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First observations of the temporal/spatial variation of the sub-auroral polarization stream from the SuperDARN Wallops HF radar

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[1] In this letter we present the first two-dimensional observations of sub-auroral ion drift (SAID) variability within the sub-auroral polarization stream (SAPS) using a new mid-latitude SuperDARN radar located at Wallops Island, VA. The radar data are complemented with observations from the DMSP F15, TIMED, and NOAA-18 spacecraft to confirm that a backscatter feature observed at the equatorward edge of the auroral oval is a manifestation of SAPS/SAID. During a several hour long period on August 6, 2005, the velocity data indicate that significant changes in the SAPS flow occurred on time scales of a few minutes. The Wallops HF radar observations demonstrate that the SAPS phenomenon is a source of small-scale irregularities extending over many hours of MLT and that the electric fields associated with SAID in particular are highly variable. **Citation:** Oksavik, K., R. A. Greenwald, J. M. Ruohoniemi, M. R. Hairston, L. J. Paxton, J. B. H. Baker, J. W. Gjerloev, and R. J. Barnes (2006), First observations of the temporal/spatial variation of the sub-auroral polarization stream from the SuperDARN Wallops HF radar, *Geophys. Res. Lett.*, *33*, L12104, doi:10.1029/2006GL026256.

1. Introduction

[2] The mid-latitude dusk/night ionosphere is a region subject to strong poleward electric fields equatorward of the auroral electron precipitation boundary; a phenomenon that has recently been named the sub-auroral polarization stream (SAPS) [*Foster and Burke*, 2002; *Huang et al.*, 2006]. SAPS is believed to occur when the inner electron and ion boundaries of the ring current separate in response to enhanced magnetospheric convection. In the sub-auroral ionosphere, where the conductivity is low, this charge separation results in a poleward electric field and enhanced westward flow in the equatorward extent of the evening convection cell. The term sub-auroral ion drift (SAID) is used to describe a localized (1–2° wide in latitude) but intense enhancement within the SAPS, where the westward flow may exceed 1 km/s. In early studies the same phenomenon was referred to as the polarization jet [*Galperin*, 2002, and references therein]. The SAID is most often seen as a spike in the westward component of spacecraft drift meter data [see, e.g., *Anderson et al.*, 2001].

[3] Most of our knowledge of SAPS/SAID has been acquired using drift meters onboard low altitude polar orbiting spacecraft or incoherent scatter radars scanning the ionosphere. On the time scale of a couple of minutes both of these techniques can only provide one-dimensional measurements within a limited region of space. For a spacecraft the measurements can only be repeated once per orbit (~100 minutes). For incoherent scatter radars the measurements are limited both by the signal-to-noise ratio of the backscatter and the speed at which the antenna can move from one orientation to another, typically constraining the temporal resolution of any wide two-dimensional coverage measurements to 10–30 minutes.

[4] For over a decade SuperDARN [*Greenwald et al.*, 1995] has been monitoring the global structure and dynamics of plasma convection and electric fields in the high-latitude ionosphere with great success using antennas in phased arrays and transmission of multi-pulse HF signals to obtain coherent scatter from field-aligned irregularities in the ionosphere. However, during disturbed and storm-time conditions the auroral zone expands equatorward of the field-of-view of these high-latitude radars, preventing the full polar cap potential from being determined. To understand what has been missed, a new radar was put into operation in early May 2005 at the NASA Wallops Flight Facility in northeast Virginia. This radar was jointly funded by The Johns Hopkins University Applied Physics Laboratory and the NASA Goddard Space Flight Center. This mid-latitude radar provides the very first extension of SuperDARN to the sub-auroral zone down to 50° magnetic latitude. In this letter we present initial observations of the temporal/spatial variability of SAPS/SAID electric fields during an event on August 6, 2005, when there were superb complementary observations in the vicinity of the radar field-of-view from the polar-orbiting DMSP-F15, TIMED, and NOAA-18 spacecraft.

2. Observations

[5] Figure 1 shows individual one-minute scans from the Wallops radar and cross-track plasma drift observations from DMSP F15. All three panels are plotted from 50–90° magnetic latitude versus magnetic local time. The Wallops field-of-view is confined by the thick solid arc segments. {The azimuthal extent of the Wallops scan has since been increased from 26° to 78°.} The Wallops line-of-sight velocity is shown for all 16 radar beam directions using a color scale where blue is toward the radar (i.e., mainly westward flow) and red/yellow is away from the radar (i.e., mainly eastward flow). To ease the comparison of these two data sets a color-coded swath of the electron

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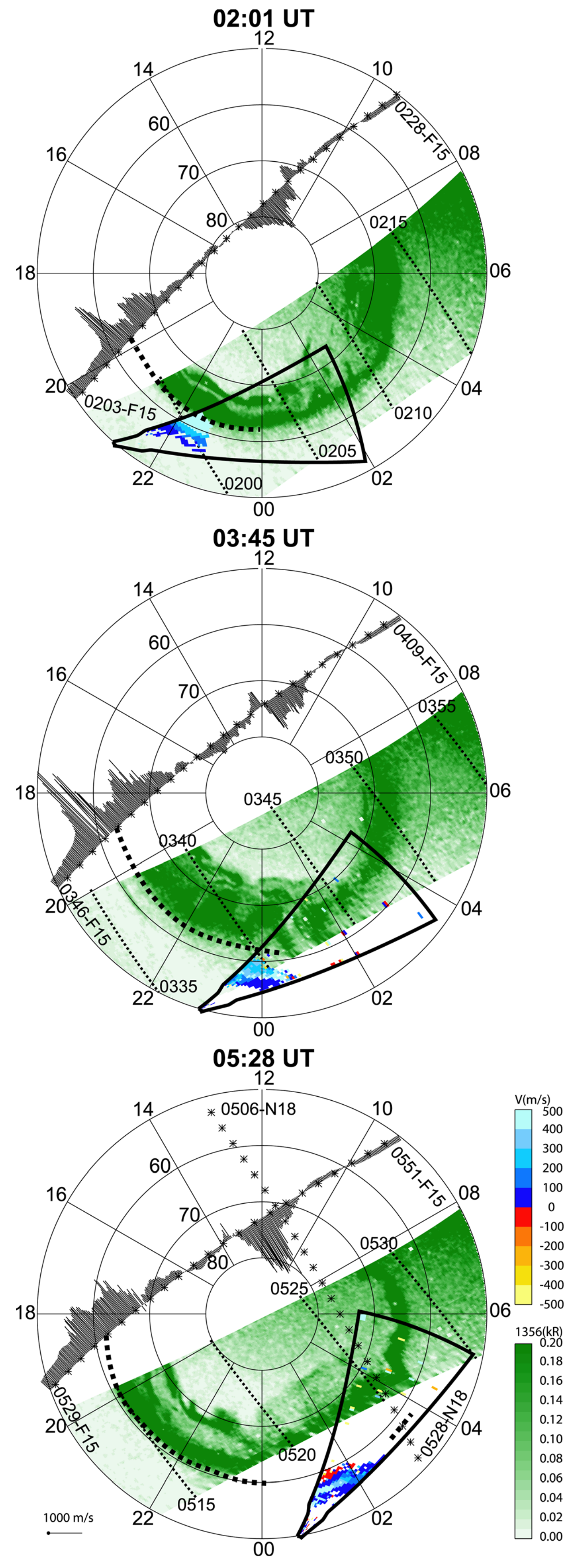

Figure 1. One minute plots of the line-of-sight velocity for three scans of the Wallops radar displayed versus magnetic latitude and magnetic local time. The field-of-view is indicated with a solid line. The radar data has been overlaid onto a swath of the 135.6 nm aurora obtained from TIMED GUVI, cross-track ion drift vectors from the DMSP F15 spacecraft, and the track of the NOAA-18 spacecraft. These spacecraft data have been used to draw thick dashed lines that indicate the equatorward edge of the electron precipitation.

aurora (135.6 nm atomic oxygen line) from the TIMED GUVI instrument has been included. In addition the equatorward edge of the auroral oval has been drawn with a dashed curve, based on observations of the electron precipitation by DMSP-F15 and NOAA-18 (data not shown) and the electron aurora by TIMED GUVI.

[6] The first panel of Figure 1 shows the situation in the early phase of the event around 02:01 UT. The electron aurora is poleward of 62–63° magnetic latitude as indicated by the dashed line. Just equatorward of the aurora (from 60–63° magnetic latitude) the flow toward the Wallops radar was >500 m/s. At the same time and at nearly the same latitudinal distance from the electron precipitation, DMSP F15 observed strong westward flows. In a narrow channel from 58.5–61.5° magnetic latitude, the high-speed flow jumped to 1800 m/s, corresponding to a density drop (not shown) from 2×10^4 to 8×10^3 ions/cm^3 (at the altitude of the spacecraft). Flows of 400 m/s did extend down to at least 45° magnetic latitude with a minimum of 320 m/s around 52° magnetic latitude. This example shows that the Wallops radar observed both the SAPS and the high-speed SAID channel. The apparent velocity difference within the SAID (500–1000 m/s versus 1500 m/s) can be partly explained in terms of geometry. Assuming that the flow is mostly zonal, the line-of-sight velocity from the Wallops radar will be an underestimate of the total east/west flow by a factor given by 1/sin (θ) where θ is the angle between the beam direction and the magnetic meridian; at 57° magnetic latitude θ is 37° for the most northward and almost 90° for the most eastward beam direction. In addition there may be a westward gradient in the SAPS flow magnitude as has been reported statistically by *Foster and Vo* [2002].

[7] The second panel of Figure 1 shows the next DMSP F15 and TIMED crossing. Poleward of 41.5° magnetic latitude the DMSP F15 cross-track drift was around 300 m/s, with the high-speed flow reaching over 2500 m/s between 56–61° magnetic latitude, coinciding with a density drop from 2×10^4 to 5×10^3 ions/cm^3. The ion/electron precipitation seen by DMSP F15 was poleward of 62–63° magnetic latitude, and TIMED GUVI shows that the equatorward edge of the auroral oval did not extend below 61–62° magnetic latitude near Wallops Island. Again the radar saw the high-speed SAID embedded within a region of lower flow consistent with the extension of the SAPS/SAID from the dusk into the midnight sector.

[8] The third panel of Figure 1 shows the last DMSP F15 and TIMED GUVI conjunction, in addition to a nearly simultaneous crossing of the eastern part of the Wallops field-of-view by the NOAA-18 spacecraft. Indicated with a

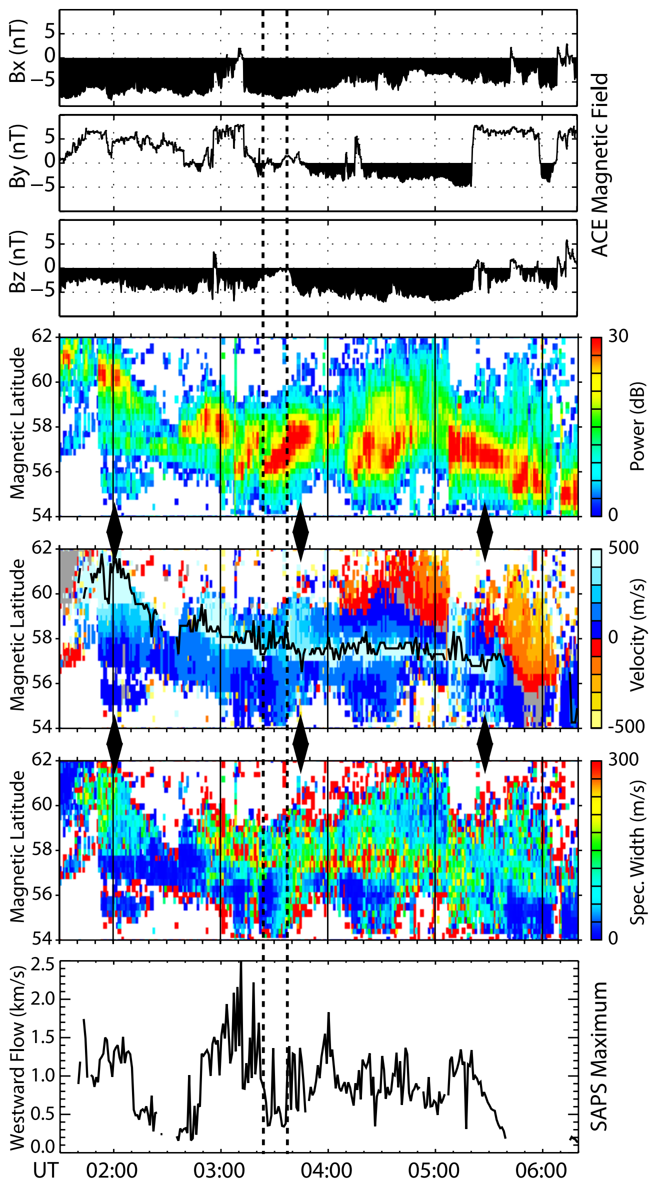

Figure 2. (first, second, and third panels) Components of the interplanetary magnetic field from the ACE spacecraft, shifted in time relative to the other panels to account for the solar wind propagation time from the spacecraft to the Earth. (fourth, fifth, and sixth panels) Wallops beam 4 backscatter power, line-of-sight velocity, and spectral widths versus magnetic latitude and time. In the velocity panel blue colors represent drifts toward the radar (i.e., westward flow), red colors represent drifts away from the radar (i.e., the eastward flow), and gray color blanks out ground echoes. (seventh panel) Temporal variation of the highest flow within the SAPS at the location indicated with a line in the velocity panel. Diamonds refer to three times that are studied in more detail in Figure 1, and vertical guide lines indicate features described in the text.

dashed curve on the NOAA-18 track is the equatorward edge of the electron precipitation around 58° magnetic latitude. To the west of the Wallops field-of-view the TIMED GUVI data shows that the equatorward edge of the auroral oval had expanded to around 60° magnetic latitude. Further west the DMSP F15 spacecraft observed a cross-track drift of around 400 m/s poleward of 44° magnetic latitude. Between 53–59° magnetic latitude the drift was around 1000 m/s, corresponding to a density drop from 1.7×10^4 to 8.5×10^3 ions/cm^3. In the radar data the SAID was still observed around 57° magnetic latitude and extended beyond 0200 MLT. It should also be noted that on the poleward side of the SAID there is an area of red color indicating plasma drifting away from the radar at speeds of around 100 m/s, corresponding to a drift that is poleward and/or eastward. A few minutes after 05:28 UT this area expanded equatorward, got wider in latitude, and eventually dominated the radar field-of-view. Given the location (around 0200 MLT) we interpret this as mostly eastward flow on the poleward side of the Harang discontinuity. There is also an interesting detail in these Wallops data; the flow velocity is higher in the western part of the field-of-view than in the eastern part, which suggests that we are looking into the easternmost edge of the SAID near the transition region between the dusk and dawn convection cells. The DMSP and Wallops observations also indicate that the SAPS extended over more than six hours of magnetic local time and across midnight to at least 02 MLT. A wide MLT distribution is confirmed by observations from DMSP satellites in the Southern Hemisphere (not shown) and is consistent with the statistical study of *Foster and Vo* [2002].

[9] Having established the SAPS/SAID character of the observations we discuss the nature and sources of the variability. The entire event occurred during a time period of Kp = 4 and Dst between −15 to −28 nT. The solar wind density was 4–6 ions/cm^3, the temperature 2×10^5 K, and the velocity 480–520 km/s (data not presented). The first, second, and third panels of Figure 2 show the interplanetary magnetic field from the ACE spacecraft, where we have shifted the ACE data (first, second, and third panels) by 50 minutes relative to the other panels to account for the solar wind propagation time from ACE near [226, −11, 20] Re to Earth's magnetosphere along the X-direction. This time shift is consistent with observed changes in the SAID flow (e.g., a near disappearance of the SAID at 03:25–03:35 UT that began around 50 minutes after a sudden decrease in Bz magnitude and persisted until Bz swung more negative, indicated with dashed lines in Figure 2). Both Bx and Bz were negative during our event; By started out positive but gradually turned negative before flipping back to positive.

[10] The fourth, fifth, and sixth panels of Figure 2 show 4 hours and 50 minutes of data from beam 4 of the Wallops radar, and we have marked with diamonds the three times shown in Figure 1. Beam 4 is aligned to the northeast, providing wide latitudinal coverage of the zonal flows. As indicated with gray in the velocity panel of Figure 2 the radar only detected ground echoes on this beam prior to 01:40 UT. At that time the radar suddenly started to see strong flows in the ionosphere between 59–62° magnetic latitude. Along the line-of-sight these flows were between 500–1000 m/s toward the radar, as indicated with bright blue and corresponding to a predominantly westward drift. Simultaneously the spectral width approached 150 m/s in the area of highest flow. Following a transmitter frequency

change at 01:52 UT, the backscatter power from the area of highest flow was 20–30 dB over the background noise. At the same time the radar started to see a region indicated with dark blue of low flow (<200 m/s) from 55–59° magnetic latitude and equatorward of the high velocity flow. This area of low flow was observed more or less continuously for four hours, as the band of >500 m/s line-of-sight velocity gradually migrated equatorward. We notice that starting around 03:00 UT an area of low flow is also seen on the poleward side of the >500 m/s flow. We further notice that poleward of 59° magnetic latitude and starting around 04:10 UT (close to magnetic midnight) a region of flow away from the radar (red and yellow colors) appears to correspond to eastward flow. This band of flow away from the radar gradually migrated equatorward, until it extended all the way down to 56° magnetic latitude around 06:00 UT as the radar field-of-view gradually approached the morning convection cell.

3. Discussion

[11] Observations of sub-auroral irregularities and westward flows possibly associated with SAPS were reported in the European sector by *Hosokawa et al.* [2002]. Our study is the first to confirm the association of HF coherent backscatter with SAPS, and to continuously monitor changing sub-auroral flows in two dimensions during disturbed conditions over an MLT range that extends from dusk to past midnight. The fact that the HF radar monitors the SAPS so well indicates that there is a continuous supply of decameter-scale irregularities associated with the mid-latitude density trough. Modeling work by *Keskinen et al.* [2004] shows that density gradients associated with the trough walls can generate small scale structures via the ion temperature gradient and gradient drift instabilities. They also found that fluctuations in density, ion temperature, and electric field can result from the ion frictional instability acting within the trough itself.

[12] One striking feature of this event is how the latitudinal extent of the SAID appears to vary with time. One may think that some of this variation could be due to transmitter frequency changes, since the radar was running a fast sounding mode allowing the frequency to switch every 15 minutes based on an automatic search. Frequencies from 10.4 to 13.0 MHz were used, and significant changes of the transmitter frequency occurred at 01:52, 02:37, 03:07, 03:22, 04:07, 05:08, and 05:38 UT. Apart from these times any variation in the latitudinal extent of the SAID cannot be explained by the radar operations. We have therefore strong reason to believe that a sudden narrowing of the SAID at 03:05 UT from over 2° to 1° width in latitude (two radar scans before the frequency changed), a transient weakening or disappearance of the SAID from 03:25 to 03:35 UT, a sudden broadening of the SAID to over 2° wide in latitude at 03:35 UT, and the return back to 1° wide in latitude at 03:40 UT are all evidence of real changes within the SAPS. We note that the low velocity component of the SAPS tends to persist while the SAID undergoes dramatic variations in just a few minutes.

[13] The SAID appears to be mostly L-shell aligned, so in the seventh panel of Figure 2 we show the maximum westward flow versus time as determined by assuming the net flow is along the L-shell. Except for a period of reduced data coverage around 02:10–02:50 UT, when the SAID appears to have moved to the north of where the radar was receiving backscatter, the coverage in the data set is excellent. The estimated maximum SAID flow fluctuates on time scales of minutes between 500 m/s and 2 km/s. The near disappearance of the SAID at 03:25–03:35 UT (westward flow <0.5 km/s) appears to correspond to a time of reduced Bz magnitude as indicated with vertical dashed lines in Figure 2. It is therefore expected that the convective dawn-dusk electric field in the magnetosphere would be significantly reduced, lowering the electric fields also at mid-latitudes. Once the southward magnetic field recovered the SAID quickly returned. This suggests that the behavior of the interplanetary magnetic field plays an important role in modulating the ionospheric electric fields even at mid-latitudes.

[14] We note that in this region magnetosphere-ionosphere (M-I) coupling is also a significant factor. Using ion drift meters on the Atmospheric Explorer and Dynamics Explorer 2 spacecraft *Anderson et al.* [1991] reported that SAID events typically last 0.5–3 hours, and it was long thought that the SAID was a rather constant feature throughout its period of existence. Later, *Anderson et al.* [1993] demonstrated a close relation between SAID and substorms, which are known to be associated with a long list of phenomena that are dynamic and which may be internally driven. The Wallops radar data show several examples of significant and transient variations in the SAID flow not directly related to solar wind changes. One example is the increase from 1.3 km/s at 02:50 UT to 2.5 km/s at 03:10 UT. Another example is the increase from 0.8 km/s at 03:50 UT to 1.8 km/s at 04:00 UT and back to 0.8 km/s at 04:10 UT. A third example is the variability (0.4–1.4 km/s) seen from 03:10 to 05:20 UT. Observations of rapidly changing electric fields have been provided in the form of coherent sidelobe echoes from incoherent scatter radars at Millstone Hill [*Foster and Erickson*, 2000; *Erickson et al.*, 2002; *Foster et al.*, 2004] and Irkutsk [*Mishin et al.*, 2002]. Using data from individual DMSP satellite crossings, *Mishin et al.* [2003] also presented observations of strong oscillations in electromagnetic fields and plasma density, which appear to be due to Alfvén, electromagnetic ion-cyclotron (EMIC), and electrostatic waves. Surface Alfvén waves can also be generated at the steep transverse gradient in the background plasma density near the plasmapause and may lead to electric field oscillations in the sub-auroral ionosphere. Simulations by *Streltsov and Foster* [2004] show that when the perpendicular electric field interacts with the low-conducting night ionosphere, ionospheric feedback instability may lead to intense small-scale structures in both the electric field and the parallel current density. It is therefore thought that the inner magnetosphere and the sub-auroral ionosphere may continuously respond to each other, like in an Alfvénic resonator, and ultimately cause the electric field of the sub-auroral ionosphere to fluctuate.

4. Conclusion

[15] The new Wallops HF radar has detected backscatter at sub-auroral latitudes that are associated with SAPS. The

ionospheric plasma flows correlate well with DMSP F15 observations of SAPS/SAID activity. For the first time we see both how the latitudinal extent and the SAPS flow velocity change on time-scales of minutes over large distances (~hundreds of km) and extended time intervals (~hours). Some of the variability appears due to IMF factors while other variability may derive from processes internal to the M-I system.

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References

Anderson, P. C., R. A. Heelis, and W. B. Hanson (1991), The ionospheric signatures of rapid subauroral ion drifts, *J. Geophys. Res.*, *96*, 5785–5792.

Anderson, P. C., W. B. Hanson, R. A. Heelis, J. D. Craven, D. N. Baker, and L. A. Frank (1993), A proposed production model of rapid subauroral ion drifts and their relationship to substorm evolution, *J. Geophys. Res.*, *98*, 6069–6078.

Anderson, P. C., D. L. Carpenter, K. Tsuruda, T. Mukai, and F. J. Rich (2001), Multisatellite observations of rapid subauroral ion drifts (SAID), *J. Geophys. Res.*, *106*, 29,585–29,599.

Erickson, P. J., J. C. Foster, and J. M. Holt (2002), Inferred electric field variability in the polarization jet from Millstone Hill *E* region coherent scatter observations, *Radio Sci.*, *37*(2), 1027, doi:10.1029/2000RS002531.

Foster, J. C., and P. J. Erickson (2000), Simultaneous observation of E-region coherent backscatter and electric field amplitude at F-region heights with the Millstone Hill UHF radar, *Geophys. Res. Lett.*, *27*, 3177–3180.

Foster, J. C., and W. J. Burke (2002), SAPS: A new characterization for sub-auroral electric fields, *Eos Trans. AGU*, *83*, 393.

Foster, J. C., and H. B. Vo (2002), Average characteristics and activity dependence of the subauroral polarization stream, *J. Geophys. Res.*, *107*(A12), 1475, doi:10.1029/2002JA009409.

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.

Galperin, Y. I. (2002), Polarization jet: Characteristics and a model, *Ann. Geophys.*, *20*, 391–404.

Greenwald, R. A., et al. (1995), DARN/SuperDARN: A global view of the dynamics of high-latitude convection, *Space Sci. Rev.*, *71*, 761–796.

Hosokawa, K., M. Sugino, M. Lester, N. Sato, A. S. Yukimatu, and T. Iyemori (2002), Simultaneous measurement of duskside subauroral irregularities from the CUTLASS Finland radar and EISCAT UHF system, *J. Geophys. Res.*, *107*(A12), 1457, doi:10.1029/2002JA009416.

Huang, C., S. Sazykin, R. Spiro, J. Goldstein, G. Crowley, and J. M. Ruohoniemi (2006), Storm-time penetration electric fields and their effects, *Eos Trans. AGU*, *87*(13), 131.

Keskinen, M. J., S. Basu, and S. Basu (2004), Midlatitude sub-auroral ionospheric small scale structure during a magnetic storm, *Geophys. Res. Lett.*, *31*, L09811, doi:10.1029/2003GL019368.

Mishin, E. V., J. C. Foster, A. P. Potekhin, F. J. Rich, K. Schlegel, K. Yumoto, V. I. Taran, J. M. Ruohoniemi, and R. Friedel (2002), Global ULF disturbances during a stormtime substorm on 25 September 1998, *J. Geophys. Res.*, *107*(A12), 1486, doi:10.1029/2002JA009302.

Mishin, E. V., W. J. Burke, C. Y. Huang, and F. J. Rich (2003), Electromagnetic wave structures within subauroral polarization streams, *J. Geophys. Res.*, *108*(A8), 1309, doi:10.1029/2002JA009793.

Streltsov, A. V., and J. C. Foster (2004), Electrodynamics of the magnetosphere-ionosphere coupling in the nightside subauroral zone, *Phys. Plasmas*, *11*, 1260–1267, doi:10.1063/1.1647139.

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