Radio tomographic imaging of the northern high-latitude ionosphere on a wide geographic scale

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[1] Several chains of receivers, measuring total electron content (TEC) during passes of satellites in the U.S. Navy Ionospheric Measuring System (NIMS), are operated at northern high latitudes by members of the International Ionospheric Tomography Community (IITC). Results are presented here of nearly simultaneous latitude-altitude images of the ionosphere over Scandinavia, Greenland, and Alaska, generated from IITC data obtained on 20 September 2001 and interpreted in the context of an IMF-dependent convection model. The images are compared with output from a coupled thermosphere-ionosphere-plasmasphere model and also with maps of high-latitude TEC generated from GPS measurements. With B_z and B_y both weakly negative, the images and map reveal plasma features of a two-cell convection pattern rotated slightly to earlier local magnetic times. The tomographic images provide details of map features such as a tongue of ionization created by solar EUV radiation on the dayside and entrained by convection into the polar cap from the western Russian sector. Combining latitude versus altitude tomographic images generated in different longitudinal sectors from polar-orbiting beacon satellites such as those of NIMS with TEC maps from GPS offers an emerging opportunity for polar aeronomic studies, especially if further related to synoptic convection measurements. The results also demonstrate the potential role of wide-scale radio tomography in the verification of ionospheric models.

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1. Introduction

[2] Radio tomography is a relatively new experimental technique, developed in recent years to image structures in the electron density of the ionized atmosphere. The particular application of the method used here involves the monitoring of signals from satellites in low Earth orbit at a linear chain of stations to measure the total electron content along the intersecting ray paths. The resultant data set is then inverted in a reconstruction algorithm to create an image in two dimensions of the spatial structures in the ionospheric electron density. Progress in the development of the technique can be followed in a number of review papers [*Kersley and Pryse*, 1994; *Leitinger*, 1999; *Pryse*, 2003]. Radio tomography has been demonstrated to have relevance both to the study of the geophysical processes controlling the ionized atmosphere and to radio science applications of propagation effects on practical radio systems. Several of the former studies have been at high latitudes where the images of signatures in the ionized atmosphere have been used to investigate effects of space weather on the terrestrial environment. Recently, the efforts of individual research groups working in the field have been coordinated through the auspices of the International Ionospheric Tomography Community (IITC). The present paper reports results

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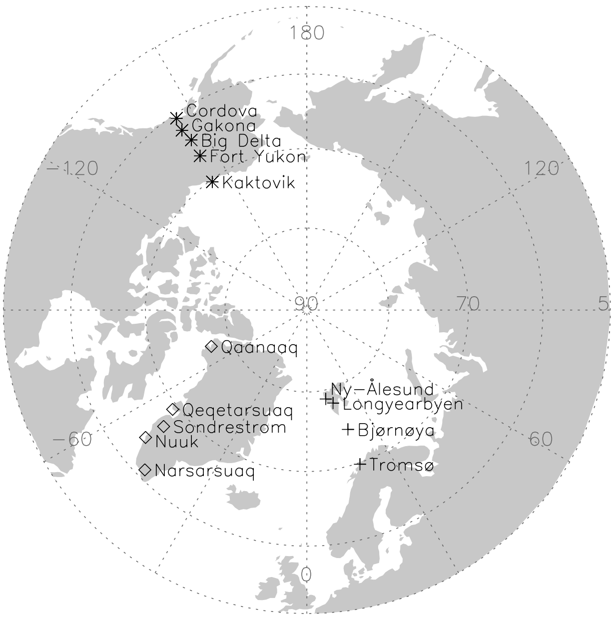

Figure 1. Map showing the locations of the three chains of satellite receiving stations making the measurements used for the radio tomographic studies.

from the first experimental campaign of the group, aimed at using the tomographic method to investigate the structure of the ionosphere at high latitudes on a wide geographic basis.

2. Experiment and Analysis

[3] Most of the current activity in the field of experimental radio tomography makes use of radio transmissions from satellites in the Navy Ionospheric Monitoring System, a constellation of six satellites in polar orbits at altitudes of about 1100 km. Monitoring of the signals on 150 and 400 MHz enables measurement of the electron content along the ionospheric ray paths by means of the differential carrier phase technique. During the IITC campaign, three groups operated the chains of ground receiving stations at northern high latitudes shown in the map of Figure 1. The University of Wales, Aberystwyth (UWA) were responsible for four receiving systems located in the European sector at sites in northern Scandinavia, ranging from Tromso (70°N) poleward to Ny Alesund (79°N). The Applied Research Laboratories (ARL) of the University of Texas at Austin operated a chain of four stations in western Greenland, covering geographic latitudes from 61°N to 69°N, to which have been added data from a station operated at Qaanaaq (77°N) by NorthWest Research Associates Inc. (NWRA). The third chain, in Alaska with five receivers between about 61°N and 70°N, was established and maintained by NWRA in collaboration with the Geophysical Institute of the University of Alaska, Fairbanks.

[4] The dates 19 and 20 September 2001 were chosen for the first campaign to coincide with internationally coordinated World Days, when observations from different instruments monitoring a wide range of geophysical parameters were likely to be available to aid interpretation of the tomographic results. The receiving systems at all of the sites operated automatically to make measurements using a random selection of satellite passes, giving wide temporal coverage of conditions in the ionosphere at each of the geographic sectors throughout the period of interest. The analysis of the observations from the different station chains was carried out by each of the groups concerned. Tomographic images of the electron density in a height versus latitude plane in the longitude sector of the station chain were generated for each of the passes recorded. Using well-established techniques, information about the spatial distribution of the ionization can be obtained for a latitudinal range that extends some 5° to 7° wider than that of the stations, beyond which the fidelity of the image degrades gradually. While there were some differences in detail to the procedures used, the reconstruction algorithms were all based essentially on the discrete inverse theory (DIT) method described by *Fremouw et al.* [1992].

3. Results

[5] The procedure outlined above produced a wealth of information about spatial structures seen in the electron density in different sectors of the high-latitude ionosphere on the days in question. A limited selection of observations is presented here to demonstrate the potential of such coordinated semiglobal measurements using the radio tomographic technique. The results are related to those from an independent experimental technique and also to model studies of the high-latitude ionosphere.

[6] Tomographic images obtained from the three receiver chains just after 0800 UT on 20 September 2001 are presented in Figures 2a–2c. The ionosphere over northern Europe, imaged from a satellite pass at about 0806 UT (Figure 2a), shows a horizontally stratified structure with a broad minimum in electron density at the layer peak centered at about 68°N geomagnetic latitude. Farther to the north, the densities maximize around 75°N, the peak value being about 10^{12} m^{-3}, with a second minimum to be seen at about 79°N. The tomographic image from western Greenland at about 0815 UT (Figure 2b) shows an ionosphere of different character. Electron densities to the south are low in a horizontally stratified ionosphere with a peak between 350 km and 400 km altitude. A broad trough can be seen, culminating in a steep poleward wall at

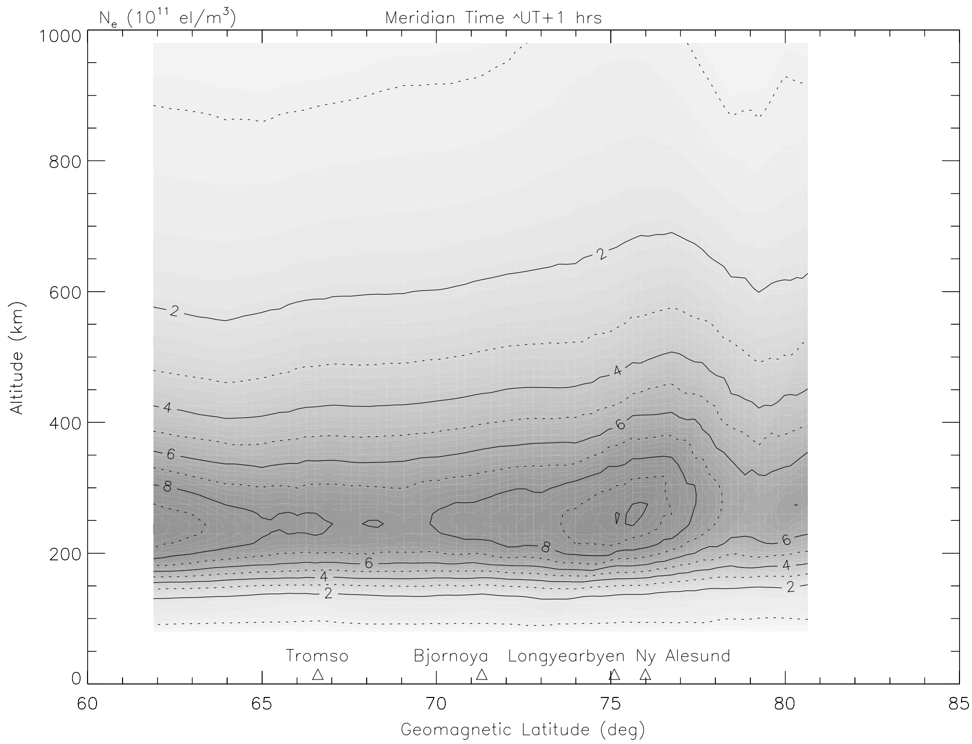

Figure 2a. Tomographic images of electron density obtained from satellite passes just after 0800 UT on 20 September 2001 from the station chains in the European sector.

about 79°N geomagnetic latitude and a marked enhancement near the northern extremity of the image. The electron densities found in the image from the Alaskan sector (Figure 2c), obtained around 0809 UT using observations monitored at the southern stations of the chain, reveal a stratified ionosphere to the south, with a very narrow trough of depleted densities near 67°N geomagnetic latitude a localized enhancement near 68°, another depletion near 70°, and denser plasma to the north.

[7] Interpretation of these results, made at essentially the same universal time but widely separated in geographic locations, requires understanding of their context in the frame of the physical processes controlling the dynamics of the ionosphere at high latitudes. Plasma convection, driven by the interaction of the solar wind with the magnetosphere, is one such key mechanism. Measurements of the interplanetary magnetic field by the ACE satellite, upstream in the solar wind, confirmed that B_z was weakly negative ($\sim$1 nT) at the time of the observations, after allowing for an appropriate time delay between the ACE location and the ionospheric response. It is thus likely that a two-cell convection pattern was established, drawing plasma from the dayside for subsequent transport across the polar cap in the antisunward flow. B_y was also weakly negative ($\sim$1 nT), so the resultant asymmetry of the convection pattern would be expected to rotate the throat region slightly to earlier local magnetic times [*Cowley*, 1997]. Figure 3 shows a polar plot, in geomagnetic coordinates, of the equipotentials of the convection pattern at northern high latitudes, obtained from the model by *Weimer* [1996] for conditions appropriate to the present study. The approximate tracks of the ionospheric intersections of the ray paths from the satellites to the three receiver chains are also shown. While caution must be exercised in examination of the detailed features of the modeled pattern, particularly at latitudes lower than those of the twin cells at polar latitudes, nevertheless the pattern can be used on a large scale to interpret the tomographic images. It should be noted that experimental observations to provide confirmation of the convection pattern would have been useful. However, actual measurements of plasma drifts at high latitudes from the SuperDARN radars were not available for the time of interest here.

[8] It can be seen from Figure 3 that the observations in the European sector represent a transect through the dayside cusp ionosphere just before magnetic noon. In Greenland, the image corresponds to a section through the dawn convection cell in the morning sector. The Alaskan observations are at earlier local times, with the southern part of the image plane cutting across the

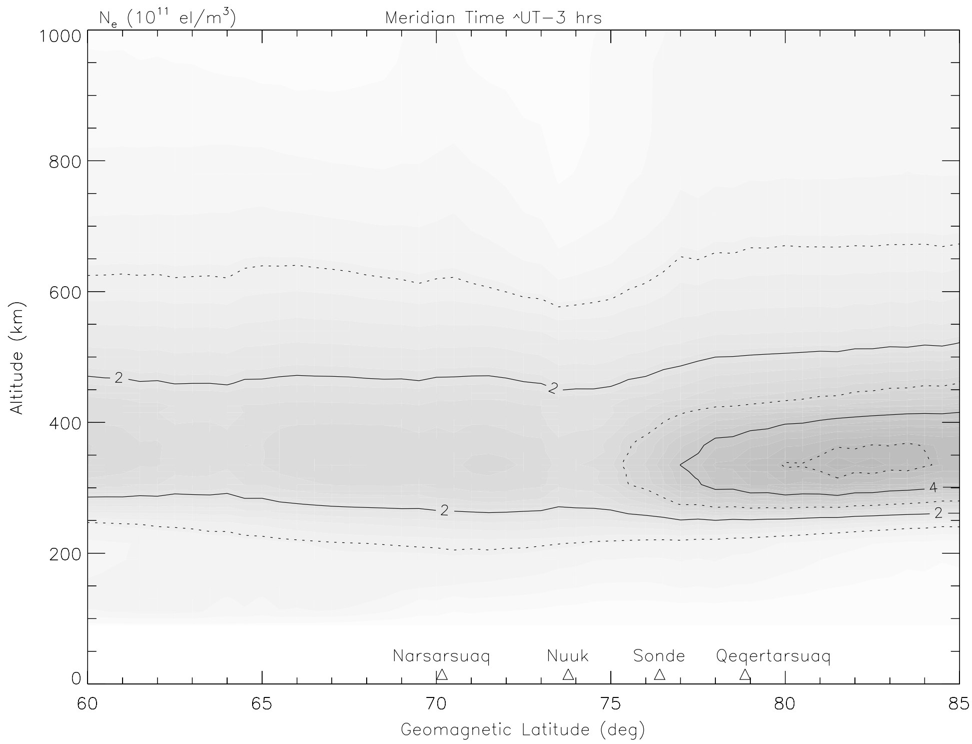

Figure 2b. Same as Figure 2a but for station chains in Greenland.

auroral zone at the edge of the afternoon convection cell in the late evening. Using this understanding of the geometry of the sections in relation to physical processes operating in the high-latitude ionosphere, it can be inferred that the image from the European stations (Figure 2a) shows a broad trough about 68°N geomagnetic latitude in the region where the flux tubes are likely to be returning from the nightside near the edge of the dawn cell of the high-latitude convection pattern. The density enhancement, between about 70°N and 77°N, with a maximum near 75°N, may well correspond to a section through a tongue of ionization from the dayside afternoon sector being drawn into the throat region of the high-latitude convective flow.

[9] The image from the Greenland stations (Figure 2b) shows low densities in a trough with a poleward wall surmounted by an enhancement. Figure 3 confirms that the section imaged here intersects the dawn cell of the convection pattern. It is thus possible that the depleted densities at latitudes less than about 76°N geomagnetic latitude relate to flux tubes returning from the nightside in darkness within the dawn cell. Farther to the north, the enhanced densities seen in the image may be linked to a tongue or possibly a patch of high-density plasma that has been caught in the antisunward flow of the central polar cap. It can be noted that the height of the layer peak is greater than 300 km, so the lifetime of the plasma could be many tens of minutes.

[10] The image from the stations in Alaska (Figure 2c) also shows a trough extending from near 67°N to about 71°N geomagnetic latitude, albeit containing a localized enhancement. Figure 3 confirms that this image is of the ionosphere at the auroral zone edge of the dusk convection cell. In this sector, the sunward return convection at high latitudes and corotation to the south combine to produce counterstreaming flows where the plasma on slow-moving flux tubes depletes in darkness enabling the formation of the main trough in the nightside ionosphere. The latitudinally narrow enhancement residing in the trough region is characteristic of structures observed rather frequently in this premidnight sector of the auroral zone.

[11] Further interpretation of the tomographic observations can be aided by model studies. The Sheffield University version of the coupled thermosphere ionosphere plasmasphere model (CTIP) model has been used to estimate the electron densities for conditions appropriate to the present experimental tomographic observations. CTIP is a "first- principles" global model of the coupled thermosphere-ionosphere-plasmasphere system, details of which can be found in papers by *Millward et al.* [1996] and *Fuller-Rowell et al.* [1996]. In the model,

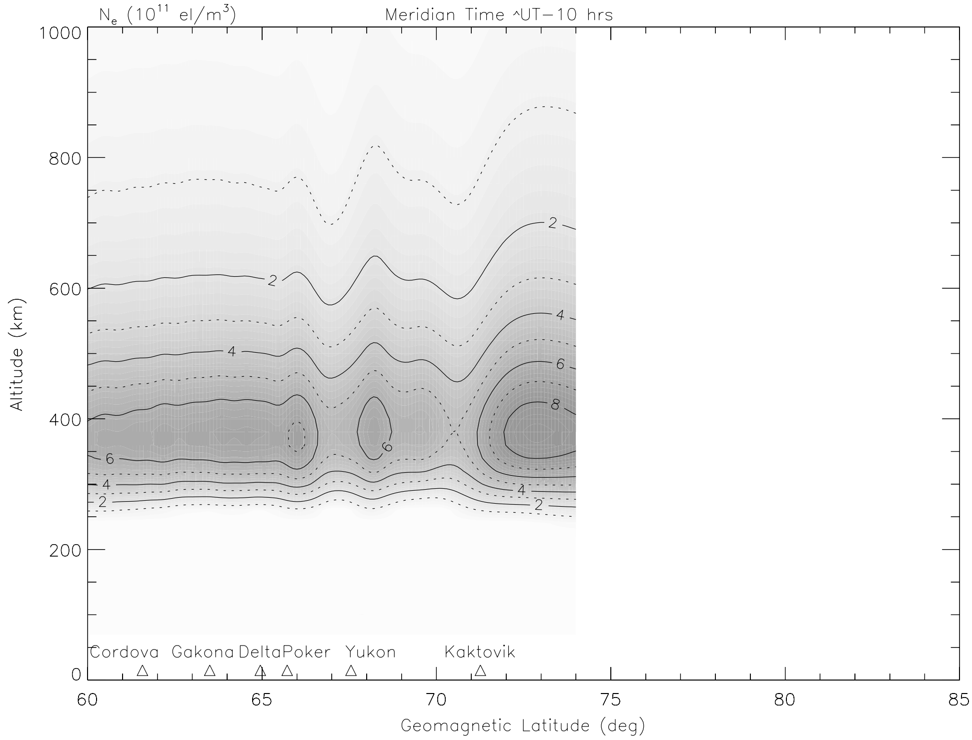

Figure 2c. Same as Figure 2a but for station chains in Alaska.

the coupled equations of momentum, energy and continuity are solved at fixed grid points to calculate values of density, temperature, and velocity of the neutral atmosphere, and of the O+ and H+ ions, in open flux tubes at high latitudes and closed flux tubes in the plasmasphere. Output quantities including ion and neutral densities, temperatures, and velocities are determined on a geocentric grid. The resolution is 2° in latitude, 18° in longitude and one scale height, from a lower boundary fixed at 80 km and 1 Pa.

[12] The results of the CTIP model runs, appropriate to the conditions of the current study, are presented as polar plots of electron densities at 350 km for northern high latitudes. The universal time corresponds to 0800 UT, with Figure 4a plotted for the geographic/LT frame, while Figure 4b gives the same results in a geomagnetic latitude/MLT reference frame. It is beyond the purposes of the present initial study to compare details or to discuss the ability of the model to give precise replication of the experimental observations; nevertheless, the general form of the model plots can be used to aid interpretation of the tomographic images.

[13] Figure 4a shows that, in the European sector, the section of the image cuts through the morningside of the daytime sunlit ionosphere at lower latitudes and intersects a region of high-density plasma extending westward at high latitude. The corresponding plot in the geomagnetic reference frame shows that this feature is indeed the tongue of ionization of solar-produced plasma from the dayside being carried in the cross-polar flow by the high-latitude convection. For Greenland, the model results of Figure 4a suggest that the section being imaged is effectively through the auroral oval into the enhanced densities at higher latitudes, consistent with the tomographic observations.

[14] The situation over Alaska is more complex. The model results indicate that the convective flow is that of the dusk cell just before the Harang discontinuity, with the scan along the edge of depleted densities in the middle of the image and somewhat higher densities at the highest latitudes. The experimental results show midlatitude densities decreasing poleward near midpass to a trough containing an isolated blob-like enhancement and then densities increasing at the highest latitudes. While detailed comparisons are beyond the current capabilities of the model, a possible interpretation is that the isolated enhancement represents a polar cap patch of high-density plasma that has been transported across from the European sector in the antisunward convection, although the image suggests a structure linked to local soft precipitation as a possible mechanism.

[15] Another comparison can be made between the tomographic results and maps of total electron content (TEC) for the northern polar sector, created from mea-

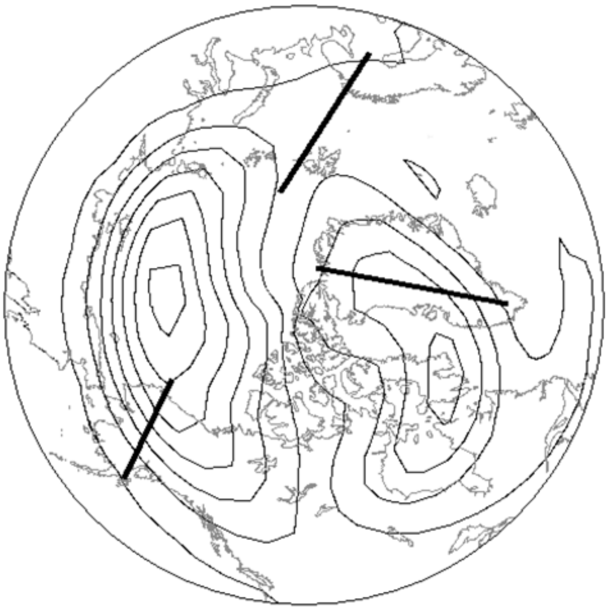

Figure 3. Polar plot containing the approximate transects for the image planes of the European, Greenland, and Alaskan observations shown in Figures 2a–2c, superposed on an electric potential pattern for the high-latitude convection for the prevailing conditions, obtained from *Weimer* [1996]. The latitude ranges from 57°N to the pole.

surements using GPS satellites using the technique developed by *Jakowski* [1996]. The observational data were provided by the growing global network of GPS ground stations of the International GPS Service (IGS). After determining the total electron content along a number of ray paths, using a Kalman filter technique for calibrating the ionospheric delay of GPS signals [*Sardón et al.*, 1994], the slant TEC is mapped to the vertical by a single-layer approximation for the ionosphere at 400 km altitude. Using the GPS ground stations of the European and northern high-latitude IGS network, between 60 and 200 data points of TEC are obtained, covering the northern polar cap at latitudes greater than 50°N. To map the TEC, a preliminary model for the polar TEC has been established, in a similar way to the one developed earlier for the European area [*Jakowski*, 1996]. Using this procedure, polar maps of vertical TEC were derived for a grid consisting of 768 points within the range 50°N to 90°N. It is estimated that the errors in the mapping should be less than some 3 TEC units, enabling the study of large-scale ionospheric phenomena [*Jakowski et al.*, 2002].

[16] Figure 5a shows such a map, contoured from GPS TEC observations made at 0800 UT on 20 September 2001. The plot has similarities to the general form of the

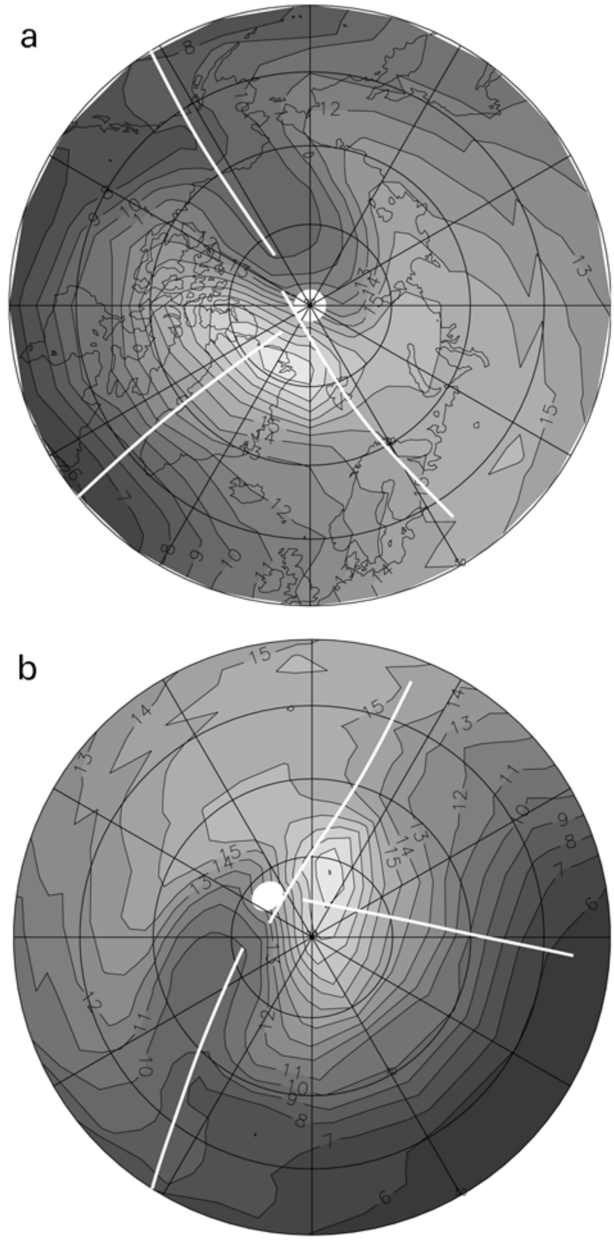

Figure 4. Polar plots for northern high latitudes of electron densities at 350 km altitude estimated from the CTIP model for conditions appropriate to 20 September 2001 at 0800 UT on (a) a geographic frame and (b) a geomagnetic reference frame, with magnetic noon at the top and geomagnetic latitudes at 10° intervals. Higher densities correspond to the lighter gray scale shadings.

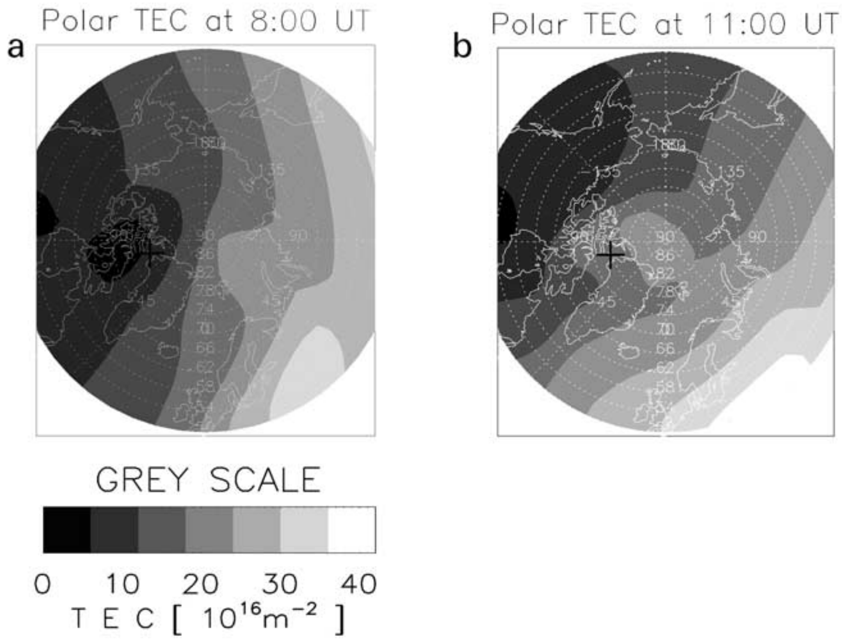

Figure 5. Polar plots of total electron contents at northern geographic latitudes obtained from observations of GPS satellites at international geodetic reference stations on 20 September 2001 at (a) 0800 UT and (b) 1100 UT.

electron densities seen in the model output, with high TECs on the sunlit dayside and depleted values on the nightside. However, an interesting detail is evidence for the onset of a tongue of enhanced plasma extending poleward from the western Russian sector. This observation confirms the interpretation of the increased densities seen in the tomographic image to the north of Svalbard as being related to plasma created by solar EUV radiation on the dayside that is being entrained by convection into the polar cap. The GPS measurements suggest that the lowest electron contents are found to the west of Greenland, a result broadly confirmed by the densities seen in the respective images. However, it can be noted that the GPS mapping technique from observations at a limited number of widely separate stations is not able to replicate detailed structures like the blobs imaged in the northern sectors of the observations from both the Greenland and Alaskan chains.

[17] It is of interest to note that there was no evidence of a tongue of ionization in an earlier GPS map for 0700 UT, but in subsequent hourly plots the feature can be seen to advance across the polar cap, becoming clearly detached in the form of a patch on the dawnside of the magnetic pole by 1100 UT (Figure 5b). A later tomographic image from the European chain shows greatly depleted densities to the north with no evidence for intersection with a tongue of ionization, in keeping with the GPS observations. By contrast, images from Greenland for several passes between 0900 UT and 1100 UT all show very high densities to the north, as does one from Alaska somewhat after 1400 UT. The Greenland image from the pass at 1045 UT illustrates this feature as a discrete structure at the northern edge, with high densities and a layer peak at a high altitude, separated by a depletion from the plasma building up in the sunlit morning ionosphere to the south.

4. Discussion

[18] Radio tomographic imaging of the ionized atmosphere to date has been confined in the main to investigations using observations made at a single chain of stations. The present paper represents a first attempt to relate the tomographic images obtained at essentially the same universal time from three station chains giving coverage of a wide sector of the northern polar region. The results from this first coordinated study shown here demonstrate the potential of the tomographic technique to investigate large-scale structures in widely separate sectors of the high-latitude ionosphere. It is clear that tomographic imaging opens up the possibility of identifying characteristic features in the plasma distribution, like the depleted troughs, enhanced blobs and ionization tongues, of the complex structures that

form the polar ionosphere. Boundaries between different plasma regimes in flux tubes linked to vastly separate regions of space can be identified in tomographic images [e.g., *Walker et al.*, 1998; *Pryse et al.*, 1999] so that use of observations from several chains of stations opens up the possibility of relating boundaries seen in the different geomagnetic sectors at the same time. A later study concerns the important topic of the structure of the polar ionosphere under northward IMF [*Middleton et al.*, 2005].

[19] It has been shown that radio tomography has an important role to play in the validation of ionospheric models, not only the empirical and parameterized types used for the mitigation of propagation effects on practical radio systems [*Dabas and Kersley*, 2003], but also the first-principles models based on solution of the underlying physical equations of the coupled ionosphere and thermosphere [*Idenden et al.*, 1998]. While the earlier study was confined to comparisons with observations from a single chain of stations, the results presented here demonstrate the potential of using observations from multiple stations in the validation of the wider geographic aspects of the model behavior. At the current stage of development little is known about the detailed ability of even the best available physical models faithfully to replicate actual conditions. However, it is clear from the present work that the tomographic results represent a powerful tool in the verification of the development of global ionospheric models, not only the physical model (CTIP) used here, but also the assimilative models that are currently under development [*Bust et al.*, 2004].

[20] Another encouraging aspect of the current study is the successful validation of the GPS mapping technique to give information on the basic features of the high-latitude ionosphere. The method is based on the use of observational data from a limited number of stations in the inhospitable environment of the high Arctic. Nevertheless, the comparisons with the actual tomographic results provide confirmatory evidence for the ability of the GPS technique to replicate the large-scale structures, though details are beyond the current state of development. Such comparisons are of importance since the mapping of TEC from GPS observations is playing an increasing role in the provision of corrections for propagation effects in radio systems applications.

5. Conclusions

[21] The study reported here represents the first attempt to try to relate radio tomographic observations from widely separate regions of the northern high-latitude ionosphere. The experimental observations show characteristic features that have been interpreted with the aid of a coupled thermosphere ionosphere model and also linked to maps of TEC obtained from GPS observations. They demonstrate the potential of such wider use of tomographic imaging to understand the origins and dynamics of large-scale structures in the complex polar ionosphere.

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