Analysis of geomagnetic field data during periods of increased solar activity and magnetic storms

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Abstract. We present and describe an automated method for analysis of magnetic data and the detection of geomagnetic disturbances based on wavelet transformation. The parameters of the computational algorithms allow us to estimate the characteristics of non-uniformly scaled peculiar properties in the variations of the geomagnetic field that arise during periods of increasing geomagnetic activity. The analysis of geomagnetic data on the eve and during periods of magnetic storms was carried out on the basis of the method according to the network of ground stations. Periods of increasing geomagnetic activity are highlighted which precede and accompany magnetic storms. The dynamic of variation of the geomagnetic field in the auroral zone is considered in detail.

1. Introduction
Analysis of geomagnetic data and the study of processes in the magnetosphere provide valuable information about the state of electromagnetic fields in near-Earth space during periods of increased solar activity [1]. The complexity of processing and analysis of geomagnetic data is associated with their complex nonstationary structure, with the presence of local features of different amplitude and duration. These features contain important information about the occurring processes in the magnetosphere. The use of traditional methods and approaches does not allow us to research the rapidly-variable structure of geomagnetic field variations in detail and leads to the loss of meaningful information. One of the most effective modern methods of data analysis is the wavelet transform [2-5]. This mathematical apparatus is the basis of the research method.

Wavelet transform is widely applied in tasks of the analysis of magnetic data [4-9]. Application of this mathematical apparatus allows to study short-period fluctuations of the geomagnetic field, nonstationary changes in the parameters of the solar wind and interplanetary magnetic field [6,10]. The wavelet transform is now successfully used for the tasks of denoising the geomagnetic data [4,5,11], extraction of the periodic components caused by the Earth’s rotation [4,5], algorithm was developed for automatically determining the periods of the initial phase of a magnetic storm [12].
Based on the analysis of the wavelet spectrum of variations of the geomagnetic in the article [13] the method of prediction of strong geoeffective solar flares is proposed. The authors of this article actively apply the wavelet transform: the model of variations in the geomagnetic field was proposed on the basis of the wavelet packets [10], automated methods for detecting disturbances of the geomagnetic field have been developed based on the discrete and continuous wavelet transforms [8-10,14,15]. The proposed approach allowed for the first time to automatically reproduce the procedure for calculating the geomagnetic activity index K (K-index) by the method of J. Bartels [8,16]. This study is a continuation of the previous works. The paper presents the results of data processing and analysis from a geomagnetic station network in Russia («Yakutsk» YAK, «Paratunka» PET, http://www.intermagnet.org), equatorial station («Guam» GUA, USA, http://www.intermagnet.org) and stations of the auroral zone («Abisko» ABK, Sweden, «Fort Churchill» FCC, Canada, «Narsarsuaq» NAQ, Greenland и «Yellowknife» YKC, Canada, http://www.intermagnet.org). The results of the analysis were compared with the interplanetary environment parameters (the interplanetary magnetic field data and the solar wind parameters were analyzed, https://omniweb.gsfc.nasa.gov/ow.html). The results of the work confirmed the possibility of synchronous appearance of weak magnetic perturbations preceding the onset of strong magnetic storms.

2. Description of the method

The geomagnetic field variation can be represented as a combination of functions [8,9]:

\[ f(t) = f_{\text{trend}}(t) + f_{\text{pert}}(t) + e(t) = \sum_{n} c_{m,n} \phi_{m,n} (t) + \sum_{j=1}^{n} g_j (t) + e(t), \]

where the component \( f_{\text{trend}}(t) = \sum_{n} c_{m,n} \phi_{m,n} (t) \) describes the geomagnetic field variations during quiet periods; \( \phi_m = \{\phi_{m,n}\}_{n\in\mathbb{Z}} \) is the basis of the smoothing scaling function; \( f_{\text{pert}}(t) = \sum_{j=1}^{n} g_j (t) = \sum_{j=1}^{n} d_{j,n} \Psi_{j,n}(t) \) describes geomagnetic perturbations that occur during periods of increasing geomagnetic activity; the coefficients \( c_{m,n} = \{f, \phi_{m,n}\} \) and \( d_{j,n} = \{f, \Psi_{j,n}\} \); \( m \) is the scale level of decomposition; \( \Psi_j = \{\Psi_{j,n}\}_{n\in\mathbb{Z}} \) are the wavelet basis; \( I \) is a set of indices; \( j \) is the scale parameter; component \( e(t) \) is noise.

The representation (1) will be called the geomagnetic field variation model. The method for identifying the model component \( f_{\text{trend}} \) (see Equations (1)) is described in [8,9].

As an approximation basis, the Daubechies basis of order 3 is used, which was determined by minimizing the approximation error [8]. The results of the model assess (1) on the example of data from «Paratunka» station (Kamchatka Region) are presented in [8,10,15,16]. In this work, the component \( f_{\text{trend}} \) is not used.

As a measure of magnetic disturbance, the value of [17]:

\[ A_j = \max_n\{d_{j,n}\} \]

(2)

Then geomagnetic disturbances (define a set of coefficients \( \{d_{j,n}\}_{j=1} \) in (1)) can be identifying on the basis of threshold functions \( F_1 \) and \( F_2 \) [9]:

\[ f(t) = f_{\text{trend}}(t) + \sum_{j=1} F_1(d_{j,n}) \Psi_{j,n}(t) + \sum_{j=1} F_2(d_{j,n}) \Psi_{j,n}(t) + e(t). \]

(3)

\[ F_1(x) = \begin{cases} 0, & \text{if } |x| \leq T_{j,\text{pert}^{-1}} \text{ or } |x| > T_{j,\text{pert}^{-1}}^2 \\ x, & \text{if } T_{j,\text{pert}^{-1}}^2 < |x| \leq T_{j,\text{pert}^{-1}} \end{cases} \]

\[ F_2(x) = \begin{cases} 0, & \text{if } |x| \leq T_{j,\text{pert}^{-2}}^2 \text{ or } |x| > T_{j,\text{pert}^{-2}}^2 \\ x, & \text{if } |x| > T_{j,\text{pert}^{-2}}^2 \end{cases} \]

(4)
The threshold $T_{j_{max}}$ determines infirm geomagnetic disturbances, and the threshold $T_{j_{max}–2}$—strong geomagnetic disturbances. The procedure for assessing thresholds $T_{j_{max}}$ and $T_{j_{max}–2}$ based on minimizing the a posteriori risk is described in [9].

Continuous wavelet transform can be used to obtain more detailed information on the properties of the analyzed function $f$ [17,18]:

$$ (W_f(b,a))=|a|^{1/2} \int_{-\infty}^{\infty} f(t)\Psi \left( \frac{t-b}{a} \right) dt, \Psi - \text{wavelet}, f \in L^2(R), a,b \in R, a \neq 0. \quad (5) $$

Since the wavelet function $\Psi$ has a zero mean value, then, when the scale $a$ converges to zero, the wavelet coefficients $(W_f(b,a))$ characterize the local properties of the function $f$ in the neighborhood of the moment of time $t=b$ [18,19].

Following equation (2) as a measure of the intensity of geomagnetic disturbances at time $t=b$, it is logical to determine the amplitude of the wavelet coefficients:

$$ v_{b,a}(t)=\left| (W_f(b,a)) \right|. \quad (6) $$

Then the field perturbation intensity at time $t=b$ can be estimated based on the value:

$$ V_b(t)=\sum_a (W_f(b,a)). \quad (7) $$

Following equation (3) and taking into account the nonstationary structure of geomagnetic data, we used adaptive thresholds to identify disturbances, first proposed in [10]:

$$ P_a\left( (W_f(b,a)) \right)=\begin{cases} \left( W_f(b,a) \right), & \text{if } (W_f(b,a)) \geq T_a \\ 0, & \text{if } (W_f(b,a)) < T_a \\ -(W_f(b,a)), & \text{if } (W_f(b,a)) < -T_a \end{cases}, \quad (8) $$

where $T_a=U \times S_{a'}$—threshold function, $S_{a'}=\frac{1}{l-1} \sum_{l=1} a'_a \left( (W_f(b,a))-(W_f(b,a)) \right)^2$, $(W_f(b,a))$ is the average value calculated in the gliding window of duration $l$, $U$ is the threshold coefficient.

Then the intensity of positive and negative perturbations at time $t=b$ can be estimated as:

$$ E_{b+} = \sum_a P_a\left( (W_f(b,a)) \right), \quad (9) $$

3. Experimental results and discussion

In the work, the geomagnetic data of minute resolution from the Russia’s stations network: «Yakutsk» YAK, «Paratunka» PET, equatorial station «Guam» GUA, USA and stations of the auroral zone «Abisco» ABK, Sweden, «Fort Churchill» FCC, Canada, «Narsarsuaq» NAQ, Greenland и «Yellowknife» YKC, Canada (see Table 1 and Figure 1).

| Observatory   | IAGA code | Geographical latitude | Geographical longitude | Geomagnetic latitude | Geomagnetic longitude | Local time (LT) |
|---------------|-----------|-----------------------|-----------------------|---------------------|-----------------------|-----------------|
| Yellowknife   | YKC       | 62°28.8’N             | 114°28.8’W            | 67°12.0’N           | 28°51.0’W            | UTC–6           |
| Fort Churchill| FCC       | 58°45.5’N             | 94°05.3’W            | 67°12.0’N           | 28°51.0’W            | UTC–5           |
| Narsarsuaq    | NAQ       | 61°11.7’N             | 45°25.0’W            | 69°00.0’N           | 38°49.2’W            | UTC–2           |
| Abisco        | ABK       | 68°21.7’N             | 18°43.4’E            | 66°04.8’N           | 113°53.4’E           | UTC+2          |
| Yakutsk       | YAK       | 61°57.6’N             | 129°39.4’E           | 52°54.0’N           | 162°23.4’E           | UTC+09         |
| Guam          | GUA       | 13°35.4’N             | 144°52.5’E           | 5°58.8’N           | 143°03.0’E           | UTC+10         |
| Paratunka     | PET       | 52°58.3’N             | 158°15.0’E           | 46°19.8’N           | 136°52.2’E           | UTC+12         |
In order to analyze geomagnetic activity in the auroral zone, we used the index geomagnetic activity AE, AU, AO и AL (http://isgi.unistra.fr) [20,21]. In order to analyze the equatorial current system, we used the Dst-index (http://isgi.unistra.fr) [22]. The results of our analysis were compared against data of interplanetary magnetic field and parameters of the solar wind (https://omniweb.gsfc.nasa.gov/ow.html). The results of data processing during the magnetic storm on July 09, 2017 and October 10, 2017 are presented below in detail.

The first analyzed event on July 09, 2017 (see Figure 2-4) was caused by the arrival of a heterogeneous stream flowing from a large coronal hole (http://spaceweather.com). On the eve of the storm July 08 from 7.30-22.20 UT during periods of oscillation of the IMF Bz component (Fig. 2c) changed within +/-1.5 nT there is an increase in the values of the indices of auroral activity (Fig.2a) and the occurrence of short-term weak geomagnetic disturbances at the analyzed stations (Fig.2f и 3d,e). Allows us to suggest a connection of the detected geomagnetic perturbations with the non-stationary changes in the interplanetary environment parameters and auroral activity intensification. In the morning hours of July 9 around 01.15 UT, when the IMF Bz component turned south and reached a value of -10 nT (Fig. 2c), the solar wind speed increased sharply from 325 to 395 km/s, and short-period perturbations were identified (Fig.2f,g и 3d,e) at all geomagnetic stations. This allows us to assume the relationship of the selected disturbances with nonstationary changes in the parameters of the interplanetary medium. With the advent of high-speed flow, the solar wind speed gradually increased to 420 km/s, the fluctuations of the IMF Bz component increased to ± 12 nT.

The initial phase of the storm was accompanied by an increase in the Dst-index (Fig. 2d), and auroral activity (Fig. 2a). During the main phase of the storm, perturbations of maximum intensity were observed at all the stations under analysis (Fig. 2f,g и 3d,e). At the same time, due to the different location of the stations, the perturbation dynamics at each station slightly differed. At the equatorial station GUA, short-period perturbations occurred during the initial and main phases of the magnetic storm. In the period of increasing oscillations Bz-components (Fig. 3c), an increase in the indices of auroral activity is observed (Fig. 3a) and the occurrence of strong disturbances at the stations YAK и PET (Fig. 3d,e), the intensity of which reached the maximum values at the station YAK (Fig. 3e).

Analysis of auroral zone data (see Figure 4) shows a correlation between increases in auroral activity indices and fluctuations of the IMF Bz component (Fig. 4b,d) with increases in geomagnetic disturbances at stations in the morning and at night (Fig. 4a, c). We can also note the correlations of the detected geomagnetic perturbations with the AE-index not only in their occurrence times, but also in their intensities. This is probably related to the increase in the intensity of the currents of the western electrojet in the auroral region [23].

Figure 1. Geographical position of observatories that provided data used in this study.
Figure 2. Processing results of the data for July 08–10, 2017:

a) auroral indices AE, AO, AL and AU; b) speed of solar wind; c) Bz-component of interplanetary magnetic field, red color indicates positive values, blue – negative; d) Dst-index; e) H-component of the magnetic field; f) wavelet spectrum of geomagnetic disturbances in the areas of stations PET, YAK and GUA (operation (5)); g) absolute values of intensity of disturbances in the areas of stations PET, YAK and GUA (operation (7)). The vertical dashed line indicates the onset of a magnetic storm.
Figure 3. Processing results of the data for July 08–10, 2017:

a) auroral indices AE, AO, AL and AU; b) speed of solar wind; c) Bz-component of interplanetary magnetic field, red color indicates positive values, blue – negative;
d) calculations following (8), red color indicates positive perturbations, blue – negative;
e) calculations following (9), red color indicates positive perturbation, blue – negative;

The vertical dashed line indicates the onset of a magnetic storm.
Figure 4. Results of the analysis of data of stations of the auroral zone:

a) H-component of the magnetic field; b),d) auroral indices AE, AO, AL and AU and Bz-component of interplanetary magnetic field, red color indicates positive values, blue – negative; c) wavelet spectrum of geomagnetic disturbances of stations of the auroral zone (operation (5)). The vertical dashed line indicates the onset of a magnetic storm.

The second analyzed event on October 10, 2017 (see Figure 5-7) was caused by the arrival of a heterogeneous stream flowing from a large coronal hole (http://spaceweather.com). On the eve of the storm, the solar wind speed was 322 km/s, the IMF Bz component changed within +/- 0.9 nT. Analysis of the results of geomagnetic data processing shows that weak geomagnetic disturbances were observed at the analyzed stations on the eve of the event, a slight increase in the indices of auroral activity on October 10 in the period from 11:00 - 13:20 UT was accompanied by weak disturbances of the geomagnetic field at the stations being analyzed (Fig. 5f,g; 6d,e). The coincidence of periods of increased geomagnetic activity at the analyzed stations with periods of increasing indices of auroral activity, observed against the background of increasing fluctuations of the Bz component (Fig. 5b), suggests a relationship between selected geomagnetic disturbances and unsteady changes in the parameters of the interplanetary medium and increased auroral activity.

At the end of the day October 10, despite the fact that the Bz component was the northern (about 19:10 UT), short-term disturbances were observed at all analyzed stations (Fig. 6d,e). Similar results were noted earlier in [24], it was shown that an increase in the solar wind parameters can be observed before sharp turns of the IMF to the south, leading then to magnetic storms [25].

At the initial stage of the storm, the value of the Dst-index increased moderately (see Fig. 5d). The initial phase of the storm was accompanied by an increase in geomagnetic activity at stations of middle and high latitudes (YAK, PET), and a simultaneous increase in auroral activity. Note that during the main phase of the storm, the geomagnetic field variations structure differed at the middle and high latitudes (YAK, PET) and equatorial GUA stations that is probably due to their location (see Fig. 6e).
Figure 5. Processing results of the data for October 10–12, 2017:
a) auroral indices AE, AO, AL and AU; b) speed of solar wind; c) Bz-component of interplanetary magnetic field, red color indicates positive values, blue – negative; d) Dst-index; e) H-component of the magnetic field; f) wavelet spectrum of geomagnetic disturbances in the areas of stations PET, YAK and GUA (operation (5)); g) absolute values of intensity of disturbances in the areas of stations PET, YAK and GUA (operation (7)). The vertical dashed line indicates the onset of a magnetic storm.
Figure 6. Processing results of the data for October 10–12, 2017:

a) auroral indices AE, AO, AL and AU; b) speed of solar wind; c) Bz-component of interplanetary magnetic field, red color indicates positive values, blue – negative;
d) calculations following (8), red color indicates positive perturbations, blue – negative;
e) calculations following (9), red color indicates positive perturbation, blue – negative;

The vertical dashed line indicates the onset of a magnetic storm.
Analysis of processes in the auroral zone (see Fig. 7) shows the relationship of the selected disturbances (Fig. 7c) with the periods of fluctuations of the IMF Bz component (Fig. 7b,d), which correlated both in time and in intensity with increases of geomagnetic activity at the stations. The results of data processing (Fig. 7c) make it possible to determine the position of the maxima of electrojets by longitude, and show a picture of their interaction.

Figure 7. Results of the analysis of data of stations of the auroral zone:

a) H-component of the magnetic field; b), d) auroral indices AE, AO, AL and AU and Bz-component of interplanetary magnetic field, red color indicates positive values, blue – negative; c) wavelet spectrum of geomagnetic disturbances of stations of the auroral zone (operation (5)). The vertical dashed line indicates the onset of a magnetic storm.

4. Conclusions

On the basis of the proposed method, we performed a spatio-temporal analysis of the dynamics of geomagnetic disturbances during magnetic storms on July 09 and October 10, 2017. Our experimental results clearly indicate high sensitivity of the suggested technique and the possibility of its application for the in-depth study of the dynamics and spatio-temporal distribution of the geomagnetic perturbations (based on processing data from a network of geomagnetic observatories) for different levels of storminess of the geomagnetic field. Our results indicate the effectiveness of the proposed method for analyzing processes in high latitudes.

During the periods preceding the beginning of magnetic storms, weak geomagnetic perturbations synchronously appearing at the stations and correlating with the AE-index, both in occurrence times and in intensity, were detected. Analysis of the processes in the auroral zone showed a connection between the identified geomagnetic disturbances and the parameters of the interplanetary magnetic field and indices of the auroral activity.

In papers [10,13,15 and etc.], the possibility of the appearance of weak geomagnetic disturbances, which often occur before strong magnetic storms, is noted, what is of interest in space weather problems. According to the authors, an interesting result is the confirmed fact of an increase in the solar wind parameters and following increase in geomagnetic activity before a sharp turn of the IMF to the south. Similar results were noted earlier in [10] and [24].

In the future, the authors plan to continue the study with the increase in statistics and the number of stations analyzed.
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