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EISCAT Magnetometer Cross and Theoretical Studies Connected with the Electrojet Current System

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Abstract

Magnetic data obtained by the EISCAT magnetometer cross in northern Scandinavia are discussed. The data are and will be used mainly for studies of ionospheric and magnetospheric current systems. In this paper some preparatory studies are briefly discussed. An auroral electrojet current system model consisting of a horizontal line current and of field-aligned currents is presented in greater detail. The amplitudes of the components of the electromagnetic field caused by the model on the earth's surface are considered as functions of a spatial wave number describing the changes of the electrojet current along the line. The earth is assumed to be homogeneous in this paper. Using the model, it is indicated that in the presence of an electrojet system the apparent resistivity parameter commonly used in electromagnetic induction studies of the earth may clearly differ from that of the so-called plane wave case. The differences become significant at large periods starting from about one minute, and a particularly clear deviation from the plane wave case is seen when the horizontal distance from the electrojet to the point of observation equals the inverse of the above-mentioned wave number.

1. *Introduction*

Electric currents flowing in the ionosphere and magnetosphere of the earth can be studied e.g. by observing the geomagnetic field on the earth's surface. From the mathematical point of view the determination of the currents from these magnetic data is a difficult inverse problem which does not necessarily have a unique solution. However, a comparison of the data with results obtained by suitable model computations certainly yields information about the real (i.e. not only equivalent) ionospheric-magnetospheric currents.

The so-called EISCAT magnetometer cross situated in northern Norway and Finland in the auroral zone has produced magnetic data usable in the investigation of ionospheric-magnetospheric currents since 1982. In this paper, we briefly describe the

EISCAT cross and its data. Some previous studies making the "background" for research of ionospheric-magnetospheric currents by magnetic observations on the earth's surface are also summarized.

Finally in this paper, a theoretical model of an auroral electrojet current system is discussed, and numerical results are shown. Special attention is paid to the apparent resistivity parameter used in electromagnetic induction studies of the earth.

Thus, this paper outlines groundbased magnetometer data available and presents an electrojet current system model. So elements usable in the determination of real currents flowing in the ionosphere and magnetosphere are given. The subject of a subsequent paper would be putting the elements together, i.e. fitting model parameters to measured data.

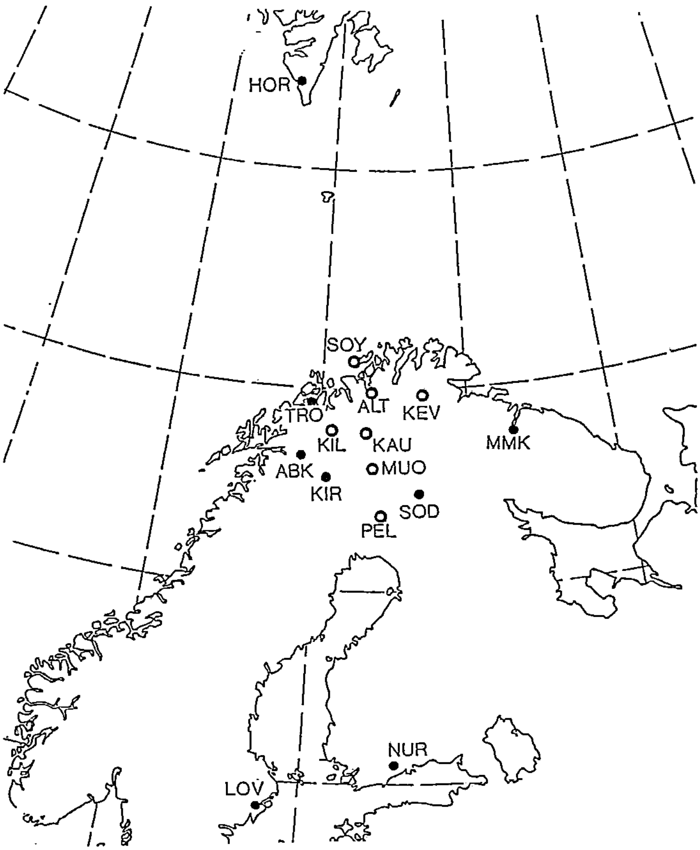

Fig. 1. EISCAT magnetometers (o) and other digitally-recording magnetometers (•) in Finland and nearby areas.

2. *EISCAT magnetometer data*

Since 1982 a network of 3-component flux-gate magnetometers (*Lühr et al.*, 1984) from the University of Braunschweig, West Germany, has been running in the northern parts of Finland and Norway (Fig. 1). This network is known as the EISCAT magnetometer cross.

The EISCAT magnetometer data are 20 s mean values on merged tapes in the so-called IAGA format (*IAGA News* No. 20, p. 112). Times for which there are data available from the different stations are shown in Fig. 2. As can be seen, the network has been rather reliable, thanks to good instruments, to good service from the Sodankylä Observatory and to the yearly service from the University of Braunschweig. The data processing is carried out at the Department of Geophysics of the Finnish Meteorological Institute.

Using nearby observatory values, accurate base lines are calculated for the EISCAT magnetometers. The original idea to include also digital data from the Nurmijärvi and Sodankylä Observatories into the same data set has not been realized because of practical difficulties. However, one-minute mean value data are available separately from the two observatories.

3. *Background studies*

A geomagnetic variation (excluding the slow secular change) is produced by two different contributions: the primary part caused by ionospheric and magnetospheric sources and the secondary part caused by currents and charges induced in the earth. It is useful to separate these two contributions both in studies of ionospheric-magnetospheric

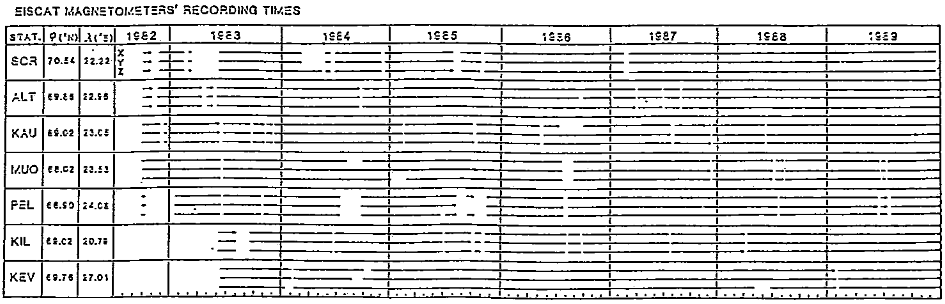

Fig. 2. Times of usable data from the EISCAT magnetometer stations.

current systems and in studies of the structure of the earth. Also, when using magnetic variation data it is necessary to know whether they are affected by nearby anomalies in the conductivity of the earth. The latter question was studied as a collaboration by the Polish Academy of Sciences and the Finnish Meteorological Institute at the Nurmijärvi Observatory (*Jankowski et al.*, 1986), and a similar study was started at the Sodankylä Observatory recently.

As stated above, the determination of an ionospheric-magnetospheric current system using magnetic data recorded on the earth's surface is a complicated inverse problem, and then e.g. the so-called Kisabeth method can be used (*Kisabeth*, 1972).

To get some idea of the magnetic field produced by an electrojet on the earth's surface, a simple horizontal line current may be considered. This is done in a rough and schematic manner in Fig. 3 in which both a time-independent and a time-varying line current are discussed and the corresponding horizontal and vertical magnetic components are shown as functions of space or time. The current may have a constant location or be moving, and the earth induction is taken into account either by assuming the earth's conductivity to be perfect or by describing a finite conductivity by an "effective" mirror current.

The basic line current model of an electrojet has been further developed by including the possibility of changes in the direction of the current flow (*Pirjola*, 1982, 1985a, 1985b; *Lehto*, 1984). Numerical results based on a special case of Lehto's electrojet system model consisting of an electrojet and vertical currents are depicted in Fig. 4 (*Pirjola*, 1985b). *Häkkinen and Pirjola* (1986) have generalized Lehto's model even further by letting the "vertical currents" have any direction, which means that the real inclination and declination can be used for field-aligned currents. In all these papers a layered-earth model was mainly used.

4. *On the electromagnetic field caused by an electrojet system*

Let us describe an electrojet by a horizontal line current whose length is L, and assume that it has a harmonic time dependence (angular frequency ω) and a harmonic space dependence along the line (wave number q). Using a Cartesian coordinate system fixed to the earth in which the z-axis points downwards and the y-axis is parallel to the line current, the current density of the electrojet is expressed by

$$\mathrm{J}(x,y,z,t) = J e^{i(\omega t - qy)} \delta(x)\, \delta(z+h) \left[\theta(y+L/2) - \theta(y-L/2)\right] \hat{\mathrm{e}}_y \tag{1}$$

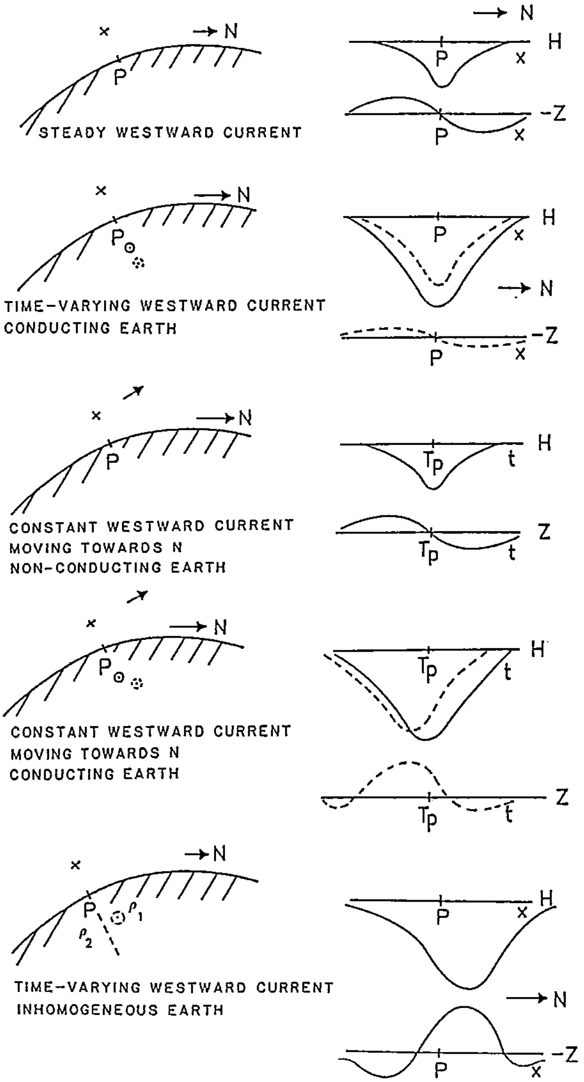

Fig. 3. H and Z components of the magnetic field on the earth's surface in the case of a horizontal line current in the ionosphere. × : the line current ⊙ : the mirror current when the earth is a perfect conductor ◌: "effective" mirror current when the earth has a non-zero resistivity. The last case: resistivities ρ_1 and ρ_2, $\rho_1 < \rho_2$. Dashed curves correspond to cases where the earth has a non-zero resistivity. In cases where the current is moving the magnetic field at the point P is expressed as a function of the time t. At $t = T_p$ the current is above P. In cases of a non-moving current the magnetic field is given as a function of the north space coordinate x.

where δ and θ denote the Dirac delta and the Heaviside step function, respectively. The earth's surface is assumed to be the xy-plane (local studies), and h gives the height of the electrojet. The xz-plane is situated at the centre of the electrojet, and J contains the magnitude and phase of the current. To avoid an unacceptable accumulation of charges in the ionosphere, the electrojet is supplemented by field-aligned currents which make the divergence of the current density vanish. Hence, the present model is a special case of the general model discussed by *Häkkinen and Pirjola* (1986). The electrojet expressed by formula (1) has a fixed east-west location and extension ($-L/2 \leq y \leq L/2$) with respect to the earth's surface, which means that the rotation of the earth below the ionospheric-magnetospheric current system is neglected. Thus the model is clearly suitable for phenomena fast enough, i.e. for periods much less than L/v where v is the rotation velocity of the earth at the area investigated; typically L/v can have a value in the order of 1000 to 10000 s.

For simplicity, we now assume that the earth is homogeneous. Using formulas presented by *Häkkinen and Pirjola* (1986) the electromagnetic field produced on the earth's surface can be calculated. Let us assume that the relevant parameters have the

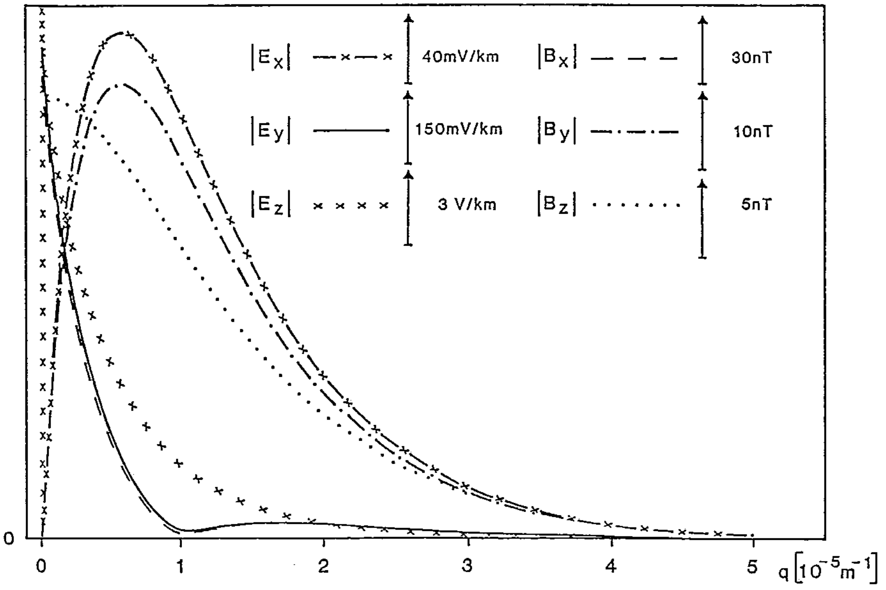

Fig. 4: Amplitudes of the total electric and magnetic fields on the earth's surface caused by a current system containing an infinitely long horizontal line current electrojet and vertical currents. The height and intensity of the electrojet are 100 km and 100 kA, respectively. The time dependence is harmonic with a period 20 s. The earth is assumed to be homogeneous (conductivity $10^{-2}\ \Omega^{-1}\mathrm{m}^{-1}$). The parameter q on the horizontal axis is the spatial angular frequency of the changes of the electrojet in the direction of the current flow, the changes being assumed to be harmonic. The distance from the point below the electrojet is 100 km (*Pirjola*, 1985b).

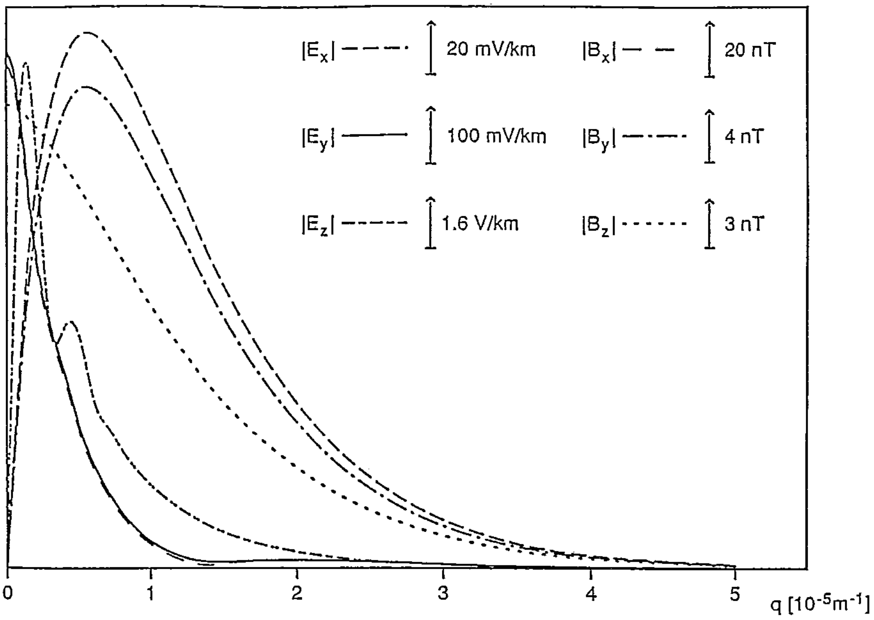

Fig. 5. This figure corresponds to Fig. 4 but now the horizontal current has a finite length 4000 km and the vertical currents are replaced by field-aligned currents with an inclination 77.5° and a declination 6.0°.

following values: $J = 100$ kA, $h = 100$ km, $L = 4000$ km, $\sigma_0 = 2\cdot10^{-14}\ \Omega^{-1}\mathrm{m}^{-1}$, $\mu_0 = 4\pi\cdot10^{-7}\ \mathrm{VsA^{-1}m^{-1}}$, $\varepsilon_0 = 8.854\cdot10^{-12}\ \mathrm{AsV^{-1}m^{-1}}$, $\sigma = 10^{-2}\ \Omega^{-1}\mathrm{m}^{-1}$, $\mu = \mu_0$, $\varepsilon = 5\varepsilon_0$, $I = 77.5°$, $D = 6.0°$, $\omega = 2\pi/20\mathrm{s}$, $x = 100$ km, $y = 0$. The symbols $\sigma_{(0)}$, $\mu_{(0)}$ and $\varepsilon_{(0)}$ denote the conductivity, permeability and permittivity, respectively, and subscript 0 refers to the upper half-space (the air). The inclination and declination of the field-aligned currents are denoted by I and D. Regarding the choice of the values of the parameters, *Pirjola* (1985a) can also be referred to. It should be noted here that ε does not have any effect in practice at geomagnetic frequencies. The value of the conductivity of the earth given above can be considered as a kind of an "average" value of the conductivity distributions presented by *Jones* (1980) and *Jones et al.* (1983) for Scandinavia. On the other hand, the use of a homogeneous earth assumption is just a rough approximation in Scandinavia (see e.g. *Hjelt et al.*, 1986), and so an exact choice of the value of the conductivity is certainly not so important.

The amplitudes of the electromagnetic field on the earth's surface are given as functions of the wave number q in Fig. 5. The choices of the values of the parameters mean that Fig. 5 is comparable to Fig. 4. The two figures are rather similar, but the values of the components are smaller in Fig. 5 than in Fig. 4, and some differences in the positions of the maxima and minima exist. The greatest differences occur in the behaviour of $|E_z|$ (which is, however, a component usually not measured in practice): At the maximum q has a much larger value and the maximum value is much smaller in Fig. 5 than in Fig. 4. As pointed out by *Pirjola* (1985b), the highest value of $|E_z|$ in Fig. 4 is much larger than the top of the figure.

It seems that $|E_z|$ in Fig. 5 also has a smaller maximum (~ 5 V/km) at $q \sim 10^{-9}$ m^{-1} not included in the accuracy of the figure. The behaviour of $|E_z|$ at about $q = 4 \cdot 10^{-6}$ m^{-1} in Fig. 5 is also different from that in Fig. 4. Probably the differences between Figures 4 and 5 are due to the finite length of the electrojet in Fig. 5 rather than to the (small) difference in the direction of the field-aligned currents. The value $L = 4000$ km used must be considered large; and in practice e.g. $L = 1000$ km could be used for an electrojet as well, still increasing differences from the case of infinite length.

5. *Apparent resistivity near an auroral electrojet*

The apparent resistivity is a parameter commonly determined from electromagnetic data for studies of the structure of the earth (e.g. *Kaufman and Keller*, 1981, pp. 75–104). Its use is based on the assumption of a laterally-homogeneous, i.e. uniform, primary field (a so-called plane wave assumption). Source effects violating the plane wave assumption and affecting electromagnetic and geomagnetic induction studies of the earth have been extensively discussed in the literature since the publication of the basic paper of magnetotellurics of *Cagniard* (1953) (e.g. *Waut*, 1954, 1962; *Price*, 1962; *Hermance and Peltier*, 1970; *Quon et al*, 1979; *Mareschal*, 1981, 1986; *Osipova*, 1983; *Osipova et al.*, 1989).

To study the source effects of an electrojet current system on the apparent resistivity, we now assume that $L = 500$ km, $q = 5 \cdot 10^{-6}$ m^{-1} and $I = 90°$ (vertical currents). Fig. 6 shows the apparent resistivity calculated by the plane wave formula from $|E_y|$ and $|B_x|$ as a function of the period $T = 2\pi/\omega$ with x as a parameter of the different curves. The other parameters have the same values as above.

Because the earth is assumed to be homogeneous the correct plane wave apparent resistivity equals the real resistivity $\sigma^{-1} = 100\ \Omega$m. Fig. 6 indicates significant deviations from the plane wave case at long periods. It should be noted here the fact indicated above that the acceptability of the model becomes questionable at long periods because of the neglect of the rotation of the earth and the limit period L/v mentioned above has a value of about 2800 s now. Moreover the height $h = 100$ km may be considered somewhat small, i.e. an extreme case, for a line current electrojet model (*Hermance and Peltier*, 1970). Anyway in spite of these slight shortcomings, Fig. 6 clearly shows that a straightforward use of the apparent resistivity may lead to incorrect conclusions in induction studies at and near auroral latitudes.

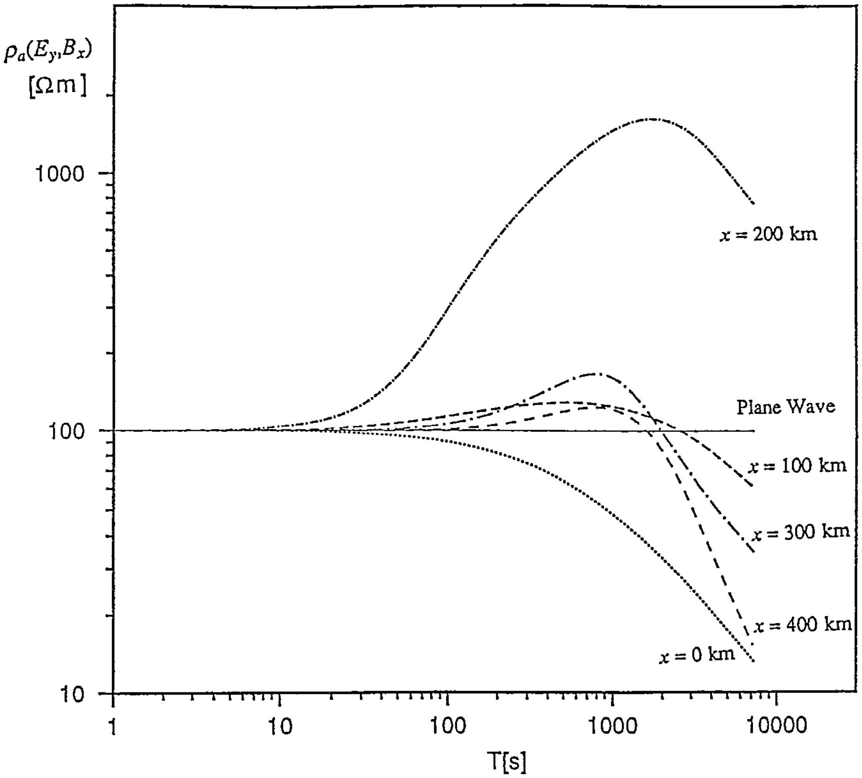

Fig. 6. Apparent resistivity as a function of the period of harmonic oscillation at different distances x from an electrojet system situated above a homogeneous earth with a resistivity 100 Ωm. The inverse of the wave number q describing spatial variation along the electrojet equals 200 km. Other details of the electrojet system are given in the text. With respect to the y-coordinate parallel to the electrojet the location of the point of observation on the earth's surface is at the centre of the electrojet (y = 0). The apparent resistivity was calculated using the electric field component parallel to the electrojet E_y and the perpendicular magnetic component B_x.

In particular, the curve x = 200 km is very different from the plane wave case. We have performed numerical calculations by two different and independent methods, and both indicate similar results. So the surprising curve x = 200 km cannot be due to numerical effects. The values of the apparent resistivity at T = 1000 s are about 290 and 825 Ωm for x = 150 and 250 km, respectively, being thus smaller than the value for x = 200 km, but clearly larger than the plane wave apparent resistivity. It should be noted that q^{-1} is equal to 200 km which evidently means some kind of a "resonance" when x = 200 km. On the other hand however, the field is also dependent on other lengths. So the situation is complex, and further studies are needed before definite conclusions can be drawn.

According to Figures 4 and 5, the ratio of $|E_y|$ to $|B_x|$ seems to be practically independent of q which shows that the apparent resistivity would not vary with q. This conclusion is, however, drawn only from the figures, and a more accurate analysis concerning Fig. 4 and presented in Table II of *Pirjola* (1985b) indicates that the apparent resistivity will not be independent of q, but a "resonance" is again seen at $q^{-1} = x = 100$ km.

Osipova (1983) has also investigated the effect of an electrojet on studies of electromagnetic induction in the earth. The apparent resistivity curves shown in her Fig. 12a are similar to those presented in Fig. 6 showing e.g. a "resonance" at an intermediate distance (= 1.6 times the height of the ionospheric source). In accordance with the results of this paper, the smallest apparent resistivity values are obtained in the vicinity of the source. Deviations from the plane wave behaviour start at somewhat larger periods in Osipova's Fig. 12a than in Fig. 6 of this paper which is evidently due to the ten times smaller value of the resistivity of the earth used by Osipova.

Osipova's electrojet model is different from ours in particular with respect to the return (or leakage) currents: Osipova uses equivalent currents flowing in the same horizontal plane as the electrojet, while we consider real field-aligned currents. Equivalent currents can be used for the magnetic field and obviously also for the horizontal electric field on the earth's surface, and so they are acceptable e.g. in studies of the apparent resistivity.

Osipova also shows that the apparent resistivity calculated from $|E_x|$ and $|B_y|$ is less different from the plane wave resistivity than that determined from $|E_y|$ and $|B_x|$. The same general conclusion is also indicated by our (still unpublished) calculations of the other apparent resistivity. (When comparing Osipova's results to those of this paper it should be noted that the coordinate system used by Osipova is different from the present one.)

6. *Conclusions*

The so-called EISCAT magnetometer cross consisting of seven stations has been operating at auroral latitudes in northern Scandinavia since 1982. The data are digital 20 s mean values and available for most times (Fig. 2). EISCAT magnetometer data will be used for the determination of currents flowing in the ionosphere and magnetosphere.

Fig. 3 presenting the magnetic variation observed on the earth's surface and caused by a simple ionospheric line current is useful in qualitative investigations. The effect of the real finite conductivity of the earth is also indicated.

Theoretical modeling of the electrojet system is discussed in this paper. Numerical results based on a model consisting of a line current electrojet of finite length and of field-aligned currents are presented. The results are qualitatively similar to those obtained by an infinitely long electrojet, but clear quantitative differences exist indicating that the finite length has to be taken into account when measured data are fitted to theoretical results.

The apparent resistivity usually determined in electromagnetic induction studies of the earth is calculated based on the model of a line current electrojet of finite length. It is shown that significant deviations from the so-called plane wave apparent resistivity may occur at long periods starting from the order of a minute. So special care is necessary when induction studies are performed at auroral latitudes.

Our theoretical work is continuing by numerical computations in which the earth is assumed to be composed of several layers, and an extension from a line current to a sheet current electrojet is being included.

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