Innovation

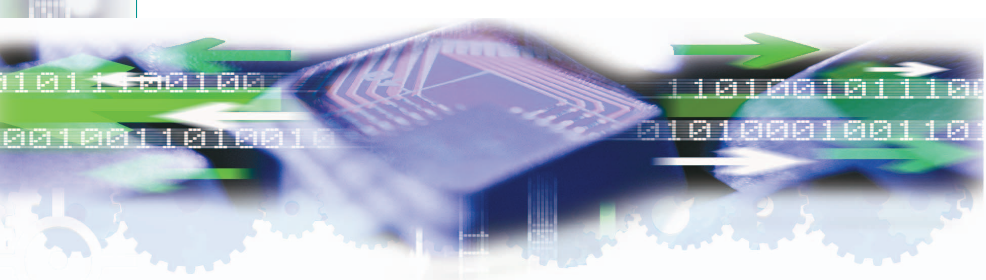
Monitoring the Ionosphere with GPS

Space Weather

Anthea Coster, John Foster, and Philip Erickson

"Stormy today, clearing up tomorrow." That may sound like a typical forecast given by your local TV meteorologist, but it could just as well be a forecast of space weather. Here on Earth, high winds, heavy rains, deep snow, and other forms of severe weather can disrupt our daily lives. Conditions on the Sun and in the solar wind, magnetosphere, and the ionosphere can also affect our lives through the effects they have on satellites, communications, navigation, and power systems. Scientists are now studying space weather with a wide range of tools to try to learn more about the physical and chemical processes taking place in the upper atmosphere and beyond. One of these tools is GPS.

The signals from the GPS satellites travel through the ionosphere on their way to receivers on or near Earth's surface. The free electrons populating this region of the atmosphere affect the propagation of the signals, changing their speed and direction of travel. By processing the data from a dual-frequency GPS receiver, it's actually possible to estimate just how many electrons were encountered by the signal along its travel path — the total electron content (TEC). TEC is the number of electrons in a column with a cross-sectional area of one square meter centered on the signal path. If a regional network of ground-based GPS receivers is used, then a map of TEC above the region can be constructed. The TEC normally varies smoothly from day to night as Earth's dayside atmosphere is ionized by the Sun's extreme ultraviolet radiation, while the nightside ionosphere electron content is reduced by chemical recombination. But the ionosphere can experience stormy weather just as the lower atmosphere does. Smooth variations in TEC are replaced by rapid fluctuations, and some regions experience significantly higher or lower TEC values than normal. In this month's column, we look at how GPS is being used to study such storms and how it is furthering our understanding of the Earth–Sun environment. — *R.B.L.*



Space weather and associated disturbances in Earth's magnetic field can produce large gradients in the total electron content (TEC) in the mid-latitudes. For single-frequency GPS users, these large gradients in the TEC are of concern because they can make the ionosphere difficult to model and remove, thereby affecting GPS-derived position accuracy. The presence of these gradients can also affect carrier-phase differential GPS (DGPS) and real-time kinematic (RTK) applications because the ionospheric term in the observation equations may not cancel, thus making unknown ambiguities difficult to resolve. In addition, large gradients in the TEC are frequently associated with ionospheric scintillation events that can cause amplitude and phase fluctuations of the received signal. In severe conditions, these fluctuations can cause the receiver to lose lock.

Until now, the physical mechanisms that cause these large TEC gradients to form in the mid-latitudes have been poorly understood. However, by combining data from the global network of continuously operating dual-frequency GPS receivers, the development of these TEC perturbations can be monitored, and our understanding of the physical processes involved has been greatly enhanced.

This article discusses the effects of geomagnetic storms on GPS observations and measurements and focuses on one in particular, the March 31, 2001, storm. The first of the article's four sections presents a brief background of space weather and its effects on GPS. This section also reviews how GPS observables are used to measure TEC. The second section presents a map of the TEC over North and South America based on GPS data collected during this geomagnetic storm. The TEC map clearly illustrates a phenomenon known as *storm enhanced density* (SED), which is driven by processes in Earth's magnetosphere and is associated with large gradients in the ionospheric and plasmaspheric TEC. The next section presents data from additional sensors that support the GPS TEC observations and connect the observed SED phenomenon with other space-weather processes. The final section discusses some specific effects on GPS observations that arose from the March 31 storm.

Background

Space weather — the variability of Earth's space environment — can adversely affect the integrity and performance of man-made systems such as GPS. Solar drivers of space weather include solar flares, coronal holes, and coronal mass ejections (CMEs). These disturbances are the key ingredients of strong geomagnetic storms on Earth. Outbursts of charged particles and electromagnetic energy from CMEs and solar flares propagate through the solar wind, the tenuous material blowing outward from the solar atmosphere. Earth's magnetosphere, which is the region of space influenced by Earth's magnetic field, shields Earth from most of this erupted material. However, some of the energy from solar disturbances does enter the magnetosphere, disrupting its configuration, particle populations, and the important coupling between the outer magnetosphere and the inner layers of Earth's atmosphere.

Regions of particular importance are Earth's ionosphere and plasmasphere. The ionosphere is the region of free electrons (plasma) located approximately 100–2,000 kilometers above Earth's surface and created by the action of extreme ultraviolet (EUV) sunlight on the gases of the upper neutral atmosphere. The plasmasphere is a doughnut-shaped region of low-temperature plasma that co-rotates with Earth and is located in the innermost regions of Earth's magnetosphere. The plasmasphere is the high-altitude extension of the ionosphere. The interaction of the solar wind, magnetosphere, plasmasphere, and ionosphere during storm-time conditions is complex and coupled, and our understanding of the

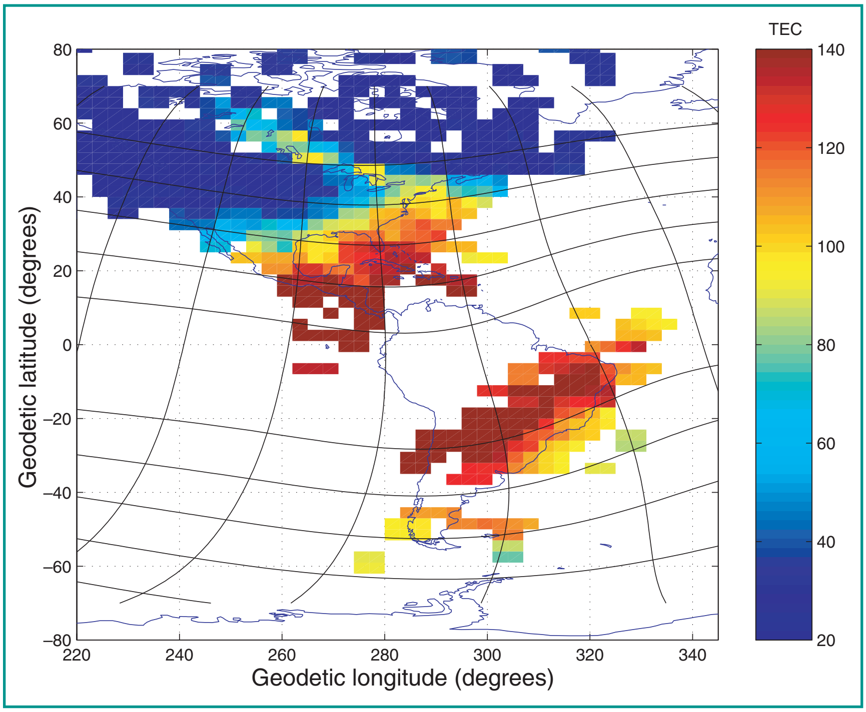


FIGURE 1 A map of total electron content determined by a network of GPS receivers on March 31, 2001, at 19:30 UTC shows the plume of storm-enhanced density stretching across the Great Lakes and into Canada.

many processes involved is continually evolving.

For GPS users, the impact of space weather can usually be attributed to disturbances in the ionosphere as well as the plasmasphere, which in turn can cause degradation in range measurements and in severe circumstances, loss of lock by the receiver of the GPS signal. As GPS signals propagate through the ionosphere, the propagation speed and direction of the GPS signal are changed in proportion to the varying electron density along the line of sight between the receiver and the satellite. The accumulated effect, by the time the signal arrives at the receiver, is proportional to the integrated TEC, the number of electrons in a column stretching from the receiver to the satellite with a cross-sectional area of one square meter. This in turn affects the GPS range observable: a delay is added to the code measurements and an advance to the phase measurements. To achieve very precise positions from GPS, this ionospheric delay/advance must be taken into account.

One can take advantage of the very same ionospheric delay/advance that causes problems for the majority of GPS users. By measuring this delay, properties of the ionosphere can be inferred, and these properties can be used to monitor space-weather events. The ionospheric range delay/advance is (to first order) a function of both the TEC along the line of sight from the receiver to the satellite and the inverse carrier frequency squared. By computing the difference in the range measurements made at two frequencies, the TEC is measured.

GPS currently operates at 1575.42 MHz (L1) and 1227.6 MHz (L2). Additional factors that must be accounted for in this calculation are the system instrumental delays between the L1 and L2 signals caused by both the satellite and receiver hardware. These values must be solved for and removed from the measurement to determine accurate TEC values from GPS data. By combining data from multiple GPS ground stations, one can produce maps of the TEC as a function of latitude and longitude. These maps can be used to monitor the gradients in the TEC that develop during time periods of geomagnetic storms.

Knowledge of these TEC gradients is important to various GPS users. When a GPS signal encounters large gradients in TEC, the ionospheric error in the range measurement is difficult to model and remove (required for single-frequency GPS users), or in the case of differential GPS, it cannot be canceled out. For DGPS or RTK users, differences as small as two TEC units over the baseline (one TEC unit is 10^{16} electrons/meter^2) can make resolution of ambiguities difficult. (A TEC unit is approximately equivalent to 0.162 meters of range delay at L1, or 1 meter of delay at L1 is equivalent to 6.159 TEC units).

Gradients in the TEC can be caused by traveling ionospheric disturbances, bubbles, plumes, streams, or sharp borders in the TEC. Small structures within the ionosphere — frequently associated with large-gradient regions — can cause scintillation. For GPS users, scintillation is observed as amplitude and phase fluctuations in the received signal. Severe scintillation effects in either amplitude or phase can cause a GPS receiver to lose lock.

Large gradients in TEC and scintillation are primarily associated with the equatorial and polar regions. However, large gradients in TEC and scintillation can be observed at mid-latitudes during moderate to severe geomagnetic disturbances. Because the majority of GPS users are located at mid-latitudes, the disturbances caused by large geomagnetic storms can potentially affect the average GPS user.

The March 31, 2001, geomagnetic storm was preceded by two coronal mass ejections and an X-class solar flare (a major sudden eruption of energy) that had occurred two days earlier. On the day of the storm, charged particles reached Earth and induced disturbances in the geomagnetic field. The planetary geomagnetic index, Kp, is a global measure of the disturbance of the geomagnetic field by auroral ionospheric currents. It is based on a quasi-logarithmic scale. Values of 4 and greater indicate moderately disturbed conditions. On this day, the Kp index was at disturbed levels (greater than 5) throughout the day and into the first part of the following day. It reached a value of 9− ("9 minus" is close to its maximum, indicating severely disturbed geomagnetic conditions) between 3:00 and 9:00 UTC.

TEC Storm Maps

We have combined dual-frequency data from more than 125 ground-based GPS receivers to construct maps of the vertical TEC as a function of latitude and longitude during the storm. Each map represents the state of the ionosphere averaged over approximately five minutes. Sequentially combining these maps allows us to produce a time history of TEC perturbations in two dimensions.

Figure 1 shows a single TEC map associated with TEC gradients. Large gradients in the TEC are clearly apparent over the continental United States from approximately 16:00 to 22:00 UTC, with the peak gradients in the TEC observed between 19:00 and 19:30 UTC. As shown in the maps, between 17:00 and 22:00 UTC a plume of TEC moved northward and westward out of the larger region of enhanced TEC (TEC greater than 100 TEC units) in the southeast corner of the United States. In Figure 1, the TEC plume is observed from the New England coast across the Great Lakes region and into central Canada. The GPS map of this TEC plume provides a two-dimensional picture of the ionospheric phenomenon SED, which was initially identified in the early 1990s using observations from the Millstone Hill Observatory's (Westford, Massachusetts) incoherent scatter radar.

The data used to produce these maps included data from both the International GPS Service and the Continuously Operating Reference Stations (CORS). The CORS network is coordinated by the U.S. National Geodetic Survey. The data were accessed by means of publicly available data archives on the World Wide Web. The line-of-sight TEC values were converted to vertical TEC values using a simple mapping function and were associated to an ionospheric pierce point latitude and longitude, assuming the ionosphere to be compressed into a thin shell at the peak ionospheric height of 350 kilometers. GPS satellite and receiver biases were estimated and removed from the data. Maps of TEC were prepared at 5-minute intervals. The vertical TEC has been binned in 2 × 2–degree latitude/longitude bins and color coded between 20 and 140 TEC units. No smoothing was used; the high level of detail is primarily attributed to the persistence of a well-organized connected structure and to the large quantity of data processed.

To emphasize the global nature of these space-weather phenomena, Figure 1 shows data from both hemispheres. Isocontours of geomagnetic latitude and longitude at the shell height illustrate the connection between magnetically conjugate locations in the North and South American sectors. Latitude contours at 10-degree intervals from 20 to 60 degrees north and south are shown. For example, 35 degrees latitude and 290 degrees longitude are magnetically conjugate to −60 degrees latitude and 305 degrees longitude. The series of maps illustrates that as the enhanced TEC values of the storm-perturbed equatorial anomaly (defined below) move farther north (over Florida), the conjugate extent of this enhanced TEC is also moving farther south (over Argentina and Chile).

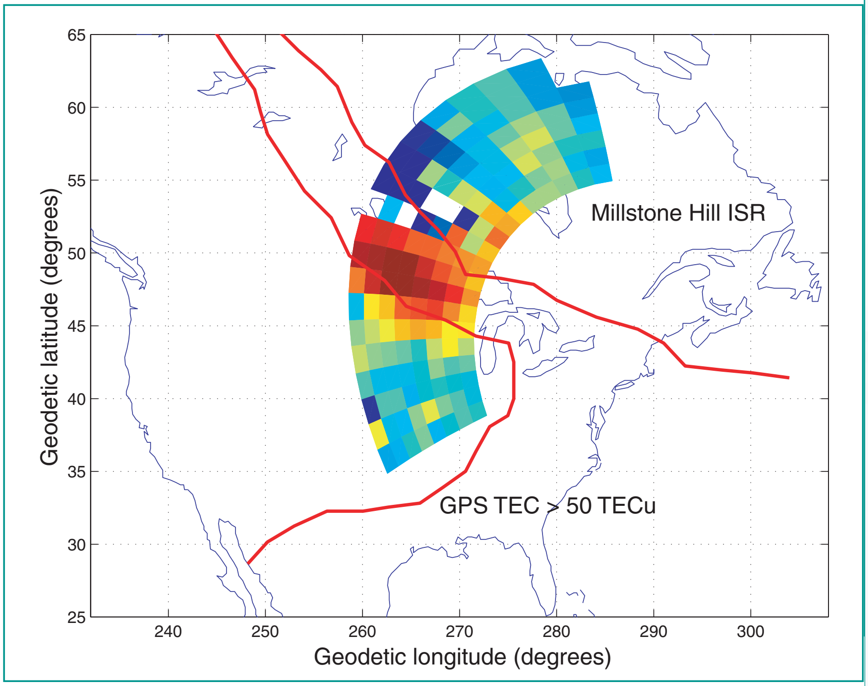


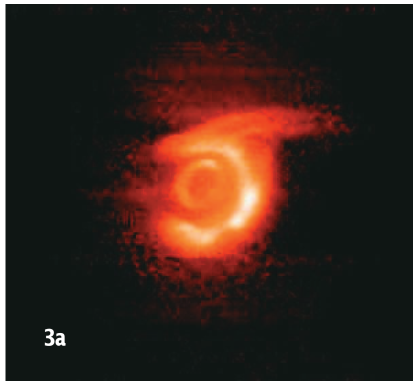
FIGURE 2 Intense sunward ion flux was measured by the Millstone Hill incoherent scatter radar at 19:30 UTC on March 31, 2001. The color coding indicates a range of flux values from 10^{13} to 10^{15} electrons/meter^2/second. The red contours indicate the area in the GPS-measured total electron content (TEC) map where TEC values exceed 50 TEC units.

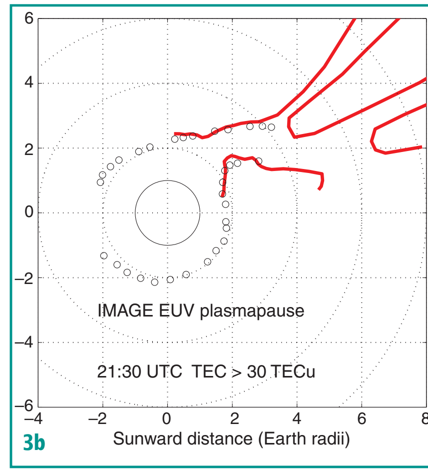
A large geomagnetic storm produces two separate effects. The first occurs when strong-penetration eastward electric fields redistribute plasma in the equatorial ionosphere, magnifying what is commonly referred to as the *Appleton,* or *equatorial, anomaly.* The Appleton anomaly can be described as an electron density depletion that develops at the geomagnetic equator along with regions of enhanced electron density that typically peak at approximately 15–20 degrees north and south geomagnetic latitude. During a large geomagnetic storm, strong eastward electric fields near the equator lift up equatorial plasma (due to $E \times B$ forces in which E is the electric field vector and B is the magnetic field vector) to higher than normal altitudes. Eventually, the uplift from the $E \times B$ force is overcome by the force of gravity, which pulls the plasma down along magnetic field lines.

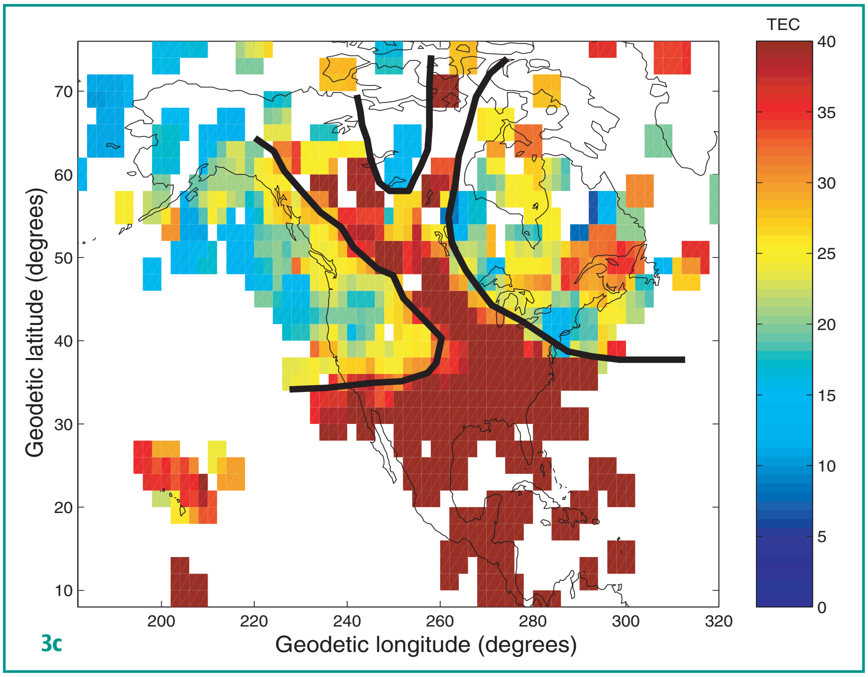
These effects combine to deposit equatorial plasma farther north and south than normal, enhancing the off-equator density concentrations that exist when the ionosphere is quiescent. The enhancement explains the very large TEC values observed over Florida in North America and, correspondingly, over Argentina and Chile in South America. According to this model, one would also anticipate depleted TEC values close to the geomagnetic equator, although we lack access to GPS receivers in this region to confirm this assumption.

The second effect results from a complex interplay between electrodynamic processes in the inner magnetosphere and the ionosphere that leads to the development of the subauroral polarization stream (SAPS). The SAPS electric fields are established along the outer boundary of the plasmasphere, known as the *plasmapause,* and are directed radially outward at the equator, which, tracing along magnetic field lines, maps to a poleward direction at higher latitudes. The SAPS electric fields overlap the plasmasphere, stripping away its outer layer and redistributing previously equatorial plasma to a higher latitude. The plume of low-latitude plasma is then advected rapidly westward and poleward by the $E \times B$ drift developed by the strong SAPS electric field. The result of this complex sequence of events is the space-weather SED plume extending across the Great Lakes into Manitoba as illustrated in Figure 1.

FIGURE 3a, b, c Data collected at approximately 21:20 UTC on March 31, 2001, by the IMAGE satellite and by the ground-based GPS network show the correlation of observed storm-time features: (a) IMAGE satellite extreme ultraviolet image of plasmasphere and plasmaspheric plume; (b) equatorial projection of storm-enhanced density (SED) feature and plasmaspheric plume; (c) GPS total electron content map showing SED feature.







Magnetospheric Connections

Data from other sensors support our interpretation of the GPS TEC observations and also establish connections with Earth's magnetosphere and plasmasphere.

The Millstone Hill incoherent scatter radar (ISR) operated continuously during the March 31, 2001, storm. The Millstone Hill radar is located at a mid-geomagnetic latitude near 55 degrees. Throughout the storm period, the radar used a full south-to-north elevation angle scan to monitor ionospheric features over a wide range of latitude. Each of these scans was repeated for 45 minutes and provided observations of temperature, electron density, and electron and ion velocity as a function of altitude. Using the Millstone Hill ISR electron density measurements, we can compute the TEC up to 800 kilometers. These data are discussed later in the article.

Radar azimuth scans to the west were also made that sampled both the ionospheric density and plasma $E \times B$ velocity inside the SED plume. **Figure 2** presents an ISR measurement of the ion flux measured at the same time as the GPS TEC measurement shown in Figure 1. Ion flux is a product of both electron density and velocity. In Figure 2 the flux is color coded, with red indicating the largest values. Of note is the intense sunward ion flux observed across the region corresponding to the SED plume. The ISR data indicate that the SED plume, mapped by the GPS data, is rapidly advecting sunward, in agreement with the scenario presented earlier.

The second set of ancillary data associated with the GPS TEC map was collected by NASA's Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) satellite. This satellite, with an apogee altitude of 7.2 Earth radii, can image Earth's plasmaphere by using sunlight at a wavelength of 30.4 nanometers resonantly scattered from singly ionized helium (He^+) in the plasmasphere. Ionized atomic hydrogen (H^+) — a proton — is the principal ion within the plasmasphere, which accordingly is sometimes called the *protonosphere*. Singly ionized helium accounts for 3–30 percent of the plasmaspheric material. The brightness of the resonantly scattered 30.4-nanometer feature is directly proportional to the He^+ column abundance. Images generated from data acquired at apogee can therefore show the structure of the entire plamasphere.

Figure 3a shows an image taken at 21:21 UTC on March 31, 2001, which can be interpreted as follows: The Sun is on the right, and Earth's shadow extends through the plasmaphere on the left. The bright ring near the center is the northern aurora. The feature of note is referred to as a *plasmaspheric drainage plume,* which is composed of plasmaspheric material seen stretching sunward. This plasmaspheric drainage plume represents plasma that is eroded from the outer plasmasphere during storm-time conditions described earlier.

The data in **Figure 3b** represent the magnetic equatorial projection of the plasmapause and the plasmaspheric drainage plume seen in the IMAGE EUV observations along with the 30 TEC unit contour line of the GPS map shown in **Figure 3c.** These data are projected into the equatorial plane using simple dipole mapping. The observations from the ground using GPS clearly maps to the plasmaspheric plume as viewed from space. SED is therefore the ground-based signature of the erosion of the outer plasmasphere caused by strong storm-time subauroral polarization electric fields. The ground-based GPS receivers are in fact observing and being affected by a magnetospheric space-weather phenomenon.

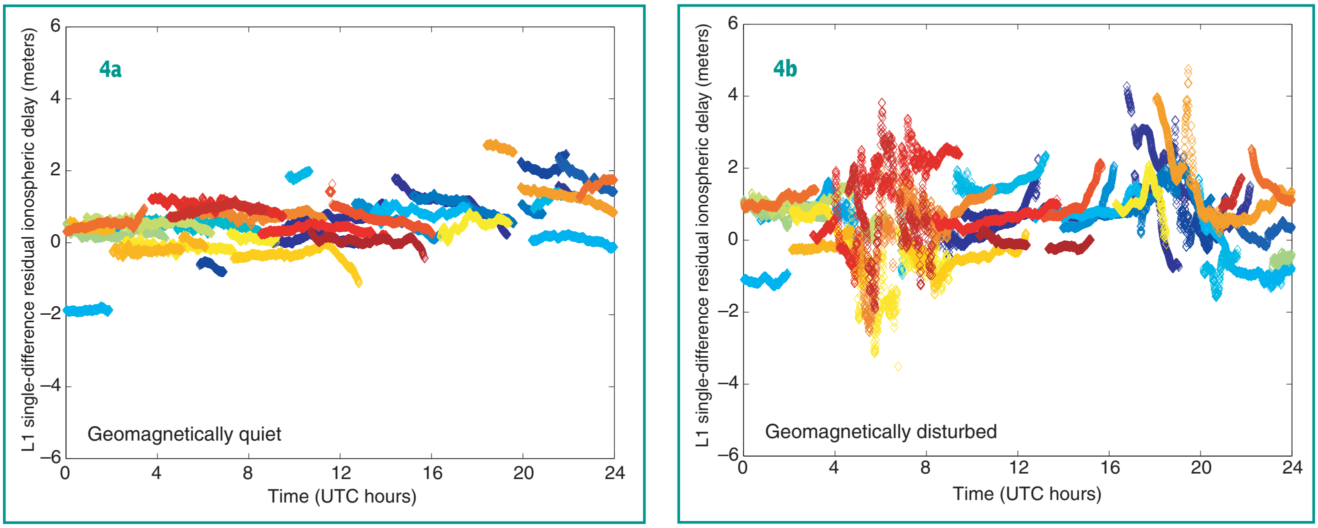


FIGURE 4a, b Illustration of the effect of geomagnetically disturbed conditions on cancellation of the ionospheric delay over the approximately 200-kilometer baseline between Westford and Chatham, Massachusetts: (a) geomagnetically quiet time (March 26, 2001); (b) geomagnetically disturbed time (March 31, 2001).

Storm-Time Ionospheric Effects

The average GPS user is primarily interested in storm-time phenomena as they affect particular GPS receivers. So how do gradients in the TEC affect GPS users? The first example of these effects shows the large gradients that appear over an approximately 200-kilometer baseline between GPS receivers at Westford and Chatham, Massachusetts. **Figure 4** shows the residual ionospheric delay in meters at the L1 frequency (1575.42 MHz) on a quiet day (March 26, 2001) contrasted with the residuals observed on a geomagnetically disturbed day (March 31, 2001). Each color represents a different GPS satellite, and the value of differential delay at L1 measures the difference in the measured line-of-sight TEC (converted to units of meters at L1) at the two receivers to a particular GPS satellite.

DGPS and RTK applications require the ionospheric term to cancel out to correctly resolve carrier-phase ambiguities. Very large differential delays, as much as 4 meters at L1, were observed between several of the satellites on March 31, 2001. The two time periods associated with the large differential delays are associated with the highest Kp values on that day.

Data from several receivers in the northeast region of the United States were examined for loss of lock on March 31, 2001. Unlike other geomagnetic storms during which multiple receivers experienced loss of lock to some degree (for example, on July 15, 2000), the majority of receivers we examined tracked throughout the disturbed time periods. However, we did observe one example of loss of lock in data collected by the Chatham (CHT1) GPS receiver. These data are shown in **Figure 5**, which compares the number of satellites tracked on both L1 and L2 on March 31, 2001, to the number of satellites tracked five days earlier. As many as seven GPS satellites were not in track during the first time period of geomagnetic activity, between 5:00 and 7:00 UTC on March 31 (see Figure 4b).

The last observation of note involves the measured distribution of TEC during geomagnetically disturbed conditions. TEC distribution affects the use of GPS data in two ways: The first involves the incorporation of GPS TEC measurements in ionospheric models, which typically assume that 80–90 percent of TEC is below 1,000 kilometers. The additional TEC contribution is accounted for by the plasmasphere. The second effect of TEC distribution involves the design of the mapping function used to map or project the measured GPS line-of-sight TEC to an estimated vertical TEC. The majority of mapping functions used in GPS processing are based on a single-layer approximation that assumes an ionospheric peak altitude of between 350 and 450 kilometers.

The amount of TEC above 800 kilometers was measured by comparing the Millstone Hill ISR's estimate of TEC in the ionospheric E and F regions with the GPS TEC measurement. The Millstone Hill ISR is sensitive to the electron density only up to altitudes of 800–1,000 kilometers, whereas the GPS TEC measurement measures out to 20,000 kilometers.

Further Reading

For an introduction to space weather, see

- "A Primer on Space Weather," by the Space Environment Center, National Oceanic and Atmospheric Administration, Boulder, Colorado, <http://www.sec.noaa.gov/primer/primer.html>.

For discussions about broad scientific, technological, industrial, commercial, and programmatic topics related to space weather as well as reviews of current space-weather research, see

- *Space Weather*, P. Song, H.J. Singer, and G.L. Siscoe, eds., The American Geophysical Union, Washington, D.C., 2001.

For further information about the transport of ionospheric plasma and monitoring the phenomenon with GPS, see

- "Storm-Time Plasma Transport at Middle and High Latitudes," by J.C. Foster, *Journal of Geophysical Research*, Vol. 98, 1993, pp. 1675–1689.
- "Ionospheric Signatures of Plasmaspheric Tails," by J.C. Foster, P.J. Erickson, A.J. Coster, J. Goldstein, and F.J. Rich, *Geophysical Research Letters*, Vol. 29, No. 13, 2002, 10.1029/2002GL015067.

For other recent *GPS World* articles about the ionosphere and GPS, see

- "GPS, the Ionosphere, and the Solar Maximum," by R.B. Langley, *GPS World*, Vol. 11, No. 7, July 2000, pp. 44–49.
- "Mapping the Low-Latitude Ionosphere with GPS," by M. Fedrizzi, E.R. de Paula, I.J. Kantor, R.B. Langley, M.C. Santos, and A Komjathy, *GPS World*, Vol. 13, No. 2, February 2002, pp. 41–47.

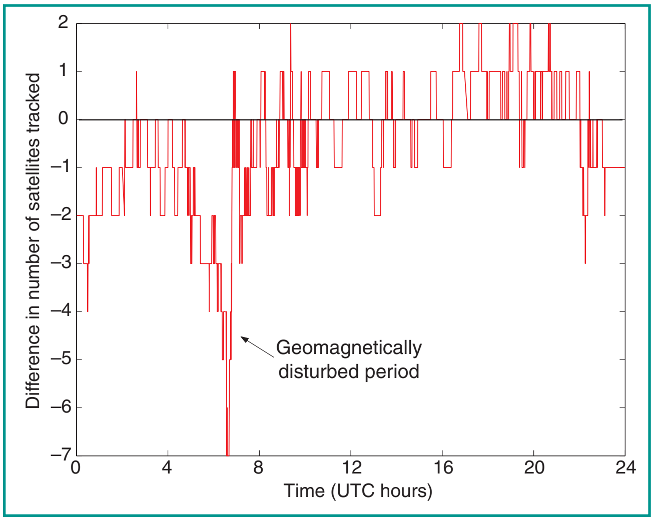


FIGURE 5 A comparison of the number of satellites in track by a GPS receiver at Chatham, Massachusetts, on March 31, 2001, to the number of satellites in track on March 26, 2001, illustrates the difficulty the receiver had tracking satellites during a period when the geomagnetic field was significantly disturbed.

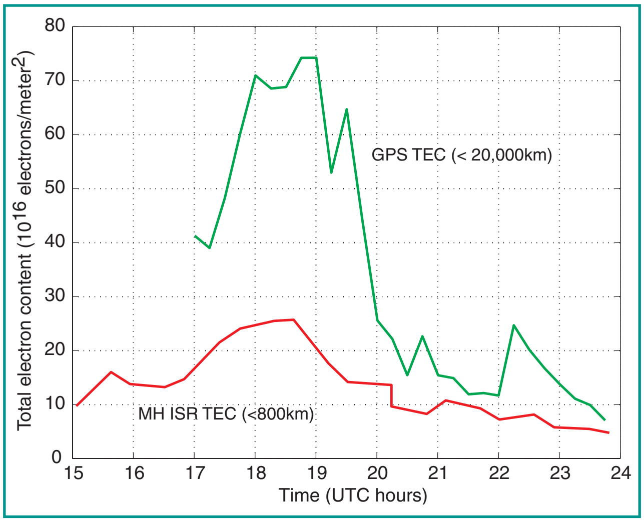


FIGURE 6 TEC measured out to 20,000 kilometers by GPS and TEC measured by the Millstone Hill incoherent scatter radar out to 800 kilometers showed a large increase in the electron content in the upper ionosphere and plasmasphere during the March 31, 2001, storm.

As shown in **Figure 6**, during the time period of the SED phenomenon, greater than 50 percent of the TEC at Millstone Hill was observed to be above 800 kilometers (the measured GPS TEC value was 65–70 TEC units compared with 20 TEC units measured by the ISR).

Summary

GPS, when data are processed in a way that emphasizes the spatial and temporal variability of the overlying medium, is a powerful tool for studying space-weather phenomena whose effects directly affect the North American continent. The SED TEC plumes, seen in GPS data, map directly into the dramatic plasmaspheric plumes observed in the EUV images collected by NASA's IMAGE satellite. The GPS TEC maps support the explanation of SED as an ionospheric signature of the erosion of the outer plasmasphere by electric fields. Continued monitoring of space weather using GPS will further enhance our understanding of the dynamic processes taking place in the ionosphere and their effects on communications and navigation, electric power grids, and other technological systems.

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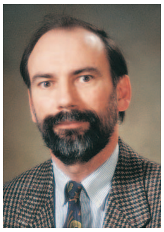
Philip Erickson received his B.S. and Ph.D. in electrical engineering from Cornell University in Ithaca, New York. In 1995, he joined the staff of the Atmospheric Sciences Group at MIT's Haystack Observatory. At Haystack, he is involved with the scheduling, software, and hardware subsystems that operate Millstone Hill, one of four American longitude sector megawatt–class incoherent scatter radars. Erickson conducts studies of topside light ion behavior and E-region irregularities using Millstone Hill data.



"Innovation" is a regular column featuring discussions about recent advances in GPS technology and its applications as well as the fundamentals of GPS positioning. The column is coordinated by Richard Langley of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, who appreciates receiving your comments and topic suggestions. To contact him, see the "Columnists" section on page 2 of this issue.