GPS-based remote sensing of the geospace environment: horizontal and vertical structure of the ionosphere and plasmasphere

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ABSTRACT

Transmissions of the Global Positioning System (GPS) satellites can be used to measure the total electron content (TEC) between a receiver and several GPS satellites in view. This simple observable is yielding a wealth of new scientific information about ionosphere and plasmasphere dynamics. Data available from thousands of ground-based GPS receivers are used to image the large-scale and mesoscale ionospheric response to geospace forcings at high-precision covering all local times and latitudes. Complementary measurements from space-borne GPS receivers in low-Earth orbit provide information on both vertical and horizontal structure of the ionosphere/plasmasphere system. New flight hardware designs are being developed that permit simultaneous measurement of integrated electron content along new raypath orientations, including zenith, cross-track and nadir antenna orientations (the latter via bistatic reflection of the GPS signal off ocean surfaces). We will discuss a new data assimilation model of ionosphere, the Global Assimilative Ionosphere Model (GAIM), capable of integrating measurements from GPS and other sensors with a physics-based ionospheric model, to provide detailed global nowcasts of ionospheric structure, useful for science and applications. Finally, we discuss efforts underway to combine GPS space-based observations of plasmaspheric TEC, with ground-based magnetometer measurements, and satellite-based images from NASA's IMAGE satellite, to produce new dynamic models of the plasmasphere.

1. INTRODUCTION

It is well known that transmissions of the Global Positioning System (GPS) satellites can be used to measure precisely the integrated electron content between a GPS receiver and several GPS satellites in view simultaneously. This simple observable is yielding a wealth of new scientific information about ionosphere and plasmasphere dynamics as driven by changing solar wind conditions and solar flares. In this paper, we discuss GPS observations obtained from ground and space-based platforms, the scientific results that are emerging from these new observations, and the space weather implications of ingesting these data into a new generation of ionospheric data assimilation models patterned after numerical weather prediction models in the troposphere.

2. OVERVIEW OF GPS IONOSPHERE REMOTE SENSING

The GPS system provides information on the delay of a radio signal propagating through charged particle media such as the ionosphere and plasmasphere. The delay D (nsec) is related to the integral of electron density $N_e(\mathbf{x})$ (number of electrons per cubic meter) along the (nearly) straight-line path between GPS satellite transmitter and a receiver:

$$D = 40.3\int_{\mathbf{r}}^{\mathbf{t}} N_e(\mathbf{x})ds \quad (?)$$

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where the integral is along the path between receiver position **r** and transmitter position **t**, with path element ds. The delay D is measured directly by the instrument, but the science is based on interpreting the delay in terms of the electron density path integral, along a precisely known path geometry (again, with geometrical information provided by the GPS)[1,2].

Path-integrated density has proven to be extremely useful scientifically because it reveals a great deal of information about plasma structure over a range of spatial scales, and GPS is robust under a broad range of geomagnetic conditions (only rarely are GPS data lost due to scintillation of the signal). Plasma structure, in turn, is extremely sensitive to the geophysical environment in which it forms and is transported, and reveals information about the solar spectrum, thermospheric composition, density and winds, electric fields, auroral precipitation, and a number of physical phenomena that cause plasma instabilities and resultant small-scale structures to form within the plasma. Therefore, studying plasma structure using GPS is becoming an important tool for understanding the interrelationships of a wide range of geophysical phenomena that determine the Earth's geospace environment.

The following features of GPS are used to advantage for scientific investigations of the ionosphere and plasmasphere:

1. ***Continuous Global Coverage:*** typically 6-8 satellites of the GPS constellation are visible from the ground over all parts of the Earth at all times, transmitting a signal that can be received under all weather conditions. This aspect of GPS is finding great use in providing a global context to other localized or more specific space science measurements to improve our understanding of the ionosphere-thermosphere-magnetosphere system[3].
2. ***High precision and accuracy:*** GPS TEC accuracies are in the range 1-3 TECU (1 TECU = 10^{16} el/m^2), and TEC precision is of order 0.01 TECU or better using geodetic quality receivers, providing data very useful for scientific investigations of the ionosphere, plasmasphere and small perturbations therein.
3. ***Sensitivity to vertical plasma distribution:*** TEC acquired from a low Earth orbiter in either occultation or zenith viewing geometry provides information about the vertical plasma structure, achieving sub-km vertical resolution profiles for occultations[4].
4. ***Sensitivity to mesoscale plasma structure:*** Existing dense networks of ground-based GPS receivers provide information on plasma structure at tens of km scale size, and side-viewing antennas on low Earth orbiters provide complementary meso-scale information as GPS links move horizontally through plasma structures.
5. ***Sensitivity to small-scale ionospheric irregularities:*** Scintillation of the L-band GPS signal provides information on the location and, for some studies, the scale size and velocity of small-scale (~100s meters) irregularities that arise in the ionosphere at high (auroral) and low latitudes (for different reasons), and at mid-latitudes during geomagnetically disturbed periods[5,6].

A schematic representation of the GPS measurement system is shown in Figure 1 within the context of the physical regimes that are being studied. GPS satellites orbit at 20,200 km altitude, and are often beyond or near the outer edge of plasmasphere (the tenuous extended region of the ionosphere beyond about 1000 km altitude consisting primarily of H+ ions).

There are two general acquisition geometries that have been used for GPS-based science: zenith acquisition from upward-viewing GPS antennas placed on the ground or in space (Figure 1a); and occultation-based acquisition (Figure 1b) in limb geometries as a GPS satellite occults behind the Earth as observed from an orbiting GPS receiver. Zenith acquisition from a fixed (ground) or moving (space) platform provides information on horizontal plasma structures, and occultation geometry provides information primarily on vertical structure. Horizontal structure can also be obtained from space from an antenna oriented perpendicular to the LEO velocity vector, and from signals reflected off of the oceans. The latter provide information on TEC below the satellite to complement super-satellite TEC obtained from the zenith-viewing spacecraft antenna.

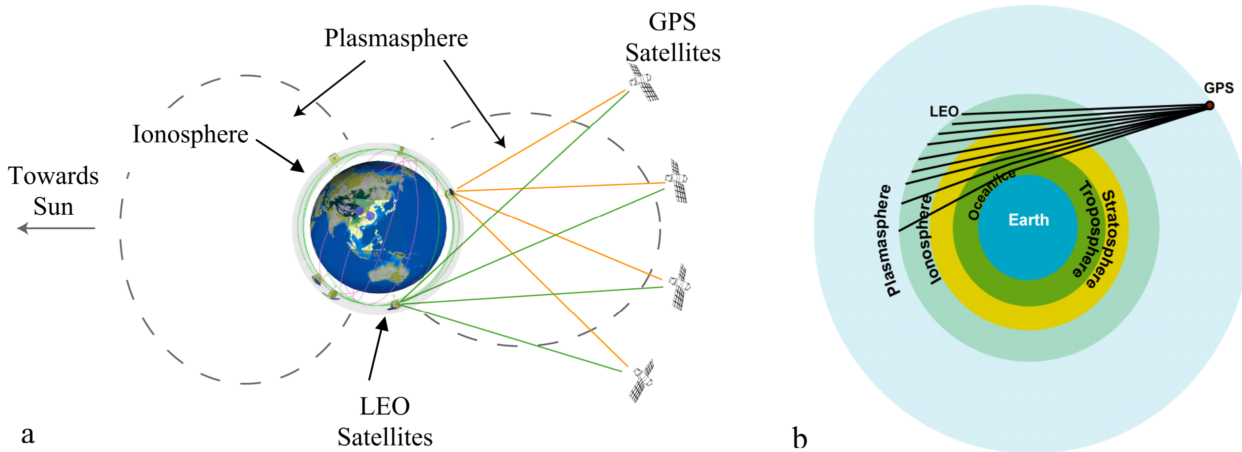

Figure 1: Schematic representation of total electron content measurement geometries provided by GPS for low-Earth orbiting (LEO) receivers and from the ground. (a) zenith and side-viewing acquisition. (b) occultation geometry. Not shown is acquisition of reflected signals.

3. GROUND-BASED MEASUREMENTS

The scientific value of ground-based GPS measurements is intimately tied with the fielding of extensive global networks of GPS receivers, primarily for global geodesy and plate tectonics research[7]. The space science community has been able to take great advantage of this development, leading to a new type of space science instrument: the globally distributed array of instruments that provides measurements simultaneously at a variety of latitudes, longitudes and local times to practically image the global ionospheric response to magnetospheric penetration electric fields and thermospheric composition changes, among other physics, with extremely high precision. These data are proving highly complementary to observations from low Earth orbiting space platforms, which provide sub-orbital coverage with a repeat time of 100 minutes (approximately) for a given latitude and only sample a narrow range of local times, but are not limited to continental/island-based coverage as are the ground network.

An example of new science being achieved with ground-based GPS networks is improved understanding of the effect of polar-equatorial electrical coupling during intense geomagnetic storms. Increases in magnetospheric convection due to changing conditions in the solar wind cause electric fields to penetrate the equatorial ionosphere from high latitudes[8]. These "prompt penetration" fields are directed eastward in the daytime, causing large upward drift velocities of plasma near the geomagnetic equator. The rising plasma enters altitudes where recombination rates are very low, thereby increasing TEC overall as solar photons create new plasma at lower altitudes (~< 200 km). The continuous daytime equatorial measurements available from the global GPS network provide a means of tracking the transient ionospheric response to these prompt penetration fields. Figure 2 shows a continuous time series of the average vertical TEC within a low latitude region at 1400-1600 local time (thick black line). Before the onset of conditions leading to the major geomagnetic storms that occurred on October 29 and October 30, the average TEC fluctuated in the range 30-100 TECU. On both storm days, a few hours after the solar wind magnetic field turned southward, creating a large interplanetary electric field that could penetrate the magnetosphere (medium-thickness trace), the TEC is seen to increase rapidly, to values of about ~180 TECU. This TEC increase originating at low latitudes is called the "super-fountain" effect. These TEC increases are too rapid to be caused by thermosphere recirculation and wind-induced dynamo electric fields. Using the extensive coverage of the global GPS network, the relationship of the prompt ionospheric response to solar wind electric fields can be studied far better than has been possible in the past.

In certain global regions, the density of GPS receivers is high enough to measure meso-scale structure embedded within the larger-scale increases caused by the super-fountain effect indicated in Figure 2. Tongue-like features have been observed to extend all the way to the poles, demonstrating there is probably a strong connection between equatorial plasma and polar plasma patches, a connection difficult to confirm before the globally distributed ground-based network provided simultaneous coverge over entire hemispheres. An example of a so-called plasma "tongue" is shown in Figure

3 using data from the 400-site Continuously Operating Reference Network (CORS) operated by the Coast Guard in the Continental US. It is clear from this image that the enhanced equatorial plasma is connected to a high latitude plasma tongue via a mid-latitude channel structure connecting the two regions. The high latitude extent of the tongue crosses the geomagnetic pole. The structure at mid-latitudes has been connected to plasmaspheric drainage plumes[9]. GPS data makes it possible to understand the dynamic behaviour of these global-scale interconnected regions in a manner than has not been possible before.

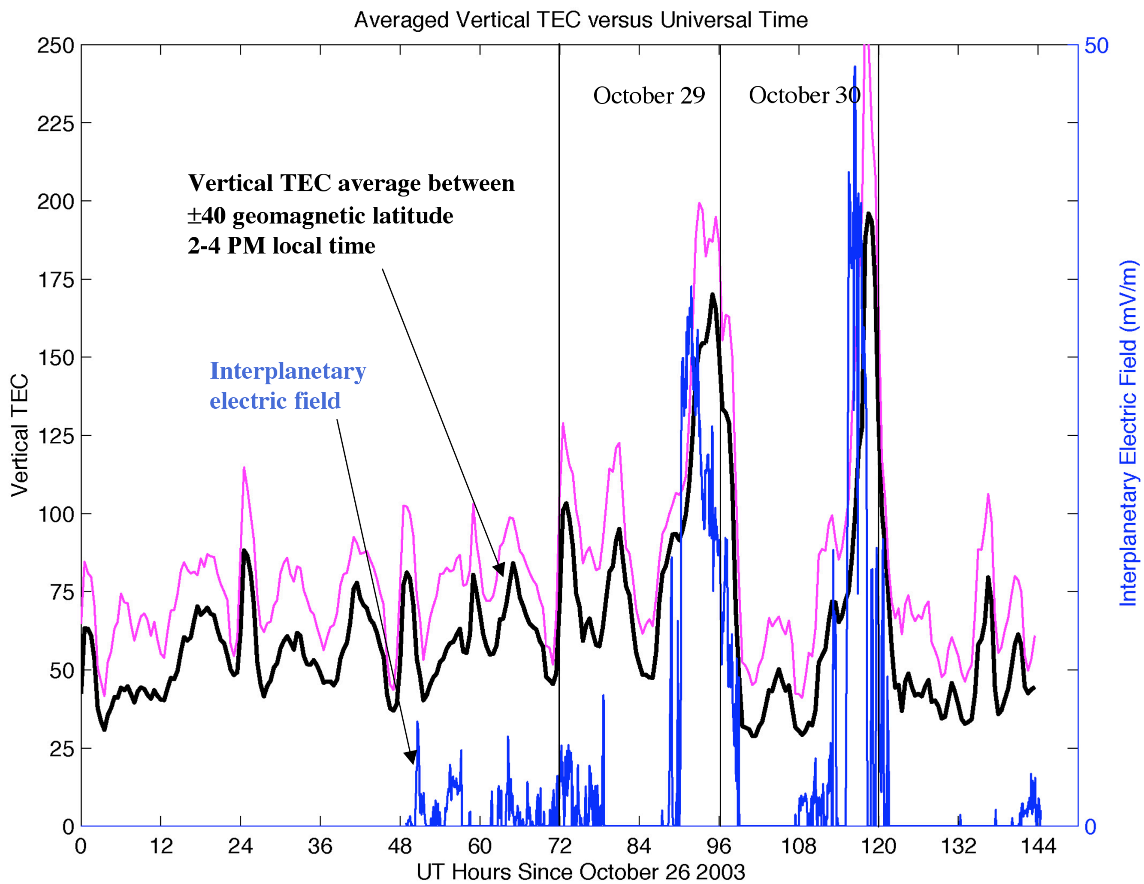

Figure 2: Time series of TEC measured from the global GPS network (black trace) between ±40 degrees geomagnetic latitude and 1400-1600 local time. The large TEC increases in this latitude/local time region are associated with the onset of increased interplanetary electric field (IEF, medium weight trace) due to an interplanetary coronal mass ejection (magnetic cloud) that caused geomagnetic storms on October 29 and October 30, 2003. The uppermost trace is the TEC average (black trace) plus one standard deviation of all measurements used in the average, showing clearly that the TEC increase associated with IEF increase is statistically significant.

The global GPS ground coverage is also useful for monitoring highly transient events such as the ionospheric response to intense solar flares. There are always at least several receivers in local daytime to capture the ionospheric response to a flare that might last no longer than a few minutes. An example is shown in Figure 4 obtained from the NKLG GPS receiver at low latitude. The top panel shows the X-ray flux of the flare as capture by the X-ray instrument on the GOES geosynchronous satellite. The bottom panel shows the abrupt TEC increase due to the flare, relative to a recent quiet day, by differencing the TEC obtained during the flare period with a TEC average of previous days without the flare.

The rapid increase in X-rays measured by GOES is associated with intensity increases due to the flare in the UV to X-ray portions of the solar spectrum, causing enhanced photoionization of the ionosphere at a variety of altitudes. The overall increase in TEC is clear from NKLG. Detailed study of the TEC increase and its vertical distribution, possibly measurable from GPS occultation measurements obtained from low Earth orbit, should provide useful information on the spectrum of the flare that is difficult to obtain by direct measurements.

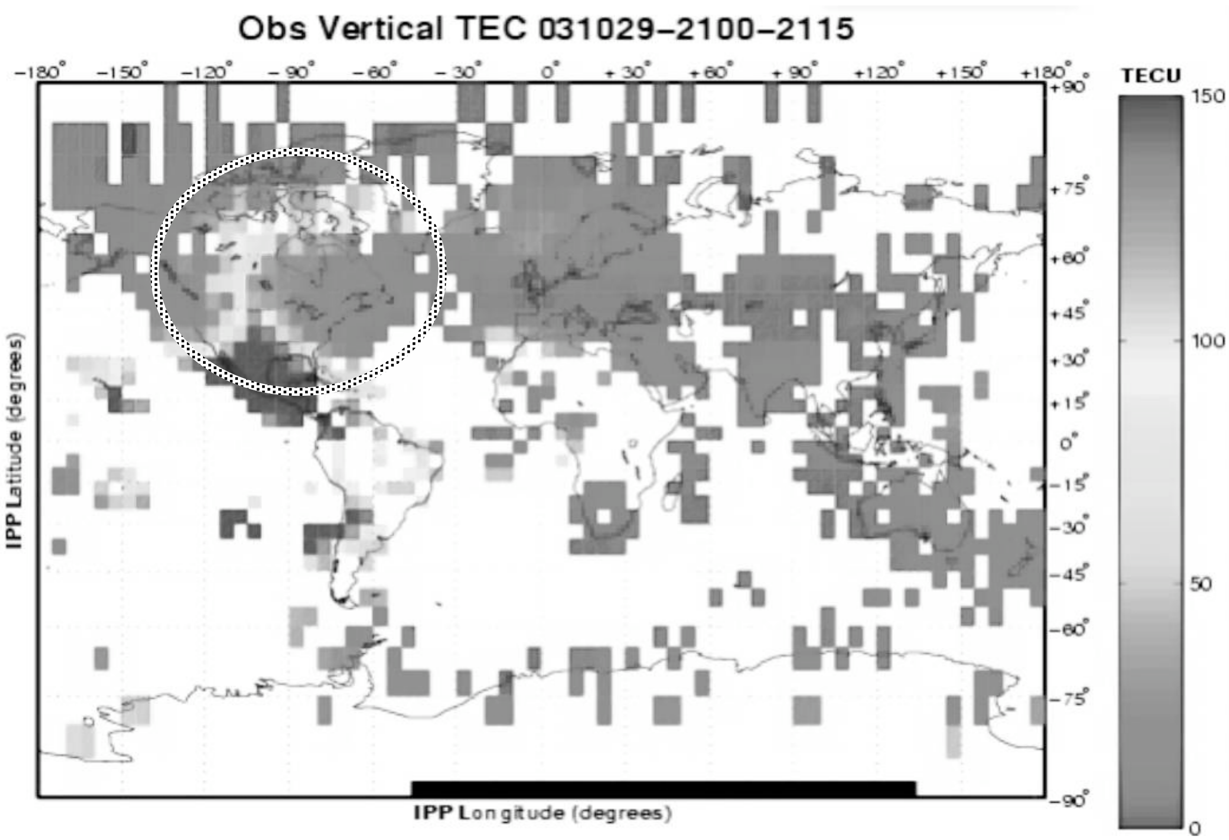

Figure 3: A global map "snapshot" of total electron content acquired from the global GPS network, including the dense receiver network over the US on October 29, 2003 from 2100-2115 UT. The US data shows a plasma tongue extending from an enhanced region of low latitude plasma towards the geomagnetic pole (seen within the oval indicator).

4. SPACE-BASED MEASUREMENTS

GPS receivers on low-Earth orbiters provide unique capabilities not available from the ground-based measurements, for example, providing information about plasma vertical structure. The possibility of deploying constellations of GPS space-borne receivers, because of their relatively low cost of reproduction, is another factor in favor of GPS contributions to space science.

4.1. Occultation Geometry

The earliest application of space-borne GPS receivers to ionospheric remote sensing was using the occultation geometry (Figure 1b)[4]. The Doppler shift of the GPS L1 frequency is measured and can be related to the bending of the signal caused by vertical refractive index gradients in the ionosphere. Using the assumption of spherical symmetry (refractive index varies only with radius), the refractivity profile is obtained from the bending angle profile by applying the Abel transform as described in [4].

An example profile obtained by this method is shown in Figure 5. We note in particular the retrieval of fine-scale vertical structure in the E-region, an important region of the ionosphere where conductivities are usually largest and the majority of ionospheric currents flow. The E-region conductivities play a major role in determining potential drops across geomagnetic field lines, which has an impact on the growth of low-latitude plasma depletions[10]. Statistical studies have shown that electron density retrieval errors due to the spherical symmetry assumption typically range from 10-20% near the F-region peak ionospheric density, and therefore techniques that account for horizontal structure have been developed[4,11]. The most promising new techniques rely on data assimilation models that combine space-based and ground-based data with a first-principles ionospheric model to produce a best-fit three-dimensional electron density structure constrained by the model physics, as described in Section 5.

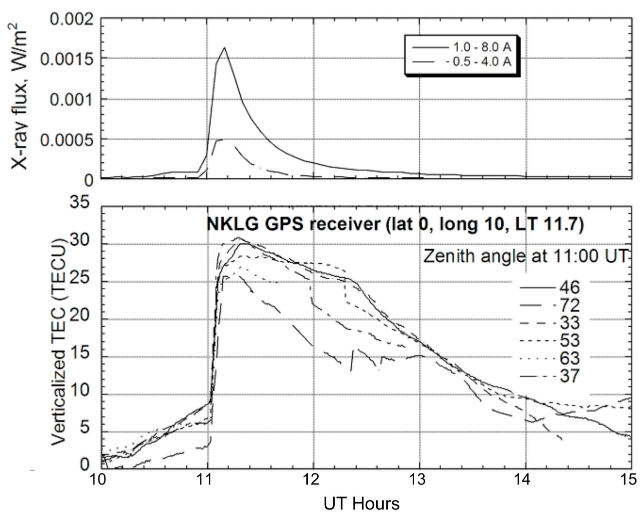

Figure 4: Increase in solar X-ray flux as measured by the GOES satellite (top panel) and corresponding TEC increase due to the flare as measured by the GPS receiver NKLG (bottom panel).

4.2. Zenith Antenna

TEC obtained in occultation geometry is not the only application of spaceborne GPS. Figure 6 shows possible antenna placements on board spacecraft for acquiring signals in the following geometries: fore/aft–occultation geometry (as described above); zenith-viewing to obtain TEC above satellite altitude; nadir-viewing for oean-reflected GPS signals that traverse the ionosphere; and side-viewing antennas that scan the horizontal structure of the ionosphere. These different cases will be discussed in turn.

The zenith viewing antenna configuration is processed similarly to the ground-based data, except that the "receiver" platform is rapidly sweeping a latitude/longitude swath as the TEC above satellite altitude is recorded. These data are very useful because they cover continuous latitudinal swaths without gaps over both land and ocean areas, and when combined with ground-based data can be used to infer gross changes in the vertical structure of electron density.

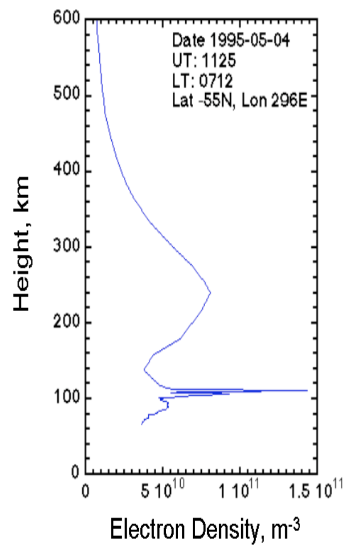

Figure 5: Electron density profiles obtained by the GPS/MET occultation experiment, from [4].

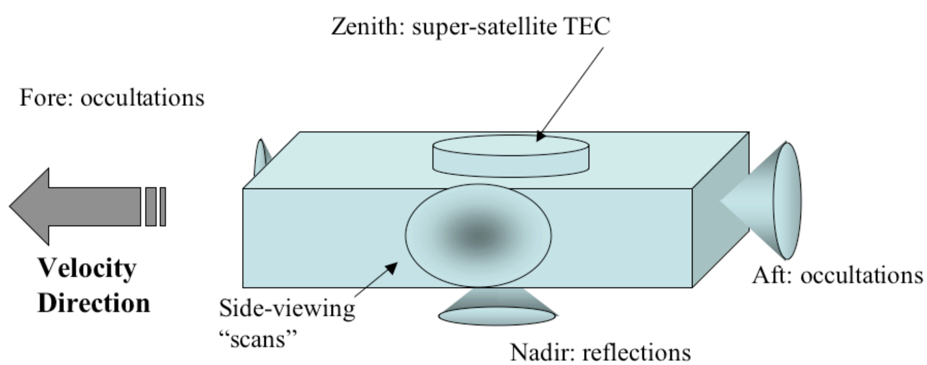

Figure 6: Schematic representation of GPS antenna locations and orientations onboard a low-Earth orbiting spacecraft.

An example showing dynamic changes associated with geomagnetic storms is shown in Figure 7. The traces are calibrated TEC values using dual-frequency data obtained from the zenith viewing antenna onboard the CHAMP satellite orbiting at 400 km altitude, scaled from slant delay to estimates of vertical TEC above CHAMP. (A simple geometrical factor based on a constant density slab is used to perform the scaling. Although crude, this approximation is sufficiently accurate as demonstrated by the generally good agreement of the different traces within each pass). The lowest trace is representative of the typical quiet ionosphere as a function of latitude, clearly displaying the two peaks of the equatorial anomaly feature as a function of latitude. These TEC peaks are caused by tidally generated eastward directed electric fields causing vertical plasma uplift at the magnetic equator due to **ExB** (electrodynamic) drift. Plasma pressure and gravitational forces redistribute the plasma poleward along field lines, forming the anomaly TEC peaks, located approximately ±12 degrees away from the true magnetic equator. This is called the equatorial plasma "fountain effect".

Before the next orbit reached daytime, a magnetic cloud in the solar wind impinged on the Earth's magnetopause at approximately 1910 UT causing an additional east-west electric field within the dayside ionosphere, associated with the evolving geomagnetic disturbance. This creates a "super-fountain" effect in the daytime sector that overwhelms the pre-existing fountain effect. The lighter trace in Figure 7, obtained between times 2012 and 2032 UT, shows a very significant, prompt ionospheric response to the enhanced electric field. The third trace, about 100 minutes later, shows even more TEC increase due to the super-fountain. The origin of the additional TEC is daytime plasma generated at lower altitudes where ionization rates peak (~100-200 km). The generated plasma is rapidly uplifted to altitudes of reduced recombination rate where the plasma persists and does not decay. Also shown in Figure 7, at about 39 N latitude, are an average of measurements from ground-based GPS receivers in the vicinity of the CHAMP ground tracks at 1840 UT and 2012 UT (round dots). Comparing the ground-based TEC to the corresponding space-based TEC confirms the plasma uplift hypothesis, since a greater fraction of the total TEC (measured from the ground) is evidently above CHAMP altitude after onset of the geomagnetic event.

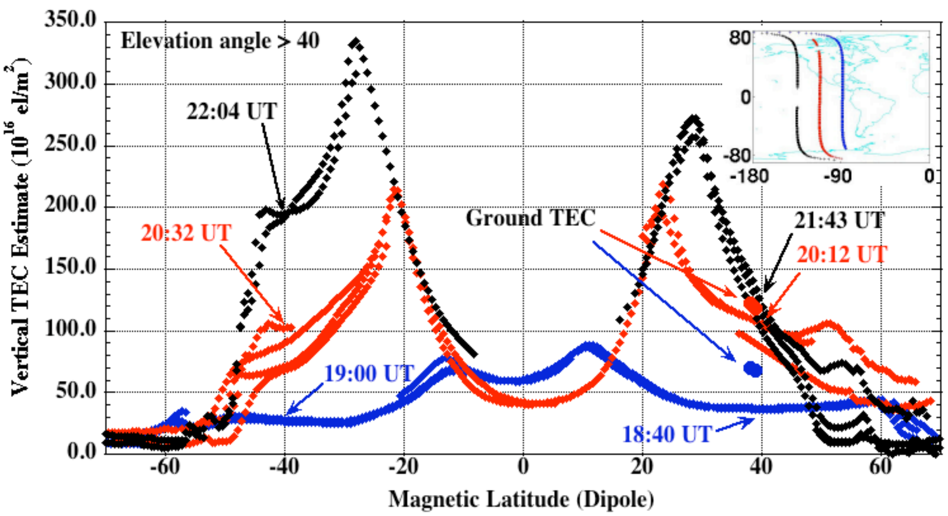

Figure 7: Estimates of vertical TEC above the CHAMP satellite obtained from the zenith viewing antenna before and after onset of the geomagnetic disturbance. Ground-based vertical TEC measured in the vicinity of the corresponding CHAMP ground track is shown as round circles, near 1840 and 2021 UT (the darker circles are associated with the 1840 UT pass).

The altitude of the zenith viewing antenna determines what region of the ionosphere/plasmasphere system is sensed by these measurements. The JASON ocean altimetry satellite carries a BlackJack GPS receiver currently orbiting at 1336 km altitude, above ionospheric altitudes and well into the plasmasphere under normal conditions, where H+ is the dominant ion. The plasmasphere has been receiving a great deal of attention recently because of stunning images being returned by the IMAGE satellite showing the dynamic behavior of this region and its boundary, the plasmapause, under both quiet and disturbed conditions. Recently, data from the upward viewing JASON receiver were processed to reveal dynamics changes to plasmaspheric total electron content before, during and after geomagnetic storms[12].

4.3. Nadir Antenna – Reflections

The upward viewing GPS antenna provides excellent spatial sampling of TEC structure from the vantage point of a rapidly moving GPS receiver located within the ionosphere/plasmasphere system. The altitude distribution of the electron density cannot be obtained directly from these measurements alone. To provide vertical information along the satellite ground track, it is worth considering GPS transmissions reflected from the ocean, into the nadir antenna (Figure 6). Ionospheric remote sensing using reflected GPS was first proposed by Katzberg (see e.g. Katzberg and Garrison 2001).

A detailed study of ocean altimetry by Hajj and Zuffada[13] using reflected GPS provides information on coverage and SNR as a function of antenna gain. To provide a 3 TECU measurement precision in 4 seconds requires at least 25 dB of antenna gain, or an antenna diameter of 1.5 meters, which is substantial. However, an antenna array is desirable because a large single-element antenna would have too narrow a field of view and would not track a sufficient number of satellites. Therefore, the GPS reflection application would benefit from an electronically-steered array that dynamically maximizes gain along a few GPS satellite directions. Such an array is technically possible although would require over 200 elements to achieve the necessary gain, assuming a single element of the array has a patch antenna-like gain of 3dB.

The measurement coverage from reflections and occultations is shown in Figure 8, for a receiver in low Earth orbit at about 450 km altitude, assuming 30-second measurement cadence for the reflections. This diagram highlights the excellent coverage possible from a reflection geometry, which is comparable to the zenith-antenna measurements and provides complementary information. Since the reflected signal arrives within a cone of the zenith direction, a simple geometrical model could be used to combine the measurements from different angles into an estimate of nadir TEC below satellite altitudes.

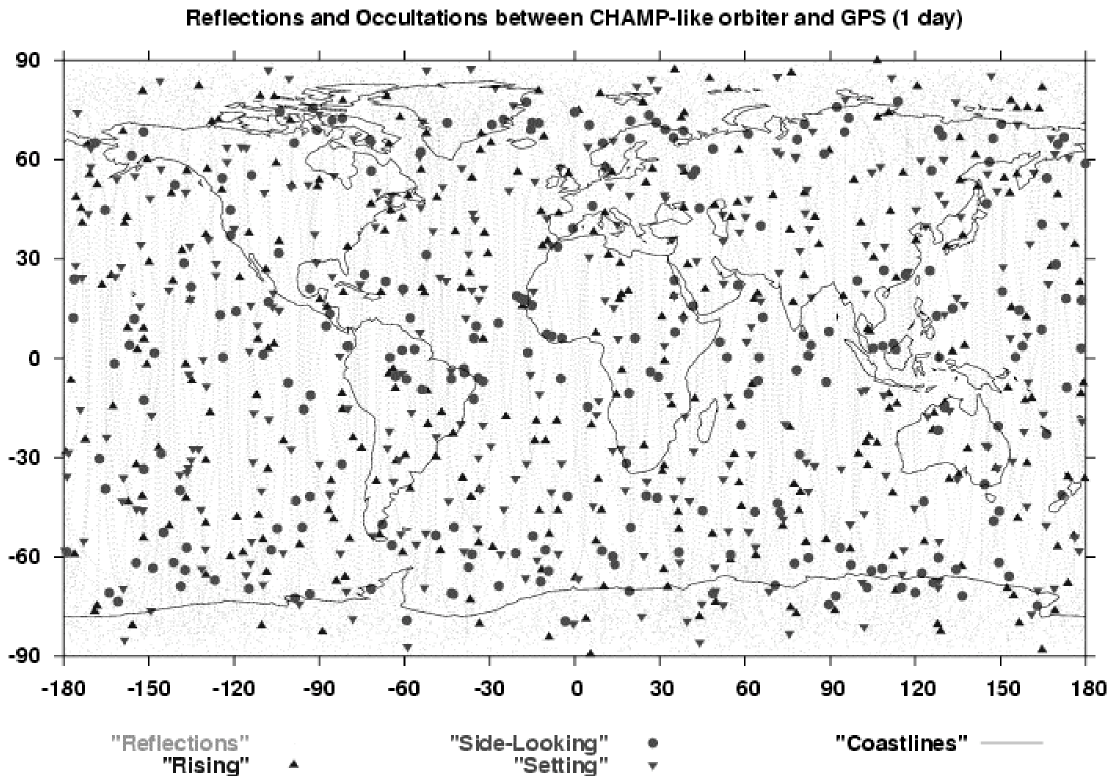

Figure 8: Measurement locations for reflections and occultations for a low-Earth orbiter at 450 km assuming 30-second cadence for the reflected data. “Rising” and “Setting” refers to fore and aft occultation antennas, respectively.

4.4. Side-Viewing Antenna: Plasma “Scans”

Antennas oriented towards the cross-track direction of the S/C can provide useful ionospheric data about the horizontal structure of electron density possibly at a range of altitudes. These are unique data that could complement the analysis of horizontal structure from ground-based networks. Figure 9 shows the geometry of a scan and other GPS links, showing how the TEC line-of-sight moves in latitude and longitude for a satellite in a near-equatorial, low-inclination orbit at 700 km altitude (such as the Brazilian EQUARS satellite). The latitude and longitude of several lines-of-sight, projected to Earth-fixed coordinates every thirty seconds, are shown for a five-minute sample of the orbit.

Superimposed is an idealized geographical structure of size similar to the TEC tongue structures obtained at mid-latitude during storms as discussed in Section 3 (similar to Figure 3). The zenith-viewing raypaths are shown in the lightest color, forming “Vs” as they are projected onto the ground along the height range 700-1000 km altitude (1000 km is the upper boundary of the simulation). Raypaths from the fore/aft occultation antennas are clearly seen in this 5-minute snapshot, as the raypaths in the NE/SW orientation that show very little horizontal displacement.

The side-viewing raypaths are those having the largest horizontal displacement during the five minutes. There are four sets of these raypaths, indicating four GPS satellites in view of this particular location. A shape matching the orientation and size of observed TEC tongue structures is superimposed to fix the scale. The horizontal cuts through this structure via the TEC scans shown in Figure 9, provides information on such regions of highly structured TEC. As seen in a previous example (Figure 7), ground-based data (where available) can be used to complement the space-borne perspective.

Side-viewing antennas have not yet been implemented on a space platform, although this is a simple extension of existing technology. Retrieval research is ongoing to determine the information content of these data under different ionospheric conditions, and how the data complement the more traditional TEC acquisition geometries.

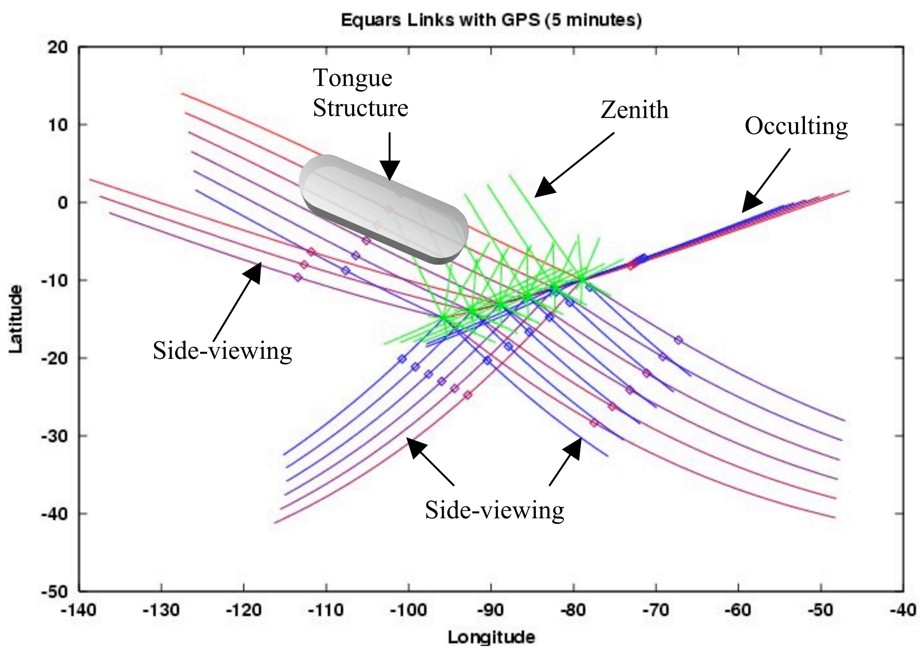

Figure 9: Simulation showing raypath geometries projected to the Earth’s surface. Raypaths from upward, forward, aft and side-viewing antennas are included. The oval/rectangular shape in the upper left is superimposed to illustrate how the raypaths at 3-second cadence sample mesoscale structures such as TEC tongues mentioned earlier (Figure 3).

5. DATA ASSIMILATION

The previous examples show that GPS can provide important new scientific measurements providing insight into physical processes of the Sun-Earth interaction and geospace. The large quantity of GPS data available on a continuous basis, possibly in near real-time, make it useful for practical applications affected by the ionosphere and its dynamic variation, also known as “space weather”. To use these data effectively, and to combine it with other ionospheric data that might be available in near real-time, ionospheric data assimilation techniques have recently been developed and applied to the ionosphere, analogous to numerical weather prediction models used in meteorological applications.

The Global Assimilative Ionosphere Model (GAIM) is such a model jointly developed at the University of Southern California and at JPL[14,15,16]. (Another GAIM was developed under the same sponsorship by a consortium led by R. Schunk at Utah State University). USC-JPL/GAIM contains an Eulerian (fixed-grid) physics-based model of the ionospheric electron density, combined with optimization modules that adjust either: 1) the electron density or 2) parameters in the physics model, to bring model output into alignment with observations. The model output can therefore more accurately represent the instantaneous ionospheric structure as sampled by the data sources, compared to unadjusted physical or climatological models. The physical basis of the model permits realistic short-term forecasts and also tends to constrain the best-fit solutions to physically realistic density structures.

The globally distributed GPS data sets are well suited to drive the GAIM model, which can also ingest non-GPS data types such as in-situ electron densities and ultraviolet radiances derived from imagers. Figure 10 shows an example of electron density profile adjustment using GAIM. Profiles from the GAIM model are plotted before and after assimilation of space-based and ground-based GPS data in a near equatorial region. Before assimilation (so-called "climate" output), the model does not match the direct Abel-based retrieval of electron density. After assimilation of only ground-based TEC, the electron density profile adjusts to smaller values because the climate estimate of TEC is too high, but the vertical structure after adjustment is similar to climate (although scaled). Ingesting only space-based occultation TEC from the IOX satellite has a greater impact on the vertical structure, as can be seen by a significant reduction in the height of the density peak, from approximately 400 to 350 km altitude. The full assimilation of ground and space data results in a profile that is fairly close to a retrieval of electron density based on the simple Abel inversion discussed in Section 4.1. However, the GAIM profile is more realistic because it does not contain unphysical negative densities, as can occur with the Abel retrieval due to the lack of spherical symmetry around the occultation tangent point. In addition, the peak density of the GAIM output is somewhat smaller than the Abel, possibly because of the influence of the ground TEC. This conjecture cannot be verified because of the lack of ground truth data in this case.

Figure 11 shows an example of driver estimation using GAIM, that is, adjustment of parameters of the physics model that generates electron densities. In this simulation experiment, electric fields near the equator, directed primarily in the zonal direction, are adjusted based on ground-based equatorial TEC data. The simulated TEC measurements are generated using GAIM assuming a realistic network of receivers in the low latitude region, using the "weather" electric field model (see Figure). The assimilation test is performed to assess whether GAIM can recover this "weather" electric field based on TEC data alone. At the start of the assimilation cycle, GAIM output is initialized based on the "climatological" electric field pattern. After eight assimilation cycles of ingesting ground-based TEC data, GAIM largely recovers the perturbed electric field pattern used to generate the assimilated data (i.e. GAIM outputs the "estimation" pattern which is close to the "weather" pattern in Figure 11). This initial test is encouraging and more development of driver estimation (e.g. meridional thermospheric winds) will continue.

6. CONCLUSIONS AND PROSPECTS

In this paper, we have discussed several scientific applications of GPS occultation remote sensing and technological developments that will provide new information. In many cases, the receiver technology is mature and work is needed on retrieval algorithms to fully exploit the technique. With the advent of the six-satellite COSMIC constellation due for launch in late 2005, a new era of GPS-based remote sensing of the ionosphere will be entered with the possibility of updating an assimilative model such as GAIM in near real-time to achieve unprecedented nowcasts of ionospheric conditions and physics[17]. The addition of other data types, such as the ultraviolet imager data from the NASA TIMED satellite, DMSP and the NPOESS satellites, will further increase accuracy. All this is possible using GAIM. We also plan to focus specifically on plasmaspheric electron content, assuming IMAGE data of the plasmapause are available and magnetometer readings at the foot of field lines that measure integrated field-line mass density, to combine with GPS data and unravel the three-dimensional density structure of the plasmasphere.

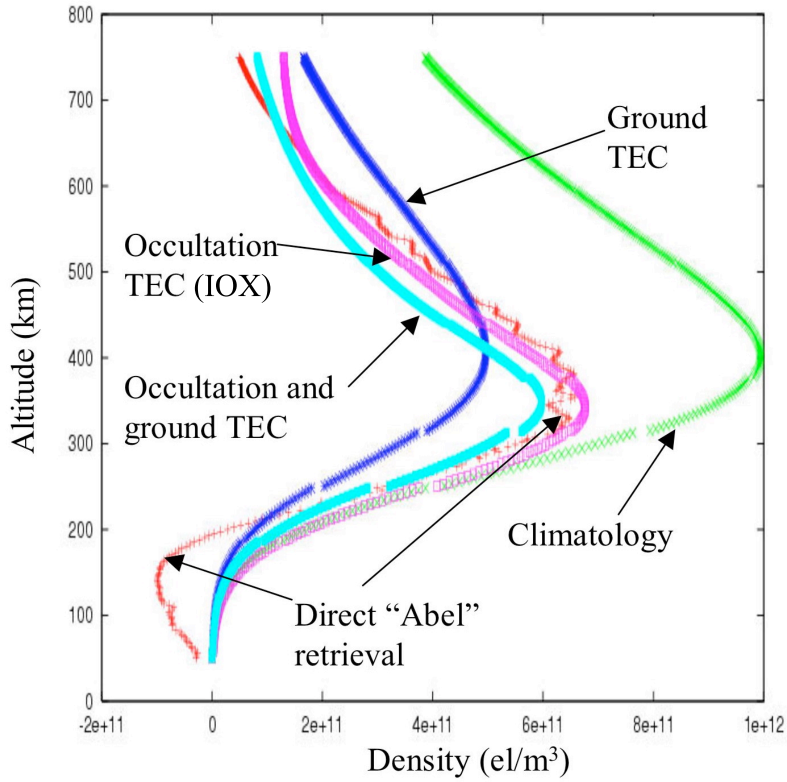

Figure 10: Electron density profiles after various data types are input to GAIM, including no data input ("climatology").

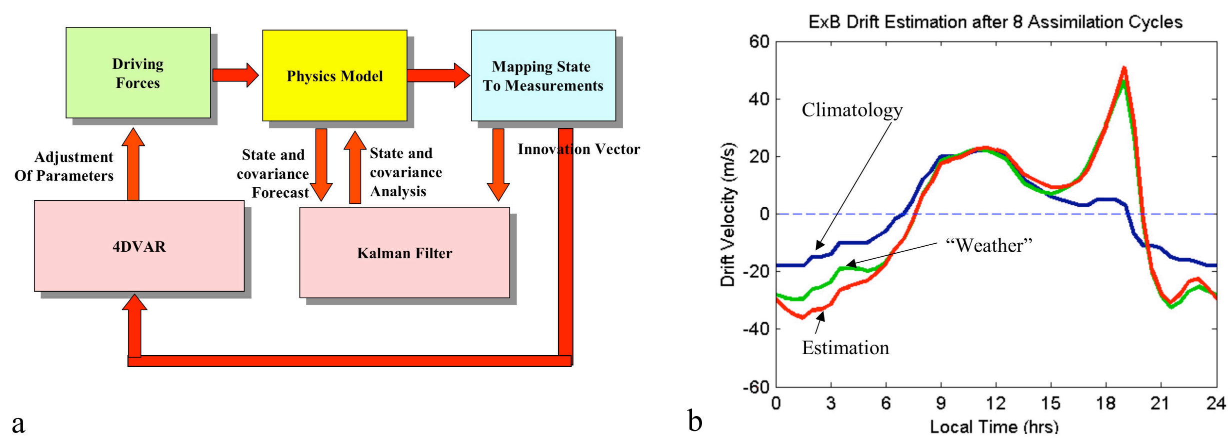

Figure 11: Block diagram of the GAIM model, showing different functions including Kalman filter and optimization module for driver estimation (4DVAR). In figure 11 (b), is shown the GAIM estimate of vertical ExB plasma drift at the equator after eight assimilation cycles. The input data are ground-based low latitude TEC simulated using the "weather" pattern of drift. The model was initialized using the climatolgical drift pattern.

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REFERENCES

1. Mannucci, A.J., B.D. Wilson, D.N. Yuan, C.H. Ho, U.J. Lindqwister, and T.F. Runge, A global mapping technique for GPS-derived ionospheric total electron content measurements, *Radio Science*, 33 (3), 565-582, 1998.
2. Mannucci, A.J., Iijima, B. A., Lindqwister, U. J., Pi, X., Sparks, L., Wilson, B.D., GPS and Ionosphere, in *Reviews of Radio Science, 1996-1999*, edited by W.R. Stone, Oxford University Press, London, 1999.
3. Ho, C.M., A.J. Mannucci, L. Sparks, X. Pi, U.J. Lindqwister, B.D. Wilson, B.A. Iijima, and M.J. Reyes, Ionospheric total electron content perturbations monitored by the GPS global network during two northern hemisphere winter storms, *Journal of Geophysical Research-Space Physics*, 103 (A11), 26409-26420, 1998.
4. Hajj, G.A., and L.J. Romans, Ionospheric electron density profiles obtained with the global positioning system: Results from the GPS/MET experiment, *Radio Science*, 33 (1), 175-190, 1998.
5. Straus, P.R., P.C. Anderson, and J.E. Danaher, GPS occultation sensor observations of ionospheric scintillation, *Geophysical Research Letters*, 30 (8), 2003.
6. Kintner, P.M., B.M. Ledvina, E.R. de Paula, and I.J. Kantor, Size, shape, orientation, speed, and duration of GPS equatorial anomaly scintillations, *Radio Science*, 39 (2), 2004.
7. Zumberge, J.F., and G. Gendt, The demise of selective availability and implications for the International GPS Service, *Physics and Chemistry of the Earth Part a-Solid Earth and Geodesy*, 26 (6-8), 637-644, 2001.
8. Nopper, R.W., and R.L. Carovillano, Polar-Equatorial Coupling During Magnetically Active Periods, *Geophysical Research Letters*, 5 (8), 699-702, 1978.
9. Foster, J.C., P.J. Erickson, A.J. Coster, J. Goldstein, and F.J. Rich, Ionospheric signatures of plasmaspheric tails, *Geophysical Research Letters*, 29 (13), art. no. 1623, 2002.
10. Kelley, M.C., V.K. Wong, G.A. Hajj, and A.J. Mannucci, On measuring the off-equatorial conductivity before and during convective ionospheric storms, *Geophysical Research Letters*, 31 (17), 2004.
11. Schreiner, W.S., S.V. Sokolovskiy, C. Rocken, and D.C. Hunt, Analysis and validation of GPS/MET radio occultation data in the ionosphere, *Radio Science*, 34 (4), 949-966, 1999.
12. Mannucci, A.J., G.A. Hajj, I.L. Harris, B.A. Iijima, X.Q. Pi, B.T. Tsurutani, B.D. Wilson, L.D. Zhang, M. Moldwin, W.D. Gonzalez, *Eos Trans. AGU*, 84 (46),Fall Meet. Suppl., Abstract SM52C-02, 2003.
13. Hajj, G.A., and C. Zuffada, Theoretical description of a bistatic system for ocean altimetry using the GPS signal, *Radio Science*, 38 (5), 2003.
14. Hajj, G.A., B.D. Wilson, C. Wang, X. Pi, and I.G. Rosen, Data assimilation of ground GPS total electron content into a physics-based ionospheric model by use of the Kalman filter, *Radio Science*, 39 (1), 2004.
15. Wang, C.M., G. Hajj, X.Q. Pi, I.G. Rosen, and B. Wilson, Development of the Global Assimilative Ionospheric Model, *Radio Science*, 39 (1), 2004.
16. Pi, X.Q., C.M. Wang, G.A. Hajj, G. Rosen, B.D. Wilson, and G.J. Bailey, Estimation of E x B drift using a global assimilative ionospheric model: An observation system simulation experiment, *Journal of Geophysical Research-Space Physics*, 108 (A2), 2003.
17. Hajj, G.A., L.C. Lee, X.Q. Pi, L.J. Romans, W.S. Schreiner, P.R. Straus, and C.M. Wang, COSMIC GPS ionospheric sensing and space weather, *Terrestrial Atmospheric and Oceanic Sciences*, 11 (1), 235-272, 2000.