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MOVEMENTS OF RADIO AURORA

by

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Abstract

Bistatic measurements of radio aurora between Mikkeli and Sodankylä have been analysed and the results compared with calculated reflection conditions. Bending of radio waves in the E region of the ionosphere and change in the inclination of the geomagnetic field due to the auroral electrojet have been estimated. Meridional and longitudinal motions of auroral ionization have been deduced from the measurements.

1. Introduction

Backscattering of radio waves from auroral ionization, called radio aurora, has been discussed by numerous authors. Extensive summaries of the results obtained so far can be found *e.g.* in [5] and [9].

The author treated the geometry of auroral reflections in the monostatic (radar) case for some locations in Finland in a previous study [7]. In the meantime, similar calculations for the bistatic case (transmitter and receiver separated) have been performed for some chosen pairs of locations. In this paper results from bistatic measurements between Mikkeli and Sodankylä will be discussed and compared with calculated scattering conditions.

2. Measurements

During the period March—August 1963 (*i.e.* six months) the field strength of the FM transmitter Mikkeli 1 of the Finnish Broadcasting

Company on 88.9 Mc/s was monitored at Sodankylä. A map of the measuring arrangement is shown in figure 1.

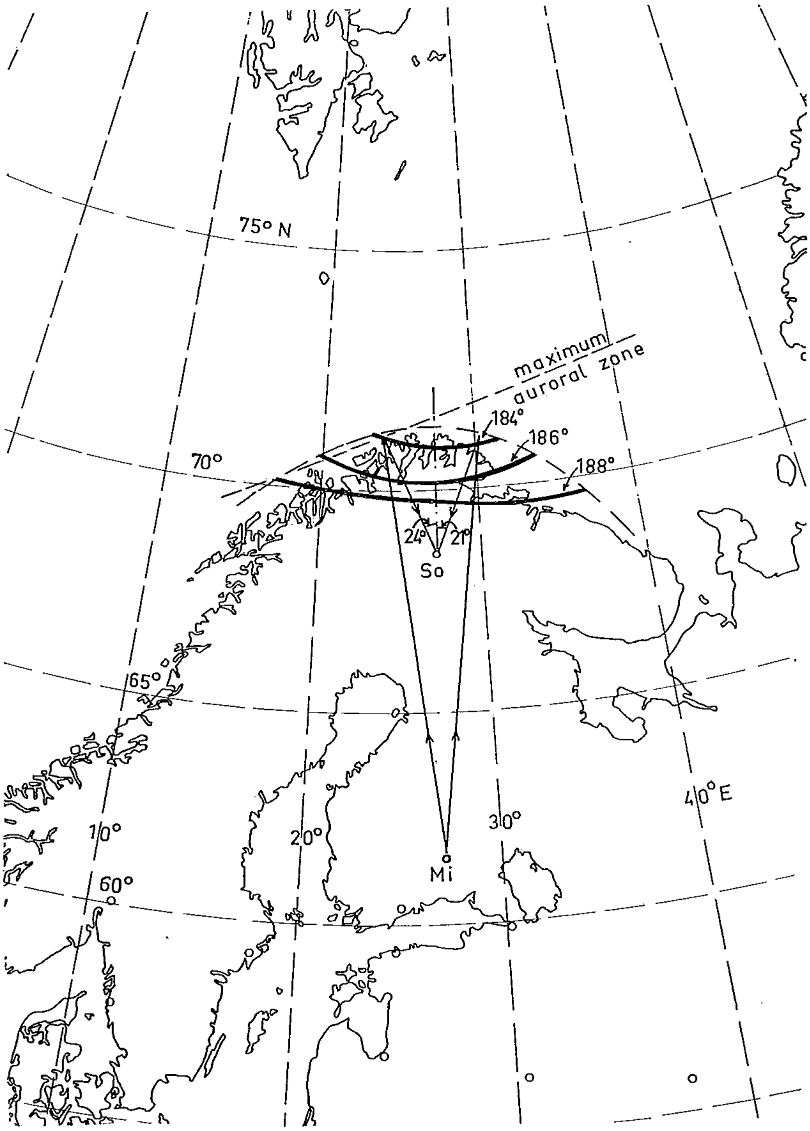

Fig. 1. Map of the bistatic measurement of radio aurora between Mikkeli (Mi) and Sodankylä (So).

The geographic coordinates of the transmitter are 27°19′E, 61°43′N. Its ERP is 9 kW and its antenna has an almost circular radiation pattern in the horizontal plane.

The location of the receiver was 26°39′E, 67°22′N. A commercially available FM tuner (Philips NG 5501) was used as receiver; it was connected to an Esterline-Angus ink recorder. Two four-element yagis were connected alternately for 7½ minutes to the input of the receiver by means of a clock work. Thus a 7½-minute sample of the field strength from two directions was obtained four times an hour. The angle between the antennae was set at 45°. As the half-power beam width of the antennae was also 45°, the beams crossed at half-power points close to the geographic north direction.

3. *Location of the scattering centres*

In the radar case the condition for strongest auroral scattering is that the angle between the radar beam and the direction of the magnetic field (propagation angle β) is as close to 90° as possible.

In the bistatic case the corresponding condition can be shown to be that the sum of the angles which the arriving and scattered waves form with the field line must be as close to 180° as possible. These sums can be determined for each pair of stations in the following way. First the propagation angles for scattering at a certain altitude are determined for a net of points for each station separately. Then a set of curves of constant propagation angle are drawn by connecting the points with the same value of β. A transparent overlay, containing the curves for one of the stations, is placed on the set of curves for the other station and the sums of propagation angles are determined. In figure 1 the thick curves connect projections of points where this sum has some constant values in the case of the pair Mikkeli and Sodankylä and an scattering altitude of 100 km (surface field approximation [7] was used). The smallest sum obtained in this case is 184°, far from the optimum value 180°. The broken curve denotes the horizon of Mikkeli for an altitude of 100 km. Although the most frequent altitude of auroral ionization is 110 km [9], the altitude 100 km was deliberately used in the calculations because it offered better geometric conditions for echoes.

It is seen from figure 1 that the auroral scattering is restricted in our case to a fairly small area. This area is limited in the north by the horizon of Mikkeli and in the south by the rapidly growing sum of propagation angles.

The value 184° for the sum does not offer any ideal condition for auroral backscattering. The condition of specularity, however, is not strict. It is shown in the appendix that the backscattered energy is still detectable if the deviation from 90° in the radar case is less than 2°. This corresponds to a deviation of about 4° from 180° in the bistatic case.

Other possibilities for explaining the occurrence of echoes in spite of poor reflection geometry are obtained when bending of radio waves in the ionosphere and change in inclination due to the auroral electrojet are considered (see appendix). The former effect can reduce the propagation angle by about 2°, the latter by a few degrees.

By the way of summary, it can be stated that the auroral backscattering is in our case most likely obtained from above the north coast of Norway, from a distance of about 300 km. Some possibilities of obtaining echoes from closer ranges due to changed reflection conditions exist.

4. *Results*

4.1. Sample recordings

Although the line-of-sight distance to the transmitter was 700 km and the antennae were approximately in the northerly direction, the possibility of receiving tropospheric waves from the transmitter with the backlobes of the antennae existed. It was thus necessary to distinguish between auroral echoes and tropospheric waves. This distinction could be made by means of the following criteria:

a) Auroral backscatter is invariably connected with geomagnetic disturbance, tropospheric propagation is not.

b) The fading of auroral backscatter is slower than that of tropospheric waves.

c) The auroral backscatter has a pronounced diurnal variation as compared with that of tropospheric waves.

If any doubt remained as to the nature of the received waves, the corresponding periods were not considered in the analysis.

Three typical excerpts from recordings are shown in figure 2. The trace in *a* results from tropospheric propagation, *b* shows a typical recording of auroral backscattering in the afternoon and *c* the same at

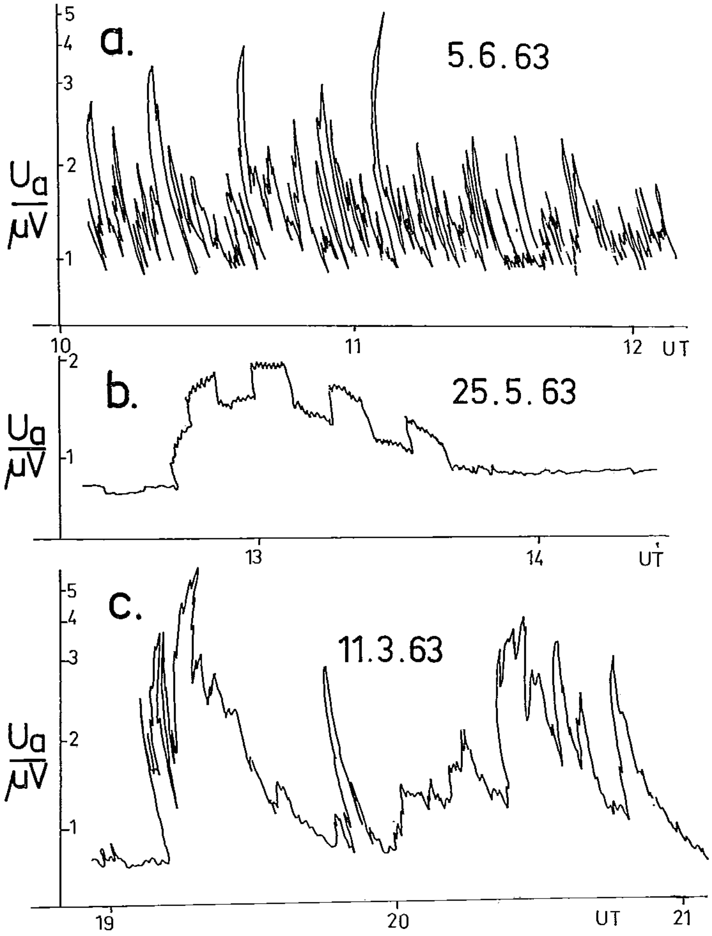

Fig. 2. Typical recordings at Sodankylä: Tropospheric waves (*a*), as well as auroral echoes in the afternoon (*b*) and at night (*c*).

night. The variation of field strength in the afternoon was of simple shape, with clear jumps at the switching times of the antennae. At night the variation was less regular and the switching times barely visible.

4.2. Diurnal variation of the auroral echoes

The number of those $7\frac{1}{2}$-minute periods during each hour of the day when auroral echoes were present (antenna voltage exceeded 1 μV) was counted separately for both directions. The resulting mean diurnal variations in the occurrence of the echoes are shown as histograms in figure 3. Because of a pause in the transmissions after midnight, the variations are given between 4 and 22 hours U.T. only.

The minima in the histograms of figure 3 occur at 8—9 and 16—17 hours U.T. These times agree well with those obtained by EGELAND [5] at Kiruna, Sweden, about 300 km in the direction WNW from Sodankylä.

No clear temporal difference in the occurrence of echoes from the two directions could be expected because the auroral phenomena depend on local time and the difference in the local times of probable backscattering volumes was about 20 minutes (≈ 5° longitude, see figure 1!). The temporal resolution of the method was not good enough to detect this difference. Usually echoes were received from both directions simultaneously. At night the direction of stronger echoes changed rapidly and fairly irregularly, and no direction seemed to be preferred. In the afternoon, however, the echoes from NNW were often stronger (as in figure 2). A look at figure 1 suggests a possible explanation for this

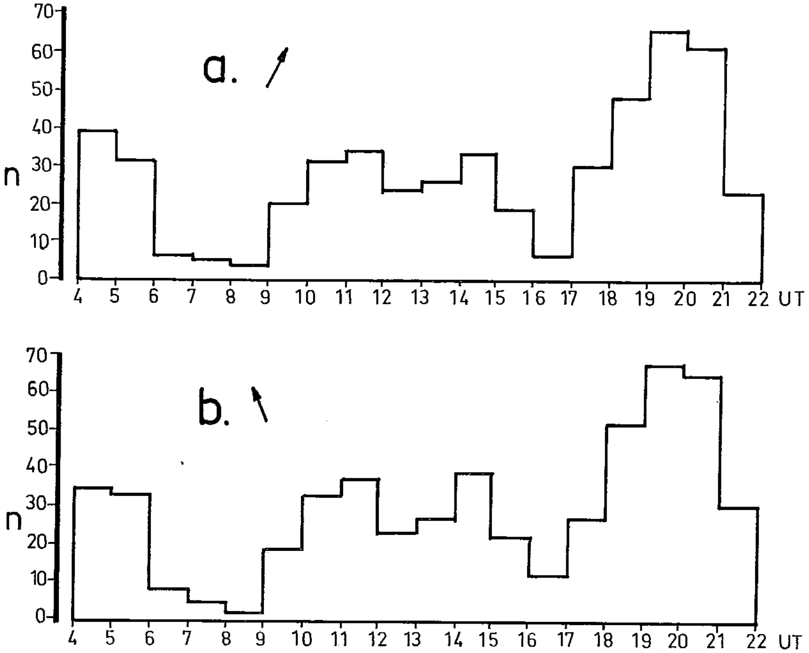

Fig. 3. Diurnal variations in the occurrence of auroral echoes in the two directions, NNE (*a*) and NNW (*b*).

phenomenon. We assume that the auroral ionization follows the direction of visual auroral zone and slants, therefore, from ENE to WSW. In the afternoon the auroral disturbance belt, performing movements in the meridional direction, often stays fairly far in the north, perhaps north of the maximum auroral zone, while at night it comes farther to the south [6]. In the former case the NNW antenna is more likely to catch echoes from the ionization, in the latter, both antennae have more or less the same possibility of reception.

4.3. Connection with geomagnetic activity, north-south motions

It is generally known that the radio aurora is connected with geomagnetic disturbances. The most accurate comparisons in this respect known to the author are those by Bullough *et al.* [4]. They compared auroral echoes received at Jodrell Bank (gm coordinates 56°N, 83°E) with magnetic recordings at Eskdalemuir (58.5°E, 83°E) and found an almost perfect temporal fit. The differences in time between auroral echoes and magnetic bays were of the order of 20 minutes and could be explained by means of longitudinal movements of auroral clouds, the velocities being of the order of 500 m/s.

Eskdalemuir was located about 500 km to the east from the scattering clouds but at approximately the same gm latitude. In our case comparison is made with geomagnetic recordings of Sodankylä, some 300 km to the south from the scattering centres. No detailed comparison has been attempted in individual cases but a mean trend has been studied by means of long-time averages.

In figure 4 the sum of histograms of figure 3 is compared with the mean course of geomagnetic storms (deviation of the horizontal component, ΔH) in the period 1958—60 at Sodankylä [6]. As the »characteristic times» (times for the beginning and end of the bays and for the maximum deflections) showed little variation from year to year, the curve in figure 4 can be assumed to hold true also for the year 1963.

The afternoon maximum of the histogram in figure 4 seems to be connected with the positive bay, the nightly maximum with the negative bay of the magnetic disturbance. But a time shift of two to three hours is obvious: The auroral echoes appear before the deflection in the H component. The echoes observed in the morning, after the pause in the transmission, seem, on the contrary, to follow the negative bay.

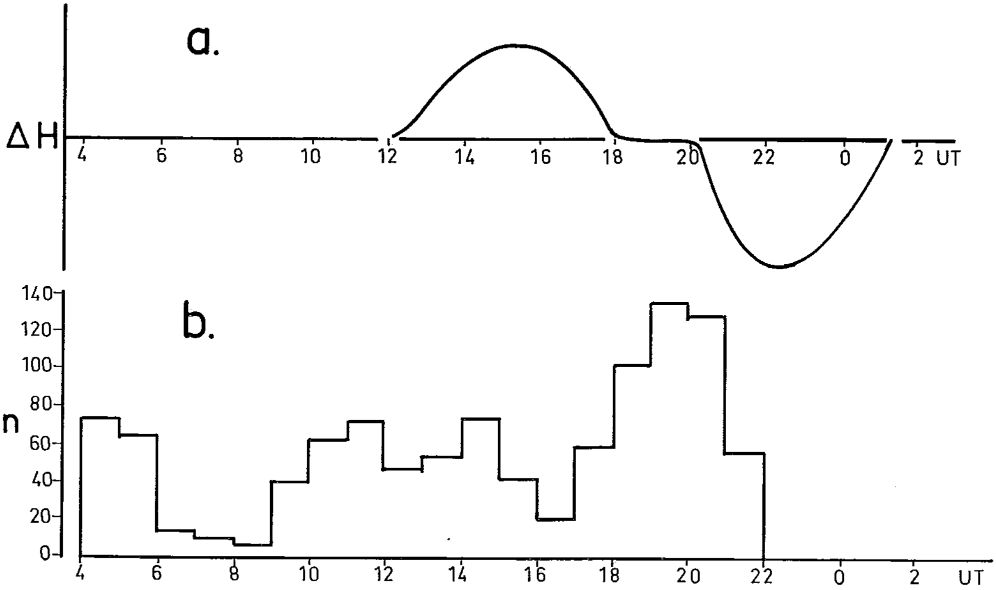

Fig. 4. The sum of histograms in figure 3 (*b*) compared with the schematic mean variation in the horizontal component of the geomagnetic field at Sodankylä during magnetic storms in the years 1958—60 (*a*).

It is natural to assume that the geomagnetic disturbance is caused by moving auroral ionization (auroral electrojet). The observed time difference between auroral echoes and geomagnetic disturbance suggests a north-south movement of this ionization. When the ionization is located close to the maximum auroral zone, auroral echoes can be observed, but the geomagnetic disturbance is slight at Sodankylä, about 300 km south of the zone. When the ionization moves southwards, the geometric scattering condition is more and more violated and the echoes become weaker. At the same time, the geomagnetic disturbance becomes stronger due to the greater proximity of the current.

A movement of the ionization towards the north should cause the echoes to follow the magnetic disturbance. Unfortunately, this effect is masked off by the nightly echoes in the case of the positive bay and by the pause in the transmission in the case of the negative bay. The morning echoes, though, might have been caused by ionization which had returned from south to the favourable scattering location.

From the time difference between the echoes and the maxima in the geomagnetic disturbance and from the distance of the optimum scattering location from Sodankylä (It is assumed that the current is located more or less overhead at Sodankylä during the greatest deviation in H) an apparent mean meridional velocity of the ionization of 100—150 km/h can be calculated. This value is fairly low as compared with those of other authors. For instance, TIURI [8] measured a mean Doppler shift of about 150 Hz in his measurements with an antenna towards the north on a frequency near 100 Mc/s. The corresponding north-south velocity v of ionization can be calculated from the formula [5]

$$v = \tfrac{1}{2}\,\lambda\,\Delta f \tag{1}$$

where

λ = wave length of the radio waves
Δf = Doppler shift

A value 225 m/s or 800 km/h is obtained for v. This is about 5 to 8 times higher than the value obtained above. But it must be borne in mind that our method delivers a long-time average of the velocity where velocities of different magnitudes and directions are grouped together. Detailed studies in individual cases are necessary for reliable values of the velocity.

4.4. East-west motions

With the two antennae variations in the field strength of auroral backscattering in two directions could be determined. The analysis of the recordings showed that the ratio of the field strengths was very changeable. Sometimes the field strength was greater in one direction, sometimes in the other. It was interesting to see whether this ratio changed systematically. For this purpose the top antenna voltages during each 7½-minute period were scaled and differences between two successive values formed. In figure 5 these differences are shown graphically in some cases. Line segments above the base line mean that the field strength in NNE was greater, those below the base line that the field strength in NNW dominated.

If we assume that the variation in the difference of the two field strengths was caused by motion of the auroral ionization, the measure-

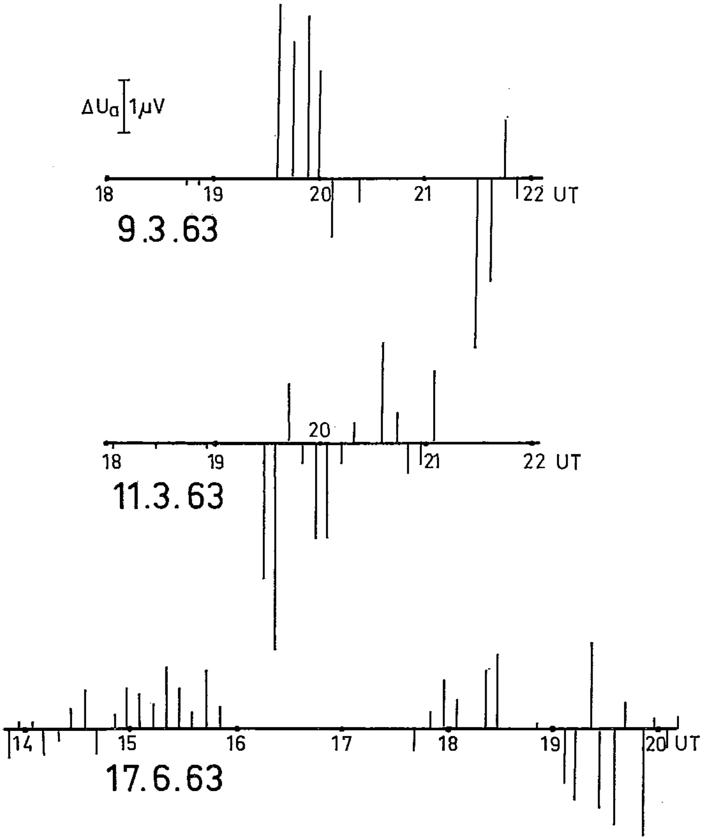

Fig. 5. The difference of the voltages in the two antennae in some cases at Sodankylä.

ment on March 9 would indicate a motion first towards the west (19^{30} to 20^{30} U.T.), then towards the east (21^{30} to 22^{00} U.T.). On March 11 the general movement would have been towards the east, on June 17 twice towards the east and once towards the west. The velocities of the movements are difficult to determine because the width of the antenna beams does not allow the auroral clouds to be located accurately. Velocities of the order of hundreds of kilometers per hour can be estimated.

Because the moving charged particles are predominantly negative, it would be expected that the motion be towards the west during the positive phase and towards the east during the negative phase of the magnetic disturbance [4]. But this rule is valid only when the geomagnetic measurements are made below the moving ionization. In our case the geomagnetic field was measured about 300 km south of the moving ionization, and a poor agreement with the rule was observed.

There is one weakness in the measuring method. The appearance and disappearance of ionization without any movement would fool us to believe in real motion. The adding of a third antenna in the north-direction would have greatly reduced this possibility.

5. *Summary*

The relatively frequent occurrence of auroral echoes between the station pair Mikkeli—Sodankylä in spite of the poor predictions based on the calculated geometry has been explained by means of the finite scattering beam width of auroral irregularities, bending of radio waves in the ionospheric E(or E_s) layer and change of the inclination due to the auroral electrojet. An attempt has been made to deduce north-south movements of auroral ionization by comparing the statistics of auroral echoes with the statistics of geomagnetic disturbances. The right direction has been obtained but the magnitude of the velocity is too low. East-west motions have been studied by comparing the strength of echoes received by the two antennae used in the measurement.

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APPENDIX

A. The dependence of backscattered energy on the off-perpendicular angle.

According to the Booker-Gordon theory [2] the energy scattered back from auroral ionization depends on Δ, the deviation of the propagation angle β from 90° in the radar case according to the function

$$\exp\left(\frac{-8\pi^2L^2\Delta^2}{\lambda^2}\right) \tag{2}$$

where

L = the correlation distance of the electron density along the axis of symmetry of the irregularities
λ = wave length of the incident radiation.

By using the value of about 10 m for L given in [2] and the value 3 m for λ we can construct a curve giving the relative backscattered energy as a function of Δ (figure 6). The value of Δ which causes the backscattered energy to decrease to e^{-1} (37 %) is seen to be about 2°. Thus a deviation of two degrees from 90° does not cause too serious a decrease in the received energy. As Δ enters in the second power into the expression (2), the received energy decreases very rapidly if Δ is still increased. For instance, if $\Delta = 4°$, the energy is about 2 % of the maximum value.

B. *The effect of ionospheric bending on the propagation angle.*

The bending of radio waves in horizontally stratified ionosphere obeys Snell's law

$$\sin i_0 = n \sin i \tag{3}$$

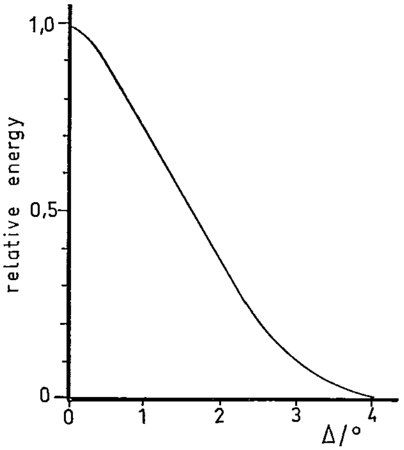

Fig. 6. The variation of the relative energy scattered back from auroral ionization *vs.* the off-perpendicular angle Δ.

where

i_0 = angle of incidence into the ionosphere
n = coefficient of refraction at the place where i is to be determined (figure 7 a)

i = angle between the wave normal and the vertical direction

n is obtained from the formula

$$n = \left[1 - \left(\frac{f_N}{f}\right)^2\right]^{\frac{1}{2}}. \tag{4}$$

Here

f_N = the plasma frequency at the place in question
f = the wave frequency

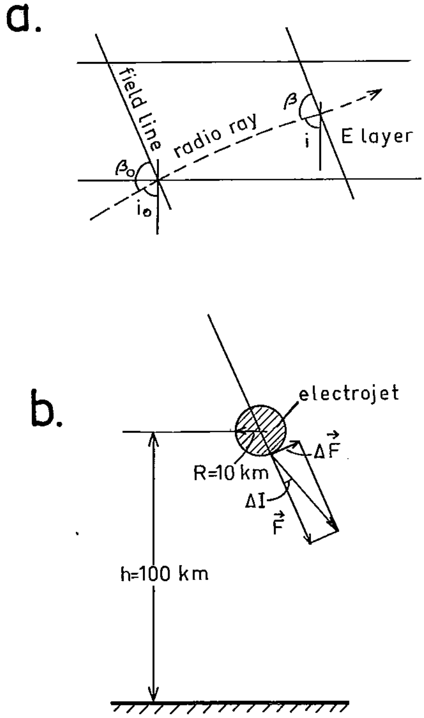

Fig. 7. The bending of a radio ray in an ionized layer (*a*) and the change in the inclination of the geomagnetic field due to the auroral electrojet (*b*).

In our case we study the bending in the E (or E_s) layer at a frequency of about 100 Mc/s. The greatest bending is observed at the maximum of the layer where a value of 10 Mc/s for f_N is seldom exceeded. Inserting $f_N = 10$ Mc/s and $f = 100$ Mc/s we get

$$n = \left[1 - \left(\frac{10}{100}\right)^2\right]^{\frac{1}{2}}$$
$$= 0.995$$

i_0 varies is our case between about 70° and 80° [7]. The latter value gives the maximum difference between i_0 and i:

$$\sin 80° = 0.995 \sin i$$
$$i = 81.8°$$
$$\Delta i = i - i_0 = 1.8° = \beta_0 - \beta$$

Thus a maximum bending of about 2° can be obtained in our case. The bending reduces the propagation angle for both stations. As a consequence, the sum of the angles is reduced by bending, but not more than 4°.

C. *The effect of the auroral electrojet on the propagation angle.*

The influence of the auroral electrojet can be estimated as follows.

It is now generally assumed that the electrojet flows inside or very close to the auroral arc [3]. In what follows, the jet is approximated by a homogeneous current cylinder with a radius of 10 km. Approximately the same cross sectional area is thus obtained as in [3] although the shape of the cross section is different. The value of the current can be calculated from the known magnetic disturbance. We assume an overhead current and take the upper limit for $K = 6$, which is often achieved during an auroral disturbance. It is $\Delta H = 600\,\gamma$. Now, it is known that about 2/3 of this value (here denoted $\Delta H'$) is caused by an ionospheric current, the rest by an induced earth current [1]. We get $\Delta H' = 400\,\gamma = \frac{1}{\pi}\frac{\mathrm{A}}{\mathrm{m}}$. The total current I of the electrojet is obtained from

$$I = 2\pi h \Delta H' \tag{5}$$

where h = altitude of the electrojet

We take $h = 100$ km and get

$$\begin{aligned} I &= 2\pi \cdot 10^5\,\mathrm{m}\ \frac{1}{\pi}\,\frac{\mathrm{A}}{\mathrm{m}} \\ &= 2 \cdot 10^5\,\mathrm{A} \end{aligned}$$

The magnetic field of this current is greatest at its surface. If we denote this field by ΔF (See figure 7 *b*), we get

$$\begin{aligned} \Delta F &= \frac{I}{2\pi R} \\ &= \frac{2 \cdot 10^5\,\mathrm{A}}{2\pi \cdot 10^4\,\mathrm{m}} \qquad (6) \\ &= \frac{10}{\pi}\,\frac{\mathrm{A}}{\mathrm{m}}\,. \end{aligned}$$

The magnitude F of the geomagnetic field at Sodankylä is about $50\,000\,\gamma = \frac{125}{\pi}$ A/m. The greatest change in the inclination is obtained in the case where the auxiliary field is perpendicular to the normal field. In that case the change in inclination (ΔI) is

$$\begin{aligned} \Delta I &= \mathrm{tg}^{-1}\left(\frac{\Delta F}{F}\right) \\ &= \mathrm{tg}^{-1}\left(\frac{10}{125}\right) \qquad (7) \\ &= 4.5^\circ \end{aligned}$$

This value gives, of course, only the order of magnitude of ΔI because of the crude assumptions made. But it can safely be concluded that changes of the order of a few degrees can take place in the inclination near the auroral electrojet.

Reduction in the inclination causes an equally great reduction in the propagation angle in the magnetic meridian plane. A reduction occurs below a current towards the east (figure 7 *b*) and above a current towards the west. As the auroral electrojet flows towards the east in the afternoon and towards the west at night (the movement of electrons is in the opposite sense), the scattering altitude is lower in the afternoon than at night for stations where a reduction in the propagation angle from the static value improves the scattering conditions (as *e.g.* for Sodankylä).

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