Measured Ionospheric Delay Correction for Code-based GPS Time Transfer

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ABSTRACT

The use of dual-frequency multichannel receivers in GPS time and frequency transfer applications is increasing. Instead of using the modeled ionospheric delay correction or using the IGS ionospheric map, we can obtain the ionospheric delay corrections from the receivers' dual-frequency measurements.

For time and frequency transfer based on the pseudo-range measurements (code-based GPS time and frequency transfer), the CGGTTS format data are used for remote clock comparisons. All of the delays involved in measuring the difference between a local clock and GPS time must be calibrated for time transfer applications. If the receiver delay for the dual-frequency measurements is not calibrated or if the delay has changed, the measured ionospheric delay corrections will add uncertainty to the time transfer results. In this paper, we study the measured ionospheric delay correction for code-based GPS time transfer.

I. INTRODUCTION

In GPS time transfer applications, all of the delays in the path of the GPS signal, including the receiver delay and the ionospheric delay, must be removed from the pseudo-range measurements between a receiver's reference clock and the GPS time.

In this paper, we treat the receiver delay as a sum of the antenna, antenna cable, and receiver delays. The receiver delay may change as a function of time, local environment, and the quality of the components.

The ionospheric delay and its variation are due to solar radiation and activity. The ionosphere adds group delay to the propagation of GPS pseudorandom noise (PRN) codes and advances the phase of GPS carrier frequencies. It can also bend the signal path to make the path a little longer than a straight path, and can rotate the polarization of the PRN code signal. The ionospheric delay varies at different times of the day (daytime or nighttime), locations (latitude of the receiver relative to the equator), and seasons. Significant deviations from the normal ionospheric delay occur during solar flares and geomagnetic storms (interaction between solar activity, the ionosphere, and the Earth's magnetic field).

The Klobuchar model characterized by eight broadcast coefficients and algorithm [1], [2] have been used for ionospheric delay corrections since the beginning of GPS. This approach removes about 50 percent of the ionospheric errors under normal solar activity and is still used by most of the single frequency GPS time and frequency transfer applications. Because the ionospheric effect on GPS signals is dispersive (frequency dependent), far more accurate ionospheric delays to GPS PRN codes can be obtained by dual-frequency pseudo-range measurements. With the availability of dual-frequency GPS receivers and the development of codeless and semi-codeless techniques in the late 1990s, the International GNSS (Global Navigation Satellite System) Service (IGS) now produces a global map of total electron content (TEC) in the IONosphere map EXchange (IONEX) format [3] based on the measurements from the dual-frequency receivers in the IGS worldwide tracking network. Using the IONEX map, we can compute the ionospheric delay for receiving PRN codes from a specific GPS satellite in an explicit location at a given time. This approach can remove more ionospheric error than that using Klobuchar model in all of the solar activity conditions. Due to the resolution of the IONEX map (in both epoch time and grid increments), some errors remain in the results. The IONEX final product has a few days of latency. In recent years, most of the international timing institutions are equipped with dual-frequency, multichannel receivers. Instead of using the modeled ionospheric delay correction or the IONEX map, the receivers can obtain ionospheric delay locally from the linear combination of the dual-frequency measurements. This is the most accurate approach in eliminating the ionospheric delay which is also available in near real-time.

GPS timing receivers record the difference of a reference clock and GPS time (REF – GPST) based on the pseudo-range measurements of the L1 frequency in the format recommended by the Consultative Committee for Time and Frequency (CCTF) Group on GNSS Time Transfer Standards (CGGTTS) [4], [5]. Version 1 of the CGGTTS format is only for GPS measurements, but version 2 expands the measurements to include the GLObal NAvigation Satellite System (GLONASS) developed and maintained by the Russian Federation. The difference of REF – GPST obtained from the measurements to each GPS satellite in a 16-minute session is shown in the REFGPS or REFSYS column. The REFGPS/REFSYS are corrected with all of the delays associated to the measurements. The modeled ionospheric delay is shown in the MDIO column. The measured ionospheric delay is shown in the MSIO column. The reference signal delay (REF DLY), the antenna cable delay (CAB DLY) and the receiver delays for GPS L1 and L2 frequencies (INT DLY$_{L1}$, and INT DLY$_{L2}$) are reported in the CGGTTS file header. The use of measured ionospheric delay correction in REFGPS/REFSYS is indicated by the parameter of the Ionospheric Measurement System (IMS), also in the file header. For REFGPS/REFSYS corrected with MDIO, we have to add the MDIO back and then subtract the MSIO from the REFGPS/REFSYS in order to use the MSIO correction.

In recent years, there is a procedure used in practice for generating the version 2 CGGTTS format data from the Receiver INdependent EXchange (RINEX) formatted data produced by dual-frequency, multichannel GNSS receivers [6]. The REFGPS/REFSYS obtained from this approach are the “ionosphere-free” difference of REF - GPST based on the measurements of the L1 frequency. The ionospheric delay correction for the ionosphere-free (P3) difference is the linear combination of the pseudo-range measurements on L1 and L2 frequencies. To maintain backward compatibility with existing common-view and all-in-view software, both the MDIO and MSIO columns contain the same value of measured ionospheric delay on the L1 frequency using the P3 method.

II. ERROR IN IONOSPHERIC DELAY CORRECTION

The ionospheric delay in the GPS pseudo-range measurements varies between daytime and nighttime, at different latitudes of the receiver locations, and in different seasons. Significant deviation from the normal ionospheric effect happens during solar flares and geomagnetic storms. At the National Institute of Standards and Technology (NIST) in Boulder, Colorado, USA (latitude of 40 degrees north), the averaged ionospheric delay for the GPS L1 C/A codes’ pseudo-range measurements ranged from about 5 ns (at nighttime) to about 60 ns (at daytime) in February 2014. The ionospheric delay reached 90 ns during a geomagnetic event on MJD 56715 (February 27, 2014). The ionospheric delay corrections obtained from the MDIO, MSIO of the IGS IONEX map, and the P3 method for MJDs from 56711 to 56720 (February 23 to March 4, 2014) are shown in Figure 1. In this section, we study the error in ionospheric delay corrections using these three techniques.

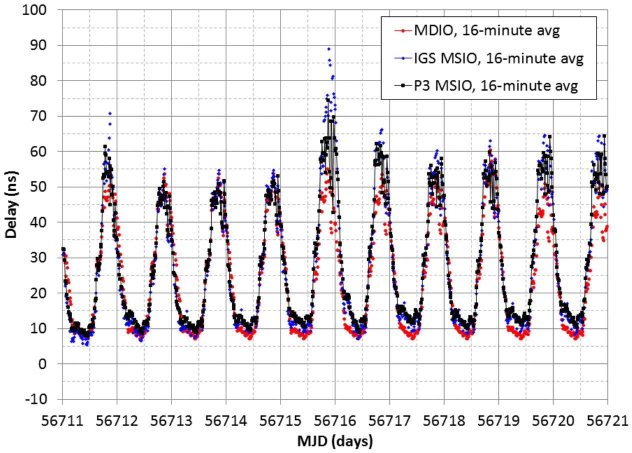

Figure 1. Ionospheric delay corrections for the UTC(NIST) – GPST measurements.

Figure 2 shows the differences between the NIST time scale (UTC(NIST)) and GPS time (GPST) with the MDIO, MSIO of the IGS IONEX map, and the P3 method corrections from MJD 56711 to MJD 56720 (February 23 to March 4, 2014). The differences are obtained from the pseudo-range measurements of the L1 C/A codes. Each point in a difference plot is an average of the measurements to all the GPS satellites in view during a 16-minute session. The time stamps of the differences are in Coordinated Universal Time (UTC), which is seven hours ahead of the US Mountain Standard Time. We see that UTC(NIST) – GPST with the MDIO correction (shown in red) still contains a large amount of residuals of the ionospheric delay, as indicated by the diurnal structure. The peak on MJD 56715 (February 27, 2014) was due to a geomagnetic event, that started in late morning and lasted until early evening in Colorado. The MSIO corrections using the IGS IONEX map (shown in blue) removes most of the diurnal structure and the impact of the geomagnetic event. However, the difference contains 2 to 10 ns of short term variations most likely due to the resolution of the IONEX map. The MSIO correction using the P3 method (shown in black) produces the best result of removing the ionospheric delay from the UTC(NIST) – GPST difference. On MJDs 56712 and 56713 (February 24 and 25, 2014), the ionosphere was relatively quiet and the peak-to-peak variation in the difference is about 2 ns. The difference still shows diurnal structure with up to 6 ns peak-to-peak on other days. The diurnal could be contributed by other effects such as the delay variation of the receiving equipment or multipath.

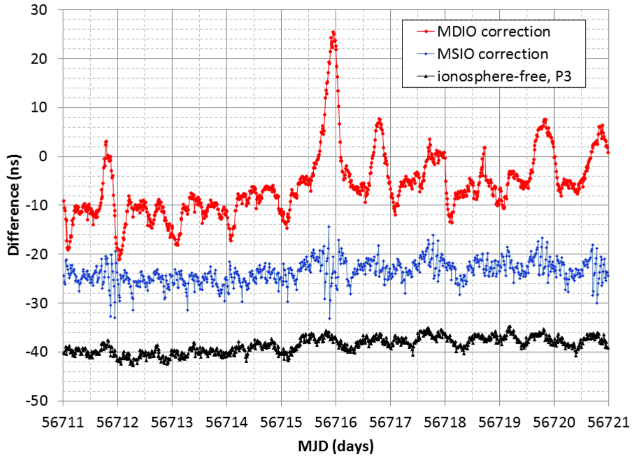

Figure 2. Differences of UTC(NIST) – GPST with different ionospheric delay corrections. The differences are offset for better illustration of the error.

III. ERROR IN THE P3 MEASURED IONOSPHERIC DELAY CORRECTION

The ionosphere-free measurements for time transfer applications are computed from the linear combination of

$$P3 = \frac{f_1^2}{f_1^2 - f_2^2} \cdot (P_1 - \ INT\ DLY_{L1}) - \frac{f_2^2}{f_1^2 - f_2^2} \cdot (P_2 - \ INT\ DLY_{L2})$$

$$= 2.54 \cdot (P_1 - INT\ DLY_{L1}) - 1.54 \cdot (P_2 - INT\ DLY_{L2})\,, \qquad (1)$$

where f_1 = 1575.42 MHz, f_2 = 1227.6 MHz are the GPS L1, L2 frequencies respectively, P_1, P_2 are the pseudo-range measurements on f_1 and f_2 frequencies, and the $INT\ DLY_{L1}$, $INT\ DLY_{L2}$ are the receiver delays for the P_1 and P_2 measurements. In the P3 CGGTTS format data files, the modeled and measured ionospheric delays for the measurements on the L1 frequency are obtained from the difference of (P_1 – $INT\ DLY_{L1}$) – $P3$. In addition to the P3 CGGTTS data, some dual-frequency receivers also use this measured ionospheric delay from the P3 method as the MSIO in the regular CGGTTS data files. Because the ionospheric delay obtained from the P3 method includes the receiver delays, any variation and error in $INT\ DLY_{L1}$ and $INT\ DLY_{L2}$ will affect time transfer results. The error in REF – GPST due to the errors in $INT\ DLY_{L1}$ and $INT\ DLY_{L2}$, is given by

$$\Delta(REF - GPST)_{P3} = -\Delta(INT\ DLY_{L1}) - [2.54 \cdot \Delta(INT\ DLY_{L1}) - 1.54 \cdot \Delta(INT\ DLY_{L2})], \quad (2)$$

where the first term is due to the error in the receiver delay correction of $(REF - GPST)_{P3}$ and the last two terms are the error in ionospheric delay correction caused by receiver delay error. The minus sign is due to the fact that receiver delay and ionospheric delay are subtracted from the pseudo-range measurements.

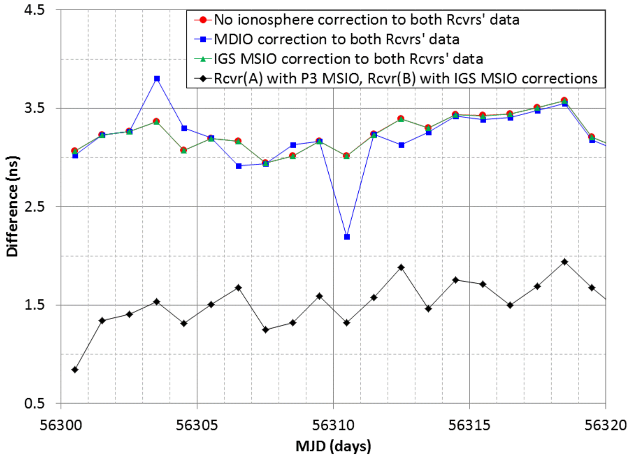

Figure 3. Common-clock, common-view differences with different ionospheric delay corrections. It demonstrates the error in ionospheric delay correction caused by the error in receiver delay affects the time transfer result.

In Figure 3, we show the effect of error in the receiver delay on the ionospheric delay correction obtained from the P3 method. Rcvr (A) and Rcvr (B) are two receivers operated in the same timing laboratory. Rcvr (A) is a dual-frequency, multichannel receiver, and Rcvr (B) is a single frequency, multichannel receiver. The two receivers' antennas are 8.7 m apart, so the GPS signals received by the two receivers should have almost the same ionospheric delay. Both receivers make the L1 C/A codes' pseudo-range measurements of the laboratory's reference clock – GPST, and report the measurements in CGGTTS format files. We compute the common-clock, common-view differences using no ionospheric delay correction, the MDIO, and the IGS MSIO corrections of data from the two receivers. We also compute the common-clock, common-view difference of the Rcvr (A) data with the P3 MSIO correction and the Rcvr (B) data with the IGS MSIO correction. Because the GPS time, reference clock, and ionospheric delay in the two measurements are completely canceled in the common-clock, common-view difference, the difference should be zero for each of the ionospheric delay correction methods if the two receivers are calibrated. The non-zero common-clock, common-view differences in Figure 3 indicate the two receivers are not calibrated with respect to each other. The differences with no ionospheric delay correction (shown in red), MDIO correction (shown in blue) and IGS MSIO correction (shown in green) are grouped together. Because these differences only involve the measurements on the L1 frequency, the non-zero difference comes from the error in the $INT\ DLY_{L1}$ correction of REF - GPST. There is an offset of about -1.5 ns between these differences and the difference when Rcvr (A)'s ionospheric delay correction was obtained from the P3 method. This offset indicates an error in Rcvr (A)'s $INT\ DLY_{L2}$ used in the P3 ionospheric delay correction. Notice also there is a slope of about 0.5 ns in each of the differences over the 20 day period. This observation shows that the two receiver delays changed with respect to each other or possibly multipath changes.

The receiver delay variation due to the daily or seasonal local environment change adds noise, and the delay change due to the components aging or malfunction introduces time steps in time transfer results. Figure 4 shows the common-view differences between UTC(NIST) and a remote clock based on the P3 measurements. The distance between the remote clock location and NIST is more than 7,500 km. The P3 measurements at NIST were made by the NIST primary receiver and the P3 measurements in the remote clock location were made by two receivers, Rcvr (A) and Rcvr (C). The latitude of the remote clock location is about 39 degrees north. The antennas for Rcvr (A) and Rcvr (C) are separated by about 4.7 m. All of the receivers are dual-frequency, multichannel receivers. The slope of the two differences in Figure 4 comes from the frequency offset between UTC(NIST) and the remote clock. From Figure 4, we see the difference using Rcvr (A) included a time step of more than 3 ns from MJD 56377 to MJD 56378 (March 26 and 27, 2013). Because there is no time step in the difference using Rcvr (C) and no change in the Rcvr (A) settings, the time step was caused by the receiver delay change of Rcvr (A).

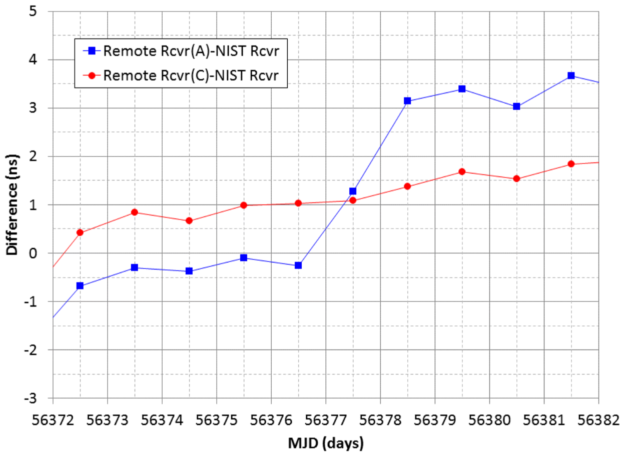

Figure 4. Common-view differences of P3 measurements between UTC(NIST) and a remote clock. The P3 measurements of the remote clock were made by Rcvr (A) and Rcvr (C). The P3 measurements at NIST were made by the NIST primary timing receiver. Rcvr (A)'s receiver delay change causes the time step in the Rcvr (A) – NIST Rcvr common-view difference.

Figure 5 shows the common-view difference between the remote clock and UTC(NIST) with pseudo-range measurements from the Rcvr (A) and the NIST receiver. The pseudo-range measurements from Rcvr (A) are corrected with the P3 MSIO (shown in blue) and the IGS MSIO (shown in red). The pseudo-range measurements from NIST receiver are corrected with the P3 MSIO. We see the difference using the Rcvr (A) measurements with IGS MSIO corrections also took a time step at the same time (from MJD 56377 to MJD 56378), but the time step is about 2 ns. Because the pseudo-range using the IGS MSIO corrections only involves the $INT\ DLY_{L1}$ in the REF – GPST correction, we estimate the $INT\ DLY_{L1}$ changed by -2 ns. Using Equation (2) with $\Delta(REF - GPST)_{P3}$ = 3 ns and $\Delta INT\ DLY_{L1}$ = -2 ns, the change of $INT\ DLY_{L2}$ is approximately -2.6 ns.

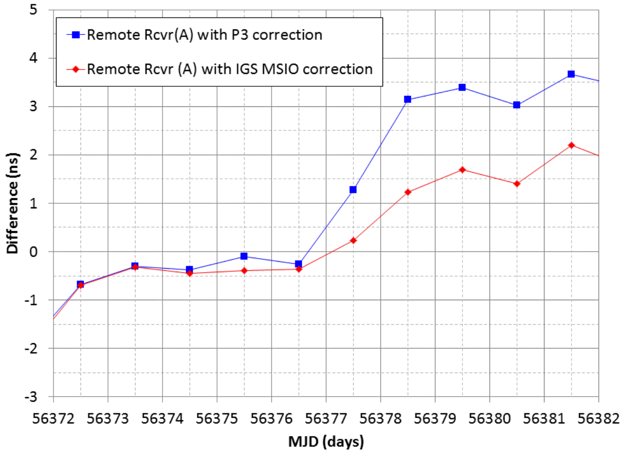

Figure 5. Common-view differences between UTC(NIST) and a remote clock. The pseudo-range measurements from Rcvr (A) are corrected with the P3 MSIO and the IGS MSIO. The pseudo-range measurements from NIST receiver are corrected with P3 MSIO. Both differences show a time step of different size, indicating the Rcvr (A)'s receiver delays of L1 and L2 frequencies are both changed.

IV. SUMMARY

Ionospheric delay must be corrected in the pseudo-range measurements for time transfer applications. Without the correction, the daytime pseudo-range measurements would contain errors as large as tens of nanoseconds. The pseudo-range measurements with the MDIO correction still contain a large amount of residual of ionospheric delay. For the measurement at NIST, the variation of the pseudo-range measurements with the MDIO correction is of the order of 10 ns from daytime to nighttime. The MDIO correction also performs poorly during daytime solar flares or geo-magnetic storms. For single frequency receivers, the use of the IGS MSIO correction greatly improves the ionospheric delay correction. The dual-frequency receivers can obtain ionospheric delay from the dual-frequency measurements. The ionosphere-free or P3 MSIO is the best method for ionospheric delay correction. However, the P3 MSIO correction requires the use of receiver delays. The receiver delay variation on either one frequency or both frequencies will introduce uncertainty in the ionospheric delay correction and therefore in the time transfer result. To maintain time transfer accuracy, it is important to monitor the receiver delay locally and to calibrate the receiver delay periodically.

This paper includes contributions from the U.S. Government and is not subject to copyright.

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