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On the Dependence of Radar Aurora Amplitude on Ionospheric Electron Density

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Abstract. Radar aurora amplitudes have been correlated with mean electron density measurements by means of ionosondes during two geophysically widely different events. A similar, roughly linear relationship was found between the two quantities in both cases. On the other hand, the amplitude seems to be almost independent of the ambient electric field, once it is well above the instability threshold.

Key words: Radar aurora amplitude – Electron density.

Introduction

Greenwald et al. (1973) found a linear relationship between the 50 MHz auroral backscatter amplitude and ionospheric current density in the backscattering region. Subsequent papers (Gray and Ecklund, 1974; Greenwald et al., 1975; Siren et al., 1977; Baumjohann et al., 1978; Mareschal et al., 1979), where an appreciable data set was used, confirmed this linear relationship in general but Greenwald et al. (1975) found that sometimes it breaks down. The reason for such a linear relationship is, on the whole, not clear; Greenwald (1979) has used the findings of Sudan and Keskinen (1979) as an explanation: for rather large-scale gradient-drift irregularities a linear relationship may exist between irregularity amplitudes and the ambient ionospheric electric field. On the other hand, André (1980) found experimentally, for the 140 MHz band, an inverse relationship between radar auroral amplitude and electric field when the latter was well above the instability threshold.

Recently, Starkov et al. (1980) and Uspensky et al. (1982) have suggested that the experimentally found linear relationship between radar amplitude and ionospheric current density, quoted above, is a special case of a more common relationship between radar amplitude and mean electron density in the backscattering region. The present paper aims at checking this result.

We start from the equation for the effective volume cross-section for radar wave backscattering from the ionosphere (Booker, 1956; Flood, 1967; Farley, 1971). The essential part of this equation is:

$$\sigma_v \sim N^2 \langle (\Delta N/N)^2 \rangle F(\psi, \theta) \qquad (1)$$

where N = mean electron density in the backscattering region,
$\langle (\Delta N/N)^2 \rangle$ = mean square of relative small-scale spatial electron density fluctuations, $\Delta N(2k)$, k = wave vector,
$F(\psi, \theta)$ = normalized aspect angle and azimuth angle anisotropy function (radar aspect angle = angle between the geomagnetic field line an the radio ray; azimuth angle = angle between the mean irregularity drift velocity and the radio ray).

The RHS of Eq. (1) is the three-dimensional spatial power spectrum of the electron density fluctuations. The anisotropy function depends on the geometry of scattering only. If its variation is small (or is constant), σ_v depends mainly on the first two terms, viz. N^2 and $\langle (\Delta N/N)^2 \rangle$.

Uspensky et al. (1982) have found in one event a rather weak dependence between the small-scale electron density fluctuations $\langle (\Delta N/N)^2 \rangle^{1/2}$ and the E field above instability threshold and suggest that the radar amplitude is mostly controlled by ionospheric electron density. To answer the question of whether this is more generally the case we study below two events where the electron density could be determined by ionosonde measurements. The auroral radar data are from STARE (Scandinavian Twin Auroral Radar Experiment); we have used results from the Finnish STARE station at Hankasalmi.

Observations

11 December 1977

This event has been studied in detail by André (1980). The STARE amplitudes, as seen by the Finnish radar, are shown in Fig. 1; these have been taken from André's paper. The data were obtained in a region 100 km × 100 km, with its southern border located about 50 km north of Tromsö. We have included in Fig. 1 the STARE E-fields; the shaded stripe depicts the E-field threshold for instability (15–20 mV/m) (Siren et al., 1977; Cahill et al., 1978; Moorcroft, 1979), and we see that the E-field was well above the threshold during the whole event.

For this event the azimuth angle varies between 100 and 120 degrees. If we assume that the azimuth-dependence of radar amplitude obeys approximately the equation, found from experimental statistics (André, 1980),

$$F(\theta, \psi \approx 0) = 10(1 + \cos 2\theta) \text{ dB} \qquad (2)$$

then in the above-mentioned azimuth range the $F(\theta, \psi)$ variations would be about 4.4 dB or approximately the same as the scatter of radar amplitude values in Fig. 1a, i.e. influence of azimuth angle variations on radar amplit-

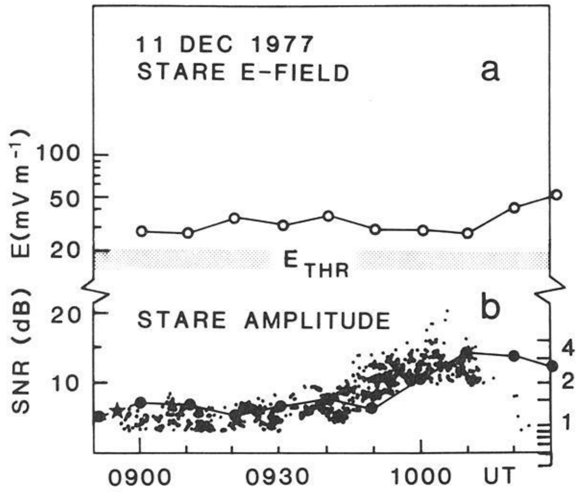

Fig. 1a and b. Data for the event 11 Dec 1977: **a** STARE E field magnitude, **b** STARE backscatter amplitude from the Finnish radar (scattered small dots), as well as the electron density from the MMK ionosonde (heavy dots) and from the TRO ionosonde (star)

ude in this case would be rather weak; probably it is even smaller than given by Eq. (2), as during rapid variations of the azimuth angle around 0900–0915 and 0935 UT the amplitude changes are rather small.

The influence of the aspect angle anisotropy $F(\psi, \theta \approx \pi/2)$ is also small because in the limited area in question the aspect angle is small and approximately constant. Thus, in what follows, we can concentrate on the first two terms on the RHS of Eq. (1) only.

Sudan and Keskinen (1979) and Greenwald (1979) have come to the conclusion that the effective mean electron density variations are linearly related to the ionospheric E. field. Our data in Fig. 1 disagree with this conclusion, since there seems rather to be an anticorrelation between the E-vield and radar amplitude variations. Thus it seems to us that, for over-threshold E-fields, variations in N and θ can explain the main part of radar amplitude variations.

We have checked this assumption by using ionosonde data. The ionosonde in Tromsö (geographic coordinates 69.7° N, 19.0° E) was measuring near the backscatter region (70.0–71.0° N, 18.0–20.0° E). Unfortunately, only one sounding was made per hour, and at 0955 UT no numerical value for f_bE_s (a measure of the electron density in the E region) was obtained due to the lacuuna phenomenon (a gap in the ionogram trace). At 0855 UT $f_bE_s = 3.1$ MHz.

The ionosonde at Murmansk (69.0° N, 33.0° E) was sounding every 10 min. At 0900 UT Murmansk obtained the value of 3.0 MHz for f_bE_s, i.e. about the same value as at Tromsö 5 minutes earlier. It seems to us that the E_s layer had, in this case, about the same density above both stations, and we assume that the same condition prevailed during the next hour.

The electron density values, obtained from ionosonde data, have been added to Fig. 1 (Murmansk = heavy dots, Tromsö = a star). The same logarithmic scale was used for N as for radar amplitude, the N curve being shifted along the vertical axis for best possible fit with the intensity.

Radar amplitude and electron density are seen to exhibit fairly similar temporal variations. The increase around 0940 in both curves is particularly conspicious (though a time shift of about 5 minutes is seen, possibly caused by the spatial separation of Murmansk from Tromsö area. Approximately the same time shift was seen in the signature of backscatter appearance over Tromsö and Murmansk, as recorded by radars of the Polar Geophysical Institute).

We may conclude that a satisfactory agreement exists during this event between backscatter amplitude and electron density in the backscattering region, irrespective of variations of the electric field, once it is above the instability threshold.

16 March 1978

This event was observed around three months later than the previous one. The technical characteristics of the Finnish radar were approximately the same as before; thus we are able to compare quantitatively the two independent and geophysically different events. (Note that the first event was observed in the morning sector when the ionosphere was sunlit, the second one in the growth phase of a substorm in the premidnight sector.)

The geophysical situation for the 16 March event has been described by Kustov et al. (1979) and Uspensky et al. (1982). The substorm was in the growth phase at 1756–1830 UT. In the STARE viewing area a stable and almost unstructured eastward current flow was observed. The most equatorward auroral arc in this area moved equatorward for an unusually long time. Equatorward of this arc diffuse luminosity existed. The current density on the equatorward side of the arc was 3–5 times higher than on the poleward side. The local breakup over the STARE viewing area occurred at 1833–1835 UT.

In the interval 1755–1830 UT we have data from five ionosondes: Tromsö (TRO), Kiruna (KIR) (67.8° N, 20.4° E), Sodankylä (SOD) (67.4° N, 26.6° E) Murmansk (MMK) and Loparskaya (LPY) (68.6° N, 33.0° E). The TRO and KIR ionosondes were measuring immediately under the STARE viewing area and 30 km south of it, respectively, making one sounding per hour. The SOD ionosonde was located around 70 km east of the eastern border of STARE viewing area and measured once every 30 minutes. The MMK and LPY ionosondes were measuring about 320 km to the east of SOD every 15 minutes.

During the time interval (35 minutes) used here, a homogenous current flow has been deduced from the SMA (Scandinavian Magnetometer Array) data (Uspensky et al., 1982). The electron density was fairly uniform in the whole longitudinal range of ionosonde measurements. For example, at 1800 UT f_bE_s was 4.6 MHz at LPY and f_oE_s 4.5 MHZ at KIR and 5.3 MHz at SOD. (On the two last stations, no F-layer trace was seen, therefore f_bE_s could not be scaled, f_oE_s being the upper limit for f_bE_s, the lower limit being about 0.7 MHz less.) So, we think that we can project SOD, MMK and LPY ionosondes along the auroral arc into the STARE viewing area.

Both Events

In Fig. 2 we show data for both events together. The main aim of the picture is to show the quite satisfactory agreement between the absolute values of the electron densities and the radar aurora amplitudes in the two different sets of data. A dashed line has been added to the figure, depicting an assumed linear dependence between electron density

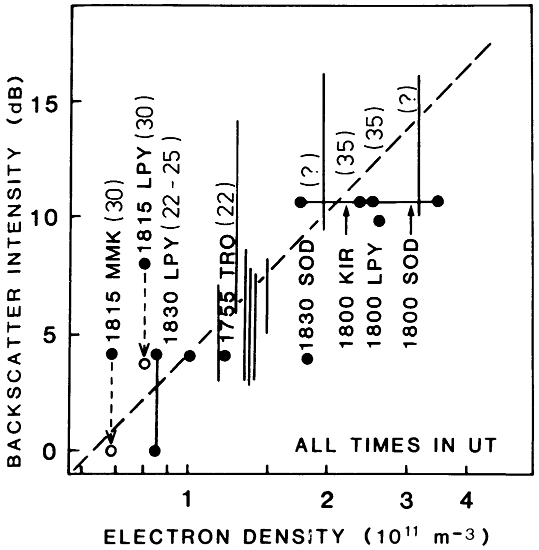

Fig. 2. Backscatter amplitude vs. electron density plot for 11 Dec 1977 and 16 March 1978 data. The scatter ranges of December data are shown by means of thin vertical lines, the March data are shown by means of heavy dots with the time of measurement and the abbreviated name of the ionosonde station. Where necessary, the backscatter amplitude for March data has been corrected for azimuth dependence to correspond to the azimuth angle 90° The estimated standard deviations for March 16 data are ± 2 dB in SNR and 10% in N. The numbers in parantheses give the electric field intensity (in mV m^{-1}) for the respective measurements

and backscatter amplitude. For the location of the March points, the following explanations are necessary:

At 1755 UT N was 1.2×10^{11} m^{-3} at TRO. The backscatter amplitude measured by the Finnish STARE radar just above the ionosonde was 8 dB. The azimuth angle of the mean irregularity drift velocity was $\theta = 117°$, thus the azimuth angle correction is 4 dB (Eq. 2) and the corrected value (for $\theta = 90°$) 4 dB.

For LPY N was 2.8×10^{11} m^{-3} at 1800 UT. By projecting LPY parallel to the arc we found a minimum SNR = 8–12 dB. No azimuth correction is necessary in this case, because these values were obtained at about $\theta = 90°$. We have plotted the mean of 8 and 12 dB, i.e. 10 dB.

For KIR N was $(1.8\text{–}2.5) \times 10^{11}$ m^{-3}, and the backscatter SNR = 12 dB for the nearest point to KIR. The azimuth angle there is circa 75°, and the SNR, corrected for azimuth dependence, 10.7 dB. We have estimated the same SNR for SOD, the projection of which lies a little more to the south of the viewing area of STARE than that of KIR; the corresponding $N = (2.8\text{–}3.5) \times 10^{11}$ m^{-3}. We have indicated in Fig. 2 for SOD and KIR the possible ranges of N, caused by the uncertainty in f_bE_s, by means of a horizontal bar.

At 1815 UT LPY and MMK were located 50–80 km poleward of the arc. Both ionosondes observed the E_s-layer electron density to decrease (to 0.8×10^{11} and 0.7×10^{11} m^{-3}, respectively). For the MMK ionosonde the projection gives the SNR of 4 dB, for LPY that of 8 dB. The latter value in particular is somewhat higher than expected. We explain these high values as follows:

Around 1813–1814 UT a sudden, short-lived increase in SNR occurred poleward of the arc. This increase was seen by the Finnish STARE radar and also by the Polar Geophysical Institute 46 MHz PPI radar at Essoyla. Also LPY all-sky data seem to show a short-lived, localized diffuse luminosity in this area around the same time. Thus we conclude that at 1815 UT the possibility of projecting ionospheric data along the arc temporarily breaks down and that the SNR's obtained by projection have to be reduced. We have indicated this fact in Fig. 2 by moving the MMK and LPY values for 1815 UT downward by 4 dB to correspond to SNR-values just before and after the temporary disturbance (4 dB is the gradation in SNR used in our set of data).

At 1830 UT N was 1.8×10^{11} m^{-3} for SOD and 0.85×10^{11} m^{-3} for LPY. The minimum SNR value for the SOD projection was 4 dB, that for LPY was smaller because the backscatter disappeared. This is why we have indicated for LPY the SNR interval 0–4 dB.

Discussion

In the two events studied here the variations of backscatter amplitude can very satisfactorily be explained by variations of electron density in the backscattering region. In addition, as seen in Fig. 2, the two events yield, in spite of the very different geophysical conditions, approximately the same linear dependence between these quantities and a good mutual agreement in absolute values (within the bounds of the long-term stability of radar characteristics). On the other hand, as we have shown here for the 11 December 1977 event and as has been shown by Uspensky et al. (1982) for the 16 March 1978 event, the amplitudes seem to be nearly independent of the E-field, once it is above the instability threshold.

Uspensky et al. (1982) suggest that the linear relationship found earlier between radar amplitude and ionosheric current density (Greenwald et al., 1973; Greenwald et al., 1975; Siren et al., 1977; Baumjohann et al., 1978; Mareschal et al., 1979) is a special case of the more general relationship between radar amplitude and mean electron density. Our result seems to be in quite satisfactory an agreement with this suggestion. Its should be noted also that Haldoupis (1981) has suggested that Pi2-variations of radar auroral amplitudes most likely are due to conductivity modifications because the former did not coincide with electric field variations.

The small dependence (or independence) of the backscatter amplitude on the ionospheric E.-field may be a result of nonlinear saturation of the growth of plasma instabilities. Some attempts to develop quasi-linear and non-linear theories which are able to explain a saturation of the Farley-Buneman instability have been made e.g. by Kamenetskaya (1971), Weinstock and Sleeper (1972), Sato (1972, 1976, 1977), Rogister and Jamin (1975), Volosevich and Liperovsky (1979) and Volosevich et al. (1979). A more extensive description of this problem can be found in the recent review by Fejer and Kelley (1980). We do not attempt to discuss the results of these papers in detail here but we conclude that it is difficult to apply quasi-linear mechanisms in our study. As to non-linear theories, Volosevich et al. (1979) have found that for waves with fixed mutual phases a linear E-field dependence exists, but in the random phase case the question is unresolved (Rogister and Jamin, 1975; Volosevich and Liperovsky, 1979). Thus we conclude that the question of the dependence of spatial electron density variations on the ionospheric E-field (for irregularities of one-meter scale or shorter) remains open.

It seems to us that possibilities exist to determine, with some accuracy, the ionospheric electron density from auroral backscatter amplitudes, at least in the 140 MHz band. At any rate, our results obtained for aspect angles near 90° and for azimuth angles deviating less than 30° from perpendicularity point in this direction.

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