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The principal object of this research program was the investigation of ionospheric plasma waves and turbulence at mid and high latitudes using the M.I.T. Millstone Hill UHF radar. A three-year program of radar observations and analysis investigated plasma wave and turbulence occurrence characteristics, the relationship of turbulence to the auroral dynamics and structure associated with stable auroral red arcs, validation of ionospheric radiotomography techniques used for determining ionospheric structure, and the possible enhancement of plasma waves due to lightning-induced effects. Monostatic and bi-static radar experiments were performed to collect data on *E* region turbulence for use in these investigations. A unique body of observations was obtained for investigating flow angle and magnetic aspect angle characteristics of *E* region turbulence. Techniques and results have been described in the published literature, as indicated below.

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MILLSTONE HILL RADAR STUDIES OF PLASMA WAVES AND TURBULENCE

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for the period
1 August 1992 - 31 October 1995

Executive Summary

F49620--93-1-0019

Millstone Hill Radar Studies of Plasma Waves and Turbulence

The principal object of this research program was the investigation of ionospheric plasma waves and turbulence at mid and high latitudes using the M.I.T. Millstone Hill UHF radar. A three-year program of radar observations and analysis investigated plasma wave and turbulence occurrence characteristics, the relationship of turbulence to the auroral dynamics and structure associated with stable auroral red arcs, validation of ionospheric radiotomography techniques used for determining ionospheric structure, and the possible enhancement of plasma waves due to lightning-induced effects. Monostatic and bi-static radar experiments were performed to collect data on *E* region turbulence for use in these investigations. A unique body of observations was obtained for investigating flow angle and magnetic aspect angle characteristics of *E* region turbulence. Techniques and results have been described in the published literature, as indicated below.

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1) del Pozo, C. F., J. C. Foster, and J.-P. St. Maurice, Dual-Mode *E* Region Plasma Wave observations from Millstone Hill, *J. Geophys. Res., 98,* 6013-6032, 1993.

2) Groves, K. M., M. C. Lee, and J. C. Foster, Nonlinear Ionospheric Propagation Effects on UHF Radio Signals, in *Physics of Space Plasmas (1991)*, pp 377-391, Sci. Pubs., Cambridge, MA, 1993.

3) Uspensky, M. V., A. V. Kustov, G. J. Sofko, J. A. Koehler, and J. C. Foster, An Alternative Look at the Aspect Sensitivity of Auroral Radar Backscatter: A Forward Scatter Effect, *J. Geophys. Res., 98,* 7721-7728, 1993.

4) Foster, J. C., M. J. Buonsanto, J. M. Holt, J. A. Klobuchar, P. Fougere, W. Pakula, T. D. Raymund,V. E. Kunitsyn, E. S. Andreeva, E. D. Tereshchenko, and B. Z. Khudukon, Russian-American Tomography Experiment, *Int. J. Imag. Sys. Tech.*, *5*, 148-159, 1994.

5) Foster, J. C., M. J. Buonsanto, M. Mendillo, D. Nottingham, F. J. Rich, and W. Denig, Coordinated stable auroral red arc observations: Relationship to plasma convection, *Journal of Geophysical Research*, *99*, 11429, 1994.

6) W. A. Pakula, P. F. Fougere, J. A. Klobuchar, H. J. Kunzler, M. J. Buonsanto, J. M. Roth, J. C. Foster, R. E. Sheehan, Tomographic Reconstruction of the Ionosphere over North America with Comparisons to Ground-Based Radar, *Radio Sci.*, *30*, 89-103, 1995.

7) Foster, J. C., Millstone Hill Observations of Coherent Backscatter near Perpendicular Magnetic Aspect Angle, Proc. *Workshop on E-region Plasma Instabilities*, MPI Lindau, 1995.

8) Jackel, B., D. Moorcroft, J. Foster, and P. Erickson, Bistatic Coherent Backscatter from the Auroral E-region at 440 MHz, Proc. *Workshop on E-region Plasma Instabilities*, MPI Lindau, 1995.]

Project Overview

Permission was given to begin work under AFOSR Grant # F49620-93-1-0019 during a three-month pre-award period which began August 1, 1992. Millstone Hill Radar experiments were performed (September, 1992) using an alternating-code technique in order to assess this new capability for use as a plasma-wave diagnostic. Additional experiments were performed at fixed antenna position and with real-time interaction in order to investigate phenomena found near perpendicular flow angle when looking very close to perpendicular magnetic aspect angle conditions.

In the second year, budget reductions curtailed the level of activity from that experienced previously. No further radar experiments were performed to investigate coherent backscatter from *E*-region heights, but analysis of existing data was emphasized, particularly of a June 5, 1991 data set which featured observations at near-perpendicular flow angle. It was found that a strong dependence of backscatter characteristics on magnetic aspect angle is observed near flow-angle perpendicularity.

During the final year of this project, work was extended to include bistatic coherent backscatter experiments done in cooperation with researchers at the University of Western Ontario and using the portable MIDAS-C data acquisition system. Bistatic experiments using receiving antennas at both the University of Western Ontario and the Algonquin Observatory were performed.

Several projects were conducted in collaboration with researchers from Phillips Laboratory Geophysics Division. A study of mid-latitude magnetosphere-ionosphere coupling processes and the formation of stable auroral red arcs (SAR arcs) identified the occurrence of sporadic bursts of *F* region plasma wave turbulence in the dynamic region immediately equatorward of the arc and trough. Ionospheric structure was further investigated during storm conditions during radar experiments to verify techniques used for ionospheric radiotomography. In the final year work was directed towards identifying radar backscatter signatures from lightning-induced effects in the upper atmosphere.

Millstone Radar Overview

The Massachusetts Institute of Technology maintains an extensive upper atmosphere research facility at Millstone Hill, located 35 miles northwest of metropolitan Boston. For atmospheric science, the Millstone Hill facility consists of a high-powered UHF (440 MHz) radar system and its associated computer, engineering, and analysis facilities. The UHF radar program, which is operated by the M.I.T. Haystack Observatory Atmospheric Sciences group, consists of two 2.5 MW UHF transmitters, a fully steerable 46 meter antenna, a zenith-directed 68 meter fixed antenna, and dedicated computer and analysis facilities. Principal operational support derives from the National Science Foundation Upper Atmosphere Facilities Program for incoherent scatter investigations of large-scale processes in the thermosphere, ionosphere, and magnetosphere. Because of its great sensitivity, wide field of view, and good magnetic aspect angle coverage, the Millstone UHF radar is well located to observe the development of field-aligned *E* region irregularities and the characteristics of the electrojet currents and electric fields which drive them. Its sensitivity is such that coherent echoes from *E* region plasma waves and irregularities can be observed over a 90 dB dynamic range.

Scientific Accomplishments

a). Coherent Backscatter Experiments

On September 9 and 17, 1992, coherent echoes were collected using the MIDAS data acquisition system on the Millstone Hill UHF radar. The September 9th experiment was run with a fixed antenna position directed towards the position of maximum coherent backscatter sensitivity. The event rose very quickly to maximum power level in 10 min while the detected plasma-wave phase velocity rose from 200 m/s to 500 m/s over the next 2-hr period and then dropped as the event started to break up. This experiment demonstrated the utility of the alternating-code technique for coherent backscatter experiments.

The September 17, 1992 experiment investigated the perpendicular flow velocity/zero aspect angle effects seen during experiments on June 5, 1991. Azimuth scans at a number of elevation angles were made to provide a grid of azimuth/aspect data at several altitudes. There was little altitude difference in the characteristics of the phase velocity observed during the experiment.

b). Flow and Aspect Angle Studies of 440 MHz E Region Spectra

> [Foster, J. C., Millstone Hill Observations of Coherent Backscatter near Perpendicular Magnetic Aspect Angle, Proc. *Workshop on E-region Plasma Instabilities*, MPI Lindau, 1995.]

Azimuth and elevation scanning experiments with the 46-m steerable antenna were used to investigate the spectral characteristics of 34-cm coherent backscatter from the auroral *E* region as a function of both magnetic aspect angle, θ, and flow angle. In elevation scans at perpendicular flow angle, we found a marked altitude difference in the backscattered spectra near perpendicular aspect angle. Spectra above the peak of the layer at 112 km altitude (Figure 1b) exhibit a single peak with fairly uniform negative Doppler (~200 m/s) as θ was varied from $-3°$ to $+5°$. In contrast, at 103 km altitude (Figure 1a), below the peak of the layer, the Doppler was large and positive ($>+500$ m/s) for $|\theta| > 2°$ and abruptly turned negative (~ -300 m/s) for $|\theta| < 2°$. Examination of the spectra at 104 km (Figure 2) reveals a transition between two narrow spectra with opposite Doppler sign as a function of aspect angle near perpendicularity and a transition region where narrow spectra of both signs were recorded at the same time. Spectral widths of 200 m/s - 500 m/s were characteristic of these studies and two such spectra, with opposite-sign Doppler, are evident at altitudes near 104 km near the phase velocity transition. For the June, 1991 study, the variation of the spectra with altitude is shown in Figure 3.

When flow angle, the angle between the measured **E**×**B** direction and the radar **k** vector, was varied through perpendicular while holding perpendicular aspect angle, there was an abrupt change in sign from positive to negative Doppler as a function of flow angle at altitudes both above and below the layer peak, rather than a cosine-function variation as is seen when apect angle is away from strict perpendicularity [*del Pozo et al.*, 1993]. Also, the flow angle at which the abrupt Doppler transition takes place differed greatly for altitudes above and below the peak. In addition, we observed very little variation in the amplitude of the backscattered signal with changing flow angle.

We found that the transition from positive to negative phase velocity (line of sight Doppler), as a function of flow angle, was abrupt when viewed near perpendicular aspect angle, but was smooth (sinusoidal) when viewed at aspect angles > 2°. There is a pronounced altitude dependence of the phase velocity when viewed near perpendicular aspect angle and at perpendicular flow angle. Narrow spectra with greatly different Doppler velocities are observed above and below the center of the irregularity layer (at altitudes of 103 km and 113 km). These observations are consistent with the existence of different irregularity processes at high and low altitudes under very strong electric field conditions. The narrow beamwidth of the Millstone Hill radar system permits the differentiation of populations narrowly separated magnetic aspect angles and altitudes.

c). SAR Arc Investigation

[Foster, J. C., M. J. Buonsanto, M. Mendillo, D. Nottingham, F. J. Rich, and W. Denig, Coordinated stable auroral red arc observations: Relationship to plasma convection, *Journal of Geophysical Research*, *99*, 11429, 1994.]

A study of the mid-latitude features associated with the occurrence of a Stable Auroral Red arc (SAR arc), Figure 4, led to the finding that radar echoes indicative of enhanced ion-acoustic wave growth in the topside *F* region are observed in the region of steep density and plasma drift speed gradients at the magnetosphere/ionosphere boundary delineated by the arc and its associated topside ionospheric trough (Figure 5). This observation suggests that the currents and mechanisms associated with large electric fields which accompany sub-auroral ion drifts (SAID) events contribute to the frequent occurrence of enhanced ion acoustic spectra near the equatorward edge of the trough.

The magnitude and spatial breadth of the sunward convection region associated with the trough and SAR arc are nearly identical in satellite and radar observations. It was concluded that there is a close spatial and temporal association between three types of subauroral low-altitude phenomena - the SAR arc, the SAID event, and the fossil (convection-related) trough - and that this is indicative of the interrelationship of the magnetospheric processes and boundaries which are involved in their formation.

d). Ionospheric Radiotomography

[Foster, J. C., M. J. Buonsanto, J. M. Holt, J. A. Klobuchar, P. Fougere, W. Pakula, T. D. Raymund,V. E. Kunitsyn, E. S. Andreeva, E. D. Tereshchenko, and B. Z. Khudukon, Russian-American Tomography Experiment, *Int. J. Imag. Sys. Tech.*, *5*, 148-159, 1994.]

[W. A. Pakula, P. F. Fougere, J. A. Klobuchar, H. J. Kunzler, M. J. Buonsanto, J. M. Roth, J. C. Foster, R. E. Sheehan, Tomographic Reconstruction of the Ionosphere over North America with Comparisons to Ground-Based Radar, *Radio Sci.*, *30*, 89-103, 1995.]

In order to intercompare various techniques used in reconstructing tomographic images, and to benchmark those results with direct observations obtained by the incoherent scatter technique, an experimental campaign and subsequent analysis program – the Russian-American Tomography Experiment (RATE) – were implemented in late 1993 under NSF support. Russian experiment teams from the Polar Geophysical Institute in Murmansk and Moscow State University joined with American investigators from the Phillips Laboratory and the Massachusetts Institute of Technology and an array of four receiving stations was set up in the northeastern United States and in eastern Canada to obtain data for the tomographic reconstructions. Phase-difference and total-phase tomographic reconstruction techniques were employed and resulting ionospheric deconvolution intercompared. The spatial/altitude distribution of ionospheric electron content was observed by the MIT Millstone Hill incoherent scatter radar which scanned the ionosphere in a plane parallel to the satellite overflights. These results have been used as a basis data set for the further development of the radiotomographic technique. The RATE campaign encompassed a major geomagnetic storm and the combined radar and ionospheric tomography diagnostics have been used to examine large-scale mid-latitude irregularities during storm conditions. Figure 6 presents latitude/altitude plots of electron density as observed by the Millstone Hill radar (top) and as reconstructed in the TEC radiotomographic analysis (Transit, middle) and in the phase-difference

Cicada analysis (RATE, bottom). There is reasonable agreement between the density observed and derived values.

e). Bi-Static Experiments

> [Jackel, B., D. Moorcroft, J. Foster, and P. Erickson, Bistatic Coherent Backscatter from the Auroral E-region at 440 MHz, Proc. *Workshop on E-region Plasma Instabilities*, MPI Lindau, 1995.]

A bistatic radar capability for the examination of the characteristics of plasma waves and turbulence was successfully established in conjunction with colleagues at the University of Western Ontario (UWO) in London, Ontario. The remote receiving sites made use of the portable MIDAS-C radar signal processor developed at the Haystack Observatory (under separate funding) along with a wide-beam receiving antenna located at UWO or the sensitive, narrow-beam radio telescope antenna at the Algonguin Observatory. In total, twelve (12) bistatic experiments have been performed and a total of 24 hours of radar operations were devoted to this activity. A particularly large event was recorded on April 7, 1995 and is the subject of ongoing analysis.

f). Radar Backscatter Associated with Lightning-Induced Phenomena

A collaboration was begun during the summer of 1994 with the Ionospheric Effects branch of the Geophysics Division of the Phillips Laboratory to investigate the 34-cm radar backscatter signatures associated with sprites and other lightning-induced phenomena. During both 1994 and 1995, Phillips Laboratory instrumentation was set up at the Millstone radar site and the radar was maintained in ready-standby mode for the months of July and August. Appropriate experimental conditions were monitored using the national weather radar network (accessible over the Internet) and the National Lightning Detection Network (NLDN) and a series of late-afternoon experiments were performed using the NLDN to determine the radar antenna-pointing direction. Although no appropriate storm cells were observed during the dry summer of 1995, initial results are promising and more detailed experimental modes and observations are being planned.

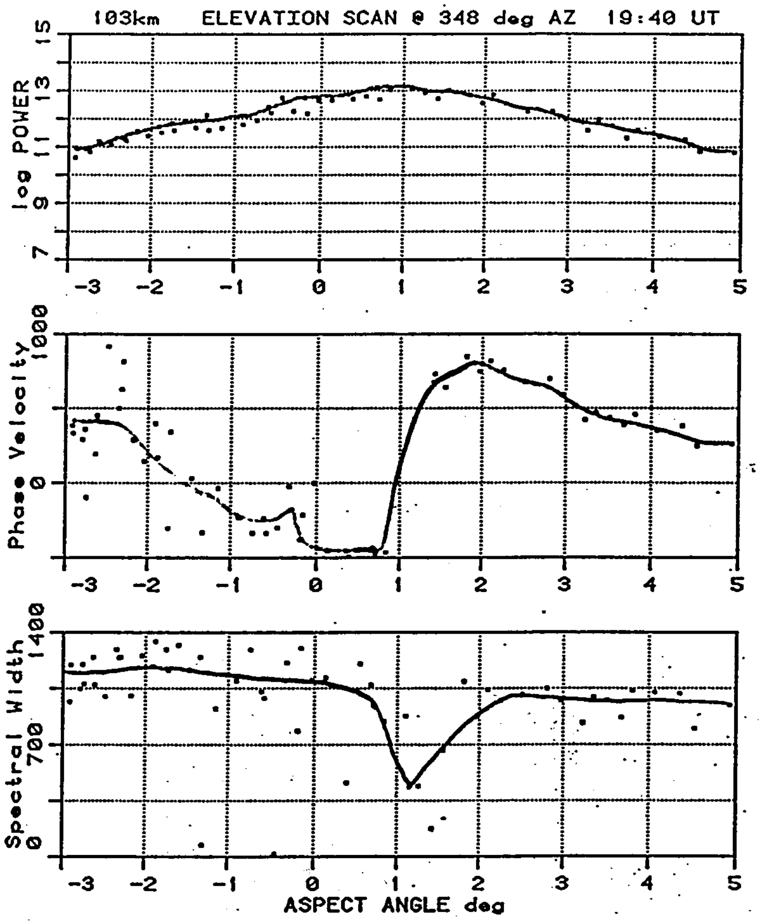
figure captions

Figure 1a. At 103 km altitude, below the peak of the layer, the Doppler phase velocity was large and positive (> +500 m/s) for $|\theta| > 2°$ and abruptly turned negative (~ –300 m/s) for $|\theta| < 2°$.

Figure 1b. Spectra above the peak of the layer at 112 km altitude exhibit a single peak with fairly uniform negative Doppler (~200 m/s) as aspect angle was varied from –3° to +5°.

Figure 2. Spectra observed near 104 km altitude reveal a transition between two narrow spectra with opposite Doppler sign as a function of aspect angle near perpendicularity and a transition region where narrow spectra of both signs were recorded at the same time. Spectral widths of 200 m/s - 500 m/s were characteristic of these studies.

Figure 3. Spectra with opposite-sign Doppler are evident at altitudes near 104 km near the phase velocity transition. For the June, 1991 study, the variation of the spectra with altitude is shown in Figure 3.



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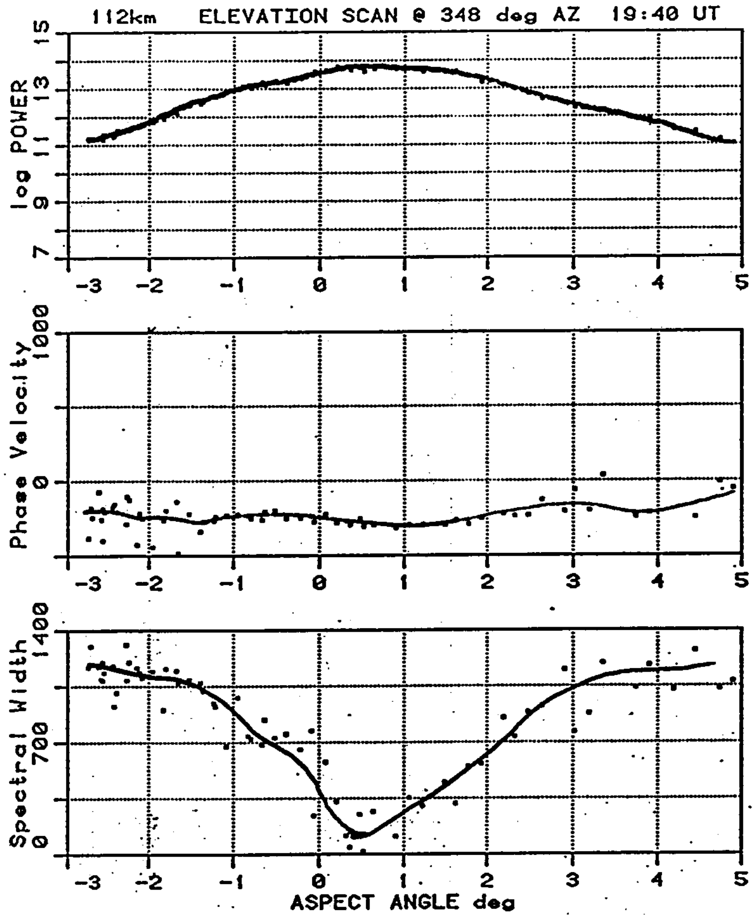

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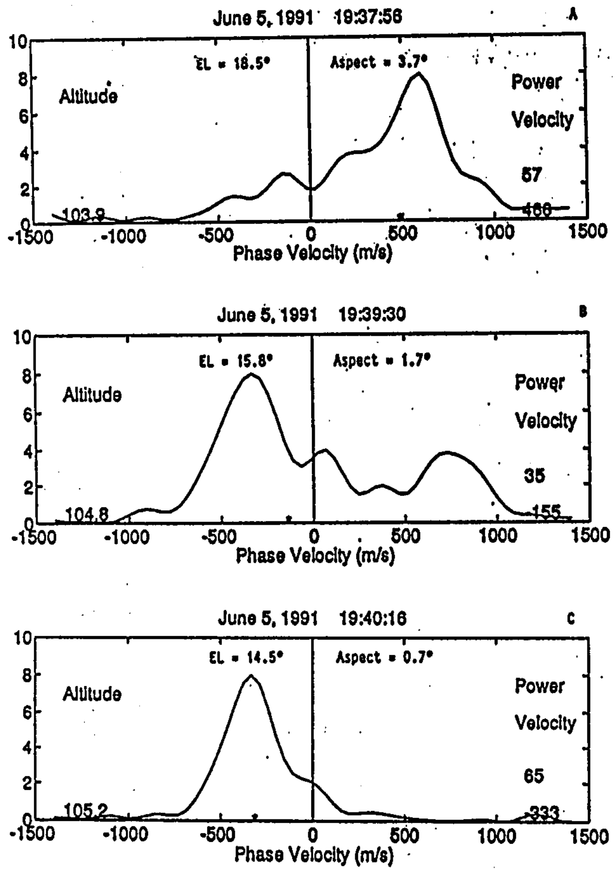

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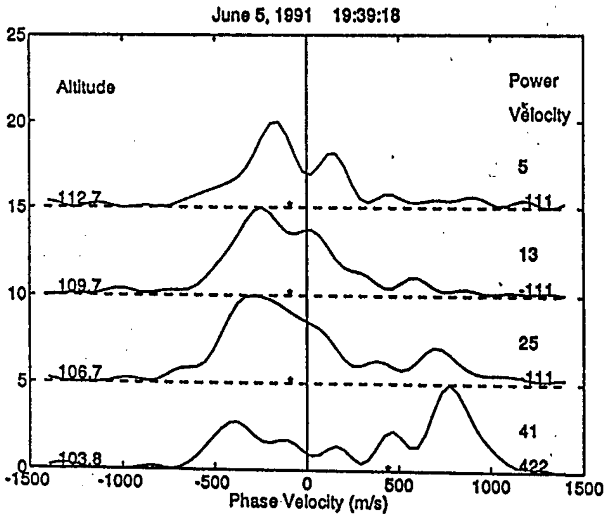

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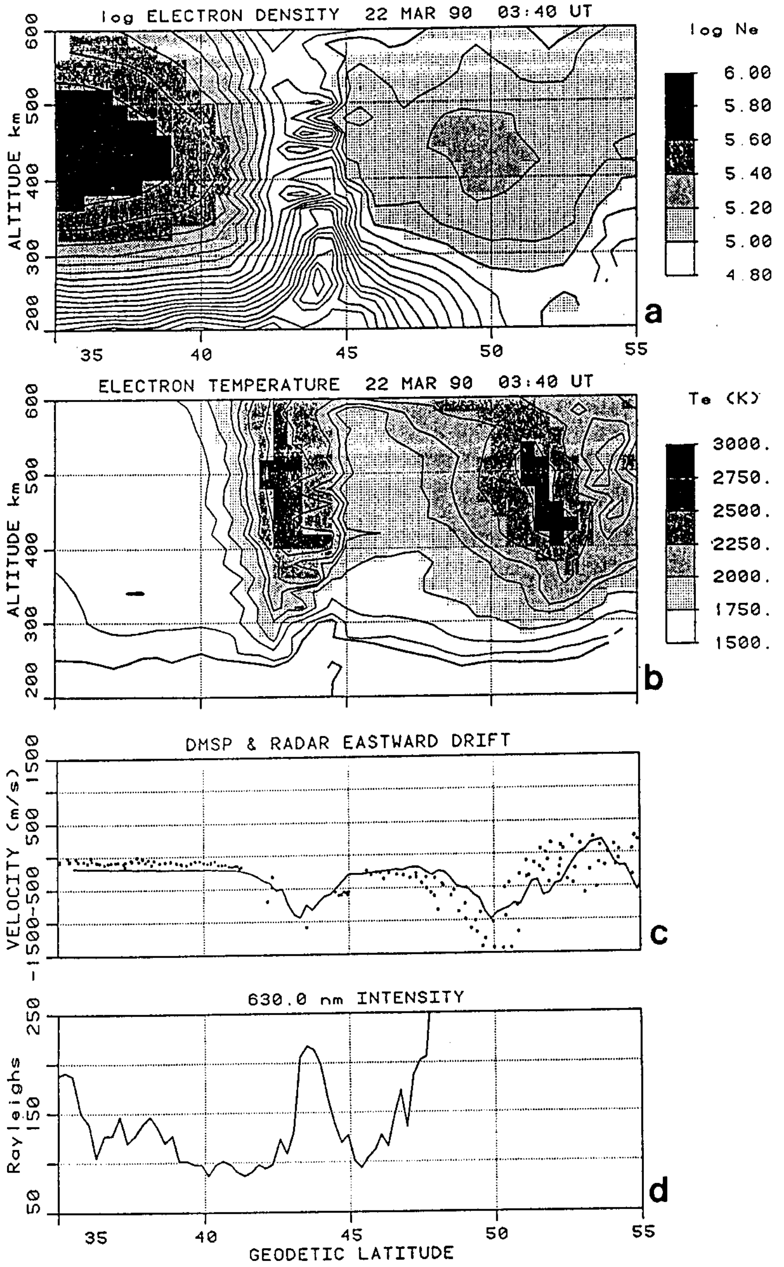

Figure 4 (a) and (b) Millstone Hill Radar elevation scan observations of the electron density trough and co-located electron temperature enhancement. (c) DMSP F9 drift meter horizontal velocity (line) and radar convection velocity observations (points) showing a discrete region of enhanced westward convection associated with the trough and SAR arc. (d) The 630.0-nm intensity defines the SAR arc centered at 43.5°. (Foster et al., 1994, SARarc)

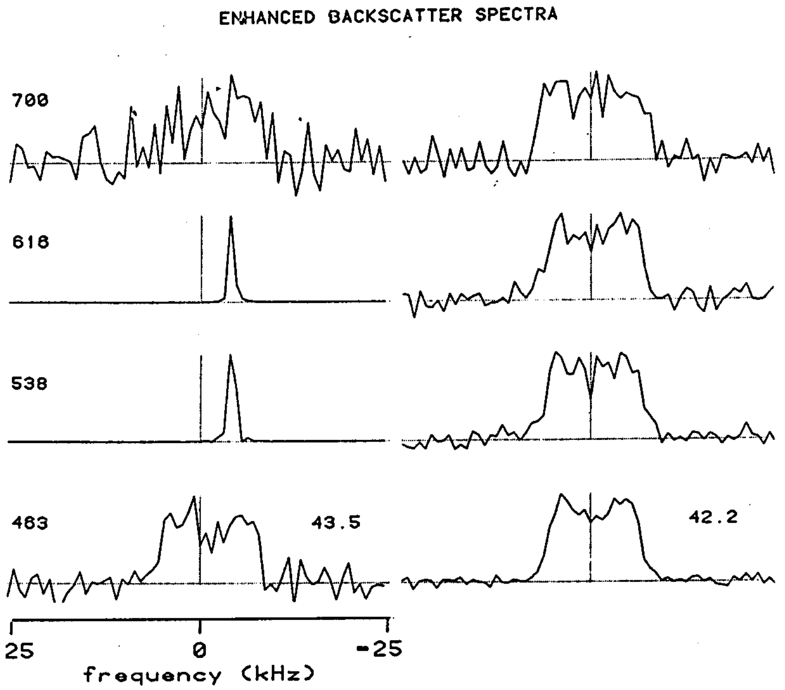

Figure 5 Backscatter radar spectra at four altitudes display an ion-acoustic enhancement characteristic of a field-aligned current carried by upward streaming thermal electrons. To the left are shown perturbed spectra near 600 km altitude at the 43.5° latitude position of the SAR arc, while at the right are unperturbed spectra near 42°. (Foster et al., 1994, SARarc)

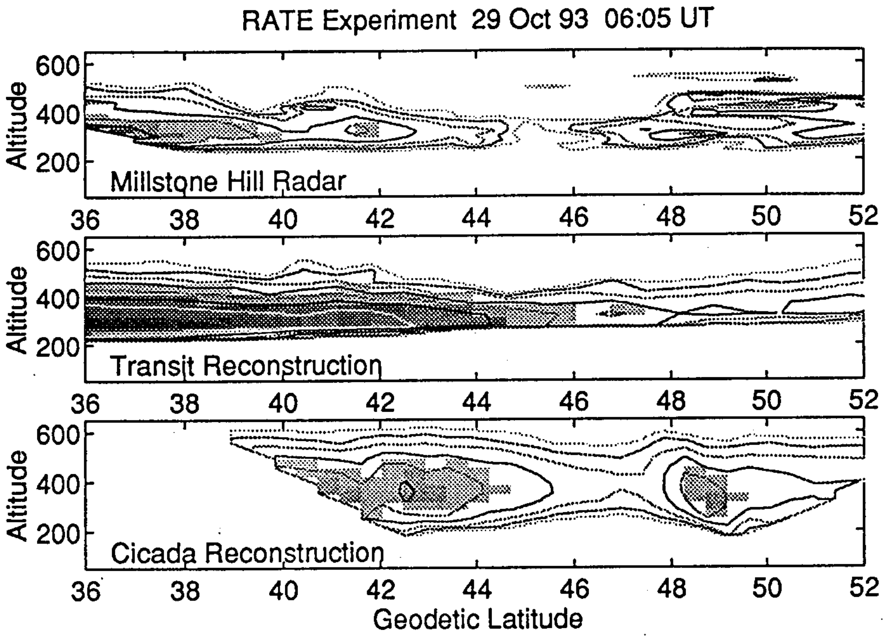

Figure 6 Latitude/altitude plots of electron density as observed by the Millstone Hill radar (top) and as reconstructed in the TEC analysis (Transit, middle) and in the phase-difference Cicada analysis (RATE, bottom). A $\log_{10}$ density scale is used and there is reasonable agreement between the density observed and derived values. A broad ionospheric depletion (trough) is seen near 46° (Foster et al., 1994, RATE)