REGIONAL GPS MAPPING OF STORM ENHANCED DENSITY

Anthea Coster [(1)], **John Foster** [(2)], **Phil Erickson** [(3)], **Frederick Rich** [(4)]

[(1)] *Millstone Hill Radar, MIT Lincoln Laboratory, 244 Wood Street, Lexington, MA, 02420-9108, USA*
Tel: 781-981-5658, Fax: 781-981-4591, Email: coster@ll.mit.edu

[(2)] ***MIT Haystack Observatory, Atmospheric Sciences, Off Route 40, Westford, MA, 01886, USA***
Tel: 781-981-5621, Fax: 781-981-5766, Email: jcf@haystack.mit.edu

[(3)] ***As (2) above, but Tel: 781-981-5769, Fax: 781-981-5766, Email: pje@haystack.mit.edu***

[(4)] ***AFRL/VSBXP, 29 Randolph Rd, Hanscom AFB, MA, 01731-3010, USA***
Tel: 781-377-3857, Fax: 781-377-9950, Email: frederick.rich@hanscom.af.mil

ABSTRACT

During geomagnetic disturbances, intense storm-time electric fields of magnetospheric origin extend across mid-latitudes establishing the sub-auroral polarization stream [1]. The effect is to redistribute the ionospheric plasma through advection across both latitude and local time. Strong increases and sharp spatial gradients in total electron content (TEC) are observed. The ionospheric response to several geomagnetic storms is monitored with TEC measurements from more than 120 GPS receivers scattered throughout the U.S., Canada, and South America. The GPS data are used to construct a time history of TEC perturbations in two dimensions during storm time conditions.

INTRODUCTION

Space weather is defined as conditions on the Sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-based and ground-based technological systems, [2]. The conditions being referred to are solar flares, coronal mass ejections (CME), magnetospheric storms and substorms, and the low altitude effects of those disturbances (auroral activity, ionospheric scintillation and total electron content (TEC) variations, ionospheric joule heating, etc.) The development of ionospheric storm enhanced density (SED) is just one example of a space weather phenomenon, [3]. This paper presents a study of the development of the SED effect following two X class solar flares. The first solar flare took place on 14 July 2001, and was responsible for one of the largest solar-terrestrial disturbances in the past 11 years. Major ionospheric effects, including SED, were observed on 15-16 July 2001, when the solar charged particles reached the earth's magnetosphere. A second solar flare took place on 29 March 2001. Severe ionospheric disturbances, including another example of SED, were observed on 31 March 2001. These two storms are used to illustrate the ionospheric SED phenomenon. Both storms are described briefly.

GEOMAGNETIC STORM SUMMARY

15-16 July 2000 Storm.

On 14 July 2000, an X-class solar flare occurred on the sun. Associated with this flare was an Earth-directed coronal mass ejection with energies up to 100s of MeV. This solar storm was one of the largest events in the previous nine years. The solar flare/CME led to a severe geomagnetic storm on the earth with significant ionospheric effects. When the storm actually reached the earth on late 15 July 2000, the global Kp index which measures magnetic activity was 9, the highest level, for three consecutive 3-hr time bins. The Kp index remained at disturbed levels for some time following.

31 March 2001 Storm

On 29 March 2001, another X-class solar flare occurred on the sun. Associated with this flare were two coronal mass ejections. The geomagnetic index, Kp, reached 9-, close to maximum levels on 31 March 2001 between 3 and 9 UT, two consecutive 3-hr time bins. The Kp remained at high levels (greater than 6) throughout the day on 31 March, and into the first part of 1 April (where the Kp was at or above 5). Perhaps because of the time of day when this storm first hit the earth, the maximum TEC measured within the US was somewhat smaller than it was during the 15-16 July 2000 storm, however SED and the sub-auroral polarization stream are clearly evident [1].

INSTRUMENTATION

Observations from three different sensor types are discussed. During the 15-16 July 2000 storm and the 31 March 2001 storm, the Millstone Ionospheric Scatter Radar located in Westford, Massachusetts and operated by the Massachusetts Institute of Technology was continuously collecting observations of temperature, electron density, and electron and ion velocity. The Millstone radar is located at mid-latitude near L=3 (55° invariant latitude). The longitude of the facility is significant (288.5°) because the north geomagnetic pole is offset from the geographic pole in such a way that auroral magnetic latitudes reach their lowest extent in geographic latitude in the sector observed by the radar. Throughout both storm periods, the radar was using a full south to north elevation scan to monitor ionospheric features over a wide range of latitude. These scans were repeated each 45 min and provide both TEC and density measurements over a 20-30 degree latitude span.

Also located at Millstone Hill is a GPS receiver operated by MIT Lincoln Laboratory and used in real-time ionospheric modeling for satellite tracking operations. A second GPS receiver, originally installed by MIT Lincoln Laboratory, is located at the FPS-85 radar at the Eglin AFB. The GPS TEC measurements from these sensors were combined with TEC measurements from several other (~120) GPS receivers scattered throughout the U.S., Canada, and S. America. The data from these additional GPS receivers are accessible via the SOPAC data archive on the World Wide Web (http://sopac.ucsd.edu/).

The final data set analyzed came from the Defense Meteorological Satellite Program (DMSP). DMSP satellites are in a near polar, sun synchronous orbit at an altitude of approximately 830 km above the earth and with an orbital period of approximately 101 minutes. These satellites have instrumentation on board to monitor the meteorological, oceanographic and solar-terrestrial physics environment. This paper analyzes measurements of ion density and ion drifts made by the SSI/ES instrument on the DMSP satellites. The SSI/ES is an improved version of the Special Sensor for Ions and Electrons (SSI/E).

STORM ENHANCED DENSITIES

SED is characterized by an increase in TEC and peak height of the F-region profile. Storm time SED is a pronounced feature of Millstone Hill ionospheric observations, [3]. It is associated with the transport of solar-enhanced plasma from lower latitudes. The SED is observed equatorward of the evening sector trough, in the region of sunward plasma convection. The integrated column density (TEC) is enhanced by a factor of 2 to 4 and is spatially extended along the sunward convection trajectory. SED is associated with velocities of 800 m s^{-1}, giving a ~2 hour transit time from its source at low latitudes to the polar cap at noon and a plasma flux of 10^{14} $m^{-2}s^{-1}$. It has been shown in [1] that storm enhanced density results from the erosion of the outer plasmasphere by strong sub-auroral polarization stream electric fields. SED/TEC plumes seen in the ionosphere map directly into the magnetospheric determination of the boundaries of the plasmapause and plasmaspheric tail determined by EUV imaging from the IMAGE spacecraft, [1].

OBSERVATIONS OF SED

Figure 1 plots the incoherent scatter data associated with the 15 July 2000 event. The plot shows electron density at 600-km altitude as a function of latitude and time. This value of the electron density correlates well with TEC, [4]. Notice the enhanced electron density beginning at around 17:30 UT (the initial commencement of the storm) followed by three more bands of increased electron density.

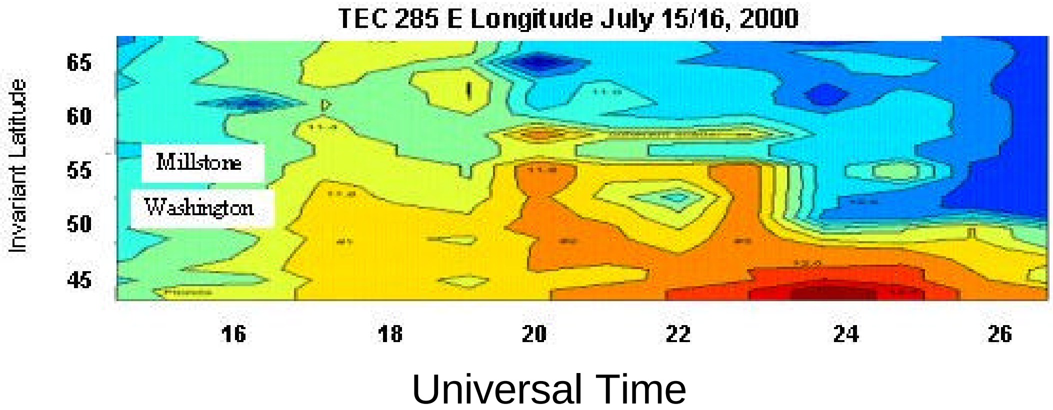

Figure 1. Electron density at 600 km measured by the Millstone Hill Incoherent Scatter radar as a function of time in hours past 0 UT on 15 July 2000 and invariant latitude.

Figure 2 shows data collected from measurements on-board the DMSP F13 satellite as it traveled through the mid-latitude American sector. These data were collected at 22:30 U.T. The bottom plot shows the electron/ion density at 830 km as a function of invariant latitude. Higher values of electron density are shown at lower latitudes corresponding to the equatorial anomaly; lower values are shown in the trough region at 50 degrees invariant latitude and above. The middle plot shows the Ion Drift Meter (IDM) ion velocity measurements as a function of invariant latitude in meters/second in the approximate east-west direction at the DMSP satellite altitude of 830 km. The polarization jet, an area of enhanced westward convection [5] is shown here in the region between 45 and 50 degrees invariant latitude. The polarization jet is typically about 3-5 degrees in latitude, and features velocities of about 500-1000 m/s. The plasmapause is shown at about 50 degrees invariant latitude. Further north, the more structured auroral convection patterns are shown. Note between 45.5° and 47° degrees invariant latitude, both elevated densities and elevated velocities exist. The computed flux, shown in the top plot, is calculated by multiplying the velocities associated with the polarization jet with the electron density associated with the plasma. A clear increase in the ion flux is shown in this region of 45.5° and 47°, corresponding to a region of SED.

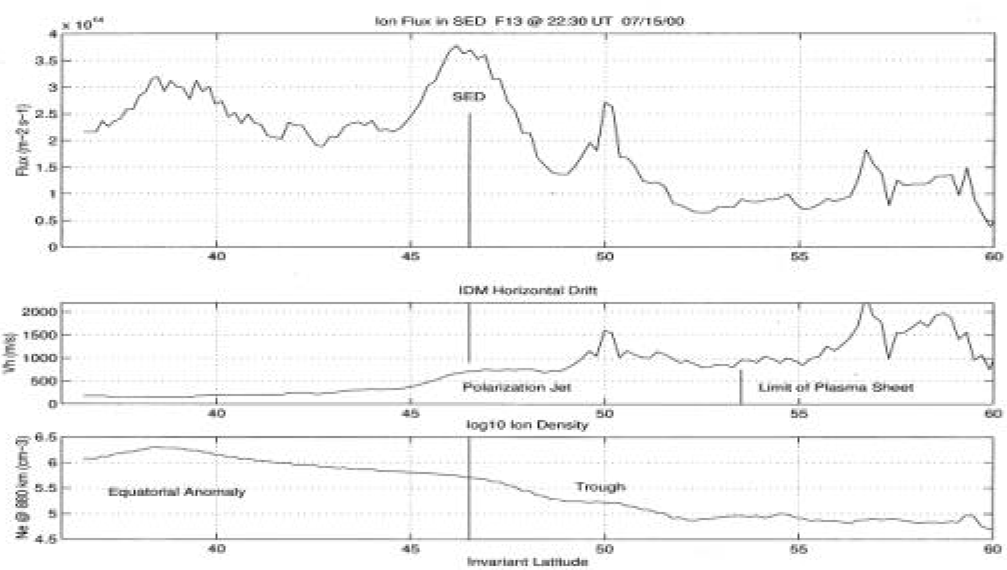

Figure 2. DMSP F13 measurements from an overflight at 22:30 UT on 07/15/00. The bottom plot shows the electron/ion density at 830 km as a function of invariant latitude. The middle plot shows the horizontal ion velocities (~east/west) as a function of invariant latitude. The top plot shows the computed ion flux, again as a function of invariant latitude, derived from multiplying the ion density times the ion velocity.

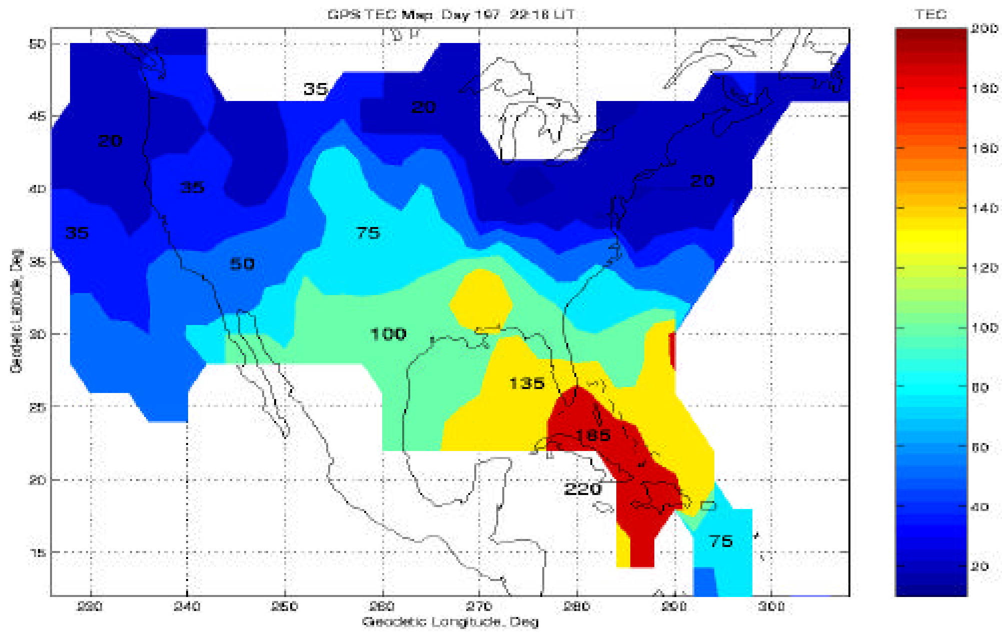

Figure 3. TEC values as a function of latitude and longitude derived from greater than 50 GPS receivers located across the U.S. on 15 July 2000 at 22.15 UT.

CONCLUSIONS

The combination of GPS mapping with DMSP observations and incoherent scatter is providing new insights into the ionospheric/magnetospheric connection. The GPS data have been used to construct a time history of TEC perturbations in two dimensions. The data clearly show plasma advection from the lower latitudes bringing in storm-enhanced density (SED). During both storms studied so far, plasma is transported to higher latitudes and to earlier local times – approaching the noon meridian. TEC values ~ 100 TEC units are evident in the region immediately equatorward of the trough. The analysis of the 15-16 July 2000 and the 31 March 2001 storms will continue, along with analysis of data sets from other disturbed time periods. In particular, research will continue to focus on understanding the development of storm-enhanced density and on the production of enhanced TEC values in the Florida sector.

ACKNOWLEDGEMENTS

This work is sponsored by the Air Force under Air Force Contract AF19628-00-C-0002 Opinions, interpretations, conclusions, and recommendations are those of the author and are not necessarily endorsed by the United States Air Force. The Millstone Hill Observatory is supported by a co-operative agreement between the National Science Foundation and the Massachusetts Institute of Technology.

REFERENCES

[1] Foster, J. C., P. J. Erickson, A. J. Coster, J. Goldstein, and F. J. Rich, "Ionospheric Signatures of Plasmaspheric Tails," G.R.L., in press, 2002.

[2] Anon., "National Space Weather Program, The Strategic Plan," FCM-B30-1995, Washington D. C., August 1995.

[3] Foster, J. C., "Storm-Time Plasma Transport at Middle and High Latitudes," J. Geophys. Res., 98, 1675-1689. 1993.

[4] Foster, J.C., personal communication, 2001.

[5] Smiddy, M., M. C. Kelly, W. Burke, F. Rich, R. Sagalyn, B. Schman, R. Hays, and S. Lai, "Intense Poleward-directed Electric Fields Near the Ionospheric Projection of the Plasmapause," Geophys. Res. Lett., 4, 543, 1977.