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Letter to the Editor

Simultaneous observations of the ionospheric footprint of flux transfer events and dispersed ion signatures

G. Provan, S. E. Milan, M. Lester, T. K. Yeoman, and H. Khan

Department of Physics and Astronomy, University of Leicester, University Road, Leicester LE1 7RH, UK

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Abstract. We perform a case study of a favourable conjunction of overpasses of the DMSP F11 and F13 spacecraft with the field of view of the Hankasalmi HF coherent scatter. At the time, pulsed ionospheric flows (PIFs) were clearly observed at a high-latitude in the radar field of view. The PIFs were associated with medium spectral width values and were identified as the fossilized signatures of pulsed dayside reconnection. Simultaneously, DMSP spectrograms from the two spacecraft showed dispersed ion signatures, observed equatorwards of the PIF signatures. We identified dayside high-latitude magnetosphere boundaries; these boundaries agreed well with those defined using the algorithm on the JHU/APL auroral particle website (Haerendel et al., 1978; Newell and Meng, 1988, 1995; Newell et al., 1991a, 1991b, 1991c; Traver et al., 1991). We conclude that in this case study the dispersed ion signatures map to regions of very newly-opened flux. It is only when this flux has convected polewards that the signatures of the PIFs with medium spectral widths are observed by the HF radars. These particular PIF signatures map to regions of mantle precipitation, i.e. recently reconnected flux.

Key words. Ionosphere (ionosphere-magnetosphere interaction) – Magnetospheric physics (magnetopause, cusp and boundary layers; plasma convection)

1 Introduction

The magnetospheric cusp has been widely studied using precipitating ions and electrons, as measured by low-altitude spacecraft, such as DMSP (e.g. Newell and Meng, 1992). During intervals of southward IMF, dayside reconnection at the magnetopause leads to magnetosheath plasma entering the magnetosphere along open field lines, resulting in dispersed ion signatures being observed in the low altitude cusp. These features are characterised by a monotonic increase in ion energy as the latitude decreases This is a result of the highest energy ions arriving first in the ionosphere and being observed at the lowest latitude, an effect known as the velocity filter effect (Rosenbauer et al., 1975). If the dayside reconnection is pulsed (i.e. flux transfer events (FTEs) are occurring: Russell and Elphic, 1978, 1979), then Cowley et al. (1991) predicted "steps" in the ion dispersion, so-called "cusp ion steps", which have been observed by a number of authors (e.g. Newell and Meng, 1992; Lockwood et al., 1993)

In recent years, the magnetospheric cusp region has been extensively studied using HF radars. In particular, studies have concentrated on the ionospheric signatures of pulsed dayside reconnection at the magnetopause boundary. Poleward-moving regions of antisunward flow measured by HF radars, suggested to be associated with FTEs, have been studied at high-time resolution by Pinnock et al. (1995), and Rodger and Pinnock (1997). Similar pulsed ionospheric flow (PIFs) signatures have also been observed in the line-of-sight l-o-s velocity from the Hankasalmi SuperDARN radar (Provan et al., 1998). These PIFs were identified as the ionospheric signatures of FTEs, created at the footprint of newly reconnected field lines as they are pulled antisunward by the magnetosheath flow. Lockwood et al. (1993) identified a sequence of poleward moving events in the data from the European Incoherent Scatter (EISCAT) radars. These were identified as the ionospheric signatures of FTEs, and the equatorward edge of one of these events was found to be co-located with a cusp ion step, as identified by a DMSP spacecraft. The equatorward edges of several of the FTEs, as observed by Pinnock et al. (1995), were also found to be co-located with cusp ion signatures. Yeoman et al. (1997) observed strong HF radar backscatter with antisunward convective flows, co-located with DMSP particle signatures of the cusp and poleward-moving optical transients that are characteristic of pulsed reconnection during FTEs. Such auroral features have previously been identified with FTEs (Sandholt et al., 1986, 1990), and cusp ion steps were observed in the spectrograms from a DMSP spacecraft, simultaneously with these poleward-moving auroral transients. Neudegg et

Correspondence to: G. Provan: gp3@ion.le.ac.uk)

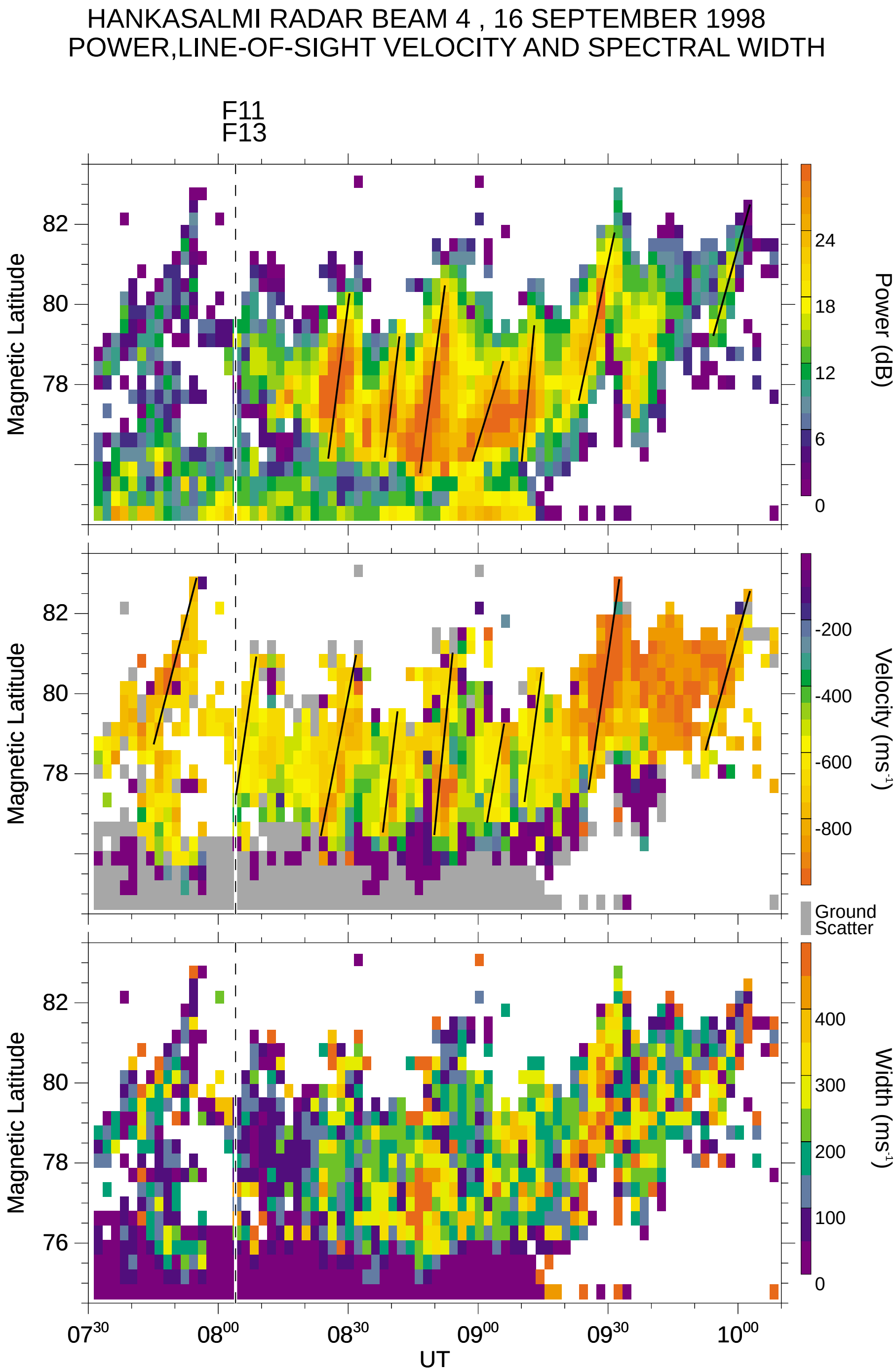

Fig. 1. The backscattered power, line-of-sight (l-o-s) velocity and spectral width observed by beam 4 of the Hankasalmi radar on the 16 September 1998, 07:30 to 10:10 UT. The power is colour-coded, with blue representing the smallest power and red representing the greatest power. The l-o-s velocity is directed away from the radar, with blue indicating the smallest velocity magnitude and red the largest. The spectral width is also colour-coded with blue indicating the smallest spectral widths and red the largest.

al. (2001) studied the UV aurora and ionospheric flows during FTEs.

Although there is ample evidence that PIFs are the ionospheric signatures of FTEs and occur on open field lines, there is still debate about how closely these ionospheric signatures map to the actual reconnection site at the magnetopause boundary. Here, we present simultaneous observations of PIFs by the Hankasalmi SuperDARN radar and dispersed ion signatures observed by the DMSP F11 and F13 spacecraft, which include a possible cusp ion step. These observations allow us to identify different dayside boundary regions, and to show that in this case, the PIF signatures are observed just poleward of the dispersed ion region and map to a region of mantle precipitation.

2 Data presentation

Figure 1 presents the backscattered power, the l-o-s velocity and the spectral width observed along beam 4 of the

Hankasalmi SuperDARN HF radar, from 07:30 to 10:10 UT on 16 September 1998. The power is colour-coded with blue representing the smallest power and red representing the greatest power. Since all of the flow observed by beam 4 during this interval is directed away from the radar, only negative l-o-s Doppler shifts are shown, with blue indicating the smallest velocity magnitude and red/yellow indicating the largest velocity magnitude, while grey indicates backscatter from the ground. The spectral width is also colour-coded with blue indicating the smallest spectral widths and red indicating the largest. During the study interval, the Hanksalmi radar is pointing roughly along a magnetic meridian, within ± 1.5 hours of local noon. The radar observes backscatter at relatively high magnetic latitudes, between 75° and 83°. PIF signatures are observed in the l-o-s velocity and are characterized by large (typically > 600 m/s) antisunward velocities, which also have a phase motion directed away from the radar. The PIFs are observed poleward of a region of ground backscatter. Some of the PIFs are marked by hand on the l-o-s velocity plot with black lines. Periodic enhancements are also observed in the backscatter power between 08:20 and 09:30 UT; some of these are also marked with black lines. The enhancements are observed simultaneously with the PIFs (although not all PIFs show a corresponding enhancement in backscatter power), and have an average recurrence rate of 10 min. Such enhancements are typical of the HF radar signature associated with FTE activity (Pinnock et al., 1995; Baker et al., 1995; McWilliams et al., 2001). The PIFs are associated with an average spectral width of ~ 200–250 m/s; this is somewhat smaller than the spectral widths associated with several previous HF observations of pulsed flows (e.g. Pinnock et al., 1995; Baker et al., 1995; Milan et al., 2000). Provan et al. (1998) presented the spectral width distribution observed within a region where PIFs were identified. The distribution had a modal value of ~ 350 m/s. However, McWilliams et al. (2001) reported observing PIFs in the HF radar data; the spectral widths associated with the PIFs were relatively high at the equatorward edge of the PIFs, but decreased with increasing latitude. Recently, Davies et al. (2001) observed pulsed periodic enhancements in backscatter power in the HF radar data. These signatures of pulsed reconnection were observed simultaneously with signatures of dayside reconnection in the data from the EISCAT VHF radar. The HF signatures were observed at high-latitudes and were associated with narrow spectral widths. The authors concluded that in this instance, the enhancements in the backscatter power trace fossil signatures of transient reconnection rather than revealing the footprint of an active reconnection itself. In the current interval, ground backscatter at the equatorward edge of the PIFs means that it is difficult to accurately identify the equatorward edge of the PIFs. This fact, together with the relatively high-latitude at which the PIFs are observed, leads us to conclude that the PIFs observed in this interval are fossils of the ionospheric structuring that takes place at the ionospheric footprint of the merging gap during pulsed dayside reconnection. Also marked in Fig. 1 is the time (08:04 UT) when both the F11 and F13 spacecraft were passing through part of the field of view of the Hankasalmi radar.

At 07:00 UT, the WIND spacecraft was located at $X_{\text{gsm}} = 182\,R_E$, $Y_{\text{gsm}} = 3.5\,R_E$ and $Z_{\text{gsm}} = -12.1\,R_E$; a time lag of 74 ± 5 min between when the IMF is observed by the satellite and when it impinges on the subsolar magnetopause has been calculated using the method outlined by Khan and Cowley (1999). The IMF conditions between 07:30 and 10:10 UT were studied. The IMF B_Z component was negative for the entire interval, except for a brief positive excursion at 08:00 UT, when it fluctuated between 0 and 6 nT. The IMF B_Y component was positive for the entire interval, with an average value of ~ 4 nT.

Figure 2 presents the ion and electron spectrograms for the F11 DMSP low-altitude spacecraft for the time interval of 07:55:00 to 08:04:30 UT, and for the F13 spacecraft, for the interval of 07:58:00 to 08:08:30 UT for 16 September 1998. Both spacecraft are flying through magnetic local noon, from a region of low-latitude to high-latitude and back to low-latitude again (the spacecraft tracks are indicated on Figs. 3a and 3b). Different dayside boundary regions have been identified based on their plasma characteristics. Both spacecraft initially observed regions of low flux of hard electron precipitation, identified as the central plasma sheet (cps). From 07:57:00 to 07:58:40 (08:00:30 to 08:01:30) UT, the F11 (F13) spacecraft observes a region of precipitating hot electrons, indicative of closed field lines. This region has been identified as the boundary plasma sheet (bps) region. From 07:58:40 to 08:00:10 (08:01:30 to 08:02:30) UT the F11 (F13) spacecraft observes a distinctive region where the ion energy is lower than in the bps region, but not de-energized as in the mantle region; this region is identified as the LLBL region. The F11 (F13) spacecraft observes de-energized ion precipitation from 08:00:10 to 08:01:20 (08:02:30 to 08:05:20) UT; these are indicative of open field lines and have been identified as mantle precipitation. At 08:01:30 (08:05:30) UT, the F11 (F13) spacecraft observes an increase in the flux of low energy ions, and some distinctive dispersed ion precipitation features, where the ion energy is seen to increase as the latitude decreases. These features have previously been identified as dispersed ion signatures, and are associated with magnetopause reconnection for southward directed IMF B_Z (Newell and Meng, 1991d). After passing through the dispersed ion region, the spacecraft flies again through the cps region. The boundaries between the different regions have been labeled from 1 to 7 for the F11 spacecraft, and from a to g for the F13 spacecraft. The dayside boundaries identified here agreed well with those defined using the algorithm of Newell and co-workers, as presented on the JHU/APL dayside boundary website.

Figure 3a presents the l-o-s velocity as observed by all of the beams of the Hankasalmi radar at 08:04 UT, in a magnetic latitude and local time coordinate system. Beam 4 is marked with a black line. Using a beam-swinging technique (Villain et al., 1987), which assumes that the flow along a given L-shell is constant with respect to the L-shell, velocity vectors have been deduced and are shown on the plot. They show

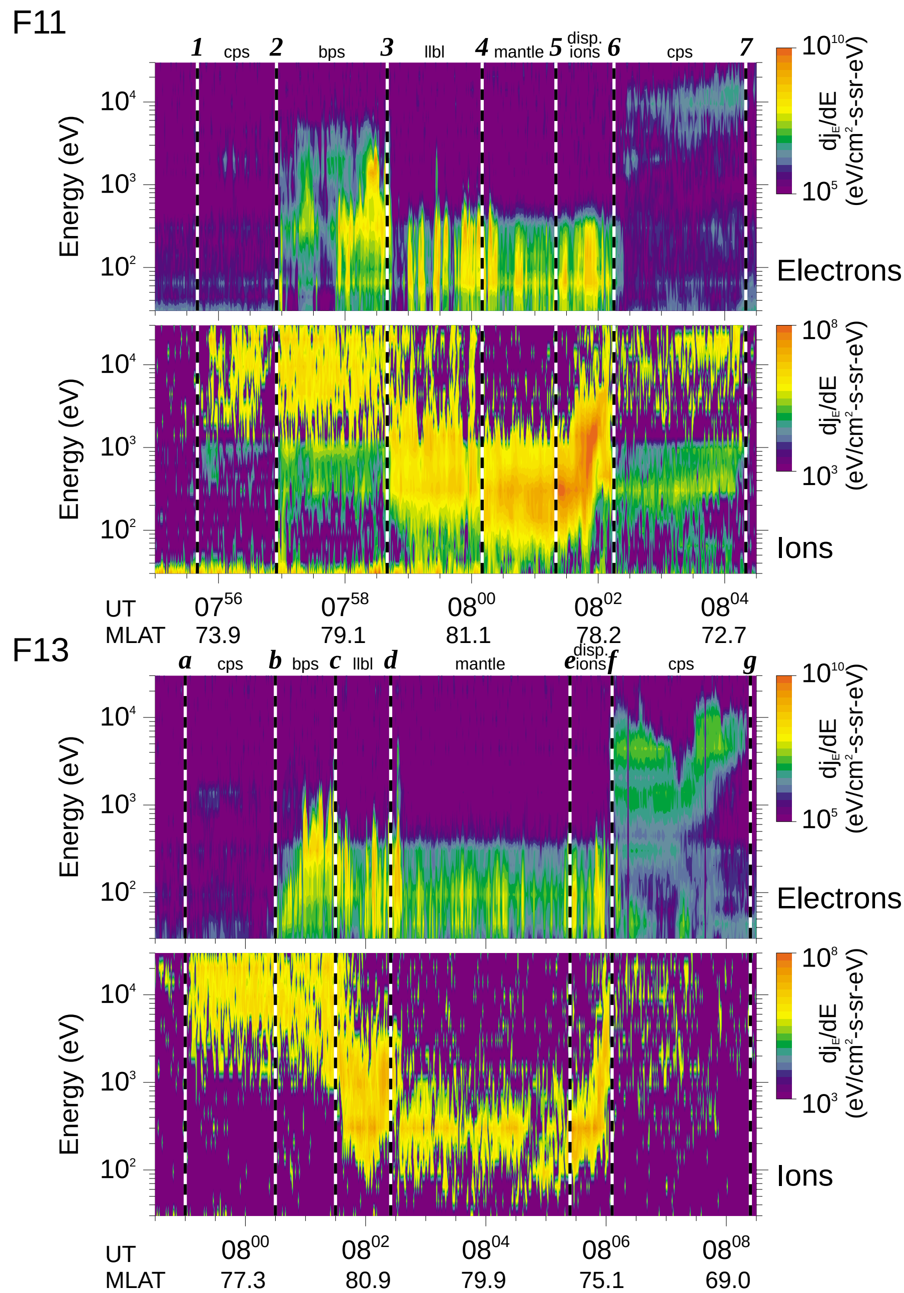

Fig. 2. The ion and electron spectrograms for the F11 DMSP low-altitude spacecraft for the time interval 07:55 to 08:04:30 UT, and for the F13 spacecraft for the interval 07:58 to 08:08:30 UT for 16 September 1998.

a general poleward and westward flow, consistent with the prevailing positive IMF B_Y conditions (Svalgaard/Mansurov effect, Svalgaard, 1973). Overlaid are the tracks of the F11 and F13 spacecraft for the time interval shown in Fig. 2. Indicated on the tracks are the dayside boundary regions as defined from the ion and electron spectrograms. The findings presented in Fig. 3a are shown as a schematic in Fig. 3b. The figure presents the deduced locations of the dayside boundary regions, with the tracks of the DMSP spacecraft overlaid. Also shown is the field of view of the Hanksalmi radars and the derived beam-swinging vectors.

Figures 3a and 3b clearly show that the radar backscatter within which PIF signatures are observed, corresponds to the region of mantle precipitation, located polewards of the region in which the dispersed ion signatures are observed. It is our belief that the dispersed ion signatures map to the region with the most recently reconnected field lines, and the observed PIFs are the fossilised signatures of the pulsed dayside reconnection. Previously, Pinnock et al. (1995) observed the equatorward edge of the ionospheric signature of FTEs, as observed by the Halley HF radar, co-located with the DMSP observations of the cusp ion steps to a ± 0.5 latitude. Similarly, Lockwood et al. (1993) showed that cusp ion steps lie on the equatorward edge of one of a sequence of potential signatures of flux transfer. In this case study, ground scatter observed in the radar field of view makes it impossible to ac-

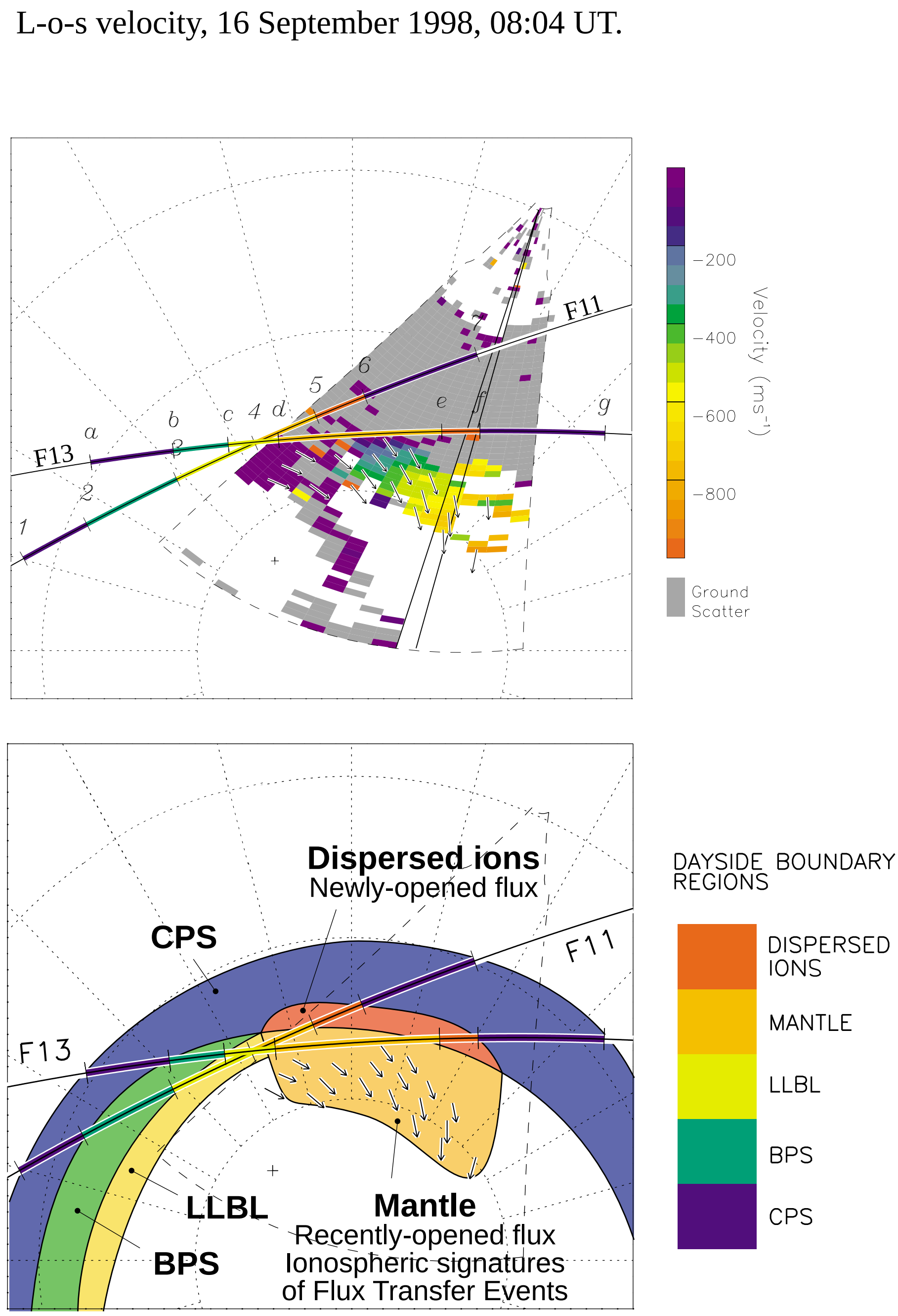

Fig. 3. **(a)** Polar plot of the l-o-s velocity as observed by all the beams of the Hankasalmi radar at 08:04 UT. The plot is in a geomagnetic/MLT coordinate system, and the radar is pointing towards local noon. Beam 4 is marked with a black line. Beam-swinging vectors are overlaid on the plot. Also overlaid are the tracks of the F11 and F13 spacecraft for the time interval shown in Fig. 2. Indicated on the tracks are the dayside boundary regions as defined from the ion and electron spectrograms. **(b)** A schematic illustration of the results presented in Fig. 3a. The diagram presents the tracks of the F11 and F13 spacecraft, and the different dayside boundary regions. The field of view of the Hanksalmi radars and the derived beam-swinging vectors are also shown on the plot.

curately identify the latitude of the equatorward edge of the PIFs.

3 Summary

Both DMSP spacecraft and HF radars have been shown to be powerful tools in the study of the dynamic cusp region. In this study, observations from these two instruments have been combined in order to study the cusp region during an interval of southward IMF B_Z. Previously, Pinnock et al. (1995) observed PIFs in HF radar data. These signatures have been shown to be the ionospheric signatures of FTEs (Neudegg et al., 1999). They originate immediately adjacent to the cusp region (identified by its persistent high HF radar spectral width, Baker et al., 1995), and propagate into the polar cap. The PIFs presented in this paper had medium spectral width values, and were observed at a relatively high-latitude. It was not possible to accurately determine their equatorward edge due to ground scatter that contaminated the data. The PIFs have been identified as the fossilised signatures of dayside reconnection, observed as the field lines are being pulled antisunward by the magnetosheath flow. Davies et al. (2001) have also reported observing similar fossilized signatures of pulsed dayside reconnection in the HF radar data. These observations were associated with signatures of pulsed reconnection in the data from the EISCAT VHF radar. Observations of dispersed ion signatures in the DMSP data, detected simultaneously with the PIFs, have allowed for their identification of the different dayside boundary regions, showing that the smaller spectral width region where the PIFs are observed is the region previously defined as the mantle, located poleward of the dispersed ion region. We believe that the dispersed ion signatures map to the regions of very newly-opened flux created by dayside reconnection. Only when these flux tubes have convected polewards were they detected as PIF signatures in the HF radar data.

Provan et al. (1999) performed a statistical study on the extent and location of PIFs, as observed in the HF radar data. Their observations on the occurrence of these newly-opened field line signatures suggested that the dayside merging gap is far wider and extends to higher latitudes than the cusp proper, as proposed by the Newell and Meng (1992). The results presented in this paper reconcile these two studies, showing that while PIF signatures with high spectral widths map to regions with the most recently reconnected flux, PIF signatures, with medium spectral widths observed at higher latitudes, are the fossilized signatures of such pulsed reconnection.

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