An Improved ionospheric Correction Method for Wide-Area Augmentation Systems

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Biographies

Anthony J. Mannucci is a member of the technical staff in the GPS Networks and Operations Group at the Jet Propulsion Laboratory in Pasadena, CA. He has played a principal role in development of the global ionospheric mapping technique, and has spent the last four years developing and characterizing ionospheric calibration systems for deep space tracking and Earth-based satellite applications. He has over ten years of experience developing high accuracy measurement techniques in a variety of technical areas. Currently, he is focusing on increasing the accuracy of GPS-based global ionospheric maps by improving the models and estimation strategy. Dr. Mannucci received a Ph.D. degree in physics from the University of California at Berkeley in 1989.

Brian Wilson, a member of the GPS Networks and Operations Group at the Jet I'repulsion Laboratory in Pasadena, CA, has been studying the ionosphere using GPS for five years, He is the Cognizant Design Engineer of the operational ionosphere calibration software for the Deep Space Network, which is used to correct navigation radiometric data for ionospheric delay effects. Brian is a co-developer of the global ionospheric mapping (GIM) technique, which assimilates GPS data from 60+ globally distributed sites to produce sub-hourly maps of total electron content. Currently, he is working to improve the accuracy of GIM by incorporating an improved physical ionosphere model, and validate its accuracy by comparisons with independent ionosphere measurements from Very Long Baseline Interferometry and the TOPEX ctual-frequency altimeter.

Dah-Ning Yuan is a member of the technical staff in the Tracking Systems and Applications section at the Jet Propulsion laboratory (JPL) in Pasadena, California. He has been studying the ionospheric data assimilation problem for the past 2 years using total electron content (TEC) data derived from a world-wide network of dual-frequency GPS receivers. Prior to devoting his time to research in physical ionosphere modeling, he was involved in implementing SLR (satellite laser range) and DORIS (Doppler Orbitography and Radio Positioning Integrated by Satellite) data processing techniques for the TOPEX/Poseidon project in the Navigation Systems Section at JPL. He obtained his Ph.D. in Aerospace Engineering from the University of Texas at Austin in 1991. His graduate research concentrated on development of an Earth gravity field model for TOPEX/Poseidon precision orbit determination using satellite tracking, satellite altimeter, and surface gravity anomaly data.

Abstract

A powerful approach for generating ionospheric corrections in wide area differential GPS applications has been developed, that can be applied to the Federal Aviation Administration's Wide Area Augmentation System (WAAS). This approach has been used to support ionospheric calibration for NASA's Deep Space Network and will be supporting real-tirne operations for global ionospheric specification and, possibly, single-frequency satellite altimeter calibration. It is a real-time, grid-based technique relying on a computationally efficient Kalman-type filter to produce accurate, smoothly varying ionospheric correction maps over the coverage area. Formal error maps are also computed, providing vertical delay errors over the WAAS grid, which are useful in integrity monitoring. This solution to the ionospheric correction problem is self-calibrating, since GPS transmitter inter-frequency biases are obtained as a by-product of the mapping procedure. This contrasts with other techniques in which bias values must be provided from some additional source.

Simulated data were generated for the proposed configuration of 24 WAAS reference GPS stations, using a well-tested climatological ionosphere model (Bent) to compute ionospheric total electron content (TEC) during conditions typical near the peak of the solar cycle, Slant TEC delays often exceed 30 meters over the continental US (CONUS) during solar maximum, but the simulations indicate that the corrections are accurate to 0.25-0.5 meter over the CONUS, Alaska and Hawaii (this includes any errors in estimating the transmitter biases). Our technique is therefore useful for en-route navigation and precision approach, the latter requiring 1.5 meter correction accuracy.

Introduction

We have developed a powerful and accurate method of exploiting data from a dense GPS receiver network to generate high resolution "snapshot" images of the ionospheric vertical delays anywhere within the coverage area. The mapping technique has been used to support operational ionospheric calibrations for NASA's Deep Space Network and will support real-time operations for a global network of G]% receivers that monitor ionospheric total electron content (TEC). The correction method relics on a Kalman filter implementation and can automatically produce formal error maps. It is therefore ideally suited for incorporation into a real-time correction system such as the Federal Aviation Administration's wide area augmentation system (FAA WAAS). It is a grid-based algorithm with a built-in interpolation scheme to provide corrections at any point within the continuous coverage area, and is well adapted to provide a real-time estimate of both the ionosphere and the errors at the specified set of WAAS grid points.

In this paper, wc will summarize our wide-area ionospheric correction technique, which is based on the Jet Propulsion Laboratory's GPS Inferred Positioning System software (GIPSY), extended to include the triangular interpolation technique for ionospheric corrections (TRIN). This method has been described in a previous Institute of Navigation Proceedings paper (Mannucci *et al.*, *1993,* hereafter known as Paper 1). We will summarize the specific advantages of our method, in particular the use of a grid that is fixed with respect to the Sun rather than co-rotating with the Earth, We will present simulation results that demonstrate the GIPSY/TRIN method is capable of 0.25-0.5 meter correction accuracy over the continental US (CONUS) during conditions typical of solar maximum. Finally, we will indicate how the GIPSY/TRIN software could be incorporated into the FAA's real-time WAAS.

The G] PSY/TRIN Method for Computing the Real-Time Ionospheric Correction

The GIPSY/TRIN ionospheric correction algorithms have been described in a previous Institute of Navigation Proceedings (Paper 1), and only features of particular relevance to WAAS will be summarized here. We will discuss several unique features of the GIPSY/TRIN method: 1) tbc use of a Sun-fixed, rather than Earth-fixed grid for the initial interpolation step; 2) the use of a triangular grid, not a rectangular one and 3) the instrumental inter-frequency bias estimation capability.

Ionospheric total electron content is extracted from GPS by computing the difference between satellite-receiver range measured at the two GPS frequencies, 1.1 and 1.2 (see Paper I). The line-of-sight measurements of ionospheric delay arc interpolated to form a wide-area correction map that applies to the entire coverage area. The GIPSY/TRIN method employs a "shell" model of the ionosphere: the ionospheric electrons are assumed to be concentrated in a thin shell at a fixed height of about 350 km. The delay due to this shell is parametrized in terms of a set of vertex values uniformly distributed over a spherical surface, in a triangular tiling scheme. The grid is Sun-fixed so that it does not rotate with respect to the basic structure of the ionosphere.

Each ionospheric measurement from a GPS receiver in the network is modeled as a simple linear combination of the grid vertex parameters in the following form:

$$I_{rs}(t_i) = M(E)\sum_{i=1}^{3} W_i(\phi_{pp},\lambda_{pp})V_i + b_r + b_s \qquad (1)$$

where $I_{rs}(t_i)$ is the real-time measurement from receiver *r* and satellite s at time t_i, *Vi is* the value of the TEC at vertex *i* (i.e. parameter *i)* and *M(E)* is the obliquity factor relating slant delay to vertical for elevation angle *E*. The factor *Wi* (ϕ_{pp},λ_{pp}) *is* a distance-weighting function that relates the TEC at the ionospheric pierce point location (ϕ_{pp},λ_{pp}) to the TEC at the three vertices of the intersected tile. This function is based on a simple bi-linear interpolation scheme (see Paper I). This "measurement model" is used in the GIPSY Kalman filter for estimating the vertex parameters *Vi* from the real-time data. The final two terms, b_r and b_s, refer to the instrumental inter-frequency (1.1/1.2) bias in the ground receiver and satellite transmitter respectively. These biases can be estimated simultaneously with the ionosphere delays or held fixed to a priori values.

The ionospheric mapping proecss makes extensive use of the stochastic estimation features of the GIPSY Kalman filter. As measurements become available, the zenith, ionospheric delay at every point of the triangular grid over the c.overage area is re-estimated. (For current NASA operations where GIPSY/TRIN is used, this coverage area is the entire globe.) The vertex parameters are modeled as Gauss-Markov stochastic processes, so that the updated values at each grid point are correlated with their values at the previous time step (i.e., they are not estimated entirely independently at each step, so that the recent history of measurements contributes to tile current estimate). Since a distance weighting function is used in equation 1, the vertex TEC values are also correlated spatially with the values at adjacent grid points. This results in stable and smoothly varying ionospheric maps.

Sun-Fixed Grid

The FAA WAAS specification requires that the ionosphere delay be specified over an Ear-th-fixed grid covering the CONUS coverage area (the grid spacing, varies between 5 and 10 degrees). Most correction techniques interpolate the TEC measurements from the GPS receivers in the WAAS network in an Earth-fixed coordinate system (e.g. Brown, 1989; Kee *et al.*, 1991).

However, the ionosphere varies much more slowly in a Sun-fixed reference frame, so interpolation over a grid fixed with respect to the Sun produces more accurate correction maps. In a final step, translation to the Earth-fixed WAAS grid can be performed rapidly with no loss of precision since the Sun-fixed correction map overlaps the liarth-fixed grid.

The temporal stability of the ionosphere in a Sun-fixed reference frame is demonstrated in Figures 1 and 2, which are plots of the diurnal variation of TEC over three widely separated sites in the North American continent sharing similar geomagnetic latitudes: Goddard (49.97 geomagnetic latitude, -76.83 geographic longitude), North Liberty (51 .93, -91 .57) and Quincy (46.44, -120.94). The zenith delay over each site was determined by evaluating the GIPSY/TRIN global map solution directly overhead each station for a relatively active day in March 1993 (solar sunspot number = 67.1, F1O.7 flux = 140). The usual diurnal variation in the ionosphere causes the TEC above each station to be markedly different at the same universal time (figures 1 a and 1 b). This causes large changes in successive Earth-fixed correction maps. However, when zenith TEC is plotted in terms of local time (equivalent to using Sun-fixed coordinates), the differences between the stations is significantly reduced (figures 2a and 2b), showing that all three stations undergo similar diurnal variations. Therefore, correction map variations arc much smaller in Sun-fixed coordinates, and the correlation time between successive maps is longer. This leads to more accurate wide-area corrections when Kalman-filter updating is used.

In addition to reduced variability, the ionospheric pierce points of the TEC measurements cover a larger portion of the ionospheric shell when a Sun-fixed grid is used, as shown in figure 3a and 3b. These are plots of ionospheric penetration points for the WAAS reference stations during a three-hour period using an elevation cutoff of 20 degrees. A higher density of ionospheric pierce points is evident for the Sun-fixed grid. The Earth rotates underneath the Sun-fixed grid, so the Sun-fixed longitude of each station changes with time, allowing a single station to cover an additional 15 degrees of longitude per hour. Since the Earth-fixed grid rotates with the stations, gaps in the coverage may persist indefinitely, potentially leading to large inaccuracies.

Triangular Grid

The WAAS specification requires that the ionospheric corrections are computed for a set of fixed points over a rectangular grid, that covers the CONUS region and extends into southern latitudes. Most proposed correction methods also use a rectangular grid for interpolation between the. measurements, which is disadvantageous for two reasons. First, the distance between the grid points determines the spatial correlation scales that can be reproduced in the TEC map. For a rectangular grid, this will be latitude-dependent in a manner which does not match the cm-relation scales in the ionosphere. Second, a scheme based on rectangular grids cannot be expanded to cover the entire globe and therefore is naturally limited in extent. If the WAAS correction algorithms arc based on Earth-fixed grids, and the coverage region is expanded in the future, the basic interpolation algorithms may require significant modification. In contrast, a triangular grid covers the sphere uniformly and is used in GIPSY/TRIN since it is a global mapping technique. A triangular grid can be used to form corrections over a limited region as well, and the correction map can of course be evaluated at a set of rectangular grid points that overlap the coverage area.

Self-Calibration

Ionospheric measurements using dual-frequency GPS receivers are affected by inter-frequency biases which, if left uncalibrated, can corrupt the measurements by as much as 5 meters. These biases, which affect both the receivers and the satellite transmitters, can be accurately estimated using the GIPSY/TRIN technique. Numerous comparisons between global map solutions and independent measurements of TEC show that the biases are determined to better than 0.5 meter accuracy, even for periods when the solar sunspot numbers were a factor of 3-5 larger than current values (see Wilson *et al.*, 1994; Mannucci *et al.*, 1994), Therefore, in contrast to other proposed ionospheric correction methods, the GIPSY/TRIN method is self-calibrating, and does not require that biases be provided from an external source. However, should more accurate bias values be available, they can be used to directly calibrate the data.

Even if receiver and satellite calibrations arc available from an independent source, it is still useful to estimate these biases off-line (i.e. not in real-time) on a regular basis. A frequently-updated database of bias values can be used to detect anomalous changes in the receiver and satellite hardware. Therefore, wc would recommend that bias estimation be performed frequently for the WAAS network for the purpose of integrity monitoring.

Simulation Results

To assess the suitability of GIPSY/TRIN for applications such as the FAA's wide area augmentation system, a simulation using the proposed configuration of 24 WAAS remote stations was performed for conditions typical of solar maximum, when slant ionosphere delays over CONUS frequently exceed 30 meters. Line-of-sight TEC measurements were synthesized every 5 minutes, based on the proposed WAAS station geometry and assuming a full GPS constellation of 24 satellites. The Bent ionospheric model (Bent *et al., 1976)* was used for generating realistic ionospheric delays for each satellite-receiver line of sight. The GIPSY/TRIN method was applied to the simulated data and a correction map was formed over an extended region covering the CONUS, Alaska and Hawaii. Comparing the correction map with the model, the simulation results show that the GIPSY/TRIN global mapping technique is accurate to 0.2 S-0.5 meters over the CONUS and in the vicinity of the Alaskan and Hawaiian GPS stations. This indicates that GIPSY/TRIN is suitable for en-route navigation and precision approach. For the latter case, 1.5 meter correction accuracy is required near land (WAAS Specification, 1994). Greater accuracy will generally be achieved away from the peak of the solar cycle.

For each slant measure.ment, the vertical TEC values predicted by the Bent model were multiplied by the elevation-dependent slant range factor, assuming the usual cosecant (thin shell) obliquity factor $M(E)$:

$$M(E) = \{1 - [\cos E/(1 + h / R_E)]^2\}^{-1/2} \qquad (2)$$

where E is the elevation angle, h is the height of the shell and R_E is the radius of the Earth. For the simulated data, the shell height was not held constant, but was set equal to the height of peak electron density predicted by the Bent model. Using varying heights h in the mapping function is realistic, since in practice the exact equivalent shell height or mapping function is not known. When forming the correction map, however, the standard fixed shell height of 350 km was used.

The Bent model was run for a day representative of solar maximum conditions, in Ibis case February 15, 1991. For this day, the model predicted daytime vertical delays exceeding 14 meters over the US and slant delays exceeding 30 meters. Solar activity inputs were: solar sun spot number of 176.5; 1:10.7 flux value of 243.0. These numbers are factors of 3-10 above current solar minimum values.

A new grid solution was produced every 30 minutes rather than every 5 minutes as would be done in an actual WAAS implementation, in order to reduce the disk storage requirements for the comparison. Accuracy of the corrections will generally improve with more frequent solutions. The station and satellite biases were assumed to be unknown and were estimated using the self-calibration capability of GIPSY/TRIN. Each data point was given the same data weight and an elevation cutoff of 20 degrees was used.

Figure 4 is a contour plot of the residual difference between the Bent model and the correction map, for the interval 20:00-20:30 UT. This figure is a typical case of a daytime residual plot. The GIPSY/TRIN ionospheric correction method produces an accurate representation of the simulated data set over North America and in the vicinity of Hawaii and Alaska. The maps are completely data driven and an a priori ionospheric value of zero was assumed to initialize the mapping procedure. This accounts for the fall-off in accuracy in the extreme Northern and Southern areas of the map, where no data was collected (see (he coverage maps in Figure 3). In practice, a more realistic a priori ionosphere available from a climatological model would be used to smoothly continue the maps outside the area directly covered by the measurements. However, to avoid confusion in interpreting the results, we did not use any a priori information from an ionosphere model in this work.

Figure 5 is a plot of the residual root mean square (RMS) difference between the correction maps and the Bent model, computed over two rectangular-shaped regions for all 48 maps generated at 30-minute intervals. The extended region covers the same area shown in figure 4, and includes areas not covered by GPS data (primarily in the northern and southern edges of the region). The RMS residual for this region is an overestimate of the expected error for a WAAS implementation since it covers regions where no GPS data were available. To determine more realistic errors for the FAA's WAAS, the RMS has also been computed for a rectangular-shaped region restricted to (he CONUS where data coverage is more complete (this area is outlined in figure 3a). For both regions, the accuracy of the GIPSY/TRIN method is generally better than 1 meter. Over the smaller region where there is more complete data coverage, the agreement is better than 0.4 meter for all the maps. Note that the residuals were computed using the inter-frequency bias values estimated by the GIPSY/TRIN method itself and did not rely on external calibration values. Smaller residuals can be expected if these biases are fixed to values determined off-line from several days of data, which would be possible in an actual WAAS implementation.

Applying GIPSY/TRIN to the FAA's WAAS Implementation

A real-time implementation of the GIPSY/TRIN method could be applied directly to the ionospheric correction component of WAAS. The formation of an ionospheric correction for the WAAS user is essentially a two-step process. First, a selected set of delays and errors at the grid points must be generated as part of the slow correction (every 5 minutes would be sufficient). This is the critical task which can be performed by GIPSY/TRIN with high accuracy. Second, the updated grid values are broadcast to a user who will convert them to a line-of-sight correction at the user's location. interpolation between the grid values to form the user correction is a less demanding task which can be executed with standard interpolation techniques and is not addressed here.

The data flow for producing the ionospheric correction and errors at the grid locations is shown in figure 6. The data are input to the real-time implementation of the GIPSY filter along with an estimate of the receiver and satellite 1,1/1,2 delay biases. (These biases can be obtained from an independent source or estimated off-line with the GIPSY filter.) Filtering is a recursive estimation process in which a previously estimated ionospheric delay map is incrementally adjusted with new data at regular intervals, nominally every 5 minutes for WA AS. The updates take oniy a few seconds of CPU time, The process is initialized with the Bent ionospheric model (other models can also be used) so that when it is started up for the first time, adjustments arc made to reasonable a priori values rather than to arbitrary or zero values. After a fcw update intervals, the great data strength of the WAAS GPS receiver network will cause the estimated maps to be fully determined by the data, with no further dependence on the a priori model.

At each step, the updated map and associated errors are stored for use at the next time update. The GIPSY/TRIN vertex points arc not in general collocated with the WAAS grid, and the maps must be evaluated at the Earth-fixed WAAS grid locations. Since the GIPSY/TRIN correction map overlaps the WAAS grid, this can be accomplished in a few milliseconds with no loss of precision. Finally, a selection criterion is applied to determine which updated grid point values should be sent to the user. The selection should be based on a comparison between each of the latest updated grid values and an average of the prior set of values.

Summary

A wide area ionospheric correction method used to support operational ionospheric calibrations for NASA's Deep Space Network has been applied to the FAA's proposed wide area augmentation system (WAAS). Simulation results show that, even under conditions typical of solar maximum, the GIPSY/TRIN ionospheric correction method is accurate to 0.25-0.5 meter and therefore meets the WAAS specification calling for 0.5 meter accuracy in the slow ionospheric correction. This accuracy was obtained using the inter-frequency biases estimates produced in the fit. in an actual WAAS implementation, the bias values would be estimated off-line using data from several days, resulting in even better accuracy.

It should be emphasized that the solar flux, which drives the formation of the ionosphere, is currently near the minimum of the solar cycle, or a factor of 3-10 less than maximum. Simulations were performed for this study since tests using current data from a network similar to WAAS are not indicative of performance during more challenging periods. Further work should be performed to test the system under conditions characteristic of major ionospheric storms, which occur infrequently but cause instabilities in the ionosphere that can degrade correction performance.

The GIPSY/TRIN technique can be readily incorporated into a real-time correction scheme for the WAAS. Since the algorithm is grid-based anti has a built-in interpolation scheme, vertical ionospheric delays and errors can be evaluated at each of the fixed WAAS grid points in real-time.

Acknowledgments

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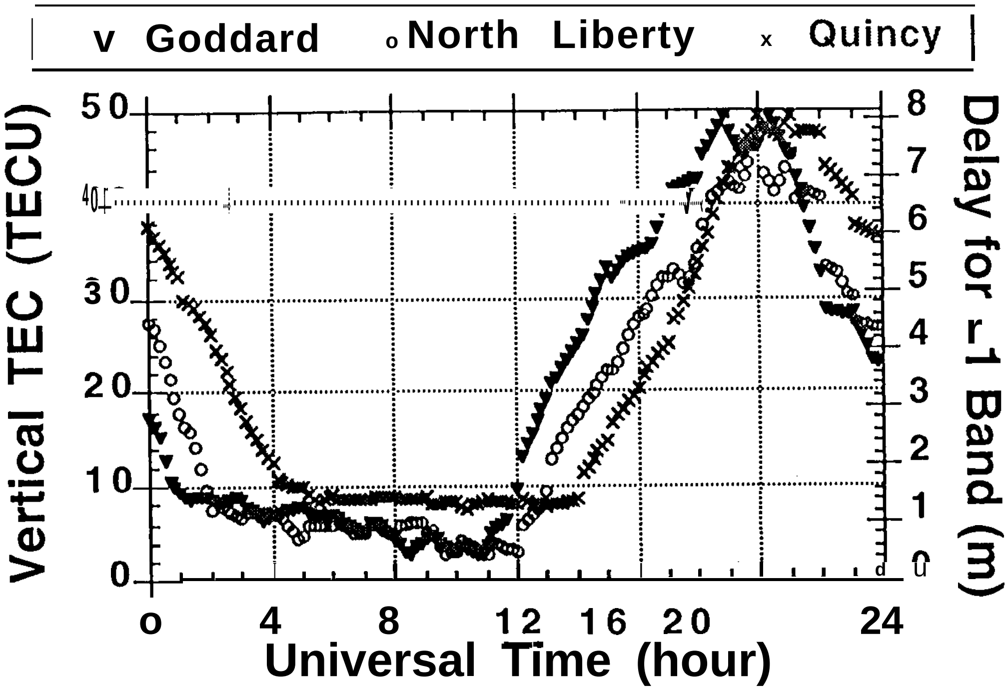


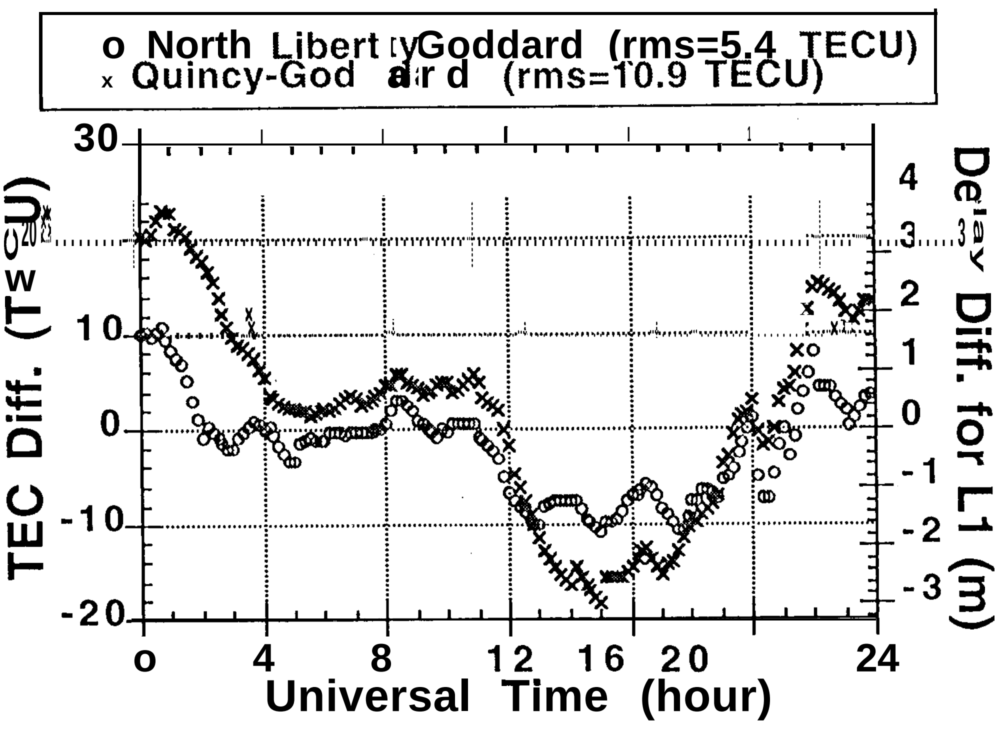


Figure 1. **This** figure is a plot of the diurnal TEC variation over three North American receivers in the GPS global network, plotted as a function of universal time, for March 13, 1993. Each receiver shares similar geomagnetic latitude (Goddard. geomagnetic latitude 49.97, geographic longitude -76.83; North Liberty 51.93, -91.57 and Quincy 46.44, -120.94). In (a), the total TEC is plotted; in (b), the difference with Goddard is plotted. Earth-fixed correction maps over the WAAS coverage area must follow these large diurnal variations.

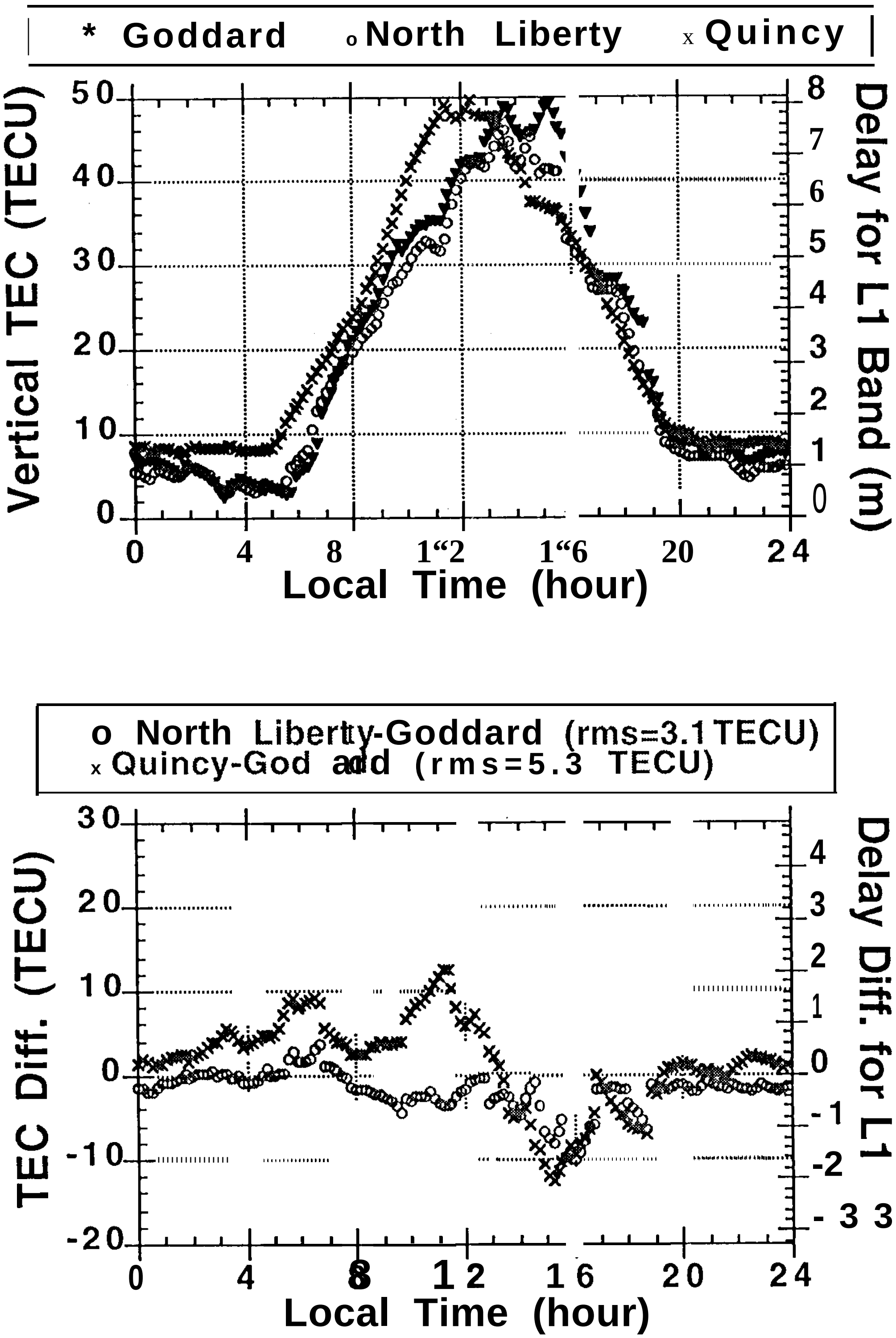
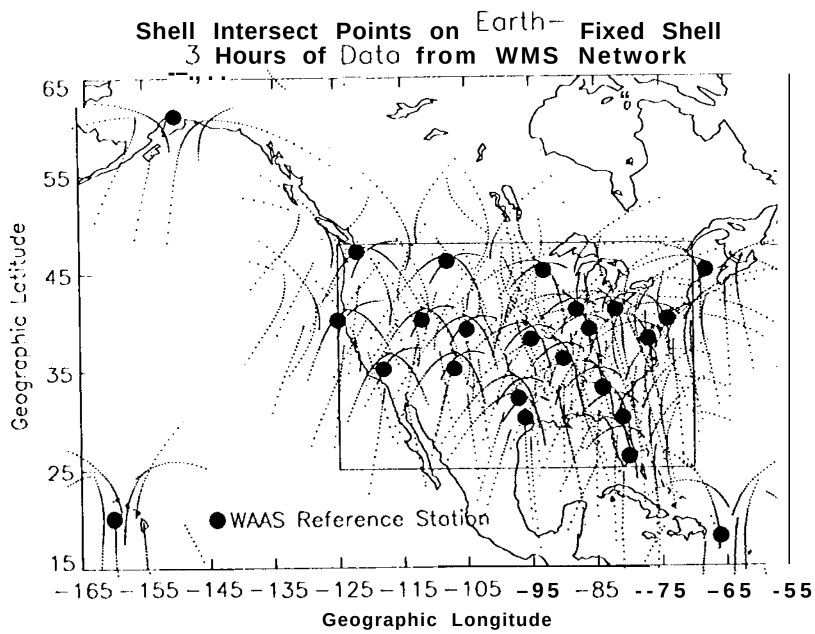


Figure 2. This plot is similar to figure 1, but the diurnal TEC variation is plotted as a function of local time. Comparison with figure 1 indicates that Sun-fixed (local time) correction maps have smaller gradients than the Earth-fixed maps.



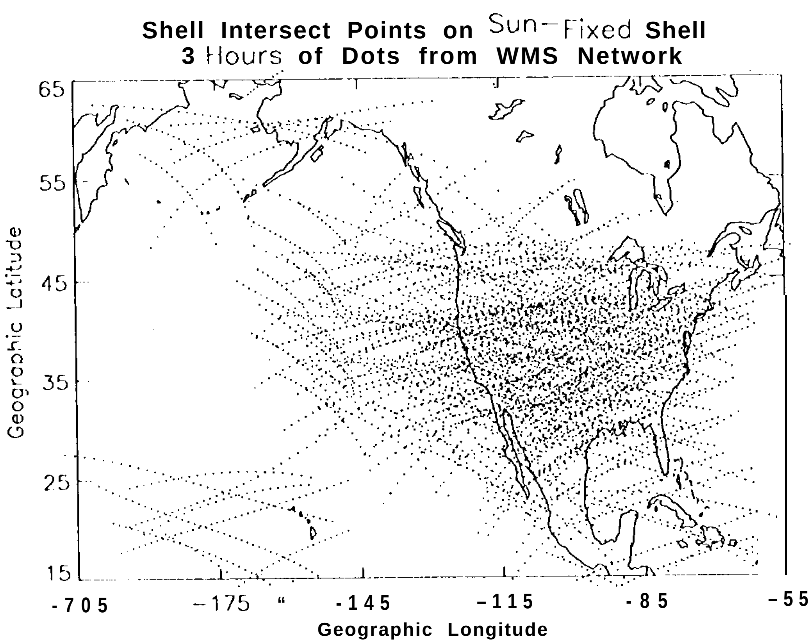


Figure 3. These plots show the locations of the shell intersect points for a 3 hour span of data simulated for March 21 , 1997 using the proposed configuration of 24 WAAS reference receivers. In (a), the coverage is shown of for an Earth-fixed shell. In (b), coverage is shown over a Sun-fixed shell. The shell height was assumed to be 350 km, and the elevation cutoff was 20 degrees. The continent map is placed to reflect the position of the Earth after an elapsed time of 2.5 hours.

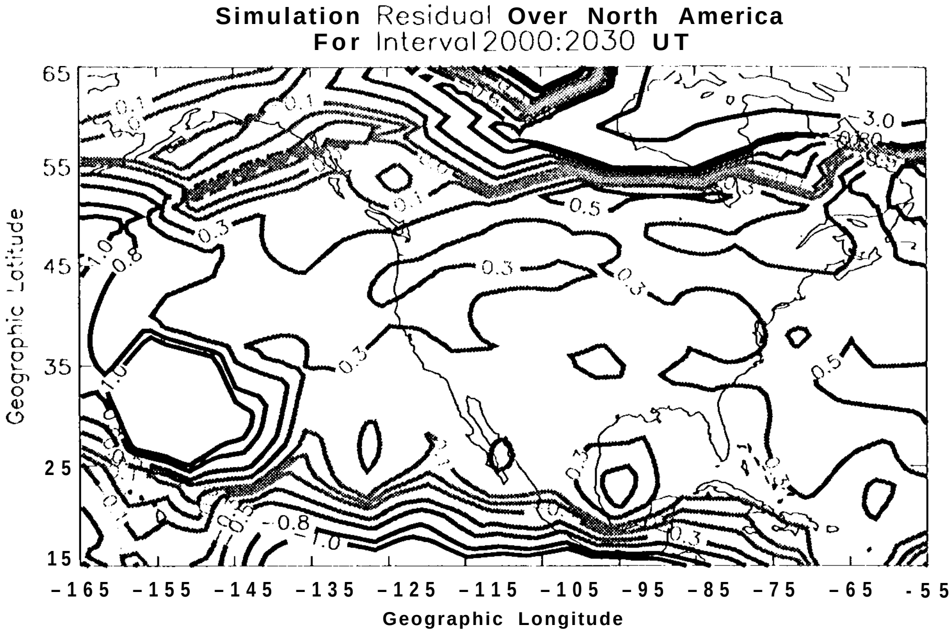


Figure 4. This is a plot of the residual difference between the Bent model TEC used in the simulations and the correction map produced by the GIPSY/TRIN technique. This typical daytime residual map covers the period 20:00-20:30 universal time. The correction maps are generally accurate to 0.3 meter or better, except in regions where no measurements were available (see the coverage maps in Figure 3).

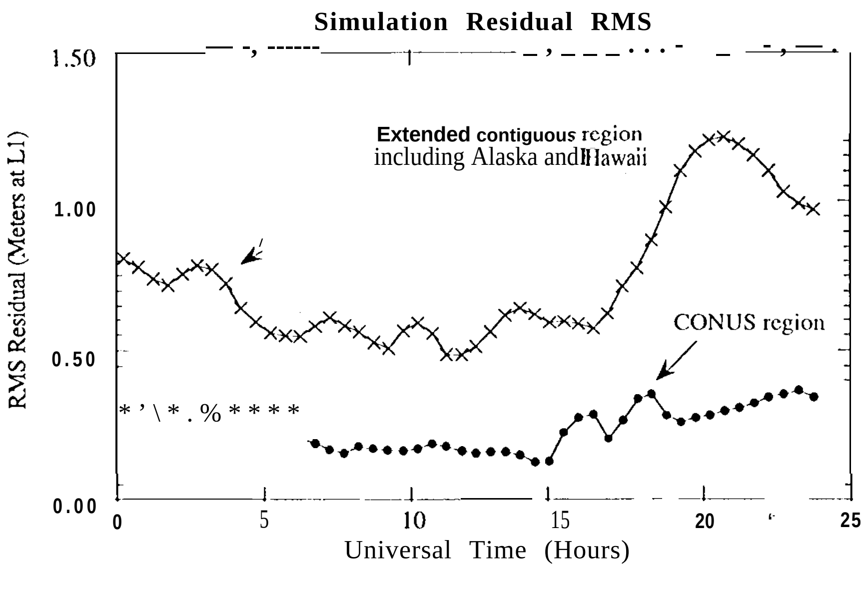


Figure 5. This is a plot of the root mean square residual between the Bent model TEC and the correction map, for each of the 48 correction maps generated in the simulation. The RMS was computed for 1 xl degree grids over two regions: an extended region covering the CONUS and Alaska and Hawaii, defined by the southwest corner at (15.0, -165.0) and the northeast corner at (65.0, -55.0), geographic latitude and longitude. The other rectangular-shaped region was restricted to cover the CON US, where ionospheric measurements are always available: SW corner at (25.0, -125.0) and NE corner at (48.0, -70 o).

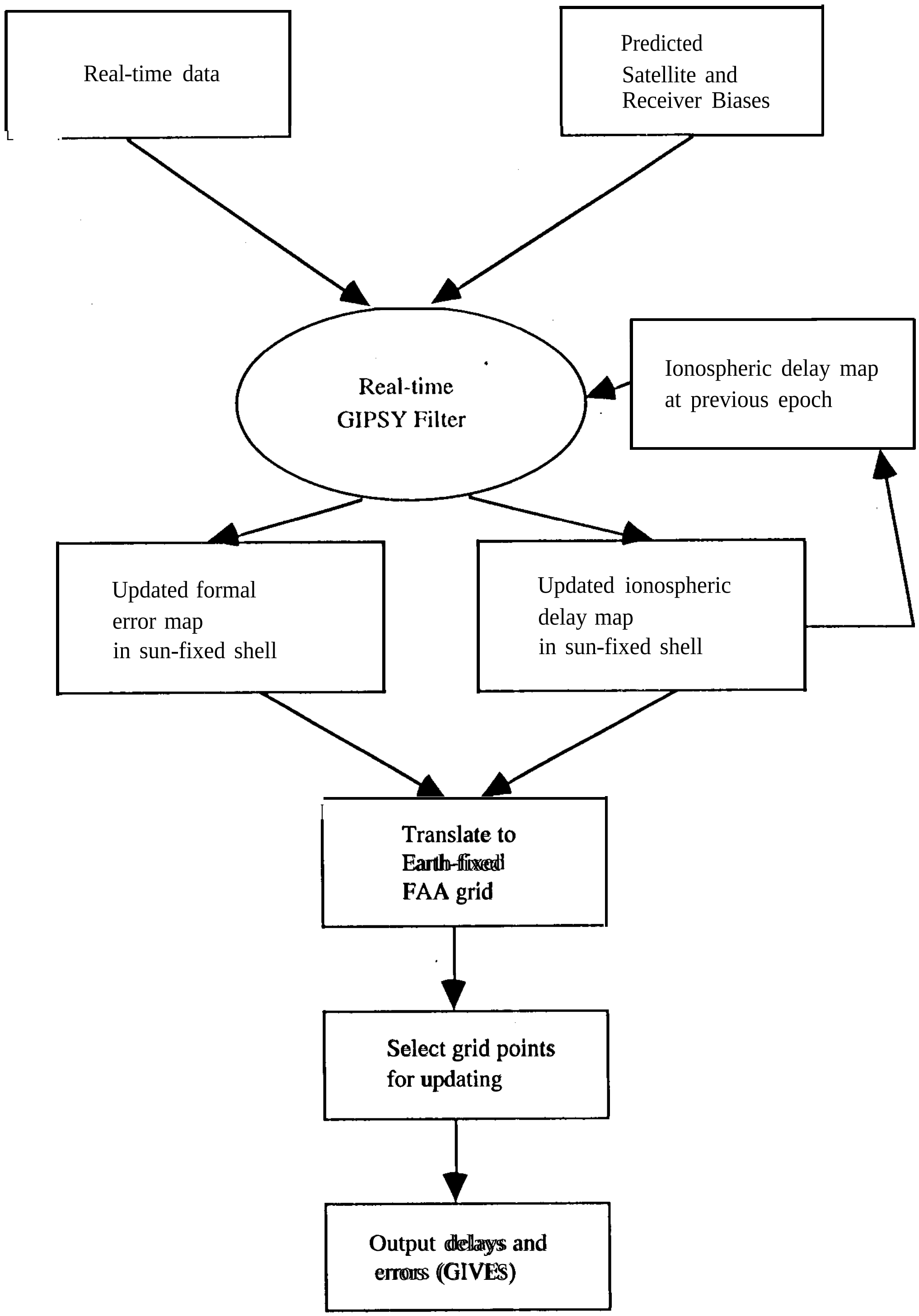


Figure 6: Data flow diagram showing the process involved for forming the grid delay corrections and errors for the FAA's proposed WA AS.