TIME SEQUENCE OF QUASIPERIODIC GEOMAGNETIC DISTURBANCES DURING SUBSTORMS

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Abstract. Based on the data from the 2D IMAGE network and magnetic stations located in Russia, a study was conducted of a sequence of quasi-periodic geomagnetic variations with an amplitude of up to 600 nT and a duration of ~20 min that arose in the post-midnight sector during a minor global magnetic storm. It was shown that geomagnetic variations arose against the background of substorms at the same corrected geomagnetic latitude Φ′ ~ 65° sequentially one after another and moved by ~20° in longitude to the east, with a new variation occurring when the previous one moved by ~10°. It was shown that the ionospheric source of these variations is a pair of Hall current eddies, each of which has an elliptical shape with a major axis in the north-south direction. The estimated size of the ionospheric source is ~940 km in the west-east direction (each Hall current vortex is ~470 km) and ~1000 km in the north-south direction. The centers of the ionospheric sources of these variations moved eastward at a speed of ~0.8 km/s. It is shown that each geomagnetic variation is accompanied by a burst of Pi1-2 geomagnetic pulsations. It is suggested that the observed geomagnetic variations are created by magnetic fields of ionospheric current systems of microsubstorms.

Keywords: *microsubstorm, ionospheric current systems*

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1. INTRODUCTION

The presented work studies a sequence of quasiperiodic geomagnetic variations with the amplitude up to 600 nT and duration~ 20 min, which appeared in the postmidnight sector during a small global magnetic storm. Such phenomena can be considered as microsubstorms or as geomagnetic pulsations Ps6

A typical substorm, determined from bay-like perturbations of the magnetic field, often contains several single-type stages of 10-20 min duration, called elementary substorm beginnings [Vorobyev and Rezhenov, 1975], multiple substorm beginnings [Pytte, 1976], or microsubstorms [Sergeev et al., 1978]. Each microsubstorm corresponds to a burst of Pi2 pulsations [Sergeev, 1978], [Kokubun and Iijima, 1975]. At the onset of a microsubstorm, a Birkeland current system arises, consisting of a pair of longitudinal currents (inflow and outflow) and associated ionospheric currents, manifested in geomagnetic perturbations in the auroral zone and at lower latitudes [Sergeev et al., 1978].

In [Zaitsev and Kartashev, 1983], a sequence of 3-4 geomagnetic disturbances with an amplitude of up to ~250 nTL and a duration of ~30 min is studied using data from 145^{o} magnetometers installed along the geomagnetic meridian. An assumption is made that the observed geomagnetic perturbations are created by local ionospheric currents superimposed on the auroral electrojet

In [Baumjohann et al., 1981], a system of equivalent currents of microsubstorms (microsubstorm duration less than 30 min) consisting of a chain of Hall currents, which drifts with the velocity of magnetospheric convection, was constructed. A pair of ionospheric current vortices corresponds to a pair of longitudinal currents entering and leaving the ionosphere.

In [Andre and Baumjohann, 1982], [Buchert, 1990] geomagnetic pulsations of Ps6, which have similar features to microsubstorms, are studied, where the model of the Birkeland current system is also considered.

In the presented work, magnetic keograms and instantaneous 2D distributions of amplitudes of magnetic field components are used using data from a large number of magnetic stations to estimate the sizes of ionospheric magnetic field sources of these geomagnetic variations, to determine their location and velocity of displacement

2. EXPERIMENTAL DATA

In this paper, we used data from 38 three-component magnetic stations - 32 stations from the two-dimensional European IMAGE network, 5 magnetic stations temporarily installed by SPbF IZMIRAN in Russia (KUZ, KEM, LEH, SEG, MED), and the permanent magnetic station KAP

(IZMIRAN). All magnetic stations used in this article are shown Fig. 1 in corrected geomagnetic coordinates. The geomagnetic coordinates of the Russian stations and the KAP station are presented in Table 1.

The magnetic stations in Fig. 1 are located in the interval of corrected geomagnetic coordinates (Φ' = 54 - 76°; Λ' = 85 - 121$^{(o)}$), which corresponds to the interval of geographic coordinates (φ = 58 - 79$^{(o)}$N; and λ = 5 -35$^{(o)}$ E). The temporal resolution of the data at the IMAGE network stations is 10 s, at the other stations 1 s (reduced to 10 s for further processing).

Fig. 1.

Table 1.

Fig. 2 presents the changes of *Dst*- and AE-indexes for the 7-hour interval 23:00 - 06:00 UT 04-05.09.2012. The beginning of the world magnetic storm is observed around 21 UT 04.09.2012. The minimum of Dst-index (-66 nTl) was reached at 08 UT 05.09.2012 and further increased. Intensifications in the AE-index suggest the presence of substorms at the background of the global magnetic storm.

Fig. 2.

Fig. 3.

Fig. 3 for the 7-hour time interval 23:00-06:00 UT 04-05.09.2012 presents the magnetograms of *X-, Y-* and Z-components *of* the magnetic field recorded
at 5 magnetic stations located from west to east along the geomagnetic parallel Φ' ~64° in the range of geomagnetic longitudes Λ'= 93.5-114° (Fig. 1). The thin lines in Fig. 3 are the raw data, the bold lines are the data smoothed by the sliding window. From Fig. 3 we can see that the magnetic storm is manifested at all 5 stations and around 02 UT *the X-component of* the magnetic field reaches its minimum value. In the two-hour time interval of 00:20-02:20 UT in Fig. 3, quasi-periodic variations of the magnetic field with a duration of~ 20 min with the amplitude up to 600 nTL are observed in the *Y*- and Z-components. At PEL and SOD stations (Fig. 3), the variations have the maximum amplitude in the Y-component *of* the magnetic field

Fig. 4.

Fig. 4 presents magnetograms of the *X-, Y-* and *Z-components of* the magnetic field recorded at 9 magnetic stations located along the geomagnetic meridian Λ'~ 110° in the range of geomagnetic latitudes Φ'= 60- 4° for the same 7-hour time interval on the same scale. The thin lines in Fig. 4 are the original data, bold lines are the data smoothed by the sliding window. Geomagnetic variations of 18-22 min duration are clearly observed in the *Y*- and Z-components (Fig. 4) at this meridional chain of stations in the time interval 00:20-02:20 UT in the interval of geomagnetic latitudes 61.5-67.9° (from station KUZ to station NOR in Fig. 1). The maximum amplitude in the Y component of these disturbances reaches~ 600 nT (Fig. 4) at stations KEV and IVA (Λ' ~ 109°). At station LOZ

($\Lambda' \sim 114^{o}$), the amplitude of variations in the Y *component does* not exceed 300 nTL, and at station KAP ($\Lambda' \sim 122^{o}$), variations are no longer observed. The smoothed curves in the X-component *of* the magnetic field (Fig. 3, Fig. 4) show that these quasi-periodic disturbances are superimposed on the field of two magnetic substorms (00:00-03:00 UT 05.09.2012) with amplitudes up to 400 nTL

3. DATA PROCESSING RESULTS

The raw data were prefiltered in the period range T = 800 -1500 with a bandpass filter with a finite impulse response. The filtering allows us to exclude higher-frequency and lower-frequency variations of the magnetic field and isolate the studied quasi-periodic variations of the magnetic field

In Fig. 5 in the time interval 00:00-02:30 UT 05.09.2012 presents the magnetic keograms geomagnetic longitude-time (left) and geomagnetic latitude-time (right). The keograms show the temporal evolution of the longitude and latitude profile of the magnetic field variation amplitudes with a step of 1 min

Fig. 5.

The left keogram shows that positive and negative extrema of the magnetic field variations in the *Y*- and Z-components appear at the same geomagnetic longitude~ 95^{o} and disappear at longitude~ 115^{o} after~ 20 min (the average duration of the studied variations). The sloping line on the Z-component keogram shows this effect. On average, the displacement of the magnetic field extrema along longitude is $\Delta\Lambda' \sim 20°$

From the keogram in Fig. 5 (right) shows that the position of the magnetic field source centers did not change with time and is located at the geomagnetic latitude $\Phi' \sim 65°$. The magnetic field variations in the *Y*- and Z-components are shifted in phase with each other by a quarter of a period (~ 5 min), which is characteristic of the passage of Hall current eddies over a magnetic station [Oberts and Raspopov, 1968]. For both positive and negative values, these variations on average occupy the latitude interval $\Delta\Phi' \sim 9^{\circ}$. The variations in the *X-component* occupy a wider zone and the extreme values are mainly located south and north of latitude $\Phi' \sim 65$. °

By converting the coordinates from degrees to km, we determine estimates of the sizes of ionospheric sources

$$Lx = 111.1\Delta\Lambda' \cos(\Phi')$$

$$Ly = 111.1\Delta\Phi' \qquad (1)$$

Lx is the size of the magnetic field of the ionospheric source in the W-E direction

Ly is the size of the source in the S-N direction

$\Delta\Lambda' \sim 2\,0°$, $\Delta\Phi' \sim 9°$ are the source dimensions in degrees of geomagnetic longitude and latitude, $\Phi' \sim 65°$ is the geomagnetic latitude of the source center.

The constant factor 111.1 is equal to the length of the equatorial arc of a circle of 1° at earth radius $R_E = 6371$ km.

Applying (1), we obtain estimates of the size of the magnetic field of ionospheric source in the longitudinal direction $Lx \sim 940$ km (470 km for each Hall vortex), in the latitudinal direction $Ly \sim 1000$ km, which agrees with the estimate of the size of ionospheric sources of microstorms, given in the article [Baumjohann , 1981].

The average drift velocity of the investigated 20-minute variations of the magnetic field can be defined

$$V = Lx/T \quad (2)$$

Given that the duration of one oscillation is $T \sim 1200$ s, the average drift velocity $V \sim 0.8$ km/s, which is in agreement with the magnetospheric convection velocity.

Fig. 6 shows the instantaneous two-dimensional distributions on the Earth's surface of the amplitude values of magnetic field variations in the *X-, Y-*, and Z-components with a step of 150 s. To construct Fig. 6 we used data from all 38 magnetic stations shown in Fig. 1. The region in which the two-dimensional distributions are plotted occupies the interval of geomagnetic latitudes 54-75° and longitudes 86-121°. The raw data were filtered by a bandpass filter in the period range of 800 - 1500 s. The bivariate distributions were determined for all stations of the bivariate network at the times indicated in the frames of Fig. 6.

Fig. 6.

If the ionospheric source of the magnetic field variations observed at the Earth's surface is a pair of current Hall vortices, the extrema in the Z-component in Fig. 6 are located in the centers of these Hall current vortices and coincide also with the regions of the inflow and outflow longitudinal currents creating these vortices in the ionosphere. In frames 00:42:30 and 00:45:00 of Fig. 6, we simultaneously observe in the Z-component a two-dimensional distribution of the magnetic field part of one current vortex going eastward (one negative eastern extremum) and a pair of current vortices arising later (two western extrema). A new Hall vortex emerges when the previous pair has moved eastward and has not yet ceased to exist. In Fig. 5 (left keogram), two extrema of different signs from one pair of current vortices and one extrema from the previous pair exist in the *Z*- and Y-components at the same moment of time.

On the frames 00:47:30 (Fig. 6, lower frames), the magnetic field created by one ionospheric source - two extrema in the *Z-component*, three extrema in the *Y-component* - was almost completely placed. On the same frames one can see the phase lag of field variations in the *Y-component* from the Z-component. Thus, the center of the negative extremum in the *Y-component* has the longitude~ 107° Å, the position of the tangent point of the isolines of the Hall current fields in the *Z-component* has the same longitude, which means the phase lag *of the* Y-component in a quarter of the period (~ 5 min.) relative to the Z-component

4. DISCUSSION

As mentioned in Section 1 (Introduction), the sequence of quasi-periodic geomagnetic variations with a duration of~ 20 min is considered as microsubstorms or Ps6 geomagnetic variations in previously published works. These phenomena have some identical features.

The presence of a burst of Pi2 pulsations [Sergeev et al., 1978] is a necessary condition to consider a local geomagnetic perturbation of microstorms. In Fig. 7 above shows the amplitude dynamic spectrum of variations of the *Y-component of* the magnetic field in the frequency range Pi1-2, and below - the magnetogram of *the Y-component* at station IVA during the period 23:00-02:40 UT 04 -05.09.2012. In Fig. 7, one can observe a good correlation of the Pi1-2 bursts with the manifestations of 20-min geomagnetic variations in the magnetic field.

Fig. 7.

In [Sergeev, 1978; Kokubu and Iijima, 1975], it is assumed that the magnetic field of a microsubburi on the Earth's surface is created by a local Birkeland current system. The three-dimensional magnetosphere-ionosphere current system consists of a pair of longitudinally separated longitudinal currents (inflow and outflow). The longitudinal currents are connected by Pedersen currents and create a pair of ionospheric vortex Hall currents of opposite direction. On the Earth's surface, the magnetic field of the Pedersen currents is leveled by the magnetic field of the longitudinal currents (we assume that the longitudinal currents flow along the vertical axis *Z*).

In the paper [Baumjohann , 1981], a system of equivalent currents of the microstorm sequence is constructed. It consists of a chain of Hall vortices with characteristic size of 1000 km and drifts at the rate of magnetospheric convection. Each pair of ionospheric current vortices corresponds to a pair of longitudinal currents flowing in and out of the ionosphere.

The same model of the current system for resonant geomagnetic pulsations Pc5 was discussed in [Korutepko and Ismagilov, 2024]. It was shown in [Maltsev and Lyatsky, 1982] that the Alfven wave can be represented as a pair of alternating longitudinal currents flowing on opposite walls of the magnetic tube in which the Alfven wave propagates. The longitudinal currents create Hall eddy currents in the ionosphere, whose magnetic field is registered on the Earth's surface. The dimensions of the ionospheric source *Ps5* were ~250 km in the EW direction *Lx* and ~670 km in the SN direction Ly

Current vortices are observed in the ionosphere on much larger scales. It was found in [Gromova et al., 2024] that the beginning of all investigated substorms at the IMAGE meridian was accompanied by the development of a nighttime current vortex with clockwise rotation, which is an indicator of the intensification of downward longitudinal currents. At the time of the maximum of substorm intensity, a similar but more extensive eddy current was observed in the morning sector, which is probably characteristic of intense substorms

Fig. 8.

A simplified model of the ionospheric Hall ionospheric currents and magnetic fields for the three field components produced by these currents at the Earth's surface is presented in Fig. 8. In the upper part of Fig. 8, small circles show the regions of inward and outward longitudinal currents in projection on the Earth's surface. The dotted lines mark elliptical regions occupied by eddy Hall currents. The arrows indicate the direction of the Hall currents. Isolines of the distribution of amplitudes *H, D*, and *Z* components of the magnetic field on the Earth's surface of different sign are shown by ellipses. Figure 8 shows that one ionospheric source (a pair of Hall vortices) creates on the Earth's surface two extrema in the distribution on the Earth's surface of the Z component of the magnetic field, three extrema in the D component and four extrema in the distribution of the *H* component (a pair above and below the zones of vortex Hall currents). If the ellipses of eddy currents are strongly stretched in the south-north direction, the magnitude of the D-component (created by currents flowing in the latitudinal direction) at latitudes near the centers of eddy currents will significantly exceed the magnitude of *the* H-component, which can be clearly seen in Fig. 3 and Fig. 4. This model also assumes a phase shift of the *D* component relative to the *Z* component by a quarter of the period, which is observed in Fig. 6 (frame 00:47:30 UT) - the central extremum in the *Y* component is located at geomagnetic longitude 107^o, at the same longitude the extremums in the *Z component* touch, which corresponds to the model in Fig. 8.

The average duration of one studied quasi-periodic geomagnetic perturbation on the magnetograms in Figures 3, 4 (time interval between extrema of the same sign) is~ 20 min. Figures 5 and 6 show that the magnetic field of two consecutive perturbations exists simultaneously and each subsequent perturbation occurs when the previous one has not yet ceased to exist. This probably excludes the possibility of generation of microstorms by a resonant mechanism

Figure 3 shows that the maximum amplitudes of the 20-min variations are observed at stations PEL (Λ'~ 105^o) and SOD (Λ'~ 107$^{o)}$. At stations DON (Λ'~ 95$^{o)}$ and LOZ (Λ'~ 114$^{o)}$, the amplitudes of the variations are significantly smaller. Probably, the studied quasi-periodic variations of the magnetic field originated to the west and ceased to exist to the east of the area where the magnetic stations used are located.

The keograms (Figures 4 and 5) clearly show that all investigated quasi-periodic variations of the magnetic field appear at the same geomagnetic latitude~ 65^o and at the same geomagnetic longitude~ 95^o. After~ 20 min (the average duration of the variations studied), each variation shifts eastward at~ 20^o and terminates at geomagnetic longitude~ 115^o. The next variation in the sequence

(with the opposite sign of the extremum) occurs when the previous variation has shifted~ 10° (Fig. 5, left side) eastward. The same displacement
is also observed in Fig. 6

Microsubburies have the following features [Sergeev, 1978, Sergeev et al. 1978]:

- microsubstorms occur in the background of a substorm;
- to each microsubstance corresponds the occurrence of the Birkeland system of currents;
- each microsubburst corresponds to a burst of Pi1-2 pulsations;
- each microstorm is accompanied by the appearance of diffuse (discrete) forms of auroras and the formation of a bulge in polar auroras [Sergeev, 1978; Sergeev et al., 1978].

The difference between microstorms and substorms is in the duration of the phenomenon and occur at the background of substorms. The amplitude of the microstorm magnetic field in the auroral zone is maximum in the Y- and Z-components *of* the magnetic field.

The geomagnetic variations of *Ps6* belong to the class of irregular magnetic pulsations Pi3 (period T >150 s). The *Ps6* pulsations [Saito, 1978], [Saito and Yumoto, 1978] have similar features to microsubstorms:

The Ps6 oscillation sequence occurs against the background of a substorm and has a comparable duration and amplitude; in the auroral zone, the maximum amplitude is observed in the D component of the magnetic field; microsubstorm and the *Ps6* event correspond to the appearance of the Birkeland system of currents [Gustaffson, 1981], [Andre and Baumjohann, 1982], [Baumjohann, 1981]; they are accompanied by the appearance of diffuse and discrete forms of auroras and the formation of a bulge in polar auroras [Andre and Baumjohann, 1982], [Tagirov, 1989].

Differences between microsubstances and *Ps6*:

each microsubstorm is accompanied by a burst of Pi2 pulsations, for *Ps6* it was not established;

Ps6 event is associated with flares and the formation of Ω -structures observed at the polar boundary of the post-midnight diffuse polar aurora, for microstorms has not been established.

In [Sergeev, 1978], it is suggested that the spatial and temporal development of microsubstorms can be caused by a discontinuity in the plasma layer of the magnetospheric tail [Schindler, 1974], [Galeev and Zelenyi, 1976]. In [Sergeev et al., 1978], we discuss the sequential occurrence of this instability in more and more distant regions of the magnetospheric tail. In Figure 7, we observe the simultaneous existence of ionospheric sources of two quasiperiodic variations of the magnetic field (microsubstorms or *Ps6*) whose centers are located at the same geomagnetic latitude.

In [Yamamoto et al., 1992], omega-bands and flare structures observed at the polar boundary of the electron diffuse glow discharge are considered. Using two-dimensional electrostatic particle modeling, it is shown that the omega-bands and flare structures can be identified with spatial modulations of the distribution of energetic electrons by electric dipoles evolving at the polar boundary of the hot plasma. A series of dipoles are generated due to charge separation (induced by magnetic drifts) in hot particles when the polar boundary of the hot plasma is disturbed by the Kelvin-Helmholtz instability. Growing electric dipoles can spatially modulate the cluster of energetic electrons, leading to the formation of omega-bands, flares, and longitudinal currents in these phenomena.

In the event under study, each new quasi-sinusoidal oscillation with period *T*~ 20 min occurs at the same geomagnetic longitude and latitude as the previous one.

We hypothesize that the observed sequence of geomagnetic variations are a sequence of microstorms, but this problem requires more careful study.

5. CONCLUSION

Using data from the two-dimensional IMAGE network and magnetic stations located on the territory of Russia (38 stations), a study of the sequence of quasi-periodic geomagnetic variations with the amplitude up to 600 nTL and duration of~ 20 min, which appeared in the post-midnight sector during a small global magnetic storm, was carried out. The expansion of the southeastern part of the study area at the expense of the Russian magnetic stations allowed us to obtain an almost complete instantaneous two-dimensional distribution of the microstorm magnetic field at the Earth's surface.

The quasi-periodic geomagnetic variations occurred at the background of substorms at the same geomagnetic longitude ~95° and latitude ~65° one after another in succession, with a new variation appearing when the previous one moved by ~10° in longitude and did not cease to exist yet.

It was established that the ionospheric source of these geomagnetic variations is a pair of Hall current vortices, each of which has an elliptical shape with a larger axis in the north-south direction. The estimated size of the ionospheric source is ~940 km in the east-west direction (each Hall current vortex~ 470 km) and ~1000 km in the north-south direction. The centers of ionospheric sources moved in the eastward direction with a velocity~ 0.8 km/s.

It is shown that each geomagnetic variation is accompanied by a burst of Pi1-2 geomagnetic pulsations.

A comparison of the features of microstorms and geomagnetic variations of Ps6, which have many coinciding features, is presented. An assumption is made that the investigated sequence of quasi-periodic geomagnetic variations is created by the magnetic field of the ionospheric current systems of the sequence of microstorms, but it is not excluded that the investigated phenomenon is a burst of geomagnetic pulsations of Ps6. Clarification of this question requires a more careful study.

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Table 1. Coordinates of Russian stations

№ n/a	Magnetic station	Φ′, deg	Λ′, deg
1	KUZ	61.51	112.29
2	KEM	61.05	112.8
3	LEH	60.1	112.1
4	SEG	59.63	111.68
5	MED	58.84	111.65
7	KAP	59.7	120.9

Figure captions

Fig. 1. Location of magnetic stations.

Fig. 2. *Dst*- and AE-indices 04-05.09.2012.

Fig. 3. Magnetograms of *X*-, *Y*- and Z-components *of* magnetic field perturbations at 5 stations located along the geomagnetic parallel ~ 64°.
Bold lines are smoothed data.

Fig. 4. Magnetograms of *X*-, *Y*- and Z-components *of* magnetic field perturbations on 04-05.09.2012 at 9 magnetic stations located from north to south along the geomagnetic meridian ~110°.
Bold lines are smoothed data.

Fig. 5. Keograms for three components of magnetic field variations in the time interval 00:00 - 02:15 UT 05.09.2012. Left: geomagnetic longitude-time keogram, right: geomagnetic latitude-time keogram.

Fig. 6. Instantaneous two-dimensional distributions of amplitudes of variations amplitudes of *X-, Y-* and Z-components of the magnetic field in the time interval 00:40:00-00:47:30 UT 05.09.2012. The data were filtered over a range of periods T = 800-1500 s.

Fig. 7. Amplitude dynamic spectrum of variations of the *Y-component of* the magnetic field in the frequency range Pi1-2 (top) and magnetogram of the *Y-component* at station IVA. 23:00-02:40 UT 04 - 05.09.2012

Fig. 8. Model of the distribution of components of magnetic fields generated by Hall currents on the Earth's surface. Small circles show the regions of flowing in and out longitudinal currents. Dotted lines mark elliptical regions occupied by vortex Hall currents.

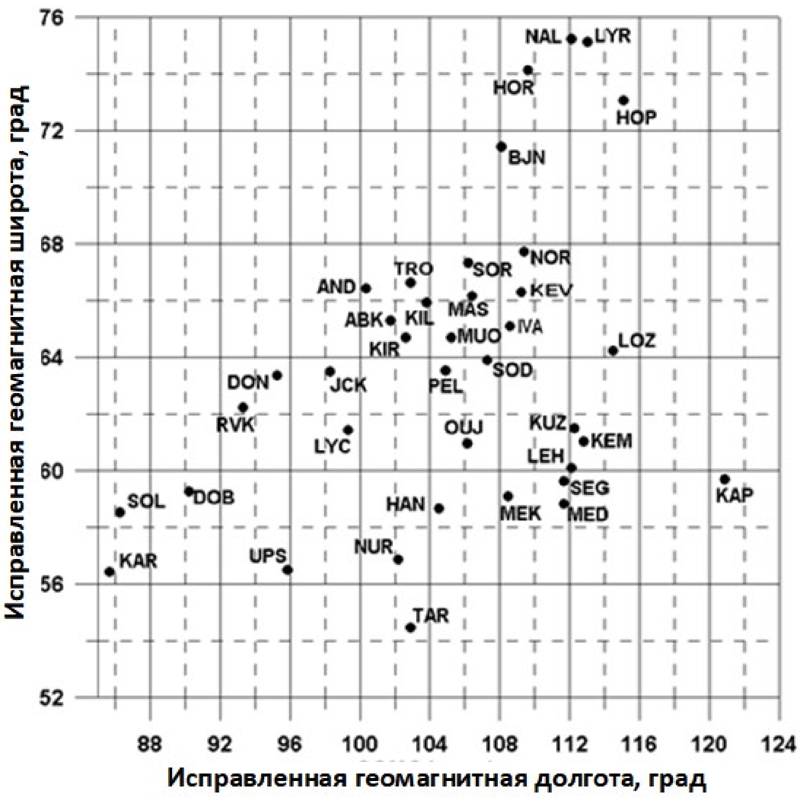

Fig. 1.

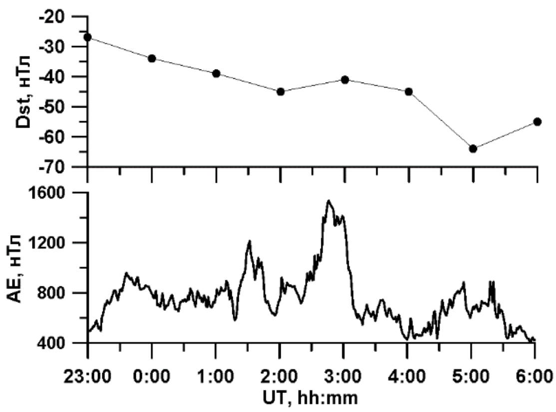
Dst, нТл
-20
-30
-40
-50
-60
-70
AE, нТл
1600
1200
800
400
23:00
0:00
1:00
2:00
3:00
4:00
5:00
6:00
UT, hh:mm

Fig. 2.

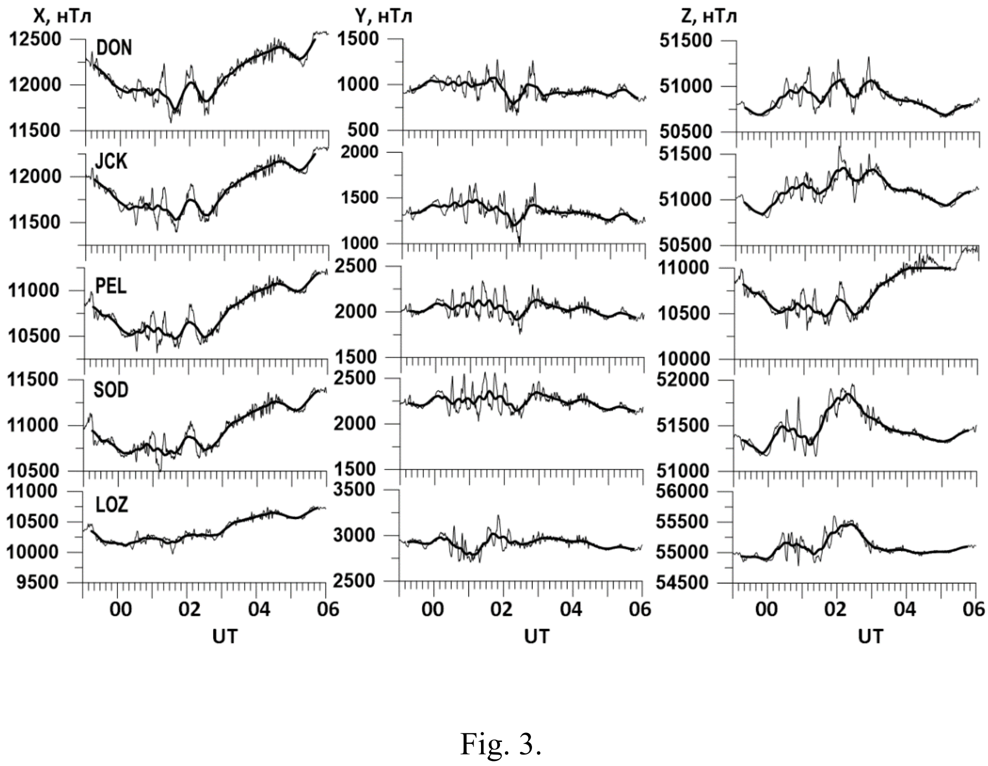
X, нТл
Y, нТл
Z, нТл
DON
JCK
PEL
SOD
LOZ
00
02
04
06
UT

Fig. 3.

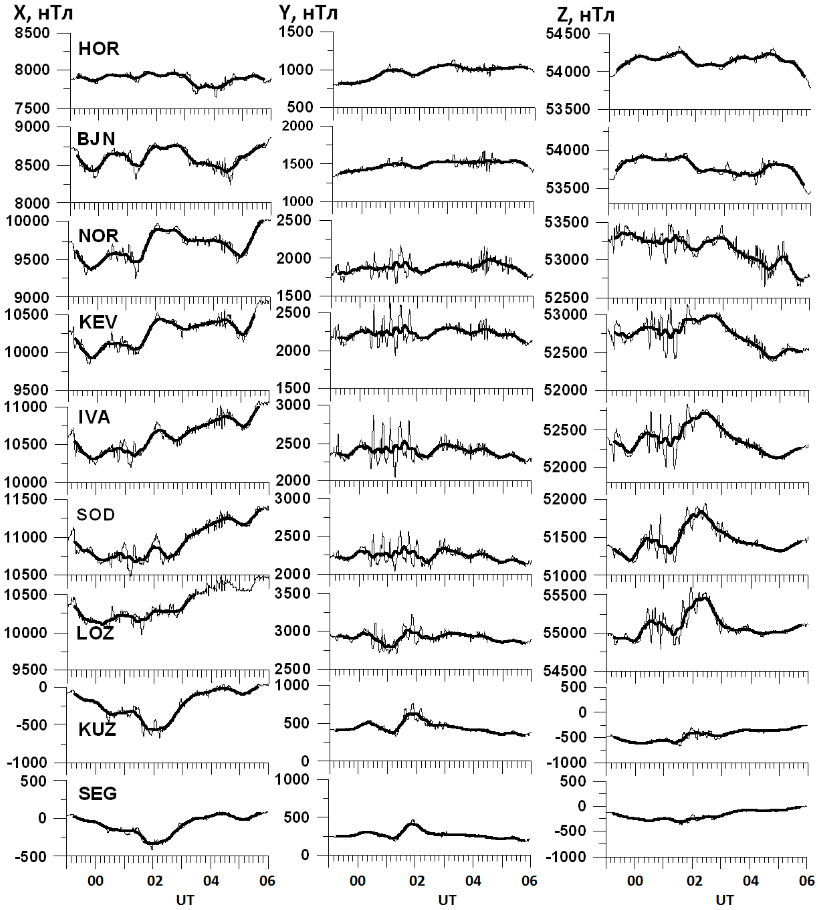
X, нТл
Y, нТл
Z, нТл
HOR
BJN
NOR
KEV
IVA
SOD
LOZ
KUZ
SEG
UT

Fig. 4.

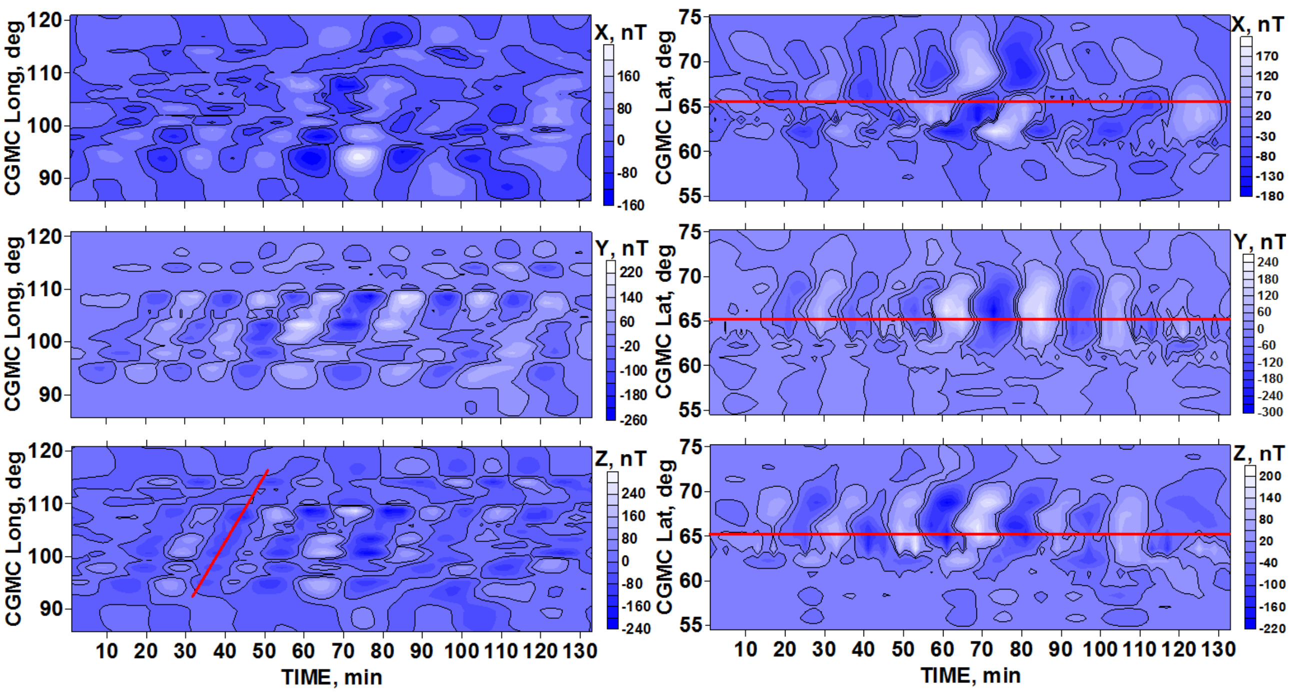
CGMC Long, deg
CGMC Lat, deg
X, nT
Y, nT
Z, nT
TIME, min

Fig. 5.

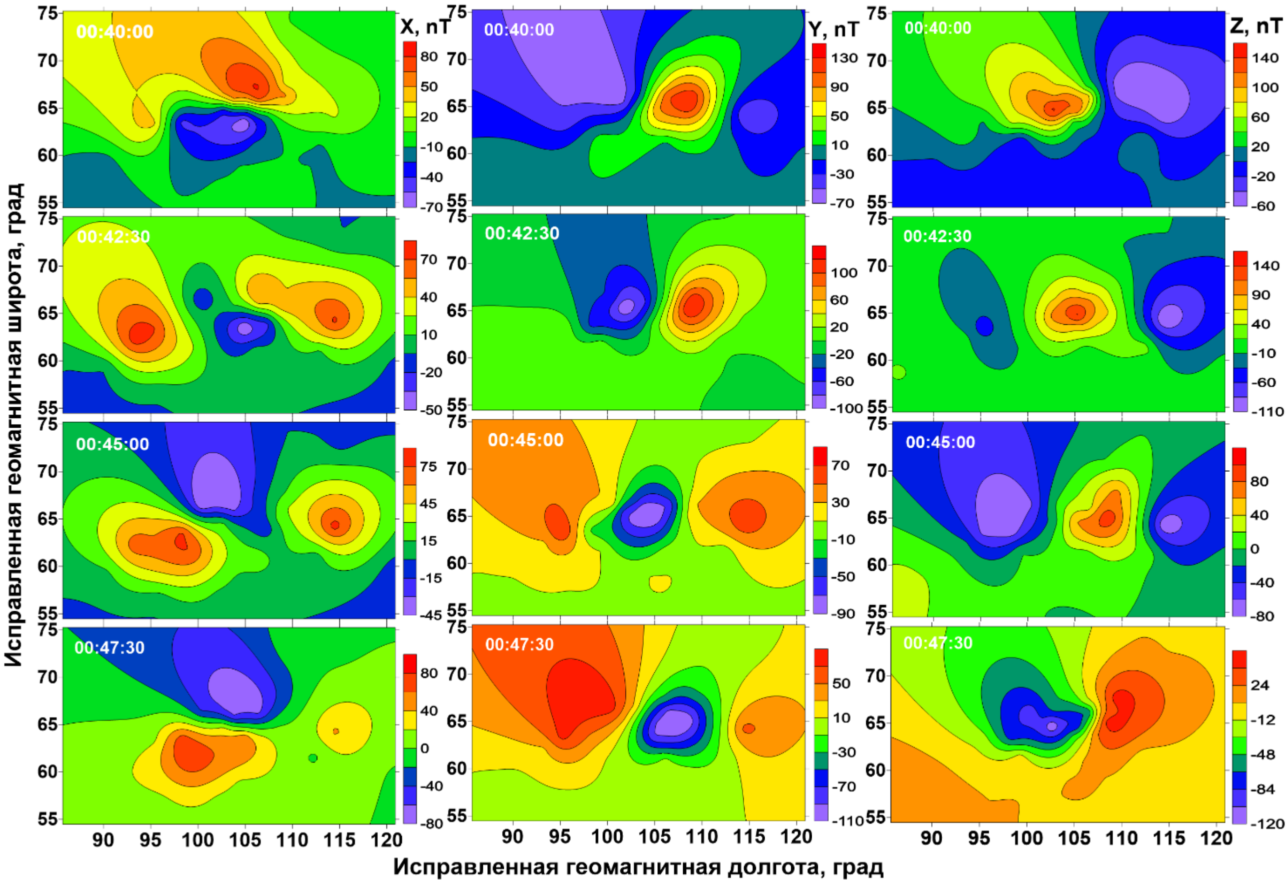
Исправленная геомагнитная широта, град
Исправленная геомагнитная долгота, град
X, nT
Y, nT
Z, nT
00:40:00
00:42:30
00:45:00
00:47:30

Fig. 6.

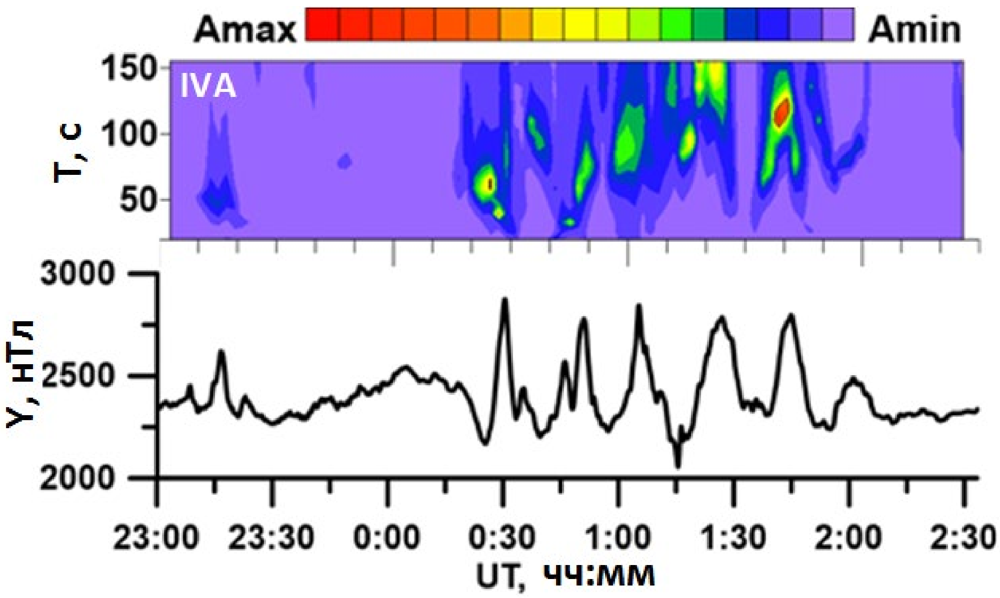
Amax
Amin
IVA
T, c
Y, нТл
UT, чч:мм

Fig. 7

Fig. 8.