The Usefulness of WADGPS Satellite Orbit and Clock Corrections for Dual-Frequency Precise Point Positioning

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BIOGRAPHY

Hyunho Rho received an M.Sc. in 1999 in geomatics from Inha University, South Korea. He is currently a Ph.D. candidate in the Department of Geodesy and Geomatics Engineering at the University of New Brunswick (UNB), where he is investigating ways to improve ionospheric modeling for wide area differential GPS (WADGPS) and precise point positioning with WADGPS corrections.

Richard Langley is a professor in the Department of Geodesy and Geomatics Engineering at UNB, where he has been teaching since 1981. He has a B.Sc. in applied physics from the University of Waterloo and a Ph.D. in experimental space science from York University, Toronto. Prof. Langley has been active in the development of GPS error models since the early 1980s and is a contributing editor and columnist for GPS World magazine. He is a fellow of the ION and shared the ION 2003 Burka Award. He is also a fellow of the Royal Institute of Navigation and the International Association of Geodesy.

ABSTRACT

In this paper, we examine the accuracies of the WAAS and CDGPS orbits and clocks as well as investigate the possibility to use those WADGPS corrections in the precise point positioning domain.

The methodology, which fully takes into account the different satellite antenna phase-center offsets used by the different agencies, assesses the CDGPS and WAAS satellite orbit and clock correction accuracies with respect to the International GNSS Service (IGS) precise orbit and clock products. Experimental results with a continuous five days worth of data show that user range errors observed with the WAAS satellite orbit and clock corrections is at about the 50 cm level and using the CDGPS satellite orbit and clock corrections, the user range errors are about the 20 cm level. The analyzed results also show that the WAAS satellite orbit and clock corrections are highly correlated and it is not valid to separately use them for a correction or validation.

Precise point positioning (PPP) results obtained with the IGS, CDGPS and the WAAS satellite orbits and clocks are presented. PPP with IGS products produces the most accurate user results. The tests with the WADGPS corrections show that WADGPS orbit and clock corrections can be used for a PPP process with the carrier-phase observables. However, it will be limited by slower parameter convergence compared to using IGS products and there might be a challenge for kinematic PPP.

INTRODUCTION

A number of satellite-based augmentation systems (SBAS) (e.g., WAAS, EGNOS, MSAS and the Canada-wide Differential GPS (CDGPS) Service) are in operation and more are planned for the future. These free services provide real-time DGPS corrections across countries and continents by bringing quality geo-referencing capabilities to L1 single-frequency GPS users. However, these WADGPS satellite orbit and clock corrections can also be used to improve the GPS positioning accuracy for dual-frequency users by carefully take into account the satellite clock referencing issue as well as properly handling the increased noise level of the ionosphere-free measurement combination [Rho and Langley, 2005].

Although the previous study has provided essential insights, some questions remain to be answered: what is the actual accuracy of the WADGPS orbit and clock corrections? Is it possible to use the WADGPS satellite orbit and clock corrections for precise point positioning using carrier phase?

To help answer for these question, we first derived the methodology which fully takes into account the different satellite antenna phase-center offsets used by the different agencies to rigorously assess the CDGPS and WAAS satellite orbit and clock correction accuracies. The assessments of the CDGPS and WAAS corrections were separately conducted by comparing the corrected broadcast orbits and clocks to the IGS precise orbit and clock products. In the following sections, a sensitivity of the different antenna offsets to the WADGPS corrected orbits and clocks was precisely analyzed and the overall characteristics as well as the user range errors (UREs) of the CDGPS and WAAS orbit and clock corrections are presented. Since our ultimate goal in this research is to see the possibility of using the WADGPS satellite orbit and clock corrections in the precise point positioning (PPP) domain, the estimated parameters using the extended UNB RTCA/MRTCA correction software have been precisely analyzed. Analysis of the effects by using different accuracy of the satellite and clock products in the positioning domain is also presented. Finally, conclusions and plans for future research are specified.

ORBIT AND CLOCK PRODUCTS FOR GPS POINT POSITIONING

For standard GPS point positioning with a few meters to ten meters level of accuracy [IS-GPS-200, 2006], the broadcast ephemeris data is used to compute the satellite position. The accuracy, in one sigma, of the broadcast ephemeris is currently about 1.6 m and approximately 2.1 m accuracy could be accessible for the broadcast clock [IGS, 2007].

However, to improve the positioning accuracy, a better accuracy of ephemeris and clock data should be used. One possibility to improve the broadcast orbit and clock data is to apply SBAS corrections. Better than two meter level of accuracy could be achievable for single-frequency users by using SBAS corrections. Currently in North America, two different SBAS systems, WAAS and CDGPS, are in operation and provide real-time satellite orbit and clock corrections (as well as ionospheric corrections for single-frequency users).

In the case of CDGPS, orbit corrections are computed by using data from the IGS “hourly” global network as well as a regional ground network [CDGPS ICD, 2003]. The clock corrections with respect to their reference clock are computed by using data from the ground network. The CDGPS ground network consists of about 14 stations in Canada, the so-called Canadian Active Control System (CACS), and 15 additional reference stations located outside of Canada since May, 2007. The MRTCA, modified Radio Technical Commission for Aeronautics (RTCA), format has been adopted to provide better precision of real-time orbit and clock corrections than the standard RTCA format in NAD83(CSRS) coordinate system. The resolution of satellite orbit and clock corrections is 0.0039 m [CDGPS ICD, 2003].

In the case of WAAS, the corrections are based on data from their ground network. Currently 34 reference stations including nine new stations are in operations and used to generate the real-time WAAS corrections. On September 29, 2007, WAAS has included additional nine new international reference stations (WRS) into the WAAS network [FAA, 2007]. WAAS provides the real-time satellite orbit and clock corrections with the resolution of 0.125 m using RTCA format [WAAS MOPS, 1999].

However, to achieve the highest possible accuracy in the positioning domain with the data from a single station, precise satellite orbit and clock products (such as those from IGS) should be used. In general, a precise point positioning process can attain positioning solutions with centimeter to decimeter accuracy using undifferenced pseudorange and carrier phase [Kouba and Héroux, 2001; Gao, 2004]. The precise orbit and clock data from IGS is generated based on a global network of permanent tracking stations (more than 200 stations) and their final product accuracy is less than about 5 cm for orbits and 3 cm for clocks.

To illustrate the differences in those satellite orbit and clock products which were considered in this research, we summarize them in Table 1. In Table 1, the accuracies of the broadcast orbit and clock data and the IGS products refer to IGS [2007] and the WAAS and CDGPS orbit and clock accuracies are based on the assessment in the following sections of this paper.

Table 1. Summary of the different orbit and clock products.

	corrections	Solution	Datum	Latency	Accuracy
BRD	Orbit	Global	WGS84	Real-time	1.60 m
	Clock				2.10 m
IGS	Orbit	Global	IGS05	~13 days	< 0.05 m
Final	Clock				0.03 m
WAAS	Orbit	Regional	WGS84	Real-time	~1.3 m
	Clock	Regional			~1.3 m
CDGPS	Orbit	Global+ Regional	NAD83 (CSRS)	Real-time	~ 0.05 m
	Clock	Regional			~ 0.03 m

ACCURACY OF THE WADGPS ORBIT AND CLOCK CORRETIONS

The GPS control segment computes the orbit with respect to the center of mass point of each satellite but transforms the results to the effective antenna phase centers [Ray and Senior, 2005]. Since the observables of GPS users refer to the antenna’s phase center, those offsets are not officially provided [IS-GPS-200, 2006]. However, as the assumptions of some sets of antenna phase center offsets are different for different analysis centers and different systems, it is necessary to account for any differences when we are comparing satellite orbit and clock values from different sources.

To evaluate the accuracy of the CDGPS and the WAAS orbit and clock corrections, the accuracy of the broadcast orbits (BO) and clocks (BC) as well as the orbits and clocks after the CDGPS (CO and CC) and the WAAS (WO and WC) corrections [CDGPS ICD, 2003, WAAS MOPS, 1999] have been applied are determined. Since the CDGPS orbit corrections are generated in the NAD83 (CSRS) reference frame, the transformed IGS precise ephemerides from ITRF05 to NAD83 coordinate system were used as truth for the CDGPS analyses [Craymer, 2006]. To evaluate the broadcast and WAAS orbit and clock accuracy, the final precise ephemerides from IGS were used as a truth. The assessment of the CDGPS and WAAS orbit and clock corrections were conducted by comparing the corrected BOs and BCs to the IGS precise orbit (IGSO) and clock (IGSC) products. However, as an important issue in these comparisons is the different satellite antenna phase-center offsets used by the different agencies, we first derived the methodology which can precisely take into account those effects.

Methodology

As the IGS precise products are referenced to the center of mass, we use the center of mass as a fundamental reference point and transform the broadcast and the WADGPS corrected orbits and clocks to the reference point.

All of the following equations are expressed in meters.

$$BO(comp) = BO(eph) + APC(user) \tag{1}$$

$$BC(comp) = BC(eph) + APC(user)^{*} \tag{2}$$

$$CO(comp) = BO(eph) + CDGPS - XYZ + APC(user) \tag{3}$$

$$CC(comp) = BC(eph) + CDGPS - CLK + b_{P1C1} + APC(user)^{*} \tag{4}$$

$$WO(comp) = BO(eph) + WAAS - XYZ + APC(user) \tag{5}$$

$$WC(comp) = BC(eph) - WAAS - CLK + b_{P1C1} + APC(user)^{*} \tag{6}$$

where

$comp$: computed values.

eph : broadcast ephemeris.

$user$: user-defined antenna phase-center offsets, i.e., IGS or National Geospatial-Intelligence Agency (NGA) antenna phase-center offsets.

APC : antenna phase-center offsets transformed to the ECEF frame.

APC^{*} : antenna-Z offset which is directed from the satellite center of mass towards to the Earth.

$CDGPS - XYZ$ and $WAAS - XYZ$: CDGPS and WAAS long-term satellite orbit corrections in ECEF frame.

$CDGPS - CLK$ and $WAAS - CLK$: combined CDGPS and WAAS fast and long-term clock corrections at the antenna phase-center.

b_{P1C1} : satellite P1-C1 bias (in this research, P1-C1 bias used from the Center for Orbit Determination in Europe (CODE) [2007] is used).

Note that first, the sign between CDGPS [CDGPS ICD, 2003] and WAAS [WAAS MOPS, 1999] clock corrections are different and second, the P1-C1 bias correction term is used in the equation (4) and (5).

As long as the IGS clock data are referenced to P1P2 ionosphere-free measurements and WADGPS clock corrections are referenced to C1, the P1-C1 bias should properly takes into account in the above equation (4) and (6) [Rho and Langley, 2005; Collins et al., 2005].

Now, the IGS precise satellite orbit is computed as:

$$IGSO(comp) = IGSO(SP3) \tag{7}$$

To compare the IGS satellite clock values with other results using different antenna phase-center offsets later see equation (10), the correction is also applied to the IGS clock data:

$$IGSC(comp) = IGSC(SP3) + APC(IGS)^{*} \tag{8}$$

where

$SP3$: IGS final precise orbit and clock data in SP3 format

$APC(IGS)^{*}$: values from the IGS ANTEX file, igs05_1402.atx

Next, we compute the broadcast and WADGPS-corrected orbit and clock with respect to the IGS products:

$$DX\_orb = XO(comp) - IGSO(comp) \tag{9}$$

$$DX\_clk = XC(comp) - IGSC(comp) \tag{10}$$

where

DX_orb : final orbit errors in ECEF frame.

DX_clk : final clock errors.

X : specific orbit and clock products, i.e, broadcast or WADGPS corrected orbits and clocks.

Finally, to generate the range errors for broadcast and WADGPS corrected satellite orbit and clock products, the user range error (URE) is computed for each satellite:

$$URE(comp) = PRC(sat) - DX\_clk(sat) \tag{12}$$

where

$$PRC(sat) = DX\_orb * (\frac{LOS}{|LOS|}) \tag{13}$$

where

PRC is the pseudorange correction errors and CLK represents the clock error for each satellite for the different products.

$\frac{LOS}{|LOS|}$ represent the line of sight vector between a satellite and a user position. In this research, the user position was assumed to be located on the earth and right below the satellite, i.e., the same coordinate with the specific satellite in latitude and longitude but the height is zero (assumed user located right on the datum).

To compute final URE, the average of the all satellites $UREs$ was subtracted, i.e., $URE = URE - mean(URE)$ because that is equivalent to a clock error which will be absorbed by the receiver clock in a least squares solution.

Effects of antenna phase-center offsets

To characterize the effects of the different antenna phase-center offsets in the comparison of two different sets of satellite and orbit corrections, the broadcast and WADGPS-corrected orbit and clock errors were computed with respect to the IGS products. In this comparison, IGS precise orbit and clock data was assumed as truth. As the WADGPS corrections are estimated with respect to the GPS broadcast ephemeris and clock, another purpose of this comparison is to see if they are following the same conventions as the GPS control segment.

Two different sets of offsets, IGS and NGA were considered. The IGS has adopted uniform values of the offsets for each block of satellites (see [IGS, 2007]). However, the NGA also provides their own offset estimates (see [NGA, 2007]). The offsets used by the NGA are similar to those of the IGS for Block II and Block IIA satellites, however, the differ significantly and are distinct for each Block IIR satellite, most being around 1.5 m – 1.6 m or near 0.0 m.

The following Figure 1 shows the computed broadcast orbit and clock errors separately using the IGS and NGA offsets. In Figure 1, the left panel shows the broadcast orbit and clock errors computed by using the NGA offsets and the right panel shows those errors computed by using the IGS offsets

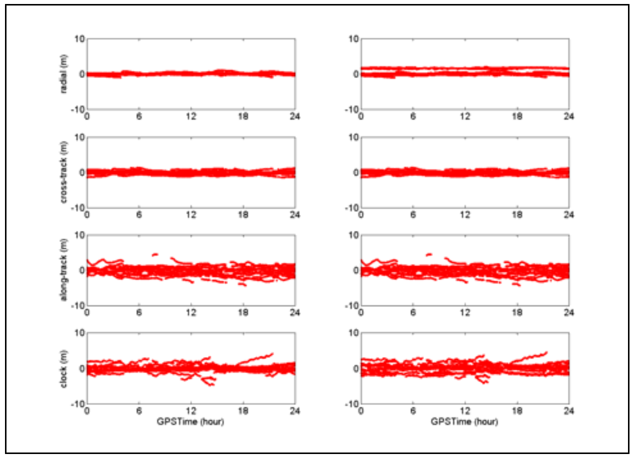

Figure 1. Broadcast orbit and clock errors on July 23, 2007. The left panel shows the broadcast orbit and clock errors computed by using the NGA offsets and the right panel shows those errors computed by using the IGS offsets.

In the right panel, when the IGS offsets are applied to the broadcast orbit and clock, the effect of the unmatched offsets was observed as a certain level of biases from the different block of satellites in the radial component errors. Those biases were observed for those Block IIR satellites which had a difference of 1.5 m - 1.6 m with respect to the NGA offsets. However, those biases did not appear-when the NGA antenna offsets were applied (see left panel). Another effect of the unmatched offsets was observed for the clock errors. The broadcast clock errors with NGA antenna offsets (see left panel) are more precise and accurate than the clock errors computed using IGS offsets (see right panel).

These results show that the broadcast orbit and clock data have a better match with the NGA antenna offset conventions. It also shows the unmatched antenna offset effects can be observed in the radial orbit errors and clock error components (range error components).

To see if the WADGPS-corrected orbits and clocks are following the same conventions as the broadcast data, i.e., NGA conventions, each component of the WADGPS-corrected orbit errors and clock errors were computed with respect to the IGS products.

The following Figure 2 shows the CDGPS- and WAAS-corrected orbit and clock errors which were computed by using the NGA conventions (left panel) and by using the IGS conventions (right panel). In both panels, the red colors show the WAAS-corrected results and the green colors represent the CDGPS-corrected results.

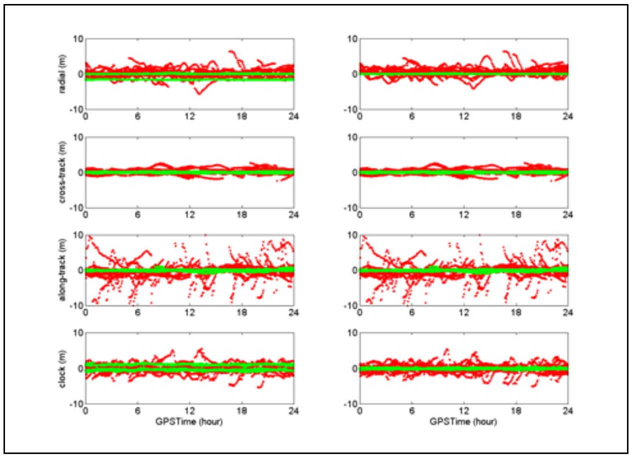

Figure 2. CDGPS- (green) and WAAS- (red) corrected orbit and clock errors on July 23, 2007.

In Figure 2, the same unmatched antenna offset effects were observed in the CDGPS-corrected orbit and clock errors which were computed by using NGA offsets (see left panel). However, those bias effects appeared when the NGA conventions were used rather than when the IGS conventions were used like for the broadcast results. It shows that the CDGPS orbit and clock corrections are a better match with the IGS conventions. It could be explained that the CDGPS computes orbit corrections using data from the IGS "hourly" global network as well as a regional ground network as we stated above. In using the IGS hourly data, they use a same conventions as IGS.

In the case of the WAAS-corrected orbit and clock errors, the above identified antenna offset effects were not clearly observed. As the WAAS corrected orbit and clock errors are widely varying in time compared with the other orbit and clock products, the effects might be hiden. However, the WAAS orbit and clock have a better accuracy when the errors are computed using the NGA conventions (see Table 2). It shows that WAAS is following the same conventions as the GPS control segment.

User Range Error (URE)

To see the actual range errors of the WADGPS-corrected orbits and clocks, we computed the UREs using equation (12).

The following Figure 3 shows that the time series of the UREs for the broadcast orbits and clocks (top panel), WAAS-corrected satellite orbits and clocks (middle panel) and CDGPS-corrected satellite orbit and clock products (bottom panel).

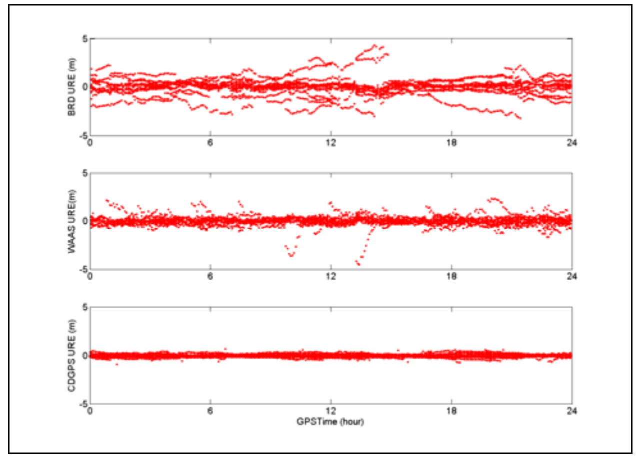

Figure 3. User range errors on July 23, 2007

In the top panel, the broadcast UREs show wide ranges of variations and long-term drifts in time. Those variations were caused by the less precise broadcast clock errors rather than relatively precise orbit errors (see Figure 1, in which the broadcast clock errors have much bigger errors than orbit errors and overall patterns in time are similar with the time series of UREs).

In the middle panel, we observed the UREs of WAAS-corrected satellite orbits and clocks are significantly better than the individual orbit and clock errors (also see the following Table 2). The improvement in UREs indicates that there exist strong correlations between orbit and clock corrections (see Figure 2, where the magnitudes and the overall variations of the WAAS-corrected orbit errors are similar with those of the WAAS-corrected clock errors). As the UREs account for both the orbit and the clock errors, those highly correlated error terms are cancelled out and the true WAAS error is revealed. The following Table 2 also shows that the r.m.s. of the WAAS orbit and clock errors have similar values and the UREs for WAAS-corrected results are at about the 46 cm level. Those results clearly indicate that the WAAS orbit and clock corrections are highly correlated and it is not valid to separately use them for a correction or for a validation.

In the bottom panel, CDGPS orbit and clock corrections showed good performance in correcting broadcast ephemeris and clock. The r.m.s. of UREs for this day was at about the 16 cm level (see Table 2).

To clearly identify the effects of the different antenna offset in terms of the magnitude of the errors as well as to see the overall accuracy of the different satellite and orbit products, we computed the r.m.s. of the errors for each error component for each satellite orbit and clock product on the single day, July 23, 2007.

Table 2. Summary of the r.m.s of the orbit and clock errors. The colored lines highlight the statistics with the better matched antenna offsets.

r.m.s (m)	offset	Radial	along-track	cross-track	clock	URE
BRD	NGA	0.222	1.196	0.491	0.880	0.857
	IGS	0.869	1.196	0.490	1.186	0.857
WAAS	NGA	1.200	2.349	0.747	1.181	0.462
	IGS	1.259	2.349	0.747	1.243	0.462
CDGPS	NGA	0.845	0.188	0.151	0.711	0.163
	IGS	0.035	0.188	0.150	0.165	0.163

The statistics in Table 2 show the unmatched antenna offsets can be observed only for the most effective range error components, the radial orbit errors and clock errors. Table 2 also shows that the better matched antenna offsets have better accuracies for the specific satellite orbit and clock products. However, when the URE were computed, those inconsistencies cancel, i.e., the URE values for matched or unmatched antenna offsets are the same and the true broadcast and WADGPS errors are revealed. That shows the different antenna phase-center offsets only become an issue when satellite orbit and clock products are compared with different sets of corrections.

Finally, to see the consistency of the WADGPS orbit and clock errors, a continuous five days of data was processed from July 23, 2007 to July 27, 2007. Since the radial and clock errors are the most significant components in the range errors, we generate the r.m.s. of the errors in the radial and clock components and UREs. Figure 4 shows the computed results.

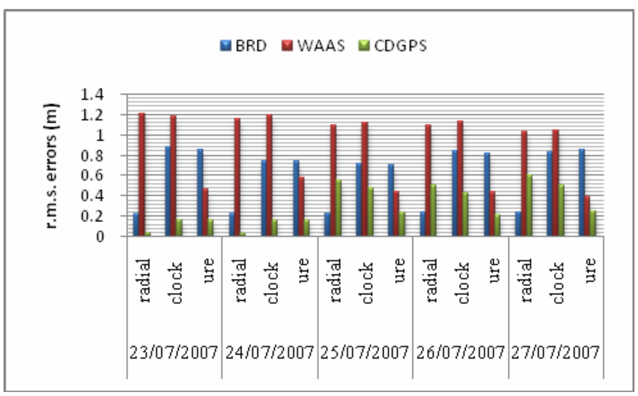

Figure 4. r.m.s. errors for the radial orbit component, clock and URE from July 23, 2007 to July 27, 2007.

Figure 4 shows first that the individual WAAS-corrected orbit and clock accuracies are not better than broadcast results for the continuous 5 days. However, we can see the true WAAS errors were revealed when we computed the UREs. The day to day variations of the r.m.s. of WAAS UREs were about 0.18 m (from 0.40 m to 0.58 m) and they were at about the 0.11 m level (from 0.75 m to 0.86 m) for the broadcast URE. Figure 4 also shows that the daily r.m.s. of the radial component errors and the clock errors for the WAAS-corrected results are highly correlated in terms of magnitude of r.m.s. errors for the continuous five days.

In the case of CDGPS-corrected orbit and clock errors, the results show good performance not only in the individual errors but also in the r.m.s of UREs. However, there was a certain level of degradation observed in the CDGPS-corrected orbit and clock. The CDGPS radial and clock errors from July 25 to July 27 were almost three times bigger than July 23 and July 24 results. Some abnormal CDGPS corrections were observed at UNB for certain periods for those three days. However, the day-to-day variations for the r.m.s. of UREs were about 0.11 m (from 0.16 m to 0.23 m) in the continuous five days.

PRECISE POINT POSITIONING WITH WADGPS CORRECTIONS

Since our ultimate goal in this research is to see the possibility to use the WADGPS satellite orbit and clock corrections in the PPP domain, we used the extended UNB RTCA/MRTCA correction software to generate the precise point positioning results.

UNB RTCA/MRTCA Correction Software

UNB RTCA/MRTCA corrections software was originally developed to see the CDGPS and WAAS performance anywhere in North America [Rho et al., 2003]. Any RINEX observation data from any station can be used as input and RTCA [WAAS MOPS, 1999] or MRTCA [CDGPS ICD, 2003] archived correction message are used to correct the raw pseudoranges. The correction scheme, explained in the CDGPS ICD [2003] and the WAAS MOPS [1999] were followed for the most part. The only difference is that the UNB3 tropospheric model with Niell mapping functions [Niell, 1996] were used rather than Black and Eisner mapping function, which is currently used in WAAS [WAAS MOPS, 1999].

The first extension was made to make it use the WADGPS orbit and clock corrections for GPS dual-frequency data processing. The newly developed point positioning model which fully takes into account the satellite clock referencing issue and a sequential forward smoothing filter which utilizes the fully combined uncertainly for both systematic and random errors in the smoothing process were implemented [Rho and Langley, 2005].

Recently, a dual-frequency precise point positioning algorithm has been implemented. The ionosphere-free combinations in both undifferenced carrier-phase and pseudorange measurements are used as observables. The set of parameters, receiver coordinates in ECEF frame, neutral atmospheric delay with Niell mapping function, carrier-phase ambiguities and receiver clock are estimated in a sequential least-squares sense [Kouba and Héroux, 2001]. Both precise orbit and clock data (such as those of the IGS or Natural Resources Canada (NRCan)) as well as WADGPS (CDGPS and WAAS) orbit and clock corrections are optionally used. All solutions incorporate corrections for solid earth tides, ocean loading, periodic relativistic effects, phase wind-up, satellite antenna phase-center offsets and differential code bias.

Data Testing and Analysis

In the following, data processing and analysis were conducted to assess the performance of different satellite orbit and clock corrections. In this test, one day of GPS data acquired on July 23, 2007 at IGS station, Algonquin Park (ALGO) was processed. The station ALGO is located about 160 km west of Ottawa, Ontario, Canada (N 45.95580 in latitude and W 78.07137 in longitude) and equipped with an AOA Benchmark ACT receiver, a Dorne Margolin AOAD/M_T choke-ring antenna and a meteorological sensor as well as hydrogen-maser atomic clock. The station ALGO was selected because the coordinates of the stations are precisely determined with respect to ITRF2005 [JPL, 2007] and NAD83(CSRS) [NRCan, 2007] and the well equipped instruments could help to mitigate the errors in the measurements. For example, the choke-ring antenna can mitigate the multipath effects to a certain extent and the external hydrogen-maser atomic clock helps stabilize the receiver clock and as a result, helps to precisely estimate it in the estimator.

PPP with WADGPS corrections

To assess the performance of different satellite orbit and clock corrections, the data was processed with the WADGPS orbit and clock corrections as well as IGS precise orbits and clocks. In the PPP process, we used a unit weight for the carrier phase, 0.002 m, and pseudorange 1 m. As long as the definitions and the magnitudes of uncertainties which are provided by CDGPS [CDGPS ICD, 2003] and WAAS [WAAS MOPS, 1999] are different, the purpose of this test is to see the results using equal weights.

The following Figure 5 shows precise point positioning results with the different satellite and clock corrections at the station ALGO on July 23, 2007.

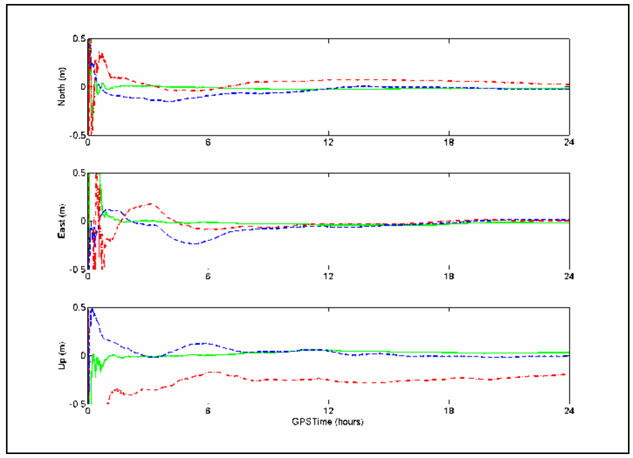

Figure 5. Precise point positioning results (static case) with IGS products (green), CDGPS corrections (blue) and WAAS corrections (red) at station ALGO on July 23, 2007.

In Figure 5, the coordinate estimates with the IGS products converged to the centimeter level within about 30 minutes. After the convergence, all positioning results with the IGS products are accurate at sub-centimeter level. As shown in Table 3, centimeter accuracy positioning results have been achieved by using IGS precise orbit and clock products. However, the estimated sigma values seem too optimistic compared with the actual coordinate errors.

Table 3. Dual-frequency precise point positioning results with the different satellite orbit and clock corrections.

unit: m	IGS	CDGPS	WAAS
Bias North	-0.020	-0.029	0.024
Bias East	-0.018	0.008	0.003
Bias Up	0.029	-0.01	-0.193
Sigma N	0.001	0.002	0.004
Sigma E	0.001	0.002	0.006
Sigma U	0.001	0.002	0.006

As the accuracy and precision of the WADGPS satellite orbits and clocks products are not better than the IGS products (see Table 2 and Figure 3), the convergence for coordinate estimates with the WADGPS products took a much longer time compared with the results using the IGS products. The overall performance of the CDGPS (blue) and WAAS (red) corrected results in the horizontal components are comparable. However, the up component estimates using the WAAS satellite orbit and clock corrections were biased at about the 19 cm level. Some part of bias might be explained by the different quality of the corrections. As a dominant error source in the range components is the clock correction accuracy, some of that bias in the up component might be explained by the different quality of the satellite clock accuracies (see

Figure 3 and Figure 4). However, we need to further investigate this.

Estimated troposphere zenith path delays

To see the different accuracy in the estimated troposphere zenith path delays (zpd) with the different sources of orbit and clock corrections, the relative accuracy of the estimated troposphere delays were analyzed. We used the tropospheric delays obtained from the NRCan GSD PPP software as a reference using the same data on the same day [NRCan PPP, 2007]. The accuracy of the NRCan tropospheric estimates are usually in the maximum 3 cm level compared to the IGS combined zenith path delay [Kouba and Héroux, 2001].

Figure 6 shows the estimated tropospheric zpd with the different orbit and clock corrections and also shows the difference in the estimated zpd with respect to the NRCan zpd.

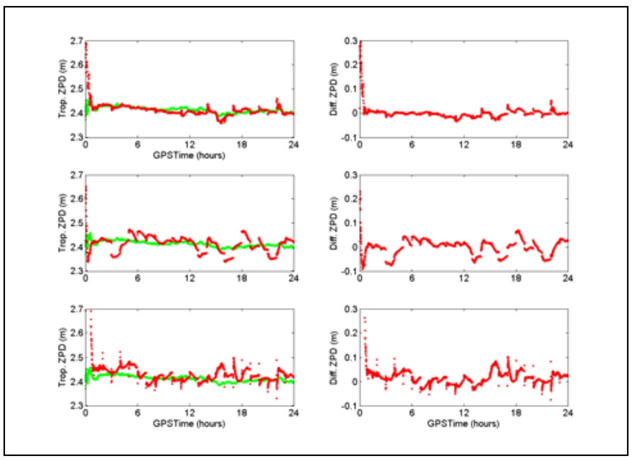

Figure 6. Estimated tropospheric delays with the different orbit and clock products at station ALGO on July 23, 2007. The top panel shows the results with the IGS products, the middle panel shows the results with the CDGPS corrections and the bottom panel shows the results with the WAAS corrections. The green colors show the troposphere delays from the NRCan PPP software.

In Figure 6, there is good agreement observed in the estimated troposphere zpd between UNB PPP results and NRCan results. We estimated the troposphere zpd every 10 minutes using a forward filter. However, as the NRCan PPP is continuously estimating the tropospheric zpd by a using random walk process and applies a backward filter to finalize their parameters [Kouba and Héroux, 2001], the estimated tropospheric delays are smoother than the UNB PPP results. The statistics shows that the mean difference is 0.002 m and the r.m.s was observed to be about 0.01 m (see Table 2). In the case of CDGPS results, the overall behavior of the estimated tropospheric zpd appear unbiased however, the long-term variations were observed in time compared with the IGS and WAAS results. This might be explained by the UREs which were corrected by CDGPS and which showed a long term variations (see Figure 3). The statistics in Table 4 also show that the most of the differences in the r.m.s were affected by the long-term variations. Finally for the WAAS results, the overall behavior of the estimated tropospheric zpd fluctuate more and many spikes are observed compared with other results. The jumps or spikes could be caused by the scattered corrections (or less precise corrections) in the URE (see Figure 3). The statistics in Table 2 also show that a bigger bias than others were observed until 1 hour after the first epoch. The higher variability in the corrections requires more time for converge to the parameter. However, the statistics did change at the few mm level after an hour from the first epoch.

Table 4. Statics in the difference in the estimated troposphere zpd at the station ALGO on July 23, 2007

Unit: meters		PPP-NRCan	WAAS-NRCan	CDGPS-NRCan
+0 hrs	mean	0.000	0.039	0.000
	std. dev	0.027	0.318	0.035
	r.m.s	0.027	0.320	0.035
+1 hrs	mean	-0.004	0.016	0.000
	std. dev	0.011	0.024	0.030
	r.m.s	0.011	0.029	0.030
+6 hr	mean	-0.005	0.012	0.002
	std. dev	0.012	0.024	0.029
	r.m.s	0.013	0.027	0.029

Residual Analysis

To more clearly see the effects of the different satellite orbit and clock products in the positioning domain, we further analyzed the carrier-phase residuals. Since the advantage of the PPP is to use the carrier phase by estimating the float ambiguity for each satellite, the effect of the different satellite orbit and clock products easily can be seen in the carrier-phase residuals.

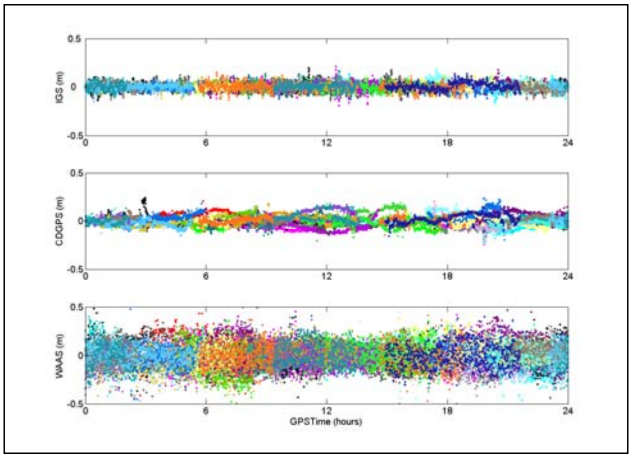

Figure 7. Residual errors for the PPP results at station ALGO on July 23, 2007. The scale of the WAAS residuals were fixed to ± 0.5 m to see the detailed view.

Figure 7 shows the carrier-phase residual errors at station ALGO on July 23, 2007. As we expected, the smallest residual errors were observed with the positioning results with IGS products. The residual errors with the IGS products show that there are no significant patterns for any satellite arc. The overall variation of the residual errors are within the ± 0.10 m level and a maximum of 0.20 m and a minimum of -0.19 m were observed over the entire day. An r.m.s of the residual errors of 0.034 m was observed. However, the residual errors with the CDGPS orbit and clock corrections are not consistent in time but show long-term variations. This might show that the accuracy of the CDGPS orbit and clock corrections is not constant in time and we might can see the long-term residual error effects in the positioning solutions (see Figure 5, there are about 4 hours variations appeared and clearly can be seen in the height component. However after the ambiguities for the satellites were stable (fixed), those variations in the measurement domain no longer significantly impact the positioning solutions). However, the magnitude of the residual errors using the CDGPS corrections are (quiet) comparable with the residual errors using the IGS products. The overall residuals are varying within ± 0.20 m and the r.m.s. of the residuals for the entire day was 0.053 m. A maximum of 0.240 m and a minimum of -0.244 m were observed. Finally, in the case of the residuals with the WAAS corrections, the characteristics of the residual errors could be identified as a larger scatter of residuals with similar long-term variations as with the CDGPS residuals. There are systematic long-term patterns in the satellite arc for specific time periods. And the overall pattern of the residuals is similar to the CDGPS results but more largely scattered. Since the PPP process considers all sources of errors, the large scatter of residuals might indicate that the resolution of the WADGPS corrections is an important factor and could degrade the accuracy as well as the precision of the PPP solutions [Rho and Langley, 2005]. The overall r.m.s. of the residuals (since the mean of residuals is zero, we might call it, std.dev) was 0.147 m and a maximum of 1.982 m and a minimum of -2.192 m was observed.

Convergence of the sigma for the station coordinates

Another important issue for PPP is the converge time. The main advantage of using WADGPS corrections for the PPP process might be use of the corrections in a real-time fashion. In this context, the converge time issue is another important factor for WADGPS PPP. The convergence time could be defined by that the time which is needed to precisely separate a specific parameter from the measurements and from all correlated parameters. So we might call it the separability or decorrelation time for the specific parameter. Since all the parameters are correlated in the filter (design matrix), a certain amount of time is needed to separate a parameter from the others.

Figure 8 shows the converge time of the sigma for the stations coordinate in the north, east and up components. Since the final goal of the PPP is to precisely estimate the position, we further analyzed the convergence of sigma in the positioning domain.

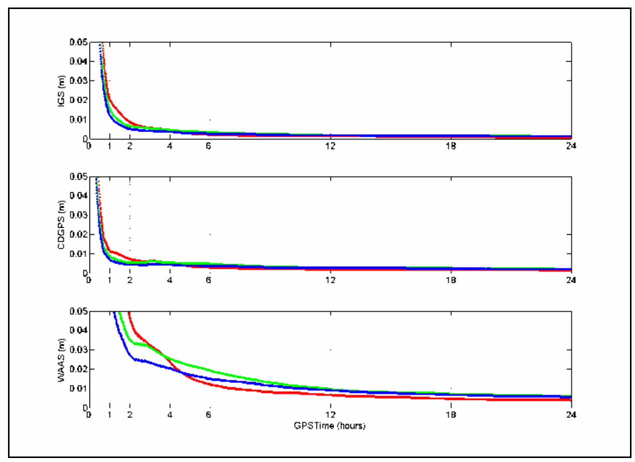

Figure 8. Convergence of the sigma with the different satellite orbit and clock corrections. The red color shows the sigma for the north component and the green color represents the east component. Finally the blue color shows the up component of the sigma in time.

Figure 8 shows that the convergence time of those sigma in the PPP results with the IGS products and the CDGPS corrections is comparable. The 0.02 m level of sigma can be reached in less than an hour and all the sigma values in north, east and up components were observed to be at about the 0.01 m level. However, in the case of WAAS, the level of 0.02 cm was reached about six hours after the first epoch was estimated. These results might show the PPP solutions with the WAAS corrections needs a longer time to have a same level of precision with the PPP solutions compared with the CDGPS corrections. Even though the magnitude of the sigma value is too small to distinguish the difference in the positioning domain, the overall behavior of the WAAS sigma is keep to decreasing even at the end of the day. This result might show that the PPP with the WAAS corrections will be limited by slower ambiguity convergence and there might be a challenge for kinematic PPP with WAAS corrections.

CONCLUSIONS

The methodology which fully takes into account the different satellite antenna phase-center offsets used by the different agencies has been carefully considered to rigorously assess the CDGPS and WAAS satellite orbit and clock correction accuracies with respect to the IGS precise orbit and clock products. With the adopted method:

By analyzing the clock and radial orbit errors:

- We found the CDGPS orbit and clock corrections have a better match with the IGS conventions of the antenna phase-center offsets and the broadcast ephemeris and clock have a better agreement with NGA conventions. Finally, we found WAAS appears to the same conventions as the GPS control segment.

By analyzing the user range errors with a continuous five days worth of data:

- CDGPS orbit and clock corrections showed good performance in correcting both broadcast ephemeris and clock.
- WAAS orbit and clock corrections are highly correlated and it is not valid to separately use them for a correction or for a validation.

By precisely analyzing the PPP results using different satellite orbit and clock corrections for one single station (a limiting factor):

- WADGPS orbit and clock corrections can be used for a PPP process with the carrier-phase observable.
- However, it will be limited by slower parameter convergence compared to using IGS products.
- PPP with the WAAS corrections might be more limited by slower parameter converge than using CDGPS corrections and there might be a challenge for kinematic PPP.

FURTHER RESEARCH

To obtain better performance using WAAS orbit and clock corrections in PPP, it might be valuable to research ways to improve the resolution issue in the correction domain.

Since the main advantage of using WADGPS corrections in PPP is to enable a real-time process, a test with kinematic processing might be valuable and needs more detailed analysis.

In terms of data processing, more days and more stations need to be processed to examine the repeatability of the results presented here and to expand the processing capabilities of this technique.

ACKNOWLEDGMENTS

The research reported in this paper was supported by the Natural Sciences and Engineering Research Council of Canada. The authors would like to thank IGS and NRCan's GSD for providing the GPS data. We also would like to thank NRCan's Paul Collins for providing data and many useful comments.

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