# Geomagnetic Measurements at the Pleshchenitsy Geophysical Observatory (Minsk, Republic of Belarus)

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**Abstract.** Continuous observations of the geomagnetic field elements have been carried out at the Pleshchenitsy Geophysical Observatory in Belarus since 1960 in order to study the annual mean values of the magnetic field components. The paper presents the secular variations of the geomagnetic field elements $D$, $H$, $Z$, $F$ within the period of 1960–2020 in comparison with the results of the earlier investigations (starting from 1875). A significant long-term increase of some geomagnetic field components was revealed suggesting a continuous movement of the Earth's magnetic pole. So, during the last 63 years the magnetic declination has been increased on the average with a gradient about 4 arcmin/year, along with this during the last 14 years its increase became faster and exceeded 8 arcmin/year. The total geomagnetic field vector modulus has been also tending to increase with time, namely, from 49621 to 51485 nT for the period under consideration. In addition, the periodic change of the degree of the geomagnetic field disturbance was determined, which may be due to the solar activity variations within the 11-year cycles. AQ1

**Keywords:** geomagnetic field elements · geomagnetic field disturbance · solar activity cycle

## 1 Introduction

Data obtained by instrumental measurements suggest that the annual mean values of the geomagnetic field elements are continuously changed [1–4]. Such long-term variations are called secular variations. The secular variations of the geomagnetic field components are essentially influenced by the position of the Earth's magnetic pole in the Northern Hemisphere under the effect of three independent sources: two major magnetic anomalies (the Canadian and Siberian ones) and the main (dipole) field of the Earth [5]. As it was estimated for the years of 2015–2018, a speed of the magnetic pole movement was not uniform and varied within 37–72 km/year [6]. However, the magnetic field sources are located not only inside the Earth, but also in the circumterrestrial space. These sources are responsible for regular (diurnal, seasonal, 11-year) variations as well as irregular

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variations due to the solar activity influence upon the magnetosphere and ionosphere of the Earth [3, 7]. Just these irregular variations cause the geomagnetic activity.

The geomagnetic activity is formed as a response of the processes occurring in the magnetosphere to the changes of the character of the solar wind streams, i.e., in fact, reflects the solar corona structure transformation during the solar activity development. The most pronounced manifestations of the solar activity (magnetic storms) are associated with the influence of coronal mass ejections and high-speed solar wind streams [8]. So, the next peak of the solar activity is expected to occur at the beginning of 2026 [9]. The geomagnetic disturbances in many cycles reach their maximum frequency not near the maximum of the sunspot numbers, but some years later [10, 11]. This is due to the fact that the maximum number of storms with a gradual beginning, that are caused by high-speed solar wind streams flowing from the coronal holes, takes place 2–3 years after the solar activity maximum. While the storms with a sudden beginning caused by the coronal mass ejections are well correlated with the curve of the sunspot numbers. Numerically, a degree of the geomagnetic disturbance is usually described by $K$-indexes [1, 12, 13].

The effects of the impact of the space environment which are mostly pronounced during magnetic storms can cause the problems with the positioning of navigation systems, satellite electronic circuit failures, interference to radio communications, appearance of extra currents in power lines, induced currents in pipelines, damage of power systems like transformers [9, 14]. The storms are caused by an intensification of the ring current (magnetospheric electrons and ions with an energy of 10–300 keV) and its movement closer to the Earth, which results in the depression in the geomagnetic field $H$-component [15]. Therefore, the study of the magnetic field variation pattern still remains a topical problem as it serves as a basis of the surrounding outer space investigations.

## 2 Historical Investigations of the Earth's Magnetic Field in Belarus

The characteristics of the magnetic field of the Earth was measured in Minsk for the first time in 1875 by I.N.Smirnov, an Associate Professor of the Kazan University (Russia), who was among the pioneers of the magnetic survey in Belarus [16]. Later, the determinations of the values of geomagnetic elements in Minsk were repeated by the staff of the Main Geophysical Observatory (St. Petersburg, Russia) in 1904, 1924 and 1927. Subsequent measurements of the geomagnetism elements were carried out at the base observation station of the secular variations in Minsk, which was created by the Institute of Terrestrial Magnetism (now Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation or IZMIRAN) [16]. The Earth magnetic field measurements were made there in 1938, 1945, 1947, 1948, 1949, 1954, 1959. Since 1960 the absolute and variational measurements of the geomagnetic field elements are performed at the Pleshchenitsy Geophysical Observatory located in Pleshchenitsy settlement near Minsk [17], which will be described in the next section.

All the above-mentioned measurements make possible an analysis of the changes, that were experienced by individual Earth's magnetic field elements during the period from 1875 to 1960, i.e., for 85 years. For this purpose all the data of observations made at the Minsk station were reduced to the values obtained at the Pleshchenitsy Geophysical

Observatory on the basis of simultaneously determined values of the geomagnetic field elements at both stations in 1959 and 1960 [16].

The curves of the annual mean values of the field elements *D, H, Z, F* (Fig. 1) show that the magnetic field of the Earth in the region of Minsk changed considerably since 1875 till 1960. So, during this period the magnetic declination *D* changed from the western one equal to 3°2′ in 1875 to the eastern one about 1913 and reached 4°55′ till 1960. Hence, the overall change of the magnetic declination made up more than 8°. The vertical component *Z* and an absolute value of the full vector of Earth's magnetic field strength *F* have increased for the above-mentioned period by 2520 and 1980 nT, respectively (Fig. 1).

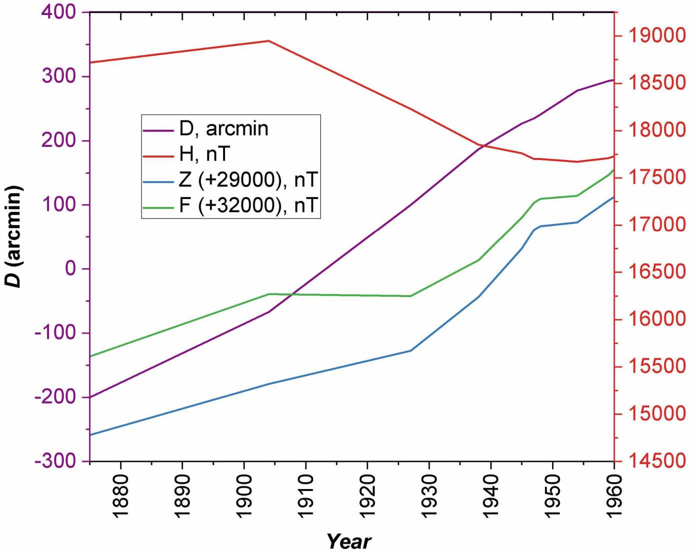

**Fig. 1.** Changes in the annual mean values of the magnetic declination *D*, horizontal *H* and vertical *Z* components, as well as of the full geomagnetic field vector *F* during the period of 1875–1960

The established increase in annual mean values of the geomagnetic field elements *D, Z, F* is mostly stipulated by the physical and chemical processes in the Earth's interior that result in the continuous migration of the Earth's magnetic poles [4–6]. In addition, the field secular variations are influenced by even faster processes due to the solar activity. The solar activity may either increase or decrease, to some extent, the secular variations of the geomagnetic field elements [2]. A combination of these two major impacts is responsible for the secular variation behaviour in certain region of the Earth's surface.

## 3 Description of the Pleshchenitsy Geophysical Observatory

The complex Pleshchenitsy Geophysical Observatory for investigation of geomagnetic field and seismic was created in 1958 within the framework of the participation of the Academy of Sciences of the Belarusian SSR in investigations for the International

Geophysical Year program and in the further international and national geophysical projects and programs. This was the first similar scientific institution in the territory of Belarus, which until 1963 was a part of the Institute of Geological Sciences of the Academy of Sciences of the Belarusian SSR. Scientific investigations in physics of the Earth as new field of research in Belarus have started at the Pleshchenitsy Observatory.

The research activity of the observatory contributed to scientific communications with the leading geophysical institutes of the former USSR. At present, the Pleshchenitsy Geophysical Observatory is a part of the Center of Geophysical Monitoring of the National Academy of Sciences of Belarus.

The Pleshchenitsy Geophysical Observatory (MNK code) is situated 65 km away from Minsk, on the northwestern outskirts of the Pleshchenitsy settlement, Logoisk district, Minsk region, Republic of Belarus. Its geographical coordinates are $\varphi = 54.4186°$N, $\lambda = 27.7958°$E.

The observations of the geomagnetic field variations since 2002 till 2009 were carried out using an automated digital magneto-variation station (manufactured by the Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Russia) which continuously recorded the time changes of the horizontal $H$, vertical $Z$ components and of the angular component, namely, declination $D$.

Since 2010 the main measuring instrument is a three-component fluxgate magnetometer LEMI-022 (manufactured by the Lvov Center of the Space Research Institute of the National Academy of Sciences of Ukraine and the National Space Agency of Ukraine), which serves to measure the northern $X$, eastern $Y$, vertical $Z$ components of the Earth's magnetic field strength and their variations in the frequency range from 0 to 0.3 Hz.

To determine the base-line values of the geomagnetic field elements $D_0$, $H_0$, $Z_0$ and $F_0$, the absolute observations are carried out with a fluxgate fDI magnetometer LEMI-204 based on a nonmagnetic theodolite 3T2KP-NM, as well as with a scalar Overhauser magnetometer MINIMAG (manufactured by Scientific Production Enterprise "Geologorazvedka", St. Petersburg, Russia). The mean squared error of angle measurement is $2''$, and the resolution of the magnetometer MINIMAG is 0.03 nT. The absolute values of the $D$, $H$, $Z$ components and full geomagnetic field vector $F$ are regularly measured. These are used to monitor the operation of the magnetic variometer and to determine the base-line values of the field elements.

At present, a three-component digital magneto-variation station "Quartz-7" (manufactured by the Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Russia) to perform variational measurements, as well as fDI-magnetometer MinGeo based on a nonmagnetic theodolite Theo-020B (MinGeo Ltd, Hungary) and a scalar Overhauser magnetometer POS-1 (Institute of Physics and Technology of the Ural Federal University, Russia) for absolute observations are adjusted with an aim to put them into operation.

## 4 Observations of the Geomagnetic Field Elements at the Pleshchenitsy Geophysical Observatory

Continuous variational observations of the geomagnetic field elements *D, H, Z* are carried out at the Pleshchenitsy Geophysical Observatory since 1960 in order to study the secular variations of the geomagnetic field in Belarus.

For processing data obtained with a fluxgate magnetometer LEMI-022, a software has been developed at the Center for Geophysical Monitoring of the National Academy of Sciences of Belarus and permits the following procedures to be performed:

- visualization of obtained data on display;
- formation of a daily table of the geomagnetic field variations with minute data;
- formation of a monthly table of the geomagnetic field variations with hourly data;
- determination of daily three-hour *K*-index values;
- determination of characteristics of the magnetic storms;
- input of new corrections to base-line values;
- export of the data processing results into the database.

Data are processed according to the standard procedure. The average values of the field elements for a day, month, year are determined from their average hourly values. So, according to the observation data, the annual mean values of the magnetic field components in 2022 were as follow: $D = 9.271°$, $H = 17749$ nT, $Z = 48329$ nT, $F = 51485$ nT.

During the whole year of 2022 an increase of the *D*, *Z*, *F* element values was observed, like as in the previous years [2]. The secular variations of the geomagnetic field elements are calculated as a difference between their annual mean values for two selected years (Table 1).

**Table 1.** Secular variations (last column) of the annual mean values of the geomagnetic field elements between the years of 2022 and 2021

| Elements | Year: 2022 | Year: 2021 | Difference |
|---|---|---|---|
| *D* (in ang. Values) | $9^{\circ}16'12''$ | $9^{\circ}08'09''$ | $0^{\circ}08'03''$ |
| *H* (nT) | 17750 | 17766 | –16 |
| *Z* (nT) | 48329 | 48258 | 71 |
| *F* (nT) | 51485 | 51423 | 62 |

The annual mean values of the *D, H, Z, F* elements of the Earth's magnetic field according to data obtained at the Pleshchenitsy Geophysical Observatory within 1960–2022 are plotted in Fig. 2.

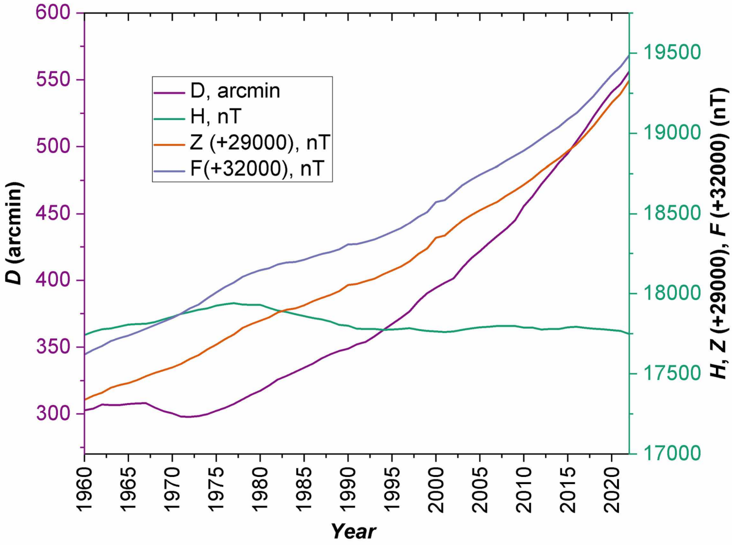

**Fig. 2.** Changes in the annual mean values of the magnetic declination *D,* horizontal *H* and vertical *Z* components, as well as of the full geomagnetic field vector *F* during the period of 1960–2022

Secular variations of the annual mean values of the geomagnetic field elements between the years of 2022 and 1960 are as follow:

- 253.56 arcmin (4°13′34″) for the geomagnetic field declination *D*; the average annual variation is 4.09 arcmin (4′5″), though since 2009 the secular variation averages 8′34″ per year, which is almost 2.1 times the average long-term variation for 63 years of observations;
- 7.4 nT for the horizontal component *H* of the geomagnetic field; the average annual variation is 0.1 nT;
- 1991.2 nT for the vertical component *Z* of the geomagnetic field; the average annual variation is 32.1 nT;
- 1864.5 nT for the full geomagnetic field vector *F*; the average annual variation is 30.1 nT.

An increase of the annual mean values of the observed geomagnetic field elements *D, Z, F* is indicative of the continuing displacement of the Earth's magnetic poles.

## 5 Analysis of the Geomagnetic Field Disturbance Carried Out at the Pleshchenitsy Geophysical Observatory

Monthly reviews of the magnetic field state composed at the Pleshchenitsy Observatory describe the magnetic field disturbance using three-hour values of the *K*-indexes (9-scores scale) and the magnetic storm characteristics. The following scale of *K*-indexes reflecting the deviation of the most disturbed component of the geomagnetic field was adopted at the Pleshchenitsy Observatory (Table 2).

**Table 2.** Scale of *K*-indexes adopted at the Pleshchenitsy Geophysical Observatory

| *K*-index value | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| Upper limit (nT) | 5 | 10 | 20 | 40 | 70 | 120 | 200 | 330 | 550 | >550 |

Magnetic storms are described by their duration (beginning and end), as well as by an amplitude of the *D, H, Z* element variations in accordance with the scale presented in the Table 3.

**Table 3.** Scale of magnetic storms adopted at the Pleshchenitsy Geophysical Observatory

| Storm type | *D* (arcmin) | *H* (nT) | *Z* (nT) |
|---|---|---|---|
| minor storm | 19–26 | 80–125 | 40–90 |
| moderate storm | 27–38 | 126–200 | 91–140 |
| major storm | 39–55 | 201–270 | 141–250 |
| severe storm | >55 | >270 | >250 |

As it is known, the impact of the solar plasma stream (solar wind) on the Earth's magnetosphere, the internal magnetospheric changes and the magnetosphere and ionosphere interaction influence the geomagnetic field disturbance which manifests itself as irregular magnetic field variations [3, 7, 8]. In this context, the dynamics of the geomagnetic field disturbance determined from the data obtained at the Pleshchenitsy Observatory were analyzed in comparison with the solar activity within four adjacent 11-year cycles: 21st (1976–1986), 22nd (1986–1996), 23rd (1996–2008), 24th (2008–2019) (Fig. 3). The solar activity is usually described by the Wolf numbers (*W*) that are sunspot relative numbers. The annual mean Wolf numbers are taken in accordance with the Solar Bulletin published by the American Association of Variable Star Observers (AAVSO) [18].

Long-term variations of the magnetic storm number suggest that phases of storm reduction are followed by phases of increasing number of storms (Fig. 3). The maximum value (62) of the magnetic storm number was observed in 1989 and the minimum one (2) was recorded in 2009. The period between the minimum values is 11–12 years that coincides with the current period of solar activity. At the same time, the maxima of

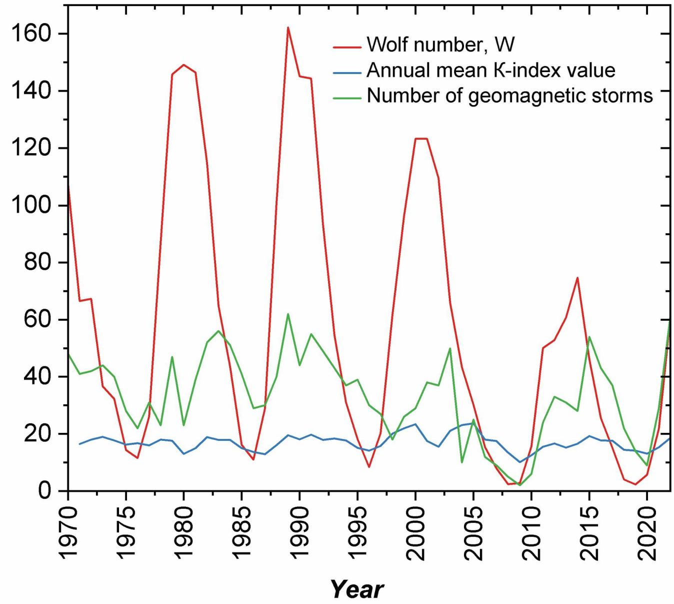

**Fig. 3.** Dynamics of the geomagnetic field disturbance

the magnetic storm number do not coincide with the maxima of Wolf numbers, but are shifted toward the phase of decreasing solar activity that is reported by other authors too [10].

It should be also noted that an increase of the geomagnetic field disturbance is observed in 2021–2022 simultaneously with and an increase of the solar activity. So, 61 magnetic storms were recorded and processed in 2022, which exceed by 32 the number of storms recorded in 2021 (29) and is 1.86 times the average value (32.8) of long-term observations over 52 years (1970–2021). During the 2023 first half-year 24 storms were recorded, which is indicative of a high degree of the geomagnetic field disturbance in the current year.

How does the frequency of solar storms correlate with the solar activity? The number of solar events in the years near the solar cycle maximum is really larger than that at the solar cycle minimum. So, up to several solar flares per day can be observed sometimes at the cycle maximum. However, it was noted that the solar flare activity and mass ejections are not rare events and they are sometimes characterized by extreme parameters in the years near the solar cycle minimum, especially, in the phase of the solar activity decrease [10, 11]. Therefore, a question about a connection between the cycles of the solar activity and its manifestation in the interplanetary environment like such high-energy processes as solar flares and coronal mass ejections requires further study.

So, in the 21st cycle of the solar activity the maximum of annual mean relative number of sunspots was observed within 1979–1980. In the subsequent years the intensity of the solar activity was decreasing and reached its minimum in 1986. Nevertheless, the geomagnetic activity during the solar activity decrease phase remained rather high and even slightly increased in 1983 as it follows from the number of recorded magnetic disturbances. The similar phenomenon was observed in the next cycles, namely, in 1995 (22nd cycle), 2003 (23rd cycle), and 2015 (24th cycle) in the solar activity reduction phase.

This phenomenon was discussed both in the earlier [20], and more recent [9, 13] works, where it was indicated that the maxima of the geomagnetic field disturbance appeared in the *W* decrease phase are mainly associated with recurrent perturbations which have gradual beginning, but the maxima of the geomagnetic field disturbance observed near the solar activity maxima should be associated with flare magnetic storms. This assumption is confirmed by long-term observations carried out at the Pleshchenitsy Geophysical Observatory.

Long-term variations of the annual mean values of total *K*-indexes show the more complicated pattern, these are also subject to fluctuations, but their period is less than the 11-year solar activity period (Fig. 4). Nevertheless, in the years when the Wolf numbers *W* have the minimum values (1976, 1986, 1996, 2008, 2019), the annual mean values of *K*-index also tends to the minimum values. In addition, with the solar activity increasing the annual mean values of *K*-index also rises, but, in most cases, with one year lag (Fig. 4). Such a delay is also noted in some other works [8, 13]. However, after the early growth stage a decrease of the annual mean values of *K*-index is observed. This drop could be sufficiently great in some cases, like in 1980 and 2001, though the solar activity in these years still remained high.

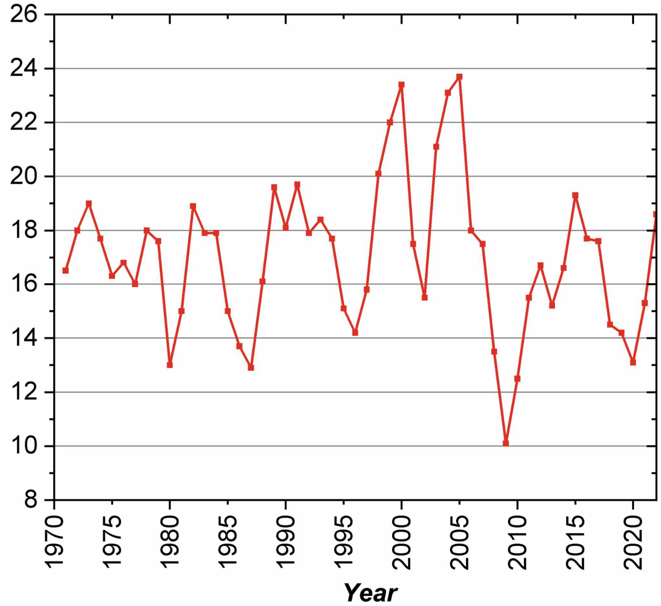

**Fig. 4.** Time series of the annual mean values of the total *K*-indexes during 1971–2022

The maximum values of the annual mean total *K*-indexes ($>$23) were recorded in 2000 and 2005, the minimum ones ($<$13) were observed within 2009–2010. In 2021–2022 a growth of the annual mean values of the total *K*-index was outlined which testifies to the onset of the next activation period within the 25th solar cycle.

Therefore, it may be concluded that a definite correlation between such a parameter of the geomagnetic field disturbance as *K*-index and the activity of the Sun takes place. However, like as in the case with the quantity of the magnetic storms, there is one or two years lag between a stage of growth and a stage of decrease with respect to the analogous phases of the11-year solar cycles, as well as more than one maximum of the *K*-index annual mean values within one solar cycle (see Figs. 3 and 4). These facts point once again to a contribution of the recurrent magnetic disturbances, which have gradual beginning, into geomagnetic activity along with the flare magnetic storms [8].

## 6 Conclusions

The main result of the work of the Pleshchenitsy Geophysical Observatory (Minsk, Republic of Belarus) is the continuous determination of the secular variations of the Earth's magnetic field elements *D, H, Z, F* on the basis of data from variational and absolute observations carried out since 1960. Annual reviews of the geomagnetic field state are composed and the annual mean values of the geomagnetic field elements *D*, *H*, *Z*, *F* are calculated. An increase in the geomagnetic field elements *D*, *Z*, *F* values observed is indicative of the continuing displacement of the Earth's magnetic pole in the Northern Hemisphere.

A periodic character of the change of the geomagnetic field disturbance which corresponds to the solar activity cycles with a shift towards the solar activity decrease phase is observed. In the average, the geomagnetic activity level in 2022 was determined to be higher than that in the previous year and the geomagnetic field was considered to be rather disturbed. AQ2

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