GPS and Ionosphere

Revised Submission to URSI Reviews of Radio Science

March 1999 edition

A. J. Mannucci
B. A. Iijima
U. J. Lindqwister
X. Pi
L. Sparks
B. D. Wilson

Jet Propulsion Laboratory, Pasadena CA
January 7, 1999

Author Contact Information:
Tony Mannucci
Jet Propulsion Laboratory
MS 138-308
4800 Oak Grove Drive
Pasadena, CA 91109

Tony.Mannucci@jpl.nasa.gov
818-354-1699 (Phone)
818-393-5115 (FAX)

1. Introduction

The **Global Positioning System** (GPS) constellation of satellites is revolutionizing the science and technology of the Earth's **ionosphere**. It is a unique and unprecedented resource for ionospheric measurements because it provides: (1) *instantaneous global coverage,* (2) *continuous operation,* (3) *high temporal resolution, and* (4) *near real-time data acquisition.* In this paper, we will review technology and selected applications of ground-based dual-frequency GPS receiver networks for ionospheric observations. Over the last few years, several groups have developed techniques for retrieving the global-scale distribution of zenith-looking **total electron content** (TEC) using GPS. At JPL, we have developed real-time and operational global mapping systems that operate continuously, forming high time resolution TEC maps characterizing the dynamic behavior of the ionosphere. Such systems will play an increasingly important role in the developing field of **space weather** [*Klobuchar*, *1997*].

This review begins with a discussion of calibrating GPS ionospheric measurements, including a newly reported technique for hardware calibration using a standard reference signal. We then describe global mapping methods applied to GPS data, with reference to both standard techniques employing a shell model of the ionosphere, and newer tomographic retrieval methods that require less restrictive assumptions about ionospheric vertical structure. Global TEC maps generated at JPL have been applied in several areas including: calibrations of ionospheric delay for satellite-based ocean altimeter observations, and studies of ionospheric disturbances or storms caused by solar eruptions. Ionospheric storm indices can be defined from analysis of the deviations of storm-time TEC maps from recent quiet-time patterns. The new indices may prove useful for characterizing the ionospheric component of space storms, traditionally characterized solely in terms of geomagnetic measurements. Eventually, we expect global maps to be useful for near-term forecasting of ionospheric storms, using empirical methods that complement the model-based approaches of the U.S. space weather program.

2. Calibrating GPS ground observations

In this section, we will discuss the important task of calibrating GPS-based ionospheric measurements. Conventional receivers with analog preamplifiers and front-end down-converters introduce nanosecond-level differences in the delay of the two GPS frequencies as the signals propagate within the circuitry of receivers and satellite transmitters. If left uncalibrated, this differential delay can be interpreted as ionospheric dispersion, significantly biasing the ionospheric measurements [*Sardon et al.*, *1994*; *Mannucci et al.*, *1998*]. We will present evidence that continuously operating GPS systems must be recalibrated often (*e.g.* daily) to counteract drifts or sudden changes in the propagation characteristics of space and ground segment hardware.

We begin by reviewing how ionospheric total electron content (TEC) observables are computed. The fundamental quantities measured by GPS receivers are the ranges or signal propagation delays between receiver and GPS satellites in view. Information from at least four satellites simultaneously is combined with the broadcast satellite ephemerides (orbital elements) to compute the instantaneous receiver position. The satellite-receiver *pseudoranges* (*pseudo* because the distance measurements are biased by the receiver's clock uncertainty) are acquired at two frequencies, f_1 (1575.42 MHz) and f_2 (1227.60 MHz), specifically to calibrate ionospheric range delays which generally fall in the range 3-300 TECU (0.5-50 m at the f_1 frequency; 1 TECU is 10^{16} electrons/m^2). Consider the following model of the four GPS observables, applied to a particular satellite *s* and receiver *r*:

$$P_1 = \rho + I/f_1^2 + \tau_1^r + \tau_1^s \tag{1}$$

$$P_2 = \rho + I/f_2^2 + \tau_2^r + \tau_2^s \tag{2}$$

$$L_1 = \rho - I/f_1^2 + \lambda_1 n_1 + \varepsilon_1^r + \varepsilon_1^s \tag{3}$$

$$L_2 = \rho - I/f_2^2 + \lambda_2 n_2 + \varepsilon_2^r + \varepsilon_2^s \tag{4}$$

where L_1 and L_2 are the recorded carrier phases of the signal (converted to distance units), and P_1 and P_2 are the pseudoranges extracted from either the C/A code (P_1 only) and/or the precise P-code (P_1 and P_2). Each observable depends on a non-dispersive delay term ρ, which lumps together the geometric distance, troposphere delays, clock errors, and non-dispersive delays in the hardware signal paths. The carrier phase terms have an integer cycle ambiguity ($\lambda_1 n_1, \lambda_2 n_2$), where n_1 and n_2 are generally unknown (λ_1 and λ_2 are the carrier wavelengths). We are ignoring the effects of antenna phase-center offsets between the two frequencies.

The ionospheric delay terms $\pm I/f_i^2$ (i=1, 2) are dispersive and affect the phase and range observables with opposite sign. The remaining terms in equations 1-4 (ε and τ) are the *dispersive* components of the satellite and receiver hardware delays at the two GPS frequencies. The so-called "ionospheric combination" for both phase and range observables is formed by differencing the phase and range observables at the two frequencies, reducing the number of equations from four to two:

$$P_I \equiv P_2 - P_1 = I(1/f_2^2 - 1/f_1^2) + b_r + b_s \tag{5}$$

$$L_I \equiv L_1 - L_2 = I(1/f_2^2 - 1/f_1^2) + (\lambda_1 n_1 - \lambda_2 n_2) + b_r' + b_s' \tag{6}$$

where the frequency-differenced dispersive biases have been expressed as a single receiver or satellite bias term.

Forming ionospheric observables from the two ionospheric combinations L_I and P_I has been described in the literature (*Mannucci*, [1998]; *Sardon and Zarraoa*, [1997]; *Lanyi and Roth*, [1988]). Briefly, the observable equals the phase combination L_I with a constant term added that compensates for the overall level ambiguity of the phase observations. The constant is the average difference $L_I - P_I$ computed for every point in a data arc. The ionospheric measurements are tied to the P_I combination, which in turn depends on b_r and b_s, the inter-frequency bias (IFB) for the receiver and satellite, respectively. The possibility of integer phase jumps that are undetected by the receiver requires that a phase break detection algorithm be used before the leveling process (for example, using the algorithm of *Blewitt* [*1990*]).

For ground receivers, it is possible to calibrate b_r using direct methods, such as injecting calibrated signals into the receiver front-end, but the same is not possible for the orbiting satellites. The satellite navigation message contains so-called group delay terms T_{GD} that are proportional to the satellite interfrequency biases in equation 5. There is considerable evidence that the broadcast values are incorrect [*Bertiger et al.*, *1998*]. The broadcast T_{GD} values are used by single-frequency GPS users to correct satellite clock estimates; they are related to the interfrequency bias b_s (expressed in TECU) as follows: $T_{GD}(\text{ns}) = 1.5 b_s / 2.85$.

Most attempts at calibrating GPS transmitter biases rely on assumptions about ionospheric behavior to separate the bias and ionospheric contributions in equation 5. This is possible because the time dependence of hardware biases and ionospheric TEC are distinct as a GPS satellite transits over a receiver. During a several-hour pass of data that spans the full range of satellite elevation angles, the ionospheric terms of equations 5 and 6 vary with elevation angle by about a factor of 3, with a fairly predictable form, primarily due to changes in the geometrical thickness of the ionized layer traversed by the signal. Assuming that the bias term $b_r + b_s$ is constant over a pass, a least-squares fit to the measurements retrieve the sum with good precision (<< 1 TECU). *Bishop et al.* [*1995*] describe a related bias estimation method that does not use least-squares. Of course, the fidelity of the ionospheric delay model influences the accuracy of the retrieved biases. Bias estimation is most accurate during solar minimum periods and in the absence of disturbed conditions, especially within the well-behaved mid-latitude regions.

To form accurate TEC observables, it is important that the IFBs remain constant over time scales characteristic of GPS transit times, typically in the range 4-8 hours (depending on latitude). The general question of bias stability is important in the context of continuously operating global mapping systems developed at JPL, since stability determines how often biases must be re-estimated to maintain accuracy.

There is considerable evidence indicating satellite biases can be quite stable, or exhibit very gradual drifts, over periods of several months [*Sardon and Zarraoa, 1997*; *Wilson and Mannucci, 1994*; *Coco et al., 1991*]. Satellite bias estimates derived daily from our global mapping process are plotted in Figure 1 for two satellites in 1997. All the estimates are bounded within about 0.2 ns (0.38 TECU) of the mean value. Other satellites were found to exhibit gradual linear drifts (see *Sardon and Zarraoa* [1997] for examples). If these typical results could be guaranteed, re-estimation of the satellite biases on a monthly basis would be sufficient for attaining sub-TECU measurement precision. In practice, satellite biases should be re-estimated at least daily, because infrequent but unanticipated variations in bias are possible. A striking example is shown in Figure 2, indicating a significant bias jump (~2 TECU) occurred for satellite PRN 10 on Nov. 29, 1996. It was subsequently learned that the jump coincided with a configuration change in the satellite clock hardware.

The stability of receiver biases is a complicated issue because of the many different receiver types available and the possible temperature environments (temperature variations can influence the IFBs). In contrast to GPS satellite biases, receiver biases can be calibrated directly. A system that continuously monitors the IFB of a receiver has been developed at JPL to support NASA's operational media calibrations for tracking sites [*Duncan et al., 1998*]; see Figure 3. A dual-frequency L-band signal with known delay is synthesized and continuously injected into the receiver front-end, and processed in a spare receiver channel simultaneously with the actual satellite signals. An observable similar to P_I (equation 5) is extracted from the synthesized signal, providing a measurement of the IFB. Calibration data for the receiver supporting the Australian tracking site is shown in Figure 4. These data show a clear diurnal variation of the bias (~ 1 TECU PP) that is probably due to temperature variation, apparently originating in the receiver hardware rather than the calibration standard [*Franklin and Duncan, 1998*].

Calibrations for most receivers in the global network are estimated once per day at JPL in an operational process that supports the GEOSAT Follow-On ocean altimetry mission (discussed below). Unmodeled sub-daily bias variations, as shown in Figure 4, will limit the accuracy of the TEC observables. To improve accuracy, we are currently investigating re-estimating biases every six hours, which reduces the precision of the estimates but may increase accuracy, because the estimates will track the varying bias.

2.1 Comparisons between GPS and Other Measurement Techniques

There is still considerable interest in comparing GPS-derived ionospheric observables with independent techniques, both to validate GPS and to augment the remote sensing capabilities of other methods. *Lanyi and Roth* [*1988*] compared GPS measurements to TEC derived from beacon satellite transmissions (Faraday-effect). This is followed more recently by comparisons at Boulder, Colorado [*Conkright et al.*, *1997*]; both techniques showed good agreement in tracking TEC changes. Peak electron density measurements (N_mF2) from ionosondes obtained simultaneously with GPS measurements were used to study the equivalent slab thickness of the ionosphere (see *Breed et al.*, [*1997*]; *Houminer and Soicher*, [*1996*]). Collocated GPS receivers and ionosondes tracking a traveling atmospheric disturbance during a major geomagnetic disturbance over Europe are reported by *Ho et al.* [*1996*]. Comparisons between GPS and incoherent scatter radar measurements of electron density are discussed by *Jakowski et al.* [*1996a*]. Measurements of vertical total electron content available since 1992 from the TOPEX dual-frequency satellite altimeter are discussed in more detail below with reference to assessing the accuracy of global ionosphere TEC maps derived from GPS.

3. Modeling GPS Observations of Total Electron Content

We have found that mapping TEC observations from the global GPS receiver network is a powerful method for producing accurate global-scale retrievals. Mapping is an empirical approach for interpolating the TEC observations by fitting a predetermined functional form to the data, using streamlined assumptions about ionospheric dynamics and structure. Our approach uses sequential weighted least-squares estimation (Kalman filtering); see *Mannucci et al.* [*1998*]. In this section, we will discuss the general methods and approximations embodied in the TEC mapping method as developed by JPL and others.

GPS provides measurements of the integrated electron density along the raypath between satellite and receiver. Mathematically, this can be expressed as:

$$I = \int_{\mathbf{x}_r}^{\mathbf{x}_s} \rho(\theta,\phi,h)\,ds \qquad (7)$$

where I is the TEC, ρ is the electron density, and the integral is along a straight raypath between receiver and satellite locations $\mathbf{x}_r, \mathbf{x}_s$ (assuming straight-line propagation causes insignificant path location errors of several meters at L-band frequencies; *Bassiri and Hajj*, [*1993*]; *Klobuchar*, [*1996*]). Viewed as a remote-sensing technique, GPS observations are used to invert equation 7 and solve for the underlying density field. Using only ground-based measurements, it has been shown that the vertical resolution of such a direct approach is limited [*Hajj, 1994*], so several reported GPS-related retrieval methods assume a simplified form of equation 7 to extract approximate distributions. The first and still most common approximation is the ionospheric "shell-model", used extensively at JPL, where only the horizontal (latitude/longitude) variation of ρ is retrieved directly. More recently, methods that also estimate the vertical distribution using GPS data have been developed, both for processing real data and in simulations [*Howe et al., 1998*; *Ruffini et al., 1998a*; *Ruffini et al., 1998b*; *Juan et al., 1997*; *Bernhardt et al., 1998*; *Rius et al., 1997*; *Hansen et al., 1997*]. These so-called "tomographic" approaches will become increasingly important as the new generation of space-based GPS receivers in low-Earth orbit are deployed, that measure TEC along raypaths traversing the ionosphere horizontally [*Hajj and Romans, 1998*; *Leitinger et al., 1997*; *Rius et al., 1997*; *Rius et al., 1998*; *Ruffini et al., 1998b*].

3.1 The Shell Model

The central approximation in the ionospheric "shell model" is the following: the horizontal variation in electron density along the raypath between satellite and receiver is ignored. This assumption permits retrieval of the vertical total electron content *between* raypaths. For measurements at high-elevation angle, the approximation is excellent, but is poorer for low-elevation measurements particularly during dusk local times, or near the equator when horizontal gradients are significant [*Tsedilina and Weitsman, 1992*; *Klobuchar et al., 1993*].

The equations governing the shell model approximation are derived as follows: since the horizontal density variation is assumed negligible along the raypath, equation 7 can be approximated by evaluating the density at a single latitude/longitude coordinate known as the "shell intersect point" θ_m, ϕ_m:

$$I \approx \int_{\mathbf{x}_r}^{\mathbf{x}_s} \rho(\theta_m, \phi_m, h) ds \tag{8}$$

The horizontal variation of ρ is fixed within the integral, so for convenience we define $\rho_m(h) \equiv \rho(\theta_m, \phi_m, h)$. Transforming the variable of integration to height, and using the geometrical transformation that relates path to height changes:

$$ds = \frac{dh}{\sqrt{1 - \frac{\cos^2 E}{(1 + h / R_E)^2}}} \tag{9}$$

equation 8 becomes:

$$I \approx \int_{h_r}^{h_s} \frac{\rho_m(h)dh}{\sqrt{1-\dfrac{\cos^2 E}{(1+h/R_E)^2}}} \tag{10}$$

where R_E is a mean Earth radius, h is the height above the Earth, and E is the elevation angle of the satellite. To derive the simplified shell model form, first note that the total electron content $I_V(\theta_m, \phi_m)$ for vertical raypaths (E= 90°) can be written as follows, without approximation:

$$I_V(\theta_m, \varphi_m) = \int_{h_r}^{h_s} \rho_m(h)dh \tag{11}$$

since for vertical raypaths the horizontal variation of density can be ignored. Combining the approximate form in equation 8 with the exact expression 11, we obtain:

$$I \approx I_V(\theta_m, \phi_m)M(E) \tag{12}$$

where *M(E)*, known as the elevation scaling or obliquity function, is defined as:

$$M(E) = \frac{\displaystyle\int_{h_r}^{h_s} \frac{\rho_m(h)dh}{\sqrt{1-\dfrac{\cos^2 E}{(1+h/R_E)^2}}}}{\displaystyle\int_{h_r}^{h_s} \rho_m(h)dh} \tag{13}$$

Equation 12 defines the shell model approximation. The retrieval problem has been simplified to estimating a horizontally-varying vertical TEC distribution $I_V(\theta_m, \phi_m)$ and computing an elevation scaling function *M(E)*. A commonly used form for the obliquity factor is derived assuming that $\rho_m(h)$ is non-zero in a thin region about the shell height. This "thin shell" factor $M_{TS}(E)$ is implicit in equation 9 that transforms the path length element *ds* to the height element *dh*; that is: $ds = M_{TS}(E)dh$.

The shell model reduces the number of dimensions of the unknown spatial field from three (latitude/longitude/height) to two (latitude/longitude). Since a unique shell intersection point can be defined for each GPS measurement, global TEC maps are formed by interpolating vertical TEC estimates between the pierce points. The vertical TEC is estimated from slant observations by scaling to equivalent vertical using a pre-determined form for *M(E)*. The interpolation between vertical TEC estimates can be described as follows: a set of basis functions is defined whose domain is the spherical ionospheric shell. The retrieved vertical TEC distribution consists of a linear combination of these functions, and the multiplicative coefficients are computed based on minimizing the residual difference between the vertical TEC data and maps evaluated at the measurement pierce points. The vector of best fit coefficients combined with the basis functions defines a global TEC distribution that provides interpolated values covering the entire sphere.

3.2 Global Mapping

Each TEC measurement T_{rs} between receiver r and satellite s is modeled by the following expression:

$$T_{rs} = M(E) \sum_{\substack{\text{all non-zero} \\ \text{basis functions i}}} B_i(\theta,\phi)C_i \qquad (14)$$

where $B_i(\theta,\phi)$ is a basis function evaluated at the pierce point latitude and longitude (θ,ϕ). The coefficients C_i are selected such as to minimize, in a least-squares sense, the difference between each measurement and the model. Not all the data are fitted simultaneously but rather in 15-minute batches. The fits are not independent; the coefficients are correlated in time as described in Section 3.4. Once the C_i are determined at each time interval, vertical TEC are mapped to any point by evaluating the summation expression for the latitude and longitude of interest [*Mannucci et al., 1998*].

An important consideration in global TEC mapping is the choice of basis functions $B_i(\theta,\phi)$. A natural choice is the use of surface harmonics, based on Legendre polynomials that are orthogonal over a sphere [*Wilson et al., 1995*; *Imel, 1994*; *Howe et al., 1998*; *Dow et al., 1996*]. A problem with this approach, as discussed in *Mannucci et al.* [*1998*], is that these basis functions possess global support; that is, each basis function is non-zero everywhere over the sphere. Fitting these functions to the GPS data, which are clustered over continents and islands, causes the global maps to adjust where data are absent, for example in ocean regions. This interferes to some extent with the persistence assumption used to generate global maps (see below). Most successful uses of surface harmonics perform the fits on long time-averages of data (12-24 hours). When placing the spherical shell in a local time reference frame, time averaging produces a dense distribution of pierce point locations as the stations rotate diurnally under the ionospheric shell. This reduces the problem of spatial data gaps, but the resultant maps cannot follow the significant dynamic variations that occur over such long time scales. The surface harmonic approach can be applied with greater time resolution over continental-scale maps, where closely spaced receivers ensure that a high density of measurement pierce points is always available [*Hansen et al.*, *1997*].

Recently, the global mapping approaches at JPL have focused on the use of basis functions with so-called "local support". Each basis function is non-zero over a limited portion of the sphere, so each data point affects the TEC retrieval over a limited neighboring region. This locality is desirable on physical grounds since dynamic changes in the ionosphere over widely separated global regions are generally uncorrelated. Long time averages to fill data gaps with pierce points are unnecessary. Recently published techniques [*Mannucci et al.*, *1998*] describe a locally supported basis set based on interpolating TEC within triangular tiles that cover the ionospheric shell uniformly, resulting in a vertical TEC distribution that is continuous; first-order or higher spatial derivatives are generally discontinuous. Another basis set used at JPL, developed by Charles Lawson, produces TEC surfaces over a sphere guaranteed to have continuous spatial derivatives at least up to second-order. These spatially smoother functions, based on bicubic splines, are used in the operational global mapping system described below. Examples of the spatial variation of a single basis function over a local region are shown in Figure 5. The spatial resolution of the maps is finer than the spatial extent of a single function, since the support regions of neighboring functions overlap. Note that the tomographic work of *Hajj et al.* [*1994*] and *Juan et al.* [*1997*] also uses locally supported basis sets, consisting of constant density pixels in the horizontal and vertical dimensions.

Another important element in global mapping is the choice of elevation scaling factor *M(E)*. The functional form used in JPL global maps currently is based on a fixed density profile $\rho(h)$ that represents a slab function with exponential tails [*Coster et al.*, *1992*]. A shell altitude of 450 km is used for computing the pierce point location. Many researchers have used the so-called "thin shell" obliquity factor of equation 9 [*Sardon et al.*, *1994*; *Wilson et al.*, *1995*; *Coco et al.*, *1991*; *Lanyi and Roth*, *1988*]. As a practical matter, it appears that the functional form of the density used to derive *M(E)* is less critical than the height at which the density profile is located. An example is shown graphically in Figure 6 where several obliquity factors are plotted for different $\rho_m(h)$. If density heights are adjusted properly, scaling factors display close agreement. The slab and extended slab functions were determined analytically. The Chapman profile was derived using numerical integration (height of maximum production = 350 km, scale height = 100 km). The slab model has a constant density between heights 300-500 km and zero density elsewhere. The extended slab parameters are described in *Mannucci et al.*, [*1998*]. In the next section, we discuss approaches that relax the shell model assumption.

3.3 Retrieving Vertical Electron Density Information from GPS

Over a pass of GPS data, the variation of measured TEC with elevation angle is sensitive to both the horizontal and vertical structure of the density field, so in principle some information about the height distribution can be inferred from the measurements. The raypaths of ground-based measurements cannot be used to resolve fine-scale (~10-100 km) vertical structure [*Hajj, 1994*], but information of a limited kind may be extracted. For example, researchers at Aerospace Corporation [*Zeitzew et al., 1998*] have performed simulation studies retrieving the height of a thin shell ionosphere, by iteratively re-evaluating regional fits over the US with varying shell heights. *Feltens* [*1998*] has used GPS ground data from global networks to estimate a height parameter within the Chapman electron density profile that is assumed to describe the global density distribution.

A different approach to estimating characteristics of the vertical electron density distribution has been developed at JPL, relying on a fully three dimensional model (not a shell model) of the ionosphere for retrieving an approximate density field (*Howe et al.* [*1998*], and *Hansen et al.* [*1997*] use a similar formulation applied to GPS data; see also *Fremouw* [*1992*] for a non-GPS application). The retrieved density is used to compute an "effective" height of the ionosphere (defined below) as a function of latitude and longitude.

We assume the electron density field $\rho(\theta,\phi,h)$ can be represented as a product of two functions that vary separately in the horizontal and vertical dimensions:

$$\rho(\theta,\phi,h) = \sum_{\substack{\text{lat/lon functions } i,\\ \text{height functions } j}} C_{ij} B_i(\theta,\phi) F_j(h) \tag{15}$$

This factored form is not completely general, but covers a sufficiently broad range of distributions as to be very useful (note that pixel-based retrieval methods , such as used by *Juan et al.* [*1997*] or *Ruffini et al.* [*1998a*] can be represented in this manner). Substituting this density form into equation 7, integrating over height and interchanging the order of integration and summation, leads to the following three dimensional model for the measurements:

$$I \approx \sum_{i,j} C_{ij} \int_{h_r}^{h_s} \frac{B_i(\theta(h),\phi(h)) F_j(h) dh}{\sqrt{1 - \dfrac{\cos E}{(1 + h/R_E)^2}}} \tag{16}$$

where the dependence of latitude and longitude with height along the raypath has been explicitly indicated.

The system of equations 16, one for each measurement, is amenable to linear least squares solution since the integral is well defined for each raypath and therefore is a calculable number for each measurement prior to obtaining the solution. The C_{ij} are fitted to the observations in the same manner as the C_i are fitted in the shell model. Both approaches are implemented in the global mapping software at JPL, which uses either the bicubic or bilinear basis functions in the horizontal dimensions, augmented by empirical orthogonal functions for the height bases $F_j(h)$ in the three-dimensional approach.

After estimating the C_{ij}, the retrieved electron density field can be computed up to the maximum height of the functions $F_j(h)$ in equation 15. However, using ground data alone, the detailed structure of vertical profiles is not uniquely determined. Therefore, we compute a single "effective height" for the electron density distribution using a procedure that depends on the height integral of the density. The height integral enters via the elevation scaling function *M(E)* (equation 13) which is sensitive to the height of a given electron density profile (see Figure 6). The height determination proceeds as follows: First, we perform numerical evaluation of the function *M(E)* over a range of elevation angles from 10° to 90°, substituting for $\rho_m(h)$ the retrieved density at a latitude and longitude of interest (equation 15). The computed obliquity function is subtracted from a series of thin-shell obliquity functions computed for shell heights in the range 100-1200 km, with a minimum step size of 5 km. Finally, the thin-shell function producing the smallest mean-square difference from the retrieved *M(E)* determines an "effective height" for the electron density distribution at a particular latitude and longitude.

Results from this height determination procedure applied over the North American continent are shown in Figure 7 for two time periods. The height retrievals differ dramatically, but do follow the expected trend of increasing height as the Sun goes into shadow. During afternoon (Figure 7a), height is relatively constant over the central continental region, which is centered in the solar illumination pattern. At the later time (Figure 7b), a transition to increased heights with nighttime onset is clear, probably due to a flattening of the distribution of electron density with height. The peak electron density at F-layer altitudes (~ 150-800 km) decreases in magnitude at night, due to the absence of ionizing radiation. After sunset, the electron density persists longer at higher altitudes where the electron-ion recombination rate decreases. Thus, the dramatic height variation as the day-night transition varies across the continent shown in Figure 7 is physically plausible, but tends to exceed the day/night height variation predicted by climatological models such as Bent or IRI95. However, these models do not include protonosphere contributions which are measured by GPS (altitude 20,200 km), where the H+ ion dominates at super-ionospheric altitudes above about 1200 km. This contribution to the TEC can be significant particularly at night. This preliminary work is encouraging in that it shows GPS-based techniques are sensitive to physical conditions within the ionosphere that affect the height distribution of electron density. We are currently pursuing quantitative validation of this approach using simulations and comparisons with independent data.

3.4 Dynamic TEC Maps - Kalman Filtering and Persistence

Determining the coefficients (C_i or C_{ij}) is done using the familiar least-squares algorithm, implemented as a Kalman filter. A complete discussion is beyond the scope of this paper (see *Gelb* [*1989*]; *Jazwinski* [*1970*]). An important advantage of this approach is that it provides a natural framework for including time-dependence in the estimation procedure, and hence the global maps themselves.

The Kalman formulation provides a method for propagating the least-squares solution *and its covariance* in time. A linear, discrete time-dependent model for the coefficients is used that relates coefficients at time index j+1 to the coefficients at the previous time index j. (For global maps, the discrete time intervals range from 15 minutes to several hours.) Grouping the coefficients as elements of a vector $\mathbf{C}$, the dynamical model has the following form [*Bierman, 1977*]:

$$\mathbf{C}_{j+1} = \mathbf{\Phi}_j \mathbf{C}_j + \mathbf{G}_j \mathbf{w}_j \qquad (17)$$

where $\mathbf{C}_j$ is the coefficient vector (the "state vector") at time step j, $\mathbf{\Phi}_j = \mathbf{\Phi}(t_{j+1}, t_j)$ is a transition matrix relating the state at time t_j to the state at time t_{j+1}, $\mathbf{w}_j$ is a vector of zero-mean random variables with covariance matrix $\mathbf{Q}_j$, and the matrix $\mathbf{G}_j$ permits linear combinations of the random variables to influence the dynamics. The two terms in this equation represent two mechanisms that cause the solution coefficients to vary in time: deterministic variation described by the $\mathbf{\Phi}_j$ matrix and additive, random forcing modeled by the $\mathbf{w}_j$.

In principle, the dynamical behavior of the TEC maps should be derived from the physical laws that govern the behavior of ionized atmospheres, represented mathematically as non-linear coupled partial differential equations [*Schunk, 1988*]. However, these equations are difficult to solve because boundary conditions are uncertain, and many atmospheric quantities, such as the concentrations of the neutral constituents must be obtained from climatological averages [*Bailey and Balan, 1995*]. The mathematical difficulties of this rigorous approach have been avoided to some extent by performing the mapping in a reference frame (solar-geomagnetic) in which ionospheric variability is significantly reduced [*Knecht and Shuman, 1985*; *Mannucci et al., 1998*]. In regions near GPS receiver sites, vertical TEC at a particular solar-geomagnetic coordinate is determined by direct measurements; in regions of the shell far from receivers, the maps are determined by the persistence of the TEC retrieved from prior times, when receivers were nearby. The observations drive the map in the presence of direct measurements, and persistence of the latest measurements is used to extend the reach of the observations to other local times. The dynamical model for this case reduces to the following simpler form:

$$\mathbf{C}_{j+1} = \mathbf{I}\mathbf{C}_j + \mathbf{w}_j \tag{18}$$

where the Φ_j matrix is set to the identity $\mathbf{I}$ (this enforces persistence), and the $\mathbf{w}_j$ are taken as white noise processes with diagonal covariance matrix $\mathbf{Q}_j$. The random component of the time variation increases the variance of the estimates with time, and determines how rapidly the influence of older maps is ``forgotten" compared with the influence of the newest data, allowing the solution to follow smoothly the most recent observations. It should be emphasized that equation 18 is a model of the time variation for the solution coefficients; it affects how the covariance is propagated (via the Q and Φ_j matrices; see *Bierman* [*1977*]; *Jazwinsky* [*1970*] or *Gelb* [*1989*]) but does not imply that random values are actually added to the solution coefficients.

The physical conditions that support persistence as a mechanism for bridging data gaps tend to be disrupted during space storms. Under disturbed conditions, ion production and recombination can vary rapidly in space and time. The electrodynamics of the low-latitude region, influenced by varying zonal electric fields, also shows relatively large variability in a local time frame even under normal conditions. Research is currently underway to investigate how the simple dynamics represented in equation 18 can be improved, in the context of the mapping approaches described here.

3.5 Aiding TEC Mapping with Climatological Models

As implemented at JPL, the data fitting approach to TEC mapping described above uses information from climatological models to constrain the solution in data sparse regions. As described in *Mannucci et al.*, [*1998*], simulated vertical TEC measurements generated over a regularly spaced grid every hour are combined with the data. This tends to smooth the solutions spatially, but does not alter the fits significantly near GPS receivers since the simulated data are assigned a low weight (high measurement variance). Another approach to using climatological models in TEC mapping has been developed by *Komjathy et al.* [*1998*; *Komjathy and Langley, 1996a*; *Komjathy and Langley*; *1996b*]. *Jakowski et al.* [*1998; 1996a; 1996b*] use GPS data to update a regional TEC model over Europe. *Reilly and Singh* [*1997*] discuss a method of updating the RIBG climatological model with GPS data.

Komjathy's method uses the IRI95 climatological model to improve upon an initial global TEC map produced using the shell model. The initial map produced hourly is used to update the effective sunspot number index input to IRI95 (IG_{12}). Iteration determines the IG_{12} index that best matches the initial map over a global set of grid points. This produces an updated IRI95 model that takes the regionally varying IG_{12} index as input; TEC is extracted by integrating the model density profiles. The IRI95 model is thus used as a "sophisticated interpolator" of the initial map that takes advantage of the sophisticated ionosphere models embedded in IRI95. Improvement is expected because the initial map is produced relatively infrequently (hourly) using the less sophisticated shell model. An attractive feature of this approach is that any initial map can be used in the update procedure; the value added from the climatological model probably depends on the quality of the initial map and is a current research topic.

4. Application to Calibrations for Ocean Altimetry

An automated process running JPL's global ionosphere mapping software (GIM) on a daily basis is currently operational, providing timely ionospheric calibration data for the ocean altimeters on the GEOSAT Follow-On (GFO) and ERS-2 satellites [*Schreiner et al., 1997; Ruffini et al., 1998b*]. These altimeters measure ocean height by measuring the time delay of radar pulses reflected off the ocean surface. The delay includes a component due to the electron content of the ionosphere that is to be calibrated and removed [*Bilitza et al., 1988*]. Using GPS TEC maps, calibrations are provided along the satellite ground track, suitably scaled to remove estimates of the TEC contributions above the satellite altitude of 800 km. This system produces a daily time-series of global maps of ionospheric TEC, and interfrequency bias estimates for the GPS satellites and receivers in the global network.

We make use of data from the global network of GPS receivers coordinated by the International GPS Service (IGS), a cooperative organization whose member institutions (including JPL) provide GPS data in a timely fashion (typically less than 1 day latency) from GPS sites they operate. The member institutions send their data to the IGS data centers each of which archives a complete set of data for the IGS GPS receivers. The IGS is thus a source of freely available, timely globally-distributed ionospheric TEC data. The distribution of receiver sites as of August 1998 is shown in Figure 8.

4.1 Operational Structure

Figure 9 is a data flow diagram for the daily GIM process. Figure 10 shows the logic of the daily process, that performs the following functions:

1. Collect globally-distributed GPS data from the JPL GPS Data Handling Facility and other IGS Data Centers.

2. Run the GIM software that edits the GPS data, extracts the TEC observables, and produces a time series of global maps of ionospheric TEC and interfrequency biases, using the Kalman-filter mapping as discussed in Section 3.4.
3. Perform automatic assessment of the maps by comparing mapped TEC to climatological ionosphere models and to TOPEX/Poseidon ionospheric data (discussed below), if available.
4. Compute altimeter ionospheric calibrations for GFO and ERS-2.
5. Deliver maps and altimeter calibrations to an ftp server.

A recent addition to this process is production of hourly global ionosphere maps on a 2x2 degree rectangular grid in the new IONEX format recently standardized by the IGS [*Dow et al., 1996; Schaer et al., 1998*].

The GFO satellite requires "quick-look" daily ionosphere calibrations within 24 hours of the end of day. In addition, a second "final calibration" is done within 72 hours of the end of day which takes advantage of GPS data that becomes available after the first calibration. Therefore GIM is run twice for each day, once to meet the 24 hour deadline, and again to meet the 72 hour deadline. Reliability of the process and the ionospheric maps produced is important, and the following measures are taken to ensure robustness and valid results:

1. The process is run simultaneously on a second platform for redundancy.
2. The comparisons against TOPEX/Poseidon TEC data and climatological ionosphere models are used as sanity checks before delivery. Data from the TOPEX altimeter (altitude 1330 km) are typically available within 8 hours of day's end.
3. Resultant maps and comparisons and other verification data are displayed on an internal web site for observation by the operators.

Global maps of ionospheric TEC include the electron density from the ground to the GPS altitude of 20200 km. However, GFO and ERS-2 both orbit at about 800 km altitude, so the electron content between 800 and 20200 km must be estimated and subtracted from the GIM to produce ionospheric calibrations for the altimeters. Electron density profiles from the International Reference Ionosphere 1995 (IRI95) [*Bilitza and Rawer*, *1998*] (up to 1400 km) are used to compute the super-satellite fraction of TEC. Other approaches, including use of the Gallagher plasmasphere model [*Gallagher et al., 1988*], are being assessed using independent TEC data from 800 km altitudes. These results will be reported elsewhere.

4.2 Assessment of GIM Accuracy

The accuracy of JPL's global maps is routinely assessed by comparison with independent vertical TEC data obtained over the Earth's oceans from instruments onboard the TOPEX/Poseidon (T/P) satellite [*Imel*, *1994*; *Christensen et al., 1994*].

The dual-frequency ocean altimeter onboard T/P orbits at an average altitude of 1330 km completing one revolution every 100 minutes. The orbit is nearly sun-fixed; at a given latitude, the local time changes about 12 minutes per day. The dual-frequency calibration is sensitive primarily to ionospheric delays; protonospheric electrons that affect GPS are not included. Nevertheless, T/P provides accurate comparison data with global coverage (estimated error is 2-3 TECU; *Imel* [*1994*]). In Figure 11 we present statistical analysis of the difference between TOPEX TEC and GIM covering four local time ranges and two geomagnetic latitude ranges: low ($|\text{latitude}| < 30°$) and middle-to-high ($|\text{latitude}| > 30°$; maximum TOPEX latitude is ~67°). These comparisons cover nearly every ascending and descending TOPEX track (~ 26 per day) during 35 days covering the period from November 2, 1997 to January 16, 1998. During this time, the local times of the equatorial crossings of TOPEX ground tracks spanned the full range local noon to midnight. Assuming that TOPEX accuracies do not vary with latitude, the comparisons indicate that GIM accuracy is reduced at low latitudes relative to mid-latitudes. This corroborates earlier results reported in *Ho et al.* [*1997*]. The GIM retrieval method has improved in accuracy since Ho's analysis, but we expect the overall trends to be similar. Note that the improved agreement at night, when the protonospheric contribution is largest [*Gallagher et al., 1988*], tends to validate our assumption that TOPEX/GIM differences are dominated by ionospheric delays. However, independent estimates of protonospheric delays would make the TOPEX comparisons more useful.

It is interesting to consider the causes of reduced GIM accuracy at low latitudes relative to mid-latitudes. Several factors probably play a role: 1) larger TEC at low latitudes; 2) fewer GPS receivers relative to the area being mapped; 3) reduced effectiveness of the persistence assumption due to increased ionospheric variability; and 4) increased errors in the scaling of slant TEC to equivalent vertical due to horizontal gradients. The results reported by *Ho et al.* [*1997*] are a useful resource when considering the relative importance of these factors. *Ho et al.* computed the distance to the nearest GPS receiver for each TOPEX/GIM comparison data point; statistics of the difference GIM - TOPEX were binned according to the receiver distance. In a simplified picture, in the vicinity of measurements TEC map accuracy is primarily limited by the shell model assumption and may scale with overall TEC level. At GIM locations far from receivers, GIM accuracy is also limited by the assumption that for a given local time TEC persists unchanged. Not surprisingly, *Ho et al.* find that GIM errors increase with distance to the closest GPS receiver, but results vary widely depending on the level of geomagnetic activity (or possibly season). For the period of high geomagnetic activity (March 10-20, 1993) the root-mean-square (RMS) difference between GIM and TOPEX was 7.4 TECU for TOPEX/GIM points within 1000 km of a receiver. The corresponding statistic for mid-latitudes is 2.6 TECU. This suggests that shell model errors are significantly larger at low latitudes. For the geomagnetically quieter period (August 6-16, 1993), the increased low latitude error is much less significant: 3.4 versus 2.0 TECU at middle latitudes. At large distances from the receivers (~ 3000 km) additional mapping errors increase the RMS difference to about 8 TECU at mid-latitudes and 16 TECU at low latitudes (geomagnetically active period). Although GIM algorithms have been recently optimized, recent statistical results (April-November 1998) show comparable trends: at mid-latitudes near receivers, GIM is accurate to 2-3 TECU; this increases to 4-5.5 TECU at large distances. For low latitudes, the errors increase from 3-4.5 TECU near receivers to about 10 TECU.

Vladimer et al. [*1997*] attempted a direct assessment of the shell model at low latitudes by converting GPS slant observations to vertical and comparing with nearby TOPEX measurements. They present cases where GPS differs from TOPEX by 10-20 TECU at satellite elevation angles as high as 33 degrees. Comparing to the results of *Ho et al.* discussed earlier, RMS differences between GIM and TOPEX within 1000 km of a GPS receiver are 7.4 TECU and 3.4 TECU for the two periods studied (corresponding to satellite elevation angles above 15 degrees). This suggests the case studies of Vladimer might be inconsistent with the statistical analysis of *Ho et al.* (using 100-km distance bins shows that GIM - TOPEX is fairly insensitive to distance within 1000 km). A possible reason is that *Vladimer et al.*'s analysis combines errors from several factors, not simply the error converting slant observations to vertical TEC. For example, errors might be introduced by spatial and time gaps between the ionospheric pierce points of GPS and TOPEX used in the comparisons. Such errors are reduced in *Ho et al.*'s analysis since the GIM algorithms are fairly effective in mapping TEC from the locations of GPS measurements to those of TOPEX.

Small biases in the GIM retrievals appear to vary systematically with local time. In both latitude ranges, the mean difference between GIM and TOPEX is smallest in the noon sector and largest in the dusk and midnight sectors. This may be due to local time height variations in the ionosphere (*e.g.* Figure 7), whereas the GIM results reported here use a single obliquity function for all local times and latitudes. In a study using data from 1993, *Yuan et al.* [*1995*] found the best overall agreement between GIM and TOPEX occurred for a shell height of 450 km and an obliquity function derived from a tapered slab model [*Coster et al.*, *1992*; *Mannucci et al.*, *1998*]. Daytime retrievals may have had a dominant influence in this study, since the larger daytime TEC values will produce relatively greater sensitivity to choice of obliquity factor. Therefore, it is not surprising that GIM produces better agreement in the mean during daytime. We are currently investigating methods of reducing the larger nighttime bias by varying the obliquity function (shell height) with local time.

5. Application to Ionospheric Science and Space Weather

It has been recognized through decades of research efforts that the ionosphere is a key component of the near-Earth space environment system. This system is composed of magnetosphere, ionosphere, and thermosphere, which are often disturbed by solar activities, such as solar flares and coronal mass ejections. The coupling between these components makes it extremely difficult to predict or to model the space weather, which in response to the solar activities presents significant changes of electric currents, plasma densities, thermospheric winds, etc.. The ionosphere is a very important component not only because it couples with the magnetosphere and thermosphere and transfers energy between them, but also due to the fact that it directly affects technology applications, such as communications and navigation systems that rely on ground-ground, satellite-ground, and satellite-satellite radio links.

In fact, geomagnetic and ionospheric disturbances have repeatedly interfered with satellite operations; the effects range from satellite anomalies, which can be expensive to investigate, to the degradation or loss of critical functions of on-board instruments. Furthermore, disruptions of Earth-to-space communications, navigation systems, cable communications and the distribution of electrical power over transmission lines have also been reported [*Siscoe et al.*, 1994; *Kappenman et al.*, 1997]. A near real-time ionospheric storm warning system could significantly reduce the costs associated with these problems by allowing evasive actions to be taken.

Global ionospheric maps of TEC data, as described in the previous sections, are an unprecedented tool for detecting, monitoring, and understanding the major disruptions of the ionosphere, known as *ionospheric storms,* on global-scales. These maps are unique in four important ways:

(1) *Simultaneous global coverage*. Simultaneous coverage of the global ionosphere renders it possible to observe correlations between storm disturbances on a global scale. For example, it is now possible to observe the relationships between disturbances in different hemispheres. Furthermore, global coverage allows the tracking of dynamical effects in the ionosphere, such as traveling ionospheric disturbances (TID), over great distances.

(2) *Continuous coverage in time*. The fact that global TEC data are available on a continuous basis presents us with an opportunity to categorize systematically the behavior of the global ionosphere over long periods of time and, in particular, to identify and to quantify statistical patterns of similarity that arise in disturbances resulting from different storm events.

(3) *High temporal resolution*. The steady inflow of new GPS measurements permits TEC map updating on time scales appropriate for tracking the evolution of the ionosphere.

(4) *Near real-time accessibility of the data*. The rapid access to GPS data allows global TEC maps of the ionosphere in real-time or near real-time, rendering detection and monitoring of ionospheric storms a reality and short-term forecasting of their evolution a realistic possibility. Near real-time hourly updates of global maps have recently been demonstrated at JPL, using the Internet to transmit the data. Real-time, five-minute map updates are currently operational, using a North American regional

GPS network and transmission over dedicated commercial lines. (Regional maps using the techniques described in *Mannucci et al.*, [*1998*] can be viewed at the following world-wide web address: http://sideshow.jpl.nasa.gov/gpsiono).

To develop an ionospheric storm warning system, it is useful to analyze the global patterns of behavior that characterize ionospheric storms and to categorize these patterns in a quantitative manner that will provide a basis for accurate forecasting. Several such studies have demonstrated the utility of the GPS network for monitoring the global evolution of ionospheric storms [*Ho et al.*, 1996; *Lu et al.*, 1998; *Ho et al*, *1998a*; *Ho et al.*, *1998b*]. In these studies, continuous observation coverage permitted TEC maps of the ionosphere to be generated at intervals of fifteen minutes. Temporal variations in TEC were determined by generating maps of the percent deviation of the storm-time TEC relative to preceding five-day quiet-time average distributions. Dynamic global patterns of activity are readily observed by displaying a sequence of such maps in animation.

In the following section we discuss ongoing efforts to perform analysis and categorization of storms using global maps of TEC data. Such efforts represent significant steps toward developing a system capable of forecasting the short-term evolution of ionospheric storms subsequent to their initial detection.

5.1 Characterization of Ionospheric Storms Using TEC Maps

In an ionospheric storm, distinct phases and patterns may be identified in the behavior of the storm-time variations of the maximum electron density (N_mF2) and the total electron content [e.g., *Matsushita*, 1959; *Mendillo,* 1971; *Prölss et al.,* 1991; *Pi et al.,* 1993]. During the initial phase, the electron density and the electron content are greater than normal, followed by a main phase when these quantities fall below their normal values. The recovery phase typically occupies from one to several days. However, the magnitudes of the changes associated with each of these phases is highly dependent on geomagnetic latitude: this classical behavior is more pronounced at high and middle latitudes. Patterns of ionospheric storms are also found to depend upon the time of day, season and hemisphere.

The magnetic indices, such as Dst, AE and Kp, are known to be poor indicators of ionospheric storm activity: the degree and direction of ionospheric changes can not generally be predicted from the changing values of the magnetic indices [*Mendillo*, *1973*]. Consequently, there is a need to develop indices to indicate the presence and characterize the strength and duration of ionospheric storms.

The disparity between storm-time and quiet-time behavior can be quantified by constructing maps that display the difference between a given storm-time global ionospheric map (GIM) and a corresponding quiet-time average. Animated sequences of such maps permit analysis of the evolution of ionospheric storms on temporal and spatial scales that have been heretofore difficult if not impossible. Preliminary results from the analysis of geomagnetic storms of the past four years suggest that it may indeed be possible to identify certain types or features of ionospheric storms in their early stages in near real-time using GPS global measurements.

Three distinct difference maps prove useful for analyzing a storm: (1) a map of the absolute difference, which emphasizes regions where the variation of the TEC magnitude is greatest, *i.e.*, at low latitudes; (2) a map of the per cent change, which places greater emphasis on TEC variation at high latitudes; and (3) a map of the TEC difference normalized by the standard deviations of the quiet-time average, which generally represents an intermediate compromise between the previous two maps. A absolute difference map is displayed in Figure 12.

5.2 Global Response to Ionospheric Storms

The presence and severity of geomagnetic storms can be inferred from the time variation of standard geomagnetic indices (*e.g.*, Dst, Ap, Kp). As discussed above, however, no comparable indices have been devised to classify ionospheric storms. We have begun to investigate the utility of using spatial averages of differenced global TEC data to construct indices of ionospheric storm severity, in a manner analogous to the use of the geomagnetic indices to measure the severity of magnetic storms [*Sparks et al.*, 1997].

We characterize TEC difference maps according to two scalar quantities M_1 and M_2 that are spatial averages over the globe:

$$
\begin{aligned}
M_1 &\equiv \Omega^{-1} \int d\phi \, d\theta \, sin\theta \left(S(\theta,\phi) - Q(\theta,\phi) \right) \\
M_2 &\equiv \left[\Omega^{-1} \int d\phi \, d\theta \, sin\theta \left(S(\theta,\phi) - Q(\theta,\phi) \right)^2 \right]^{1/2} \qquad (16) \\
&\text{where } \Omega \equiv \int d\phi \, d\theta \, sin\theta
\end{aligned}
$$

$S(\theta,\phi)$ is the storm-time TEC as a function of latitude and longitude, and $Q(\theta,\phi)$ is a quiet-time average TEC. Typically, the quiet-time average at a fixed universal time (UT) is calculated by averaging maps at the same UT for a number of quiet days prior to storm onset. In calculating M_1, regions of enhanced density may cancel regions of depletion and could, therefore, underestimate the global level of the ionospheric disturbance. In contrast, M_2 will tend to better reflect the magnitude of the disturbance but will contain no sign information. Preliminary results indicate that these averages provide a convenient, quantitative measure of the global magnitude and duration of an ionospheric storm. For example, Figure 13 compares the behavior of the Dst index to the averages M_1 and M_2 during the period encompassing the ionospheric storm of April 10-11, 1997, based on difference maps normalized by the quiet-time standard deviation. We are currently investigating candidate difference maps most useful for defining ionospheric storm indices (absolute difference of TEC as in equations 16, per-cent change in TEC, and change normalized by the standard deviation of the quiet-time distribution).

A particular advantage of ionospheric storm indices defined in this fashion is that, unlike the standard geomagnetic indices, they may be determined in near real time. Thus, in an ionospheric storm monitoring and forecasting system, such indices could provide rapid indication of the presence of large-scale ionospheric disturbances.

A disadvantage of these indices is that they depend to some degree upon the distribution of TEC measurements used to produce the maps. As discussed earlier, GIM accuracy at a given location depends on the proximity of GPS receivers. It follows that the distribution of global network sites has an influence on the storm indices. This problem can be mediated by using a canonical station distribution for computing the indices, but this prevents taking full advantage of the expanding IGS network. Another approach is to compute the storm indices separately for locations where the receiver distribution is consistently favorable, *e.g.* over the United States or Europe (*Jakowski et al.*, [*1996b*] describes European TEC mapping). The techniques described here can be readily applied to restricted regions; regional storm indices can be consistently inter-compared over long time periods.

As discussed above, it has long been known that ionospheric disturbances exhibit a strong latitudinal dependence. Categorizing ionospheric storms could take this latitudinal dependence into account by restricting the latitude region of the spatial averages in the storm index definition. Such an effort has been made, for the first time, in an analysis of a major storm event by *Lu et al.,* [*1998*]. In this study, the time dependence of percentage M_1, obtained from both data-driven GIMs and a coupled thermosphere-ionosphere electrodynamics general circulation model (TIE-GCM), exhibited a clear hemispheric asymmetry in high-latitude TEC disturbances during the storm. In the future, similar studies with these indices will help to distinguish latitude, local time, seasonal, and solar cycle characteristics of ionospheric responses to geomagnetic storms. This may advance the science of ionospheric storm studies and possibly help efforts in nowcasting and forecasting ionospheric weather that are pursued internationally.

5.3 Ionospheric Irregularity Research Using GPS

The ionospheric plasma is subject to significant structure at distance scales of meters to kilometers; such variations are not generally captured by the TEC mapping approaches described here. However, there is a significant technological impact from these *ionospheric irregularities.* Scattering of the radio energy by the irregularities and consequent interference effects cause rapid fluctuation in the phase and amplitude of radio signals. These *scintillations* have a significant impact on radio communications, navigation and radar systems. The importance of scintillations for GPS tracking has been reported in the literature of GPS applications [*e.g. Wanninger, 1993*; *Klobuchar, 1996*; *Doherty et al., 1994*; *Bishop et al., 1994*].

GPS transmissions represent robust signals of opportunity for monitoring irregularities for scientific or technological applications. A straightforward approach uses the TEC observable as defined in equation 6. Irregularities that cause scintillation at the L_1 and L_2 will frequencies will produce significant variations in the ionospheric combination L_I compared to nominal. Monitoring the time-derivative of L_I (rate of TEC or ROT) is useful for signaling the presence of irregularities. *Pi et al.* [*1997*] have produced global scale snapshots of the irregularity distribution within 1000-2000 km of global network sites, using a rate-of-TEC index (ROTI) based on the level of fluctuations in dL_I/dt. *Coker et al.* [*1995*] have shown that ROT is useful for resolving the spatial boundary of the auroral zone at high latitudes. GPS has also been used to locate and analyze plasma bubbles and irregularity regions at low latitudes [*Aarons et al., 1996*; *Kelley et al., 1996*; *Weber et al., 1996*; *Aarons et al., 1997*]. Applications of GPS for irregularity nowcasting and forecasting are discussed in *Hunsucker et al.*, [*1995*] and *Coco et al.*, [*1995*]; see also *Groves et al.*, [*1997*].

The signals of opportunity from the global network are generally 30s samples, and therefore do not provide information on the smaller irregularity scales [*Pi et al., 1997*]. However, the GPS signal contains information at higher frequencies that can be extracted with suitably designed receivers. The traditionally-defined scintillation indices σ_ϕ and S_4 [*Fremouw et al., 1978*] computed at the 50-Hz sampling rate internal to a modified commercial receiver have been reported by *Van Dierendonck et al.* [*1993*]. We can expect more such efforts in the future.

6. Summary and Future Directions

Ionospheric measurements from the Global Positioning System will continue to play an important role in ionospheric science and related applications. Long-term databases of global TEC maps, made available through the International GPS Service, are providing a new source of information for understanding ionospheric variability and space weather. As data retrieval latencies of one hour or less become possible for an increasing number of global network sites, GPS ionospheric maps will play an increasingly important role in characterizing and forecasting space weather.

The GPS system was designed for positioning so special care must be taken when extracting ionospheric observables. GPS measurements in the accuracy range 1-2 TECU are challenging due to interfrequency biases affecting the satellites and receivers. Diurnal temperature variations can modulate the receiver biases by more than one TECU peak-to-peak, but temperature controlled conditions for the ground receivers and antennas (if possible) can significantly improve stability. For the satellites, records of bias estimates spanning several years have consistently demonstrated excellent stability or slow drifts, but this behavior cannot be guaranteed. The transmitted T_{GD} values are proportional to satellite biases and used to aid single-frequency user positioning, but are based on pre-launch measurements and are currently not updated regularly. This may change in the near future as values estimated at JPL on a quarterly basis are uploaded to the satellites for inclusion in the ephemeris message. Note that biases must still be monitored at least daily as sudden changes in bias will not necessarily be updated in a timely manner.

An infrastructure has been developed at JPL for daily generation of global TEC maps, used for calibration of the altimeter measurements from the missions GEOSAT Follow-On and ERS-2 The shell model is employed where the principal assumption is that the variation of electron density horizontally along the satellite-receiver raypaths is ignored. The TEC variation between raypaths is determined by fitting basis functions with local support, that vary independently over distance scales of 500-1000 km. The data driven nature of this mapping approach is significantly more accurate than climatological models that have been used prior to GPS. Model information is still used to constrain or augment the fits, and is necessary for calibrating altimeters with altitudes (~ 800 km) significantly below GPS satellites. Vertical electron density distributions from models are used to estimate the fraction of total TEC below the satellite.

Retrieval methods using data from GPS ground networks typically use the thin shell approximation for electron density, but more sophisticated approaches are becoming more common. For example, research has begun on shell models or pre-determined density functions that are adjusted in height to fit the data. Fully three-dimensional tomographic techniques have been developed that attempt to estimate vertical as well as horizontal structure [*Juan et al., 1997*; *Ruffini et al., 1998a*]. An important benefit of extending beyond the shell model is that constellations of orbiting GPS receivers are planned that will measure TEC from raypaths that traverse the ionosphere horizontally. TEC variation as the occulting ray descends in altitude provides high-resolution vertical information about electron density structure. Only retrieval techniques with degrees of freedom in the vertical dimension can take full advantage of the anticipated ground and space-based systems [*Hajj et al., 1994*; *Leitinger et al., 1997*; *Davies and Hartmann, 1997*; *Rius et al., 1997*]. More conventional two-dimensional global maps may also benefit from orbiting receiver measurements that provide coverage over ocean regions currently unobservable from ground-based networks.

The role of GPS in space weather applications is in its infancy, but significant progress has been made. GPS provides robust signals of opportunity for monitoring ionospheric irregularities on global scales. Efforts have begun in using global maps for defining ionospheric storm indices that characterize the ionospheric component of space storms separately from the geomagnetic component. A prototype system for generating global maps in near real-time has been developed at JPL, using a subset of the IGS receiver network that provides data within one hour. Near real-time global maps are approximate snapshots of ionospheric weather patterns obtained in a timely manner, that may be extremely useful in applications adversely affected by disturbances, such as airplane navigation, surveillance activities and communications.

Research is underway to provide short-term ionospheric weather forecasts using time-series analysis methods, that complement the model-based approaches contemplated for the nation's Space Weather Program.

The global simultaneous coverage of the GPS data set is well-suited for validating dynamic physical models of the coupled thermosphere-ionosphere system [*Fuller-Rowell et al., 1997*; *Burns et al., 1995*]. These models are capable of simulating global ionosphere dynamics by unifying the disparate physics of the high, middle and low latitude regions of the upper atmosphere [*Schunk and Sojka, 1997*; *Sojka and Schunk, 1989*]. For operational space weather applications, the physical models must be incorporated into data assimilation schemes and combined with a continuous stream of global-scale data to maintain accurate nowcasts and forecasts of the space environment. With the expanding ground network, and the anticipated deployment of orbiting receiver constellations, GPS data with play an important role in the transition of space physics to space weather forecasting in the 21st century.

Acknowledgements

The authors acknowledge the valuable contributions of Christian M. Ho in the development and analysis of the TEC mapping technique. AJM benefited from useful discussions with Bruce Howe and Andrew Hansen. We thank Mark Reyes for his help. The research conducted at the Jet Propulsion Laboratory, California Institute of Technology, was performed under contract to the National Aeronautics and Space Administration.

References

J. Aarons, M. Mendillo-M, R. Yantosca, and E. Kudeki [1996], "GPS Phase Fluctuations In The Equatorial Region During The Miseta-1994 Campaign," *Journal Of Geophysical Research Space Physics*, **101**, A12, pp. 26851-26862.

J. Aarons, M. Mendillo, and R. Yantosca [1997], "GPS Phase Fluctuations In The Equatorial Region During Sunspot Minimum," *Radio Science*, **32**, 4, pp. 1535-1550.

S. Bassiri, G. A. Hajj [1993], "Higher-order Ionospheric Effects on the Global Positioning System Observables and Means of Modeling Them," Manuscripta Geodaetica, **18**, 6, pp. 280-289.

P. A. Bernhardt, R. P. Mccoy, K. F. Dymond, J. M. Picone, R. R. Meier, F. Kamalabadi, D. M. Cotton, S. Charkrabarti, T. A. Cook, J. S. Vickers, A. W. Stephan, L. Kersley, S. E. Pryse, I. K. Walker, C. N. Mitchell, P. R. Straus, Helen Na, C. Biswas, G. S. Bust, G. R. Kronschnabl, T. D. Raymund [1998], "2-Dimensional Mapping Of The Plasma-Density In The Upper-Atmosphere With Computerized Ionospheric Tomography (CIT)," *Physics Of Plasmas*, **5**, 5, pp. 2010-2021.

G. J. Bailey, and N. Balan [1995], "Some Modeling Studies Of The Equatorial Ionosphere Using The Sheffield-University Plasmasphere Ionosphere Model," *Advances in Space Research*, **18**, 6, pp. 59-68.

W. I. Bertiger, Y. E. Bar-Sever, B. J. Haines, B. A. Iijima, S. M. Lichten, U. J. Lindqwister, A. J. Mannucci, R. J. Muellerschoen, T. N. Munson, A. W. Moore, L. J. Romans, B. D. Wilson, S. C. Wu, T. P. Yunck, G. Piesinger and M. Whitehead [1998], "A Real-Time Wide Area Differential GPS System," *Navigation*, **44**, 4, pp. 433-456.

G. J. Bierman [1977], *Factorization Methods for Discrete Sequential Estimation*, New York, Academic Press.

D. Bilitza, K. Rawer, and S. Pallaschke [1988], "Study Of Ionospheric Models For Satellite Orbit Determination," *Radio Science*, **23**, 3, pp. 223-232.

D. Bilitza and K. Rawer [1998], "International Reference Ionosphere Model (IRI-95)," http://envnet.gsfc.nasa.gov/Models/EnviroNET_Models.html.

G. Bishop, A. Mazzella, and E. Holland [1995], "Application Of SCORE Techniques To Improve Ionospheric Observations," in *Proceedings of the Eighth International Technical Meeting of the Satellite Division of the Institute of Navigation*

ION-GPS 95, (available from the Institute of Navigation, 1800 Diagonal Road, Suite 480, Alexandria, VA), pp. 1209-1218.

G. Bishop, S. Basu, E. Holland, and J. Secan, "Impacts Of Ionospheric Fading On GPS Navigation Integrity", in *Proceedings of the Seventh International Technical Meeting of the Satellite Division of the Institute of Navigation ION-GPS 94*, (available from the Institute of Navigation, 1800 Diagonal Road, Suite 480, Alexandria, VA), pp. 577-585.

G. Blewitt [1990], "An Automatic Editing Algorithm For GPS Data", *Geophysical Research Letters*, **17**, 3, pp. 199-202.

A. G. Burns, T. L. Killeen, W. Deng, G. R. Carignan, R. G. Roble [1995], "Geomagnetic Storm Effects In The Low-Latitude To Middle-Latitude Upper Thermosphere", *Journal Of Geophysical Research Space Physics*, **100**, A8, pp. 14673-14691.

E.J. Christensen, B. J. Haines, S. J. Keihm, C. S. Morris, R. A. Norman, G. H. Purcell, B. G. Williams, B. D. Wilson, and G. H. Born [1994], "Calibration Of Topex/Poseidon At Platform Harvest," *Journal of Geophysical Research Oceans*, **99**, C12, pp. 24,465-24,485.

D. S. Coco, C. Coker, S. R. Dahlke, and J. R. Clynch [1991], "Variability Of GPS Satellite Differential Group Delay Biases," *IEEE Transactions on Aerospace and Electronic Systems*, **27**, pp. 931-938.

D. S. Coco, T. L. Gaussiran, and C. Coker [1995], "Passive Detection Of Sporadic-E Using GPS Phase Measurements," *Radio Science*, **30**, 6, pp. 1869-1874.

C. Coker, R. Hunsucker, and G. Lott [1995], "Detection Of Auroral Activity Using GPS Satellites," *Geophysical Research Letters*, **22**, 23, pp. 3259-3262.

A. J. Coster, E. M. Gaposchkin, and L. E. Thornton [1992], "Real-Time Ionospheric Monitoring System Using The GPS," *Navigation*, **39**, pp. 191-204.

K. Davies, and G. K. Hartmann [1997], "Studying The Ionosphere With The Global Positioning System," *Radio Science*, **32**, 4, pp. 1695-1703.

P. Doherty, E. Raffi, J. Klobuchar, M. B. El-Arini, "Statistics Of Time Rate Of Change Of Ionospheric Range Delay," in *Proceedings of the Seventh International Technical Meeting of the Satellite Division of the Institute of Navigation ION-GPS 94*, (available from the Institute of Navigation, 1800 Diagonal Road, Suite 480, Alexandria, VA), pp. 1589-1599.

J. M. Dow, T. Martinmur, J. Feltens, C. Garciamartinez, and M. B. Perez [1996], "Orbital And Other Products Of The International GPS Service For Geodynamics (IGS)," *Acta Astronautica*, **38**, 4-8, pp. 437-443.

C. Duncan, D. Spitzmesser, T. Meehan, G. Franklin, and B. D. Wilson [1998], "An Interfrequency Bias Calibrator For TurboRogue Receivers," in *Proceedings of the National Technical Meeting of the Institute of Navigation*, January 21-23, Long Beach, CA (available from the Institute of Navigation, 1800 Diagonal Road, Suite 480, Alexandria, VA), p. 659.

J. Feltens [1998], "Chapman Profile Approach for 3-D Global TEC Representation," in J. M. Dow, J. Kouba, and T. Springer (eds.), *Proceedings of the 1998 Analysis Center Workshop,* Darmstadt, Feb. 9-11, (available from the IGS Central Bureau, Jet Propulsion Laboratory, MS 238-540, Pasadena, CA 91109; igscb@igscb.jpl.nasa.gov), pp. 285-297.

G. W. Franklin, and C. Duncan [1998], personal communication.

E. J. Fremouw, R. L. Leadabrand, R. C. Livingston, M. D. Cousins, C. L. Rino, B. C. Fair, and R. A. Long [1978], "Early Results from the DNA Wideband Experiment – Complex-Signal Scintillation," *Radio Science*, **13**, 1, pp. 167-187.

E. J. Fremouw, J. A. Secan, and B. M. Howe [1992], "Application Of Stochastic Inverse-Theory To Ionospheric Tomography," *Radio Science*, **27**, 5, pp. 721-732.

T. J. Fuller-Rowell, M. V. Codrescu, B. G. Fejer, W. Borer, F. Marcos, D. N. Anderson [1997], "Dynamics Of The Low-Latitude Thermosphere - Quiet And Disturbed Conditions," *Journal Of Atmospheric And Solar Terrestrial Physics*, **59**, 13, pp. 1533-1540.

D. L. Gallagher, P. D. Craven, R. H. Comfort, "An Empirical Model Of The Earth's Plasmasphere," *Advances in Space Research*, **8**, **8**, pp. 15-24.

A. Gelb [1989], *Applied Optimal Estimation*, Cambridge, Massachusetts, MIT Press.

K. M. Groves, S. Basu, E. J. Weber, M. Smitham, H. Kuenzler, C. E. Valladares, R. Sheehan, E. Mackenzie, J. A. Secan, P. Ning, W. J. McNeill, D. W. Moonan, and M. J. Kendra [1997], "Equatorial Scintillation And Systems Support," *Radio Science*, **32**, 5, pp. 2047-2064.

G. A. Hajj, R. Ibanez-Meier, E. R. Kursinski, and L. J. Romans [1994], "Imaging the Ionosphere with the Global Positioning System," *International Journal of Imaging Systems and Technology*, **5**, 2, pp. 174-184.

G. A. Hajj and L. J. Romans [1998], "Ionospheric Electron-Density Profiles Obtained With The Global Positioning System - Results From The GPS/MET Experiment," *Radio Science*, **33**, 1, pp. 175-190.

A. J. Hansen, T. Walter, T., and P. Enge, P [1997], "Ionospheric Correction Using Tomography," in *Proceedings of the Tenth International Technical Meeting of the Satellite Division of the Institute of Navigation ION-GPS 97*, (available from the Institute of Navigation, 1800 Diagonal Road, Suite 480, Alexandria, VA), pp. 249-257.

J. K. Hargreaves [1992], *The Solar-Terrestrial Environment*, New York, Cambridge University Press.

C. M. Ho, A. J. Mannucci, U. J. Lindqwister, X. Pi, and B. T. Tsurutani [1996], "Global Ionosphere Perturbations Monitored By The Worldwide GPS Network," *Geophysical Research Letters*, **23**, pp. 3219-3222.

C. M. Ho, B. D. Wilson, A. J. Mannucci, U. J. Lindqwister, and D. N. Yuan [1997], "A Comparative Study Of Ionospheric TEC Measurements And Models With TOPEX," Radio Science, **32**, 4, pp. 1499-1512.

C. M. Ho, A. J. Mannucci, U. J. Lindqwister, X., Pi, B. T. Tsurutani, L. Sparks, B. A. Iijima, B. D. Wilson,. I. Harris, and M. J. Reyes [1998a], "Global Ionospheric TEC Variations During January 10, 1997 Storm," *Geophysical Research Letters*, **25**, pp. 2589-2592.

C. M. Ho, A.J. Mannucci, L. Sparks, X. Pi, U.J. Lindqwister, B.D. Wilson, and M.J. Reyes [1998b], "Global Ionospheric TEC Perturbations Monitored By The GPS Global Network During Two Northern Hemisphere Winter Storms," *Journal of Geophysical Research*, in press.

B. M. Howe, K. Runciman, and J. A. Secan [1998], "Tomography Of The Ionosphere - 4-Dimensional Simulations," *Radio Science*, **33**, 1, pp. 109-128.

R. D. Hunsucker, C. Coker, J. Cook, and G. Lott [1995], "An Investigation Of The Feasibility Of Utilizing GPS/TEC Signatures For Near-Real Time Forecasting Of Auroral-E Propagation At High-HF And Low-VHF Frequencies," *IEEE Transactions On Antennas And Propagation*, **43**, 11, pp. 1313-1318.

D. A. Imel [1994], "Evaluation Of The Topex/Poseidon Dual-Frequency Ionosphere Correction," *Journal of Geophysical Research O*, **99**, C12, pp. 24895-24906.

N. Jakowski, E. Sardon, E. Engler, A. Jungstand, and D. Klahn [1996a], "Relationships Between GPS-Signal Propagation Errors And EISCAT

Observations," *Annales Geophysicae Atmospheres Hydrospheres And Space Sciences*, **14**, 12, pp. 1429-1436.

N. Jakowski, E. Sardon, E. Engler, A. Jungstand, and D. Klahn [1996b], "About the Use of GPS Measurements for Ionospheric Studies," in G. Beutler, G. W. Hein, W. G. Melbourne, and G. Seeber (eds.) *GPS Trends in Precise Terrestrial Airborne and Spaceborne Applications, IAG Symposium*, **115**, New York, Springer Verlag.

N. Jakowski, E. Sardon, and S. Schluter [1998], "GPS-Based TEC Observations In Comparison With IRI95 And The European TEC Model NTCM2," *Advances In Space Research*, **22**, 6, pp. 803-806.

A. H. Jazwinsky [1970], "Stochastic Processes and Filtering Theory," New York, New York, Academic Press.

J. M. Juan, A. Rius, M. Hernandez-Pajares, and J. Sanz [1997], "A 2-Layer Model Of The Ionosphere Using Global Positioning System Data," *Geophysical Research Letters*, **24**, 4, pp. 393-396.

J. G. Kappenman, L. J. Zanetti, and W. A. Radasky [1997], "Geomagentic Storm Forecasts and the Power Industry", *EOS Tranactions of the AGU,* **78**, pp. 37.

M. C. Kelley, D. Kotsikopoulos, T. Beach, D. Hysell, and S. Musman [1996], "Simultaneous Global Positioning System And Radar Observations Of Equatorial Spread-F At Kwajalein," *Journal Of Geophysical Research Space Physics*, **101**, A2, pp. 2333-2341.

J. A. Klobuchar, S. Basu, and P. Doherty [1993], "Potential limitations in making absolute ionospheric measurements using dual-frequency radio waves from GPS satellites," in *Proceedings of the Seventh International Ionospheric Effects Symposium*, (available from J. Goodman, SRI International, 1611 N. Kent St., Arlington, VA 22209-2111), p 187.

J. Klobuchar [1996], "Ionospheric Effects on GPS," in Global Positioning System: Theory and Applications, Volume 1, ed. by B. W. Parkinson and J. J. Spilker, American Institute of Aeronautics and Astronautics, 370 L'Enfant Promenade, SW. Wanshongton DC, 20024.

J. A. Klobuchar [1997], "Real-Time Ionospheric Science - The New Reality," *Radio Science*, **32**, 5, pp. 1943-1952.

D. J. Knecht, and B. M. Shuman [1985], "The geomagnetic field," in A. S. Jursa (ed.), *Handbook Of Geophysics and the Space Environment*, Bedford (Mass.), Air Force Geophysical Laboratory, pp. 4-1-4-37.

A. Komjathy and R. Langley [1996a], "Improvement of a Global Ionospheric Model to Provide Ionospheric Range Error Corrections for Single-Frequency GPS Users," in *Proceedings of the 52nd Annual Meeting of the Institute of Navigation*, (available from the Institute of Navigation, 1800 Diagonal Road, Suite 480, Alexandria, VA), pp. 557-566.

A. Komjathy and R. Langley [1996b], "An Assessment of Predicted and Measured Ionospheric Total Electron Content Using a Regional GPS Network," in *Proceedings of the National Technical Meeting of the Institute of Navigation*, (available from the Institute of Navigation, 1800 Diagonal Road, Suite 480, Alexandria, VA), pp. 615-624.

A. Komjathy, R.B. Langley and D. Bilitza [1998] "Ingesting GPS-Derived TEC Data Into the International Reference Ionosphere for Single Frequency Radar Altimeter Ionospheric Delay Corrections," *Advances in Space Research*, **22**, 6, pp. 793-801.

G. E. Lanyi, and T. Roth [1988], "A Comparison Of Mapped And Measured Total Ionospheric Electron Content Using Global Positioning System And Beacon Satellite Observations," *Radio Science,* **23**, pp. 483-492.

R. Leitinger, H.P. Ladreiter, and G. Kirchengast [1997], "Ionosphere Tomography With Data From Satellite Reception Of Global Navigation Satellite System Signals And Ground Reception Of Navy Navigation Satellite System Signals," *Radio Science*, **32**, 4, pp. 1657-1669.

G. Lu, X. Pi, A. D. Richmond, and R. G. Roble [1998], "Variations of total electron content during geomagnetic disturbances: A model/observation comparison," *Geophysical Research Letters,* **25**, pp. 253-256.

A.J. Mannucci, B. D. Wilson, D. N. Yuan, C. H. Ho, U. J. Lindqwister, and T. F. Runge [1998], "A Global Mapping Technique For GPS-Derived Ionospheric Total Electron-Content Measurements," *Radio Science*, **33**, 3, pp. 565-582.

Matsushita, S. [1959], *Journal of Geophysical Research,* **64**, pp. 305.

M. Mendillo [1971], "Ionospheric total electron content behavior during geomagnetic storms," *Nature,* **234,** pp. 23.

M. Mendillo [1973], "A study of the relationship between geomagnetic storms and ionospheric disturbances," Planetary and Space Science, **21**, pp. 349.

X. Pi, M. Mendillo, M. W. Fox, and D. N. Anderson [1993], "Diurnal Double Maximua Patterns In The *F* Region Ionosphere: Substorm-Related Aspects," *Journal of Geophysical Research*, **98,** pp. 13677-13691.

X. Pi, A. J. Mannucci, U. J. Lindqwister, and C. M. Ho [1997], "Monitoring Of Global Ionospheric Irregularities Using The Worldwide Gps Network," *Geophysical Research Letters*, **24**, 18, pp. 2283-2286.

G. W. Prölss, L. H. Brace, H. G. Mayr, G. R. Carignan, T. L. Killeen, and J. A. Klobuchar [1991], "Ionospheric Storm Effects At Subauroal Latitudes: A Case Study," *Journal Geophysical Research,* **96,** pp. 1275-1288.

M. H. Reilly and M. Singh [1997], "Ionospheric Specification From GPS Data And The RIBG Ionospheric Propagation Model," *Radio Science*, **32**, 4, pp. 1671-1679.

A. Rius, G. Ruffini, and L. Cucurull [1997], "Improving The Vertical Resolution Of Ionospheric Tomography With GPS Occultations," *Geophysical Research Letters*, **24**, 18, pp. 2291-2294.

A. Rius, G. Ruffini, and A. Romeo [1998], "Analysis Of Ionospheric Electron-Density Distribution From GPS/MET Occultations," *IEEE Transactions On Geoscience And Remote Sensing*, **36,** 2, pp. 383-394.

G. L. Ruffini, A. Flores, and A. Rius [1998a], "GPS Tomography Of The Ionospheric Electron-Content With A Correlation Functional," *IEEE Transactions On Geoscience And Remote Sensing*, **36**, 1, pp. 143-153.

G. L. Ruffini, E. Cardellach, A. Flores, L. Cucurull, and A. Rius [1998b], "Ionospheric Calibration Of Radar Altimeters Using GPS Tomography," *Geophysical Research Letters*, **25**, 20, pp.3771-3774.

E. Sardon, A. Rius, and N. Zarraoa [1994], "Estimation Of The Transmitter And Receiver Differential Biases And The Ionospheric Total Electron Content From Global Positioning System Observations," *Radio Science*, **29**, pp. 577-586.

E. Sardon, and N. Zarraoa [1997], "Estimation Of Total Electron-Content Using GPS Data - How Stable Are The Differential Satellite And Receiver Instrumental Biases," *Radio Science*, **32**, , pp. 1899-1910.

S. Schaer, W. Gurtner, J. Feltens [1998], "IONEX: The IONosphere Map Exchange, Format Version 1," in J. M. Dow, J. Kouba and T. Springer (eds.), *Proceedings of the 1998 Analysis Center Workshop,* Darmstadt, Feb. 9-11, (available from the IGS Central Bureau, Jet Propulsion Laboratory, MS 238-540, Pasadena, CA 91109; igscb@igscb.jpl.nasa.gov) pp. 233-247.

W. S. Schreiner, R. E. Markin, and G. H. Born [1997], "Correction Of Single-Frequency Altimeter Measurements For Ionosphere Delay," *IEEE Transactions on Geoscience and Remote Sensing*, **35**, 2, pp. 271-277.

R. W. Schunk [1988], "A Mathematical Model Of The Middle And High-Latitude Ionosphere," *Pure and Applied Geophysics*, **127**, 2, pp. 255-303.

R. W. Schunk, J. J. Sojka [1997], "Global Ionosphere Polar Wind System During Changing Magnetic Activity," *Journal Of Geophysical Research Space Physics*, **102**, A6, pp. 11625-11651.

G. Siscoe, E. Hildner, T. L. Killeen, L. J. Lanzerotti, W. Lotko [1994], "Developing Service Promises Accurate Space Weather Forecasts in the Future", *EOS Tranactions of the AGU,* **75**, pp. 353-366.

J. J. Sojka, R. W. Schunk [1989], "Theoretical-Study Of The Seasonal Behavior Of The Global Ionosphere At Solar Maximum," *Journal Of Geophysical Research Space Physics*, **94**, NA6, pp. 6739-6749.

L. Sparks, C.M. Ho, A.J. Mannucci, X. Pi, and B.D. Wilson [1997], "Monitoring Ionospheric Storms Using the GPS Network," *EOS Transactions of the AGU*, **78**, pp. F148, Fall Meeting Supplement (available from American Geophysical Union, 2000 Florida Avenue, NW, Washington DC 20009).

E. E. Tsedilina, and O. B. Weitsman [1992], "Influence Of The Inhomogeneous Ionosphere On The GPS Determination Of Satellite User Coordinates," in *Proceedings of the 43rd Congress of the International Astronautical Federation*, (available from the International Astronautical Federation, 3-5 rue Mario Nikis, 75015 - Paris, France), pp. 52.

A. J. Van Dierendonck, J. Klobuchar, and Q. Hua [1993], "Ionospheric Scinitillation Monitoring Using Commercial Single Frequency C/A Code Receivers," in *Proceedings of the Sixth International Technical Meeting of the Satellite Division of the Institute of Navigation ION-GPS 93*, (available from the Institute of Navigation, 1800 Diagonal Road, Suite 480, Alexandria, VA), pp. 1333 1342.

J. A. Vladimer, M. C. Lee, P. H. Doherty, D. T. Decker, D. N. Anderson [1997], "Comparisons Of Topex And Global Positioning System Total Electron-Content Measurements At Equatorial Anomaly Latitudes," *Radio Science*, **32**, 6, pp. 2209-2220.

L. Wanninger [1993], "Effects Of The Equatorial Ionosphere On GPS," *GPS World*, July, pp. 48-54.

E. J. Weber, S. Basu, T. W. Bullett, C. Valladares, G. Bishop, K. Groves, H. Kuenzler, P. Ning, P. J. Sultan, R. E. Sheehan, and J. Araya [1996], "Equatorial Plasma Depletion Precursor Signatures And Onset Observed At 11-Degrees South Of The Magnetic Equator," *Journal Of Geophysical Research Space Physics*, **101**, A12, pp. 26829-26838.

B. D. Wilson, and A. J. Mannucci [1994], "Extracting Ionospheric Measurements From GPS In The Presence Of Anti-Spoofing," in *Proceedings of the Seventh International Technical Meeting of the Satellite Division of the Institute of Navigation ION-GPS 94*, (available from the Institute of Navigation, 1800 Diagonal Road, Suite 480, Alexandria, VA), pp. 1599-1608.

B. D. Wilson, A. J. Mannucci, and C. D. Edwards [1995], "Subdaily Northern-Hemisphere Maps Using An Extensive Network Of GPS Receivers," *Radio Science*, **30**, 3, pp. 639-648.

D. N. Yuan, A. J. Mannucci, B. D. Wilson, T. F. Runge, and U. J. Lindqwister [1995], "Shell Height And Vertical TEC Mapping Function Analysis For Ionospheric Shell Model," *EOS Transactions of the AGU*, **76**, 17, Spring Meeting Supplement (available from American Geophysical Union, 2000 Florida Avenue, NW, Washington DC 20009), pp. S87.

M. Zeitzew [1998], Private communication.

Captions

Figure 1. Daily estimates of the interfrequency biases b_s for two GPS satellites in 1997 are shown in units of nanoseconds at the L1 frequency (1 ns = 1.85 TECU). These estimates were derived from the operational global mapping process described in Section IV.

Figure 2. Daily estimates of the interfrequency bias for GPS satellite PRN 10 in 1996-1997, showing an abrupt bias change occurred on November 29, 1996. The change was subsequently linked to a hardware configuration change commanded by the space control segment.

Figure 3. Block diagram of the calibration signal generator for TurboRogue receivers. A Glonass code is used to modulate the two signal frequencies because of the relatively short repeatability of the code sequence. The calibration signals are coupled into the transmission path of the GPS transmissions, and undergo similar differential hardware delays.

Figure 4. Hardware calibration values for the Australian Deep Space Network receiver are shown for several days. A clear diurnal variation can be identified, probably due to temperature variations over the course of a day.

Figure 5. Functional form for the two types of surface basis functions extensively tested for global TEC mapping.

Figure 6. Elevation scaling functions are shown for several electron density profiles ($\rho_m(h)$ in equation 13).

Figure 7. Maps of equivalent height of the ionosphere over North America, for two periods on June 26, 1997 (geomagnetically quiet conditions), derived using the tomographic retrieval technique described in section 3.3. These maps show a definite local time dependence of equivalent height, that is consistently observed on geomagnetically quiet days.

Figure 8. Distribution of global GPS network receivers as of August, 1998. Between six and eight GPS receivers are simultaneously tracked by each receiver. The circle above each site represents the ionospheric shell area where the measurement pierce points will lie, assuming a shell altitude of 450 km and a minimum elevation angle of 10°.

Figure 9. Data flow chart of the daily global mapping process for calibrating the GEOSAT Follow-On (GFO) and ERS-2 ocean altimetry missions. GPS data are obtained within one to three days (depending on turn-around requirements) from IGS data archives or the local JPL data handling facility. To provide calibrations

along the satellite ground track, the GFO and ERS-2 ephemeris files (latitude and longitude versus time) are downloaded. TOPEX data are obtained for validation purposes. Calibration outputs are delivered via anonymous ftp. Calibration performance metrics are made available to operators via world-wide-web pages.

Figure 10. Control logic for routine production of global maps in a timely manner.

Figure 11. Error statistics of the global TEC maps along TOPEX ground tracks, assuming TOPEX vertical ionosphere measurements are "truth". The local time ranges are 6 hours each, bounded by 3am, 9am, 3pm and 9pm.

Figure 12. An absolute difference map of TEC that compares the TEC deviations relative to quiet time during the storm of April 10, 1997. The enhancement over North America is particularly large compared to other mid-latitude regions sampled by data.

Figure 13. Two global TEC indexes are compared with the global geomagnetic index Dst for the period surrounding the geomagnetic storm of April 11 1997. The TEC indices can be computed in real-time, and are based on the degree of deviation between storm-time global maps and recent quiet-time averages.