Wide Area Ionospheric Delay Corrections Under Ionospheric Storm Conditions

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Biographies

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Brian Wilson, a member of the GPS Networks and Ionospheric Systems Development Group at JPL, has been studying the ionosphere using GPS for six years and is a co-developer of the GPS-based global ionospheric mapping (GIM) technique. His current work is focused on improving and validating GIM, global ionospheric calibration of single-frequency ocean altimetry missions, real-time global WADGPS, and other remote sensing applications of GPS. He received a M.S. in physics from Caltech in 1982.

Dr. Stephen Peck is a Senior Scientist for Hughes Aircraft Co. He is responsible for the algorithm development and validation for the WAAS reference stations and WAAS master stations. He has 10 years of experience with Hughes Aircraft in the navigation field and two years experience at JPL in the GPS network operations.

Dr. Reza Ahmadi is a member of technical staff for Hughes Space and Communications Co. He is responsible for the validation of the WAAS GIVE and UIVE algorithms. He has two years of experience at Hughes working on navigation and communication satellite payloads. His academic research at UCLA was in the areas of plasma physics and statistical mechanics.

Mine Z. Hagen is the WAAS Ionospheric Corrections Software technical lead in the Command and Control Systems organization of Hughes Information Systems in Fullerton, CA. She has 13 years of experience in software intensive programs as a software and systems engineer. Currently her responsibilities are leading a team of software and systems engineers for the design, development, test and integration of the WAAS Ionospheric software. She holds a MS in Applied Mathematics and a B.S. in Mathematics and Computer Science.

Abstract

The Federal Aviation Administration's wide-area augmentation system (WAAS) for GPS positioning requires near real-time calibration of ionospheric vertical delays at a set of Earth-fixed grid points. These delays, which can exceed 15 meters under solar maximum conditions, are transmitted to users every 5 minutes to improve single-frequency user positioning. The grid delays will be estimated using the WAAS Ionospheric Software (WIS) developed jointly by JPL and Hughes, based on ionospheric delay measurements from 24 dual-frequency GPS reference receivers distributed throughout the WAAS coverage volume, The design of the WIS algorithms are briefly described We also review recent tests of the algorithms for determining, in real-time, the error in the grid delays (so-called Grid Ionosphere Vertical Error or GIVE).

Testing of ionospheric **correction algorithms is** complicated by the extreme variability of the ionosphere, arising from the 11 year solar cycle and the intermittent occurrence of ionospheric storms. Recently completed tests of the WIS using data from a real-time network of eight reference receivers in the continental United Stated indicate accuracies in the range of 15-20 cm (RMS). However, these tests were conducted using current GPS data sets (9/96) and were therefore characteristic of near solar minimum conditions,

We present the results of additional tests under more challenging conditions nearer to solar maximum, focusing on geomagnetically disturbed periods, using archived GPS data (processed in a real-time mode) obtained from a global network of dual-frequency receivers. The intent is to characterize the accuracy of WIS under a wide variety of geomagnetic and solar activity conditions. In the storm cases examined here, the maximum accuracy degradation was at most a factor of 2-3 relative to recent quiet time tests. These results suggest that accuracy requirements for precision approach may still be met for significant storms.

Ionospheric Calibrations for WAAS

The Federal Aviation Administration is developing the wide area augmentation system (WAAS) to support real-time GPS positioning for en-route and precision approach aircraft navigation, Vertical positioning accuracies of 7.6 m (2-sigma) arc required to meet (he system goals for single-frequency GPS users [estimated in El-Arini et al., 1994]. The GPS signal delays caused by the ionosphere, potentially the largest contributor to user positioning error, can exceed tens of meters during solar maximum conditions. Calibration relics on a ground network of -24 WAAS reference stations located in the continental United States (CONUS), Alaska, Hawaii and Puerto Rico, that continuously monitors the ionospheric delay over the service region, so that corrections based on real-time data can be broadcast to users.

Previous studies using the WAAS ionospheric software (WIS) have demonstrated 15-20 cm RMS accuracies in the vertical delay map [Yunck et al., 1996; Wilson et al., 1997]. The purpose of this paper is to assess how the accuracy of the ionospheric calibrations is affected by ionospheric storm conditions. These arc disturbances caused by changes in the upper atmosphere, fundamentally triggered by increases in the density or energy of particles in the solar wind, that can last for several hours to several days, with significant disturbances occurring on average about once or twice pcr month. Steeper spatial gradients and rapid variations in zenith delay can reduce the accuracy of the ionospheric calibrations inferred at **the user's position.** Archived GPS data obtained during storm and quiet conditions, and processed in a real-time mode similar to that proposed for the WAAS, has been used to study the effect of storms on the accuracy of zenith delay estimates over the coverage area.

The next section of this paper provides an overview of the ionospheric correction system being implemented for WAAS. We then describe a set of tests performed using data obtained during disturbed times that can be used to infer correction accuracy. A discussion of the grid ionosphere vertical error computation (GIVE) follows. Finally, wc discuss what these initial results suggest, and the need for additional testing to further characterize performance.

System Overview

The WAAS ionospheric correction system is summarized in Figure 1 (sw also the WAAS Minimal Operational Performance Standards [RTCA MOPS, 1996], and Bertiger et al., 1997). Dual-frequency WAAS reference stations (WRS) record data at a one second rate, which is then sent to the WAAS master stations for processing by the correction and verification software (C&V). The C&V software extracts the ionospheric delay observable from the high-rate data, which arc then compressed to a 5 minute rate for computing a map of zenith delays over the service area. The delays at the pre-defined WAAS ionospheric grid points (IGP) arc broadcast to the users. The user then computes the slant-range ionospheric corrections in the direction of each GPS satellite. To maintain system integrity, an estimate of the grid error is also computed, using high-rate data (5 seconds). This grid ionosphere vertical error (GIVE) must be less than about 3 meters to support precision approach, Larger errors are more likely to occur during particularly severe ionospheric storms conditions (see Conker et al., 1995).

Accuracy Requirements

The accuracy of the IGP vertical delays during storms will be described in this paper. Overall, the requirements flow down from the precision approach requirement of 19.2 meter or less vertical error available 99.9% of the time. Based on conservative error estimates for all components of the correction system, calculations performed at Hughes Electronics (internal documents) imply that the requirement can be met if the IGP delay errors are less than 197 cm with the same 99.9% availability. Assuming the IGP errors arc normally distributed with zero mean, this would imply a l-sigma IGP delay error of 60 cm.

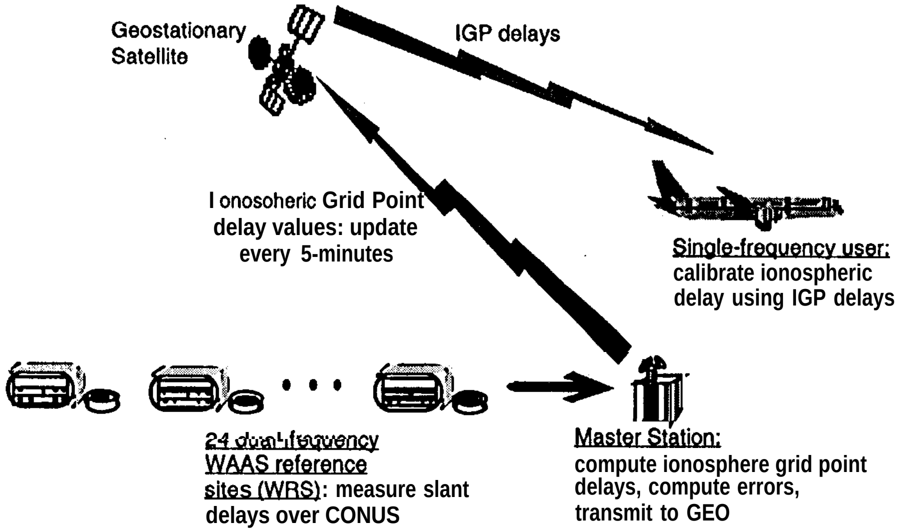

Figure 1. Ionospheric corrections for the WAAS

Algorithm Overview

The slant delays measured by the WRS sample regions of the ionosphere distinct from the IGP locations, so the fundamental tasks of the ionospheric correction algorithm are estimation of vertical delays from slant delays, and mapping of vertical delays to the IGP locations. The approach is based on forming a continuous vertical delay map over the service area, which includes as a subset the delay values at the IGP locations [Mannucci, et al., 1995]. The standard WAAS obliquity factor is used to estimate vertical delay from slant measurements (see [RTCA MOPS, 1996]). A Kalman filter implementation smoothly updates the maps in time.

A continuous delay map is formed over a spherical "ionospheric shell" that covers the service area at a fixed height of about 400 km above the Earth's surface, Each WRS measurement (6-8 satellites are generally in view of each receiver) pierces the shell at a unique "ionospheric pierce point", that, after scaling to vertical, effectively samples the zenith ionospheric delay at a discrete set of points. Mapping the sampled estimates over the entire shell is performed with high accuracy by fitting to bi-linear spline functions defined over a sphere. These functions mathematically represent a set of inter-connected "rigid plates" that tilt to follow large delay gradients and abrupt changes in gradient measured by the WRS. The one-dimensional analogy to this approach is illustrated in Figure 2, where irregularly spaced data are fit with linear segments tied together at fixed "knot" locations (for the spherical ionospheric shell, the knot locations form a triangular grid tessellating a sphere, with roughly 800 km between the knots). Accurate interpolation/extrapolation is maintained in areas of large slope without compromising accuracy in other locations, even when the ionosphere deviates from "smooth" behavior such as during storms. In contrast, polynomial-based fitting techniques (such as spherical harmonics) are subject to

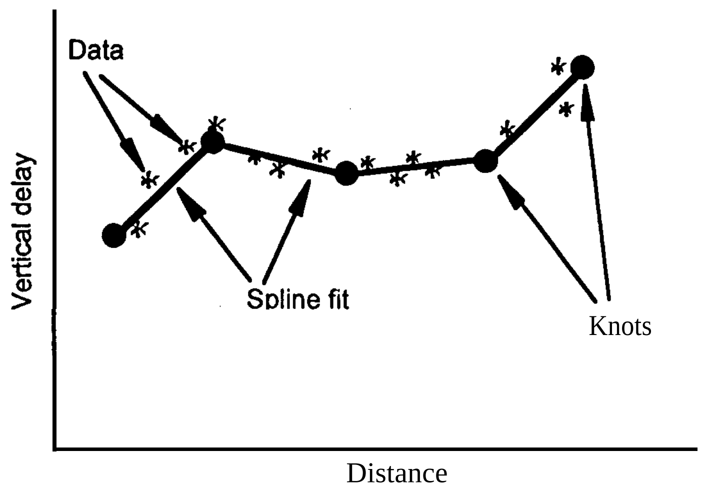

Figure 2. Schematic view of a one-dimensional spline fit irregularly spaced data,

"overshoot" or "undershoot" when large gradients appear in one area, reducing accuracy is neighboring regions.

Inter-frequency Bias Estimation

It is well known that ionospheric measurements derived from GPS range observable are corrupted by inter-frequency biases present in the receiver and transmitter hardware (Wilson et al., 1994; Sardon et al., 1994). These biases can be estimated simultaneously with the vertical delay because the delay parameters and inter-frequency bias parameters have distinct time and elevation angle signatures. As an example, over a full satellite arc that rises at 10 degrees elevation and transits near 90 degrees elevation, the obliquity factor alone predicts that the delay should change by roughly a factor of 2.5 assuming a nearly constant zenith delay. The fitting procedure adjusts the sum of the receiver and satellite bias estimates to produce the highest degree of consistency between the observed delay change and the factor of 2,5 that is predicted by the obliquity factor.

Calibration Accuracy During Ionospheric Storms: Case Studies

We have used archived GPS data to assess the accuracy of the WAAS ionospheric software (WIS) during ionospheric storm conditions. Such data are available from the GPS global network (Zumberge et al., 1994; IGS Web Page) that has been operating continuously since 1992. For most of that time, data sampled at a 30-seeond rate has been downloaded daily from the network and archived at several analysis centers, including NASA's Jet Propulsion Laboratory. We have used data from relatively dense sub-networks in the continental US (CONUS) and Europe to generate ionospheric correction maps under the conditions of dense coverage that will be true for the WAAS network. Figure 3 shows the configuration of test and reference sites, as well as the proposed locations of the WAAS reference stations,

The tests were accomplished by dividing available receivers into two groups, Data from a "reference" group, which mimics the role played by the WAAS reference stations, was used to form the correction map; a second group of test receivers was used to assess the accuracy of the calibrations. We compared estimates of vertical delay obtained from the test data, with the vertical delay predictions available from the maps. Statistics on the differences, including a comparison between neighboring storm and quiet times, are presented below.

Vertical delay was estimated by scaling each test measurement using the standard WAAS obliquity factor with a shell height of 400 km. Errors in the scaling were minimized by selecting only those measurements above 50 degrees elevation angle. The comparison was performed at the pierce point of each test measurement, of which at any time there were generally 1-3 above the 50-degree elevation cutoff. Since the test delays contain some contribution of error from the imperfect elevation scaling, the results presented are probably overestimates of the correction map vertical error.

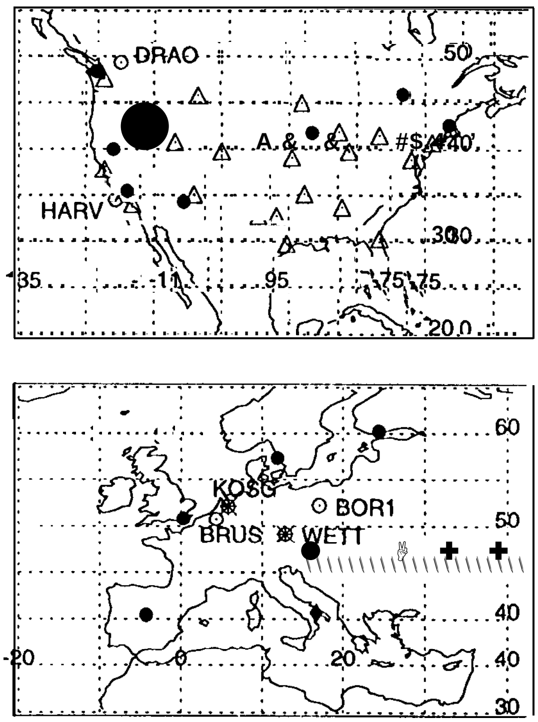

Figure 3. Locations of the test and reference receivers.
Legend:

● Reference site in Nov. 1994 (Europe), April 1994 (Europe) and March 1993 (US)

◆ Additional reference site in April 1994

△ WAAS reference station

○ Test sites in Nov. 1994 (Europe) and March 1993 (US)

✻ Test sites in Nov. 1994 and April 1994

Of course, the ionospheric pierce points of the test data are not coincident with the WAAS IGP locations. we are assuming that no special status is accorded to the IGP locations and that the accuracy of the correction maps at the test data locations is similar to the accuracy at IGP locations, given similar distances to the nearest reference site. The distance between the ionospheric pierce points of a test and reference receiver, tracking the same satellite, is **nearly** equal to the distance between the respective receivers (within a few percent).

The reference data were processed **in a real-time** mode by the WIS generating the correction maps every 15 minutes from the ionospheric observable compressed to a 5-minute rate. The maps were initialized with data from the last 4-hours of the previous day (day boundaries defined at

Date	March 6, 1993	March 9, 1993
3-hour Kp	1+1 -203-20203020	7-7-6+6-5-4+3+5-
Ap	8	64
Flux	164.00	140.60
Date	April 1, 1994	April 3, 1994
3-hour Kp	0+2o2o1+2+2+2o2-	6-6+7-606-5+7-7+
Ap	6	92
Flux	82.4	77.40
Date	Nov. 25, 1994	Nov. 26, 1994
3-hour Kp	1-1+0+0+1-0+1o1o	103-5 -6+6o4+3+2
Ap	3	36
Flux	79.40	81.00

Table 1. Geophysical parameters for the quiet and disturbed days, Kp and Ap are indices of geomagnetic disturbance based on readings from a worldwide set of geomagnetic observatories. Ap is a daily index —values approaching 100 are rare, perhaps occurring 1-2 year. Kp is recorded every 3 hours and quantized in "thirds" (+,0,-). Kp of 80 is reached during very intense storms; **eight such 3-hour periods occur per year, on average.** Flux is a measure of solar irradiance at a standard radio wavelength (10.7 cm).

Universal Time = O). The test data were also compressed to a 5-minute rate, and the ionospheric delay observable formed in a high-accuracy post-processing mode using all available data. Inter-frequency bias estimates from a global ionospheric solution involving all the test and reference receivers simultaneously were used to calibrate both data sets,

Case Study 1: Large positive ionospheric storm on November 26, 1994.

A large positive delay enhancement over Europe occurred on November 26, 1994, during a moderate geomagnetic disturbance (see Table 1 for geomagnetic indices; see Chavin, 1996 and 1996a for definitions of storm severity). The effect occurred during the early afternoon in Europe, when the diurnal ionospheric delay reaches a maximum.

The vertical delay estimates at the high-elevation pierce points of test site BOR 1 are shown in Fig. 4 for the storm day and the quiet day preceding it, The peak delay values are doubled on the disturbed day, even though the solar flux values are nearly the same; hence, we can infer that the delay enhancement is primarily a result of the storm.

The difference between the measured vertical delay and the WIS correction map is shown in Figure 5 as a scatter plot for the quiet and disturbed days, using data from all the available test sites in Europe (see Figure 3). The striking feature of these plots is that there is no significant

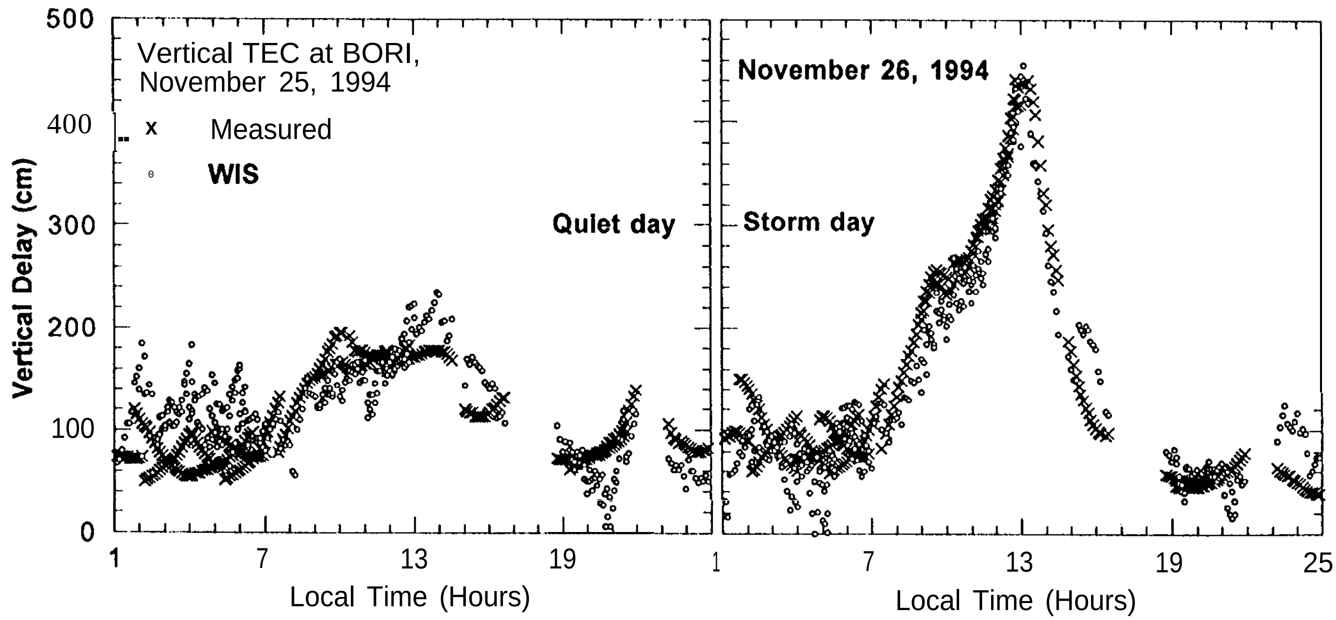

Figure 4. Vertical ionospheric delay measurements for the site BOR1, and computed vertical delay, for the November 26, 1994 storm and the preceding quiet day, difference between the storm and quiet days in terms of RMS or mean difference, even though the delay reaches significantly higher values on the storm day. In any case, the RMS difference for all the sites is well within the desired goal of 60 cm.

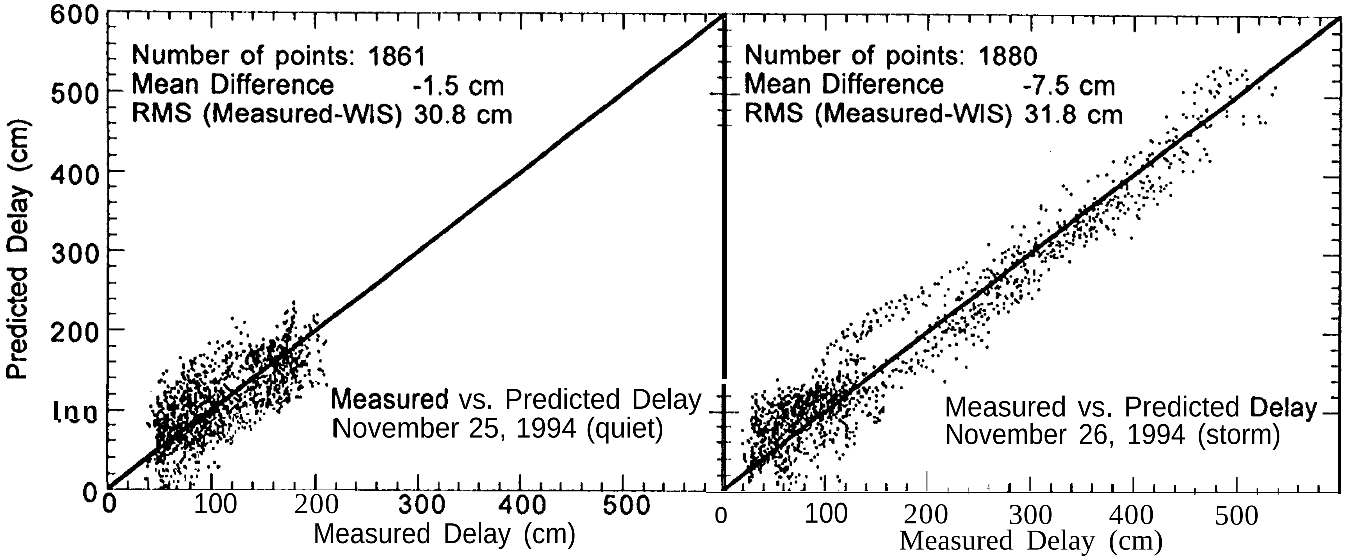

Figure 5. Scatter plots of measured vertical delay versus computed delay at the measurement pierce points, for the quiet and storm days in November, 1994.

We have also analyzed the probability distribution of residual values, which might not be gaussian. The desired accuracy goal of *60* cm RMS error assumes a zero-mean gaussian distribution for the residuals. and is actually derived from the more precise goal that 99.9% of the residuals fall within ±197 cm; an approximate derived requirement is that 99% of the residuals fall within ±156 cm. (For normal distributions, 99.9% of the errors fall within ±3.29σ; 99% of the residuals fall within ±2.6σ, and 156 = (2,6/3 .29) '197). Figure 6 shows a plot of error bounds for the site (BOR1) representing the worst ease 99% single-sided error bound, defined as follows: 99% percent of the residuals computed over a day fall within plus or minus the error bound. The other error bounds are defined similarly. Again, comparing the storm and quiet times shows a very modest increase in errors, indicating that the vertical error maps arc capable of maintaining the required accuracy through the disturbance. The error bounds and RMS statistics are all well within the accuracy requirements (the minimum and maximum errors for the storm day, also shown in Figure 6, can be compared to the 99.9% requirement).

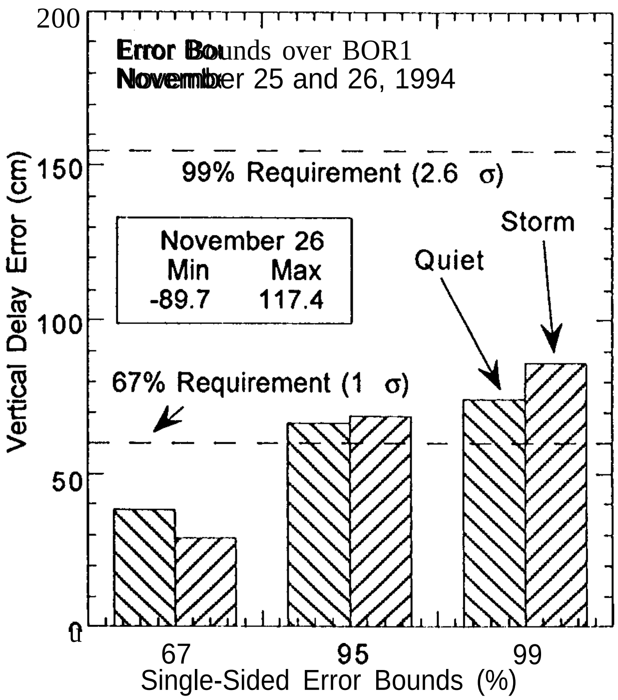

Figure 6. Bounds for the residuals, at the BOR1 site, which had the largest 99% error bound for the November 26, 1994 storm. Maximum and minimum residuals for this site are also shown,

Case Study 2: Geomagnetic storm coincident with high solar flux: March 9, 1993.

The factor-of-two increase in storm-time ionospheric delay demonstrated in the previous example nevertheless occurred during near solar minimum conditions. We have also studied a significant storm when the solar flux (F10.7) was measured to be 140.6, nearer to typical solar maximum values of ≈200. Correspondingly higher vertical ionospheric delays are shown at the Harvest site in Figure 7, for the nearest quiet day (March 6, 1993) preceding the storm day (March 9, 1993). At the two US test sites (see Figure 3), this storm is characterized by a significantly enhanced delay early on, followed by a depletion late in the day. The storm effects in Europe were not significant and are therefore not analyzed here.

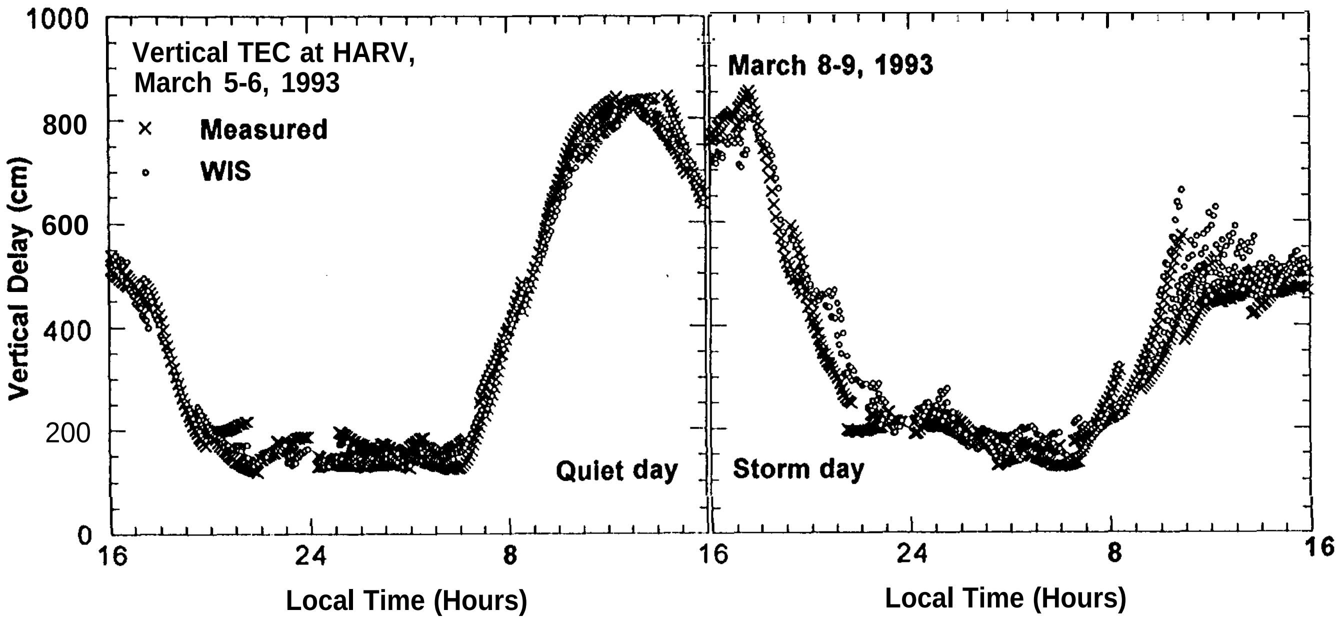

Figure 7. Vertical ionospheric delay measurements at the test site HARV, and computed vertical delay, for the March 8-9, 1993 storm and the closest preceding quiet day.

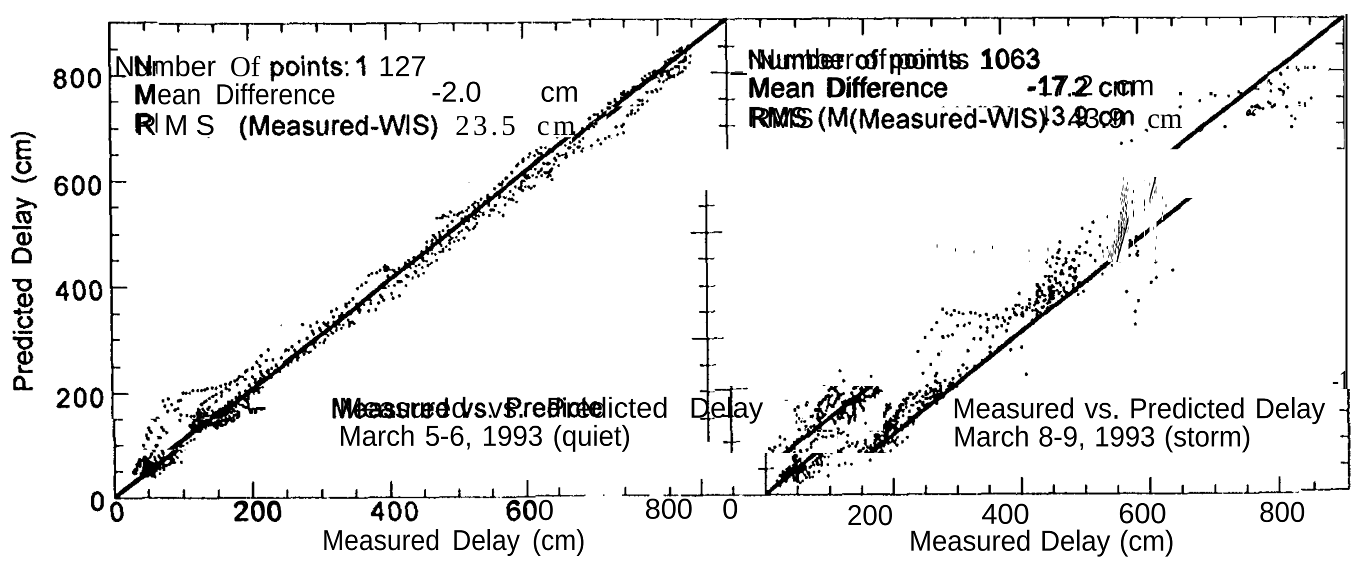

Figure 8. Scatter plot of measured versus computed delay for all test pierce points on March 6, 1993 (quiet day) and the storm day March 9, 1993.

From the scatter plot (Fig. 8) it appears that the calibration error does not increase with increased delay, although the predicted delay is biased above the measurements during the storm day. The largest errors occur during times of intermediate delay values, which is not necessarily unexpected, since the storm event appears to have reduced the ionospheric total electron content (TEC) (see Figure 7, 0900-1500 local time) while at the same time increasing the "roughness" in the TEC distribution, Errors increase because smaller scale TEC structures appearing during disturbances might be smoothed over in the correction maps; additional errors can be introduced in scaling to vertical for both the test and reference data.

The cumulative probability comparison (storm vs. quiet) is shown in Figure 9 for the storm-day site (DRAO) with the largest 99% error bound, The 1-sigma and 67% error bounds are still within the 60 cm limit, however, the extended "tails" in the error distribution cause relatively large 99% error bounds, which grow significantly during the storm, but still satisfy the WAAS requirement of 156 cm.

Since the maximum storm effect may be concentrated over a few-hour interval, it is probable that the 99% error bounds are larger for those few hours, and may temporarily exceed the 156 cm requirement. However, it is encouraging that the maximum absolute residual, which is independent of the interval under consideration, is only slightly larger than the 99.9% error bound of 197 cm, indicating the errors are reasonably bounded throughout the disturbance.

Case Study 3: Large geomagnetic storm on April 3, 1994

The final storm case involves a severe geomagnetic disturbance, during which a peak 3-hour Kp value of 7+ occurred, on April 3, 1994 (according to Chavin, 1996, such high Kp values occur approximately only 0.7% of the time). This case illustrates that geophysical conditions leading to significant geomagnetic disturbances do not necessarily cause large enhancements or depletions in TEC. The TEC over the WETT test site is shown in Figure 10 for the storm day and a preceding quiet day. The absolute or fractional changes in TEC are not as pronounced as in the November 1994 storm, although the geomagnetic disturbance is significantly greater (Ap index of 92 versus 36).

The most significant effect of this storm appears to be larger TEC gradients: note the differences bet ween simultaneous satellite measurements. A significant "spreading" effect is seen on the storm day, duc to differences in vertical TEC at separated ionospheric pierce

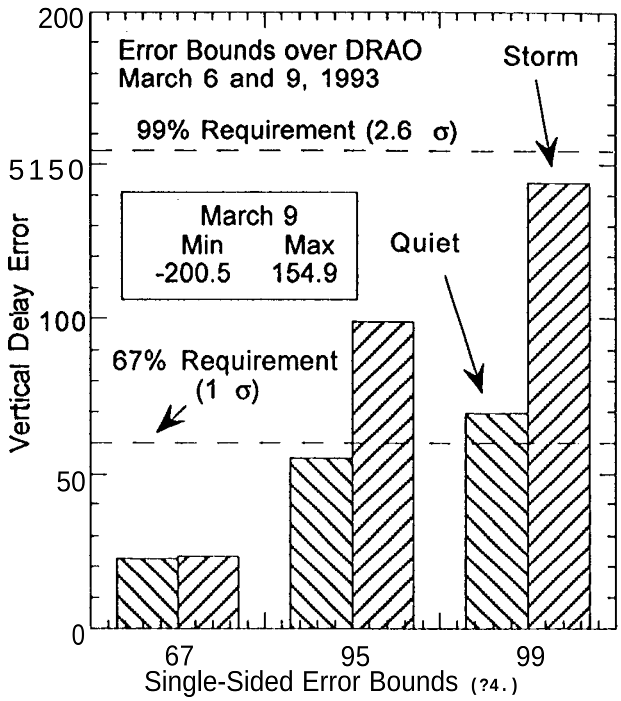

Figure 9. Bounds for the residuals, at the DRAO site, which had the largest 99% error bound for the March 9, 1993 storm. Maximum and minimum residuals also shown for the storm day.

point locations. For example, vertical TEC estimates taken at 1900 local time between satellites 17 and 22 differ by 63 cm (Figure 10). The distance between the ionospheric pierce points for these satellites is 400 km, implying a delay gradient of 15 cm/100 km, compared to a gradient of at most 4 cm/ 100 km at the same time on the quiet day.

The larger gradients after 1700 local time appear to coincide with reduced accuracy of the calibrations. However, it also happened that the two reference sites due south of WETT (see figure 3) had intermittent tracking performance. For example, the GRAZ site (directly below WETT) only tracked 3 GPS satellites near the end of the storm day, as opposed to 6 on the quiet day. The cause of this degraded performance is currently under investigation.

Computing the Grid Ionosphere Vertical Error

The ionosphere delay estimation accuracy has a direct impact on the user's experienced accuracy which generally will degrade cluing ionospheric storms. The WAAS also

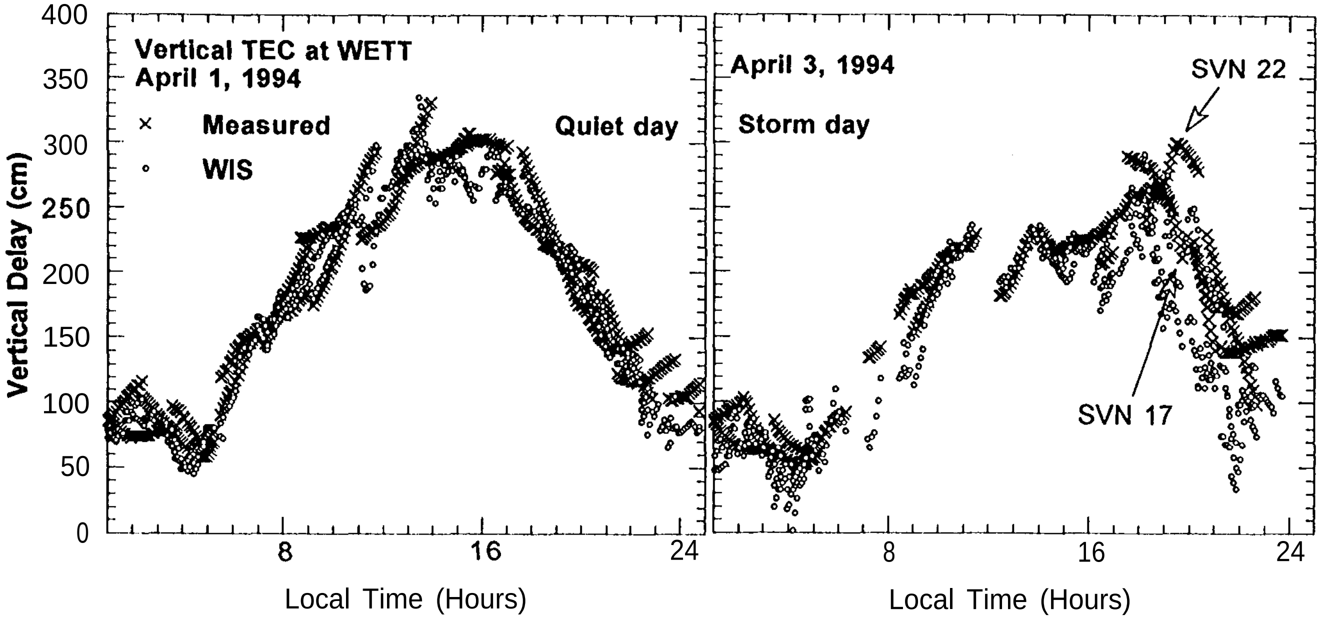

Figure 10. Vertical TEC measurements for the WETT test site, and computed vertical delays, for April 3, 1994, and a neighboring quiet day. Poor tracking of the GRAZ and MATE reference sites (both due South of the WETT reference site) may have contributed to larger errors near the end of the day.

broadcasts a GIVE value (grid ionospheric vertical error) from which the user calculates his ionospheric delay error bound, The GIVE then has a direct impact on the user's availability of precision approach. The WIS and GIVE algorithms have a significant interaction, and will be analyzed as an integrated set. In this work, wc present some analysis using the baseline GIVE algorithm and simulated data at solar maximum. It is expected that the ionospheric shell model inaccuracies are largest during solar maximum conditions. Results show the conservative nature of the baseline algorithm, and its sensitivity to measurement errors, especially multipath. This simulated data, along with real data, including the historical storm data, will eventually be used to further validate the GIVE and refine its design.

As a part of its 'slow' error corrections WAAS provides ionospheric delay model and sufficient real-time data to evaluate the ionospheric delays for each satellite using that model [1]. More specifically WAAS message type 26 shall provide vertical delays and their accuracies, Grid Ionospheric Vertical Errors (GIVES) at geographically defined Ionospheric Grid Points (IGPs). GIVE values are required to bound the actual error with 99.9% confidence. There arc 929 pre-defined IGPs for a given GEO footprint. These 929 IGPs arc divided into 5 bands, Message types 18-22 specify which band and, which IGPs (out of 190 possible) arc being transmitted in the type 26 message, Using the GIVE values the user then computes the User Ionospheric Vertical Errors (UIVEs) at each of his pierce point locations. UIVE is required to bound the user's ionospheric vertical error at his pierce point with 99.9% confidence. Performance analysis indicates that the GIVE should be less than 3 meters with a goal of 1.5 to 2 meters to support precision approach accuracy, This section addresses the performance and required confidence bounding of the GIVE algorithm using simulated ionospheric data. Our simulation results show that even during the period of high solar activity (simulated by using a large sun-spot-number in the FAIM model) the baseline GIVE algorithm is quite conservative, but may not meet performance goals if the actual multipath effects are as large as the conservative model used in this analysis.

Overview of GIVE Simulation

The GIVE algorithm used is the baseline algorithms of Mitre Co. with few exceptions [2]: Adding quantization error and absolute grid bias error to the GIVE values. The quantization error is just a constant and does not include any statistics. As we show in the next section the absolute grid bias error, is not significant either and makes the already conservative GIVE values more conservative. The ionosphere is simulated by FAIM model [Anderson et al., 1989]. The site locations usc the 24 WAAS phase 1 sites (Figure 1). The orbits of the GPS satellites are simulated using the 7 parameter almanac data [NAVSTAR GPS ICD-GPS-200, 1991]. Estimation of ionospheric vertical delays on the Ionospheric Grid Points (IGPs) is simulated by adding estimation error to the 'true' L1 frequency vertical delays (obtained by integrating the electron density produced by the FAIM model along the surface normal), Estimation error is assumed to be a first order Markov process characterized by a standard deviation (σ) of 0.3 meters and correlation time (τ) of 15 minutes. Measurement of slant delay between a satellite and receiver pair is simulated by adding measurement error to the 'true' slant L 1 frequency delay (obtained by integrating the electron density produced by the FAIM model along the Line of Sight (LOS) from receiver to tbc satellite). Measurement error is added to the computed slant delays of all the satellite receiver pairs (If the elevation angle of a satellite is less than 5 degrees that measurement is not used). The main contributors to the measurement error are: (1) The receiver error. (2) The L1 -L2 inter-frequency bias error. (3) Multipath error. Similar to estimation error, these errors are assumed to bc first order Markov processes characterized by the following σ's and τ's:

Table 1: Simulated Measurement Errors

Error Type	σ (meters)	τ (seconds)
Receiver Error	0.1	30
L1-L2 inter-frequency bias	0.1	3600
Multipath	1.0	300

GIVE values are then computed by comparing the measured slant delays to the computed delay (obtained by interpolating from the IGP delay estimates). The GIVE values arc computed on an imaginary grid located 350 km above the earth and covering North America : 10-55 degrees latitude and 225-315 East longitude. At every time step (every time step in the simulation is 5 seconds) simulated measurements of slant delays for all the satellite and receiver pairs are differenced from the grid estimated delay (which is obtained by using the MOPS interpolation algorithm from the surrounding vertical grid point delay estimates).

GIVE Simulation Results

Simulations were run for a period of 24 hours (the computational time -step was 5 seconds). Every 60 time-steps or 5 minutes the GIVE values were computed for the 190 grid points. In the next 60 time-steps the IGP estimation errors were compared to the GIVES so that by the end of the simulation run the statistics on what percentage of time the GIVES failed to bound the IGP estimation errors could be obtained. To determine how "conservative" the GIVE value is, fractions of the GIVE (1 O%, 20%, etc.) were also used to determine when these fractions of the GIVE failed to bound the estimation error. Wc find that for the case where the absolute grid bias error was not added to the GIVE values, 50% of GIVE bounds the IGP vertical delay error. When the absolute grid bias error is added 40% of GIVE bounds the IGP error. In order to see the effect of measurement errors on the GIVE performance we made runs where multipath error, receiver error and L] -L2 inter-frequency bias errors were zeroed out one by one. For example when the dominant error source (multipath) is zeroed out 80% of GIVE will bound the error. Table 2. shows the GIVE values averaged over time (24 hours) and all the grid points. When all the error sources are included in the simulation the GIVE values are between 4.5 to 7 meters with baseline Mitre algorithm and reduce to 4 to 6.5 meters without the grid bias. Also, when multipath is removed, the GIVE values were generally less than 3 meters

Table 2: Average GIVE vs run (with and without grid bias, individual error sources removed)

Error Type Removed	Average GIVE (meters) including grid-bias error.	Average GIVE (meters) no grid-bias error added
No Error source removed	5.78	5.32
Receiver Error	5.75	5.29
L1 -L2 inter-frequency bias	5.77	5.31
Multipath	2.63	2.38

Conclusions

Ionospheric storms are episodic events that can severely disrupt the normal or "quiet time" behavior of the ionosphere. These disturbances can cause degraded accuracy of the vertical ionosphere correction maps and increase the error of the grid point delays broadcast to users. The cases presented in this paper indicate that, with a well-designed correction algorithm, required accuracy goals can still be met during significantly disturbed conditions,

Ionospheric changes during storms are multi-faceted: TEC may increase, decrease or stay roughly the same but with more fluctuation and less smoothness. An important property of the WAAS algorithm is that storm-induced TEC increases, even by factors of 2-3, do not necessarily increase the errors of the IGP delay estimates. This suggests that not all "severe" storms will have an adverse effect on performance. More storm cases must be analyzed to better quantify what fraction of storms cause significant degradation,

Data that predates the advent of large GPS networks, obtained during past ionospheric storms strongly suggests there will be occasional periods when IGP accuracy goals cannot bc met (see Chavin, 1996a for examples). In these cases, the overall system will still function properly if the grid ionosphere vertical error (GIVE) correctly reflects the degraded accuracy. The GIVE can be broadcast to users rapidly and will signal when the precision approach capability is no longer available. Testing of the GIVE and IGP correction algorithms is currently underway using carefully constructed storm simulations provided by Illgen Simulation Technology.

It should bc emphasized that this paper deals with estimates of vertical delay accuracy over the fixed WAAS IGP grid. The final user ionospheric corrections in the directions to the GPS satellites will contain additional errors from mapping the IGP delay (o the user's position (so-called (JIVE), and reconstructing slant delay from vertical. Analysis of these additional contributions during storm conditions will be presented in future papers.

The baseline GIVE algorithm based on the Mitre GIVE appears to bc quite conservative. Sensitivity analysis shows that receiver multipath is the primary performance limitation. This analysis is being repeated with real data (both historical collected during storms, and current real-time data from WAAS-like receivers), If the algorithms still prove to be conservative, various modifications will be analyzed to improve performance. The simulation will continue to be used to evaluate solar maximum conditions that are not available with real data. The simulation will also be used to simulate receiver measurements in high ionosphere conditions that will be used in integrated tests (using the WAAS ionosphere estimation algorithms integrated with the WAAS GIVE and UIVE algorithms).

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