Millstone Hill coherent-scatter radar observations of electric field variability in the sub-auroral polarization stream

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[1] Coherent backscatter observations with the Millstone Hill UHF radar (MHR) are used to investigate spatial/temporal variations in the ionospheric sub-auroral polarization stream (SAPS) electric field. For the 440 MHz MHR, coherent amplitude is on average linearly proportional to electric field strength. The use of both main-beam and sidelobe returns and the great sensitivity of the MHR system permits observations spanning $3°$ of the SAPS region with 1-sec temporal and 10-km spatial resolution. For a moderately disturbed event on May 25, 2000, the SAPS channel moved steadily equatorward. Large-scale (30 mV/m peak to peak) wave-like oscillations in the electric field magnitude ($200s–300s$ periodicity) were seen to propagate across the SAPS channel throughout the hour-long event. It is suggested that such localized electric field intensifications, which exhibit many of the characteristics of the narrow SAID features described in the literature, arise as wavelike perturbations within the SAPS channel. INDEX TERMS: 2411 Ionosphere: Electric fields (2712); 2435 Ionosphere: Ionospheric disturbances; 2443 Ionosphere: Midlatitude ionosphere; 2471 Ionosphere: Plasma waves and instabilities. Citation: Foster, J. C., P. J. Erickson, F. D. Lind, and W. Rideout (2004), Millstone Hill coherent-scatter radar observations of electric field variability in the sub-auroral polarization stream, Geophys. Res. Lett., 31, L21803, doi:10.1029/ 2004GL021271.

1. Introduction

[2] Strong, latitudinally-narrow, poleward-directed electric fields at sub-auroral latitudes in the evening local time sector have been termed the polarization jets [Galperin et al., 1974] or sub-auroral ion drifts (SAID) [Spiro et al., 1979; Anderson et al., 2001]. Broader regions of sunward plasma drift, equatorward of and separated from the evening auroral convection cell, have been described by Yeh et al. [1991]. Foster and Burke [2002] introduced the term sub-auroral polarization stream (SAPS) to encompass both types of observations of subauroral electric fields, and Foster and Vo [2002] have described the statistical characteristics of the SAPS region. The large poleward-directed SAPS electric fields are formed as field-aligned currents at the inner edge of the disturbance ring current close through the low Pedersen conductance region in the sub-auroral night time ionosphere.

[3] The Millstone UHF radar (MHR) is extremely sensitive to coherent backscatter because of its design as an incoherent backscatter system with 2 MW peak transmit power and a sensitive (42.5-dB one-way gain), narrow beam ($1°$ full width at 3 dB) steerable antenna. The Millstone Hill 440-MHz UHF radar receives intense backscatter from 34-cm irregularities when viewing E region heights to the north at aspect angles near perpendicular to the magnetic field. For ionospheric electric field strength >15 mV/m, two-stream (Farley-Buneman) irregularities form near 110 km altitude as electrons are driven by the $\mathbf{E} \times \mathbf{B}$ force through the collisional ions [Farley, 1963; Buneman, 1963]. This results in strong coherent backscatter for radar signals directed near perpendicular to the magnetic field. Past studies at Millstone Hill [Foster and Tetenbaum, 1991] investigated the temporal variation of power, finding a maximum calibrated volumetric cross section of $10^{-9}m^{-1}$ (some 90 dB above the incoherent scatter background).

[4] A narrow spectrum characterizes the coherent radar returns. For the proper viewing geometry, the strength of the coherent-scatter target leads to strong sidelobe returns over an extended range of latitude [e.g., Foster and Tetenbaum, 1992; Foster and Erickson, 2000]. Coherent two-stream irregularities are confined to a limited altitude extent near 110 km and only occur in regions where the electric field strength in the E region exceeds a threshold value of $\sim$15 mV/m. For a uniform layer of irregularities, intense coherent backscatter is observed at ranges where the main beam penetrates the irregularity layer at E-region heights, while a strong sidelobe signal is seen at each range at which the unobstructed line of sight from the radar intersects the E layer at a favorable magnetic aspect angle. The intensity of the sidelobe return is reduced by the off-beam antenna attenuation factor (squared, since both transmit and receive paths are affected).

[5] Foster and Erickson [2000] used a combined coherent backscatter-incoherent scatter experiment to provide simultaneous observations of electric field magnitude and coherent backscatter parameters on the same L shell. For electric field strength varying in the range [15, 65] mV/m, they found a linear relationship between the magnitude of the logarithmic coherent power and $|\mathbf{E}|$, with slope 5 dB per 10 mV/m.

2. Observations of SAPS Variability

[6] The SAPS electric field often exhibits localized variations in intensity in addition to an underlying smooth variation spanning several degrees of latitude [Foster and Burke, 2000]. Past studies of the electric field structure within the SAPS channel (e.g., using satellite overflights) have not resolved the spatial/temporal variability of this structure. In the present study, we combine the extended
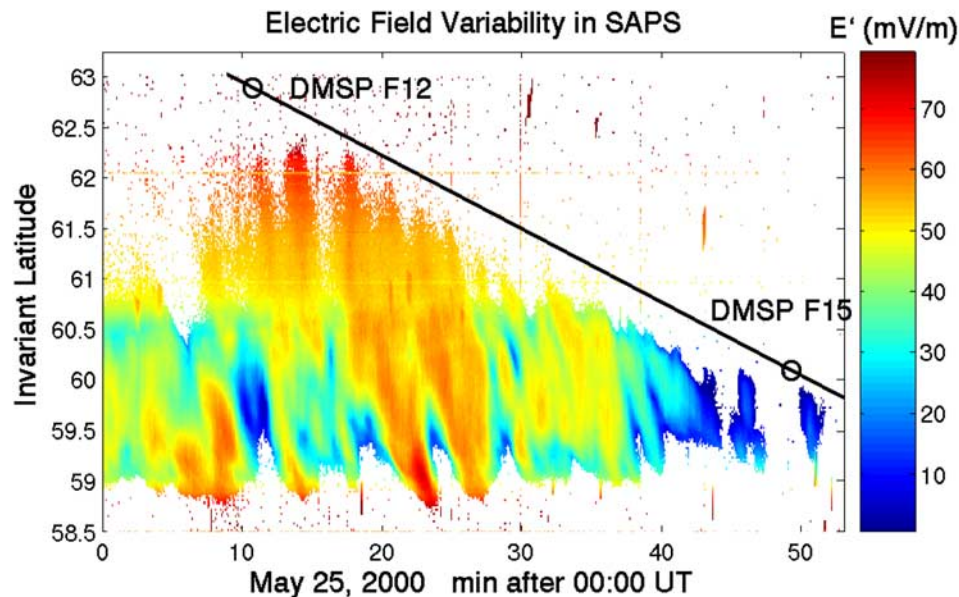
Figure 1. High resolution coherent scatter observations of electric field variability with the Millstone Hill UHF radar reveal periodic wavelike structures within the SAPS channel. The line indicates DMSP observations of the equatorward extent of auroral electron precipitation.

latitude coverage and fast temporal sampling afforded by the coherent radar technique with the relationship developed by *Foster and Erickson* [2000] to provide the first high-resolution, calibrated observations of the temporal/spatial variability of the SAPS electric field. Several recent studies have addressed related aspects of SAPS variability using different techniques.

[7] *Foster and Tetenbaum* [1991] used a fixed-beam experiment from Millstone Hill to quantify the intensity and variability of coherent backscatter parameters under SAPS conditions. They described 20-dB sinusoidal modulation of the backscatter intensity and irregularity phase velocity with ~5-min periodicity.

[8] *Erickson et al.* [2002] used a 'slit-camera' experiment to provide a detailed look at the structure and variability of the polarization stream (SAPS) electric fields as the SAPS channel receded poleward past the radar beam. Their observations indicate that the spatial extent of the SAPS electric field can change in under one minute from a widespread, structureless, distributed field, to a system of very narrow features (less than 0.1 degrees latitude; ~10 km range extent), which exhibit the observational characteristics of SAID events. They found that the localized electric fields can move up to 0.5 degrees in latitude in the span of 3–4 minutes, and have intensities which can exceed that of the more uniform electric field events by 10 to 30 dB.

[9] Sidelobe coherent backscatter with the Irkutsk research radar was analyzed by *Mishin et al.* [2002] for the September 25, 1998 storm event. This technique provided uncalibrated observations of large-scale variations in the SAPS channel, including equatorward SAPS motion and a ~10-min quasi-periodic variation with ~10 mV/m amplitude.

[10] DMSP satellite overflights were used by *Mishin et al.* [2003] to provide a detailed analysis of the spatial variations of the electric fields in the SAPS channel during

the November 6, 2001 magnetic storm. Analyses of possible wave modes were presented and spatial wavelengths of ~10 km to ~50 km and amplitudes of 10–40 mV/m were observed.

3. May 2000 Experiment

[11] During a sawtooth geomagnetic disturbance event [e.g., *Huang et al.*, 2003] in the late afternoon sector on May 25, 2000 UT, the Millstone Hill UHF radar was operated in a fixed-position mode directed perpendicular to |**B**| at 110 km to the NE (azimuth 18°). This pointing position gives maximum sensitivity for coherent returns at the early part of an event when the region of enhanced (SAPS) electric field lies poleward of the site. *Foster and Tetenbaum* [1991] have described a number of coherent-scatter experiments run in this pointing position and have described the near-sinusoidal variations in coherent amplitude which often have been observed. In this case, a short pulse was used with the fast sampling and deconvolution technique described by *Erickson et al.* [2002]. Figure 1 presents high-resolution observations of the spatial/temporal variation of the sub-auroral electric field magnitude during an interval when the SAPS convection channel progressed equatorward. The experiment sampled the latitude distribution of coherent power across a 3-deg span of invariant latitude with 10-km spatial and 1-sec temporal resolution. Latitude profiles of coherent amplitude have been converted to relative electric field strength using the relationship of *Foster and Erickson* [2000] and are displayed in range-time-intensity (RTI) format. The center of the radar beam intersects the 110-km irregularity layer near 59.5°Λ, and rapidly-increasing aspect angle below 59°Λ defines the equatorward limit of experiment sensitivity.

[12] Near-periodic intensifications of the electric field magnitude appear with similar slope throughout the interval,
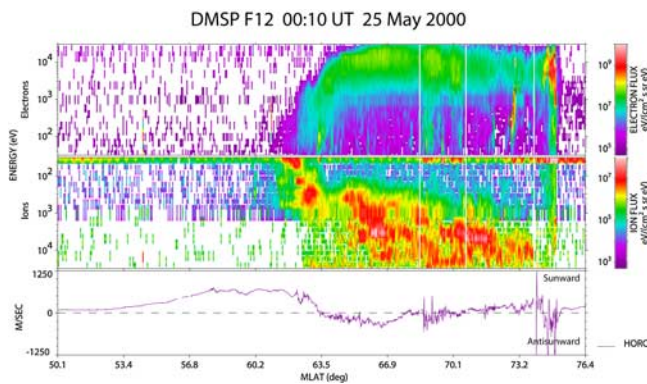
Figure 2. DMSP F12 overflight of the SAPS region at 00:10 UT May 25, 2000 identifies the broad extent of the subauroral electric field (63 deg to 53 deg MLAT).

corresponding to an apparent equatorward motion (phase velocity) of ~785 m/s. As the region of strong electric field expanded to lower latitudes during the event, the entire region of coherent returns moved to closer range, with the poleward edge of the SAPS region moving equatorward uniformly at a speed of ~150 m/s.

[13] Overflights of the post-noon convection at this time by the DMSP satellites show the pronounced double-peaked sunward convection characteristic of the formation of a sub-auroral polarization stream during disturbed conditions [*Foster and Burke*, 2002]. A DMSP F12 overflight 10° to the east of the Millstone Hill longitude at 00:10 UT is shown in Figure 2 and reveals the equatorward limit of keV electron precipitation at 63°Λ and the extent and magnitude of the sub auroral polarization stream (SAPS) convection. SAPS sunward convection (~1000 m/s) spans the low-conductance ionosphere for ~6° equatorward of the precipitation boundary. The black line immediately pole-

ward of the extent of the coherent radar returns shown in Figure 1 indicates the equatorward extent of plasmasheet precipitation identified by DMSP overflights. The DMSP observations of Figure 2 confirm that the MHR coherent returns originated in the sub-auroral (SAPS) region.

4. Backscatter Model

[14] The power/range distribution observed in these fixed beam experiments depends on the convolution of the antenna beam pattern with the latitude and altitude distribution of the irregularities. Given the radar pointing information, detailed beam shape, and an assumed spatially uniform layer of irregularities centered at a given altitude, the distribution of radar backscattered power as a function of range can be calculated. *Foster and Tetenbaum* [1991] have described such a model for the Millstone Hill system in which the aspect angle sensitivity, the altitude of the irregularities, the thickness of the layer, and the latitude extent of the layer can be varied. Figure 1 uses this model to correct the off-beam observations of Figure 1 for reduced sensitivity due to beam angle and magnetic aspect angle effects.

5. Discussion

[15] The MHR observations of Figure 1 approximate a rapid succession of latitudinal cuts across the SAPS electric field. At the fast resolution provided by the radar observations, the discrete features (SAID and other intensifications) often reported in the subauroral convection electric field are seen to move across the wider SAPS channel with wave-like characteristics. In Figure 3 we present latitude profiles of the electric field observed by MHR as a function of invariant latitude. In each case, the latitude extent of the SAPS region extends beyond the equatorward limit of the radar field of view near 59°.

[16] *Streltsov and Foster* [2004] presented results of a numerical study of the electric field oscillations in the nightside sub auroral ionosphere presented here in
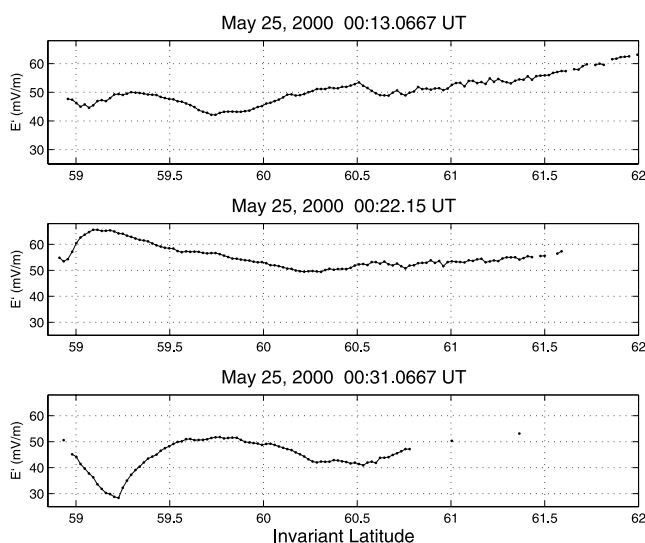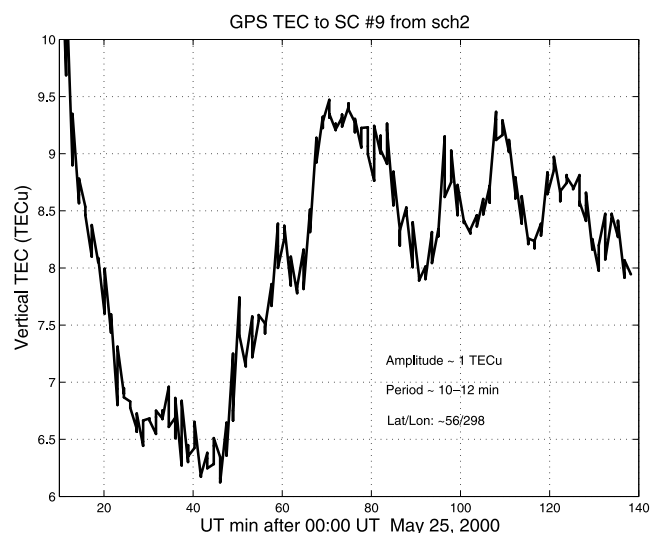

Figure 3. Millstone Hill radar coherent observations provide a sequence of latitude cuts across the poleward portion of the SAPS channel (cf. Figure 1). The latitude variation of the effective electric field is shown at three times during the event.

Figure 4. Vertical TEC derived from GPS beacon observations identify ~10-min oscillations in plasma density within the SAPS channel.
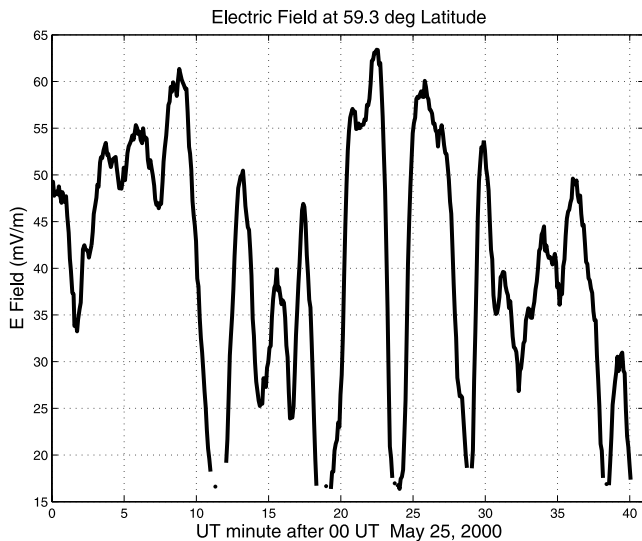
Figure 5. Observations of electric field amplitude derived from MHR coherent backscatter observations at 59.3° invariant latitude reveal large-scale (30 mV/m peak to peak) wave-like oscillations with 200s−300s quasi periodicity within the SAPS channel.

Figure 1. They interpreted those oscillations as an ionospheric footprint of the surface Alfven waves generated at the equatorial magnetosphere on a steep transverse gradient in the background plasma density associated with the plasmapause. Interaction of the large amplitude perpendicular electric field with the low-Pedersen conductance ionosphere can trigger an ionospheric feedback instability, which leads to the formation of small-scale, intense structures in both the electric field and the parallel current density in the subauroral magnetosphere. That model predicts that both ionospheric density and conductivity will oscillate in the low-conductivity SAPS channel poleward of the plasmapause density gradient. For this event, we have examined total electron content (TEC) within the SAPS channel (trough) determined from GPS signals propagating through the region of interest. Figure 4 presents observations of vertical TEC for an ionospheric penetration point several degrees equatorward of the coherent radar observing volume discussed in Figure 1. After ∼00:20 UT the GPS line of sight lies in the trough and 10−12 min oscillations in TEC with ∼1 TECu amplitude are seen. Such oscillations are consistent with the predictions of the models of *Streltsov and Foster* [2004] or *Mishin et al.* [2003], both of which associate ionospheric density oscillations with the development of the ionospheric feedback instability.

[17] In Figure 5, we present the temporal variation of the electric field strength at 59.3° invariant latitude. Large-scale (30 mV/m peak to peak) wave-like oscillations in the electric field magnitude are seen with 200s−300s quasi periodicity. The RTI presentation of Figure 1 shows that such intensifications propagate across the SAPS channel throughout the hour-long observing event. *Foster and Tetenbaum* [1991, Figures 2, 5, 6, and 7] present additional observations of near-periodic variations of the coherent scatter intensity seen from Millstone Hill. It is suggested, in agreement with *Erickson et al.* [2002], that such localized electric field intensifications, which exhibit many of the characteristics of the narrow SAID features described in the literature, arise as wavelike perturbations within the broader SAPS channel.

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