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Automated daily processing of more than 1000 ground-based GPS receivers for studying intense ionospheric storms

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[1] As the number of ground-based and space-based receivers tracking the Global Positioning System (GPS) satellites steadily increases, it is becoming possible to monitor changes in the ionosphere continuously and on a global scale with unprecedented accuracy and reliability. As of August 2005, there are more than 1000 globally distributed dual-frequency GPS receivers available using publicly accessible networks including, for example, the International GPS Service and the continuously operating reference stations. To take advantage of the vast amount of GPS data, researchers use a number of techniques to estimate satellite and receiver interfrequency biases and the total electron content (TEC) of the ionosphere. Most techniques estimate vertical ionospheric structure and, simultaneously, hardware-related biases treated as nuisance parameters. These methods often are limited to 200 GPS receivers and use a sequential least squares or Kalman filter approach. The biases are later removed from the measurements to obtain unbiased TEC. In our approach to calibrating GPS receiver and transmitter interfrequency biases we take advantage of all available GPS receivers using a new processing algorithm based on the Global Ionospheric Mapping (GIM) software developed at the Jet Propulsion Laboratory. This new capability is designed to estimate receiver biases for all stations. We solve for the instrumental biases by modeling the ionospheric delay and removing it from the observation equation using precomputed GIM maps. The precomputed GIM maps rely on 200 globally distributed GPS receivers to establish the "background" used to model the ionosphere at the remaining 800 GPS sites.

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1. Introduction

[2] Even though GPS was not originally designed as a scientific observing system, it has become during the past few years a powerful research tool for studying the temporal and spatial variability of the global ionospheric total electron content (TEC). Ionospheric measurements using GPS are readily accessible to the scientific community. GPS does not, however, provide direct measurements of TEC. To be able to derive high-precision TEC measurements using GPS, we need to estimate the satellite and receiver differential biases that "corrupt" these measurements. The research community needs ever more powerful algorithms to estimate TEC to perform process and quality checks on the large amount of GPS data currently available on a daily basis.

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[3] Over the past 10 years the number of GPS ground receivers has increased by as much as an order of magnitude. Currently, data from about 2000 GPS receivers worldwide are accessible. On a daily basis, data from about 1000 GPS receivers are available to monitor the temporal and spatial variability of the global ionosphere. Algorithms have been developed to process all these data sets. This paper addresses the issue of calibrating large numbers of GPS receivers in a time efficient manner, enabling daily monitoring of the quiet and storm time ionosphere that affects satellite-based radio navigation systems such as GPS, the Global Navigation Satellite System, and the future Galileo.

[4] In this paper, we describe a new algorithm that may be used to generate and process the large amount of GPS data that can be downloaded from the internet every day. The new stand-alone software package downloads, edits, and processes the data to generate global vertical total electron content (VTEC) animations and calibrated slant

TEC data files without user intervention. This is a potential resource for the world scientific and engineering community that can be made available on a Jet Propulsion Laboratory (JPL) ftp site.

2. Conventional JPL Global Ionospheric Mapping Bias Estimation Strategy

[5] Over the course of the past decade we have used the Global Ionospheric Mapping (GIM) software developed at the Jet Propulsion Laboratory [*Mannucci et al.*, 1998] to compute high-precision slant ionospheric delay by removing the satellite and receiver differential biases from the ionospheric observables. The estimation of the satellite and receiver biases is reviewed here briefly.

[6] Ionospheric measurements from a GPS receiver can be modeled with the well-known single-shell ionospheric model, using the following observation equation [see, e.g., *Mannucci et al.*, 1999; *Komjathy et al.*, 2002]:

$$\mathrm{TEC} = M(h,E)\sum_i C_i B_i(\mathrm{lat},\mathrm{lon}) + b_r + b_s, \qquad (1)$$

where

TEC slant total electron content measured by the linear combination of the GPS dual-frequency carrier phase and pseudorange ionospheric observables, typically expressed in TEC units (TECU); one TEC unit($=10^{16}$ el/m^2) corresponds to about 0.163 m ionospheric delay at the L1 frequency;

$M(h, E)$ thin shell mapping function for ionospheric shell height h and satellite elevation angle E (for the definition of the thin shell geometric mapping function see, e.g., *Mannucci et al.* [1998]);

B_i(lat, lon) horizontal basis functions (based on, e.g., spherical harmonics or bicubic splines) evaluated at the ionospheric pierce point (IPP) (the intersection of the ray path of a signal propagating from the satellite to the receiver with a thin spherical shell) located at latitude lat and longitude lon on the thin shell;

C_i basis function coefficients (real numbers);

b_r and b_s satellite and receiver differential biases, assumed constant over periods of 24 hours or more.

[7] The dependence of vertical TEC on latitude and longitude is parameterized as a linear combination of the two-dimensional basis functions B_i which are functions of solar geomagnetic longitude and latitude [*Mannucci et al.*, 1998]. (We note that the summation in equation (1) is over all basis functions B_i.) Using the ionospheric GPS observables based on carrier phase data [*Mannucci et al.*, 1998], a Kalman filter solves simultaneously for the instrumental biases and the coefficients C_i which are allowed to vary in time as a random walk stochastic process [*Iijima et al.*, 1999]. The basis functions currently used are based on a bicubic spline technique developed at JPL.

3. New JPL GIM Bias Estimation Strategy: Bias-Fixing Method

[8] The new bias-fixing algorithm is composed of three main parts. In the first step we estimate highly precise satellite and receiver interfrequency biases using about 200 GPS receivers worldwide. The output of this Kalman-filter-based least squares estimation scheme serves as the background ionosphere for the latter part of the estimation technique. During the first step the Kalman filter estimates the satellite and receiver differential biases for about 200 GPS receivers using GIM.

[9] In the second part of the processing, we use the 200-station-based ionosphere and correct measurements from the remaining stations (about 800) for the ionospheric contribution. Following the notation used in section 2, we define a new observation equation for each receiver in our network that isolates the bias contribution to each TEC measurement:

$$b_r = \mathrm{TEC} - M(h,E)\sum_i C_i B_i(\mathrm{lat},\mathrm{lon}) - b_s, \qquad (2)$$

where the first term on the right-hand side (TEC) is the biased line-of-sight TEC measurement, the second term is the GIM TEC prediction using a 200-site run generated previously, and the third term is the GIM satellite bias estimate computed during the prior 200-site run.

[10] In summary, we form a new observation equation by essentially removing all the unknowns in the system of normal equations, and subsequently, we solve for the receiver differential biases directly. By doing so, we estimate about 800 unknowns corresponding to the receiver differential delays in the entire global network. The remaining error sources in the bias equation (2) are the multipath and receiver noise contributions, left uncorrected in the observation equation, and the ionospheric error, residual to the GIM estimate for the site in question.

[11] In a subsequent third postprocessing step we combine all the processed data and generate our new products for the benefit of the scientific and engineering community. These currently include global or regional vertical electron content maps and satellite and receiver differential biases. This software package has been

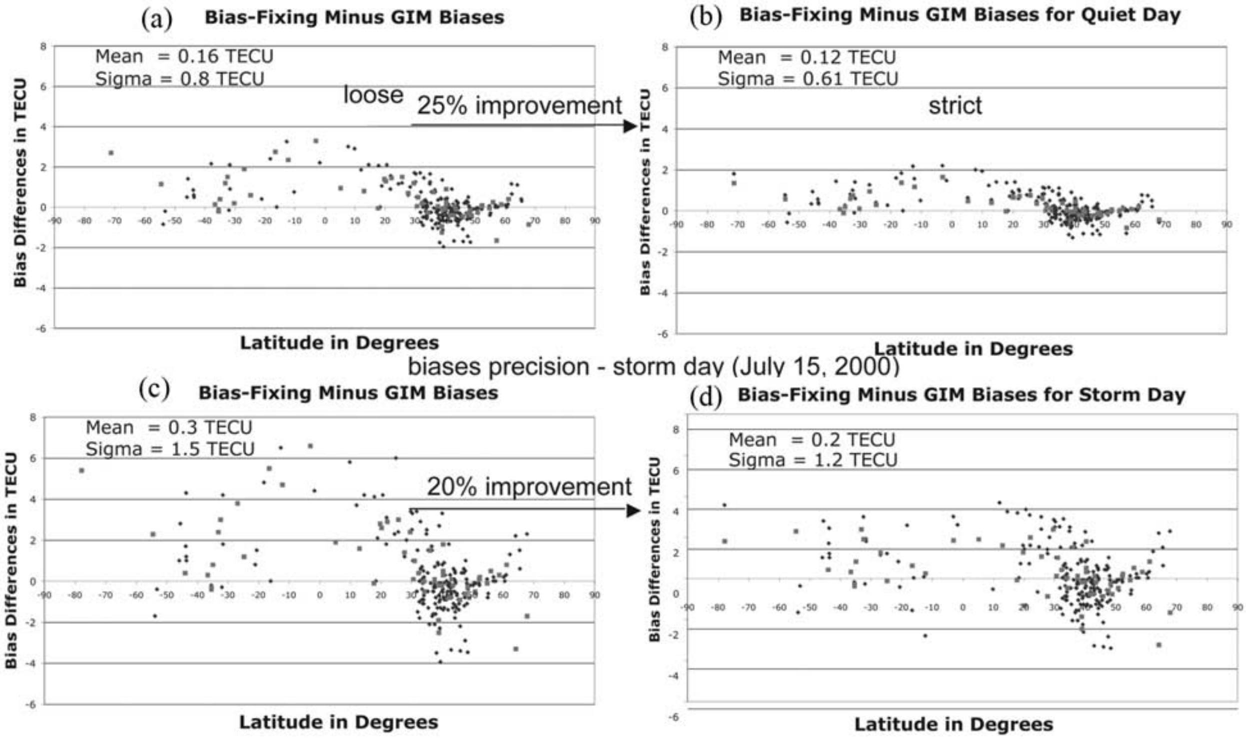

Figure 1. Bias comparison between the new bias-fixing method and the previous full estimation approach for quiet and storm day conditions and with different data-editing criteria applied. The red dots are for a 98-site set of receivers common between the two runs, and the blue dots are for the remaining 142 sites. See color version of this figure at back of this issue.

running continuously on a daily basis since October 2004, generating TEC animations that have captured the scientific community's attention. This attention is due, in part, to daily automated processing of massive amounts of GPS data that is unprecedented in its scope.

4. Comparison of Receiver Bias Estimation Methods

[12] We will first evaluate the precision of the new "bias-fixing" method by comparing it to the traditional GIM bias estimation scheme described in equation (1) which, we assume, provides us with the ground truth value. For computing ground truth we evaluate a 240-station single-shell GIM run for quiet and storm days to minimize GIM estimation error. Separately, we perform a bias-fixing run using the same 240 stations. The bias differences between the 240-station GIM and the bias-fixing run are displayed in Figure 1. Also displayed are data edited with two different criteria: (1) "loose" (Figures 1a and 1c) and (2) "strict" (Figures 1b and 1d) approaches. The loose editing criterion disables all our data-editing algorithms except for monitoring apparent rates of change in the GPS phase data (ionospheric combination L1 – L2) over consecutive data points (30-s interval). This editing uses the GPS Inferred Positioning System program "SanEdit" [*Blewitt*, 1990] (designed to check for cycle slips in the GPS phase data) but rejects data only when the phase difference L1 – L2 exceeds a value larger than 2 m. The stricter criterion also involves using cycle slip detection algorithms based on wide lane, narrow lane, and geometry-free linear combinations of the dual-frequency GPS observables, as designed for detecting and fixing carrier phase cycle slips [*Blewitt*, 1990]. The significance of using strict and loose criteria is that for bias estimation purposes it is best to use clean data; that is, strict data-editing thresholds are desirable. On the other hand, for storm time ionospheric investigations it is best to relax the editing thresholds to include as much data as possible; hence using loose data editing is preferred here. For storm time investigations it is desirable to process the data in two stages. First, we

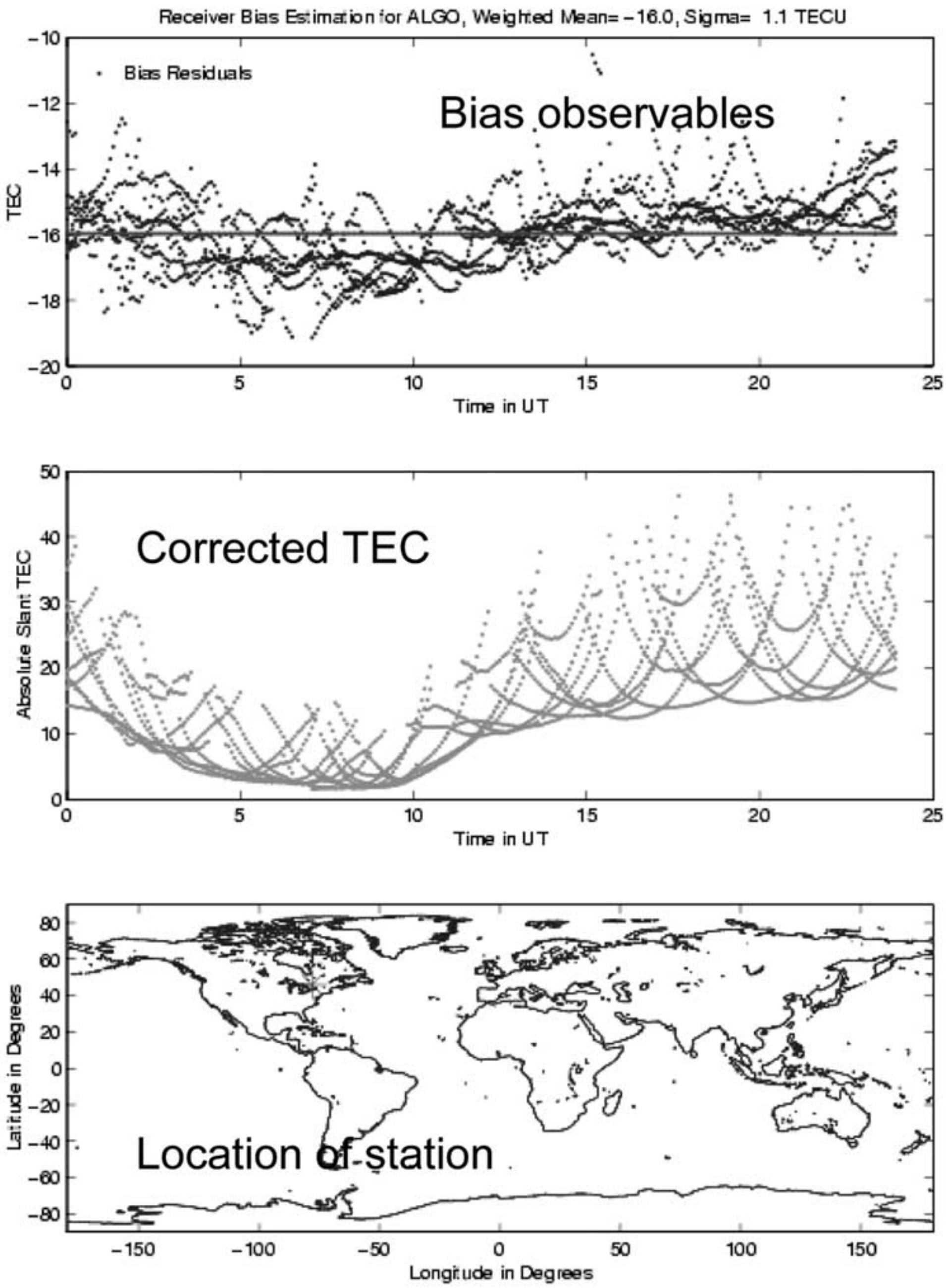

Figure 2. Example plot of bias estimation for a midlatitude station, ALGO (Algonquin Park, Ontario, Canada). See color version of this figure at back of this issue.

estimate the biases using strict data-editing thresholds. Second, we use the estimated biases to compute unbiased line-of-sight TEC measurements to conduct ionospheric studies with data edited according to the looser criterion. In Figure 1 we distinguish between quiet and storm time conditions to assess the reproducibility of new receiver bias estimates.

[13] The red dots in Figure 1 correspond to bias differences estimated with the two techniques, using a set of 98 sites that are common between the single-shell GIM run and the newer bias-fixing run, whereas the blue dots are bias differences for the remaining 240 − 98 = 142 stations used only in the bias-fixing approach. In Figure 1, there is apparently little difference between

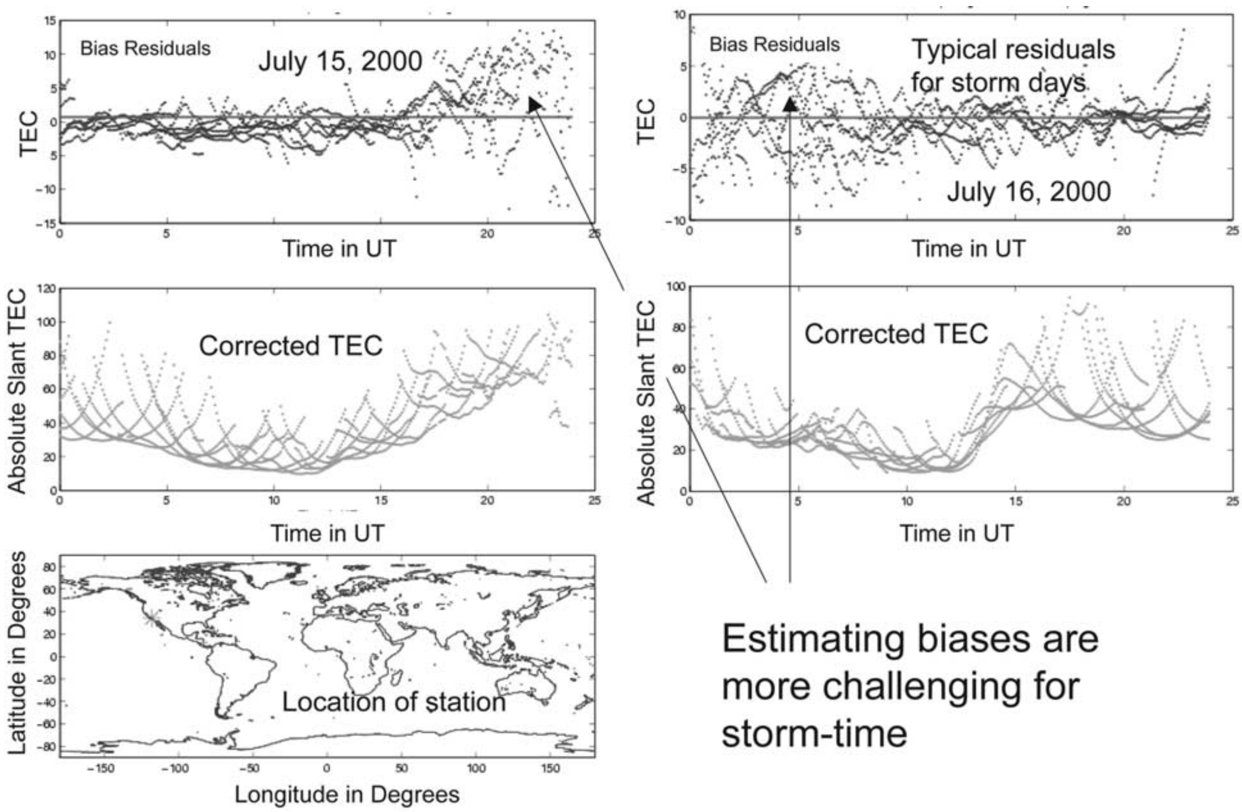

Figure 3. Difficulties in estimating biases for storm time conditions. See color version of this figure at back of this issue.

the biases for stations common to the bias-fixing run and the truth run (red) and those stations not included in the truth run (blue). We plotted the bias differences as a function of station latitudes to demonstrate separately the performance for midlatitude and low-latitude conditions. Figures 1a and 1b demonstrate the bias estimation precision for loose and strict editing criteria, respectively. For the quiet time conditions our bias-fixing method provides us with a precision better than 1 TECU for the midlatitude conditions and better than 2 TECU for low-latitude conditions. The mean and standard deviation of the bias estimates indicate that we achieve about 25% improvement in the reproducibility of bias estimates using a strict editing criterion. For the storm time conditions (Figures 1c and 1d) the precision of our bias estimates is better than 4 TECU for midlatitude conditions and better than 6 TECU for low-latitude conditions. We note that the precision of receiver differential biases given above only reflects how well the biases are reproducible or consistent with the biases obtained using the traditional GIM approach. Neither the biases obtained using the new bias-fixing method nor those obtained using the traditional GIM approach give us any indication of bias accuracy. For accuracy measures we would need calibrated GPS receivers or some other independent data source (i.e., TOPEX or Jason-1 derived TEC) to validate the TEC levels obtained from GPS.

[14] The storm time bias estimation precision appears to be degraded. This is not unexpected since the consistency of bias estimation strategies generally depends on the accuracy of the underlying ionospheric estimation method, in this case GIM. When the GIM prediction performance is poor, this will have a negative impact on the accuracy of both the bias-fixing and full estimation approaches. As a consequence of this, for operational use we propose a strategy to estimate biases prior to storm time conditions using strict criteria and then apply those biases for storm time conditions without reestimating them. This assumes that the biases do not change significantly on a day-to-day basis which is often the case [e.g., *Sardón and Zarraoa*, 1997; *Mannucci et al.*, 1999]. This strategy has helped us achieve about an overall 20–25% improved reproducibility of receiver

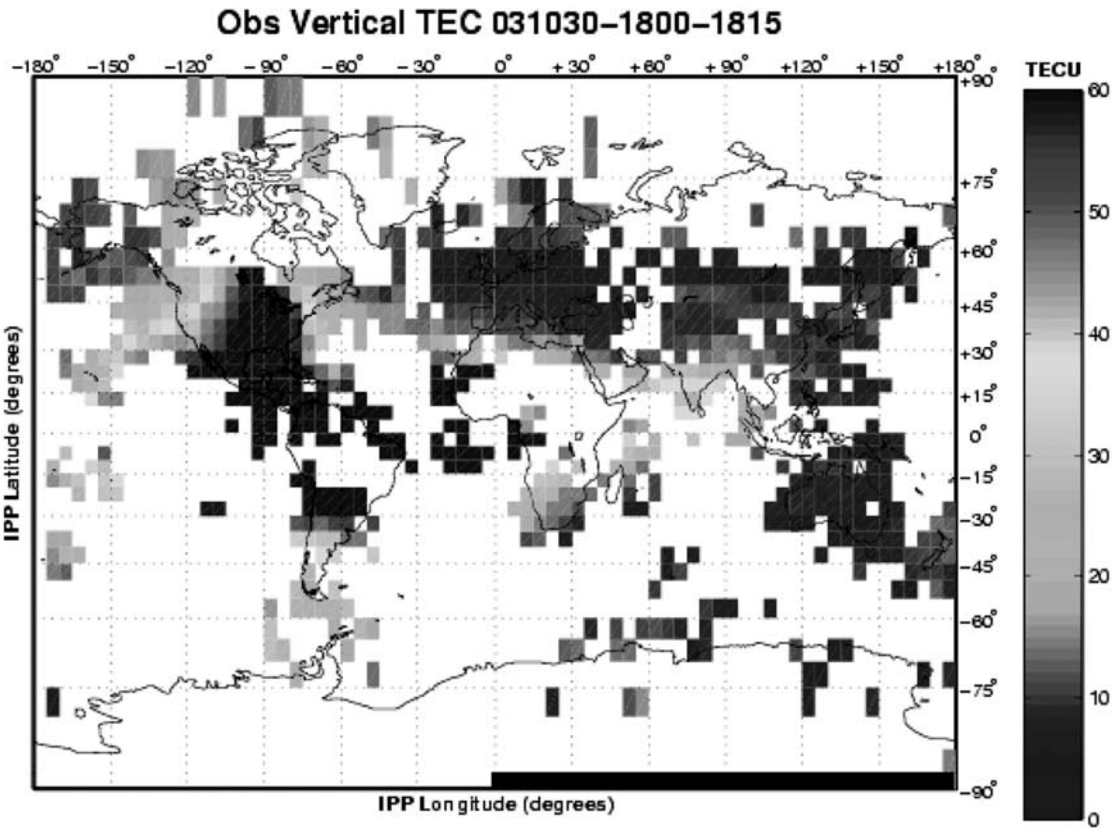

Figure 4. Example frame of daily all-site vertical total electron content (VTEC) point plot maps. See color version of this figure at back of this issue.

biases over using loose editing criteria for all data editing.

5. Slant TEC Using the Bias-Fixing Method

[15] We now analyze measured TEC using the new bias-fixing method. In Figure 2 we show an example of the estimated bias time series described in equation (2). The scatter in Figure 2 (top) time series can be caused by errors in GIM, multipath, measurement noise, and sub-daily bias drifts. Ideally, the data in Figure 2 should all lie on a horizontal line indicating the bias value for the site, but this seldom occurs. The receiver bias is estimated by fitting a straight line to the time series for 1 day, implicitly assuming that the receiver bias is constant for that day. In Figure 2 it is interesting to see a clear diurnal behavior of the receiver bias time series that may be due to local temperature effects at the site. In the near future, we plan on further improving our technique by estimating sub-daily variations of receiver differential biases. Once we have the receiver bias computed, we remove it from the raw GPS measurements and plot the slant TEC data as is shown in Figure 2 (middle). This provides us with a sanity check of the bias estimate for each station. In Figure 2 (middle) it is encouraging that all TEC values are positive and that the diurnal variation of the TEC is as expected, which reassures us that the algorithm is performing well. In Figure 2 (bottom) we show the geographic location of station ALGO (Algonquin Park, Ontario, Canada). We generate a similar plot for every station processed in the network. In case of data-processing errors these plots help us diagnose any potential problems such as poorly leveled data, receiver hardware problems, data dropouts, uncorrected cycle slips, noisy measurements, high-multipath environment, storm time conditions, etc.

[16] In Figure 3 we demonstrate the challenges in estimating biases during storm time conditions. Figure 3 is also a plot of the bias residual time series (equation (2)) but for a site that was included in the GIM bias estimation and for storm time conditions. The later part of 15 July 2000 shows large scatter in the time series mainly because of the fact that our GIM model (see equation (2), second term) introduced increased error during the ionospheric storm. On the next day the storm continued displaying

large scatter for the observable bias. Clearly, estimating biases for this day increases the magnitude of GIM error contributing to bias estimation error. The solution lies in using the quiet time data only for bias estimation and then using these estimated biases to correct for the GPS ionospheric observables for storm time behavior.

6. An Example of Recent 1000-Site VTEC Map and Discussion

[17] In summary, we process individual stations (up to about 1000 on a daily basis) to derive slant TEC as displayed in Figures 2 (middle) and 3 (middle). Our daily process collects all slant TEC data points, maps the slant data points into the vertical, and bins the data points on a 2 degree by 2 degree global grid. The mean value for every grid bin computed for a 15-min interval is plotted in a color scale. The frames are then combined, and mpeg format movies are generated and made available to the public at ftp://sideshow.jpl.nasa.gov/pub/axk/allsites/.

[18] No interpolation between pixels is performed for these animations (in contrast to GIM which produces interpolated TEC values for all locations and times). The animations are purely data driven, and no other data sources are used to generate them. Typically, this results in large data gaps in the Atlantic and Pacific regions as well as in Africa. However, no artifacts from interpolation are introduced which might produce complications for scientific analysis.

[19] Figure 4 shows an example of a global VTEC snapshot displaying the contribution of about 1000 globally distributed sites. The movies are useful tools for investigating storm time behavior such as the storm event of May 2003 [e.g., *Immel et al.*, 2005]. The VTEC map in Figure 4 shows the increased ionization in the North American sector caused by a major geomagnetic storm event, initiated by a B_z southward turning at 1650 UT on 30 October 2003 [*Mannucci et al.*, 2005].

7. Conclusions

[20] We have described a new method of estimating GPS receiver biases that can be applied to large networks of receivers (>1000) on a daily basis with unattended operation. This new bias-fixing technique allows us to compute absolute TEC estimates and to combine them to plot global ionospheric snapshots with excellent global coverage. The consistency of receiver biases is generally better than 1 TECU for midlatitude sites and better than 2 TECU for equatorial sites. A method has been devised and demonstrated for estimating biases on quiet ionospheric days and applying the results to storm time conditions.

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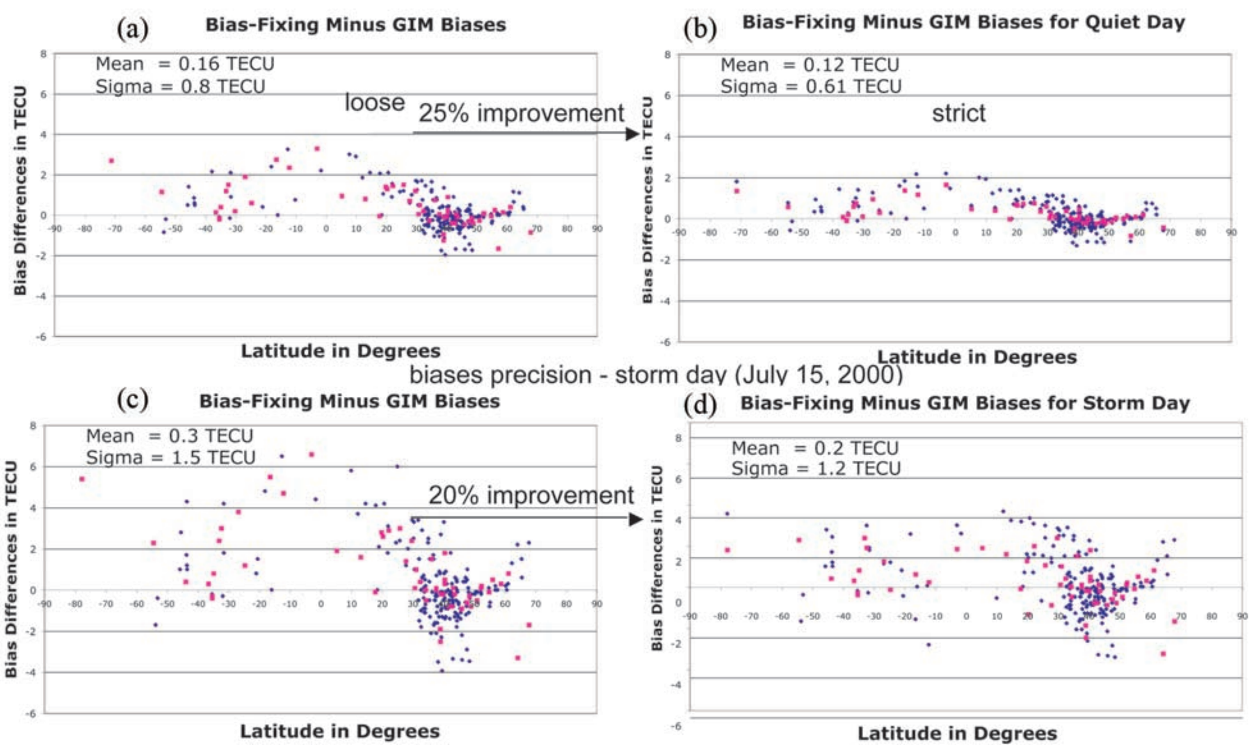

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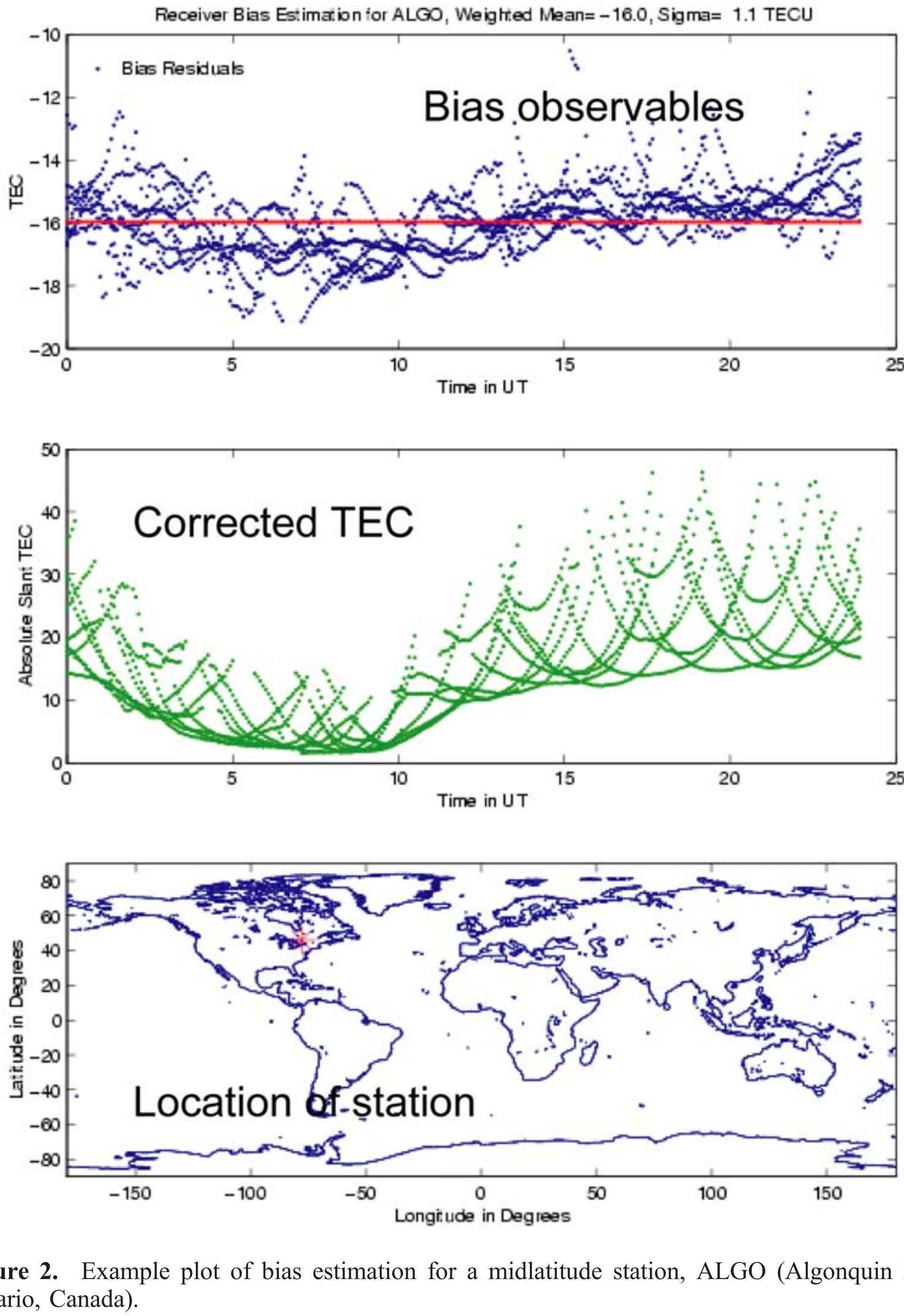

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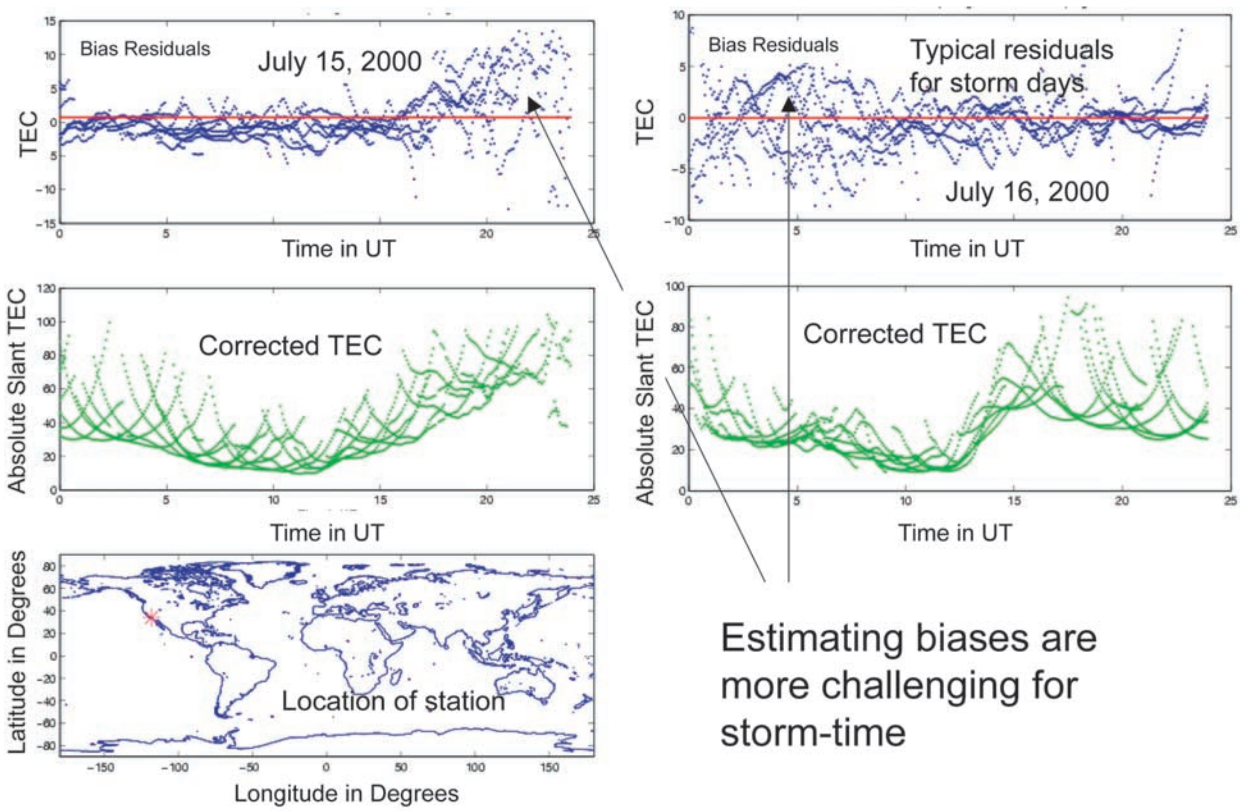

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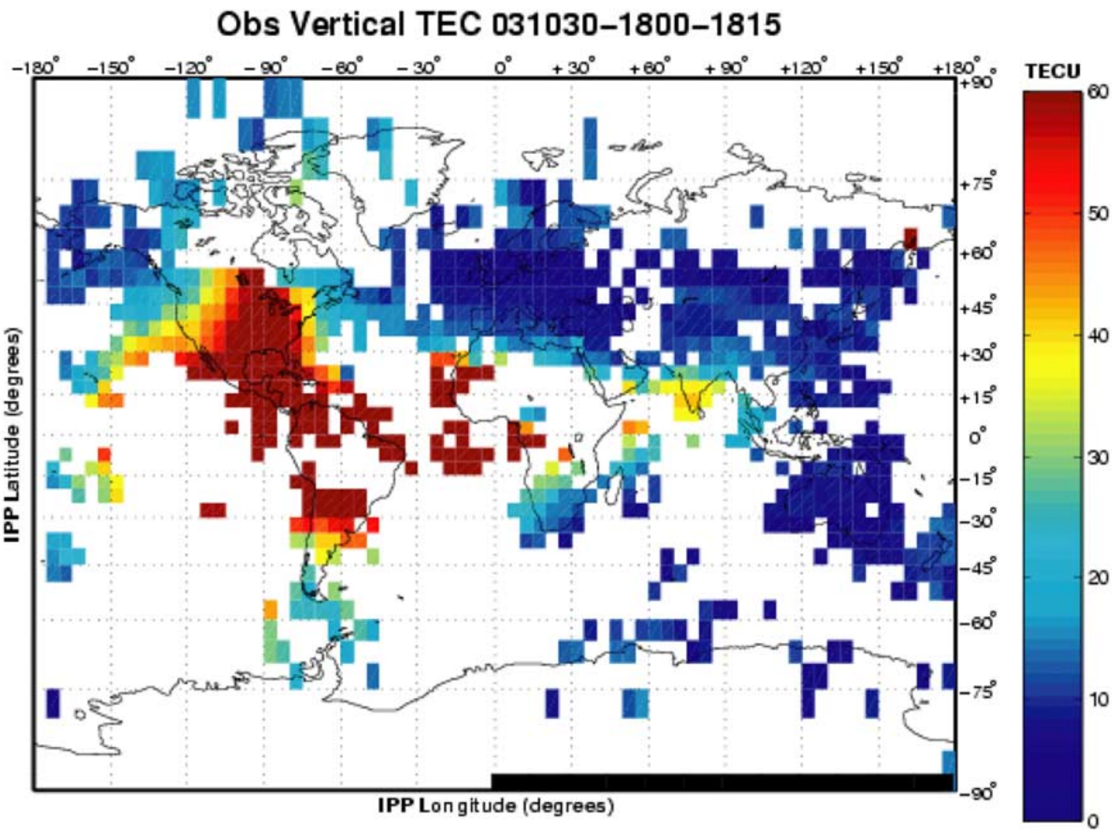

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