Assessment of WAAS Correction Data in Eastern Canada

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Abstract

As part of the research being carried out at the University of New Brunswick on assessment of the Wide Area Augmentation System (WAAS), we are evaluating the availability and accuracy of the WAAS correction data, including the ionospheric grid model and its operational implementation for users in eastern Canada. We run a continuously operating GPS receiver with WAAS capability. All data from the receiver including raw pseudorange and carrier-phase measurements at a 1 Hz rate and all WAAS messages are archived in daily files.

Each day, the WAAS ionospheric grid delay (IGD) values and the corresponding grid ionospheric vertical error (GIVE) values are extracted from the archive file to generate IGD and GIVE values at each ionospheric grid node superimposed on a coverage map of eastern North America. The overall accuracy of the WAAS correction data is assessed by computing a user position solution and comparing the result with the corresponding surveyed receiver antenna location. In addition, the GPS orbit corrections are directly assessed through comparisons with the precise ephemerides of the International GPS Service. Using WAAS correction data, we have computed the position accuracy of the single-frequency user as approximately 2 metres twice distance r.m.s. in eastern Canada on the periphery of the current WAAS coverage area.

The ionospheric grid model is being assessed over the range of solar activity intensities and involves comparison between the model and appropriate dual-frequency GPS data from permanent tracking stations, which constitutes an ionospheric "truth" system. This work will complement ongoing WAAS-related ionospheric research in Canada and will permit us to recommend, for example, the number and locations of reference stations for the future Canadian Wide Area Augmentation System.

Introduction

The WAAS ionospheric grid model is being used to calculate the ionospheric vertical delay and its errors at each grid point. The locations of grid points are specified in the Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment [WAAS MOPS, 1999]. It defines grid nodes based on geographical latitude and longitude. In general, the WAAS Master Station (WMS) uses the Ionospheric Pierce Point (IPP) vertical delay measurements in the vicinity of the grid points to estimate both the vertical ionosphere correction (Ionospheric Grid Delay – IGD) and the Grid Ionospheric Vertical Error (GIVE). Users apply the ionospheric correction values from the three or four grid points surrounding a received signal's IPP to interpolate corrections at the user position. The WAAS MOPS [1999] specifies the user's algorithm to calculate the user ionospheric vertical delays and their errors. A bi-linear interpolation scheme is employed to determine the User Ionospheric Vertical Error (UIVE) for each satellite that is monitored by the user.

A new GIVE monitoring algorithm has been developed in conjunction with the WAAS Integrity Performance Panel (WIPP) [Mannucci et al., 2000]. It uses a planar least-squares fit to data within a 1200 km radius for the ionosphere modelling at each grid point [Hansen et al., 2000]. And a Chi-square-based storm detection algorithm is applied to detect electron density perturbations (irregularities) which contribute to the range errors incurred by users using a network-based, real-time ionospheric monitoring system [Walter et al., 2000]. This new GIVE monitoring algorithm was initiated on 27 November, 2001 [Raytheon, 2001]. The most significant improvement is the increased numbers of Ionospheric Grid Points (IGPs) which are monitored with usable GIVE values less than 15 metres. Although the accuracy of WAAS grid corrections has not changed, the increased availability of User Ionospheric Vertical Errors (UIVEs) has improved not only the accuracy, but also the integrity monitoring at the user position.

This paper discusses the user positioning accuracy observed in Fredericton, New Brunswick, which is located on the periphery of the current WAAS coverage area. The results show the improvement of user position accuracy with the new WAAS GIVE monitoring algorithm and show the impact of the ionosphere on user WAAS positioning results.

Data Sources and Observations

GPS Data

For the analysis reported here, data were obtained from a continuously operating CMC Electronics AllStar L1 receiver, which normally accesses the WAAS messages transmitted by the Inmarsat Atlantic Ocean Relay West (AOR-W) satellite. The receiver is fed by an AeroAntenna AT-575-70 pole-mounted antenna. All data from the receiver including raw pseudorange and carrier-phase measurements at a 1 Hz rate and all WAAS messages are archived in daily files. A data set spanning 37 days in November and December 2001 has been used for the results presented here. The first seven days of data, from day 309 to day 315, were used to observe ionospheric storm effects on the user positioning accuracy. For the analysis of positioning accuracy of WAAS between the old and new GIVE monitoring algorithms, the data are divided into two periods: 12 November (day 316) to 26 November (day 330) and 27 November (day 331) to 11 December (day 345), respectively. The overall accuracy of the WAAS correction data is assessed by computing a user position solution and comparing the result with the corresponding surveyed receiver antenna location at the University of New Brunswick (UNB). The WAAS correction messages are based on the WGS 84 system but our surveyed antenna coordinates are given in ITRF97. No transformation has been carried out. The current difference between the WGS 84 system and ITRF97 is well below 10 cm. Figure 1 shows the UNB WAAS antenna at the centre of the photo and the locations of the UNB and East Port, Maine GPS stations, with respect to surrounding ionospheric grid points. Data from East Port has been used to study WAAS IGD accuracies.

Figure 1. UNB WAAS antenna on centre mount, and location of UNB and East Port, Maine with surrounding ionospheric grid points

Orbit Correction Data

To correct the GPS broadcast ephemeris data, we used the WAAS orbit corrections. Long term WAAS-corrections are made available in WAAS Message Type 24 and Message Type 25. A long term WAAS-correction can be applied to the appropriate satellite when the PRN of the corrections is established using Message Type 1. The corrections are only valid when the Issue of Data (IOD) of the broadcast ephemeris matches the IOD in the correction message, and only when the time interval of applicability is not longer than 360 seconds. The overall standard deviation of satellite positions computed from broadcast ephemerides including WAAS corrections for the whole day for all the satellites was computed.

Ionospheric Data

To analyse the effect of ionospheric storms on the WAAS ionospheric grid model and the accuracy of positioning results, two separate data sets were chosen to represent quiet and severe storm ionospheric conditions. The Continuously Operating Reference Station (CORS)/International GPS Service (IGS) station at East Port, Maine, near the New Brunswick border, which provides dual frequency GPS data, has been used as “truth” for comparison with the WAAS ionospheric grid model.

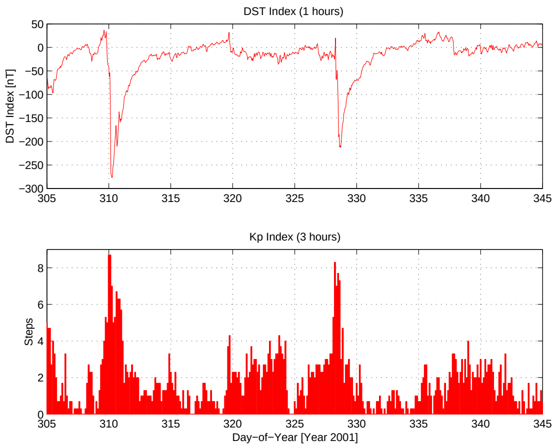

Figure 2. The disturbance storm-time index

In order to accurately evaluate WAAS ionospheric grid corrections during geomagnetic disturbances, the location and duration of enhanced ionospheric activity must be identified. Two standard indices are used. Large negative Disturbance Storm Time (Dst) index values indicate the occurrence of a geomagnetic storm. The more negative the values, the more intense the geomagnetic storm [Fedrizzi et al., 2002]. The Kp index is used to confirm geomagnetic storm time and magnitude. Figure 2 shows the Dst and Kp geomagnetic indices during the period from 1 November to 11 December 2001. The first geomagnetic storm occurred at around 04h-08h UTC on 6 November (day 310). The second geomagnetic storm occurred at around 15h-18h UTC on 24 November 2001 (day 328). The first storm values reached a maximum -277nT in Dst and 8.7 in Kp index, which are classified as a very intense geomagnetic storm [Mannucci et al., 1997]. Based on the geomagnetic indices, the data from 6 November 2001 has been chosen as representing geomagnetic storm conditions and the data from 3 November 2001 chosen to represent quiet ionospheric conditions.

Evaluation of WAAS Service Availability

Availability is the percentage of time that WAAS services are usable. We computed the availability of GIVE values at four grid points surrounding the UNB WAAS antenna and then we calculated the daily availability of UIVE from 22 November to 1 December (5 days before and 5 days after the GIVE algorithm change). The Ionospheric Pierce Point (IPP) was calculated as the intersection point between the ionospheric shell (at a height of 350 km) and the line of sight between GPS satellite and receiver at UNB. There are two reasons for doing this; one, we would like to know how much the availability of UIVE at Fredericton has improved; and two, the IGPs one grid step to the east and north side of the IGPs surrounding Fredericton did have not sufficient GIVE values required to calculate UIVE. In any case, we are interested in looking at the correlation between UIVEs and vertical errors in positioning results (to be discussed later; see Figure 6). Figure 3 shows the availability of GIVEs and the average values of GIVEs at Fredericton. Before the new GIVE algorithm was implemented, the availability of GIVEs for IGPs 70°W-50°N and 65°W-50°N was below 10% (see Figure 3). And the IGPs at 70°W-45°N and 65°W-45°N had more GIVE values with smaller errors than IGPs 70°W-50°N and 65°W-50°N. The reason for this behaviour is related to the basic WAAS error correction concept. This idea is based on a spatial and temporal correlation of errors between WAAS Reference Stations (WRSs) and users for each error component. The distance between WRSs and IGPs is a critical issue.

On day 328 in Figure 3 (right-hand panel) there is a spike at IGP 65°W-50°N and the mean values of the other three IGPs are relatively larger than those of other days. This is a storm-like effect. In fact, on this

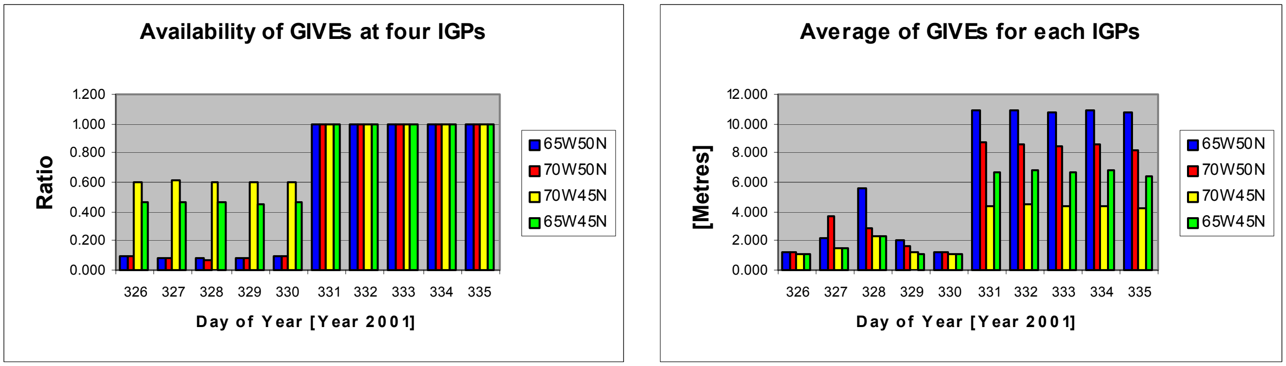

Figure 3. Availability of GIVEs at four IGPs which surround the UNB WAAS antenna and average of GIVEs for each IGP

day a geomagnetic storm occurred. The peak magnitude of the L1 GPS frequency ionospheric delays was enhanced by an amount of 4 metres compared with typical quiet day levels. The temporal and spatial gradients were large enough to increase the errors in the WAAS predicted delays (to be discussed later; see Figure 7).

After the new GIVE algorithm was initiated, the availability of GIVEs for each IGP in the vicinity of Fredericton has significantly improved. The probability of having GIVE values was 100% after day 331. This is also true for UIVE values (see Figure 4). Before the new GIVE algorithm was initiated, the availability of UIVEs at Fredericton was around 10%, but it increased to around 80% after 27 November 2001 (day 331).

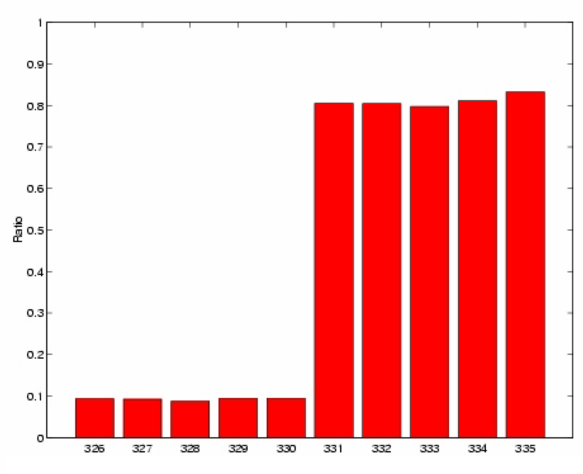

Figure 4. Availability of UIVEs at Fredericton

Table 1 shows the difference of GIVE values between four grid points well within the Contiguous United States region (CONUS) and the four grid points immediately surrounding Fredericton. We chose the IGPs based on the consistency of GIVE values at each IGP over time, looking at days when the ionosphere was not disturbed by geomagnetic storms. The CONUS GIVE values were increased under the new GIVE monitoring algorithm (in the past, they were generally less than 2 m), but the mean and standard deviation values between IGPs are consistent. In the case of IGPs immediately surrounding Fredericton, as we expected the mean and standard deviations are larger than those for the CONUS, and there are large differences, between IGPs. As we discussed before, this is related to the location of the WRSs.

28/11/2001	Mean (m)	Std. Dev. (m)
35N85W	3.63	0.24
40N80W	3.65	0.20
40N85W	3.60	0.21
35N80W	3.75	0.38

28/11/2001	Mean (m)	Std. Dev. (m)
65W50N	10.89	4.53
70W50N	8.59	4.38
70W45N	4.46	1.49
65W45N	6.77	3.84

Table 1. GIVE values from CONUS (left) and Fredericton (right) – DOY 332 (28 November 2001)

Evaluation of WAAS Position Accuracy

The horizontal and vertical position errors of our station have been analysed using WAAS-corrected position results under both the old and new WAAS GIVE monitoring algorithms. The root-mean-square (r.m.s.) errors and the error distribution with probability for each component have been generated for each day. Table 2 shows the results of a comparison between the old and new GIVE monitoring algorithms. The accuracy of the positioning r.m.s. results has improved 31 cm in horizontal and 57 cm in the vertical component. The improvement of the positioning accuracy is most likely due to the increased availability of IGPs. The increased number of monitored IGPs provides more corrections for satellites with ionospheric delays and their GIVEs.

The user position accuracy is related to receiver noise, interference and multipath, tropospheric model residual errors for both user and WMS, and also errors in WAAS correction messages, such as residual ionospheric errors, residual clock and ephemeris errors [Enge et al., 1996].

We have analysed the positioning accuracy with respect to the effect of WAAS orbit and ionosphere errors. Figure 5 shows the horizontal and vertical r.m.s. errors at our station over 37 days. As we expected, the geomagnetic storm days 305 and 328 have larger r.m.s. values in both the horizontal and vertical error components. The horizontal error was 2.60 metres and vertical error was a 3.50 metres on day 305, which was a severe geomagnetic storm day. On day 328, the horizontal r.m.s. error was 2.06 metres and the vertical r.m.s. error was 2.80 metres. The difference in the horizontal and the vertical r.m.s. errors between storm days is due to the intensity of the storms. We had a much stronger storm occurred on day 305 (see Figure 2).

(15days (day 316-330) processing for old GIVE monitoring algorithm)

	Minimum	Maximum	Mean	Std. Dev.
Daily HDOP	0.93	1.03	0.95	0.02
Daily VDOP	1.33	1.50	1.37	0.05
Daily No. of Satellites	8.52	8.88	8.74	0.10
Errors (m)				
Daily Horizontal r.m.s.	1.28	2.05	1.54	0.19
Daily Vertical r.m.s.	1.68	3.33	2.30	0.49
Daily Horizontal 95%	2.26	3.79	2.86	0.43
Daily Vertical 95%	3.59	7.54	4.76	1.15

(15 days (day 331-345) processing for new GIVE monitoring algorithm)

	Minimum	Maximum	Mean	Std. Dev.
Daily HDOP	0.93	0.95	0.94	0.01
Daily VDOP	1.33	1.35	1.34	0.01
Daily No. of Satellites	8.64	8.83	8.79	0.05
Errors (m)				
Daily Horizontal r.m.s.	1.06	1.50	1.23	0.13
Daily Vertical r.m.s.	1.28	2.51	1.73	0.36
Daily Horizontal 95%	1.91	3.11	2.29	0.31
Daily Vertical 95%	2.55	4.90	3.38	0.65

Table 2. Comparison of statistical values between old and new GIVE monitoring algorithms

We also calculated the daily satellite position error to examine the correlation between satellite orbit error and user positioning accuracy. We used the WAAS orbit correction message to correct satellite positions, which were computed with broadcast ephemerides. The IGS precise ephemerides were used as "truth" to calculate a daily WAAS-corrected satellite position error. Figure 5 shows the correlation between standard deviations of satellite positions and user positioning accuracy. The WAAS orbit correction message improves the satellite position accuracy around 60 cm in the overall standard deviation (3D). The WAAS-corrected satellite orbit errors are relatively consistent but sometimes they are larger than the broadcast ephemerides errors. For example, on the first storm day (day 310), the WAAS orbit error was relatively larger than the broadcast ephemerides error, but on the second storm day (day 328) the WAAS orbit correction had reduced the satellite position errors by around 2 metres.

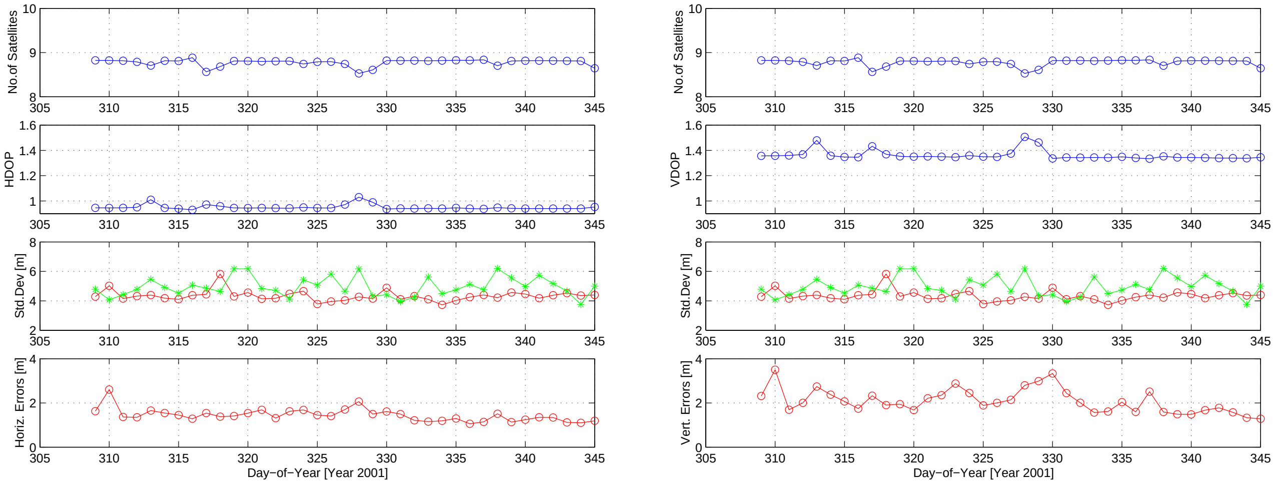

Figure 5. Daily average number of track satellites, Dilution of Precision (DOP), 3D satellite position standard deviation (* broadcast and ° WAAS corrected broadcast), and r.m.s. position error for horizontal and vertical positioning, respectively

On day 330, there is a spike in the vertical error component. Figure 5 shows there is also a spike in the standard deviation of the WAAS orbit error. This indicates that a portion of the vertical position error may be related to the WAAS orbit error. There are some spikes on other days. They may be caused by satellites which were not monitored by WAAS.

We also examined the effect of the ionosphere on the user positioning accuracy. Figure 6 shows the correlation between UIVE and vertical errors. The left panel shows the typical behaviour of vertical errors with UIVEs on 1 December 2001 (day 335). As we expected, the UIVE values are larger during daytime and relatively stable at nighttime. On 3 December 2001 (day 337) we can see a spike in the vertical position error component between 21:40 and 21:55 UTC. The absolute vertical errors during this period were larger than 10 metres. This was due to ionospheric effects. Both GIVE and UIVE values have increased. The peak UIVE value during this time period was 13.63 metres. The UIVE represents the weighted user ionospheric vertical errors at the IPPs from the surrounding three or four IGPs. This means at least one of the IGPs had a large GIVE value at this time within the 5 minute update rate. In the case of the other spike in UIVE plot (right panel), we couldn't find any correlation with vertical position results. We need more analysis to explain this spike.

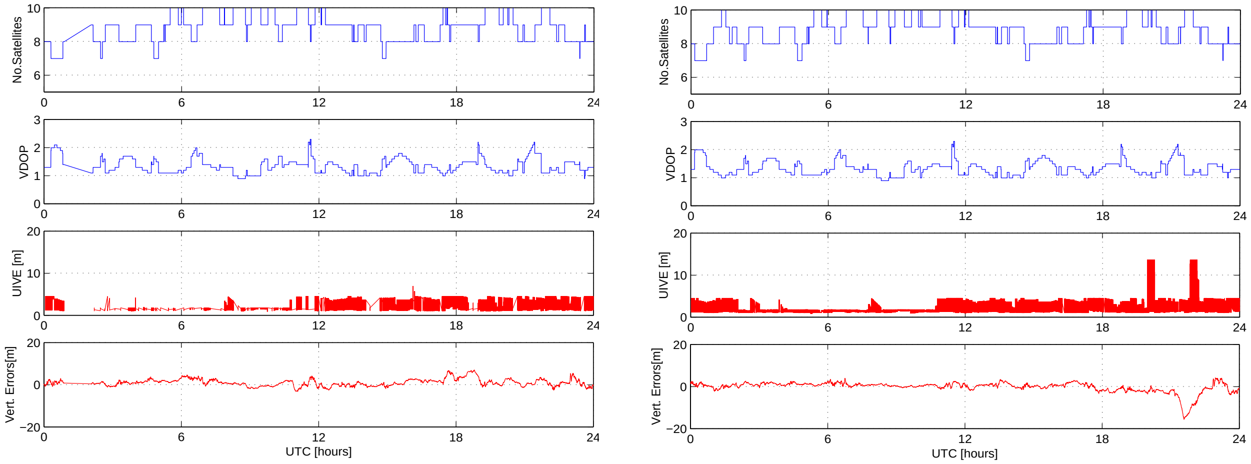

Figure 6. The correlation between the vertical error and UIVE at UNB (1 Dec. 2001 (left), 3 Dec. 2001 (right))

Assessment of the Ionospheric Grid Model

The significant geomagnetic disturbances (6 and 24 November 2001) occurred with a peak 3-hour Kp value larger than 8 and Dst value smaller than –200nT (see Figure 2). Figure 7 shows the ionospheric vertical delays at East Port (EPRT) for both a quiet day (day 307) and a storm day (day 310). For the assessment of the WAAS ionospheric grid model, we generated ionospheric vertical delays at EPRT using the dual-frequency GPS data. We used this as a "truth" for the comparison. The UNB ionospheric modelling technique [Komjathy and Langley, 1996; Komjathy, 1997], which applies a spatial linear approximation of the vertical TEC above a station using stochastic parameters in a Kalman filter estimation, has been used. To compensate for the satellite and receiver inter-frequency instrumental biases, we use the estimated values provided by JPL. The standard geometric mapping function, which is a function of satellite elevation angle at the reference station was used in our work. The local horizontal electron density gradients and the azimuthal delay variation [Conker, 1998] were not considered. For the direct comparison between WAAS ionospheric vertical delays and the "truth" values, the WAAS MOPS specified ionospheric shell height of 350 km was used. We used TEQC (the University NAVSTAR Consortium's Translate/Edit/Quality Check) software for quality checking of the data from East Port. Based on the TEQC results, we chose a data set which represented a quiet day, 3 November 2001, and another data set for the storm condition day, 6 November 2001. We compared the maximum and minimum ionospheric vertical delay values with time. In general, the peak values of ionospheric delay occur around 2 pm local standard time (UTC-4hrs in our region). We compared ionospheric vertical delays, which were calculated using surrounding WAAS IGPs, and those calculated using the GPS data. Table 3 shows the values we compared.

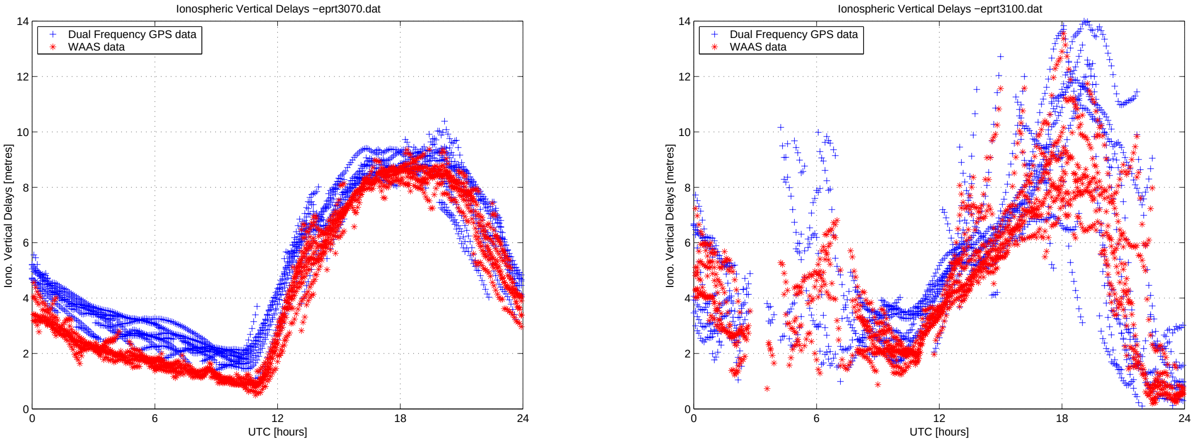

Figure 7. Ionospheric vertical delays at EPRT (quiet and storm conditions, dual frequency data (blue+) and WAAS(red *))

Figure 7 shows the ionospheric vertical delays for both geomagnetically quiet and stormy conditions. The ionospheric vertical delays of the WAAS ionospheric grid model generally are in good agreement with ionospheric vertical delays computed from dual-frequency GPS data on our quiet and storm days. The overall WAAS ionospheric vertical delays were slightly depressed compared to the dual-frequency results. The difference between the maximum values was around 1 metre during quiet geomagnetic conditions. For the geomagnetic storm condition, the ionospheric vertical delays were characterized by an enhanced delay in both WAAS and dual-frequency results. The maximum value difference was approximately 50 cm, but during the severe geomagnetic storm time, 04h – 08h UTC (see Figure 2), the predicted WAAS ionospheric vertical delays were different from the dual-frequency ionospheric vertical delays by up to 4 metres. The important thing is that the GIVE should bound this difference. The overall GIVE values during this severe storm time varied around 5 metres to 10 metres in the east side of the current WAAS coverage area in which the calculated IPPs are located. As long as the GIVE values are bounded for this ionospheric vertical delay difference caused by the geomagnetic storm effect, there is no integrity problem for the user. However, since this storm occurred before the new GIVE monitoring algorithm was initiated, we could not see the exact GIVE values for the specific satellites and time which caused enhanced ionospheric delays by geomagnetic storm effects, as there was only about 10% availability of UIVE values. During the storm time, which was early morning, there were significant fluctuations of ionospheric vertical delay. However, the most significant effect of this storm on the entire day was the large temporal gradients in the ionospheric vertical delays. As we discussed before (see Figure 5), this reduced the accuracy of user positioning results, because the accuracy of range delay corrections was reduced for WAAS.

	WAAS			GPS dual-frequency data		
03/11/2001	Local Time (2 pm)	Max.	Min.	Local Time (2 pm)	Max.	Min.
Iono. Vertical Delays (m)	8.746	9.369	0.492	9.290	10.386	1.101
UTC (hours, minutes)		19h 25m	10h 55m		20h 10m	11h
06/11/2001						
Iono. Vertical Delays (m)	12.905	13.550	0.196	13.625	13.998	0.026
UTC (hours, minutes)		18h 08m	10h 55m		19h 5m	23h 19m

Table 3. Comparison the ionospheric vertical delays between WAAS and GPS dual-frequency data

Conclusions

The distance between WRSs and IGPs is a critical issue, since the basic concept of WAAS error correction is based on a spatial and temporal correlation of errors between WRSs and users for each error component. We analysed the availability of GIVEs and found it has significantly improved with the new GIVE monitoring algorithm. Now it is possible to have UIVEs available almost 80% of the time at Fredericton, New Brunswick. But the GIVE values on the periphery of the current WAAS coverage area are significantly larger than those in the central U.S. The increased number of monitored IGPs allows for ionospheric correction for more satellites. This results in an improvement of positioning accuracy. We analysed the correlation between the user positioning accuracy and WAAS orbit correction errors as well as ionospheric behaviour. The positioning accuracy with the WAAS correction messages has improved about 30 cm r.m.s. in horizontal and 60 cm r.m.s. in the vertical. We compared the WAAS ionospheric vertical delays and the ionospheric vertical delay computed from GPS dual-frequency data at East Port, Maine. The difference between WAAS and dual frequency ionospheric vertical delays were presented; however, the severe storm occurred before the new GIVE monitoring algorithm was initiated. The lack of GIVE values has made it difficult to assess the WAAS ionospheric grid model. Examination of the current WAAS performance at the periphery of the coverage area may be helpful in determining optimal reference station locations for extending WAAS coverage into Canada.

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