On the collocation between dayside auroral activity and coherent HF radar backscatter

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Received: 20 December 1999 / Revised: 29 September 2000 / Accepted: 6 October 2000

Abstract. The 2D morphology of coherent HF radar and optical cusp aurora has been studied for conditions of predominantly southward IMF conditions, which favours low-latitude boundary layer reconnection. Despite the variability in shape of radar cusp Doppler spectra, the spectral width criterion of ≥220 m s⁻¹ proves to be a robust cusp discriminator. For extended periods of well-developed radar backscatter echoes, the equatorward boundary of the ≥220 m s⁻¹ spectral width enhancement lines up remarkably well with the equatorward boundary of the optical cusp aurora. The spectral width boundary is however poorly determined during development and fading of radar cusp backscatter. Closer inspection of radar Doppler profile characteristics suggests that a combination of spectral width and shape may advance boundary layer identification by HF radar. For the two December days studied the onset of radar cusp backscatter occurred within pre-existing 630.0 nm cusp auroral activity and appear to be initiated by sunrise, i.e. favourable radio wave propagation conditions had to develop. Better methods are put forward for analysing optical data, and for physical interpretation of HF radar data, and for combining these data, as applied to detection, tracking, and better understanding of dayside aurora. The broader motivation of this work is to develop wider use by the scientific community, of results of these techniques, to accelerate understanding of dynamic high-latitude boundary-processes. The contributions in this work are: (1) improved techniques of analysis of observational data, yielding meaningfully enhanced accuracy for deduced cusp locations; (2) a correspondingly more pronounced validation of correlation of boundary locations derived from the observational data set; and (3) a firmer physical rationale as to why the good correlation observed should theoretically be expected.

Key words: Ionosphere (ionospheric irregularities; polar ionosphere)

1 Introduction

All-sky cameras and SuperDARN HF radars with large fields-of-view, constitute powerful tools to study temporal and spatial behaviour of large-scale auroral and polar cap dynamics, and both techniques have proven potential for identification of magnetospheric boundary layers. Baker et al. (1990, 1995) combined PACE HF radar observations with DMSP particle data, and identified broad multi-component Doppler spectra to be a feature characteristic of coherent HF radar cusp backscatter. In contrast the low-latitude boundary layer (LLBL) was found to be associated with narrow single component spectra. The occurrence distribution of spectral widths peaked at 220 m s⁻¹ in the cusp and 60 m s⁻¹ in the LLBL. André et al. (1999) have published an important contribution to the understanding of the process whereby HF radar echoes from irregularities become Doppler spread, by Pc1 and Pc2 events.

Several attempts have been made to compare HF radar and optical cusp observations. Rodger et al. (1995) employed wide spectral widths as a radar cusp identifier. For the situation when IMF BZ was documented as negative, they found the equatorward boundary of the HF cusp signature to be located 0.5° on average equatorward of the optical cusp. For the other case of unknown IMF conditions, the radar cusp boundary was either embedded within or located near the poleward edge of the auroral luminosity. Yeoman et al. (1997) demonstrated a near collocation of strong HF backscatter power, poleward moving auroral forms, and energy dispersed ions for a DMSP snapshot through the winter cusp above Svalbard. Milan et al. (1999) demonstrated a good correlation between CUTLASS HF backscatter and dayside 630.0 nm aurora along the meridian swept by the scanning
photometer at Ny-Ålesund, Svalbard. They found a rather good collocation of the equatorward radar (defined by power) and optical cusp auroral boundaries, and that these boundaries showed the same motion.

The motivation for this work is to follow up on Rodger et al. (1995) and Baker et al. (1995) to validate the use of enhanced radar Doppler spectral widths as a cusp identifier around magnetic noon for one specific category of cusp aurora. The work is limited to type 1 cusp auroral activity. According to the classification by Sandholt et al. (1998), type 1 cusp aurora occur under predominantly southward IMF conditions, located typically south of ~74° MLAT, includes quasi-periodic sequences of poleward moving auroral forms (PMAFs), and is dominated by the 630.0 nm emission which indicates soft magnetosheath electron precipitation. The pattern of east–west movements of type 1 cusp activity is IMF $B_Y$ controlled (e.g. Sandholt et al., 1993; Moen et al., 1999). Moen et al. (1996) attributed the equatorward boundary of the type 1 aurora to an open LLBL, located poleward of the electron-trapping boundary. Sandholt et al. (1993) attributed the fading phase of a poleward moving type 1 auroral form to approaching the plasma mantle. LLBL, cusp and mantle precipitation regimes can be separated from each other based on differential ion energy fluxes (Newell et al., 1988), but are indistinguishable in an electron stimulated auroral display (e.g. Moen et al., 1998). Type 1 cusp aurora is interpreted as LLBL stimulated reconnection and is taken to be the auroral footprint of newly-opened magnetic flux. The transition from narrow single component to wide complex Doppler spectra of coherent HF backscatter has been proposed as a delineator of the open/closed field line boundary (Baker et al., 1995).

Hence, it is reasonable to expect a good correlation between the equatorward boundaries of radar and optical auroras for type 1 cusp activity.

Two December days near the last sunspot minimum, for which simultaneous all-sky, meridian scanning photometer, and CUTLASS Finland radar observations are available above Svalbard, form the experimental basis for this study. The 2D perspective provided by radar and optical cusp morphology provides new detailed insight regarding the relationship between the radar and optical cusp aurora. Iterative examination of the data helps extract this new insight. Our first approach is to use the criterion that the spectral width is greater than or equal to 220 m s$^{-1}$ in order to identify those radar gates which lie within the cusp (motivated by Baker et al., 1995; and Rodger et al., 1995). During intervals of strong backscatter echoes, the equatorward boundary of the radar cusp boundary indeed aligns very nicely with the equatorward boundary of the type 1 cusp. However, the spectral width boundary is poorly determined at the eastern and western edges of the radar cusp. Closer inspection reveals that boundary transitions usually stand out by virtue of changing shape and/or broadening width of the Doppler spectral profiles, while transition features are spectrally more diverse than the narrow single-peak to broad multi-peak transition reported by Baker et al. (1995).

2D observations of the developing and fading phases of the radar cusp activity then lead one to further examine the underlying working principles of radar cusp observations. Coherent HF radars obtain backscatter echoes from field-aligned plasma irregularities of decametre scale length (half the radar operating wavelength).

The generation mechanism of backscatter targets has not yet been agreed upon, but the literature has identified candidate processes including: gradient drift instability, shear instability, “stirring” or flux tube interchange, and current convective instability which can be viewed as a subset of gradient drift instabilities (e.g. Tsunoda, 1988; Basu et al., 1994). The latter mode includes field-aligned currents as an extra source of free energy in the context of interchange instabilities (Chaturvedi and Ossakow, 1981). The models have not yet added allowance for spatially structured mobility and conductivity due to structured particle precipitation. Under conditions for which plasma flow has a component in the direction of a density gradient, gradient drift instability is regarded as the dominant mode for driving the plasma unstable in the F-region auroral ionosphere (e.g. Ossakow and Chaturvedi, 1979; Basu et al., 1994).

The typical geometry for gradient drift instabilities in the Northern Hemisphere cusp, is a density gradient towards north, a convection electric field pointing eastward and a background magnetic field pointing down. It is notable that the $\mathbf{E} \times \mathbf{B}$ gradient drift geometry will become stable upon reversing the electric field or the density gradient. Our data set contains an example consistent with the latter.

Section 2 provides a brief description of the different instrumental techniques used here. The data, consisting of type 1 cusp observations during two days, are presented in Sect. 3. The first day is December 17, 1995 and the second is December 24, 1995. In Sect. 4 the auroral characteristics are first discussed with respect to their magnetospheric origin and located relative to the polar cap boundary. Then the correlation between the equatorward radar and optical cusp boundaries are studied, and transition features in the Doppler power spectra across cusp activity boundary are examined. Finally, various aspects of radar cusp and formation of backscatter are illuminated. A brief summary and concluding remarks are presented in Sect. 5.

2 Instrumentation

2.1 CUTLASS Finland HF radar

The CUTLASS Finland radar located at Hankasalmi (62.3°N, 26.6°E, 58.62°CGMLAT) has an array of 16 antennas, with both transmitting and receiving capabilities. The radar can operate in the HF band between 8 MHz and 20 MHz. The antennas in each array are phased relative to one other so as to form an antenna pattern in which maximum gain (beam position) has one of 16 azimuthal pointing directions separated by approximately 3.2°, distributed symmetrically about the radar boresite of −12° (i.e. west of geographic north).