Geophysica (1987), Vol. 23, No. 2, pp. 143–154.
Printed in Finland

550.388.2

STRUCTURE OF AURORAL ELECTROJETS BY THE DATA FROM A MERIDIONAL CHAIN OF MAGNETIC STATIONS

by

A.L. KOTIKOV, YU. O. LATOV and O.A. TROSHICHEV

The Arctic and Antarctic Research Institute
Leningrad, USSR

Abstract

An algorithm for magnetic data deduction for a meridional chain of stations is proposed. It includes the division of the geomagnetic disturbance field into external and internal parts, derivation of meridional profiles of ΔH and ΔZ components and calculation of the meridional profile of equivalent electric current density. This algorithm along with auroral absorption data gives new results on the structure of auroral electrojets. We show that the meridional profile of the equivalent current density is most complicated in the late evening-to-midnight sector: it is characterized by two westward electrojets and an eastward one between them. The eastward electrojet is observed in the latitudinal range between 69 and 72 degrees. A good correlation is observed in general between the westward electrojet and electron precipitation region. However, during the main phase of the substorm the electron precipitation region extends far to the south where no current is measured.

1. *Introduction*

It is known that there are basically two types of current systems: DP_{12} and DP_{11} (SERGEEV, 1977; PYTTE *et al.*, 1978; TROSHICHEV *et al.*, 1974). The DP_{12} equivalent current system exists during all phases of the substorm and it consists of two current cells at high latitudes with current maxima near dawn and dusk. The DP_{11} current system is associated with the substorm expansion phase. The DP_{11} disturbance is characterized by an intensification of the auroral electrojet in the midnight sector. The major feature of the DP_{11} system is a strong enhancement of the westward auroral electrojet in a latitudinally limited region on the night side of the auroral zone.

The dynamics and structure of high-latitude electrojets have been studied by using meridional chains of magnetometers. KISABETH and ROSTOKER (1973) show that the westward electrojet has a double structure near the midnight sector. LATOV (1977, 1978) used the Kara Sea (magnetic) chain of stations in USSR to show three types of the electrojet structure. The first type is characterized by a westward electrojet, the second one consists of two westward electrojets, and the third type has a complicated structure with two westward electrojets and an eastward one between them.

Earlier investigations were concerned primarily with a qualitative description of the electrojet structure. Chains of magnetometers have been able to monitor magnetic variations on a continuous basis. The difficulty with magnetic perturbations, however, is the fact that no unique solution of the current distribution is possible. One has to make assumptions to calculate the meridional profile of equivalent currents. Using simple models of two current sheets along with auroral absorption, KUZNETSOV and LATOV (1984) have considered various types of magnetic disturbances (DP_{12}, DP_{11}, $DP_{12} + DP_{11}$). It has been shown that these two modes co-exist throughout the substorm but their relative strength varies (JHILENKOV and KUZNETSOV, 1978; PETROV, 1980; KUZNETSOV and LATOV, 1984).

This work is a continuation of our previous studies (LATOV, 1978; KUZNETSOV and LATOV, 1984). A new algorithm for magnetic data obtained at a meridional chain of stations is discussed. Calculated meridional profiles of the equivalent current density are compared with auroral absorption dynamics along the same Kara Sea meridian.

2. *Method of data analysis*

As indicated above, the task is to determine the magnitude and the direction of ionospheric currents by magnetic field disturbances measured on the ground. Certain simplifying assumptions are made in our calculations:

a) The Earth is flat and the currents flow within an infinitely thin layer at a constant altitude of 100 km. This is a usual assumption in all calculations of equivalent currents in the auroral zone.

b) The currents are infinitely long and flow along the corrected geomagnetic latitude circles. This is a more rigid assumption but it may be put into practice if the meridional chain of magnetic stations is sufficiently far from the electrojet edges, *i.e.* when variations in the H component are larger than those in the D

component. It means that the conditions $\delta D \sim \delta H$ gives the limit for the applicability of our method.

c) The currents flow within the latitudinal belt which extends from $\phi' = 60°$ to $\phi' = 75°$; outside of this belt the currents are equal to zero. From the mathematical point of view this is a boundary condition for our task: the current function is zero on the edges of the specified interval. From the practical point of view this condition may usually be regarded as an actual one since the equivalent currents in the subauroral and polar cap latitudes flow in quite an opposite direction than in the auroral zone and therefore the current intensity on the poleward and equatorward boundaries of the auroral electrojet must be diminished to zero.

d) The disturbances in the magnetic field are caused both by ionospheric currents and by induction currents in the Earth.

With these assumptions, the problem to divide the disturbance field into a external and internal part is resolved by using the potential theory (MALKIN, 1930). Expressing the elements of the Newtonian potential in terms of its vertical gradients we obtain

$$V(x, y, z) = \frac{1}{2\pi} \iint_{-\infty}^{\infty} \left(\frac{\partial V}{\partial \xi}\right)_{\xi=0} \frac{d\xi d\eta}{r}$$

Defining

$$X = \frac{\partial V}{\partial x} \qquad Y = \frac{\partial V}{\partial y} \qquad Z = \frac{\partial V}{\partial z}$$

the following expressions can be written:

$$\Delta X = X_e - X_i = -\frac{1}{2\pi} \iint_{-\infty}^{\infty} Z(\xi, \eta) \frac{\xi - x}{r^3} d\xi d\eta$$

$$\Delta Y = Y_e - Y_i = -\frac{1}{2\pi} \iint_{-\infty}^{\infty} Z(\xi, \eta) \frac{\eta - y}{r^3} d\xi d\eta \tag{1}$$

$$\Delta Z = Z_e - Z_i = \frac{1}{2\pi} \iint_{-\infty}^{\infty} \left[X(\xi, \eta) \frac{\xi - x}{r^3} + Y(\xi, \eta) \frac{\eta - y}{r^3}\right] d\xi d\eta,$$

where x, y are the coordinates of the observation site, ξ, η are the coordinates on the plane, X, Y, Z are the components of the observed field on the plane, X_e, Y_e, Z_e are the components of the field of external sources, and X_i, Y_i, Z_i are the components of the field of internal sources. In our two-dimensional case $Y_e = Y_i = 0$, and therefore $X = H$, where H is a horizontal component of the geomagnetic field. It should be borne in mind that we have to deal only with the equivalent currents flowing along the corrected geomagnetic latitude.

To obtain H_e and Z_e caused by ionospheric currents (external sources) the following integrals have to be calculated first:

$$\Delta H = -\frac{1}{\pi} \int_{-\infty}^{\infty} \frac{Z(l)}{l-x}\, dl\, ; \qquad \Delta Z = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{H(l)}{l-x}\, dl \tag{2}$$

These formulas are obtained from (1), utilizing the independence of η. Taking into account $\Delta H = H_e - H_i$ and $H_{\text{observed}} = H_e + H_i = H$ (and similarly to Z) we have

$$\begin{aligned} H_e &= \frac{1}{2}\left(H - \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{Z(l)}{l-x}\, dl\right) \\ Z_e &= \frac{1}{2}\left(Z + \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{H(l)}{l-x}\, dl\right). \end{aligned} \tag{3}$$

These equations usually known as Kertz equations (KERTZ, 1954) have been explored in (PUDOVKIN, 1950) where it was shown that they do not lose validity when $x = l$. We compute the integrals (3) using numerical calculation procedure.

The division of the variation field into the external and internal parts by means of a Fourier-Hilbert transformation leads to analogous expressions. However it requires a dense net of stations and much work to do. In our case we compute the integrals (3) using the extrapolated curve obtained by a SPLINE method on the basis of data obtained by stations of a meridional chain. After that we calculate the values of H_e and Z_e for concrete points of the chain and obtain a finite set of H_e, Z_e values for computation of the current function along the meridian. This method greatly simplifies the computation procedure and gives us the possibility to obtain the current intensity profiles in a short time.

The disturbances in the magnetic field at the ground level due to ionospheric currents approximated by infinitely long currents (flowing along the corrected geomagnetic latitude circle) can be expressed now by

$$\delta H_k^{th} = \mu_0 \frac{h}{2\pi} \sum_{j=1}^{M} \frac{I_j}{h^2 + (\tilde{x}_j - x_k)^2} \tag{4}$$

and

$$\delta Z_k^{th} = \frac{\mu_0}{2\pi} \sum_{j=1}^{M} \frac{I_j(\tilde{x}_j - x_k)}{h^2 + (\tilde{x}_j - x_k)^2}$$

where x_k are the coordinates of the station, $k = 1..., N$, $\tilde{x}_j$ are the coordinates of the current, $j = 1..., M$, N is the number of stations, M is the number of currents,

h is the height of currents, δH_k^{th} is the disturbance in the horizontal component of the geomagnetic field, δZ_k^{th} is the disturbance in the vertical component of the geomagnetic field, and I_j is the j^{th} current. We are faced with an inverse problem: to find I_j from the measured values δH_k and δZ_k.

We shall regard the currents to be spread at equal distances above the latitudinal belt $60° < \phi < 75°$. Our consideration of the superposition of the fixed equidistant elementary currents simplifies the problem greatly but it does not limit its generality.

The problem is solved separately for H_e and Z_e disturbance profiles. To simplify the expressions further on we shall denote $H_e \equiv \delta H$ and $Z_e \equiv \delta Z$. In a general case, the solution is reduced to the determination of the roots of the system of linear equations which result from the minimisation of the mean square deviation of the field:

$$\psi_H(I) = \sum_{k=1}^{N} [\delta H_k - \delta H_k^{th}(I)]^2 \tag{5}$$

and

$$\psi_Z(I) = \sum_{k=1}^{N} [\delta Z_k - \delta Z_k^{th}(I)]^2 \tag{6}$$

Undoubtedly such a separate calculation for δH and δZ cannot be regarded as providing independent results as the values ΔH and ΔZ are coupled by expressions (2). However a similarity of obtained results will testify the correctness of the given method. In our case the number of the currents to be determined (M) exceeds that of the initial data (N) and we are dealing with a typical underdefined problem. Therefore there must be additional constraints otherwise there will be an infinite set of solutions or an oscillating one.

Stability of a solution means that small changes in initial data should result in small changes in the solution. To get a stable solution we shall find it in a form of a smoothed current function (TIKHONOV and ARSENIN, 1974)

$$F_H(I) = \psi_H(I) + \alpha\,\Omega(I) \tag{7}$$

$$F_Z(I) = \psi_Z(I) + \alpha\,\Omega(I) \tag{8}$$

where $\Omega(I)$ is a stabilizing functional and α is an adjustment parameter determined when the discrepancies are the lowest (VERLAN and SIZINOV, 1978). If we assume that adjacent values I_{j-1} and I_j do not differ much and the distances between the current threads are equal then the stabilizing functional will be the following (YANOVSKAYA and POROKHOVA, 1983)

$$\Omega(I) = \sum_{j=1}^{M} (I_j - I_{aj})^2 + q \sum_{j=2}^{M} (I_j - I_{j-1})^2 \tag{9}$$

Parameter q characterizes the degree of the smoothness of the analysed current function and we estimate it empirically on the conditions that solution is stable. The solution is very critical to choice of parameters q and α which may be different for every concrete meridional chain of stations. In our case $\alpha = 10^{-15}\,(\mathrm{nT/A})^2$, $q = 0{,}9$, $M = 50$ and they are constant in time. Equations (5) and (6) are solved by an iteration procedure. When parameters q, α and M are choosen incorrectly the iteration procedure does not lead to convergence.

Thus finally we have to minimize *e.g.* for the H profile the expression

$$\sum_{k=1}^{N} \left[\delta H_k - \frac{\mu_0 h}{2\pi} \sum_{j=1}^{M} \frac{I_j}{h^2 (\tilde{x}_j - x_k)^2} \right]^2 +$$

$$+ \alpha \left[\sum_{j=1}^{M} (I_j - I_{aj})^2 + q \sum_{j=2}^{M} (I_j - I_{j-1})^2 \right].$$

Values of current intensity equal to zero I_{0j} are taken as initial ones in an iteration procedure for the first moment of the examined event. The values I_{aj} so obtained for every preceding moment are taken as initial ones in an iteration procedure for the next moment of the examined substorm, etc. That is why the choice of the initial values of I_{aj} does not affect the solution but only the duration of the iteration procedure. The more exact initial values are taken the shorter the duration of the computation. The process of the iteration can be finished when $(I_n - I_{n-1})/I_n < 10\ \%$. Usually the number of iterations is not more than six. Thus having a discrete set of δH_k and δZ_k at the given stations along the geomagnetic meridian, we obtain the values of M currents which are distributed with equal distances over the chosen latitudinal belt. In fact, we have determined the meridional profile of the equivalent current density.

3. *Observations*

The data of the present study come from the magnetometer and riometer stations located along the Kara Sea geomagnetic meridian. Table 1 lists the stations and their corrected geomagnetic latitudes. Each station is equipped with a riometer operating at 32 MHz and with a standard magnetometer.

Table 1.

Station	Corrected geomagnetic coordinate	
	lat.	long.
Heiss Island	74.5°	144.2°
Vise Island	73.0°	155.0°
Uyedineniya Island	71.3°	157.7°
Izvesty TSIK Island	69.9°	157.7°
Dixon	67.9°	154.0°
Sopochnaya Karga	66.5°	156.1°
Norilsk	63.4°	159.5°

4. *Results*

Using the method of data analysis described above and data from the Kara Sea chain of magnetometers the profiles of the current density have been calculated for some events.

25 April 1985:

The distribution of the current density for the time interval 07–12 UT on April 25, 1985 is shown in Fig. 1. The distribution has been calculated independently by using both δH and δZ. The same features can be identified in both panels. One notices that the equatorial boundary of the eastward electrojet shifts southwards by 4–5 degrees whereas the poleward boundary stays more stable.

5 May, 1985:

The distribution of the current density on the basis of the measurements of the H-component is shown in Fig. 2 (top panel) together with that of auroral absorption (bottom panel). It is obvious that there is a close correlation between the dynamics of the westward electrojet (negative values) and electron precipitation.

The absorption pattern shows a typical growth phase of the substorm and three onsets of the expansion phase. During the growth phase the westward electrojet moves southwards together with the region of auroral absorption. The first expansion phase starting at 18.40 UT is characterized by a sudden increase of both the electron precipitation and electric current. The precipitation region expands both to the pole and to the equator while the westward electrojet moves

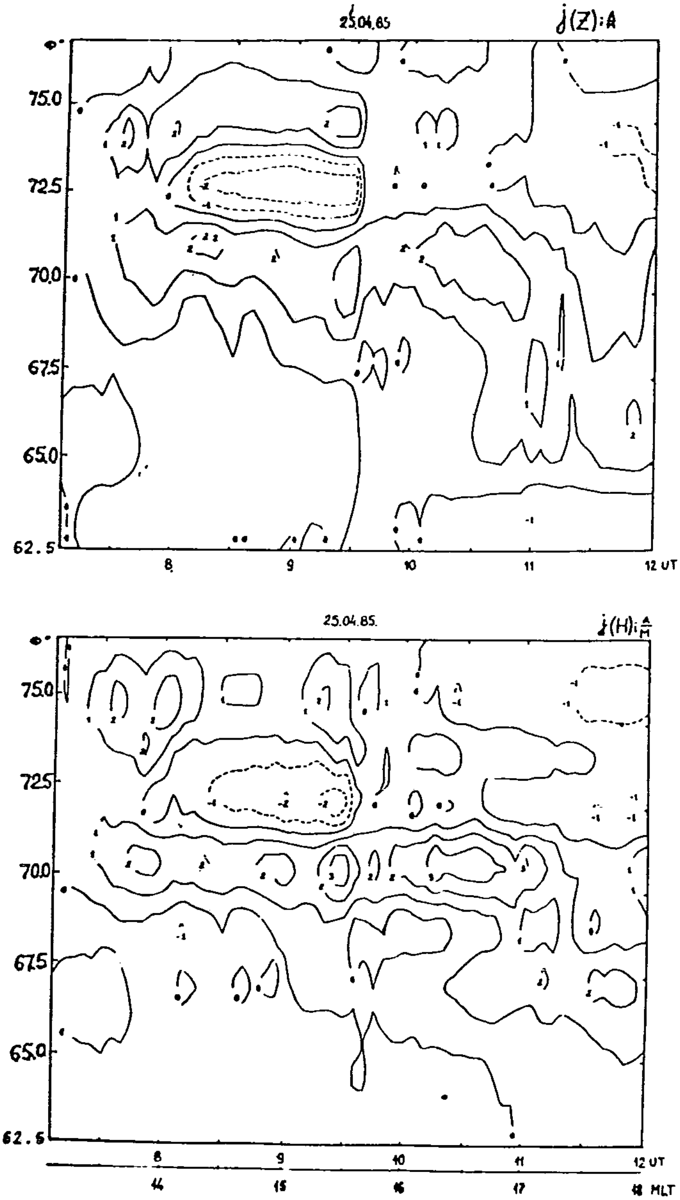

Fig. 1. Isocontour plots of the electric current density (in A/m) in the ionosphere on 25 April, 1985. Patterns have been calculated independently by using the measurements of both H and Z component of disturbance field. (Positive values: eastward electrojet, negative values: westward electrojet.)

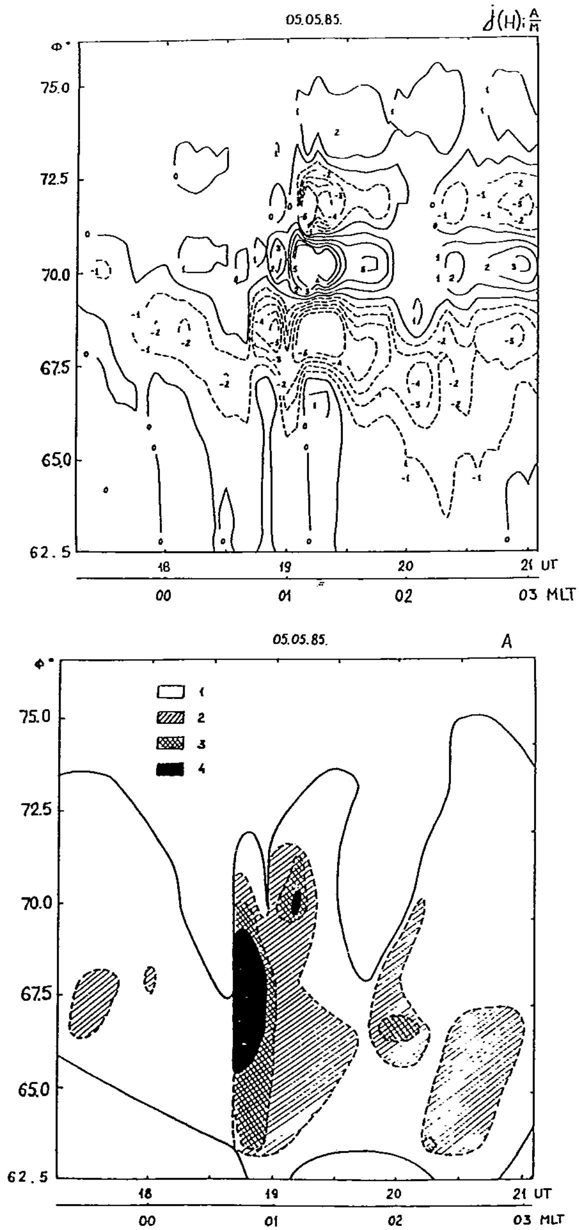

Fig. 2. Isocontour plot of the electric current density (from *H*-component, top panel) and latitudinal distribution of auroral absorption (in db, bottom panel) on 5 May, 1985 (1: A $\leqslant$ 0.5 db, 2: 0.5 $<$ A $\leqslant$ 1.0, 3: 1.0 $<$ A $\leqslant$ 2.0, 4: A $>$ 2.0 db).

only polewards. There is a considerable amount of absorption to the south from 68 degrees but only a very weak current.

The second expansion phase starts at 18.55 UT. The precipitation region spreads to higher latitudes than during the first expansion. An interesting feature of this expansion is the appearance of an eastward current between two westward currents. The eastward electrojet is located between 69 and 71 degrees.

The third expansion phase on 5 May, 1985 shows the same features as the second one. The latitudinal width of the precipitation region is, however, more extended.

6 May, 1985:

As the third example we show in Fig. 3 the distributions of the current density using both ΔH and ΔZ measurements on 6 May, 1985 together with the CNA pattern. Three expansion phases can be identified. A similar multiple current structure as on 5 May, 1985 is seen again during the last expansion. The eastward electrojet occupies the region between 69 and 72 degrees.

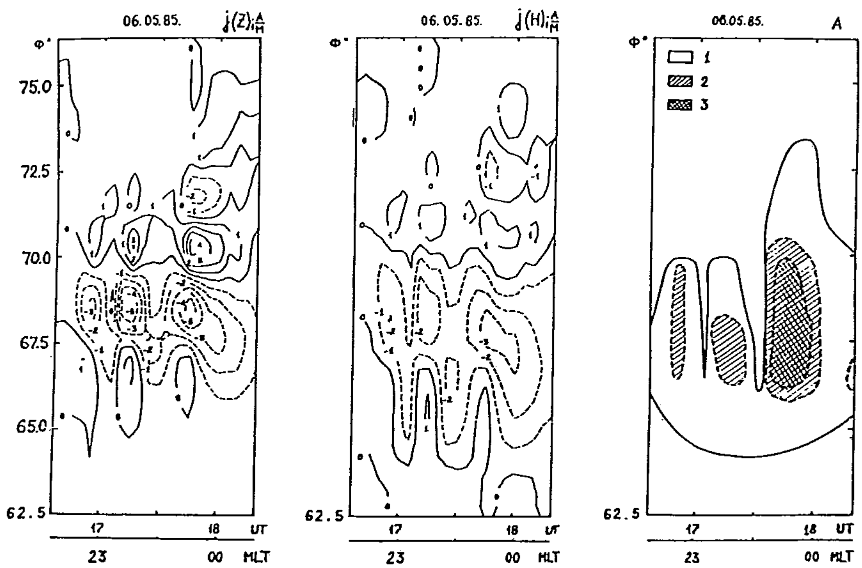

Fig. 3. The same as in Fig. 2 but for the event on 6 May, 1985. Both H and Z components have been used.

5. *Discussion*

There are two advantages in the present method in comparison with previous ones. We do not need to determine the current density function as before (Jhilenkov and Kusnetsov, 1978; Petrov, 1980; Kuznetsov and Latov, 1984). This allows a more detailed study of the fine structure of ionospheric currents. Another advantage is the division of the variation field into the fields of external and internal origin. To solve this problem by means of a Fourier-Hilbert transformation, a dense net of stations is necessary. Moreover, such a method is slow and laborious.

Three analysed cases test our method. We have applied the method independently to H and Z components. A good agreement between the distributions of the current density has been achieved and some new findings can be summarized:

1. The current structure in the midnight sector can consist of two westward electrojets with an eastward current between them.
2. The dynamics of the westward electrojet and electron precipitation region mostly coincide during the substorm. A difference is observed at the beginning of the expansion phase when the precipitation region expands both polewards and equatorwards while the westward electrojet moves only polewards.

Next we discuss the generation of multiple current structure. It is known that the meridional profile of auroral absorption may be complicated in late evening-to-midnight sector (Latov, 1978; Kuznetsov and Latov, 1984). Auroral absorption depends mainly on the electron density in the D-region whereas the currents are controlled by the conductivities in the E-region. Both regions are activated during the substorm (see *e.g.* Kuznetsov and Latov, 1984). In such a situation, the multiple structure of ionospheric currents is affected by the polarization electric fields and field-aligned currents. The polarization electric field E_p can be given by the formula

$$E_p = \Sigma_w E_0 R_j \frac{\partial^2 n}{\partial x^2}$$

where E_0 is the convection electric field, Σ_H is the height-integrated Hall-conductivity and R_j is the integrated resistance due to anomalous resistivity (see Pudovkin *et al.*, 1975), n is the electron density and x points to the south. According to the formula E_p can be quite inhomogeneous and it may even change the direction in the area of enhanced conductivity. We suggest that the multiple current structure in the midnight sector can be related to the corresponding structure of the electron precipitation into the upper atmosphere at high auroral latitudes.

REFERENCES

JHILENKOV, V.A. and B.M. KUZNETSOV, 1978: Methods for calculating parameters of auroral electrojets Geomagnetic studies, *Soviet Radio Science,* 23, 85–90.

KERTZ, W., 1954: Modelle für erdmagnetisch induzierte elektrische Ströme im Untergrund. *Nachr. Akad. Wiss. Göttingen, Math.-Phys. Kl. 2A,* 101...110.

KISABETH, I.L. and G. ROSTOKER, 1973: Current flow in auroral loops and surges inferred from ground-based magnetic observations. *J. Geophys. Res.,* 78, 5573–5584.

KUZNETSOV, B.M. and Yu.O. LATOV, 1984: The dynamics of the auroral absorption and westward electrojet during the substorm. *Magnetospheric studies,* 4, 22–25.

LATOV, Yu.O., 1977: Some features of the magnetic substorm development. *Proceedings of the AARI, 340,* 110–115.

–»– , 1978: The dynamics and structure of the westward electrojet by ground measurements. *Problems of the Arctic and Antarctic,* 53, 82–88.

MALKIN, N.R., 1930: The relationship between the gradients of Newton's potential at the plane relative to the study of gravitational and magnetic anomalies. *Izv. AN SSSR, Phys. Mat.,* 8, 757–771.

PETROV, V.G., 1980: Determination of the parameters of polar electrojets by the ground magnetic data. In: *Magnetospheric disturbances of the Earth's electromagnetic field (IZMIRAN),* 148–160.

PUDOVKIN, I.M., 1950: Using the Neiman problem to solve some questions in the practical magnetometry. *Proceedings of the RITM, 5(15),* 1–5.

–»– , RASPOPOV, O.M. and I.G. KLEIMENOVA, 1975: *The disturbances of the Earth's electromagnetic field.* Leningrad.

PYTTE, T., McPHERRON, R.L., HONES, E.W. and H.I. WEST Jr., 1978: Multiple satellite studies of magnetospheric substorms: Distinction between polar magnetic substorm and convection driven negative bays. *J. Geophys. Res.,* 83, 663–679.

SERGEEV, V.A., 1977: On the types of the events comprising magnetospheric disturbances. *Physica Solary Torrestas,* 4, 19–36.

TIKHONOV, A.N. and V.Ya. ARSENIN, 1974: *Methods to solve incorrect problem.* Moscow.

TROSHICHEV, O.A., KUZNETSOV, B.M. and M.I. PUDOVKIN, 1974: The current systems of the magnetic substorm growth and expansion phases. *Pl. Space Sci.,* 22, 1403–1412.

VERLAN', A.F. and V.S. SIZINOV, 1978: *Methods to solve integral equations with a computer.* Kiyev, Naukova Dumka.

YANOVSKAYA, T.B. and L.N. POROKHOVA, 1983: *Inverse problems in the geophysics.* Leningrad.