE CURVE-FITTING STRATEGY

This section tests the conjecture in Section III that the curve-fitting strategy can eliminate the anomaly-BD.

Here, we use the same original data set as in Section II. Now we delete 20 min of data (i.e., 6:00:00–6:19:30) from the original data set. This is actually an anomaly. Similar to Figure 1, we have an anomaly-BD of ~250 ps at this anomaly as shown by the black curve in Figure 5. Next, we repair the 20-min missing data by the curve-fitting strategy proposed in Section III. Then we run PPP with the repaired GPS data as an input. The result is shown by the red curve in Figure 5. Clearly, the anomaly-BD disappears.

The above example demonstrates that the curve-fitting strategy can eliminate the anomaly-BD. To further confirm this conclusion, we conduct the same procedures as the above for the anomalies occurring at other times, such as 7:00:00–7:19:30, 12:00:00–12:19:30. All of them show a very similar continuous time-transfer result as shown by the red curve in Figure 5. This further verifies our conclusion that the curve-fitting strategy can remove the anomaly-BD.

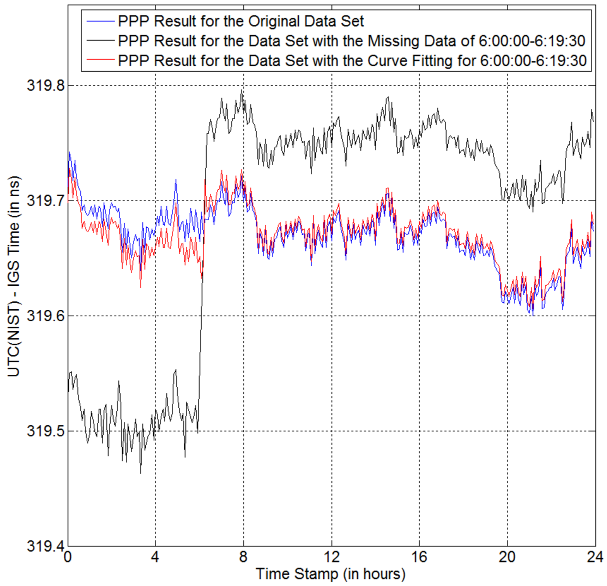

Figure 5. Curve-fitting strategy for eliminating the anomaly-BD (red curve). The blue curve is the PPP result for the original GPS-measurements data set. The black curve is the PPP result for the same data set but missing the data during 6:00:00–6:19:30.

V. DISCUSSION

We have shown in Section IV that the curve-fitting strategy can repair 20 min of data anomaly and thus eliminate the corresponding anomaly-BD. One may wonder whether this strategy works for a longer period of anomaly. As we can imagine, the curve fitting for the anomaly becomes worse and worse, as the length of an anomaly becomes longer and longer. Eventually, the curve fitting gets so bad that it is not able to repair the anomaly well. Then the PPP processing needs to re-estimate the phase ambiguities. Thus, we still have the anomaly-BD, although its magnitude may be different from the anomaly-BD without repair.

As an example, we delete 30 min of data (i.e., 6:00:00–6:29:30) from the original data set. Then we repair the 30-min missing data by the curve-fitting strategy. The result is shown by Figure 6. We can see that there is still a discontinuity in the red curve, even though we have done curve fitting to repair the anomaly. Besides, the curve-fitting result (red curve) is about 100–200 ps away from the original result (blue curve). These indicate that the curve-fitting strategy no longer works for more than 30-min of data anomaly.

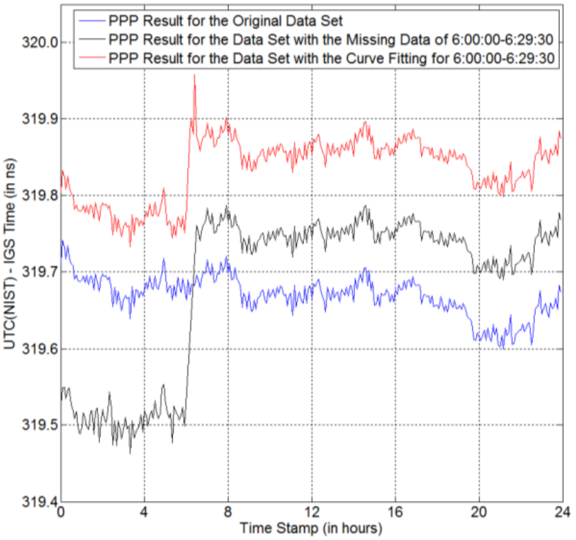

Figure 6. Curve-fitting strategy for eliminating the anomaly-BD (red curve). The blue curve is the PPP result for the original GPS-measurements data set. The black curve is the PPP result for the same data set but missing the data during 6:00:00–6:29:30.

Another important reminder that we should mention here is that the curve-fitting strategy only works well for national laboratories that have near-perfect reference clocks, or those GPS receivers with very good rubidium or cesium clocks as their references. However, this strategy does not work well for repairing the GPS data recorded by a GPS receiver without a precise reference clock. For example, a quartz oscillator can drift by more than 100 ns in an hour. If a GPS receiver only has a quartz oscillator as the reference clock, the instability of the quartz oscillator can lead to the curve-fitted GPS data being hundreds of nanoseconds or even more away from what the data should be. Therefore, PPP still needs to re-estimate the phase ambiguities after the anomaly and thus the anomaly-BD cannot be removed.

VI. CONCLUSIONS AND OUTLOOK

In summary, this paper has shown that a few minutes of GPS measurement data anomaly can lead to a boundary discontinuity of more than 200 ps. To eliminate this type of boundary discontinuity (i.e., anomaly-BD), the curve-fitting strategy is proposed. Tests show that this strategy works well for up to 20 min of data anomaly. With the repair of the data anomaly using this strategy, we improve the robustness of long-distance high-precision clock comparisons. However, if there are more than 30 min of data anomaly, the curve-fitting strategy no longer works. We thus want to find a better curve-fitting strategy and make it work for a longer term of data anomaly.

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