The Canada-Wide Differential GPS Service: Initial Performance

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BIOGRAPHY

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Amin M. Kassam is a professional engineer and land surveyor with over 20 years of experience in the geomatics and manages the geo-spatial reference program for British Columbia. Together with his team, he has helped establish British Columbia’s reputation as a leader in Canada in the establishment of real-time DGPS infrastructure and services.

ABSTRACT

The Canada-wide Differential GPS (CDGPS) Service provides wide-area DGPS corrections via L-band communications satellite across the breadth of Canada as well as parts of the United States. This real-time service is based on the GPS*C corrections generated by Natural Resources Canada using data from its network of active control stations. Testing of the service is currently underway and the service is expected to launch in the fall of this year.
In this paper, we present results of system beta testing carried out at University of New Brunswick (UNB) and elsewhere in Canada.

1. INTRODUCTION

The Canada-wide Differential GPS (CDGPS) Service provides wide-area DGPS corrections via L-band communications satellite across the breadth of Canada as well as parts of the United States. The real-time service is based on the GPS*C corrections generated by Natural Resources Canada (NRCan) using data from its network of active control stations - the Canadian Active Control System (CACS). This free service will enhance the availability of real-time DGPS corrections across Canada by bring a quality geo-referencing capability for GPS users within the Canadian Spatial Reference System (CSRS) [Kassam et al., 2002]. Initial testing of the service began in the fall of 2002 using a specially designed, compact L-band receiver.

This paper focuses on the initial performance of CDGPS. Based on the specific purposes, we have carried out four different kinds of tests. Generally for the assessment of CDGPS performance at UNB and elsewhere, we are evaluating the accuracy and reliability of the CDGPS correction data, including the satellite ephemeris and ionospheric delay corrections. The overall accuracy of the CDGPS correction data is assessed by computing a user position solution and comparing the result with the corresponding surveyed receiver antenna locations.

To analyze the accuracy of the CDGPS satellite ephemeris corrections, each corrected satellite position is directly compared with precise ephemerides, which are generated by Geodetic Survey Division (GSD), NRCan. We also compared the ionospheric delays at a user location. Ionospheric delays estimated using dual frequency data were compared with ionospheric delays which were interpolated from CDGPS and WAAS ionospheric grid delays.

To further evaluate the CDGPS receiver performance, we compared its own positioning results with those of other receivers. The positioning results from the GPS receiver module in the CDGPS receiver and those from a high quality dual frequency receiver using CDGPS corrections are compared and the results are summarized. Seven IGS/CACS stations were selected and used to analyze the CDGPS overall performance across Canada. The statistics for the selected seven stations are summarized. Finally we present the performance of the reception for CDGPS correction messages under canopy situations.

In this paper, we present the results of tests carried out at the University of New Brunswick (UNB) in Fredericton, New Brunswick and elsewhere in Canada.

2. DATA SOURCES AND PROCESSING SOFTWARE

2.1 DATA SOURCES

A data set spanning 12 days from June 7 to June 20, 2003 has been used to evaluate the accuracy of the CDGPS correction messages. On June 11 and June 16, there were local hardware problems in getting the CDGPS correction data at UNB, so this data wasn't used. To evaluate the CDGPS orbit correction accuracy, all 12 days of data have been used. The June 7, 12 (day of year (DOY): 158, 163) and June 18 (DOY: 169), 2003 were selected as representative of quiet ionospheric conditions and a disturbed ionospheric conditions, respectively (see Figure 1). Figure 1 shows the disturbance storm time (Dst) index and Kp index. The more negative the Dst values the more intense the geomagnetic disturbance. We also used the Kp index for conformation. A relatively significant geomagnetic disturbance occurred during the time from 09:00 to 12:00 on June 18 (DOY 169), 2003.

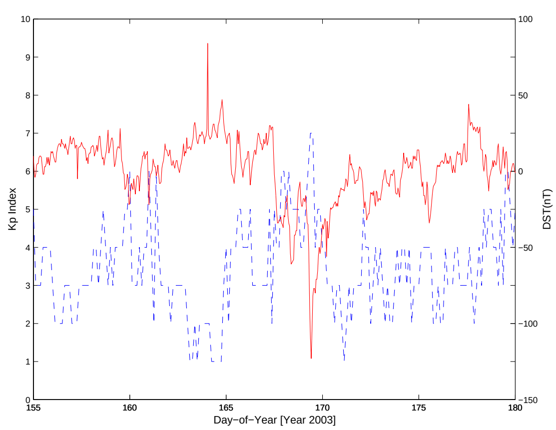

Figure 1. Dst and Kp indices from June 4 to June 28, 2003. The solid line (red) show Dst index and dashed line (blue) shows the 3 hour Kp index.

The overall performance of CDGPS was evaluated by calculating positioning results with CDGPS corrections. Forty-three days (above 12 days + July 2003) of data have been used to generate daily statistics. We chose seven IGS/CACS stations which span as much of the CDGPS service area as possible (see Figure 2).

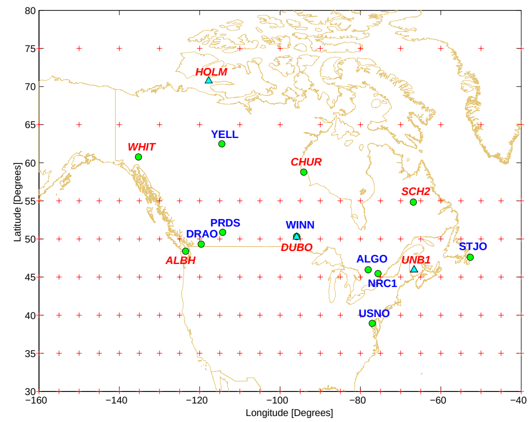

Figure 2. Twelve CDGPS reference stations (green circles), which are currently used and the selected seven IGS/CACS stations. The red characters with italic font show the selected seven IGS/CACS stations. The triangles show the non-CACS stations. Also the red cross (plus) signs show the predefined ionospheric grid points in CDGPS.

Of the selected 7 IGS/CACS stations, Whitehorse (WHIT) and Victoria (ALBH) represent the northern and south-western regions of CDGPS coverage respectively. Churchill (CHUR) and Lac Du Bonnet (DUBO) stations represent the northern and mid-southern regions of CDGPS coverage. Schefferville (SCH2) and UNB (UNB1) represent the north-eastern and south-eastern regions of the CDGPS service area. Finally, Holman (HOLM) represents the very northern part of CDGPS service area.

2.2 PROCESSING SOFTWARE

To have CDGPS (or WAAS) corrected positioning solutions for comparison purposes and analysis, we developed the UNB RTCA/MRTCA correction software. Any RINEX data can be used as an input and RTCA [WAAS MOPS, 1999] or MRTCA [CDGPS ICD, 2003] correction messages are used to correct the raw pseudoranges. The UNB RTCA/MRTCA software generates three different outputs. One is for Standard Point Positioning (SPP) results and the other two are WAAS corrected positioning (WCP) and CDGPS corrected positioning (CCP) results. The correction schemes, 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 were used rather than Black and Eisner mapping function, which is currently used in WAAS and CDGPS [WAAS MOPS, 1999]. There are certain differences in accuracy between mapping functions, especially for low elevation angles [Guo and Langley, 2003]. It should be noted that the results, presented in this paper are derived from unsmoothed pseudoranges and the functional model for processing the pseudoranges does not yet include the effects of earth tides.

3. EVALUATING THE CDGPS CORRECTIONS

The real-time CDGPS correction service is an implementation of the state-space domain concept of wide-area differential GPS positioning [Muller, 1994]. The corrections are generated by use of NRCan's CACS wide area network [Kassam et al., 2002]. The basic assumption in correcting the errors is that the error sources are spatially and temporally correlated between reference stations and user locations. Based on the above assumption, the three correction terms, satellite clock, satellite orbit and ionospheric delay are provided in vector format by use of geo-stationary satellites, MSAT-1 and MSAT-2. To improve the user positioning accuracy, the predicted satellite clocks and orbit corrections are combined with single layer (350 km) ionospheric delay corrections which are applied to the user range measurement [CDGPS ICD, 2003].

A more detailed explanation of CDGPS and CACS can be found in Kassam et al. [2002], Duval et al. [1997] and Caissy et al. [1996]. Skone et al. [1996] present any early evaluation of results from the NRCan wide area system.

To evaluate the accuracy of CDGPS corrections, the CDGPS corrected orbit have been generated on a daily basis and compared with precise ephemerides. Corrected ionospheric delays from CDGPS and WAAS ionospheric delay corrections have been compared with estimated ionospheric delays at the UNB1 (IGS) reference station.

3.1 SATELLITE ORBIT CORRECTIONS

To evaluate the CDGPS orbit correction accuracy, we determined the accuracy of the broadcast orbits (BOs) as well as the orbit after CDGPS corrections (COs). To generate the statistics for all satellites for each day during the primary test period (June 7 – June 20, 2003), the broadcast ephemerides from NASA Goddard Space Flight Center Crustal Dynamics Data Information System (CDDIS) [CDDIS, 2003] were used. The CDDIS provides daily GPS data, both observation and navigation files, retrieved from identified global core observatories using RINEX format. The final precise ephemerides from NRCan GSD were used as truth for comparison. The main advantage of NRCan GSD precise ephemerides is that they are available in the NAD83(CSRS) reference frame as well as in the International Terrestrial Reference Frame (ITFR) [NRCan GSD, 2003].

It was necessary to have the precise ephemerides in both reference frames. The precise ephemerides in ITRF were used to generate BOs and the precise ephemerides in NAD83(CSRS) were used for COs. To estimate the errors and statistics for each day, the satellite positions were calculated in Cartesian coordinates. A set of broadcast ephemerides is only used when the message is broadcast before the CDGPS orbit correction messages have arrived. After the calculation of all the positions of the satellites, we applied the CDGPS corrections to each satellite position. The Issue of Data Ephemeris (IODE), user time-out interval for the correction messages, and the User Differential Range Error (UDRE) flags were checked to validate the correction messages before we applied them to each satellite position. The UDRE values from CDGPS messages have been used to verify if there is a flag for "do not use" or "not monitored" [WAAS MOPS, 1999]. If all these conditions are satisfied, the satellite position and each error component are calculated by following equations with a daily overall 3D root-mean-square (r.m.s) error in BO and CO:
The error in each direction (X, Y and Z) is calculated, for example, the error in the orbit in the X-direction is calculated by:

$$dx = x_{PREC} - x_{BO} \tag{1}$$

with x_{PREC} : the X coordinates for precise ephemeris and

x_{BO} : the X coordinate for broadcast ephemeris

The 3D error is then computed as follows:

$$3D_{error\ i} = \sqrt{dx_i^{\ 2} + dy_i^{\ 2} + dz_i^{\ 2}} \tag{2}$$

with dx, dy and dz the errors in the BO

Then the r.m.s. error is calculated and the minimum and maximum values are computed. The r.m.s. error in the X direction is defined as:

$$RMS_{x_k} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} dx_i^{\ 2}} \tag{3}$$

where k = the satellite number
n = the number of valid values for satellite k

A similar formula is used for the Y and Z directions. The 3D r.m.s. error is defined as follows:

$$RMS_{3D\,k} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(dx_i^{\ 2} + dy_i^{\ 2} + dz_i^{\ 2})} \tag{4}$$

The overall r.m.s. error for the whole day for all the satellites can then be computed in the following way:

$$RMS_{Overall} = \sqrt{\frac{1}{s}\sum_{k=1}^{s}(RMS_{3D\,k})^2} \tag{5}$$

where s = the number of satellites with a valid r.m.s. error.

The statistics for COs are computed in a similar way. It should be noted that equation (5) is sensitive to large r.m.s. errors for specific satellites as usual in statistics with small numbers of samples. The maximum number of satellites during the test period was 28.

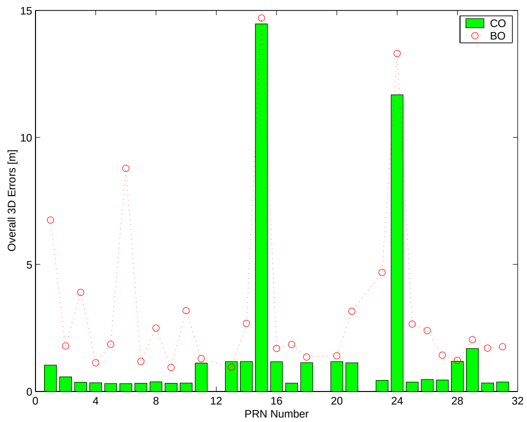

Figure 3. 3D r.m.s. errors for satellite orbit errors for June 14, 2003. Green bars show the CDGPS corrected orbit errors and red circles show the broadcast orbit errors.

Figure 3 shows that generally the errors in the broadcast orbit were well corrected by applying CDGPS orbit corrections. Also it shows the amount of error in the broadcast orbit significantly varies from satellite to satellite. However there are certain satellites, which have big errors or very small improvements even after the corrections, (e.g. PRN 15 and 24). The reason for this is there were sudden changes in satellite dynamics.

In CDGPS, corrections to the GPS broadcast orbits are determined using orbital predictions based on GPS global solutions. For each visible satellite, the most recent orbit prediction available from the International GPS Service (IGS) or NRCan (for example, ultra rapid orbit service) is used as an initial estimate. Updates to the predicted orbits are done as soon as new predictions are made available. However this scheme can not currently accommodate sudden changes in satellite dynamics and thus when broadcast orbits differ from the predicted by more than a configurable threshold value the real-time corrections are based on broadcast orbits and the orbit corrections for the corresponding satellites are zero [CDGPS ICD, 2003].

On July 14, 2003, there were two satellites, which had zero corrections for at least one epoch: PRN 15 and 24 (see Figure 4). Figure 4 shows the example of the zero correction for satellite PRN 15. The left picture, PRN 3, show the well-corrected orbit accuracy for X, Y and Z direction by CDGPS orbit corrections. Even though there are certain jumps in BO, the CDGPS orbit corrections correct it well. The right picture show PRN15 which had zero corrections for the day, July 14, 2003. It shows generally the CDGPS corrected orbit is following the borocast orbit. It would be fine, if the zero corrections would not at least make the corrected solution worse than the broadcast orbit as we can see in Figure 3 for PRN 15 and 24. Similar situations occurred quiet often during the test period of time. PRNs 15, 17 and 24 were commonly having zero corrections and the orbit accuracy was not very well improved after the corrections.

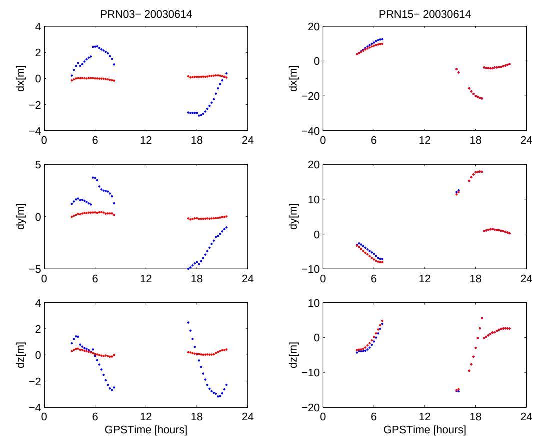

Figure 4. Example for the zero corrected satellite errors. Left picture shows the well-corrected satellite error (PRN03) and right picture shows the zero corrected satellite (PRN15) on June 14, 2003. *Blue dots* represent the broadcast orbit errors and *red dots* show the CDGPS corrected orbit errors.

The following Figure 5 shows the overall 3D r.m.s. error for BO and CO during the test period of time. The red bars shows the daily 3D r.m.s. errors for CO which have been checked for the IODE and UDRE flags as recommended by CDGPS ICD. But sometimes this condition couldn't count on the zero correction effects.

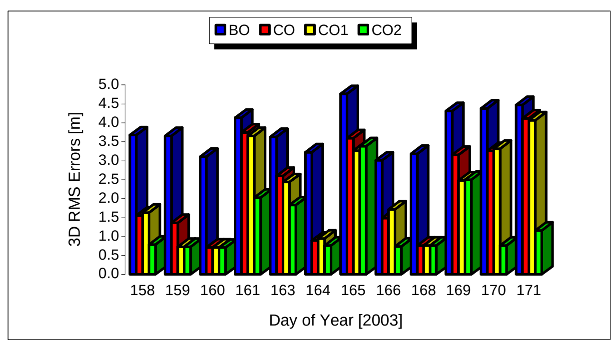

Figure 5. Overall 3D orbit accuracy during the test period.

We add one more condition, CO1. If there are certain epochs which have zero corrections, we didn't count those epochs for the daily statistics. In Figure 5, the yellow bars show the zero correction effects (CO1). On most days, the CO1 are not much improved over the CO. It is because usually there was a small number of zero corrected epochs for specific satellites and the overal accuracy for CO follws the accuracy of BO (not much improved even after the corrections) as we saw in Figure 4.

We added one more condition, CO2, to the CO1. If there is any CO1, which has a worse 3D r.m.s. error than BO, we simply excluded that specific epoch of data from the statistics. The purpose of this test was to see if there are certain improvements in terms of orbit accuracy after the corrections. If there is a large improvement between CO1 and CO2, the CDGPS-corrected orbit errors for the satellites were worse than BO.

In Figure 5, for example, we can find if there were bad quality satellites on a specific day as identified by CO. Without two to three bad quality satellites on a specific day, the overall accuracy for CO are less than 1 metre as we saw in Figure 3. So if the CO are close to BO, it indicates there are some poorly corrected satellite ephemerides (normally zero-corrected satellites by CDGPS). And by using CO1 and CO2, we can see if the corrected orbit errors were improved or not.

By including those conditions, we could see sometimes that the CDGPS corrected orbits were worse than BO. And we could see the magnitude of the contribution of bad quality satellites. In Figure 5, we can also see if the orbit errors were better than 1 metre from the first, for example on days 160, 164 and 168, the improvement by more conditions is the same or smaller. It means there were no satellites which have worse accuracies than BO and corrections worked well for those specific days.

However generally all the time CO were more accurate than BO. The overall daily 3D r.m.s. error for BO was 3.795m and CO was 2.384m. In the case of CO1 and CO2, the 3D r.m.s. error was 1.906m and 1.346m respectively. So it seems that for the data set we have analyzed, the real-time 3D r.m.s. orbit error should have been approximately 1.9m.

3.2 IONOSPHERIC CORRECTIONS

To evaluate the ionospheric corrections from CDGPS, we estimate the ionospheric delays by using dual frequency GPS data. The ionosphere is frequency dependent, so by using dual frequency data, we could estimate Total Electron Content (TEC) in TEC Units (1TECU= $10^{16}/m^2$). To reduce noise and the multipath effect in the pseudorange, we used the carrier-phase leveling technique [Komjathy, 1997]. There are slightly different approaches to reducing noise for ionospheric observables. Kee et al. [1997] and Gao et al. [2002] show slightly different ways to leveling the L1 ionospheric delays by using carrier phase smoothed ionosphere observations. Those approaches are useful if we know or can estimate the noise level for each observable. By using weights, that preliminary knowledge for noise is applied to the ionospheric delay estimation and also we can get the uncertainty for estimated ionospheric delay directly from this approach. So, we used this approach to estimate the TEC values.

We converted the estimated TEC values to the L1 ionospheric delay by applying the factor (0.162m per TEC unit) [Komjathy, 1997]. We used these estimated ionospheric delays at L1 as a truth for all comparisons.

The following Figure 6 shows the estimated slant ionospheric delays at L1 for PRN31. The day, June 12 2003, was chosen as a quiet ionospheric day (see Figure 1). The second picture shows that the noise is well reduced by the leveling technique. Also the elevation-angle dependencies in the noise are clearly shown in the second and third picture. However the estimated ionospheric delays are affected by inter-frequency biases (IFBs) in the satellite and receiver. Because the geometry free combination (P1-P2) was used to estimate ionospheric delays, the IFBs remain as critical bias terms in estimating the correct ionospheric delays.

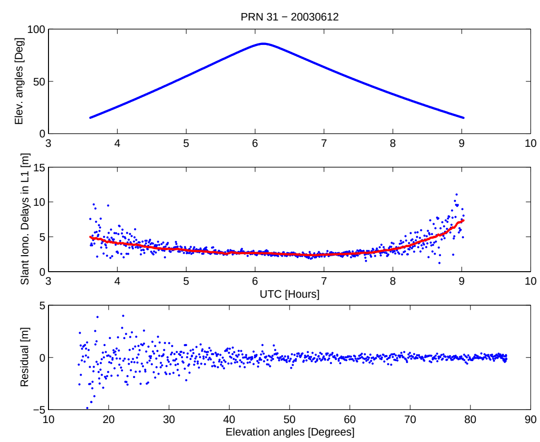

Figure 6. Estimated slant ionospheric delays and residuals for PRN 31 with 15 degree elevation cutoff angle. In the second picture, the red dots represent leveled (smoothed) slant ionospheric delays and blue dots represent slant ionospheric delays, estimated from pseudoranges.

We could obtain the satellite IFB from the navigation messages [Wilson et al., 1999]. But there is still one more term, the receiver IFB, which depends on several factors including the surrounding local temperature conditions [Chao et al., 1996]. If we ignore IFB terms in ionospheric estimation, we can simply expect around 10 nanoseconds biases [Gao et al., 2002]. In this paper, we used CODE IFB values for both satellites and the receiver at UNB [CODE, 2003].

The interpolated slant ionospheric delays for all monitored satellites at each of the ionospheric pierce points (IPPs) by use of surrounding CDGPS and WAAS Grid Ionospheric Vertical Delay (GIVD) values have been calculated. All the interpolation schemes were exactly following WAAS MOPS [1999]. The interpolated slant ionospheric delays were directly compared with estimated ionospheric delays (truth). The following Figure 7 shows the results.

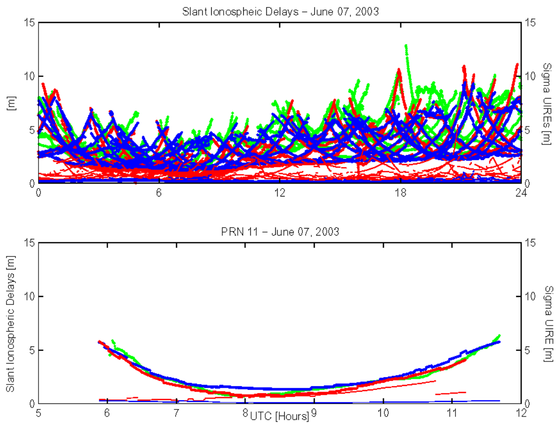

Figure 7. Estimated slant ionospheric delays for all satellites at UNB (Quiet day: June 07, 2003). The green points show the estimated slant ionospheric delays. The red and blue points represent slant ionospheric delays, which were interpolated from WAAS and CDGPS IGVDs respectively.

In Figure 7, the slant ionospheric delay ranges from almost 0 to 12.99m. The elevation cutoff angle of 5 degrees [WAAS MOPS, 1999] was used for the direct comparison with WAAS and CDGPS corrected slant ionospheric delays, throughout this analysis. The upper picture shows that the CDGPS and WAAS ionospheric delays are a bit depressed compared to truth especially during the afternoon and at night. Also the lower picture shows the slant ionospheric delays for WAAS are a bit shorter than CDGPS and truth at times. This is because PRN 11 was outside of WAAS coverage with low elevation angles after 11:11 (UTC). On the y-axis (right hand sides of both pictures), we also indicate the slant range correction error (σ_{UIRE}). The User Ionospheric Range Errors (UIRE) can be calculated by user ionospheric vertical errors multiplied by obliquity factor. It shows the slant range correction error in one sigma or the interpolated slant ionospheric delay error at each ionospheric pierce point. The maximum sigma value for CDGPS UIRE was 1.135m (mean: 0.201m) in the top panel and 1.424m (mean: 0.197m) in the bottom panel. For WAAS, it was 7.742m (mean: 0.772m) and 2.110m (mean: 0.768m) for the upper and lower panels respectively. The differences seen for the sigma value in WAAS are not surprising. Fredericton, New Brunswick is located on the periphery of the current WAAS coverage area. The uncertainty for ionospheric grid points which surround UNB would be bigger than those inside or in the middle of the WAAS coverage area.

The lower panel shows the overall WAAS and CDGPS slant ionospheric delays for PRN 11. It shows that both the CDGPS and WAAS slant ionospheric delays closely follow the truth (estimated ionospheric delays from UNB1 data). We have also examined the effects of ionospheric disturbances on the CDGPS and WAAS corrections on July 18, 2003. A relatively significant geomagnetic disturbance occurred during the time from 09:00 to 12:00 (UTC) on June 18, 2003 (see Figure 1).

Figure 8 shows the slant ionospheric delays on the disturbed day. The range for estimated slant ionospheric delays were 0.729m to 11.308m. This figure also shows that both CDGPS and WAAS ionospheric delays are depressed compared to truth. In the upper panel, there is a certain increase of noise around 10 UTC. It may be caused by miss-leveled ionospheric delay because we didn't impose any constraint in estimating ionospheric delays. Komjathy [1997] recommended not using any arc which is less than 20 minutes in length for the leveling. The variation of the WAAS slant ionospheric delays was relatively larger than the CDGPS and truth values. The ranges vary from 0m to 14.134m for all the results. The sigma value for WAAS UIRE had maximum of 6.297m (mean: 0.766m) and for CDGPS, it was 0.829m (mean: 0.309m). In the lower panel of Figure 8, the sigma value for WAAS UIRE for PRN 11 was 2.112m (mean: 0.760m) and for CDGPS, it was 1.731m (mean: 0.333m) and the difference between CDGPS and WAAS ionospheric delays and the truth was consistently within 0.5 metres after 6:00 (UTC).

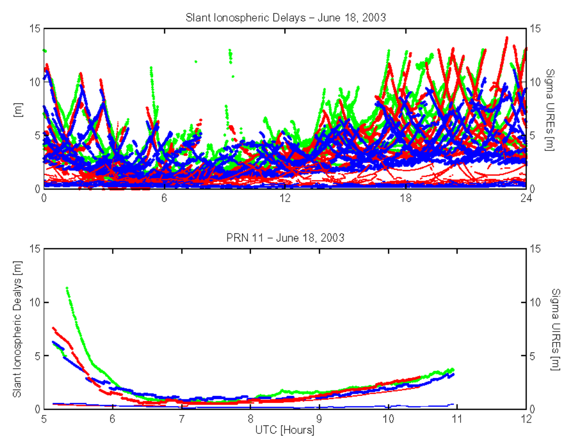

Figure 8. Estimated slant ionospheric delays for all satellites at UNB (Disturbed day: June 18, 2003). The green points show the estimated slant ionospheric delays. The red and blue points represent slant ionospheric delays interpolated from WAAS and CDGPS IGVDs respectively.

To clearly see the differences between the estimated ionospheric delays ("truth") and those of CDGPS and WAAS, we converted the slant ionospheric delays into vertical delay. However it should be noted that these delays are not exactly vertical delays at UNB. The conversion from slant to vertical delays represents the vertical delays at the IPPs (not at UNB).

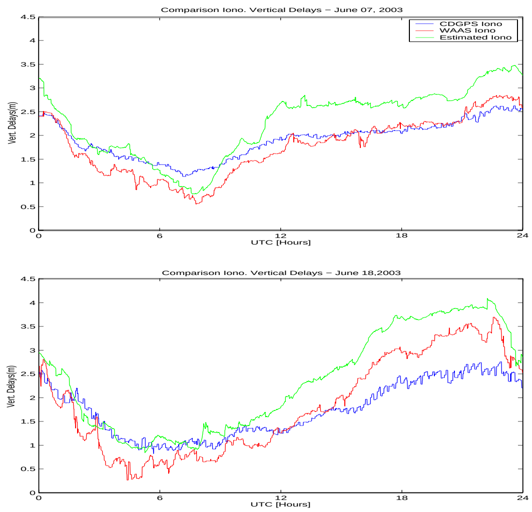

Figure 9. Mean of vertical ionospheric delays at each epoch at UNB. The upper panel shows results for the quiet day, June 07, 2003 and the lower panel shows results for the relatively geomagnetic disturbed day, July 18, 2003.

We simply took the mean of vertical ionospheric delays for IPPs for each satellite at each epoch. This means that we cannot consider the spatial variations between the UNB vertical delays and each IPP.

On June 07, 2003, both CDGPS and WAAS ionospheric vertical delays are consistent with truth within the one metre level (see Figure 9, upper panel). On June 18, 2003, the difference between CDGPS and the truth was a little larger (see Figure 9, lower panel). The maximum difference was 1.3 metres. However, overall, the CDGPS ionospheric delays look smoother than the truth. Relatively speaking, the WAAS ionospheric corrections are more sensitive to changes in the ionosphere. The overall slant ionospheric delays for this day were slightly nosier than those on June 07, 2003 and we can see there were certain variations in the vertical ionospheric delays around 9:00 to 11:00 (UTC). However, we could not see any significant effects of the geomagnetic disturbance on June 18, 2003. It might be that the geomagnetic disturbance was not that serious or just that only small effects were seen for our region.

4. PERFORMANCE EVALUATION OF CDGPS

4.1 POSITIONING RESULTS COMPARISON

We have compared positioning results between standard point positioning (SPP), WAAS-corrected positioning (WCP) and CDGPS-corrected positioning (CCP). We chose one CACS station, Churchill (CHUR) for calculating and comparing the positioning results. CHUR was selected as it is near the centre of the CDGPS coverage area and is outside the primary WAAS coverage area. We used five days of RINEX data with 30 seconds data sampling interval. The results from continuous four days, from 7 to 10 June 2003, represent results under nominally quiet ionospheric conditions. The last day, June 18, 2003, is representative of a disturbed ionospheric condition day. The purpose of this separation of the results in this way is to see if there are certain ionospheric effects reflected in the positioning results. The UNB RTCA/MRTCA correction software was used for all the processing. The SPP results were computed by using C/A code pseudoranges and broadcast ephemerides with Klobuchar ionospheric delay and UNB3 neutral atmospheric delay models. The Klobuchar model was used to reduce ionospheric effect for SPP. In the case of WCP and CCP results, the satellite clock, ephemeris and ionospheric corrections from WAAS and CDGPS were used respectively. The UNB3 prediction model was used to minimize the local neutral atmospheric (tropospheric) error for all the results, SPP, WCP and CCP.

The following Table 1 and 2 show the 95% horizontal errors and the mean bias in height (average for 24 hours on each day height errors: observed height – known heights.

Table 1. 95% Horizontal Errors for SPP, WCP and CCP at CHUR

	SPP Horiz.	WCP Horiz.	CCP Horiz.
7-Jun-03	4.006m	1.502m	1.389m
8-Jun-03	3.578m	1.535m	1.283m
9-Jun-03	3.463m	1.750m	1.132m
10-Jun-03	4.360m	1.605m	0.996m
18-Jun-03	3.544m	1.886m	1.109m
Mean	3.790m	1.656m	1.182m
Std	0.342m	0.144m	0.138m

Table 2. Mean Bias in Height for SPP, WCP and CCP at CHUR

	SPP Ht	WCP Ht	CCP Ht
7-Jun-03	0.708m	-0.457m	0.095m
8-Jun-03	0.523m	-0.372m	0.085m
9-Jun-03	-0.051m	-0.543m	0.109m
10-Jun-03	1.140m	-0.336m	0.575m
18-Jun-03	1.402m	-0.662m	0.467m
Mean	0.744m	-0.474m	0.266m
Std	0.504m	0.118m	0.211m

Both the CDGPS and WAAS corrections reduced the SPP errors and improved the positioning accuracy. The mean errors were reduced by more than 2 metres in the horizontal (95% probability) and 20 to 50 centimetres in the vertical mean bias component. In Table 2, the height differences between SPP, WCP and CCP were not that big but the standard deviations were generally reduced. We can simply think the Klobuchar model well predicted the ionospheric delays for certain days. It also could be explained by the way the comparisons were made. The updating of the coefficients for the Klobuchar model in navigation message are nominally made on a daily basis, so such modelling is useful on a daily mean basis but not for real-time situations. It should be noted that the mean bias in height is not representative of real-time accuracy. The presented results were computed based on the static case with averaging of 24 hours of positioning results. In the real-time situation, the most important thing is how consistent are the results we can get for a long period of time (see Figure 10). In Table 1 and 2, the better accuracy in CCP than WCP is not surprising. The accuracy for wide area DGPS depends on the accuracy of the corrections. The basic concept to generate the correction terms is based on the spatial and temporal correlation of errors between reference stations and users. The station CHUR is located beyond the edge of WAAS coverage in northern direction. The increased distance between WAAS reference stations and CHUR would cause corrections to be less accurate than those of CDGPS.

In Table 1 and 2, we can also see the relative consistency or repeatability of results by the standard deviation (Std). The standard deviation of both the WCP and CCP results shows that the repeatabilities are approximately 2 to 2.5 times better in horizontal and 2 to 4.3 times better in vertical than SPP.

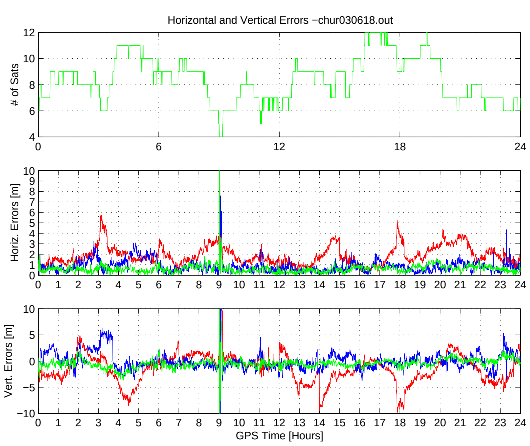

Figure 10. Horizontal and vertical errors for June 18, 2003. The green dots show CDGPS results, blue dots WAAS results, and red dots show the standard positioning results.

Figure 10 shows the horizontal and vertical errors for June 18, 2003. There are certain jumps in both the horizontal and vertical components in all solutions for SPP, WCP and CCP at around 9:00 GPS Time. The jumps could be caused by a sudden change in the number of satellites (down to 4 satellites). Also the PDOP value goes up to maximum of 30. The scale for horizontal and vertical errors in Figure 10 has been changed from original scale to see the trends in the data. Original maximum error in all solution types, which was caused by a certain spike, was 23m in the horizontal and 50m in the vertical.

On June 18, 2003, the mean height bias is relatively larger than on other days in most solution types. The height component in positioning is more sensitive to ionospheric and tropospheric delays. The same UNB3 tropospheic model was used for all SPP, WCP and CCP solutions. So the only difference with other days is if the ionosphere was disturbed for this day. The Klobuchar model can not bound a sudden change of the ionosphere. It might be the cause for more error in height in SPP for this day.

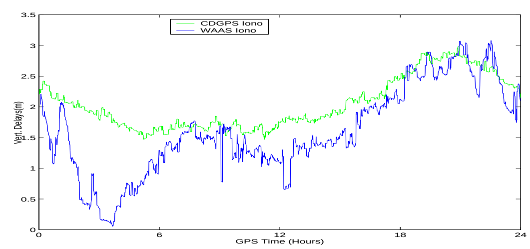

Figure 11. The difference between CDGPS (green) and WAAS (blue) vertical ionospheric delays (mean for each epoch) for June 18, 2003.

Figure 11 shows the correlation between height component errors (Figure 10) and the ionosphere in CDGPS and WAAS results. As we can see in Figure 10 and 11, there are certain correlations in variations of height component errors when the WAAS vertical ionospheric delays change by a large amount in a short time period (0 to 1 hour and 3 to 4 hours and so on in Figure 11). However, we can see again that the general behavior for CDGPS ionospheric vertical delays looks smoother than WAAS.

4.2 PERFORMANCE OF THE CDGPS RECEIVER

The quality of the receiver is one of the significant factors in terms of error handling in the positioning results. The user errors, which are separate from correction errors, should be well modeled to improve the accuracy, availability and integrity in wide area DGPS system (WADGPS). The thermal noise, interference (SNR) and multipath errors are all related with receiver quality.

The first generation CDGPS receiver has been developed by Mobile Knowledge Inc. in Kanata, Ontario, Canada [Kassam et al., 2002]. This hand-held field portable unit has an onboard GPS module and a DSP-based L-band MSAT receiver for extreme sensitivity to low signal levels that will be encountered in normal usage. The CDGPS receiver can be configured to output CDGPS-corrected receiver position in NMEA format, localized RTCM corrections to be fed to a separate GPS receiver, or modified RTCA (MRTCA) formatted corrections. Two kinds of antennas are used based on the location or situation of users. Usually, a standard patch antenna is used and optionally a higher gain quadrifilar antenna can be used for higher latitude or more demanding user condition [Kassam et al., 2002].

For the analysis reported here, the CDGPS corrected NMEA output data and raw CDGPS MRTCA correction data were obtained from a pair of continuously operating CDGPS receivers. The NMEA output data was directly compared to UNB1 (IGS) station data, which was corrected using the CDGPS MRCA correction messages using the UNB RTCA/MRTCA correction software. A Javad Legacy GPS/GLONASS receiver with a pole-mounted dual-depth choke-ring antenna is installed at the UNB1 station. Eleven days data from 7 to 20 June, 2003 were used for the statistics. The data for 11, 16 and 19 June 2003 were not included in the results (see Figure 12). There were local hardware problems on these dates. We didn't get any NMEA output data for those days.

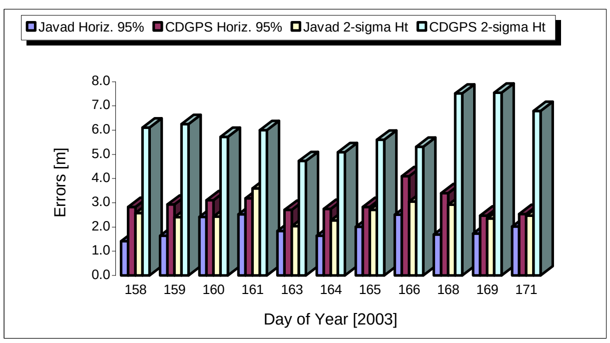

Figure 12. Positioning results from CDGPS receiver and Javad high-quality receiver at UNB.

Figure 12 shows the 95% horizontal errors for the Javad and CDGPS receiver results. It also shows the height errors at the 2-sigma level for both receivers. As we expected, the Javad receiver results are always better than the CDGPS receiver results in terms of accuracy. The mean difference in horizontal 95% errors is 1.038 metres (1.949 metres for Javad and 2.986 metres for the CDGPS receiver). And the height error difference at the 2-sigma level was 3.441 metres (2.622 metres for Javad and 6.063 metres for the CDGPS receiver).

The height differences between the receivers are the most significant. Some differences could be explained by the different type of antenna and quality of receiver. The dual-depth choke-ring antenna is much better in terms of reducing multipath effects. Other possible explanations might be the sensitivity for the signal power, receiver measurement noise, receiver clock quality and the handling of atmospheric effects.

4.3 CDGPS POSITIONING ACCURACY

To evaluate the overall performance of the CDGPS corrections in Canada, we used the seven IGS/CACS stations which cover a large part of the CDGPS service area (see Figure 2). The same set of CDGPS correction data has been used to calculate the daily statistics for all seven IGS/CACS stations each day. All seven stations have high quality geodetic receivers and antennas. In total 43 days, from June 7 to 20 (not used for June 11 and 16) and from July 1 to 31 2003, were used to generate daily statistics.

Table 3. CDGPS Overall Positioning Accuracy at Seven IGS/CACS Stations. Unit [metres].

	Horiz. 95%	Horiz. 2 d. r.m.s	Vert. 2-sigma
ALBH	1.498	1.537	2.535
WHIT	1.565	1.649	2.696
DUBO	1.500	1.565	2.473
CHUR	1.119	1.222	2.211
HOLM	1.976	2.075	3.869
UNB1	1.868	1.977	2.840
SCH2	1.422	1.464	2.229
Mean	1.564	1.641	2.693
Std	0.285	0.296	0.567

Table 3 shows positioning results obtained using CDGPS corrections. In Table 3, the overall mean accuracy for the seven IGS/CACS stations is 1.56m at 95% for horizontal errors and 2.69m at 2-sigma for vertical errors. We can also see the repeatability for horizontal and vertical coordinate by use of standard deviation (Std). CHUR has the best statistics and HOLM has a little bigger mean errors in both horizontal and vertical components. It is because HOLM is located at a high latitude (70.73629 degrees) compared to the other six stations.

In comparison, the claimed average service accuracy for the 13 CACS stations (see Figure 2 + Halifax station (HLFX)) for July in single frequency mode reported in the GPS*C Service Report [CDGPS, 2003a] was 1.265 metres (horizontal 2drms with pdop<2.5). The difference in the mean 2 d. r.m.s. of 7 stations (see Table 3) and GPS*C Service Report results might be explained by the different stations with different data sets and different conditions for the statistics or differences in data processing algorithms.

4.4 UNDER-CANOPY RECEPTION PERFORMANCE

In a wide-area DGPS correction service, the reception (i.e. penetration of the signal through the bush) is as important as accuracy. The differential GPS positioning results depend on the continuous availability of correction messages at the user position. This capability usually depends on the signal power from the geostationary satellite sending the corrections and the environment of the user. The CDGPS Service testing and reporting has always been approached from two operational aspects: accuracy and reception.

Some reception tests were carried out during the CDGPS alpha testing phase [CDGPS, 2003b]. The following material is abstracted from that report.

A test loop trail in Beban Park in Nanaimo, British Columbia has been used to characterize under-canopy reception performance of CDGPS during alpha trials. Be aware that testing under these "real-world" conditions is more variable than testing done in a controlled environment. For example, signal re-acquisition performance is not easily measured for a complicated system such as CDGPS with its many related message sequences that are required before corrections can be formed. Further, variable forest canopy conditions, especially moisture levels, will create different tracking environments.

The MSAT communication satellites have configurable power levels, and the CDGPS signal reception in Nanaimo was tested at various levels. The normal transmission power level of the Western Beam has been set at 28dB for most of the alpha testing. This changed to 39dB on 28 April, 2003, and under-canopy reception performance was characterized with testing done on the Beban test loop in the hours immediately before and after this change. Later, the MSAT power level of the Western Beam was set to 32dB, and more testing was done at this new power level.

Under-canopy reception performance was characterized for each test loop using 2 measures:

- The number of receiver RTCM corrections compared to the number expected to be received during the test time-span (expressed as a percentage).
- The maximum time gap between sequential RTCM messages received for each test loop.

Table 4. CDGPS RTCM message reception on Beban Test Loop (under-canopy)

MSAT Power Level	% RTCM message received	Maximum message gap
28dB	32%	183 sec
32dB	43%	58 sec
39dB	65%	19 sec

Table 4 summarizes the performance measures at the 3 different MSAT power levels. The values shown are the averages of the individual test loop measures. Note that the results are specific to the Beban test loop, and all testing was done with CDGPS Beta 1.6 radios with patch antennas kept approximately horizontal. It is likely that better reception performance would be experienced with a quadrifilar antenna (especially if it is bore-sighted).

As expected, the results show improved reception performance as the MSAT power is increased (see Table 4).

4.5 CDGPS Service Reliability

Note that the GPS-C service did not suffer any serious impacts from the massive power blackout which struck Ontario and several northeastern U.S. states on 14 August 2003. Both production servers in Ottawa were unaffected as were all communication links that provide data and correction to and from the production servers. A faulty uninterruptible power supply (UPS) at NRC1 in Ottawa lead to a temporary outage of the data from that station and the UPS was replaced.

CONCLUSIONS

CDGPS is now in beta testing and the service is expected to launch soon. Once the CDGPS service starts, users will be able to obtain CDGPS corrections via the MSAT-1 and MSAT-2 from geostationary satellites at any place in Canada. This free service will enhance the availability of real-time DGPS corrections and accuracy of GPS user positions across Canada within the Canadian Spatial Reference System (CSRS).

In this paper, we presented four types of test results for system testing carried out at UNB and several sites across Canada. Based on the results of our analyses, the CDGPS corrections generally reduced positioning errors significantly. In the case of the CDGPS orbit corrections, the broadcast orbit errors were reduced down to around 1.4 metres and the CDGPS ionospheric corrections do not different with respect to truth (directly estimated ionospheric delays) by more than 1.5 metres. We found there were certain satellites (one to three satellites on some days), which have relatively big errors compared with other satellites. Those satellites have zero CDGPS corrections and the quality for the broadcast orbit was also worse than other satellites. The relatively big errors, caused by certain dynamics, could not be accommodated by the CDGPS orbit correction scheme. In this case, the improvements in orbit errors were relatively small or sometime a little worse than the broadcast orbit. Without those satellites, the daily 3D r.m.s. errors are all the time better than the 1 metre level. So based on the optimum (CO1) solution, the CDGPS corrected orbit errors are around 2 metres.

By comparison between CDGPS and WAAS ionospheric delays and estimated ionospheric delays by using dual frequency GPS data, we found that the general trend for the CDGPS ionospheric corrections were a little bit smoother than WAAS or truth. It would have been nice to see the CDGPS ionospheric corrections for a more significantly disturbed ionospheric day. But unfortunately, we couldn't see the exactly how well the CDGPS ionospheric corrections are working in such disturbed ionospheric conditions. There was no significant ionospheric disturbance during the test period.

In the case of WADGPS, the accuracy for positioning results not only depend on the correction messages but also depend on how well the local error sources (SNR, multipath and tropospheric delays errors) are handled. And in many cases the local errors sources are strongly correlated with receiver quality. We tested the specially designed CDGPS receiver. Based on the comparison between the CDGPS receiver and a high quality receiver positioning results, there were certain differences. In the case of horizontal coordinates, the difference was in around the 1 metre level at the 95% probability level but the height difference at the 2-sigma level was around 3 metres. Some differences could be explained by different hardware, including the fact that we used a dual depth choke-ring antenna for high quality receiver results. It could also be explained by the different receiver qualities, sensitivity for the signal power, receiver measurement noise and the handling of atmospheric effects and so on. However, there needs to be more analysis to exactly know what causes the differences especially in height component.

Based on the comparison of positioning results at station CHUR, we found that CDGPS can improve positioning accuracy by 2.6 metres at the 95% horizontal probability level. And the CDGPS corrected results have horizontal errors of less than 2 metres at the 95% error probability level and less than 4 metres in the vertical (2-sigma level) at all seven IGS/CACS stations we used. We also presented the variation or repeatability of around 30 cm in the horizontal coordinates and 60 cm in height.

In a wide-area DGPS correction service, the reception (i.e. penetration of the signal through canopy) is just as important as accuracy. We summarized the reception performance for CDGPS at a particular test site in an area of west coast rain forest. As expected, the results show improved reception performance as the MSAT power is increased.

Further examination of the current CDGPS performance under more disturbed ionospheric conditions and on the periphery of the coverage area may be helpful to verify the CDGPS performance in difficult situations.

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