Large-Scale Plasma Structure in the Polar and Auroral Ionosphere: Experimental Observations and Modelling

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ABSTRACT

Radiotomography provides observations of ionospheric electron density structure on horizontal scales of tens to hundreds of kilometres. Routine measurements over extended periods of time and geographic areas have the potential for parameterising the structure of the polar and auroral ionosphere. Averaged electron densities characteristic of different ionospheric features, locations, local times, Universal Times, seasons, geomagnetic activity and solar conditions can be compared with ionospheric models and used to test and develop the models.

Tomographic images are presented of plasma structures characteristic of the polar and auroral ionosphere. Results from initial comparisons of the measurements with the Sheffield University Coupled Thermosphere-Ionosphere-Plasmasphere (CTIP) model are also discussed. General broad agreement is seen between the model and observations but discrepancies are also evident.

1.0 INTRODUCTION

The high-latitude ionosphere is a highly structured medium, comprising electron density irregularities over a large range of scale sizes [1]. Of particular relevance to this presentation are enhancements and depletions on horizontal spatial scales of tens to hundreds of kilometres. They include the tongue-of-ionisation drawn antisunward from the dayside ionosphere towards the polar cap, polar cap patches, boundary blobs in the evening auroral region, the main ionisation trough and the polar hole. The associated steep density gradients are of particular concern to the performance of practical navigation and communications radio systems. The basic physical processes responsible for the features are relatively well understood and include photo-production, particle precipitation and plasma transport in the high-latitude convection. However, the relative contributions of these processes at any particular time remain open to debate, and need to be established for full interpretation of the morphology of the electron density distribution at high latitudes. The variability in the occurrence, structure and location of the features means that it is not yet possible to represent them accurately in physical or empirical models.

This paper reviews polar and auroral plasma structures observed by radiotomography. Interpretations of the features were supported by measurements made by the international European Incoherent Scatter

Pryse, S.E.; Middleton, H.R.; Dewis, K.L.; Wood, A.G.; Whittick, E.L.; Balthazor, R.L. (2006) Large-Scale Plasma Structure in the Polar and Auroral Ionosphere: Experimental Observations and Modelling. In *Characterising the Ionosphere* (pp. 15-1 – 15-10). Meeting Proceedings RTO-MP-IST-056, Paper 15. Neuilly-sur-Seine, France: RTO. Available from: http://www.rto.nato.int/abstracts.asp.

(EISCAT) radar facility, the Super Dual Auroral Radar Network (SuperDARN), optical cameras and satellite particle and flow observations. Initial steps have been taken towards determining the character of the ionosphere in the European sector for comparisons with models, and outcomes from comparisons of the measurements with the Sheffield University Coupled Thermosphere-Ionosphere-Plasmasphere (CTIP) model are discussed.

2.0 IONOSPHERIC RADIOTOMOGRAPHY

2.1 Experiment

The radiotomography experiment operated by the University of Wales Aberystwyth (UWA) comprises a chain of receivers at four locations in northern Scandinavia: Ny-Ålesund (78.9ºN,12.0ºE, 76.0ºMLAT,112.3ºMLON), Longyearbyen (78.2ºN,15.7ºE, 75.1ºMLAT,113.0ºMLON), Bjørnøya (74.5ºN,19.0ºE; 71.3ºMLAT,108.8ºMLON) and Tromsø (69.8ºN,19.0ºE; 66.1ºMLAT,103.4ºMLON). These monitor the phase coherent signals from the polar orbiting satellites in the Navy Ionospheric Monitoring System (NIMS), previously known as the Navy Navigational Satellite System (NNSS), for measurement of total electron content along a large number of intersecting satellite-to-receiver ray-paths (Figure 1). Inversion of the data yields the spatial distribution of electron density over a meridional section of the high-latitude ionosphere [2]. The experiment forms part of the receiver network of the International Ionospheric Tomography Community (IITC), which has other high-latitude receivers in Alaska, Greenland, Finland and Russia (Figure 2).

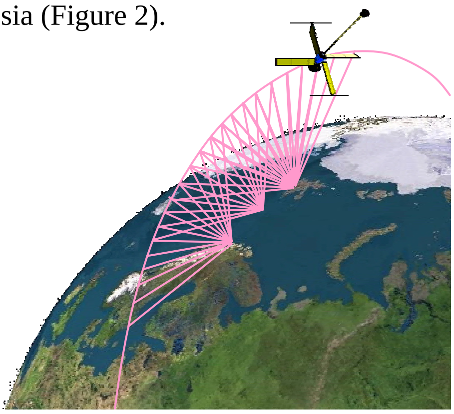

Figure 1: Geometry of the University of Wales radiotomography experiment in Scandinavia.

Figure 2: Locations of the high-latitude tomography receiver chains of the International Ionospheric Tomography Community in Alaska, Greenland and Scandinavia.

2.2 Radiotomography observations

2.2.1 Plasma distribution of the high-latitude ionosphere

The high-latitude receiver chains of the IITC have the potential to observe the spatial distribution of the polar and auroral ionospheres over extended areas and periods of time under different geomagnetic conditions. Figure 3 shows the distributions in three different local time sectors under conditions of an interplanetary magnetic field (IMF) with a southward component i.e. Bz<0 [3] and magnetopause reconnection near the equatorial plane. In this case the UWA Scandinavian chain was aligned essentially along the tongue-of-ionisation (TOI) in the noon sector, the chain in Alaska showed the structured auroral region, and Greenland receivers measured the depleted densities of the dawn sector.

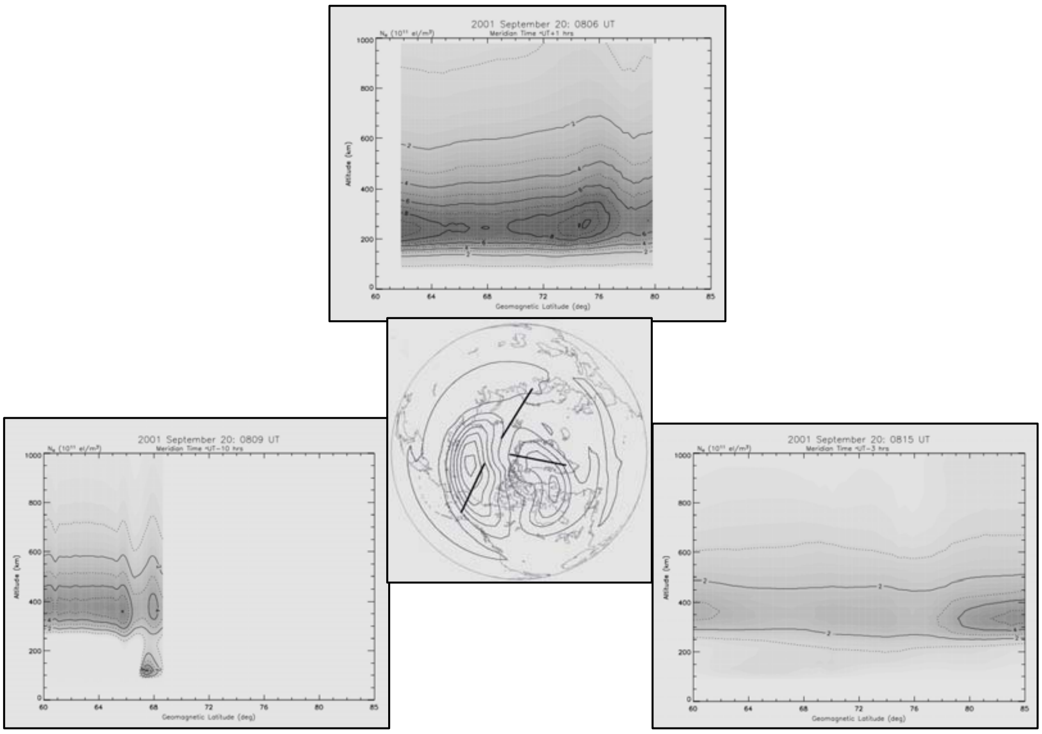

Figure 3: Tomographic images at around 0800UT on 20 September 2001. The Scandinavian (top), Alaskan (left) and Greenland (right) observations show electron density distributions characteristic of the noon, auroral, and dawn sectors respectively. [3]

In another example, under conditions of stable IMF Bz>0, the Greenland and UWA Scandinavian chains imaged meridional cross-sections through a high-latitude density enhancement in a series of consecutive satellite passes (Figure 4). The feature was interpreted as being elongated in longitude [4]. Under conditions of Bz positive it is anticipated that the polar cap plasma flow is sunward near the ionospheric footprint of the magnetospheric lobe reconnection and that the polar cap is closed to plasma inflow from lower latitudes [5]. It was concluded that the observed density enhancement comprised dayside photo-ionisation drawn poleward by weak viscous convection cells and then antisunward around the dusk-side periphery of the polar cap. A general decrease in density occurred with increasing MLT displacement from magnetic noon because of ionisation recombination.

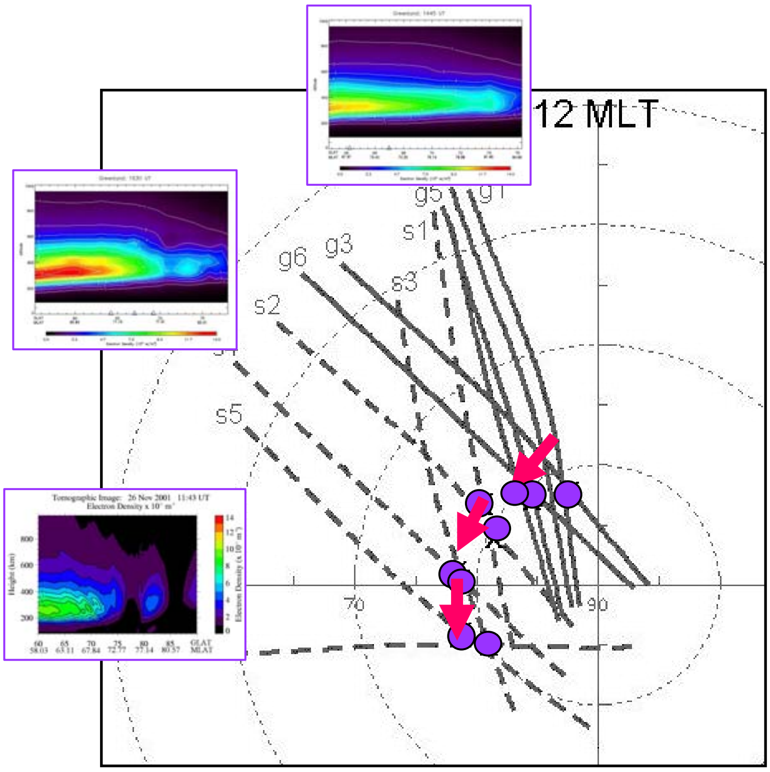

Figure 4: Tomography images from the Greenland and Scandinavian receiver chains for 26 November 2001 showing cross-sections though a tongue-of-ionisation drawn around the dusk-side periphery of the polar cap under conditions of IMF Bz positive. The purple dots on the satellite trajectories show the locations of the density enhancements observed in a series of satellite passes and the pink arrows show the implied antisunward plasma drift. [4]

2.2.2 Polar-cap plasma: source region

It is reasonably well-established that polar cap plasma in winter is comprised largely of photoionisation drawn to higher latitudes in a TOI by the plasma convection. However, the mechanism of entrainment in the flow remains open to debate, as does the modulation of the tongue to form patch-like structures by particle precipitation, flux transfer events or IMF variations. A case study, where the effects of particle precipitation could be ruled out, suggested that the build-up of TOI electron densities occurred in the post-noon sector near the equatorward edge of the high-latitude region [6]. In this instance the equatorward wall of the post-noon high-latitude trough did not show the monotonic increase of density with decreasing latitude as expected from photo-production and a decreasing solar zenith angle, but rather it exhibited a clear density enhancement superimposed on the gradient. The effect was seen in the tomographic images of three consecutive satellite passes monitored by the UWA chain (Figure 5). The variation in the latitude of the maximum of the density enhancement could be attributed to variations in the IMF Bz component. The enhancement on the trough gradient was seen more clearly in the equivalent vertical total electron content for the passes, an example of which is re-produced in Figure 6. The enhanced densities were interpreted as the source of cold polar ionisation observed at higher latitudes by the EISCAT Svalbard radar, with the plasma building up in the slow sunward flow of the post noon sector near the transition region from the high-latitude convection to the co-rotating regime of lower latitudes.

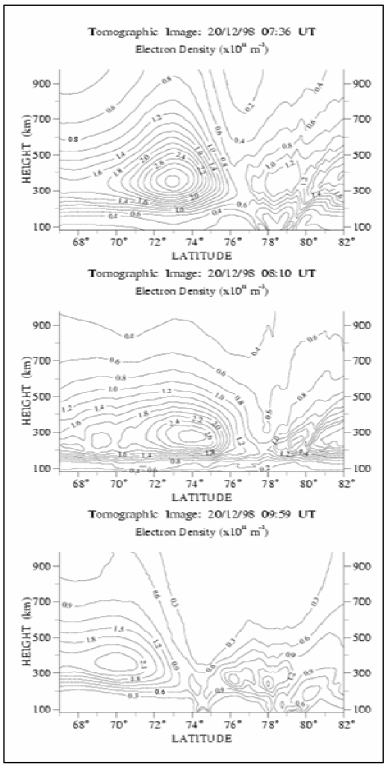

Figure 5: Three consecutive tomography images on 20 December 1998 showing the density enhancement on the equatorward trough wall. [6]

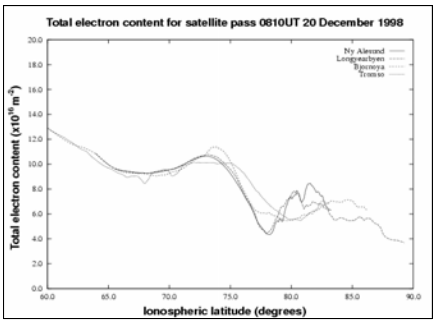

Figure 6: Equivalent vertical total electron content measured at the four receiver sites for the pass at 0810UT on 20 December 1998 showing the enhancement on the equatorward wall of the trough. [6]

2.2.3 Polar-cap plasma: influence on the nightside

High altitude F-region polar plasma enhancements with large densities have sufficiently long lifetimes to survive transit across the polar region. These may then enter the nightside auroral region through the Harang discontinuity. The resulting nightside densities are expected to be prominent in the European sector because of the offset between the geographic and geomagnetic reference systems. An early study compared electron densities in different longitudinal sectors using limited incoherent scatter radar data [7], and investigations using the Utah State University model looked at the effect of the longitude sector on the observation of the TOI [8]. It is therefore anticipated that the Scandinavian tomography chain is suitably located to study the influence of dayside plasma on the nightside. In one case example a polar cap patch identified by radiotomography was located in the antisunward cross-polar flow measured by the SuperDARN radars. When the feature was projected forward in time through the SuperDARN electric potential patterns it was reconfigured into a boundary blob. Support for the restructuring was provided by a second tomography image that revealed a coincident auroral boundary blob in the sunward return flow of the dusk cell [9], with electron densities commensurate with the ionisation decay anticipated during transit of plasma in the dark ionosphere. The reconfiguration was in accord with an early 2D modelling study [10] which showed the evolution of a polar patch in the high-latitude convection pattern.

In a second example, a series of five tomography reconstructions from the Scandinavian chain and a UK chain operating at the time, revealed large density enhancements forming the poleward edge of the main post-midnight ionospheric trough, three of which are shown in Figure 7 [11]. SuperDARN flow patterns revealed that the densities coincided with the antisunward flow through the Harang discontinuity and the post-midnight return sunward flow. Support for the dayside origin of the ionisation was provided by the EISCAT UHF mainland radar, which identified coincident patches of cold ionisation with peak altitude in excess of 400km, and a complementary modelling study (Section 3.2.2).

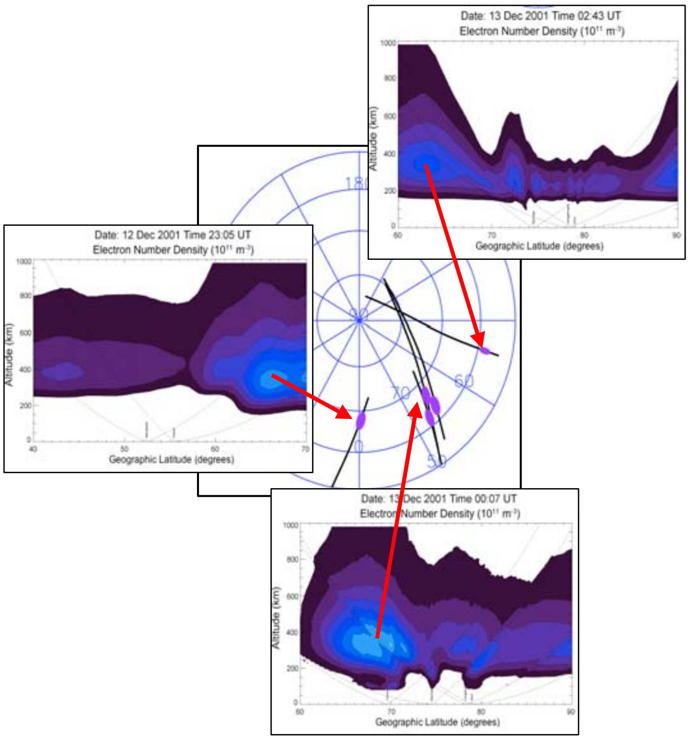

Figure 7: A series of tomographic images for 13 December 2001, which show large ionisation densities forming the poleward wall of the post-midnight main trough. The purple dots show the locations of the maximum densities of the wall on each satellite trajectory.

3.0 RADIOTOMOGRAPHY AND THE CTIP MODEL

3.1 The Coupled Thermosphere-Ionosphere-Plasmasphere (CTIP) model

The CTIP model can be used to investigate the interplay between the various processes influencing the high-latitude ionosphere: solar EUV radiation, precipitation of charged particles, electrodynamic drift, diffusion, thermospheric winds and temperature-sensitive chemical reactions. The model was developed by the University of Sheffield and University College London by the integration of a thermospheric model

[12,13] with a plasmasphere model and a high-latitude ionospheric model with plasma convection and precipitation energy inputs [14]. In brief, coupled equations of momentum, energy and continuity are solved for density, temperature and velocity of the neutral atmosphere, and of the O^+ and H^+ ions. The output quantities are given on a geocentric grid at a resolution of 2º latitude, 18º longitude and one scale height from a lower boundary fixed at 80 km at 1 Pa. Since the early development of the coupled model, various adaptations have been carried out at the University of Sheffield, University College London and the Space Environment Laboratory, USA. The model used in the current study is the Sheffield University CTIP model. Inputs appropriate for the geophysical conditions of observations were chosen from the standard selection available. The precipitation energy input was according to the classification of DMSP satellite measurements [15], and a range of 37 electric potential patterns based on Millstone Hill plasma flow measurements [16] were available to describe the high-latitude convection.

3.2 Comparisons of tomography observations and modelled ionosphere

3.2.1 Post-noon high-latitude trough

Initial comparisons of tomography measurements by the UWA chain in Scandinavia with model output have focussed on the persistent high-latitude trough under baseline quiet geomagnetic conditions in December [17]. Comparisons of averaged wintertime latitudinal variations of NmF2 from tomographic images in hourly bins of UT and the CTIP model are shown in Figure 8. The model input parameters are representative of the observing conditions. Runs were performed to cover the following criteria: both precipitation energy input and high-latitude convection switched-on (Dec_{CP}), precipitation off but convection on (Dec_C), precipitation on but convection off (Dec_P), and both precipitation and convection switched-off (Dec). Inspection of the figure shows that the model re-produces the general trough behaviour, with photoionisation on the equatorward trough wall, precipitation ionisation on the poleward wall, and a general decrease in trough latitude with increasing time. However, close inspection reveals that the auroral ionisation is substantially overestimated in the model, the latitude of the trough minimum is generally displaced from that observed, and the equatorward migration of the trough with UT spans a greater latitudinal range in the observations than in the model. A further discrepancy is the shape of the equatorward trough wall, with the densities of the observed wall being maintained at a higher level than those predicted from photoionisation and then decreasing steeply into the trough minimum.

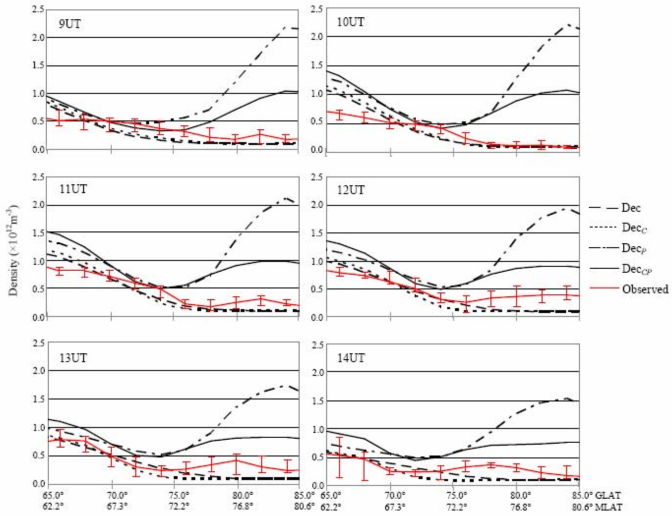

Figure 8: Latitudinal variation of NmF2 from tomography observations in Scandinavia in 1-hour bins of UT and corresponding curves from the CTIP model. Explanations of the curves are given in the text.

3.2.2 Post-midnight densities and the tongue-of-ionisation

CTIP model runs for the winter ionosphere reveal the influence of the tongue-of-ionisation and its dependence on UT. Figure 9 shows the polar ionosphere modelled with geomagnetic and solar indices commensurate with the observing conditions of the tomography images in Figure 7. The white line gives an indication of the locus of the UWA tomography chain. The panels are at 3 hourly intervals of UT throughout the day, and show that the TOI maximises near 18UT when Europe is entering the evening/nightside. Of particular interest in this instance is the panel at 0UT that shows dayside ionisation extending into the nightside and being drawn around into the post-midnight hours in broad agreement with the large densities observed on the poleward wall of the main trough in the earlier figure.

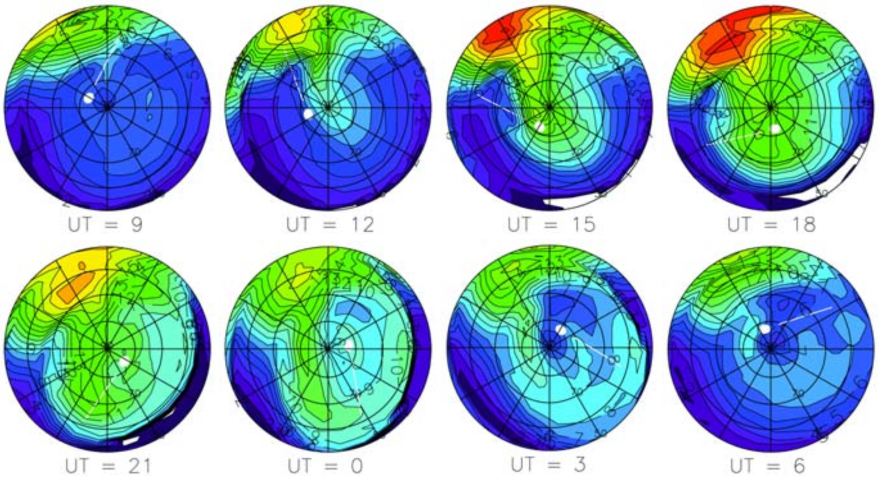

Figure 9: Polar ionosphere modelled by the CTIP model plotted as a function of MLT and MLAT. The latitude scale extends from 50 degrees to the geomagnetic pole and each panel is at 3- hourly intervals of UT.

4.0 SUMMARY

Radiotomography provides images of the spatial electron density structure of the polar and auroral ionospheres. Observations over extended periods of time and areas have the potential to characterise the density enhancements, depletions and gradients of the regions over ranges of local times, seasons, geomagnetic conditions and ultimately solar conditions. Initial studies have been carried out to compare the observed behaviour of the high-latitude dayside trough under baseline winter conditions with the trough modelled by the CTIP model. The model has also showed that the winter TOI maximises when Europe is on the nightside. In a complementary study of the mid-latitude nighttime trough, median values of trough characteristics from tomography observations in the UK have been used to parameterise trough behaviour at European longitudes [18]. Averaged parameters from radiotomography have the potential to be used for testing and developing ionospheric models.

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6.0 ACKNOWLEDGEMENTS

Financial support for the studies outlined was provided by the UK Particle Physics and Astronomy Research Council under grant PPA/G/O/2003/00017. The assistance of the University of Tromsø and the Norwegian Polar Research Institute in the UWA tomographic measurements is gratefully acknowledged. Significant contributions by the IITC are acknowledged, in particular Drs. E.J. Fremouw and J.A. Secan, NorthWest Research Associates, Dr. G.S. Bust, Applied Research Laboratories, University of Texas Austin, and the University of Alaska for observations in Alaska and Greenland. The IITC is an outgrowth of a workshop sponsored by the Polar Aeronomy and Radio Science (PARS) program sponsored by the U.S. Office of Naval Research (ONR) via a grant to the University of Alaska. KLD, AGW and ELW acknowledge receipt of PPARC postgraduate studentships.