# Method of analysis of geomagnetic data based on wavelet transform and threshold functions

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**Abstract**

The method is aimed at studying the dynamics of the magnetospheric current systems during magnetic storms. The method is based on algorithmic solutions for processing of geomagnetic field variations, for detection of local increases in geomagnetic disturbance intensity. Parameters of the algorithms allow us to evaluate the characteristics of small-scale local features emerging during geomagnetic activity slight increases and large-scale variations observed during magnetic storms. To evaluate the method, geomagnetic data from the stations located in the north-east of Russia and equatorial India were used. The method testing showed the possibility to apply it for the detection of pre-storm anomalous effects in geomagnetic data.
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*Keywords:* Wavelet transform; geomagnetic data processing; magnetic storm;

## 1. Introduction

The work is devoted to the creation of methodical and software means for the analysis of recorded geomagnetic data. At present, theoretical and experimental bases of construction of systems for data processing and analysis are intensively developing, in particular in geophysics (for example, http://www.cosmos.ru/magbase; http://matlab.izmiran.ru/magdata/; https://www.ngdc.noaa.gov/; http://smdc.sinp.msu.ru/). It is caused by the increase of human society demands in automation of data flow processing. The subjects of this investigation are complex dynamic processes in the Earth magnetosphere and ionosphere determined by the phenomena and processes of solar origin. Solar activity impact on the Earth magnetosphere has quite a complicated character. Many aspects of it are still under-investigated [1]. As long as the state of magnetospheric-ionospheric system is an important factor of space weather which affects many aspects of our life, works in this area are of high scientific interest [1]. The Earth magnetic field variations are associated with different geophysical processes in the Earth near space. During magnetic storms they contain uneven local features occurring at random times and carrying, as a rule, the main information on the processes under investigation [2-14]. Traditional methods for data analysis applying basic models of time series, different techniques of smoothing and Fourier analysis methods are not effective enough to investigate fast unsteady processes. As it was noted in the papers [15-18], they do not allow one to identify thin local features characterizing short-period oscillations during increased geomagnetic activity and to estimate their dynamic characteristics before and during storms. At present, modern mathematic methods and technologies are intensively developing in this area. Based on Data Mining application in order to improve the processes of geophysical data recording and organization of world data centers, methods for automation of expert work in this area have been developed (creation of so called “artificial experts”) to solve geomagnetic data analysis problems, to detect noise at the stage of their preliminary processing, to identify anomalies during magnetic storms, to process magnetograms etc. [19-22]. The authors apply a new approach, «discrete mathematical analysis» (DMA), which includes fundamental notions of mathematical analysis and modern approaches based on L. Zadeh’s logic. A group of scientists from India (KaleekkalUnnikrishnan) developed a technique for modeling of geomagnetic field variations for low-latitudinal stations. It is based on neural networks. The developed approach allowed them to improve the quality of the forecasting technique for magnetic storms (in 86% of cases) in comparison to the nearest method based on logistic regressive model obtained in 2005 (in 77% of cases) [23]. A group of scientists from Egypt (Space Weather Center, Faculty of Science, Helwan University, Cairo, Egypt) suggested to apply neural networks to predict the time of interplanetary shock wave propagation [24]. Based on the neural networks, the authors [25] suggested an algorithm for interplanetary magnetic field data processing and Dst-index calculation. The authors of that paper suggest an approach based on the combination of neural networks with wavelet transform and show the efficiency of joint application of mathematical apparatus data in comparison with a neural network in the problems of analysis of natural time series with complicated structures [26-29], in particular, for geomagnetic data analysis [28, 29]. It is shown in these papers that wavelet transform allows us to investigate the data structure in detail and to detect informative components which, in their turn, improve the procedure of neural network training and its performance efficiency. At present time, wavelet transform is widely used in the problems of analysis of the Earth magnetic field variations [2-5, 10, 14], in particular, in the investigation of the relations between short-period oscillations of the geomagnetic field, solar wind parameters and interplanetary field during geomagnetic storms [2], in the study of magnetic field secular variations [10] and so on. Based on the wavelet transform, we solve such problems as denoising and elimination of a periodic component from geomagnetic field variations which is caused by the Earth rotation [4]. Applying the discrete wavelet transform, the authors of the paper [3] suggested an algorithm for automatic detection of magnetic storm initial stage periods. On the basis of the analysis of geomagnetic field variation wavelet spectrum, a method for forecast of strong geoeffective solar flares was proposed in the paper [13]. In terms of wavelets, the authors of this paper suggested a new model of geomagnetic field variations [14, 30] and developed automatic algorithms do detect calm diurnal variation and to estimate disturbance intensities [30]. This approach allowed us to automate the procedure for calculation of geomagnetic activity index K, close to J. Bartels method, and to decrease the calculation error in comparison to the current methods [30]. In this paper we continue the investigation in this direction where a special emphasis is placed on the development of calculation solutions to detect and to estimate short-time anomalous increases in geomagnetic disturbance intensity which may occur before magnetic storms and have applied significance. It is also very important to apply the geomagnetic field data recorded on the ground, the analysis methods of which may significantly contribute to the current forecast methods. Taking into account incomplete prior knowledge on the dynamics of magnetospheric current systems, in particular during the disturbed periods, and the limited scope of the obtained information on the processes in the near Earth space, noises, possible equipment failures etc., the successful solution of the complicated problem of space weather forecast requires a complex of methods and technologies. The confirmation of it is the large number of papers and scientific groups which aim their efforts at creating methods for recognition and classification of the effects in geophysical observation time series with applications in space weather problems.

## 2. Description of the method

In the papers [14, 30] the authors propose geomagnetic field variation representation based on multiscale wavelet decompositions:

$$f_0(t) = \sum_n c_{-6,n}\varphi_{-6,n}(t) + \sum_{j\in D}\sum_n d_{j,n}\Psi_{j,n}(t) + \sum_{j\notin D}\sum_n d_{j,n}\Psi_{j,n}(t) = f_{trend}(t) + f_{dist}(t) + e(t), \qquad (1)$$

where $\Psi_j = \{\Psi_{j,n}\}_{n\in Z}$ is the wavelet-basis, $\varphi_j = \{\varphi_{j,n}\}_{n\in Z}$ is the basis, obtained from a scaling function, coefficients $c_{j,n}$ and $d_{j,n}$ are defined from the equations: $c_{j,n} = \langle f, \varphi_{j,n}\rangle$, $d_{j,n} = \langle f, \Psi_{j,n}\rangle$, $D$ is a set of indices of the disturbed components, $j$ is the scale, the inferior index «0» denotes that the initial discrete data belong to a domain of scale «0».

Component $f_{trend}(t) = \sum_n c_{-6,n}\varphi_{-6,n}(t)$ describes the undisturbed level of the horizontal component of the Earth magnetic field during quiet geomagnetic field, and the component $f_{dist}(t) = \sum_{j\in D} g_j(t)$ where $g_j(t) = \sum_n d_{j,n}\Psi_{j,n}(t)$ describes perturbations, arising during increasing geomagnetic activity. Component $e(t) = \sum_{j\notin D}\sum_n d_{j,n}\Psi_{j,n}(t)$ is the noise.

Minimizing the errors in the class of orthonormal functions, the Daubechies basis of order 3 was determined as the wavelet basis [30].

The set of indices $D$ can be determined on the basis of the following criteria [14, 30]:

$$j \in D, \text{ if } m(A_j^v) > m(A_j^k) + \varepsilon, \qquad (2)$$

where $m$ is the sample mean, $v$ is the index of disturbed field variation, $k$ is the index of calm field variation, and $\varepsilon$ is a positive number.

Assuming that $A_j^v$ and $A_j^k$ are normally distributed with mean $\mu^v$, $\mu^k$, $\mu^v > \mu^k$ and variances $\sigma^{2,v}, \sigma^{2,k}$, it is possible to estimate $\varepsilon_j$ as $\hat{\varepsilon}_j = x_{1-a/2}\dfrac{\sigma_j^k}{\sqrt{n^k}}$, where $\sigma_j^k$ is the variance of the greatest wavelet coefficients (for scale $j$) for quiet days (this variance is determined as a result of multiple measurements); $x_{1-a/2}$ is the $1-a/2$ quantile of the standard normal distribution; $n^k$ is the number of analyzed quiet-field variations. If $a = 0.1$, the confidence probability is $1 - a/2 = 0.95$, the quantile is $x_{1-a/2} = 1.96$, and $\varepsilon_j = 1.96\dfrac{\sigma_j}{\sqrt{n}}$.

The measure of geomagnetic disturbance of the component $g_j(t)$ on the scale $j$ is [14,30]:

$$A_j = \max_n\left(\left|d_{j,n}\right|\right). \qquad (3)$$

Taking into account that the component $f_{dist}(t) = \sum_{j\in D} g_j(t)$, where $g_j(t) = \sum_n d_{j,n}\Psi_{j,n}(t)$ describes the disturbances (see relation (1)), and the equivalence of discrete and continuous wavelet decompositions, in order to obtain more detailed information on the properties of the function $f$ under analysis, continuous wavelet transform may be applied [31, 32]

$$(W_\Psi f)(b,a) := |a|^{-1/2}\int_{-\infty}^{\infty} f(t)\Psi\left(\frac{t-b}{a}\right)dt, \ \Psi \text{ is the wavelt, } f \in L^2(R), a,b \in R, \ a \neq 0, \qquad (4)$$

In this case, when a scale $a$ vanishes, the wavelet coefficients $(W_\Psi f)(b,a)$ characterize the local properties of the function $f$ in the vicinity of the instant time $t = b$ [31, 32].

Following the relation (3) as a measure of geomagnetic disturbance intensity, it is logical to consider the wave coefficient amplitude

$$i_{b,a} = \left|\left(W_\Psi f_{b,a}\right)\right|.$$

The intensity of field multi-scale disturbances at an instant time $t = b$ is estimated on the basis of the value [14, 30]

$$I_b = \sum_a \left(W_\Psi f_{b,a}\right). \qquad (5)$$

In the case of field positive disturbances (current variation increase relatively the characteristic level), $I_b$ value is positive. In the case of field negative disturbances (variation decrease relatively the characteristic level), $I_b$ value is negative.

To *distinguish the periods of increased geomagnetic activity*, the following threshold function is applied:

$$P_{T_a}(W_\Psi f_{b,a}) = \begin{cases} W_\Psi f_{b,a}, \text{если } \left(W_\Psi f_{b,a}\right) \geq T_a \\ 0, \text{если } \left|W_\Psi f_{b,a}\right| < T_a \\ -W_\Psi f_{b,a}, \text{если } \left(W_\Psi f_{b,a}\right) < -T_a \end{cases}, \qquad (6)$$

where $T_a = U * St^l{}_a$ is the threshold function where $St^l{}_a = \sqrt{\frac{1}{l-1}\sum_{k=1}^{l}\left(W_\Psi f_{b,a} - \overline{W_\Psi f_{b,a}}\right)^2}$, is the standard deviation, $l$ is the time window length, $\overline{W_\Psi f_{b,a}}$ is the average value, $U$ is the threshold coefficient.

It is obvious that the parameters of function (5), the window length $l$ and the threshold coefficient $U$, are adjustable and determine the size of a time window within which geomagnetic disturbances are estimated and the level of determined geomagnetic disturbances, respectively.

In the paper, we use the moving time window length of $l = 720$ counts, that corresponds to 12 hours. The threshold coefficient is $U = 3$.

To estimate *the intensity of the detected disturbances* at an instant time $t = b$ according to the paper [30], we apply the value of

$$Y_b = \sum_a P_{T_a}\left(W_\Psi f_{b,a}\right) \qquad (7)$$

We make wavelet transform of value $Y_b$ (see (4))

$$\left(W_\Psi Y_{c,d}\right) := |d|^{-1/2} \int_{-\infty}^{\infty} f(t)\Psi\left(\frac{t-c}{d}\right)dt,\ d, c \in R,\ d \neq 0, \qquad (8)$$

and taking into account that a wavelet is a window function [31], we obtain a *dynamic spectrum of geomagnetic disturbance intensity*.

**Processing results of geomagnetic data during the magnetic storms on January 7, 2015 and March 17, 2015**

The data from the sites in the north-eastern segment of Russia were processed and analyzed (Table 1). These data were recorded during the strong magnetic storms which occurred on January 7, 2015 and March 17, 2015. To analyze the processes in the magnetosphere at the near equatorial latitudes, the data of the Indian HYB “Hydarabad” and CPL “Choutuppal” sites were used.

**Table 1.** Sites of the north-eastern segment of Russia

| Observatory | Code IAGA | Geographical latitude | Geographical longitude | Geomagnetic latitude | Geomagnetic longitude | Local time (LT) |
|---|---|---|---|---|---|---|
| Magadan (1) | MGD | 59°33.1′ | 150°48.3′ | 51°32.4′ | 146°2.4′ | UTC+11 |
| Paratunka (1) | PET | 52°58.3′ | 158°15.0′ | 45°51.6′ | 137°57.6′ | UTC+12 |
| Khabarovsk (1) | KHB | 48°29.0′ | 135°04.0′ | 39°15′ | 156°48.6′ | UTC+10 |
| Choutuppal (2) | CPL | 17°17.33′ | 78°55' | 8°37.2′ | 152°34.8′ | UTC+5:30 |

Note: site affiliation is indicated in brackets (1) – IKIR FEB RAS, (2) – CSIR-National Geophysical Research Institute.

Fig. 1 shows the results of data processing. This event was caused by coronal ejection of solar material (CME on January 4). Its dynamics was of classical character with clearly defined major phases of a storm in Dst-variation (Fig. 1c). Analysis of the geomagnetic disturbance intensity at the sites shows that during the initial stage of the storm, from about 07:00 UT, geomagnetic activity gradually increases and the Dst-index has positive values. Maxima of disturbance intensity (Fig. 1f) are observed during Dst-index decrease and AE-index increase characterizing the occurrence of an intensive substorm in the auroral zone.

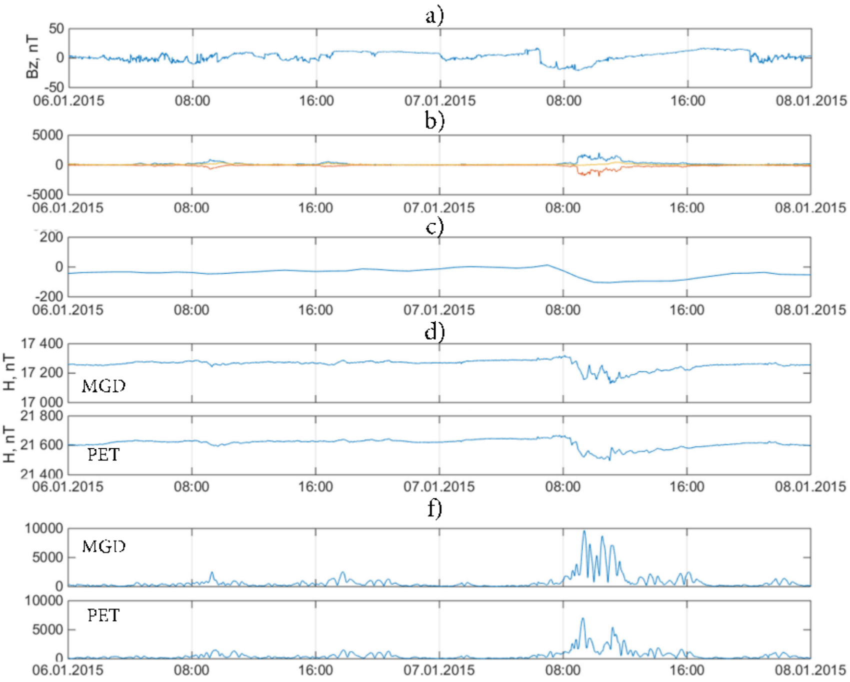


**Fig 1.** Processing results of the data for January 6-8, 2015; a) Bz component of the Interplanetary Magnetic Field; b) AE-index (yellow line), AU-index (blue line) and AL-index (red line); c) Dst-index; d) H-component of the magnetic field; f) geomagnetic disturbance intensity (relation (5)).

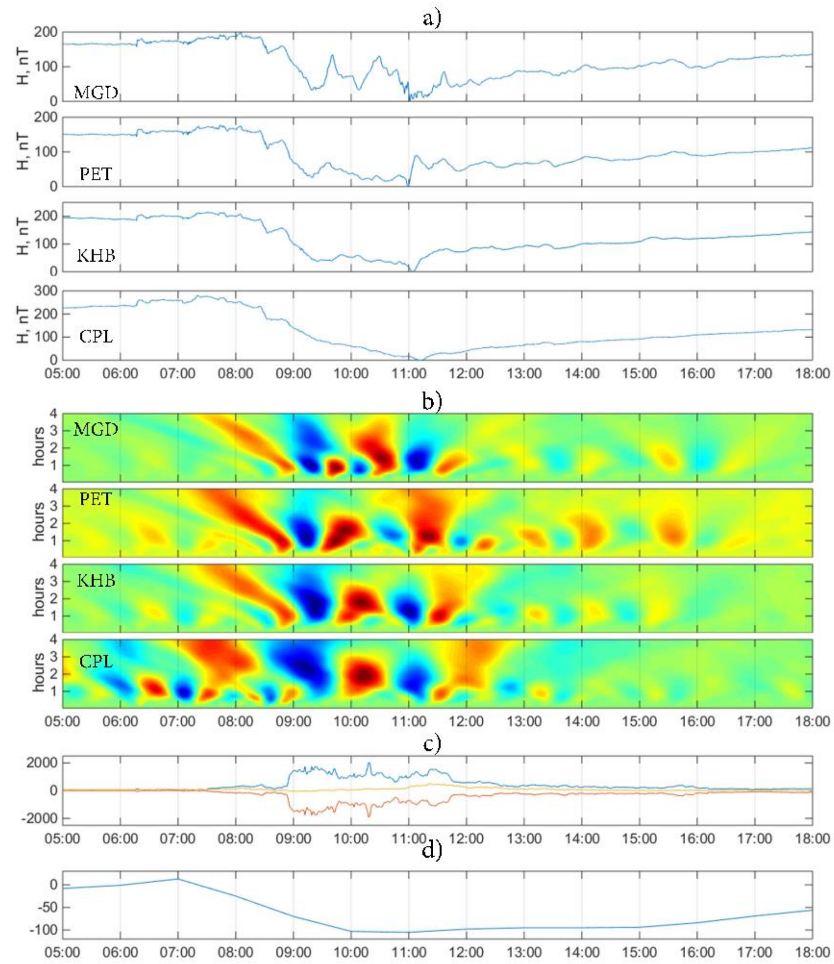


**Fig. 2.** Processing results of the data for January 6-8, 2015; a) H-component of the magnetic field; b) dynamic spectrum of geomagnetic disturbance intensity (relation (8)); c) AE-index (yellow line), AU-index (blue line) and AL-index (red line); d) Dst-index.

The dynamic spectrum of geomagnetic disturbance intensity (relation (8)) illustrated in Fig. 2 shows the regions of disturbance concentration and propagation in the areas under analysis. During the event, a general picture of the dynamics of magnetospheric current systems is observed. The beginning of the storm from 6:00 to 08:00 UT was the most clearly defined at the near equatorial site (India). During the main phase of the storm, activation areas are observed in the dynamic spectra of all the sites (Fig. 2b; red color is the intensity increase; blue color is the intensity decrease). They are likely to characterize large-scale processes in the magnetosphere probably associated with energy accumulation and release during the event. At the most northern site Magadan, local regions (from 10:00 to 11:00 UT) are distinguished. They are likely to be associated with auroral processes.

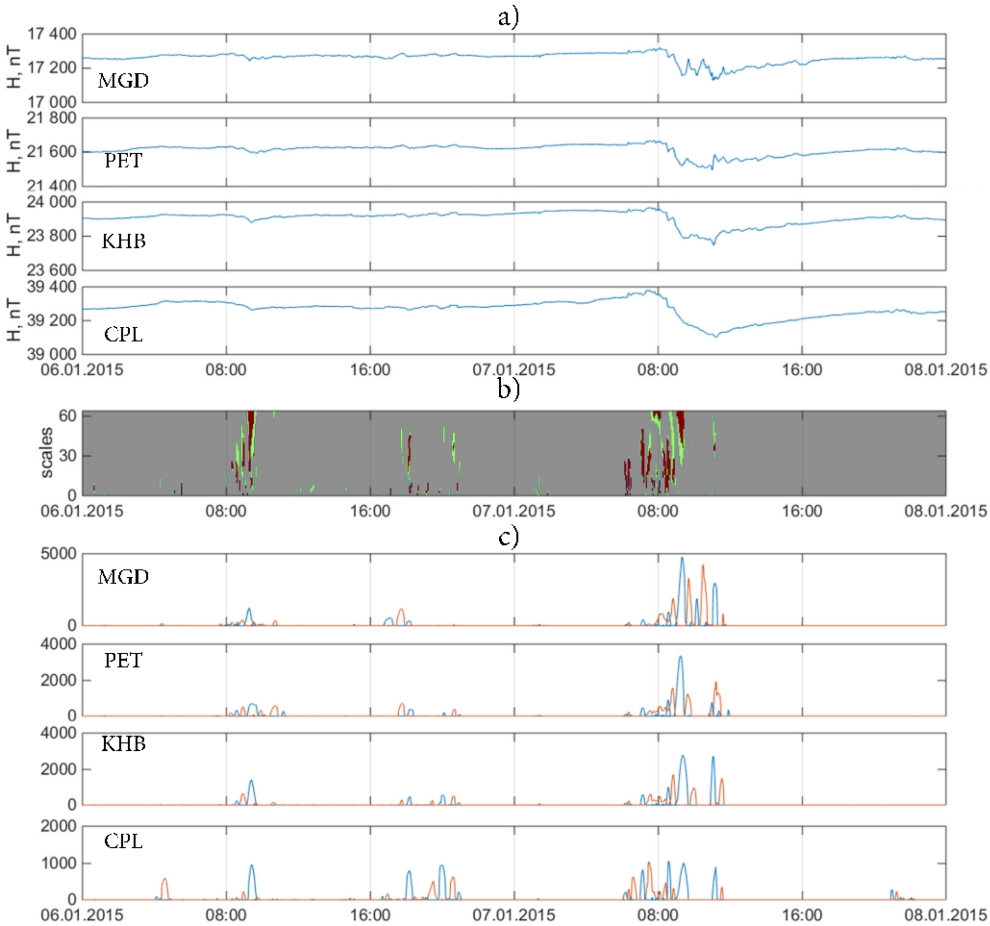


**Fig. 3.** Processing results of the data for January 6-8, 2015; a) H-component of the magnetic field; b) detection of the periods of increased geomagnetic activity (relation (6)); c) intensity of detected disturbances (relation (7)).

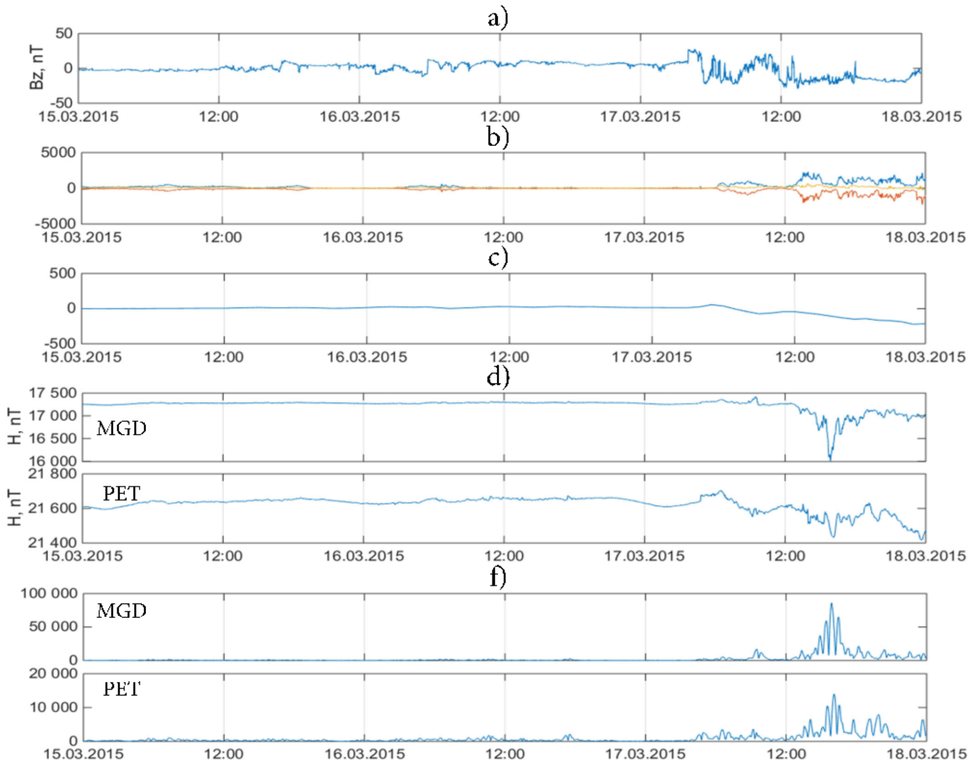


**Fig 4.** Processing results of the data for March 15-18, 2015; a) Bz component of the Interplanetary Magnetic Field; b) AE-index (yellow line), AU-index (blue line) and AL-index (red line); c) Dst-index; d) H-component of the magnetic field; f) geomagnetic disturbance intensity (relation (5)).

Fig. 3 shows the results of application of technique (6) to detect the periods of increased geomagnetic activity before and during an event. Analysis of the results shows that short-term increases of geomagnetic activity were simultaneously observed before the magnetic storms at the above mentioned sites (Fig. 3b). Their intensity increased as the event approached. We may note that at the near equatorial site (India), the intensity of the determined increases was about the same before and during the event.

Fig. 4 illustrates the data processing for the period of the second magnetic storm on March 17, 2015 which was also caused by coronal mass ejection of solar medium (CME on March 15). At MGD station, the magnetic storm began with a weak increase of geomagnetic disturbance intensity and had a more sudden commencement at two other stations. Insignificant increases in geomagnetic activity were observed before the event at PET site at local instant times. Disturbance intensity maximum values were achieved during considerable decrease of Dst-index.

The wavelet spectrum of geomagnetic disturbance intensities (Fig 5b) shows a general pattern of the event, the dynamics of which has a similar character with event described above. Increase in the disturbance intensity at all the sites occurred close to the special points (local extremum points, points of inflexion) of Dst-variation (04:00-05:00 UT; 08:00-10:00 UT, after 13:00 UT) that confirms the hypothesis mentioned above on the active processes in the magnetosphere associated with energy accumulation and release at this instant times.

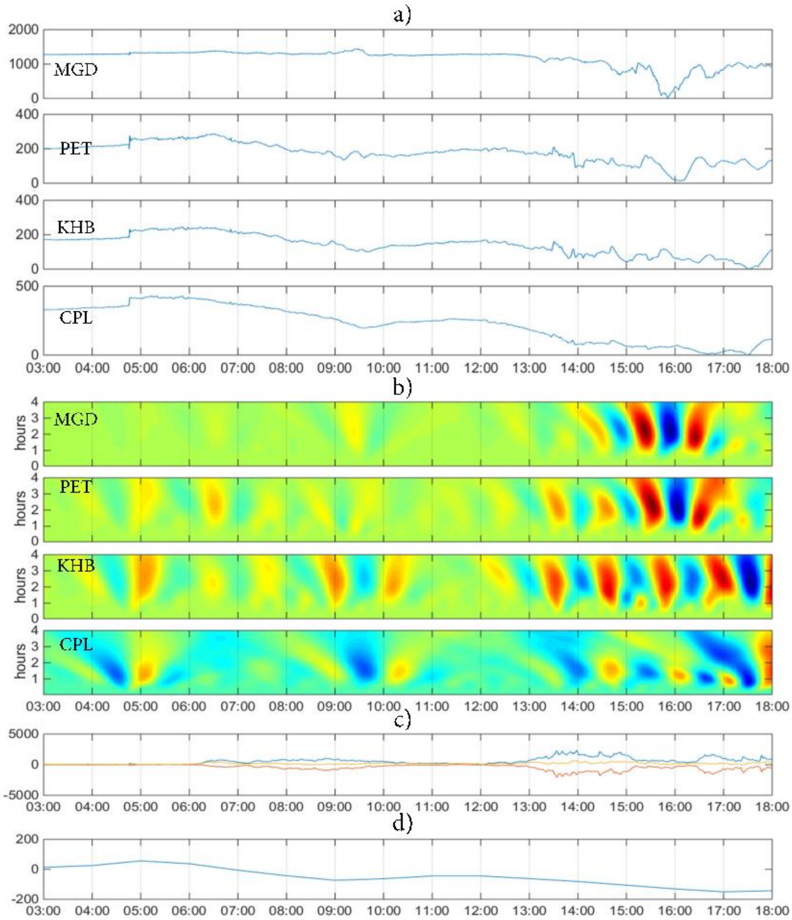


**Fig. 5.** Processing results of the data for March 15-18, 2015; a) H-component of the magnetic field; b) dynamic spectrum of geomagnetic disturbance intensity (relation (8)); c) AE-index (yellow line), AU-index (blue line) and AL-index (red line); d) Dst-index.

The results of application of the procedure (6) show the occurrences of anomalous short-time increases in geomagnetic activity before the storm (March 15 and 16) observed simultaneously at all the sites under analysis. Just like in the previous event, the disturbance intensity increased as the storm approached (Fig. 6).

## 3. Conclusions

Geomagnetic data during the magnetic storms which occurred on January 7, 2015 and March 17, 2015 were analyzed in detail applying the described method. The dynamic spectrum of geomagnetic disturbance intensity showed spatial pattern of the events and allowed us to analyze geomagnetic disturbance propagation along the observation meridian and at the near equatorial site. During the main phases of the storms, activation areas were detected. They have large spatial scales and are evidently associated with the processes of energy accumulation and release in the magnetosphere. Simultaneously occurring local increases in geomagnetic activity were detected before the events at the sites under analysis. These increases are likely to be associated with the non-stationary effect of solar wind plasma on the magnetosphere and with the on-coming interplanetary disturbance. The possibility of detection of pre-storm anomalous effects based on the results of ground geomagnetic data analysis was first described in the papers [13, 33], and mentioned in the paper [34]. According to the processing results of large experimental material and joint analysis of geomagnetic field H-component oscillations with the oscillating processes on the Sun, the authors [13, 33] showed that the success rate of the suggested forecast method for the geoeffective flare events is 90%. This result indicates high probability of possible occurrence of pre-storm anomalous features in geomagnetic data. The results of this paper also confirm the possibility of pre-storm effect and show high sensitivity and the efficiency of the method described in the article. The important aspect of the method is its capability to detect pre-storm anomalies only on the basis of ground station network data processing and the possibility of its automatic realization, in particular, in the mode close to the real time.

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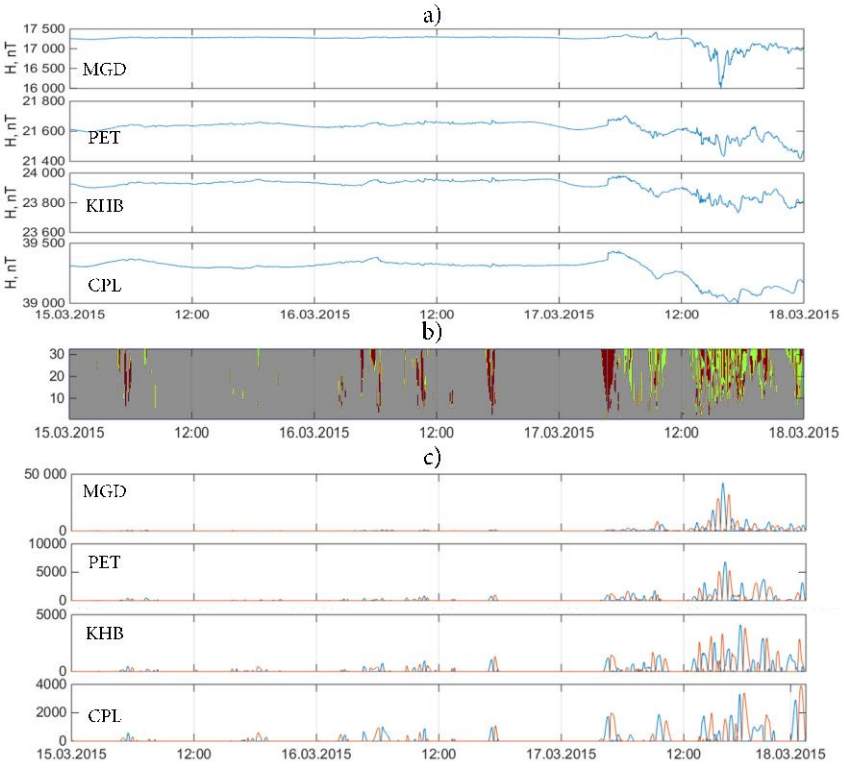


**Fig. 6.** Processing results of the data for March 15-18, 2015; a) H-component of the magnetic field; b) detection of the periods of increased geomagnetic activity (relation (6)); c) intensity of detected disturbances (relation (7)).

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