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Investigation of Dst variations in X component at mid-latitudes during three geomagnetic storms on February 2022

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Variations in the X component of the Earth`s magnetic field near the equator reflect the influence of equatorial ring current formed under the action of the charged particles of the solar wind. The traditional index describing this phenomenon is Dst. This index is obtained as an average value of the variations in different magnetometric stations located at different geographic longitudes, where the influence of local time is removed. The basic aim of present work is to investigate the dependence of the response of the X component on the local time. Due to the fact that the entry of the charged particles of the solar wind into the Earth's magnetosphere takes place in the night region of the Earth, a dependence of the response observed at a given geographic longitude on the local time must be assumed. In order to analyze Dst variations in X component at mid latitudes during three weak geomagnetic storms on February 2022, a chain of stations near the magnetic equator was considered. As a result, a methodology for reconstructing the X component is also proposed, and examples are shown for evaluating the quality of the developed model. The results thus obtained can be used to evaluate the spread of the influence of the equatorial ring current in the conditions of geomagnetic storms on various geophysical parameters.

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1. Introduction

The concept of ring current is fundamental in magnetospheric physics and is of essential importance for geophysics and in particular in the study of geomagnetic storms. The injection of ions into the terrestrial ionosphere carried by the solar wind leads to the formation of a geomagnetic storms. The injection process includes electric fields, associated with enhanced magnetospheric convection and/or magnetospheric substorm [1]. In the 20th century, it was assumed that a magnetic storm, and therefore the ring current, was made up of a series of small disturbances called substorms [2-4]. Nowadays the explanation of the ring current is related to an electric current encircling our planet at the distances between 3 to 6 Earth’s radii from the center of the same planet in the equatorial plane [5]. The direction of movement of the ring current is clockwise as viewed from the North Pole of the Earth. The movement of the particles of the ring current is earthward under the action of the dawn-to-dusk electric field and magnetic field of the Earth and during geomagnetic storm, the number of particles increase. As a result, a depletion occurs in the Earth's magnetic field.The ring current is a main factor in the study of the magnetosphere dynamics and geomagnetic storms [6]. The definition of geomagnetic storm is a disturbance of Earth's magnetosphere as a result of its interaction with high-energy particles carried by the solar wind. The presence of such disturbances related to the solar wind has an impact on the currents, plasma, and fields in Earth’s magnetosphere [7]. One of the conditions for the occurrence of a geomagnetic storm is related to extended periods of high-speed solar wind that interact with the magnetosphere, but the most important condition is a southward directed of solar wind magnetic field at the dayside of the magnetosphere, which is opposite the direction of Earth’s field. As a result, it turns out transferring of charged particles the solar wind into Earth’s magnetosphere [8]. The anomalies resulting from the storms are intense currents, changes in the radiation belts, and changes in the ionosphere [9-10].

A geomagnetic storm is defined by changes in the disturbance storm time index (Dst index), which has been used to characterize the size of a geomagnetic storm [11-14]. During quiet periods, Dst is between +20 nT and −20 nT. A geomagnetic storm has three phases: initial, main and recovery. The initial phase is characterized by Dst increasing by 20 to 50 nT in tens of minutes. The main phase of a geomagnetic storm is defined by Dst decreasing and it is classified conditionally as follows: moderate: Dst between -50nT and -100nT, strong: Dst between -100nT and -200nT, severe: Dst between-200nT and-350nT, great: Dst index under-350nT [15,16]. The totality of field-aligned currents, auroral electrojets and magnetic deviations that they produce on the ground, are used to generate a planetary geomagnetic disturbance index called Kp. This index is three hourly and is determined from geomagnetic observatories, located at high latitudes and shows changes in the horizontal component of the Earth's magnetic field. The following scale is used for evaluate the strength of the geomagnetic storm according to the Kp index: i) Kp about 5 – Minor (G1); ii) Kp about 6 - Moderate storm (G2); iii) Kp about 7 - Strong storm (G3); iv) Kp about 8 - Severe storm (G4); v) Kp about 9 - Extreme storm (G5) [17-18].

Last but not least is the influence of geomagnetic storms on the atmosphere and more specifically on the ionosphere of planet Earth [19-21]. As a result of particle precipitation from the solar wind, the additional heating and a change in the electron density occur [22-25]. It is well known that one of the most important applications of the ionosphere is the feature of

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propagating radio waves over long distances and providing long-distance radio communications. It is in the conditions of geomagnetic storms that errors in the positioning provided by GPS can appear. Another anomaly that the storms cause on the ionosphere is related to disturbances in navigation systems such as the Global Navigation Satellite System (GNSS) and creates harmful geomagnetic induced currents (GICs) in the power grid and pipelines [26].

Everything described above shows the importance for the study of geomagnetic storms in Geophysics. The purpose of the present work is to investigate the dependence of the response of the X component of the Earth`s magnetic field on local time. As a result, a methodology for the reconstruction of the X component is also proposed, with examples for evaluating the quality of the developed model in the conditions of several specific geomagnetic storms. Through the analysis and the proposed methodology, a new Dst index was obtained, which can be used in determining the influence of the equatorial ring current on basic quantities in Geophysics.

2. Data

In order to evaluate the influence of Dst variations in the X component of the magnetic field, data from the International Real-time Magnetic Observatory Network – INTERMAGNET (https://intermagnet.github.io/) are used. For the implementation of the present investigation, the created specialized software was modified for automatic and efficient downloading of considerably large databases. The other type of data used to illustrate the input parameters characterizing the geomagnetic storm, namely the planetary index of geomagnetic activity Kp and the disturbance storm time index Dst are provided from: https://omniweb.gsfc.nasa.gov/.

3. Results

In analyzing the data, we will start with the manifestation of the geomagnetic disturbances in February 2022. For this purpose, Figure 1 shows the parameters characterizing the storm as follows: Kp index (top panel) and Dst index (bottom panel). From the Figure 1 it can be seen that three geomagnetic storms occurred during the considered month. The first storm started in the early hours on 3 February 2022 when the Kp index sharply increase and exceeded 5 around 12 UT on the same day. According to the accepted classification of Kp, this storm is Minor (G1) type. The moment of increasing of Kp coincides with sudden decrease of the Dst index to almost – 80 nT, which is another confirmation of a moderate geomagnetic storm according to Dst classification and is related to the main phase of the geomagnetic storm. After noon on 3 February, a recovery phase occurs in both indices as Kp gradually drops under 3 and Dst smoothly increases and reaches values under quiet conditions. The very next day in afternoon hours on 4 February, a geomagnetic storm similar to the previous one was observed. In this case, again in the main phase of the storm, Kp exceeds 5, and at the same time, Dst is almost -70 nT. The last event that is the subject of the present investigation took place at the end of 11 February 2022. In this case, the Kp index starts to increase sharply after noon. There is a maximum value of Kp index above 5 around 21 UT. The main phase of the storm according to the Dst index coincides with maximum of Kp in time. After that, the recovery phase occurs in both indices.

The geomagnetic storms selected for analysis in the present study are of the same type in strength and manifestation according to the input parameters describing the behavior of the storms. The next step of this research is related to the selection of sufficient number of geomagnetic observatories, located as close as possible to the equator. On the basis of these stations, an analysis will be made and a methodology for the reconstruction of the X component will be proposed. In separated examples, it will also be illustrated how successfully the

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proposed model copes with the task even in the conditions of the geomagnetic storms discussed above on February 2022.

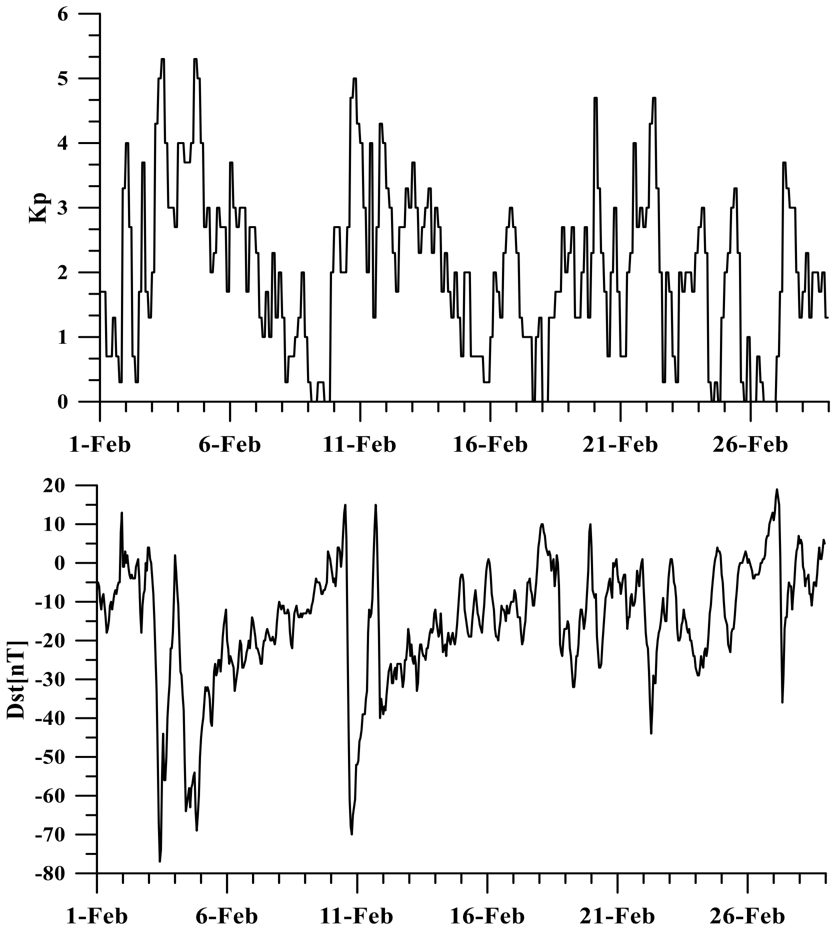

Figure 1 Parameters describing the behavior of the geomagnetic storms

CODE	GLAT	GLON	INCL
API	-13.81	-171.78	-31.65
PPT	-17.57	-149.57	-30.85
IPM	-27.17	-109.41	-35.93
PIL	-31.40	-63.88	-34.91
HUA	-12.05	-75.33	-1.44
VSS	-22.40	-43.65	-41.00
ASC	-7.95	-14.38	-44.25
ABG	18.63	72.87	27.37
GAN	0.69	73.15	-15.09
DLT	11.94	108.48	12.13
KDU	-12.69	132.47	-39.86
TAM	22.79	5.52	26.93

Table 1 List of used geomagnetic observatories from INTERMAGNET

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The analysis of variations of the X component of the Earth`s magnetic field was made on the basis of data from geomagnetic observatories involved in INTERMAGNET, listed in Table 1. The selected stations are maximally located near the equator from -31.40° GLAT to 22.79° GLAT.

The location of the selected geomagnetic observatories is shown in Figure 1. From the figure it can be seen that the stations are offset from the magnetic equator at inclinations of -44.25° to 27.37°. The X component data at each station are averaged for every one hour over the entire month of February 2022. The quiet diurnal course obtained by averaging the values over the five magnetically quiet days in that month has been removed from the data, which is a standard procedure when determining geomagnetic indices Dst and Kp.

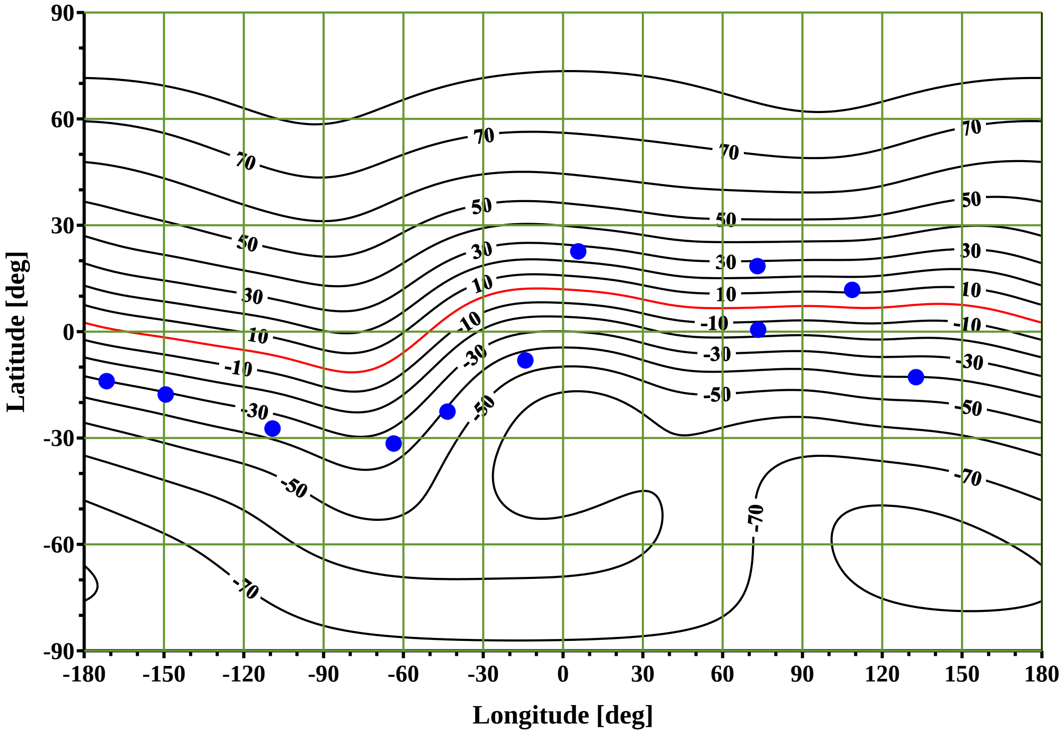

Figure 2 Maps of selected geomagnetic observatories marked with blue circles. The red line illustrates the magnetic equator

The unknown dependence of the X component response on local time is represented by its Fourier series decomposition with a fundamental period of 24 hours and 4 cosine components with periods of 24, 12, 8 and 6 hours, respectively. Farther in the present research, the dependence of the X component of the Earth`s magnetic field on the local time it will be marked as *ModDst*. The reason for this is that this dependence represents a modified Dst index, which for a given moment of time is characterized by one averaged value in local time and 4 amplitudes and phases of the components of the diurnal course. The traditional Dst index presents only the average along geographic longitude and accordingly at local time value of the variations of the X-component.

$$\mathrm{ModDst(ut)} = \mathrm{ModDst_0(ut)} + \sum_{k=1}^{4} \mathrm{Amp_k(ut)} \cos\left(\mathrm{k}\frac{2\pi}{24}\mathrm{LT} - \mathrm{Pha_k(ut)}\right)$$

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In the formula denoted by *ut* is a given moment at universal time, *LT* is the local time of a given geographic longitude at the moment ut. $ModDst_0$ is the average local time value. Amp_k and Pha_k are respectively the amplitudes and phases of the k-th harmonic of the diurnal course. The values of the averaged value, amplitudes and phases are determined by the method of least squares on the data of each moment of time, one hour before it and one hour after that moment of all 12 stations used.

Figure 3 shows a comparison between the universal and local time distributions of X variation for the periods 1-5 February (top left and right panel) and 11-13 February (bottom left and right panel) by data (left part of top and bottom panel) and the values, obtained by the formula above (right part of top and bottom panel). The coincidence of the approximation to the data is perfect. For all three magnetic storms illustrated in Figure 3, the negative response (shown in blue color according to the scale) is significant in the afternoon hours, as the minimum occurring around 18 LT. The thee geomagnetic storms occur at different times in universal time.

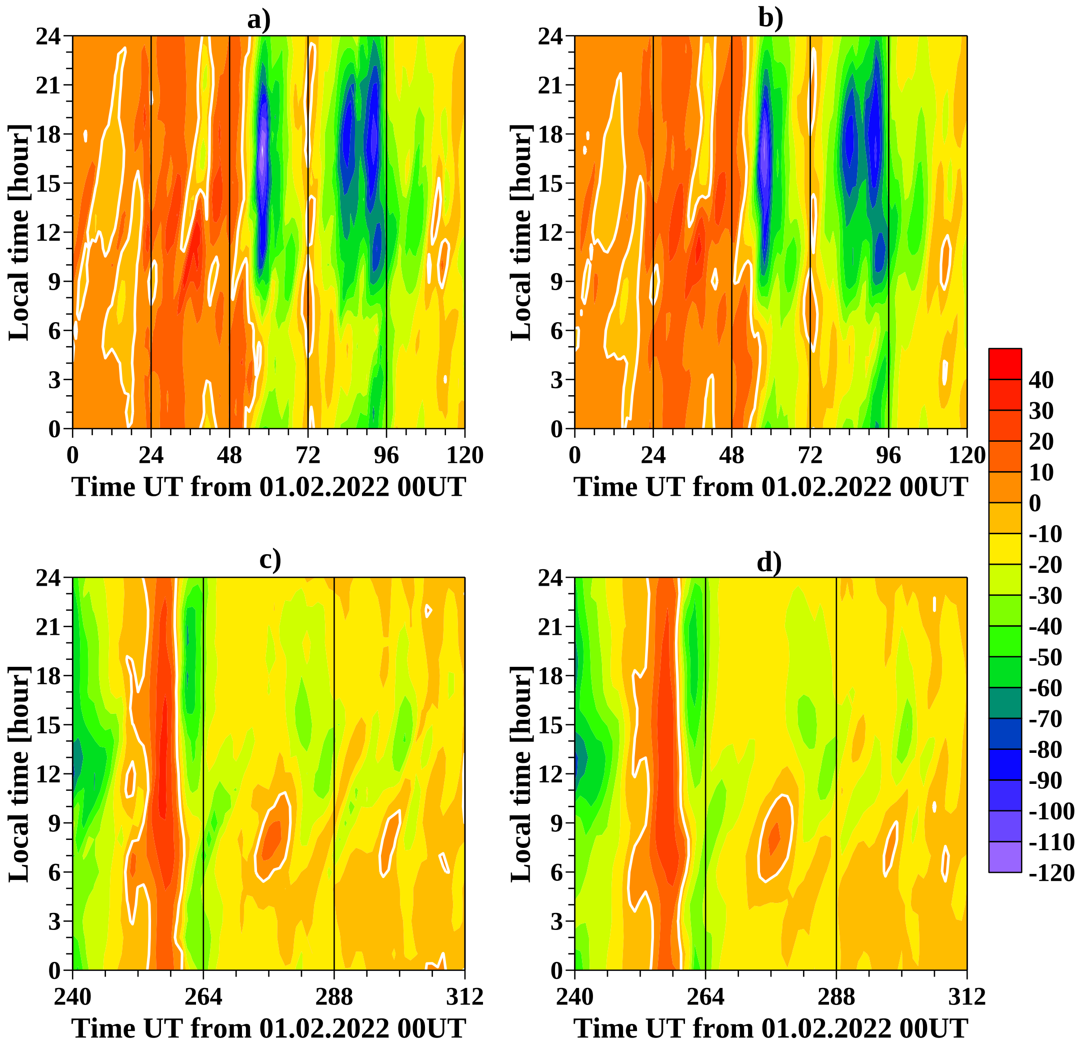

Figure 3 Comparison between the distribution of the variations in X component [nT] for the periods 1-5 February and for the 11-13 February by data a) and c) panels and by the formula described above b) and d) panels. Zero values are marked with a white line.

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The comparison between Figure 3 and Figure 1 shows that the behavior of the variation of the X component at universal time fully coincidence with the variability of Dst, which represents averaged by geographic longitude and by the local time variation. It is evident that for all three magnetic storms shown, the maximum negative value of variation is observed at local time around 18 LT. Given that storms develop at different times in universal time, it turns out that the maximum variation occurs at a different longitude each time. The fact that a pronounced minimum of the variation is observed justifies the decomposition of the dependence on local time in a Fourier series with a main period of 24 hours.

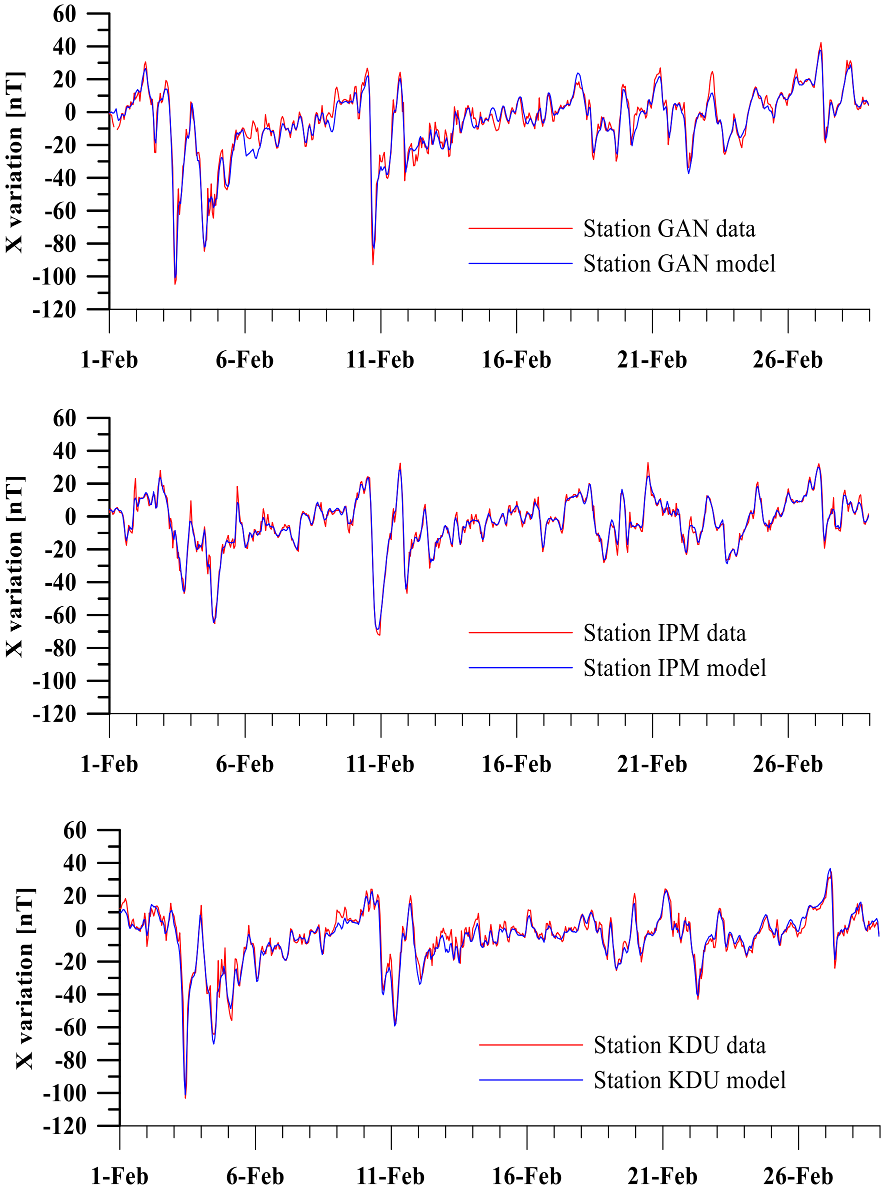

Figure 4 Comparison between the measured data for the X component from GAN, IPM, KDU stations and the corresponding values obtained by the proposed methodology

Figure 4 shows the correspondence of the proposed model to the data of three geomagnetic stations, located at different geographic longitudes to illustrate the accuracy of the methodology. It can be seen from the figure that the coincidence between the measured values of the X

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component of the Earth`s magnetic field and the values obtained by the proposed model have a very good similarity in the different geomagnetic observatories and in the conditions of the geomagnetic storms on February 2022. The comparison of the variations of all raw data marked in red color and the obtained analogous data by the model, marked in blue color, show a good confirmation of the performance of the proposed empirical dependence even in the conditions of geomagnetic storm.

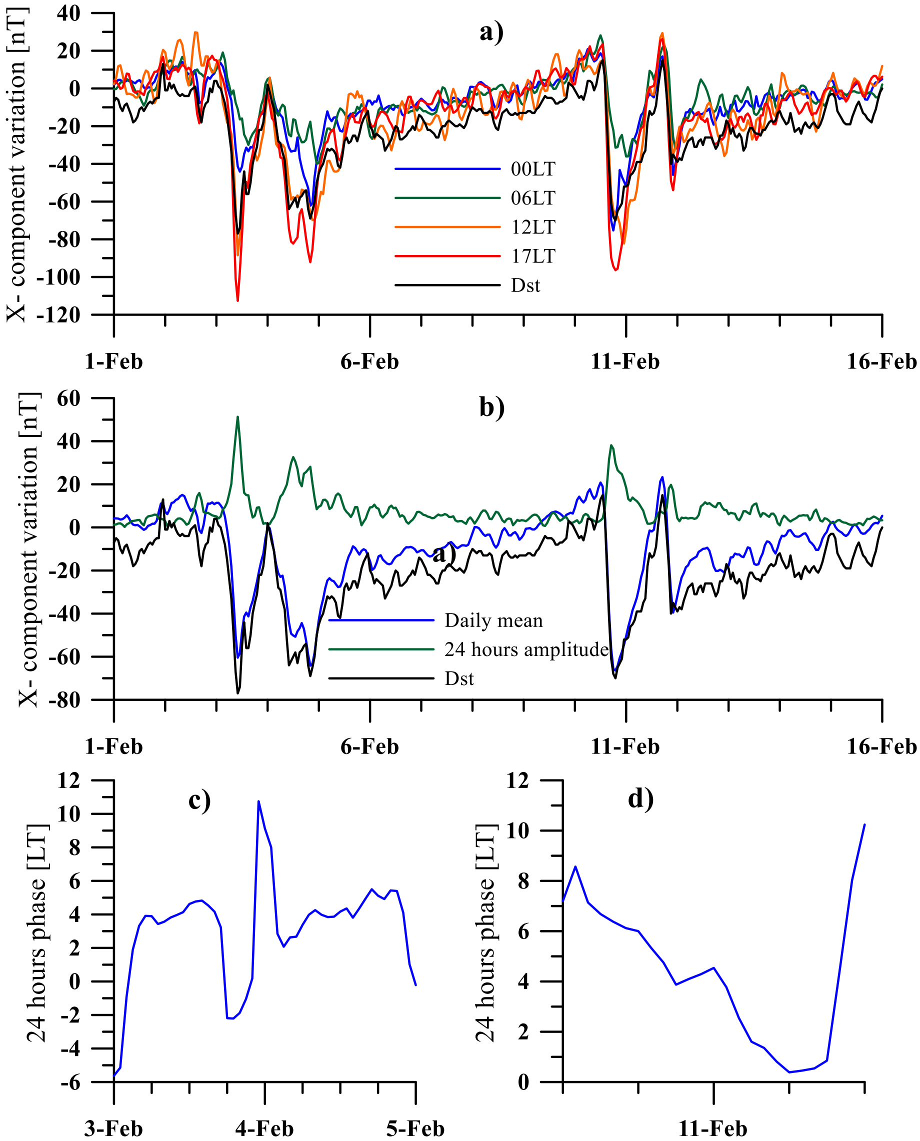

Figure 5 a) Comparison of model values and Dst index depending on local time b) comparison between the variability of the main components of the decomposition and the Dst index c) Phase of the 24h component of the storms in the period 3-5 February d) phase of the 24h component for the storm on 11 February 2022

Figure 5 a) shows the course of model ModDst values as a function of local time. Maximum response for the geomagnetic storms on February 2022 is observed around 17LT. Figure 5 b) shows the behavior of some of decomposition components. ModDst0, denoted as Daily mean, is close enough to the traditional Dst index. The diurnal amplitude marked as 24 hours amplitude is apparently activated during geomagnetic disturbances. Shown in Figure 5 c)

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the phase of the 24 h component during the three geomagnetic storms in the period 3–5 February 2022 has value of about 4LT. The last Figure 5 d) illustrates the phase of the 24 h component for the last geomagnetic storm on 11 February 2022, the subject of the present investigation. Considering that the phase in the formula is the local time of the maximum of the corresponding component, the minimum turns out to be shifted by half the period - i.e. it is about 16LT. The minimum of the total variation as shown in Figure 3 is around 18 LT. The difference is due to the fact that the distribution is not purely sinusoidal.

The explanation of the observed result, namely a maximum negative reaction is about 18 on local time, is the following: the flows of charged particles enter the equatorial magnetosphere in the night sector and rotate in the clockwise direction as seen from the Northern hemisphere, i.e. from east to west and most strongly affect geographic longitudes where the local time is before the midnight.

4. Conclusions and discussion

The dependence of the variation of the X component of the Earth's magnetic field on the local time in the corresponding magnetometric station obtained in the present study was established on the basis of three magnetic storms occurring at different times of the day according to universal time. The given examples show a satisfactory agreement of the model with the measured values in each of the considered stations. The coincidence of the phase of the main diurnal component indicates that the distribution of the variation in longitude is due to diurnal time related processes. All this is due to the fact that the flow of charged particle enters the Earth`s magnetosphere from the night sector of the Earth. The fact that the maximum of the variation is located at longitudes where the local time is a few hours before midnight is explained by the well-known fact that there are two ring currents, an inner one that flows eastward, and an outer westward current. Usually the outer is quoted: clockwise current when you look from the North Pole. It follows from this that at longitudes close to the midnight meridian in the western direction, it is normal to expect maximum of current density and, accordingly, the strongest reaction of the X component of the Earth's magnetic field.

The proposed model can be considered as a modified Dst index. The components of the diurnal dependence of the variation of the X-component are included in the updated index. The average value is very close to the traditional Dst index. The dependence on the local time (for each specific case it is easy to determine the distribution along geographic longitude) is represented by the amplitudes and phases of the diurnal components, which have a values for each hour of universal time. The main component with a period of 24 hours gives the most significant dependence on the local time, therefore also on the geographic longitude. All these results are an essential part in the interpretation of the physical processes and the main mechanisms related to the variations during geomagnetic storms in the most basic geophysical parameters.

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