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Spatial Variations of Ionospheric Conductivity and Radar Auroral Amplitude in the Eastward Electrojet Region During Pre-Substorm Conditions

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Abstract. The dependence of auroral backscatter amplitude on different ionospheric parameters (conductivity, current density, electric field) is studied by means of data recorded by STARE (Scandinavian Twin Auroral Radar Experiment), the two-dimensional Scandinavian Magnetometer Array (SMA), and auroral all-sky cameras. The observations were made on 16 March 1978 during pre-substorm conditions in the region of the eastward polar electrojet. The paper shows that in this event the auroral backscatter amplitudes in the 140 MHz frequency band were controlled mainly by spatial variations in the electron density or conductivity inside the back-scatter volume. To a certain extent also a linear relationship between backscatter amplitude and ionospheric current density was found but it is regarded as a special case of a more general relationship between electron density and backscatter amplitude. A stable discontinuity in the Hall conductivity over the most equatorward auroral arc was deduced from the data: On the equatorward side the conductivity was 3–5 times higher than on the nearby poleward side. Our conclusions are discussed in the light of some previously published results on the same subject.

Key words: Radar aurora – Eastward electrojet – Substorm growth phase – Hall conductivity – Backscatter amplitude

Introduction

During recent years the possibilities for ionospheric diagnostics by means of auroral radars have been improved considerably. A linear relationship between radar auroral amplitude and horizontal ionospheric current density was first found by Greenwald et al. (1973) and later confirmed by Greenwald et al. (1975), Siren et al. (1977), Baumjohann et al. (1978) and Mareschal et al. (1979). By means of Doppler techniques, radars have been used to record radial and two-dimensional horizontal ionospheric electric fields (see Greenwald et al., 1978; Cahill et al., 1978; Greenwald, 1979 and references therein). By investigating the different types of auroral backscatter much has been inferred on currents associated with auroras, different phases of magnetic storms or substorm activations, and the spatial location of radar auroral activity (Greenwald et al., 1973, 1975; Unwin and Keys, 1975; Tsunoda et al., 1974, 1976a, b; Tsunoda and Presnell, 1976; Uspensky, 1977; Kustov et al., 1979).

Powerful new tools like STARE (Scandinavian Twin Auroral Radar Experiment, Greenwald et al., 1978) have facilitated simultaneous temporal and spatial studies of electric fields. There are still several open questions in this field but at present the key problem seems to be to resolve the exact nature of factors affecting the amplitude of radar aurora. This is not a simple problem: the radar auroral amplitude depends on the aspect angle, frequency band (Chestnut 1968; Pyatsi, 1974) and on the azimuth angle between the line-of-sight and the mean irregularity drift velocity (André, 1980).

The data presented in this paper were obtained during a substorm growth phase in the evening sector of 16 March 1978. We have found that there exists a distinct "jump" in the Hall conductivity across the most equatorward discrete auroral arc. In some cases the conductivity "jump" is separated from the auroral arc by a gap in diffuse luminosity on the equatorward side of the arc. The picture that we obtain by means of auroral radars seems to be in agreement with the morphology of diffuse auroral luminosity (Lui and Anger, 1973; Lui et al., 1973; Lui et al., 1977; Val'chuk et al., 1979).

According to our findings the 140 MHz backscatter amplitude may not always be linearly related to the ionospheric current density. Instead, in our case a better linear relation appears to exist between the backscatter amplitude and the mean electron density in the backscatter volume. This is especially valid for electric fields exceeding 1.5–2 times the threshold value for irregularity excitation.

Experimental Description

This paper is based on ground-based data obtained during the "Auroral Breakup Campaign (ABC)" in 1978 at a number of Scandinavian and Soviet (Kola peninsula) stations (Fig. 1). Auroras were recorded by all-sky cameras at Kilpisjärvi (KIL), Kevo (KEV), Muonio (MUO), and Ivalo (IVA) in Finland and at Loparskaya (LOP) in the USSR. The dashed line in Fig. 1 marks the border of the field of view at 75° zenith angle at 100 km height for all cameras.

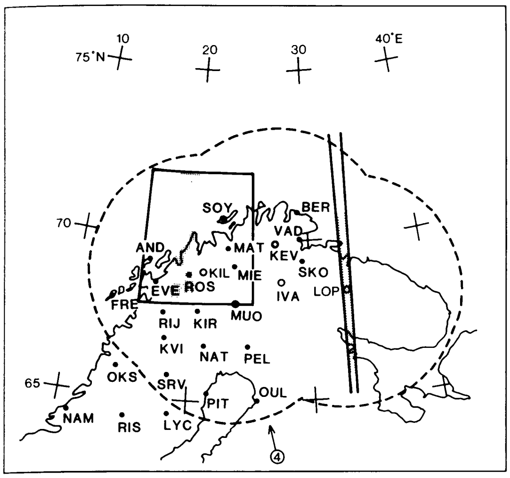

Fig. 1. Map of Northern Scandinavia and the Kola peninsula showing the geographical coverage by the STARE and Essoyla radars and the location of other instruments. The dashed line gives the field of view of the four all-sky cameras at 100 km for 15° elevation angle, KIL – Kilpisjärvi, MUO – Muonio, KEV – Kevo, FMI, Finland and LOP – Loparskaya, PGI, USSR. The near rectangular area on the left hand side is the STARE field of view and on the right hand side is the Essoyla 93 MHz antenna beam. The black points give the sites of the SMA magnetometers used in this study

The nearly rectangular region on the left hand side in Fig. 1 is the area covered by STARE measurements of irregularity drift velocities (Greenwald et al., 1978). The measurements are made in the 140 MHz band. The grey vertical strip inside the STARE region is the longitudinal interval of integration for the latitude-time pictures used in the present study (cf. Fig. 4). The intensity data are not corrected for range, antenna radiation pattern and aspect angle. If we do not take into account the aspect angles (for 110 km height in the vertical strip in Fig. 1 they are in the interval 89–91°), the correction factor, D^{-3} (D is the slant range), increases with increasing latitude. Inside the vertical strip it is 1.5 dB per 100 km, approximately.

The narrow beam on the right hand side is the antenna lobe of the 93 MHz Essoyla radar, the grey area denoting the highest sensitivity range interval of the radar. It uses a line cable antenna (Balsley and Ecklund, 1972) with the beam directed towards Loparskaya. The azimuthal width of the antenna lobe is around 1.5°. The temporal and spatial resolutions for the radars are 20 s and about 20 × 20 km for the STARE system and 2–5 s and 3 × 25 km for the Essoyla radar.

The irregularity drift velocity vectors were obtained from the Doppler shifts of the radar auroral backscatter recorded simultaneously by the STARE radars in Norway and Finland. The directions and magnitudes of the vectors were calculated by assuming that there exists the so-called "cosine-dependence" (Greenwald, 1979) of the Doppler shift magnitude on the angle between the mean irregularity drift direction and the radar wave vector k. Sudan et al. (1973), for example, have presented some theoretical evidence that the irregularity drift velocity is equal to the electron drift velocity, v_e, and hence the drift vectors are oppositely directed to the Hall component of the ionospheric current. Simultaneous STARE and in situ rocket measurements of the ionospheric electric field (Cahill et al., 1978) tend to confirm this relationship. This implies that the ionospheric electric field, E, can be determined from the radar measurements, because in the E-layer $E = -v_e \times B$ holds, where B is the geomagnetic field vector.

The black dots in Fig. 1 indicate the sites of the *S*candinavian *M*agnetometer *A*rray (SMA) stations used in this study. Most of the stations are located along roughly parallel north-south profiles. The spacing between magnetometers along these profiles and between the profiles themselves varies from 100 to 150 km. All magnetometers observe the magnetic field with a temporal resolution of 10 s. A detailed description of the SMA stations used in the present study has been given by Küppers et al. (1979).

Observations

On the evening of 16 March 1978 at about 1830 UT a substorm onset was observed at the Scandinavian and Kola peninsula stations. Details of the substorm have been described earlier by Kustov et al. (1979) and Starkov et al. (1979), who observed that the substorm began at 1827 UT to the east of the area under observation. The sharp substorm initiation was preceeded by a continuous joint equatorward motion of discrete auroral arcs and radar aurora. During the entire period intense radar aurora was located on the equatorward side of the most equatorward arc of the discrete auroral oval. The whole equatorward shift was about 2.5° in latitude. The equatorward motion began at 1756 UT and continued for about 30 min with a mean speed of about 150 ms^{-1}. The period prior to the substorm onset was relatively quiet, resembling an interval between two moderate substorms.

The SMA observations (displayed in Fig. 2 in the equivalent current arrow representation) show that between about 1800 and 1830 UT an eastward electrojet was flowing over Scandinavia. The latitudinal center of the current was located over Kiruna (67.8° N) at the beginning of this interval and about 150 km south of Kiruna at 1824 UT. Hence, the equatorward speed of the current density maximum (about 90 ms^{-1}) was less than that of the most equatorward discrete arc. Moreover, throughout the whole interval the current density was higher to the south of the arc which was located north of Kiruna.

The coordinate system indicated in the upper left corners of the diagrams in Fig. 2 has been introduced by Küppers et al. (1979) and has been named the Kiruna system. It is a Cartesian system obtained by a stereographic projection of the globe onto a tangential plane centred at Kiruna, Sweden (67.8° N, 20.4° E). The y_{KI} axis of the system, whose origin is situated at Kiruna, has been chosen as the tangent to the projection of the revised corrected geomagnetic latitude circle (Gustafsson, 1970) through Kiruna (64.8° N). The x_{KI} axis points approximately 12° west from geographic north at Kiruna.

During the period of equatorward expansion the most equatorward arc was located for an unusually long period within the STARE field-of-view. The equatorward movement of the auroral arc was observed simultaneously in both the Finnish and the Soviet sectors. The observations of aurora and radar aurora are shown in Fig. 3 in a geographical coordinate system. The solid and dashed curves indicate the location of the lower border of the auroral arc. The intensity of radar aurora on the STARE system is given by a grey scale. The radar auroras recorded by

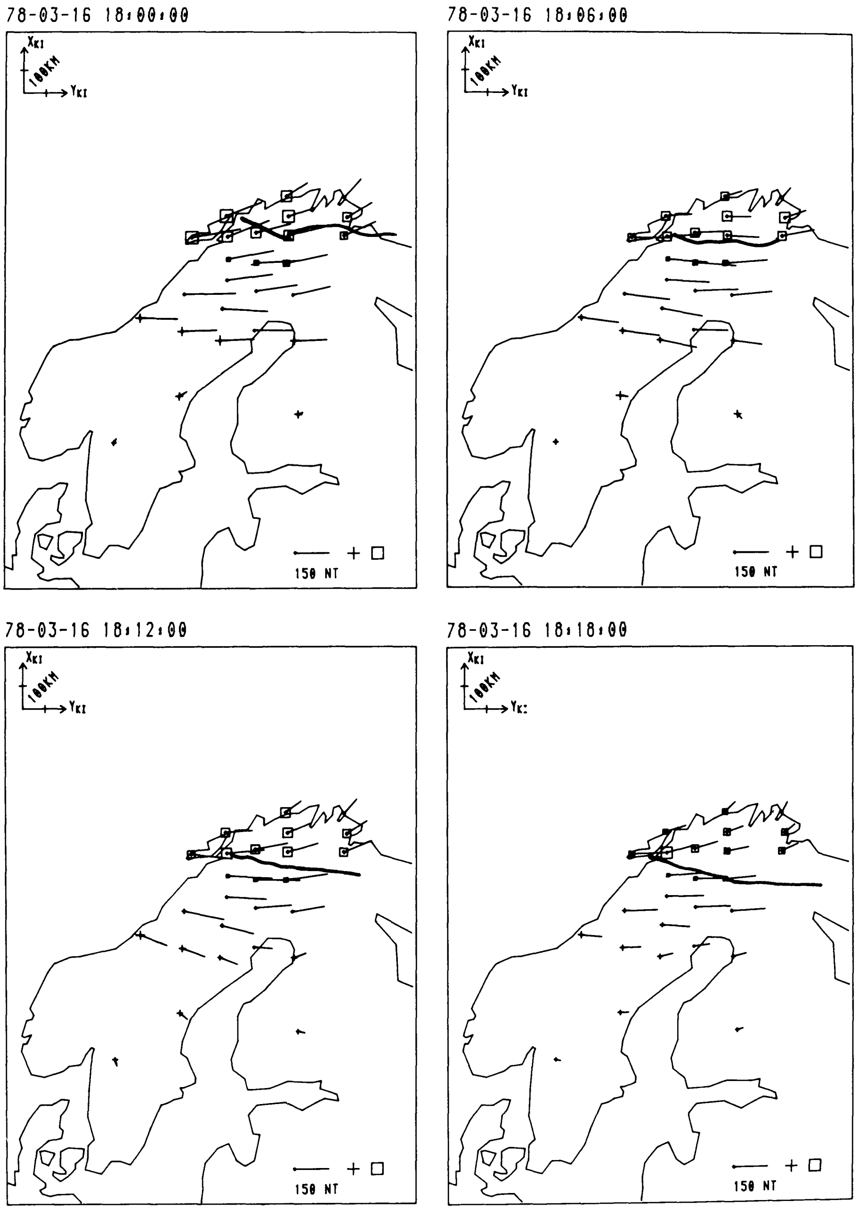

Fig. 2. Spatial distribution of equivalent current vectors on the ground for each 6 min between 1800 and 1818 UT. The axes in the upper left corners define the Kiruna system (see text). Squares and crosses denote negative and positive **Z** components, respectively. The heavy line indicates the location of the lower border of the most equatorward auroral arc

the STARE and Essoyla radars move equatorward simultaneously. The figure shows that the Essoyla radar aurora is bordered by optical aurora on the poleward side while the STARE system (Finnish radar) detected radar aurora on both sides of the arc. From the STARE frame an amplitude difference of 10–15 dB can be seen between the equatorward and poleward radar aurora, with more intense radar aurora equatorward of the arc. Since the Essoyla radar is not as sensitive as the STARE radars, the observed amplitude difference in the STARE data may be sufficient to explain the absence of radar aurora poleward of the arc in the Soviet data.

Figure 4 shows latitude-time diagrams of the STARE electric field data and radar auroral amplitudes recorded in Norway (N) and in Finland (F). The solid curves show the arc locations. The time interval of main interest to us is bounded by two arrows at 1800 and 1824 UT. In this period one observes an equatorward motion prior to substorm activation. As in the case of Fig. 3 above, the arc shown and discussed is the most equatorward arc that was observed. There are other arcs poleward of this arc that move approximately in accordance with it. Equatorward of the most equatorward arc, the northward electric field is sufficiently strong (25–35 mV/m) to exceed the threshold for excitation of the plasma waves which produce the radar back-scatter. Poleward thereof, there are somewhat higher electric field values. The east-west component of the electric field (not shown) is considerably less than the northward one, and remains at approximately the same strength on both the equatorward and poleward sides of the arc. The latitudinal electric field distribution shown in the top panel of Fig. 4 is in remarkable contrast to the radar auroral amplitude distribution shown both in the lower panels of Fig. 4 and in Fig. 3. Indeed, the radar aurora is more intense equatorward of the arc than on the poleward side, while the electric field magnitude behaves in the opposite way (higher values on the poleward side than on the equatorward side; the direction remains approximately unchanged between both sides of the arc).

It is known that the ionospheric irregularities are excited

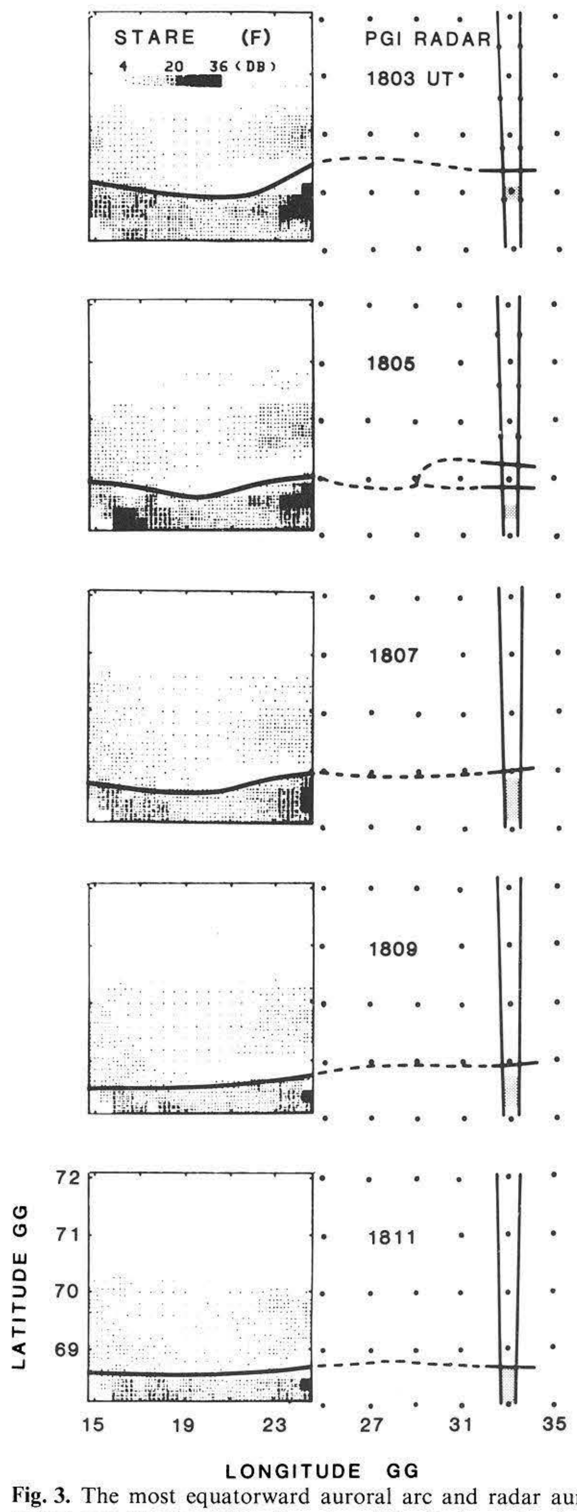

Fig. 3. The most equatorward auroral arc and radar aurora observed over Northern Scandinavia and the Kola peninsula simultaneously. The radar auroral amplitude is shown in grey scale, the heavy line and heavy dashed line denote the arc location

if the electric field exceeds a threshold value which depends on the radar frequency and is typically between 15 and 30 mV/m (Tsunoda and Presnell, 1976; Siren et al., 1977; Moorcroft, 1979; Cahill et al., 1978). In the top panel of Fig. 4 the radar aurora begins to disappear where the electric field is between 15 and 20 mV/m, in agreement with earlier STARE measurements.

Using the linear relationship between radar auroral amplitude and current density observed in several experiments (Greenwald et al., 1973; Greenwald et al., 1975; Siren et al., 1977; Baumjohann et al., 1978; Mareschal et al., 1979), we may conclude that the 10–15 dB amplitude variation across the arc implies an eastward current density on the poleward side of the arc that is 3–5 times less than that on the equatorward side. This is in quantitative agreement with Fig. 2. Since the electric field is greater in the poleward region, the current density change would be due to a conductivity difference of more than a factor of 3–5 on the two sides of the arc. This conclusion differs from that drawn by Greenwald et al. (1975) and Greenwald (1979) who considered the linear relationship of current density and radar aurora amplitude to be a consequence of electric field variations.

Quantitative Comparison between Height-Integrated Hall Current Density, Northward Electric Field, Height-Integrated Hall Conductivity and Backscatter Amplitude

The rather constant eastward direction of the equivalent current arrows in Fig. 2 and the rather constant direction of the electric field observed by STARE suggests that it is possible to apply methods of two-dimensional potential theory for computing the external part of the northward magnetic field distribution along the x_{KI} axis at ionospheric heights. This has been done earlier by Mersmann et al. (1979) and the method was later improved by Baumjohann et al. (1979) and Sulzbacher et al. (1980). Two-dimensionality in this respect means that all quantities are independent of one coordinate which in our case turns out to be y_{KI}.

In Fig. 5 we display latitude profiles along the x_{KI} axis of the A (parallel x_{KI}) and Z (vertical) components of the magnetic disturbances observed along SMA profile 4 at 1800, 1806, 1812, and 1818 UT, i.e. each 6 min throughout the interval of interest. The profiles indeed show that the maximum A component (about 200 nT) is located well south of the most equatorward discrete auroral arc.

Field separation and subsequent upward continuation is done by first Fourier analysing the A and Z latitude profiles displayed in Fig. 5, then combining A and jZ Fourier transforms (j imaginary unit), and afterwards multiplying the resultant Fourier coefficients with e^{kh} (h is the assumed height of the base of the ionospheric current layer). A subsequent Fourier synthesis yields the external magnetic north-south component V just below the ionospheric current layer. We have chosen $h = 120$ km according to the average height distribution of eastward electrojets (Kamide and Brekke, 1977).

In Fig. 6 we display the resultant V profiles at 120 km height. The above-mentioned relation between the northward magnetic disturbance maximum and the discrete auroral arc becomes even clearer. Since the electric field is northward directed, the northward external V components must be caused by an ionospheric eastward flowing Hall current. Since the vertical thickness of the Hall current that flows along the y_{KI} axis is small as compared to its latitudinal extent, the eastward electrojet may be described by a surface current density distribution $J_y(x_{KI})$. This quantity is related to the height-continued external magnetic component $V(x_{KI})$ by multiplying it with $2/\mu_0$.

The eastward height-integrated Hall current density J_y

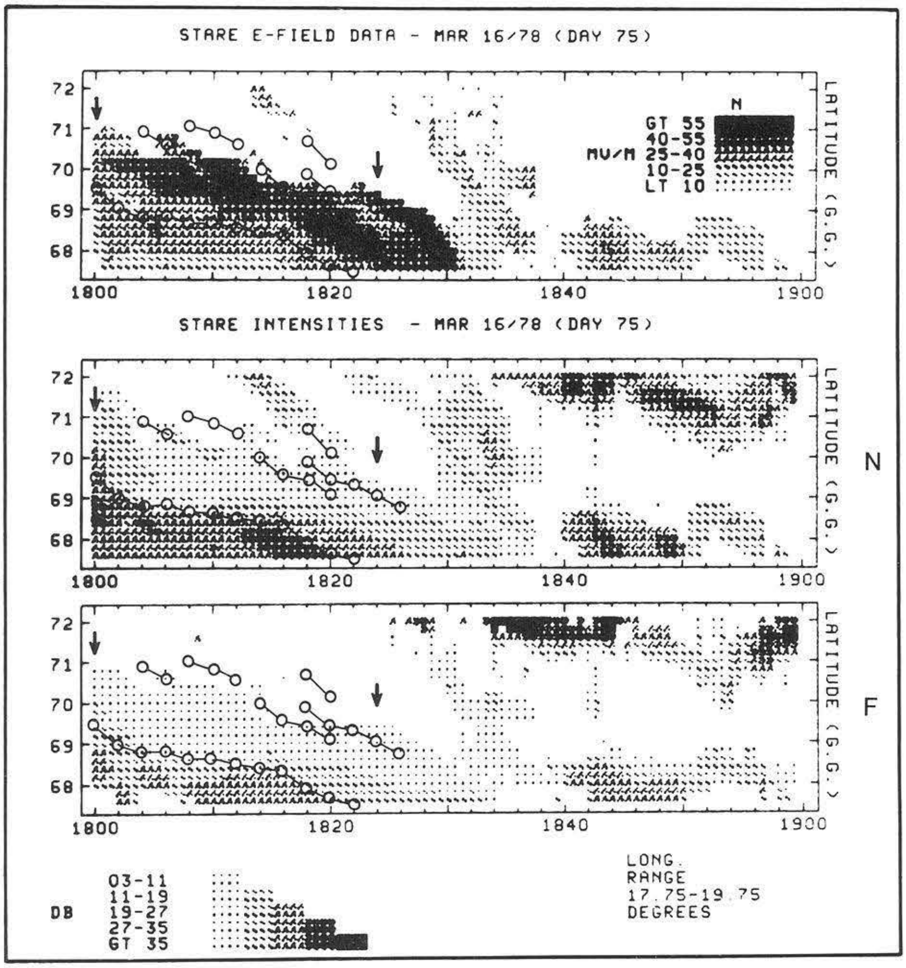

Fig. 4. The STARE latitude-time plots of the northward electric field (top panel) and the backscatter intensities (amplitudes) registered by Norwegian (N) and Finnish (F) radars (middle and bottom panels). The plots are averages of the STARE data over the longitude range 17.75–19.75° shown in Figure 1 by the vertical strip in the STARE plot. The heavy lines with open circles give the locations of discrete auroral arcs. The arrows define the interval of main interest in our study

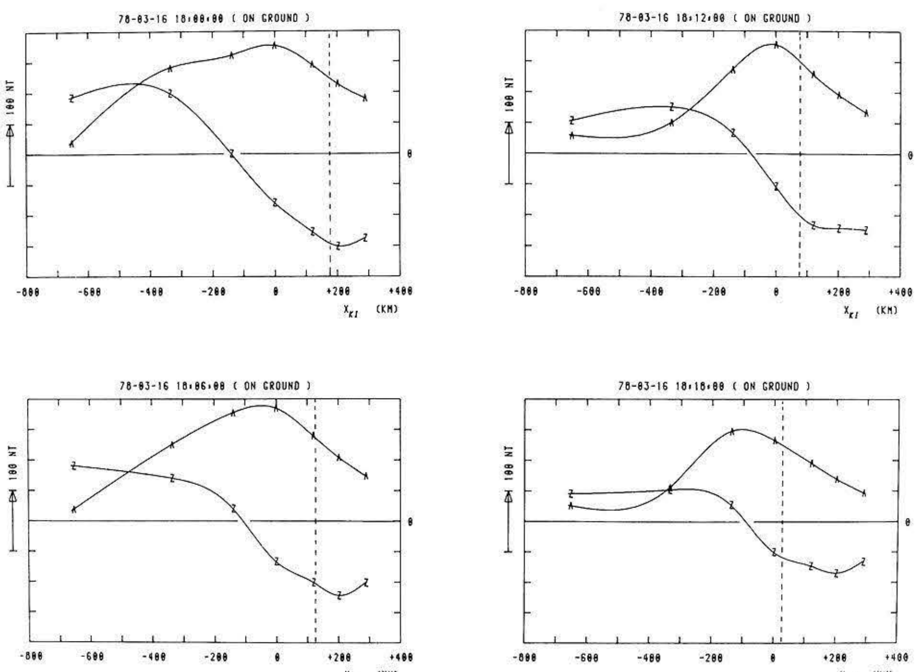

Fig. 5. Latitudinal profiles of the magnetic horizontal components parallel to the x_{KI} axis (A) and of the vertical components (Z) observed at 1800, 1806, 1812 and 1818 UT on profile 4 of the SMA. The letters denote the A and Z profiles and simultaneously give the observed values. The dashed vertical lines give the positions of the most equatorward discrete auroral arc

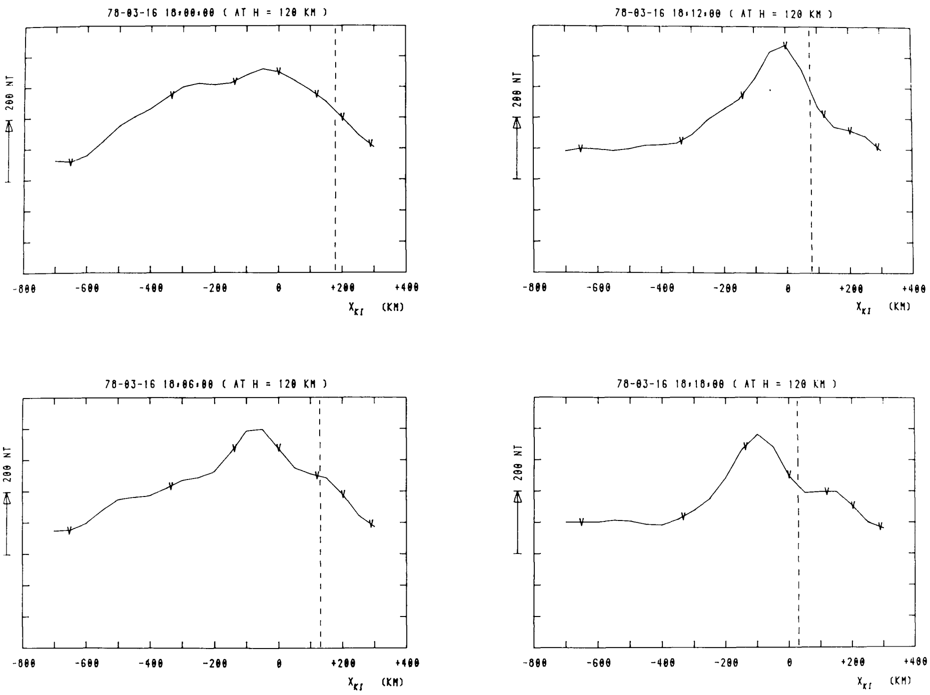

Fig. 6. Latitudinal profiles of the external magnetic horizontal components parallel to the x_{KI} axis (V) at 120 km height; otherwise as Fig. 5

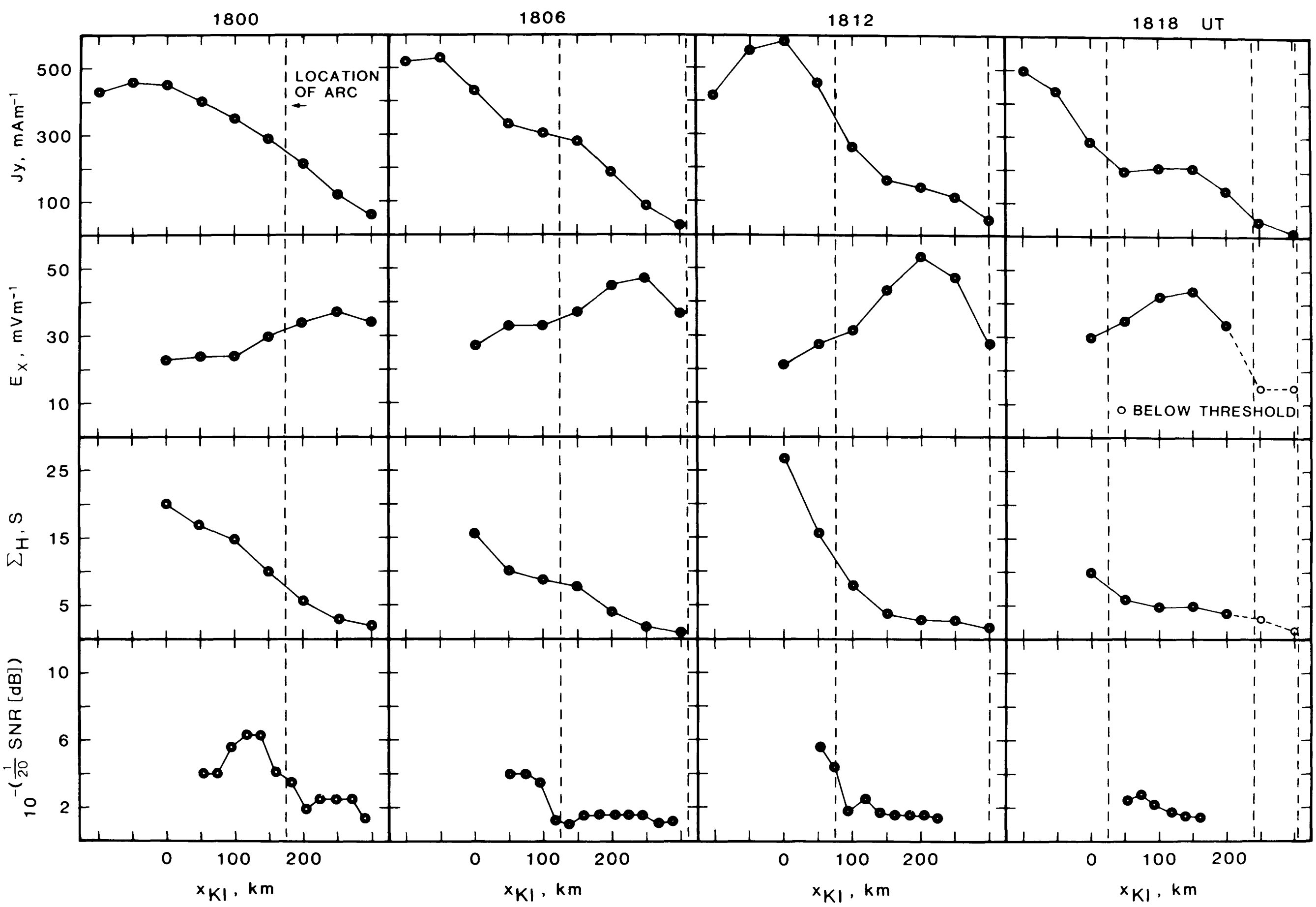

Fig. 7. Latitudinal profiles of the eastward height-integrated Hall current density perpendicular to the x_{KI} axis (J_y, upper panel), of the (northward) electric field component parallel to the x_{KI} axis (E_x, upper middle panel), of the height-integrated Hall conductivity (Σ_H, lower middle panel), and of the backscatter amplitude ($\sqrt{\sigma_v}$, lower panel) for 1800, 1806, 1812, and 1818 UT. The dashed vertical lines give the positions of the discrete auroral arcs

(parallel y_{KI}) around the discrete arc is displayed in Fig. 7 together with the northward electric field component E_x (parallel x_{KI}), the height-integrated Hall conductivity ($\Sigma_H = J_y/E_x$) and the backscatter amplitude $\sqrt{\sigma_v}$, which is here defined as $10^{-\mathrm{SNR}}$[dB]/20. The mean backscatter amplitude values were taken along a strip which runs approximately parallel with the x_{KI}-axis and where these values were smallest, i.e. where the azimuth angles θ between the line-of-sight of the radar and the mean irregularity drift velocity vectors are around 90°. The longitudinal range of the strip was two degrees.

Figure 7 exhibits clearly an anticorrelation between electric field and Hall conductivity, and electric field and radar auroral amplitude, respectively. Such a feature for the eastward electrojet has recently been mentioned by Baumjohann et al. (1980). The Hall conductivity and radar amplitude profiles seem to be well correlated. As here the Hall conductivity (compared to the E-field) is a dominating factor, a similar type of correlation can, in principle, be found between radar amplitude and current density.

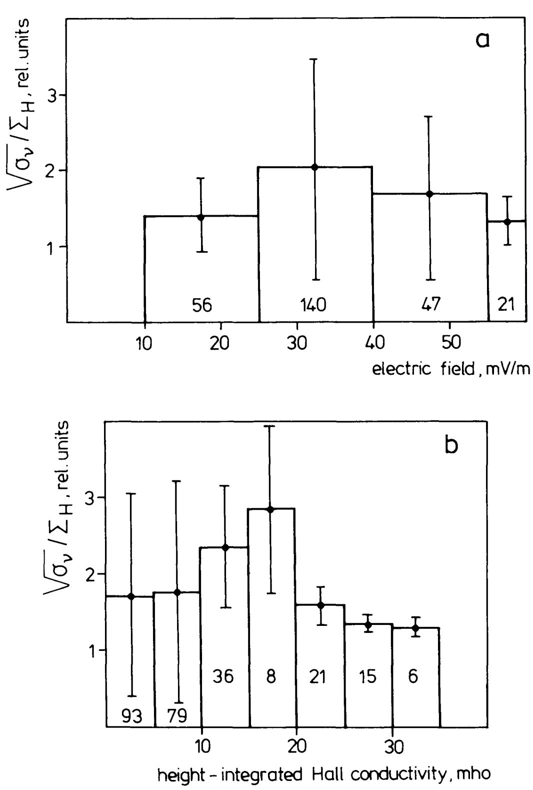

Fig. 8a and b. STARE backscatter amplitudes (from the Norway radar) normalized by the height-integrated Hall conductivities (electron densities) as functions of *a* electric field amplitude and *b* Hall conductivity. The bars show standard deviations and the numbers in the histogram boxes give the number of cases for the respective range of values. The backscatter amplitudes are corrected for aspect angle and slant range dependence

Discussion

Our event shows that the current density and radar amplitude profiles in the evening sector are more closely related to the conductivity profile than to the northward electric field profile. In this context, the following facts may be mentioned:

a The dependence of the radar amplitude on the conductivity follows directly from the equation for the radar volume cross-section since the height-integrated Hall conductivity is approximately linearly related to the E_s-layer electron density. If we exclude those terms of the equation that are not essential for our discussion, then (see Booker, 1956; Flood, 1967)

$$\sigma_v \sim N^2 \cdot <\Delta N/N)^2> \cdot F(\psi,\theta), \tag{1}$$

where $\Delta N/N$ is the fractional variation in the mean electron density N, and the term on the right hand side is a function of aspect angle and azimuth angle anisotropies. Hence, Equation (1) shows that the radar amplitude, $\sqrt{\sigma_v}$, is proportional as well to the fractional variation in the mean electron density as also to the electron density itself.

b Keskinen et al. (1979) studied numerically the nonlinear evolution of large-scale type II irregularities and found the existence of a direct proportionality between electric field values and $<(\Delta N/N)^2>^{1/2}$ (mean effective magnitude of the fractional variation in mean electron density). In their case the radar backscatter amplitude and ionospheric current density are both controlled by the electric field values, i.e. the electron density seemed to be a factor of minor importance for the fractional density variations.

We believe that the analysis of our data in Fig. 4 clearly shows that the linear backscatter amplitude – current density relationship here is mainly due to conductivity, i.e. electron density, changes (point *a*), since our results show a clear correlation between $\sqrt{\sigma_v}$ and Σ_H, while between $\sqrt{\sigma_v}$ and E a clear anticorrelation prevails. The latter apparently has its cause in the well known anticorrelation between conductivity and electric fields (e.g. Baumjohann et al., 1980).

Since the influence of the mean electron density on the backscatter amplitudes is obvious from Equation (1) and can easily be seen in Fig. 4 and if we furthermore assume that $F(\psi,\theta)$ in Equation (1) is approximately constant in our case, it remains to be checked if and how the fractional density variations are dependent on the electric field and/or the mean electron density. Since $<(\Delta N/N)^2>^{1/2}$ is proportional to $\sqrt{\sigma_v}/N$ (if $F(\psi,\theta)=$const.) and since N is roughly proportional to Σ_H we have calculated $\sqrt{\sigma_v}/\Sigma_H$ for all samples recorded by the radar in Norway between 1800 and 1814 UT and plotted these values in the form of histograms versus electric field amplitude (Fig. 8a) and height-integrated Hall conductivity (Fig. 8b) – Σ_H was calculated in the same way as for Fig. 4. Fig. 8 shows rather clearly that there is at least no simple relationship between the fractional electron density variations and electric field or electron density in our case and thus the present result does not support the findings of Keskinen et al. (1979).

Our experimental results lead us to the following conclusions. If the electric field $E(t, r)$ is constant, but the electron density varies, then $\sqrt{\sigma_v} \sim N \sim \Sigma_H \sim I_H$. This is in agreement with the linear relationship between the radar amplitude and current density found earlier by many authors (Greenwald et al., 1973; 1975; Siren et al., 1977; Baumjohann et al., 1978; Mareschal et al., 1979). However, if the electron density is constant but the electric field varies we have no reason to expect a linear relationship between the radar amplitude and the ionospheric current density. As a result of our analysis and experimental findings we consider the earlier experimentally found linear relationship between the radar auroral amplitude and the ionospheric current density as a special case of a more common linear relationship of the radar auroral amplitude and the mean electron density in the backscattering region.

It is not realistic to look for an inverse relationship between the backscatter amplitude and the electric field everywhere in experimental data. In the 140 MHz frequency band the radar amplitude is determined mainly by the electron density in the echo region while for lower frequencies, e.g. 50 MHz band, the relationship may be more complicated. This may explain the differences between the present conclusions and the earlier suggested electric field dependence (Greenwald et al., 1973; 1975) which was based on radar auroral data in the 50 MHz band.

Tsunoda et al. (1976b) have suggested that in the evening sector the location of the poleward border of the 398 MHz diffuse radar aurora depends on the particle precipitation pattern. They also noted that beyond the poleward boundary of the diffuse radar aurora echoes disappeared in spite of strong electric field in this region. The authors suggested that the electron density must be very low polewards of the boundary of diffuse radar aurora. In this work we have found a similar type of meridional electron density profile, Fig. 7.

The existence of a distinct poleward boundary of diffuse radar aurora was reported by Balsley et al., (1973), Greenwald et al. (1973), (1975), Tsunoda et al. (1974), (1976a, b), Kustov et al. (1979). Our findings allow us to consider the poleward boundary of the evening diffuse radar aurora as a persistent meridional pattern in the electron density. Indeed, in the event discussed the comparison of the electric field meridional profile with the upward continued magnetic field profile (Fig. 7) allows us to conclude confidently that the reduction in amplitude of radar aurora northward of the arc, i.e. the evening radar-aurora/aurora interface, is a result of a lower ionospheric Hall conductivity poleward of the arc as compared to the Hall conductivity equatorward of the arc.

Summary

a During the time prior to a substorm onset the height-integrated Hall conductivity has a distinct jump across the most equatorward auroral arc in the evening sector of the discrete auroral oval. In the event studied the conductivity decreases by a factor of 3–5 in going from the equatorward side of the arc to its poleward side.

b We find that the radar auroral amplitude changes proportionally to the changes in mean electron density and Hall conductivity in the regions poleward and equatorward of the arc. This occurs in regions where the E-field shows only minor changes.

c The abrupt decrease of the mean electron density on the poleward side of the most equatorward arc is the main cause of the distinct decrease in radar aurora backscatter amplitude poleward of this auroral arc.

d The analysis of electric fields and currents in the present event shows that there is a linear or nearly linear relationship between the 140 MHz radar amplitude ($\sqrt{\sigma_v}$) and the mean electron density (N) (conductivity) in the backscattering region provided that the electric field values are somewhat higher than the threshold values needed for irregularity excitation.

e Our results suggest that the earlier experimentally found linear relationship between the radar amplitude and the ionospheric current density is a special case of the more common relationship between the radar amplitude and the mean electron density in the backscattering region.

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