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A Two-Dimensional Magnetometer Array for Ground-Based Observations of Auroral Zone Electric Currents During the International Magnetospheric Study (IMS)

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Abstract. A two-dimensional magnetometer array was progressively installed in Scandinavia, from 1974 onwards, for operation during the IMS period (1977–1979). The 36 instruments, which are buried in the ground, are of the Gough-Reitzel type, i.e., classical magnetometers, with wire-suspended magnets and optical recording. The time-variation period range observable is from about 50 s to several days. In northern Scandinavia, the spacing between the stations is about 100–150 km in both the north-south and east-west directions.

For presentation and analysis of the data a special Cartesian coordinate system has been introduced (the 'Kiruna system'). It is derived by mapping the local earth's surface onto a tangential plane, with its origin close to Kiruna (geographic coordinates 67.8 N, 20.5 E).

First results from some stations show that internal contributions to the recorded horizontal geomagnetic variations are small and possibly negligible at lower frequencies. However, at frequencies above about 2 mHz the variations of the vertical component display a strong amplification near the coast, and indicate the existence of conductivity anomalies at some inland locations.

In order to demonstrate the observational capabilities of the array, equivalent overhead current configurations are presented which characterize a substorm recorded on October 7, 1976.

Key words: Magnetometer arrays – Auroral zone – Electric current systems – International Magnetospheric Study.

1. Introduction

Since the pioneering work of Birkeland (1908, 1913) geophysicists have become increasingly aware that temporal variations of the geomagnetic field within and near to the auroral zone generally display a very inhomogeneous and often rather complex spatial structure. In order to study these variations in

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greater detail, there has been a tendency to place more and more permanent or temporary magnetic observatories at high latitudes. This was true especially during the Second International Polar Year 1932–1933 and the International Geophysical Year 1957–1958. By such activities it became possible to recognize the basic larger-scale features of high-latitude magnetic disturbances (e.g., Chapman and Bartels 1940; Fukushima 1953; Akasofu 1968; Rostoker 1972).

A further important step made within the last decade was the installation of permanent or temporary north-south chains of densely spaced magnetometers. Before the IMS (International Magnetospheric Study 1977–1979), such meridian chains were installed in Alaska (Akasofu et al. 1971), Canada (Kisabeth and Rostoker 1971; Chen and Rostoker 1974), Greenland (Wilhjelm and Friis-Christensen 1976; Wilhjelm et al. 1978), north-eastern Scandinavia (Maurer and Theile 1978), and along two geomagnetic meridians in the northern part of the Soviet Union (Loginov et al. 1978). Whereas the Greenland chain led to a considerable improvement in our knowledge of polar cap magnetic variations, results from the Canadian meridian chain have been especially important in revealing the detailed temporal and spatial behaviour of auroral electrojets (e.g., Kisabeth and Rostoker 1971; Rostoker and Kisabeth 1973; Kisabeth and Rostoker 1974; Wiens and Rostoker 1975; Rostoker and Hron 1975; Hughes and Rostoker 1977). Data from the Alaska chain especially were used to investigate the relationship between auroral electrojets and field-aligned currents (Yasuhara et al. 1975; Kamide and Akasofu 1976; Kamide et al. 1976; Kamide and Rostoker 1977).

Meridian chains of magnetometers are naturally inadequate if it is intended to study magnetic disturbances whose spatial variation in the east-west direction is as large as the meridional variation. In certain cases, this disadvantage may be circumvented by assuming that the observed local time behaviour reflects the unobserved dependency on east-west coordinates. However, to date little is known about short-lived magnetic disturbances which occur during a magnetic substorm and which are highly localized in both horizontal directions. For example, such disturbances may be related to auroral events such as the westward traveling surge, the midnight break-up region, and spirals (Kisabeth and Rostoker 1973; Untiedt et al. 1978). The near-midnight sector of the Harang discontinuity (Heppner 1972), i.e., the region near the eastward end of the afternoon-evening sector eastward electrojet, may also be considered as another important example within this context. A recent publication by Kawasaki and Rostoker (1979) should also be mentioned. These authors present first results derived from a magnetometer array which consists of an east-west and a north-south chain of 7 stations altogether. Their observations particularly include regions of large magnetic perturbations associated with eastward drifting auroral structures.

In this paper, we will report on a two-dimensional array of 32 (later 36) magnetometers which has been installed within and near the Scandinavian auroral zone for ground-based observations of near-earth electric currents throughout the International Magnetospheric Study (IMS). In July–September, 1974, a similar array was operated in Canada, at comparable geomagnetic latitudes, by Bannister and Gough (1977, 1978; see also Gough and Bannister 1978). However, we believe that the Scandinavian Magnetometer Array is of special value because its supporting role in the IMS offers unique opportunities for cooperation and multi-method studies. Furthermore, it is important that this array is operated throughout the winter when simultaneous optical observations of the aurora within the same area are possible.

2. The Magnetometers and Their Arrangement

The instrument on which our array is based is of the Gough-Reitzel type (Gough and Reitzel 1967), with important modifications as partly described by Küppers and Post (1979). As in the case of classical magnetometers, the deflections of three wire-suspended magnets are optically recorded on 35 mm film. The exposure is intermittent. Its sequence has a 10-s period (except for our southernmost stations where it is 20 s), controlled by a quartz clock. To avoid aliasing effects, the magnets are partly surrounded by copper blocks which provide for strong electromagnetic damping of higher frequency oscillations. At a period of 100 s the amplitude attenuation is already negligible whereas phase distortion is of the order of 10 degrees (Küppers and Post 1979). The whole instrument, including camera, battery, and electronic control device, is housed within a 1.6-m-long airtight aluminium tube, which is buried in the ground. With the use of both a 10 s exposure cycle and Kodak RAR 2498 film, the magnetometer operates unattended for approximately 73 days. After that time, servicing is implemented, including (i) changing the rechargeable 7.5 Ah battery, (ii) changing the camera (with film), (iii) examination of the automatic calibration currents, (iv) measurement of the clock error, (v) readjustment of the quartz oscillator frequency (if necessary), (vi) resetting the clock (also only if necessary), and (vii) examination of the light traces of the three magnetic field components (position and mobility). On average, the observed clock errors are less than 5 s. Even if the assumption that the clock error is a linear function of time between two subsequent services may be rather simplistic, a time accuracy to within a few seconds can be assumed for all cases.

In general the scale values of the magnetometers are of the order of 40 nT mm^{-1} on film and are known within 0.5%. The optical resolution of the recorded traces is about 0.05 mm. The scale value and the optical resolution give a magnetic resolution of about 2 nT.

Every sixth hour (or twelfth for 20 s cycle instruments) during operation, calibration fields are applied automatically to the three components by means of small Helmholtz coils surrounding each magnet. For all three components, the range of the observable magnetic field variations is increased by adding a parallel auxiliary trace from a virtual second light source (obtained by mirror splitting). For typical instruments, the total range is about $-1{,}500$ nT to $+1{,}000$ nT for H, -500 nT to $+1{,}000$ nT for D, and -800 nT to $+1{,}200$ nT for Z, with reference to the undisturbed levels. Figure 1 illustrates a short section of film record which includes a calibration and the appearance of two auxiliary traces.

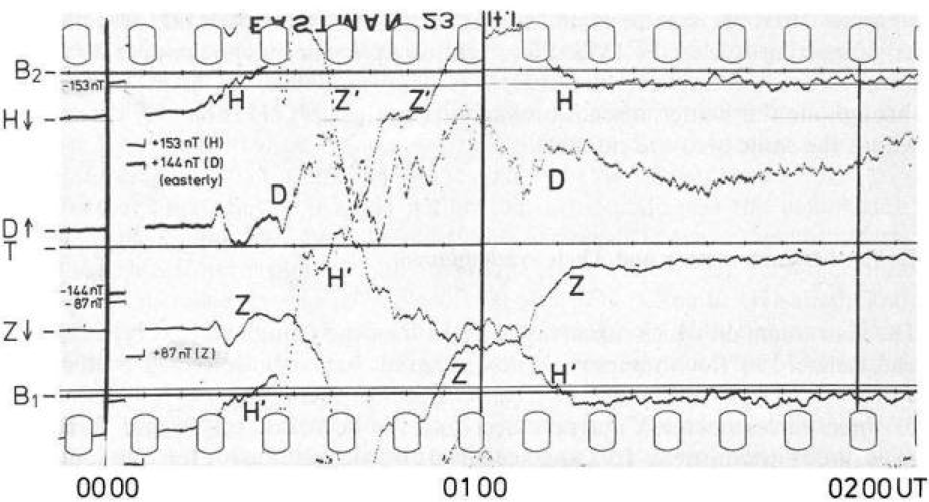


Fig. 1. Example of a record, from July 29, 1977, and station EVE (cf. Fig. 2). *H*, *D*, *Z* main traces; *H'*, *Z'* auxiliary traces; B_1, B_2 base lines; *T* temperature trace. Note that the 0000 UT time mark is a little stronger (due to longer exposure) than other hour marks. Every sixth minute the recording points are also stronger than normal. Between 0000 UT and 0006 UT calibration fields (cf. indicated values) have been applied

At the north German magnetic observatory of Wingst the three recording magnets of each magnetometer were aligned to their correct orientations with reference to magnetic north and to vertical, and the calibration coil constant (in nT mA^{-1}) for each component of each instrument was determined. At the recording site, the instrument is levelled and rotated around its vertical axis until the *D* component light trace is at the correct position. In this orientation, the variations of the local magnetic north (*H*), east (*D*), and vertical (*Z*) components are recorded. In order to convert the measured local field variations to the geographically oriented system, the local declination has to be known. This quantity (cf. Table 1 below) was measured as often as possible at the location of each magnetometer by means of a compass theodolite. To avoid errors due to a large difference between the static magnetic field at the magnetometer and the field at the theodolite, stations were installed with preference to locations where the static magnetic field gradient was less than 1 nT m^{-1} (as indicated from observations with a torsion balance).

Burying the instruments in the ground protects them from the very low temperatures in winter time. During operation, the temperatures within our instruments have never fallen below $-5°$ C. This avoids corresponding malfunction of cameras, batteries, and electronics. Furthermore, it is important that due to the very effective shielding of the ground, daily temperature variations are not able to influence our measured data in any appreciable way (Küppers and Post 1979). In order to facilitate an analysis of daily or longer variations, the majority of the instruments contains a bimetallic strip temperature sensor, the variation of which is also recorded on the film (cf. Fig. 1).

Table 1. List of stations from the Scandinavian Magnetometer Array of the University of Münster

Symbol	Name	Country	Geographic		Rev. Corr. Geom.		x_{KI} (km)	y_{KI} (km)	γ_{KI} (deg)	D (deg)	Installation
			Lat.	Long.	Lat.	Long.					
MAL	Malöy	N	62.18	5.10	60.67	88.99	−350	−887	26.2	−6.5	76/9
HEL	Hellvik	N	58.52	5.77	56.75	87.44	−735	−1033	25.5	−3.9	76/9
KLI	Klim	DK	57.12	9.17	54.96	89.37	−961	−911	22.4	−6.0	76/10
NAM	Namsos	N	64.45	11.13	62.24	94.95	−239	−509	20.8	−2.9	76/9
FLO	Flötningen	S	61.88	12.23	59.55	94.13	−527	−557	19.8	−1.0	78/7
ARV	Arvika	S	59.60	12.60	57.19	93.18	−774	−623	19.4	−1.9	76/9
ESM	Esmared	S	56.74	13.22	54.16	92.35	−1089	−694	18.7	−1.5	78/7
FRE	Fredvang	N	68.08	13.17	65.67	99.20	108	−285	19.0	−0.5	76/9
GLO	Glomfjord	N	66.90	13.58	64.44	98.55	−20	−311	18.6	−1.2	75/10
OKS	Okstindan	N	65.90	14.27	63.37	98.29	−136	−317	18.0	−0.4	76/9
RIS	Risede	S	64.50	15.13	61.89	97.95	−296	−326	17.2	−0.5	76/9
HAS	Hassela	S	62.07	16.50	59.35	97.45	−575	−338	15.9	0.5	76/9
AND	Andenes	N	69.30	16.02	66.62	102.38	202	−134	16.4	−0.1	76/9
EVE	Evenes	N	68.53	16.77	65.79	102.22	112	−129	15.7	0.4	76/9
RIJ	Ritsemjokk	S	67.70	17.50	64.90	102.06	15	−124	15.0	−1.1	76/9
KVI	Kvikkjokk	S	66.90	17.92	64.07	101.72	−75	−130	14.6	4.0	76/9
SRV	Storavan	S	65.78	18.18	62.93	101.04	−198	−150	14.4	1.7	76/9
LYC	Lycksele	S	64.57	18.68	61.67	100.55	−335	−160	13.9	1.3	76/9
MIK	Mikkelvik	N	70.07	19.03	67.14	105.12	255	0	13.6	0.7	74/8
ROS	Rostadalen	N	68.97	19.67	65.99	104.64	130	−4	13.0	2.7	74/8
KIR	Kiruna	S	67.83	20.42	64.80	104.27	0	−2	12.3	0.0	74/12
NAT	Nattavaara	S	66.75	21.00	63.67	103.82	−122	−3	11.8	3.0	74/8
PIT	Pitea	S	65.25	21.58	62.16	103.22	−291	−10	11.3	5.1	74/8
HOP	Hööpaka	SF	63.01	22.56	59.86	102.60	−545	−11	10.4	3.0	78/7
SOY	Söröya	N	70.60	22.22	67.39	107.94	287	129	10.6	4.4	75/10
MAT	Mattisdalen	N	69.85	22.92	66.62	107.77	200	139	10.0	4.5	75/10
MIE	Mieron	N	69.12	23.27	65.86	107.40	118	139	9.7	4.7	75/10
MUO	Muonio	SF	68.03	23.57	64.75	106.70	−2	131	9.4	4.7	75/10
PEL	Pello	SF	66.85	24.73	63.47	106.59	−140	159	8.3	5.5	75/10
OUL	Oulu	SF	65.10	25.48	61.77	106.07	−337	166	7.7	5.1	75/10
JOK	Jokikylä	SF	63.77	26.13	60.39	105.73	−488	177	7.1	7.5	75/10
SAU	Sauvamäki	SF	62.30	26.65	58.82	105.32	−654	184	6.7	5.1	75/10
BER	Berlevag	N	70.85	29.13	67.16	113.10	282	384	4.2	8.2	76/9
VAD	Vadsö	N	70.10	29.65	66.42	112.75	197	397	3.7	7.1	76/9
SKO	Skogfoss	N	69.37	29.42	65.70	111.95	117	383	3.9	8.8	76/9
RKS	Roksä	SF	62.57	30.26	58.95	108.29	−640	372	3.4	6.9	78/7

Country: DK Denmark, N Norway, S Sweden, SF Finland

Revised corrected geomagnetic coordinates according to Gustafsson (1970). x_{KI}, y_{KI} coordinates in the Kiruna system (cf. Fig. 2 and text)

γ_{KI} westerly deviation of the local parallel to the positive x_{KI} axis from geographic north

D measured or adopted (from published data, magnetic maps etc.) value of magnetic easterly declination

The last column gives year and month of installation. Most stations are scheduled for operation until spring 1980

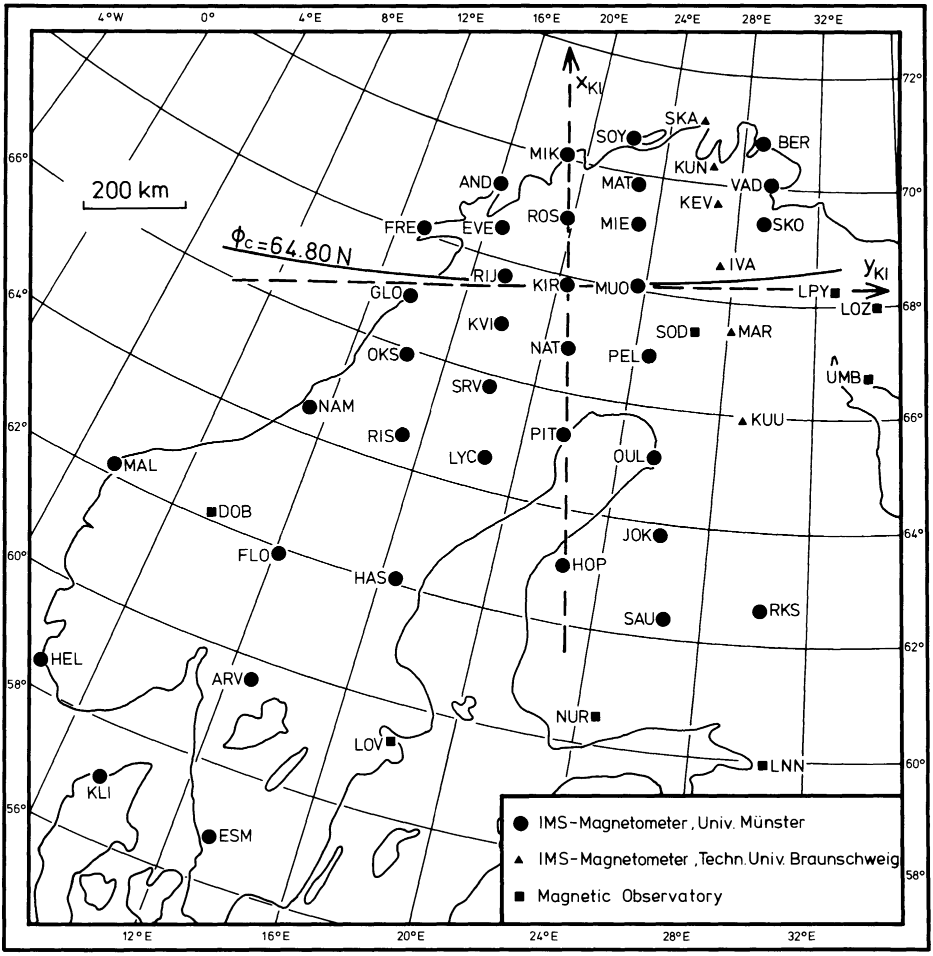


Fig. 2. Station map in geographic coordinates. Also indicated are the axes of the Kiruna system (cf. Sect. 3), and the line of constant revised corrected geomagnetic latitude $\Phi_c = 64.80$ N (after Gustafsson 1970)

Usually magnetic variations at high latitudes are studied with reference to a quiet time level. Because a large time interval of many days may exist between the magnetic event which is of interest (e.g., a specific substorm) and the closest quiet day, errors may be induced by magnetometer drifts. For most of our instruments, these drifts are caused mainly by annual temperature variations and are less than 0.1 nT/day (B. Inhester, personal communication). Occasionally, our Z components show strong anelastic behaviour. However, even in these cases the drifts are rarely larger than 1 nT/day and may easily be recognized and eliminated during data analysis by comparing the quiet time levels recorded by adjacent instruments.

The spatial distribution of our magnetometers is shown in Fig. 2, and their geographical coordinates, with other relevant information, are given in Table 1.

Most of the instruments are approximately situated along straight lines perpendicular to the lines of constant revised corrected geomagnetic latitude, as given by Gustafsson (1970). It was considered that such an arrangement would ease the analysis of the data since it could be anticipated that electrojets flowing approximately parallel to the auroral oval would predominate. In northern Scandinavia (down to LYC and OUL, cf. Fig. 2), which is situated under the statistical auroral oval around magnetic midnight, and where accordingly the most inhomogeneous magnetic field variations could be expected to occur, the spacing of our stations along the north-south lines is least and is 120 km on average. Such a separation between stations was chosen with regard to the fact that external magnetic fields with horizontal wavelengths of less than 200 km are appreciably depressed (according to the factor e^{-kh}, where $k=2\pi\lambda^{-1}$, λ is the wavelength, and $h\sim 100$ km) between the ionosphere and the ground. The results from the University of Alberta meridian chain (e.g., Kisabeth and Rostoker 1971; Rostoker and Kisabeth 1973) suggested a similar spacing. Because it was anticipated that in interesting cases east-west gradients might be as important as north-south gradients, the distance between adjacent north-south profiles was also chosen to be not much greater than 120 km. Note that this spacing is not latitude invariant because of the convergence of the profiles toward north. At the geomagnetic latitude of stations GLO-MUO (Fig. 2) this longitudinal spacing is on average 150 km.

In north-eastern Scandinavia our array is supplemented by a north-south chain of 6 digital three-component fluxgate magnetometers operated during the IMS by the Technical University of Braunschweig (Maurer and Theile 1978). The remainder of our instruments are distributed over the southern half of Scandinavia with a much wider separation between stations. Together with the existing permanent magnetic observatories, these southern stations are valuable for studying, e.g., apparent return currents of auroral electrojets, far-field effects of field-aligned currents, and electrojets flowing during phases of strong auroral oval expansion. To the north-east, it is important that the Polar Geophysical Institute at Apatity (USSR) is operating several magnetometer stations on the Kola peninsula (Fig. 2).

Our array ends abruptly at the northern coast of Scandinavia (revised corrected geomagnetic latitude 67.4 N) and thus the two Norwegian permanent magnetic observatories on Bear Island (BJN) and on Spitsbergen (NAL) are invaluable for our studies. BJN is approximately situated on our station line SAU-SOY, about 450 km to the north of SOY.

The array, which is scheduled to be in operation until spring 1980, was installed in steps, with the first north-south chain (MIK-PIT) recording from autumn 1974, and with the last stations (FLO, ESM, HOP, and RKS) added in July 1978 (cf. Table 1).

3. The Kiruna System of Coordinates and Magnetic Field Components

The main purpose of the present array is detection and analysis of local magnetic disturbance fields. Any analysis of the data by methods based on potential theory (e.g., separation into internal and external parts, or field continuation towards the source, Mersmann et al. 1979) is greatly eased if Cartesian coordinates and corresponding field components may be used. Such a *local* system, which is applicable only to data from the Scandinavian region, will now be described and will be called the 'Kiruna system'.

When defining this system, our basic postulates have been that the spherical earth's surface of the Scandinavian region should be projected onto a tangential plane by conformal mapping, and that the magnetic potential at a projected point should be equal to the potential before projection. As the common point of the sphere and of the tangential plane, and as the origin of the new coordinate system, we have chosen the station Kiruna (KIR, cf. Fig. 2), i.e., a point approximately in the middle of our array. The horizontal axes of the Kiruna system have been defined to be related to a line of constant revised corrected geomagnetic latitude Φ_c (Gustafsson 1970) in approximately the manner in which the geographic north and east directions are related to circles of geographic latitude.

The transformation of an arbitrary point P given by geographic colatitude θ and longitude λ and of its northward and eastward magnetic disturbance field components X and Y to the Cartesian coordinates x_{KI} and y_{KI} and to the corresponding field components A and B, respectively, is undertaken via the following steps:

(a) Instead of the geographic pole, KIR is adopted to be the pole of a new spherical system. Accordingly, the spherical coordinates θ_{KI} and λ_{KI} will be attributed to P. The new magnetic horizontal components are X_{KI} (pointing towards 'north' of the new system, i.e., towards KIR) and Y_{KI} (towards 'east'). They are the result of a rotation around the vertical axis at P. The new meridian $\lambda_{KI}=0$ is defined in such a way that it is perpendicular to the line $\phi_c=64.80$ N which passes through KIR (Gustafsson 1970), and that it turns approximately towards *south* from KIR.

(b) P is now transformed to P', a point on the tangential plane with the desired Cartesian coordinates x_{KI} and y_{KI}, by means of a stereographic projection (cf. Fig. 3a and b), according to

$$x_{KI}=-2R_E \tan(\theta_{KI}/2)\cos\lambda_{KI}$$
$$y_{KI}=2R_E \tan(\theta_{KI}/2)\sin\lambda_{KI}$$

where $R_E=6{,}371$ km is the adopted value of the earth's radius.

Simultaneously, the horizontal magnetic components are transformed according to

$$X'_{KI}=\cos^2(\theta_{KI}/2)\,X_{KI}$$
$$Y'_{KI}=\cos^2(\theta_{KI}/2)\,Y_{KI}$$

where the X'_{KI} and Y'_{KI} field components lie within the tangential plane (see Fig. 3a), and the X'_{KI} component points towards KIR. The factor $\cos^2(\theta_{KI}/2)$ provides for constancy of the magnetic potential (see above).

(c) By a rotation within the tangential plane (Fig. 3b) at the point P', we obtain the final horizontal magnetic field components

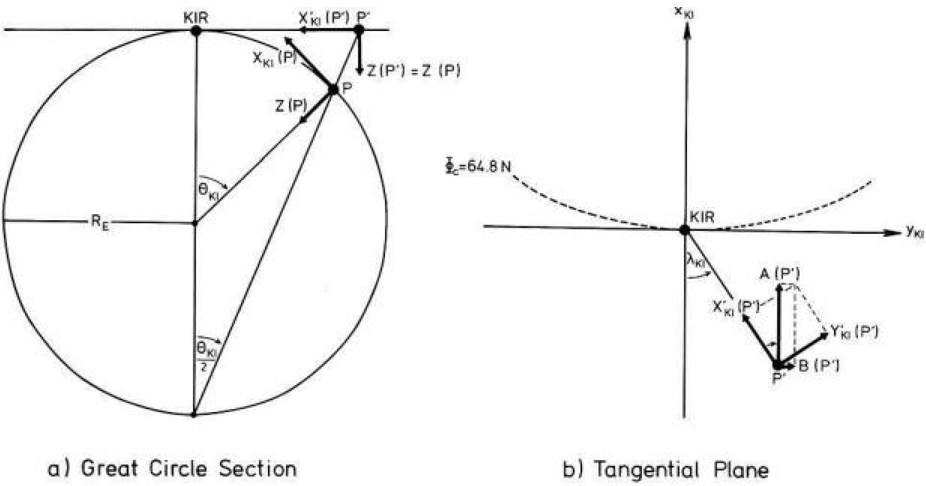


Fig. 3. Diagrams illustrating the derivation of the Kiruna system

$$A = X'_{\mathrm{KI}} \cos \lambda_{\mathrm{KI}} + Y'_{\mathrm{KI}} \sin \lambda_{\mathrm{KI}}$$
$$B = -X'_{\mathrm{KI}} \sin \lambda_{\mathrm{KI}} + Y'_{\mathrm{KI}} \cos \lambda_{\mathrm{KI}}$$

which are directed parallel to the x_{KI} and y_{KI} axes, respectively.

The vertical component Z remains unchanged throughout. Because we intend to apply this system only to data from Scandinavia, the factors representing spatial distortion or field reduction within the above equations may be assumed to be close to unity. For a station in southern Scandinavia, θ_{KI} may be 8°, for example. In this case, the distortion or reduction factors are, respectively, (for the first factor, cf. Fig. 3a)

$$2 \tan (\theta_{\mathrm{KI}}/2)/\theta_{\mathrm{KI}} = 1.0016, \quad \cos^2 (\theta_{\mathrm{KI}}/2) = 0.9951,$$

if θ_{KI} has been transformed into radians. Hence, only the rotations involved within the different steps of the transformation are important for our purposes.

For the horizontal magnetic disturbance field, the sequence of the above rotations is described completely by the angle γ_{KI}, which gives the westward deviation of the local A component direction (parallel to the x_{KI} axis, cf. Fig. 2) from geographic north. Together with the x_{KI} and y_{KI} coordinates, this angle is given in Table 1 for our array stations, and in Table 2 for other magnetic stations within and near the Scandinavian region.

4. Internal Contributions From Induced Currents

It would require much consideration if the magnetic variations recorded in Scandinavia were appreciably influenced by the magnetic fields from electric currents induced in the earth's crust and upper mantle, especially if conductivity anomalies were present (Gough 1974; see also discussion at the occasion of

Table 2. List of other magnetic stations in the Scandinavian region. For explanations, see Table 1

Symbol	Name	Country	Geographic		Rev. Corr. Geom.		x_{KI} (km)	y_{KI} (km)	γ_{KI} (deg)	Type of Station
			Lat.	Long.	Lat.	Long.				
DOB	Dombas	N	62.07	9.12	60.07	91.89	−448	−701	22.6	PMO
LOV	Lovö	S	59.35	17.83	56.43	97.12	−888	−348	14.7	PMO
TRO	Tromsö	N	69.67	18.95	66.75	104.77	212	− 13	13.7	PMO
NUR	Nurmijärvi	SF	60.50	24.65	57.05	102.88	−839	51	8.5	PMO
NAL	Ny Alesund	N	78.92	11.93	75.89	114.65	1260	87	20.5	PMO
BJN	Bear Island	N	74.52	19.02	71.34	110.34	736	116	13.7	PMO
SOD	Sodankylä	SF	67.37	26.63	63.90	108.47	− 93	248	6.6	PMO
SKA	Skarsvag	N	71.12	25.83	67.61	111.04	324	268	7.3	TMS (TUB)
KUN	Kunes	N	70.35	26.52	66.84	110.79	236	282	6.6	TMS (TUB)
KEV	Kevo	SF	69.75	27.03	66.23	110.61	167	294	6.2	TMS (TUB)
IVA	Ivalo	SF	68.60	27.47	65.05	109.94	38	298	5.8	TMS (TUB)
MAR	Martti	SF	67.47	28.28	63.90	109.76	− 89	320	5.1	TMS (TUB)
KUU	Kuusamo	SF	65.92	29.05	62.37	109.24	−264	339	4.4	TMS (TUB)
LNN	Leningrad	USSR	59.95	30.70	56.22	107.44	−934	379	3.1	PMO
RYB	Rybachy	USSR	69.90	31.90	66.09	114.23	171	482	1.6	TMS (PGIA)
LPY	Loparskaya	USSR	68.25	33.08	64.37	113.87	− 13	525	0.6	PMO
LOZ	Lovozero	USSR	67.98	35.02	64.08	115.10	− 42	606	−1.1	PMO
UMB	Umba	USSR	66.70	34.50	62.88	113.82	−185	586	−0.6	TMS (PGIA)

Type of station: PMO permanent magnetic observatory. TMS temporary (IMS) magnetic station, from Technical University of Braunschweig (TUB) or Polar Geophysical Institute at Apatity (PGIA)

the planning of North-American IMS magnetometer stations by Camfield and Gough 1976 and Lanzerotti and Sugiura 1976). Such influences would hinder a rather direct interpretation of observed magnetic fields in terms of ionospheric and near-earth magnetospheric currents, and would necessitate a field separation into internal and external parts for every study. Because of the large spacing (100–150 km) between stations, such a separation of the observed magnetic variations would not give reliable results if conductivity anomalies of a smaller scale were of importance. Fortunately, it appears from initial analyses of our data that internal contributions to the observed magnetic disturbance fields are small, or at least rather homogeneous, except for higher frequency variations near the coast. To a first approximation, the internal field may be neglected for the horizontal magnetic components. Preliminary arguments will be given in this section. A thorough analysis including an investigation of the electrical conductivity structure under Scandinavia will need appreciable effort, including magnetotelluric measurements, and is beyond the scope of this paper.

The first technique employed by us to obtain information on the importance of internal contributions to the observed magnetic fields was a two-dimensional field separation (Kertz 1954; Siebert and Kertz 1957; the formalism may also be found in Mersmann et al. 1979). Such a separation is only possible if, at the earth's surface, a field is observed which is a function of the vertical coordinate z and one horizontal coordinate (e.g. $\tilde{x}$) only. The corresponding magnetic components may be Z and $\tilde{A}$. From $\partial \tilde{A}/\partial \tilde{y}=0$, together with Maxwell's first

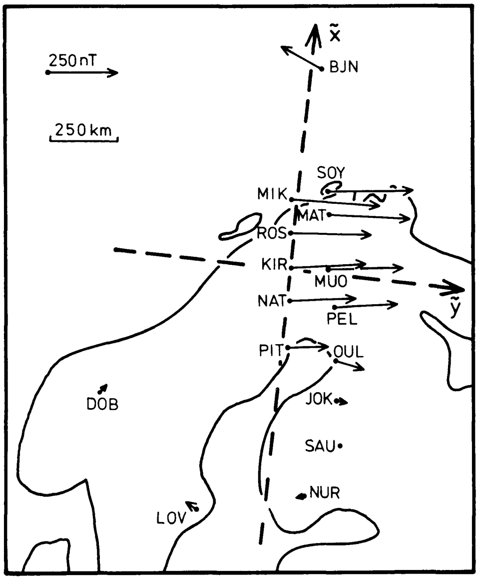


Fig. 4. Equivalent overhead current vectors (at height zero, in nT) on April 7, 1976, 1336 UT. The rotated system $\tilde{x}$, $\tilde{y}$ (the corresponding magnetic components are $\tilde{A}$, $\tilde{B}$) mentioned in the text is also shown

equation and the absence of any current flowing immediately above the earth's surface, it follows that $\partial\tilde{B}/\partial\tilde{x}=0$, i.e., $\tilde{B}=$constant along an $\tilde{x}$ profile, where $\tilde{y}$ and $\tilde{B}$ denote the remaining Cartesian coordinate or component, respectively. It should be noted that the formalism given by Kertz (1954) and Siebert and Kertz (1957) renders no physically significant separation of any quasihomogeneous part of $\tilde{A}$ or Z, since this part is formally bisected upon separation.

A local, approximately two-dimensional disturbance field may be found at certain stages of an individual substorm. A typical example is illustrated in Fig. 4 which shows the distribution of equivalent overhead current vectors (horizontal magnetic disturbance vectors turned 90 degrees clockwise) at 1336 UT on April 7, 1976, when two magnetometer chains, later forming a part of our array, were already operating. The disturbance field components have been defined as deviations from the 12–15 UT field recorded on March 22, 1976, which was the very quiet day closest to the day under consideration. The digitized magnetic data from each station were low-pass filtered, with a cut-off frequency of 4 mHz, in order to avoid errors introduced by non-two-dimensional disturbance fields in the pulsation frequency band (see below). The pattern described by Fig. 4 changes rather slowly within some tens of minutes. It shows an eastward electrojet above northern Scandinavia, but deviations from two-dimensionality are indicated to the south (NUR-OUL) and to the north (BJN). The $\tilde{x}$ axis, which is delineated in Fig. 4, was determined by minimizing the average value of $(\partial\tilde{B}/\partial\tilde{x})^2$ along the two chains of stations.

For these two chains, the observed $\tilde{x}/\tilde{A}$ and Z magnetic field components are given in Fig. 5, together with their internal parts as calculated by two-dimensional field separation. Although the applied interpolation and extrapolation of the observed field values may be somewhat unrealistic, especially to

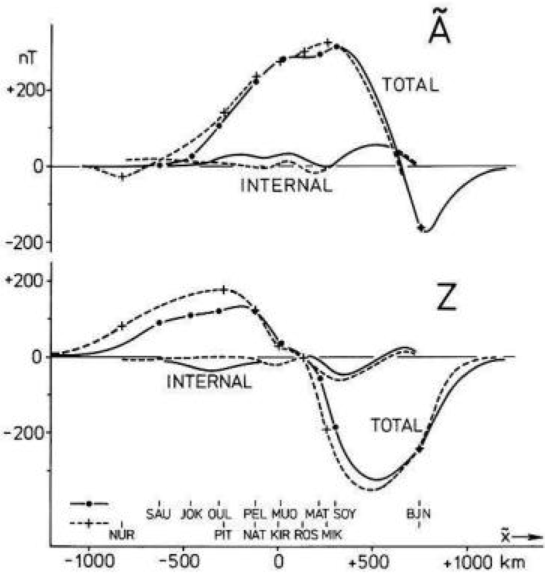


Fig. 5. Low-pass filtered magnetic disturbance components $\tilde{A}$ and Z along two approximately parallel north-south station chains (cf. Fig. 4), and the corresponding internal parts after separation, on April 7, 1976, 1336 UT. For $\tilde{A}$, see caption to Fig. 4; Z vertical component (positive downward). Observed values indicated (*crosses*: station chain NUR-MIK-BJN; *dots*: station chain SAU-SOY-BJN; cf. bottom of figure)

the far north where data were available only from one station (BJN), and although the two chains give slightly different results, it is apparent that there are no important internal disturbance field contributions present at lower frequencies within this region of Scandinavia. Note that another form of extrapolation, which would correspond to a broader westward electrojet to the north, would yield a nearly constant internal part of the order of not more than a few tens of nanoteslas, for both $\tilde{A}$ and Z, over the area of interest. The result from the analysis of another field disturbance recorded by the same two chains of stations, which supports the present conclusion, may be found in a recent paper by Mersmann et al. (1979).

Preliminary analyses of data, recorded by the whole array, utilizing the more usual Geomagnetic Depth Sounding (GDS) techniques (for a description of some of these methods see, for example, Lilley 1975), additionally showed that low frequency magnetic variations over the whole of northern Scandinavia do not indicate the presence of strong anomalies of internal conductivity structure. Also inspection of equivalent current vector diagrams derived from various magnetic events reveals no recognizable distortion of the vector patterns due to internal contributions. Hence, we are confident that at frequencies below about 2 mHz the measured horizontal magnetic fields in northern Scandinavia are not grossly perturbed by internal currents.

Unlike this slowly varying part of magnetic disturbances, the Z component of higher frequency fluctuations exhibits large internal contributions, especially

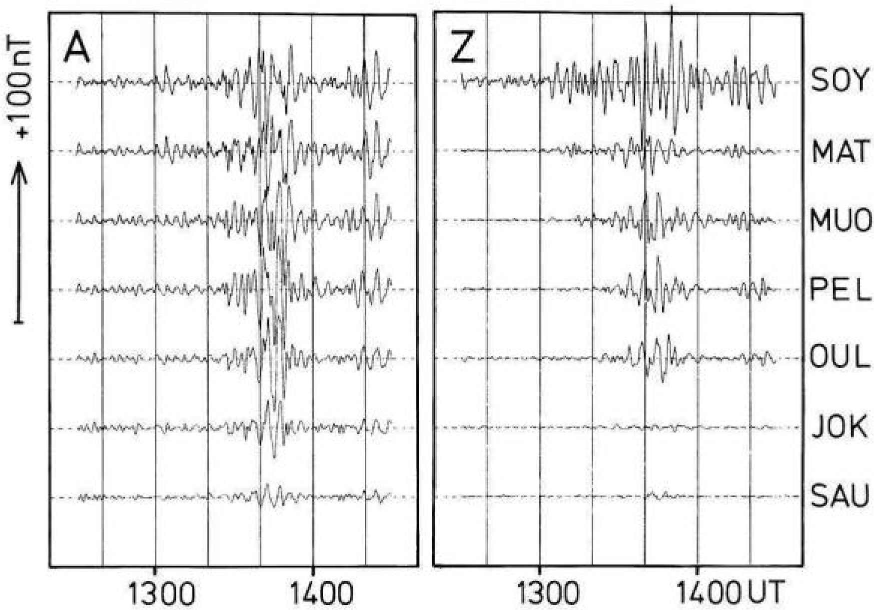


Fig. 6. High-pass filtered (≥ 4 mHz) magnetic variations on April 7, 1976, along the eastern chain of the two station chains shown in Fig. 4. *A* denotes the component along the x_{KI}-axis (cf. Fig. 2) of the Kiruna system; *Z* vertical component

near the coast. This feature is demonstrated by Fig. 6, which gives for the previously mentioned substorm of April 7, 1976, the high-pass filtered (cut-off frequency 4 mHz) *A* and *Z* variations for the chain of stations SAU-SOY (cf. Fig. 2 or 4). The *B* component is not presented here because qualitatively it behaves similarly to the *A* component shown. It is apparent that the rapid *Z* fluctuations are amplified appreciably at the coastal station of SOY. The presence of a strong coast effect within the *Z* component in northern Scandinavia has been recognized for some time by workers who have studied geomagnetic pulsations within this region (O. Hillebrand and E. Steveling, Göttingen, personal communication).

In addition, Fig. 6 shows the remarkable feature that the amplitudes of the *Z* variations are appreciably attenuated to the south of OUL. Because no corresponding drastic effect is seen in the *A* and *B* components, and because we have found a similar attenuation of *Z* high frequency activity within the same region in another case studied, we conclude that at some depth (10–100 km) within the crust or upper mantle the electrical conductivity below southern Finland is larger than that to the north (Schmucker 1973).

During the break-up phase of an auroral substorm (Akasofu 1968) near magnetic midnight at high latitudes large amplitude magnetic disturbance fields seem to be 'switched on' within a few minutes (e.g., Untiedt et al. 1978). It might be expected that such disturbance fields with a large high-frequency content exhibit anomalous amplification of the *Z* component at coastal stations, as geomagnetic pulsations do. Figure 7 illustrates that this indeed is observed.

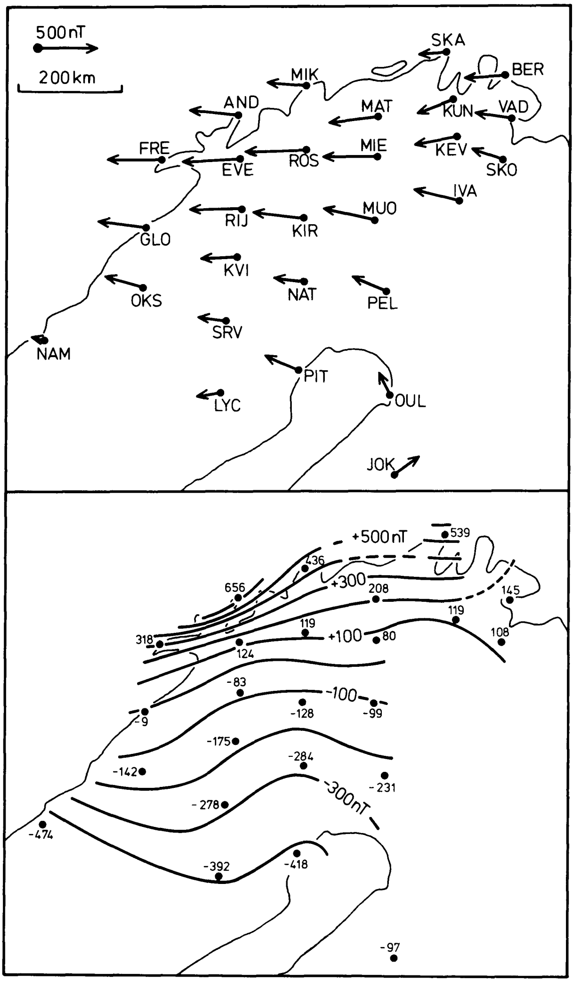


Fig. 7. Differential magnetic disturbances (values at 2147 UT minus values at 2140 UT) on December 2, 1977, from an interval of time which included a strong magnetic onset. *Top:* Equivalent current vectors (cf. Fig. 4). *Bottom:* Z values and isolines. Due to partial malfunction of instruments there are no Z values for some stations

This figure is based on the magnetic observations during an intense substorm occurring on the evening of December 2, 1977, when the auroral oval was largely expanded. At 2141 UT (~0010 MLT, according to Whalen 1970) an intense auroral break-up was observed above OUL (H.J. Opgenoorth and R. Pellinen, personal communication). Before that time a westward equivalent current flow corresponding to 200–300 nT was concentrated above southern Finland. Probably in connection with the break-up and the subsequent poleward auroral expansion (Akasofu 1968) which was also observed, a strong (up to 500 nT in the horizontal components) *additional* magnetic disturbance field was 'switched on' between 2140 and 2147 UT for which the equivalent overhead current vectors are given in Fig. 7 (top). The pattern describes a westward electrojet current flow concentrated above northern Scandinavia and some current loop in the south, possibly related to the auroral break-up (Untiedt et al. 1978). The corresponding distribution of the additional Z disturbances (Fig. 7, bottom) shows a concentration of Z isolines especially near the coastal stations AND and FRE. This concentration, together with the direction of the isolines, may be called anomalous in the sense that it does not correspond to the mentioned relatively uniform westward equivalent current flow within this region (Fig. 7, top). We feel that the anomalously large Z disturbances, which we have also found in another case, especially at AND and FRE, may be due to the fact that the deep ocean border (the 2,000 m depth isoline, say) comes very close to the Norwegian coast only within this region. Otherwise northern Scandinavia is surrounded by shallow ocean water with depths of around 300 m. This may explain why we see a clear coast effect at all coastal stations only at high frequencies.

Although we should like to emphasize that at low frequencies the internal part of magnetic variations is negligible to a first approximation, we do not state that Scandinavia is free from noticeable conductivity anomalies. Studying more data from the magnetometer array, we have, for example, met growing evidence that the phases of magnetic variations are anomalous within the region of OUL, and that there appear to be anomalous high-frequency ($\sim$5 mHz) Z responses observable in the region of OKS-RIS-SRV (cf. Fig. 2).

5. Magnetic Substorm Development Over Scandinavia on October 7, 1976

In order to demonstrate both the capability and the bounds of the magnetometer array in revealing the small-scale spatial structure of geomagnetic disturbances, this section presents a phenomenological description of several types of disturbance fields recorded during an isolated substorm which occurred over Scandinavia on the evening of October 7, 1976. Within the limits of this paper, we do not intend to present any physical interpretation of the observations. Some physical aspects of this substorm have already been discussed by Baumjohann et al. (1978).

The standard magnetogram from the observatory Kiruna (KIR) (Fig. 8) shows a mainly northward magnetic disturbance field until about 1848 UT. At the beginning, this field varies slowly but after 1834 UT it exhibits an impulsive amplification before a similarly short negative excursion. After 1900 UT another, but longer lasting, negative bay in the X component occurs. More magnetograms for this event may be found in (Baumjohann et al. 1978).

For presentation of our observational results we have chosen the well-known equivalent overhead current presentation at height zero (i.e., horizontal disturbance vectors rotated clockwise by 90 degrees). For brevity, we shall use the word 'current' instead of 'equivalent overhead current at height zero (in nanoteslas)' in the following description. However, we are well aware of the fact that the currents presented may be very different from the true spatial distribu-

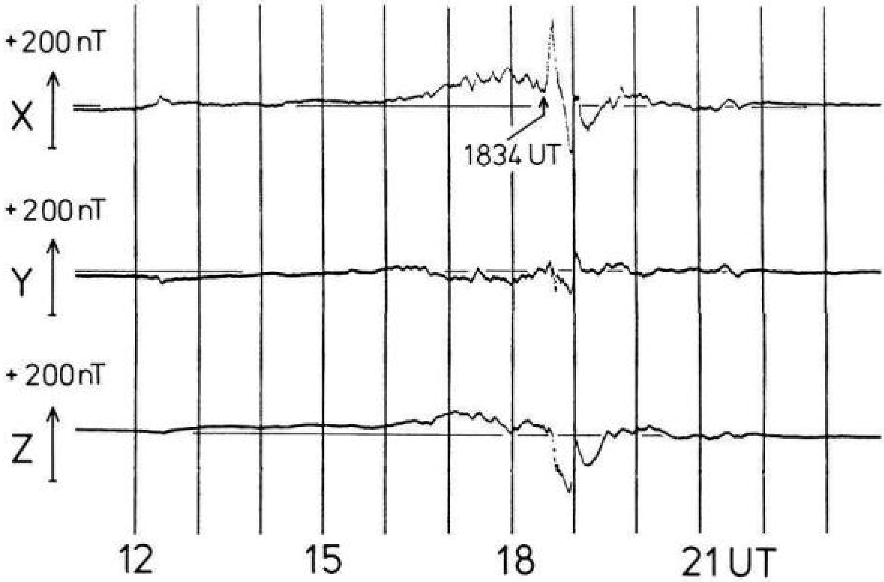


Fig. 8. Standard magnetogram from the geomagnetic observatory at Kiruna for October 7, 1976, 11–24 UT

tion of electric currents because of the appreciable height of the ionospheric main current layer (about 100 km), the possible presence of net field-aligned currents and balanced ionospheric-magnetospheric currents (e.g., Baumjohann et al. 1979) – the latter generating toroidal magnetic fields that are unobservable on the ground –, and the presence of currents induced within the earth.

During the early stages of operating the array, more data was lost than later on, due to initial difficulties in running the instruments. Hence for this event results are lacking from a few of our stations, for example the important coastal stations of FRE, AND, and BER (cf. Fig. 2). On the other hand, it is very important that we were able to include data from BJN, SOD, LOV, NUR, SKA, KUN, KEV, LPY, and LOZ, i.e., from stations that are run by other institutions (see Acknowledgements).

In order to describe the spatial evolution of the substorm over the Scandinavian area, Fig. 9a and b give a sequence of current distributions, each of which characterizes a certain stage of the development of this event up to 1900 UT. The disturbance field components have been defined and measured as deviations from the 7–8 UT quiet time levels on the same day. At KIR magnetic midnight occurred at about 2135 UT (as calculated from Whalen 1970).

Early within the substorm, until approximately 1636 UT, the current flow over Scandinavia was almost uniformly directed changing rather steadily from south-eastward (Fig. 9a, 1604 UT) to eastward, with intensity increasing toward the northeast (as defined in the Kiruna system). Simultaneously, BJN (cf. Fig. 9a, top of diagram given for 1604 UT) showed vector directions quite variable with time, eastward at the beginning and mostly northwestward later.

Afterwards, for more than one hour, the flow over northernmost Scandinavia was almost entirely eastward directed and typical of the eastward electrojet, but northwestward at BJN. The weaker currents to the south varied several times between southeastward and northeastward (Fig. 9a, 1646 and 1726 UT).

Between 1748 and 1800 UT the northernmost current vectors turned northward (Fig. 9a, 1756 UT), approaching the northwestern current direction at BJN. This branching-off of the northern part of the eastward electrojet later weakened a little (Fig. 9a, 1808 UT), until between 1820 and 1832 UT the currents at our northern stations became rather irregular (Fig. 9a, 1828 UT).

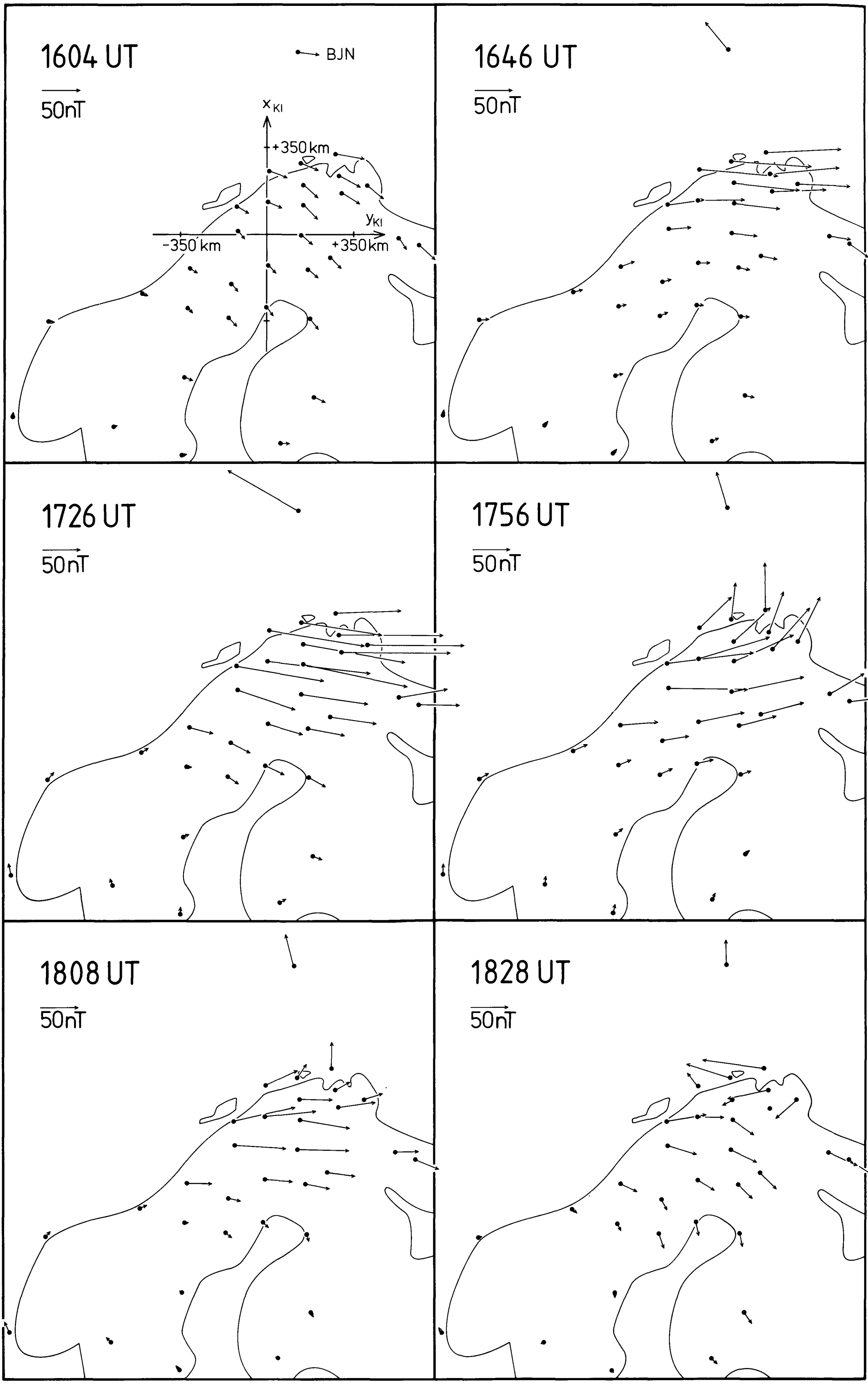
Starting at about 1834 UT (cf. Fig. 8) all the currents intensified appreciably, but their directions remained southeastward over most of Scandinavia and northwestward at BJN. Only within the region of our northern stations did dramatic changes occur. At first, a very local current vortex, somewhat elongated in east-west direction, appeared (Fig. 9b, 1836 UT), probably indicating a concentrated upward flow of field-aligned current (Untiedt et al. 1978). Later a pattern showing a spatial transition from eastward via northward to strong northwestward currents developed within a few minutes (Fig. 9b, 1837 and 1840 UT) which then appeared to travel westward (Fig. 9b, 1848 and 1854 UT) until both BJN and our northernmost stations indicated currents directed to the west (Fig. 9b, 1900 UT). At 1900 UT a remarkable U-like distortion of current was visible just to the south of the westward electrojet. Also within this time interval (Fig. 9b, 1854 UT), there was a more regional, but otherwise similar transition from eastward to northwestward currents visible over the middle of Scandinavia. We believe that our observations between about 1838 and 1854 UT were caused by the passage of the Harang discontinuity (Harang 1946; Heppner 1972; Maynard 1974; Kamide 1978; Nielsen and Greenwald 1979), i.e., the transition region between the eastward and westward electrojets.

6. Conclusions and Summary

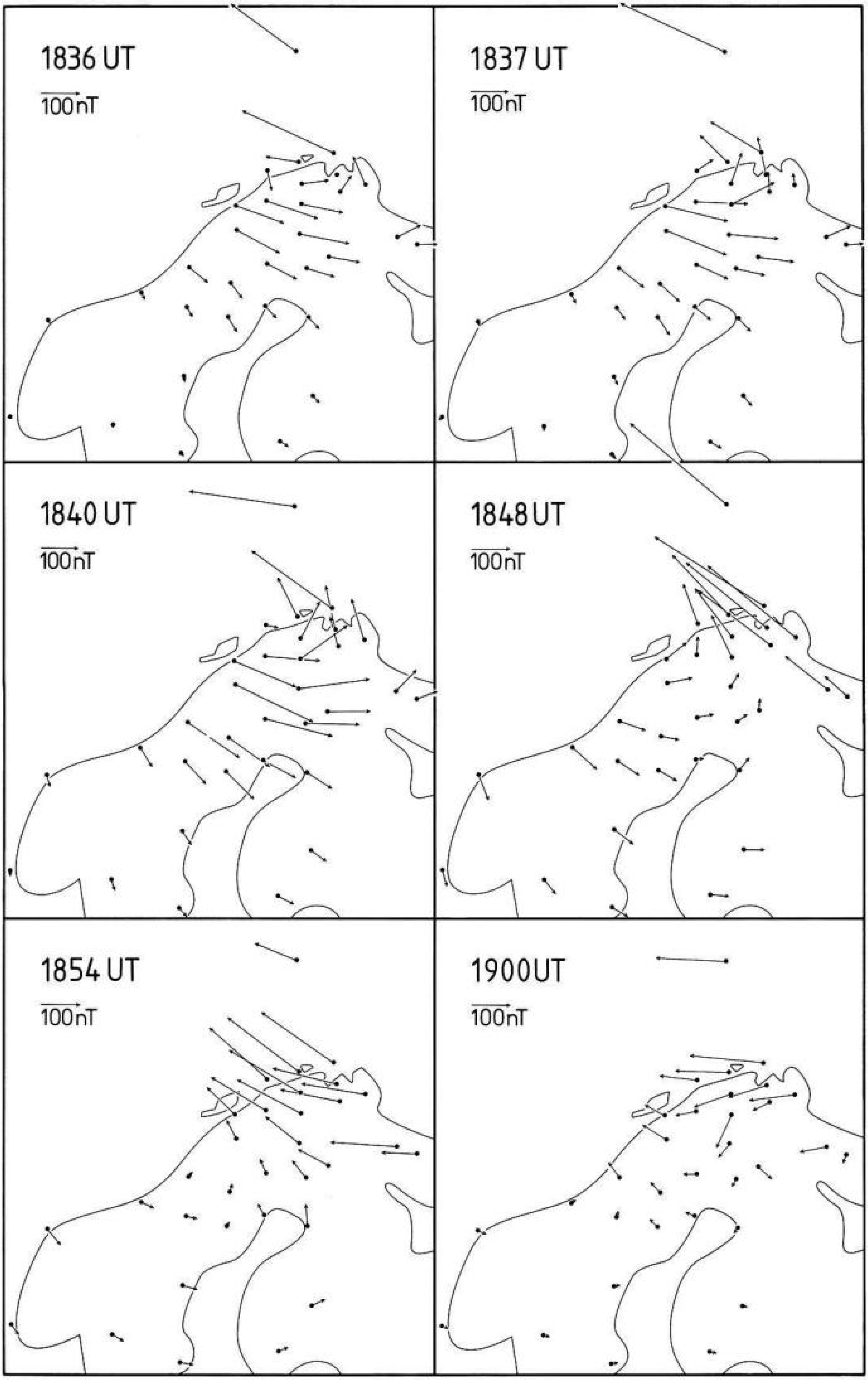
The phenomenological results presented in the preceding section (see also Baumjohann et al. 1978) clearly demonstrate that at many time instances within the course of a substorm the regional magnetic situation within the auroral zone may be adequately observed only by means of a densely spaced two-dimensional magnetometer array. This is particularly true for the O-type (Fig. 9b, 1836 UT), U-type (Fig. 9b, 1840 and 1900 UT) and X-type (Fig. 9a, 1828 UT) configurations of the equivalent current flow which have been shown. In this respect, and considering that observations by other methods have been greatly intensified within the same region over the same time, the magnetic data being acquired during the IMS by the Scandinavian Magnetometer Array facilitates new and detailed studies.

However, two limitations of the value of our magnetometer array are obvious. The optical recording on film requires time-consuming and, because of manifold crossing of traces in the case of strong disturbances, often difficult digitizing of the data. Accordingly, our array is particularly appropriate for detailed single event studies, but not well-suited for statistical investigations.

Fig. 9a and b. Equivalent current vectors over the Scandinavian region at different instances of time during the course of the magnetic substorm which occurred on October 7, 1976 (cf. Fig. 8). Note that vector scales are different between the two parts of the figure


1604 UT
50nT
BJN
x_{KI}
+350 km
y_{KI}
-350 km
+350 km
1646 UT
50nT
1726 UT
50nT
1756 UT
50nT
1808 UT
50nT
1828 UT
50nT

a



1836 UT
100nT
1837 UT
100nT
1840 UT
100nT
1848 UT
100nT
1854 UT
100nT
1900UT
100nT

b

Furthermore, the lack of stations at magnetic latitudes greater than 68 N restricts, under not-too-disturbed conditions (i.e., a moderately expanded auroral oval), studies of magnetic disturbances to the southern part of the night-time auroral oval and to subauroral variations at local times other than near magnetic midnight.

With respect to the internal magnetic disturbance field contributions in the Scandinavian area it is concluded that these are negligible at lower frequencies (≤ 1 mHz) and are mainly negligible also in the horizontal components at higher frequencies (~ 5 mHz). The vertical component, Z, often is most indicative of horizontal conductivity variations. At higher frequencies, the behaviour of this component implies the existence of a crust-mantle conductivity structure which is very different beneath southern Finland as compared to northern Scandinavia, with OUL defining approximately the demarcation line between the two regimes. Also indicated, by analyses of data from the total array, is the presence of a conductivity anomaly in the region of OKS-RIS-SRV. Perhaps due to the fact that the water surrounding Scandinavia is shallow, except near the stations FRE and AND which are very close to the continental edge, there is hardly any recognizable coast effect at low frequencies. At higher frequencies the Z variations are greatly amplified at all coastal stations, but this does not appear to lead to a corresponding major perturbation of the horizontal magnetic disturbance vectors.

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Installing the many magnetometers and operating them over several years would not have been possible without a vigorous and substantial participation of other members of our institute and particularly of many of our students in the field work. For their very active, responsible and in most cases manifold help in this respect we have to thank H.J. Opgenoorth, W.D. Pelster, J. Heller, B. Inhester, K.-H. Glaßmeier, R. Helm, H. Hopf, U. Mersmann, M. Herzog, M. Keil, R. König, H. Stuhldreyer, O. Hennecke, H. Sulzbacher, H. Dornseif, K. Brüning, and H. Knese.

Almost half of the instruments were constructed especially for this project; the others had to be altered for our purpose. All this has been done by W. Bartsch, H. Dornseif, R. Giesbert, R. Helm, O. Hennecke, H. Knese, and W. Wilting. Difficult instrumental problems were solved particularly by R. Helm and W. Wilting.

We are indebted also to the Deutsches Hydrographisches Institut at Hamburg for the permission to calibrate and test our instruments at its magnetic observatory Wingst.

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In this paper, on several occasions we have been able to present magnetic data from additional stations. We are much obliged to Mr. St. Berger (Tromsö), Dr. F. Eleman (Stockholm), Dr. E. Gjoen (Bergen), Dr. G. Gustafsson (Kiruna), Dr. E. Kataja (Sodankylä), Dr. G.A. Loginov (Apatity), Mr. H. Maurer (Braunschweig), and Dr. C. Sucksdorff (Helsinki) for placing the corresponding magnetograms at our disposal.

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References

Akasofu, S.-I.: Polar and magnetospheric substorms. Dordrecht: Reidel 1968

Akasofu, S.-I., Wilson, C.R., Snyder, L., Perreault, P.D.: Results from a meridian chain of observatories in the Alaskan sector (I). Planet. Space Sci. **19**, 477–482, 1971

Bannister, J.R., Gough, D.I.: Development of a polar magnetic substorm: A two-dimensional magnetometer array study. Geophys. J.R. Astron. Soc. **51**, 75–90, 1977

Bannister, J.R., Gough, D.I.: A study of two polar magnetic substorms with a two-dimensional magnetometer array. Geophys. J.R. Astron. Soc. **53**, 1–26, 1978

Baumjohann, W., Greenwald, R.A., Küppers, F.: Joint magnetometer array and radar backscatter observations of auroral currents in northern Scandinavia. J. Geophys. **44**, 373–383, 1978

Baumjohann, W., Untiedt, J., Greenwald, R.A.: Joint two-dimensional observations of ground magnetic and ionospheric electric fields associated with auroral zone currents. 1. Three-dimensional current flows associated with a substorm-intensified eastward electrojet. J. Geophys. Res., submitted 1979

Birkeland, K.: The Norwegian aurora polaris expedition 1902–1903, Vol. 1: On the cause of magnetic storms and the origin of terrestrial magnetism, Sect. 1. Christiania: Aschehoug 1908

Birkeland, K.: The Norwegian aurora polaris expedition 1902–1903, Vol. 1: On the cause of magnetic storms and the origin of terrestrial magnetism, Sect. 2. Christiania: Aschehoug 1913

Camfield, P.A., Gough, D.I.: Comment on use of anomalous stations for IMS. EOS Trans. Am. Geophys. Union **57**, 850, 1976

Chapman, S., Bartels, J.: Geomagnetism, Vol. I. Geomagnetic and related phenomena. Oxford: Clarendon Press 1940

Chen, A.J., Rostoker, G.: Auroral-polar currents during periods of moderate magnetospheric activity. Planet. Space Sci. **22**, 1101–1115, 1974

Fukushima, N.: Polar magnetic storms and geomagnetic bays. J. Fac. Sci. Univ. Tokyo **8**, 293–412, 1953

Gough, D.I.: Effects of induction in the earth upon measurements of external time-varying magnetic fields. EOS Trans. Am. Geophys. Union **55**, 595–599, 1974

Gough, D.I., Bannister, J.R.: A polar magnetic substorm observed in the evening sector with a two-dimensional magnetometer array. Geophys. J.R. Astron. Soc. **55**, 435–450, 1978

Gough, D.I., Reitzel, J.S.: A portable three component magnetic variometer. J. Geomagn. Geoelectr. **19**, 203–215, 1967

Gustafsson, G.: A revised corrected geomagnetic coordinate system. Ark. Geofys. **5**, 595–617, 1970

Harang, L.: The mean field of disturbance of polar geomagnetic storms. Terr. Magn. Atmos. Electr. **51**, 353–380, 1946

Heppner, J.P.: The Harang discontinuity in auroral belt ionospheric currents. Geophys. Publ. **29**, 105–120, 1972

Hughes, T.J., Rostoker, G.: Current flow in the magnetosphere and ionosphere during periods of moderate activity. J. Geophys. Res. **82**, 2271–2282, 1977

Kamide, Y.: On current continuity at the Harang discontinuity. Planet. Space Sci. **26**, 237–244, 1978

Kamide, Y., Akasofu, S.-I.: The auroral electrojet and field-aligned current. Planet. Space Sci. **24**, 203–213, 1976

Kamide, Y., Akasofu, S.-I., Rostoker, G.: Field-aligned currents and the auroral electrojet in the morning sector. J. Geophys. Res. **81**, 6141–6147, 1976

Kamide, Y., Rostoker, G.: The spatial relationship of field-aligned currents and auroral electrojets to the distribution of nightside auroras. J. Geophys. Res. **82**, 5589–5608, 1977

Kawasaki, K., Rostoker, G.: Perturbation magnetic fields and current systems associated with eastward drifting auroral structures. J. Geophys. Res. **84**, 1464–1480, 1979

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

Kisabeth, J.L., Rostoker, G.: Development of the polar electrojet during polar magnetic substorms. J. Geophys. Res. **76**, 6815–6828, 1971

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

Kisabeth, J.L., Rostoker, G.: The expansive phase of magnetospheric substorms. 1. Development of the auroral electrojets and auroral arc configuration during a substorm. J. Geophys. Res. **79**, 972–984, 1974

Küppers, F., Post, H.: A second generation Gough-Reitzel magnetometer. J. Geomagn. Geoelectr., accepted 1979

Lanzerotti, L.J., Sugiura, M.: Reply. EOS Trans. Am. Geophys. Union **57**, 850, 1976

Lilley, F.E.M.: Magnetometer array studies: A review of the interpretation of observed fields. Phys. Earth Planet. Inter. **10**, 231–240, 1975

Loginov, G.A., Vasilev, E.P., Grafe, A.: Some results of the investigation of magnetic variations of the auroral electrojets concluded from observations of the geomagnetic meridian project (GMP). Gerlands Beitr. Geophys. **87**, 249–262, 1978

Maurer, H., Theile, B.: Parameters of the auroral electrojet from magnetic variations along a meridian. J. Geophys. **44**, 415–426, 1978

Maynard, N.C.: Electric field measurements across the Harang discontinuity. J. Geophys. Res. **79**, 4620–4631, 1974

Mersmann, U., Baumjohann, W., Küppers, F., Lange, K.: Analysis of an eastward electrojet by means of upward continuation of ground-based magnetometer data. J. Geophys. **45**, 281–298, 1979

Nielsen, E., Greenwald, R.A.: Electron flow and visual aurora at the Harang discontinuity. J. Geophys. Res. **84**, 4189–4200, 1979

Rostoker, G.: Polar magnetic substorms. Rev. Geophys. Space Phys. **10**, 157–211, 1972

Rostoker, G., Hron, M.: The eastward electrojet in the dawn sector. Planet. Space Sci. **23**, 1377–1389, 1975

Rostoker, G., Kisabeth, J.L.: Response of the polar electrojets in the evening sector to polar magnetic substorms. J. Geophys. Res. **78**, 5559–5571, 1973

Schmucker, U.: Regional induction studies: A review of methods and results. Phys. Earth Planet. Inter. **7**, 365–378, 1973

Siebert, M., Kertz, W.: Zur Zerlegung eines lokalen erdmagnetischen Feldes in äußeren und inneren Anteil. Nachr. Akad. Wiss. Göttingen, Math.-Phys. Kl. 2A: 87–112, 1957

Untiedt, J., Pellinen, R., Küppers, F., Opgenoorth, H.J., Pelster, W.D., Baumjohann, W., Ranta, H., Kangas, J., Czechowsky, P., Heikkila, W.J.: Observations of the initial development of an auroral and magnetic substorm at magnetic midnight. J. Geophys. **45**, 41–65, 1978

Whalen, J.A.: Auroral oval plotter and nomograph for determining corrected geomagnetic local time, latitude, and longitude for high latitudes in the northern hemisphere. Environmental Res. Papers, No. 327, Air Force Cambridge Res. Lab., Bedford, Mass. 1970

Wiens, G.R., Rostoker, G.: Characteristics of the development of the westward electrojet during the expansive phase of magnetospheric substorms. J. Geophys. Res. **80**, 2109–2128, 1975

Wilhjelm, J., Friis-Christensen, E.: Magnetometer chain in Greenland. Geophys. Papers, R-48, Danish Meteorol. Inst., Copenhagen 1976

Wilhjelm, J., Friis-Christensen, E., Potemra, T.A.: The relationship between ionospheric and field-aligned currents in the dayside cusp. J. Geophys. Res. **83**, 5586–5594, 1978

Yasuhara, F., Kamide, Y., Akasofu, S.-I.: Field-aligned and ionospheric currents. Planet. Space Sci. **23**, 1355–1368, 1975

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