Quantitative Investigation of Ionospheric Density Gradients at Mid Latitudes

J. C. Foster
Atmospheric Sciences Group
MIT Haystack Observatory

BIOGRAPHY

John Foster is Associate Director for Atmospheric Sciences of the Massachusetts Inst. of Technology Haystack Observatory in Westford Massachusetts. He holds a Ph.D. in Physics and has 30 years experience in studies of earth's ionosphere, magnetosphere, space weather effects, magnetosphere/ionosphere coupling phenomena, and incoherent scatter radar techniques. Dr. Foster is Group Leader of MIT's Millstone Hill Observatory.

ABSTRACT

The sub-auroral ionosphere, at the magnetic latitudes which characterize the northeastern United States, is subject to severe *F*-region ionospheric density structuring due to the space weather effects of magnetospheric disturbance electric fields. Communications and navigation systems relying on trans-ionospheric propagation must be able to compensate for the effects of the sharp changes (> 10x) in total electron content (TEC) associated with the ionospheric trough and storm-time disturbance effects at mid latitudes. An accurate characterization of these gradients and their variability is needed in the design and evaluation of navigation systems utilizing trans-ionospheric propagation in this regime. A study is underway at the MIT Haystack Observatory using the Millstone Hill incoherent scatter radar database to investigate the spatial extent and temporal evolution of TEC and density altitude/latitude structure at mid and sub-auroral latitudes as a function of solar cycle, season, and level of geomagnetic activity.

The Massachusetts Institute of Technology maintains an extensive radar research facility at Millstone Hill, located 35 miles northwest of metropolitan Boston at 42.6˚ N latitude, 288.5˚ E longitude. Multi-megawatt UHF transmitters and a fully-steerable 46-m antenna provide wide-ranging spatial coverage, spanning >30˚ of latitude and 4+ hours of local time at *F*-region heights. The facility is situated at 54˚ geomagnetic latitude such that its extensive field-of-view for ionospheric observations encompasses the full extent of mid-latitude, sub-auroral, and auroral features and processes. The Millstone Hill incoherent scatter radar has been in operation through three solar cycles and its data characterize ionospheric features and response over the altitude range 100 km to 1000 km with a typical altitude/spatial resolution of 50 km. Long-term operations as a part of the international Incoherent Scatter World Day program have built up a database of radar elevation scans which sample a span of 15˚ - 25˚ latitude with better than 1˚ latitude resolution and ~35 km altitude resolution. Data from each radar elevation scan is used to produce vertical TEC in the altitude range 150 km - 650 km with better than 1˚ latitude resolution.

Density gradients associated with the deep, narrow ionospheric trough which forms during disturbed conditions are ~10 TEC units / degree latitude. Storm enhanced density (SED), the bulk redistribution of *F*-region plasma by disturbance electric fields, can result in TEC > 100 over New England

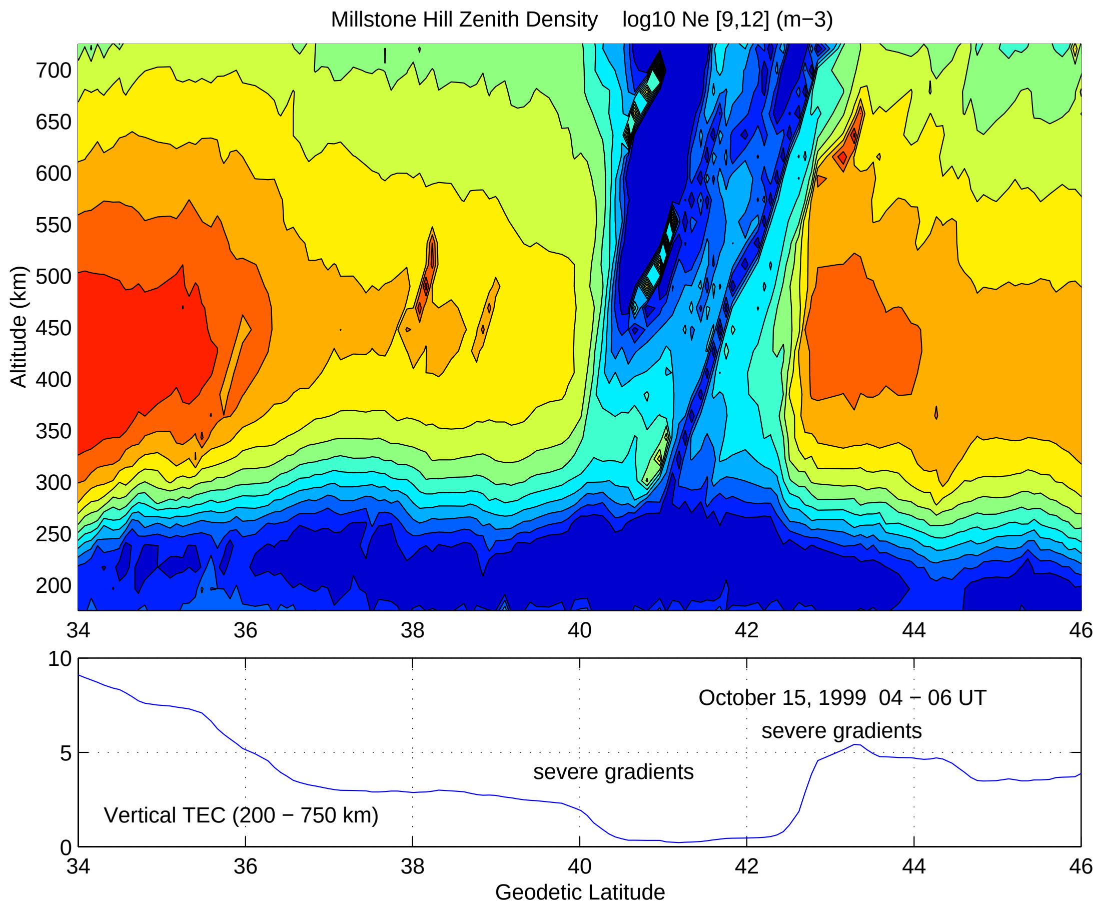

Figure 1. Steep ionospheric density/TEC gradient observed over Millstone Hill (42.5 N, 288.5 E).

and TEC gradients of ~50 TEC / degree latitude.

INTRODUCTION

The sub-auroral ionosphere, at the magnetic latitudes which characterize the northeastern United States, is subject to severe *F*-region ionospheric density structuring due to the space weather effects of magnetospheric disturbance electric fields [*Foster*, 1995]. The sub-auroral ionosphere is not subjected to the precipitation-induced localized ionization enhancements which characterize the auroral oval. Instead, **ExB** plasma motions advect ionospheric plasma with significantly different TEC characteristics through this region [*Foster*, 1993], and chemical recombination of ions in the presence of large electric fields [*Schunk et al.*, 1976] reduces plasma density producing the deep nighttime ionization trough. This paper presents an overview of such mid-latitude phenomena, as observed by MIT's Millstone Hill incoherent scatter radar, and characterizes the spatial gradients of F-region total electron content (TEC) which are associated with their occurrence.

MILLSTONE HILL INCOHERENT SCATTER RADAR

The Massachusetts Institute of Technology maintains an extensive radar research facility at Millstone Hill, located 35 miles northwest of metropolitan Boston at 42.6˚ N latitude, 288.5˚ E longitude. Multi-megawatt UHF transmitters and a fully-steerable 46-m antenna provide wide-ranging spatial coverage, spanning >30˚ of latitude and 4+ hours of local time at *F* region heights. The facility is situated at 54˚ geomagnetic latitude such that its extensive field-of-view for ionospheric observations encompasses the full extent of mid-latitude, sub-auroral, and auroral features and processes.

The location of Millstone Hill is such that significant ionospheric structure falls well within the radar's field of view. The ionospheric total density trough is observed nearly overhead at Millstone Hill each night and the equatorward offset of the north geomagnetic pole nearly along the Millstone Hill meridian brings high-latitude and auroral phenomena into the Observatory's near field of view during geomagnetic storms (e.g. *Buonsanto et al.* [1992]). During disturbed conditions, intense convection electric fields occur at previously sub-auroral latitudes resulting in the formation of a deep, narrow *F*-region ionization trough. Equatorward of this, sunward advection of plasma from later local times and lower latitudes leads to a region of Storm-Enhanced Density (SED) [*Foster*, 1993] in which TEC can exceed average values by a significant amount. These processes contribute to the formation of steep, localized plasma density gradients whose position and characteristics depend strongly on the magnetosphere-ionosphere coupling in that longitude sector.

The Millstone Hill incoherent scatter radar has been in operation through three solar cycles and its data characterize ionospheric features and response over the altitude range 100 km to 1000 km with a typical altitude/spatial resolution of 50 km. Long-term operations as a part of the international Incoherent Scatter World Day program have built up a database of radar elevation scans which sample a span of 15˚ - 25˚ latitude with better than 1˚ latitude resolution and ~35 km altitude resolution. Data from each radar elevation scan is sorted to produce vertical TEC in the altitude range 150 km - 650 km with better than 1˚ latitude resolution. The principal characteristics of each scan (gradients, trough location, geomagnetic activity conditions) are determined and cataloged and this reduced data set is analyzed to determine the best characterization of ionospheric gradients (depth of trough, location, variability) as functions of solar cycle, season, local time, and level of disturbance

IONOSPHERIC TROUGH ASSOCIATED WITH ENHANCED ELECTRIC FIELD

During geomagnetic disturbances, the electric fields and particle populations which characterize the auroral region expand equatorward and their effects are felt at previously sub-auroral latitudes. Intense convection electric fields appear in the expanded auroral oval (e.g. *Yeh et al.*, [1991]) and are responsible for density depletion and iono-

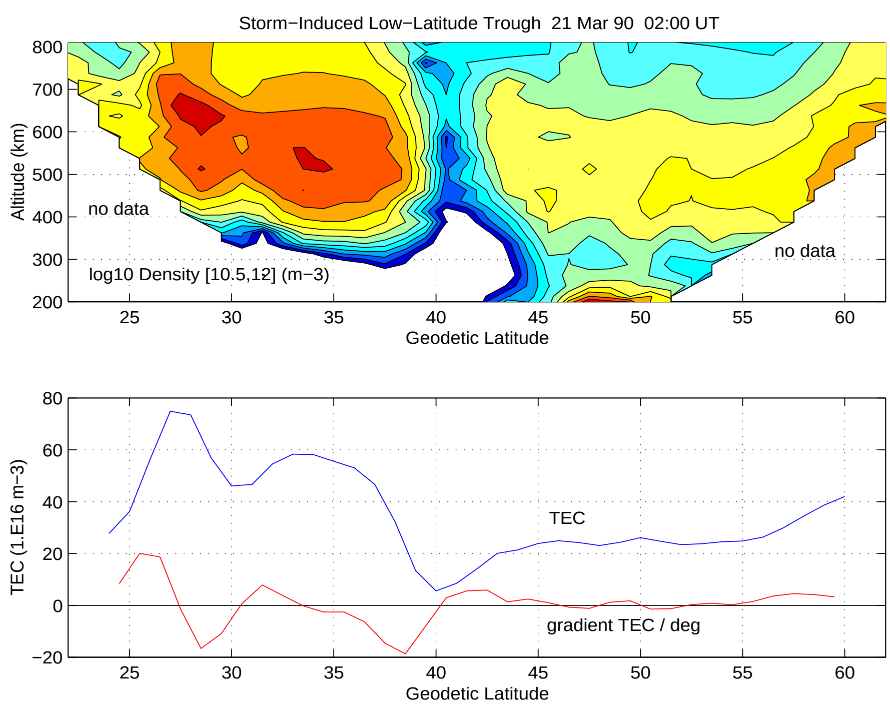

Figure 2. Millstone Hill elevation scan across ionospheric trough during disturbed conditions.

spheric trough formation due to the effects of enhanced recombination [*Schunk et al.* 1976]. A polarization jet [*Galperin et al.*, 1974] or SAID event is defined as westward convection with magnitude in excess of 500 m s^{-1}, equatorward of the auroral precipitation, and often associated with an ionospheric trough [*Spiro et al.*, 1979]. SAID are associated with disturbed conditions, and specifically with substorm recovery [*Anderson et al.*, 1993]. The high velocities due to intermittent or repetitive SAID events lead to mid-latitude trough formation, leaving a longitudinally extended, conjugate fossil trough [*Evans et al.*, 1983] which persists through the night, corotating with the earth.

A sequence of local radar experiments conducted in October, 1999 provided high-temporal resolution *F*-region profiles through the region near the disturbance-induced ionospheric trough. The Millstone Hill zenith-directed antenna was used and full vertical profiles were obtained every 2 min through three consecutive nights with similar (Kp = 3) geomagnetic conditions. SAID formation during the equatorward penetration of magnetospheric ring-current energetic particles [*Foster*, 1995] produces a nearly uniform equatorward motion of trough across the radar beam. The steep walls of the ionospheric trough are evident in Figure 1 on October 15, 1999. Any line-of-sight measure of TEC or density versus range can cut across sharp density gradient features, masking the true nature of the gradients. The SAID and its ionospheric effects are magnetic field aligned phenomena, and a true measure of the gradients need to take into account the inclination of the local magnetic field. The uniform motion of the trough across the radar beam was used to convert the radial (vertical) profiles into magnetic field-aligned profiles. Integrating the density-altitude profiles between 200 km and 750 km gives a good estimation of the *F*-region contribution to TEC, and this is shown in Figure 3 along with a determination of the latitude gradient in TEC associated with this event. Latitude gradients of 5 TEC - 10 TEC units per degree of latitude are indicated.Storm Enhanced Density (SED)

Global electric field models indicate a dominant two-cell pattern of plasma convection whose equatorward portion transports ionospheric plasma sunward toward the noon meridian from both the

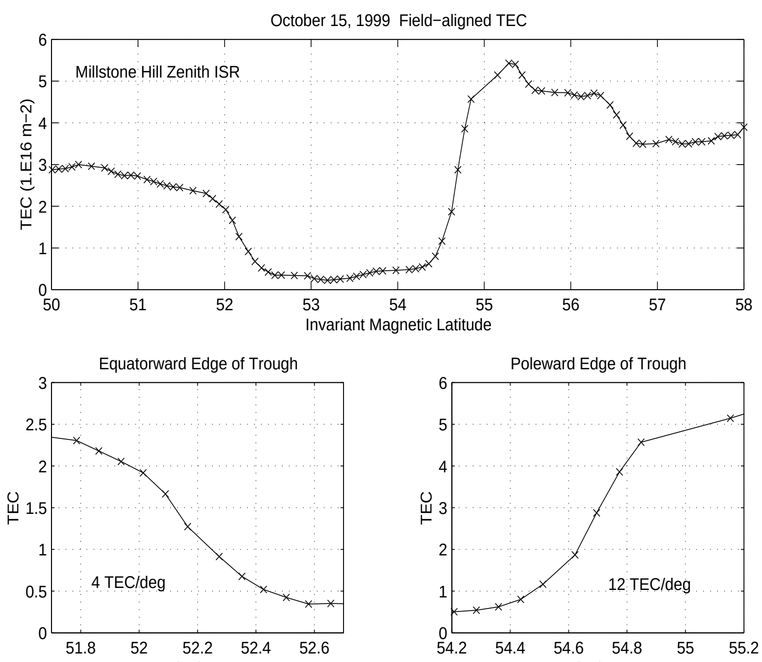

Figure 3. Field-aligned TEC and TEC gradients observed at 42.5 N latitude on October 15, 1999.

dawn and dusk auroral and subauroral regions. The effects of plasma transport, and the linkage to the overlying magnetosphere, dominate ionospheric characteristics at these latitudes. With increasing activity level, and particularly during geomagnetic storms, the equatorward extent of such effects expands to lower latitudes [e.g., *Foster et al.*, 1986]. Associated with the large-scale enhancement of the ionospheric convection electric field during disturbed geomagnetic conditions, solar-produced F region is transported sunward and poleward from a source region at middle and low latitudes in the afternoon sector, producing a latitudinally narrow region of storm-enhanced plasma density (SED) and increased total electron content which is advected toward higher latitudes in the noon sector [*Foster*, 1993[. The Millstone Hill incoherent scatter radar regularly observes SED as a spatially continuous, large-scale feature spanning local times between noon and midnight and at latitudes between the polar cap and its mid- or low-latitude source region. This feature accounts for the pronounced enhancement of ionospheric density near dusk at middle latitudes observed during the early stages of magnetic storms (called the dusk effect) and constitutes a source for the enhanced *F*-region plasma observed in the polar cap during disturbed conditions. Within the region of SED, TEC is greatly enhanced and steep latitude gradients of TEC occur

Millstone Hill radar observations during the great magnetic storm of February 8, 1986 (Kp = 9) spanned the entire interval of mid-latitude disturbance with wide-ranging elevation scans and sweeping azimuth scans which detailed the evolution of intense mid-latitude electric fields [*Yeh et al.*, 1991] and their ionospheric consequences [*Yeh et al.*, 1990]. Storm enhanced density was tracked at latitudes from Canada to the Caribbean [*Foste*r, 1993] and associated TEC > 100 $*10^{-16}$ m^{-2} (cf. Figure 4). Latitude gradient in TEC, observed with the region of SED near 45˚ N geodetic latitude, was ~50 TEC/deg. The February 8, 1986 event represents a severe example of the ionospheric density perturbation that can occur over the continental US during large geomagnetic storms. The study by Foster [1993] presents the related conditions and occurrence frequency associated with storm enhanced density over the northeastern US. SED is regularly seen throughout the afternoon sector at Millstone's longitude and can be identified at all disturbance levels down to Kp = 2. For disturbed conditions (Kp > 4) the latitude of SED occurrence at a given local time decreases by 6˚ for an increase of 2 in the Kp index. The latitude at which the SED is observed at each level of Kp decreases with increasing local time at a rate of 2.5˚ h^{-1}.

CONCLUSIONS

Steep ionospheric density and TEC gradients are observed at sub-auroral and mid latitudes associated with the ionospheric trough and with advecting density enhancements during geomagnetically disturbed conditions. Latitude gradients in TEC associated with the equatorward and poleward walls of the trough are ~10 TEC units/degree of latitude, while gradients associated with regions of greatly-enhanced TEC (storm enhanced density, SED) are observed as great as ~50 TEC units/ degree of latitude. Communications and navigation systems relying on trans-ionospheric propagation must be able to compensate for the effects of such sharp gradients in total electron content.

MIT's Millstone Hill Observatory research facility is optimally situated for observations of these important space weather phenomena. A thirty-year database of mid-latitude incoherent scatter radar observations is being used to characterize such effects. Related research results and information are accessible at (www.haystack.edu/homepage.html).

ACKNOWLEDGEMENTS

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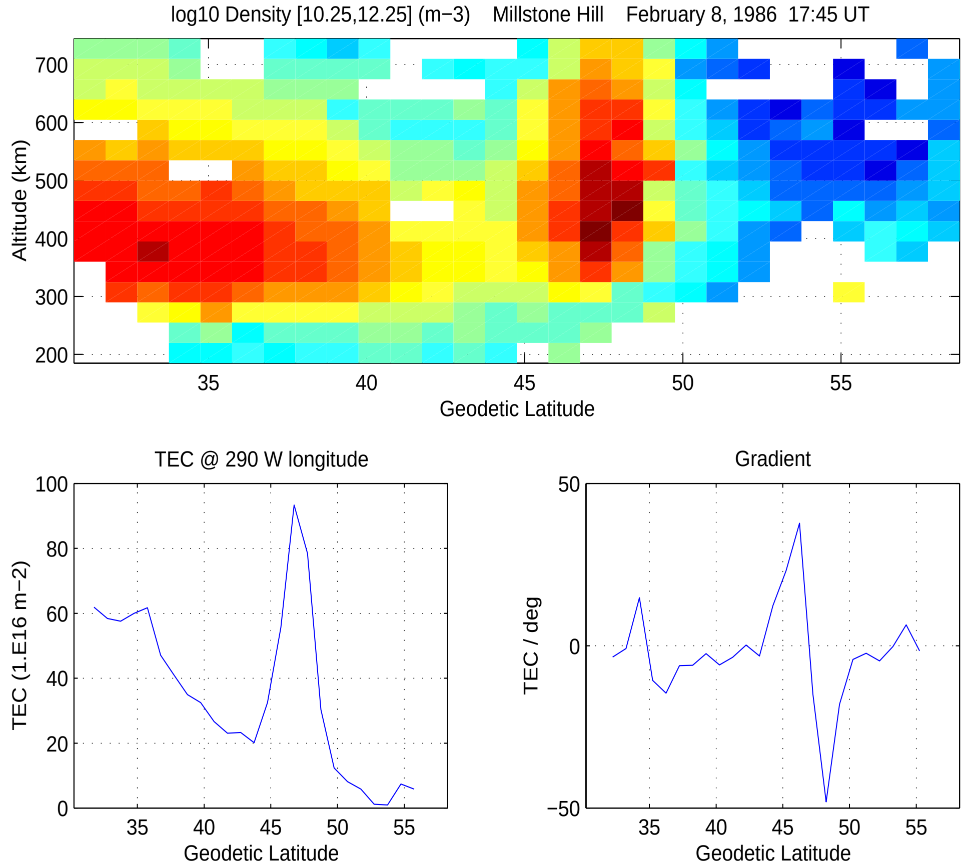

Figure 4. N-S elevation scan through the ionospheric F region with the Millstone Hill incoherent scatter radar during the major geomagnetic disturbance on February 8, 1986. Sunward-convecting solar-produced plasma produced a distinct region of storm enhanced density (SED) immediately poleward of the site. TEC in the region of SED reached 100 TEC units and latitude gradients exceeded ~50 TEC / deg.

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