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# DEVELOPMENT OF GEOMAGNETIC FIELD INDUCTION MODULE MAPS FOR THE TERRITORY OF UKRAINE

Knowledge of Ukraine`s geomagnetic field is based on magnetic surveys of the geomagnetic field induction module $B$ and its power and angular components, as well as on observations or calculations of their anomalous values. The article describes the methods for constructing a digital map of the induction module of the geomagnetic field $B$. The map of module $B$ for the epoch of 1969.5 is developed, which is the ground to create the maps of module $B$ and its anomalies $\Delta B$ for an arbitrary epoch. The results of the ground absolute magnetic survey of 1969–1972, the analytical model of the main geomagnetic field $B_{IGRF}$, as well as the map of the anomalous magnetic field on a scale of 1: 1 000 000 were used to construct the map of the geomagnetic field induction module $B$. The digital map of the module and anomalies of the geomagnetic field induction module $B$ for the 1969.5 epoch was obtained by calculating the correction based on their difference values at the points of the absolute reference network. It was spread by interpolation according to the 1×1 km matrix to the entire data array for the territory of Ukraine. The geomagnetic field induction module $B$ for the 2005.5 epoch was calculated by adding to its values in the 1969.5 epoch the calculated values of the field dynamics $B_{IGRF}$ and the "magnetizing" effect of anomalies of the induction module $\Delta\Delta B$. The developed map is an approximate representation of the magnetic field modulus, since the amount of remanent magnetization was not taken into account during the calculation, which may cause minor deviations of the calculated and observed field values. The induction module of the geomagnetic field $B$ in the epoch of 1969.5 varies in the range of 46.500–62.000 nT, and in the epoch of 2005.5 – 47.000–63000 nT, increasing from the southwest to the northeast of the territory of Ukraine. Its maximum values are observed in the areas of regional and local magnetic anomalies, in particular in the area of the Kryvyi Rih-Kremenchuk anomalous strip and the southeastern edge of the Kursk anomaly. The dynamics of the $B_{IGRF}$ field for the period of 1969.5–2005.5 is characterized by values from 700 nT in the east of the territory of Ukraine to 950 nT in the west, and the magnitude of the magnetizing effect $\Delta\Delta B$ varies within ±10 nT, reaching maximum values (up to 100–190 nT) in the regions of intense magnetic anomalies. The digital map of the geomagnetic field induction module $B$, developed in 2005.5, has been verified. This was done by measuring the values of module $B$ in the magnetic observatories of Kyiv, L'viv, and Odesa, as well as in the Repeat Stations of the I$^{st}$ and II$^{nd}$ classes. The results showed that there was only a small difference (–20–40 nT) between the calculated and measured values of modulus $B$. Their most significant differences are spatially correlated with areas of modern activation of the Earth's crust on the territory of Ukraine and electrical conductivity anomalies.

*Key words*: geomagnetic field induction module $B$, magnetic survey, magnetic maps, analytical model of the IGRF-DGRF field, repeat station.

## Introduction

Information about Ukraine`s geomagnetic field is based on magnetic surveys of the induction module of the geomagnetic field $\boldsymbol{B}$ and its components $\boldsymbol{B_Z}$, $\boldsymbol{B_X}$, $\boldsymbol{B_Y}$, $\boldsymbol{B_H}$, $\boldsymbol{D}$, $\boldsymbol{I}$, as well as observations or calculations of their anomalous values.

The internal magnetic field of the Earth is the vector sum of the main magnetic field $\boldsymbol{B_{IGRF}}$ (the field of the Earth's core) and the anomalous magnetic field $\Delta\boldsymbol{B}$ (the field of the Earth's lithosphere). In magnetic surveys, the induction vector modulus of the Earth's magnetic field $\boldsymbol{B}$ is currently measured (previously, anomalies of its vertical component $\Delta\boldsymbol{B_Z}$ were also measured). Then these measurements are used to develop maps of the anomalous magnetic field ΔB, which are widely used to solve various geological and geophysical tasks. The development of maps of the anomalous magnetic field for a certain epoch is a rather difficult task in terms of bringing to the same level the existing magnetic surveys of different time and different scales of individual areas. In addition, the map of the anomalous magnetic field is not sufficient to solve relevant problems of navigation and assessment of environmental ecology. In this regard, the authors proposed a constructing methodology and built a digital map of the induction module of the geomagnetic field $\boldsymbol{B}$ for the territory of Ukraine in the epoch of 1969.5. It is the basis for the development of maps of the anomalous magnetic field $\Delta\boldsymbol{B}$, calculation

of power and angular components of the geomagnetic field, etc. The geomagnetic field induction module map $\boldsymbol{B}_{1969,5}$ as a foundation for creating geomagnetic field induction module maps and anomalies $\Delta\boldsymbol{B}$ for an arbitrary epoch. As an example, we designed a map of the induction module $\boldsymbol{B}$ and its anomalies $\Delta\boldsymbol{B}$ for the epoch 2005.5.

## Purpose

The purpose of the scientific research is to develop digital maps of the induction module of the geomagnetic field B and its anomalies ΔB in the epoch 1969.5 and to use them as a reference (source) for the construction of appropriate maps for an arbitrary epoch. Develop a calculation technology and build a map of the geomagnetic field induction module in the 2005.5 epoch, taking into account the dynamics of the $B_{IGRF}$ field and the magnitude of the magnetizing effect of anomalies $\Delta\boldsymbol{B}$ for 36 Year.

**Output data.** To construct maps of the geomagnetic field induction module for different epochs, various measurements are required. These include absolute values of the geomagnetic field, secular variations, maps of anomalous magnetic field, and estimation of the magnitude of the submagnetizing effect, namely:

- the results of the ground absolute magnetic survey of 1969–1972. The network of reference points (in the number of 1.460) had an average density of 1 point per 400 km$^2$; the absolute values of the modulus of the vector $\boldsymbol{B}$ are brought to the epoch of 1969.5. The root mean square error of the survey for $\boldsymbol{B}$ is s = ±6.0–6.5 nT [Pashkevich, Solov'ev, 1971; Krutykhovska et al., 1973];
- analytical model of the main geomagnetic field $B_{IGRF}$. [DGRF/IGRF Geomagnetic Field Model 1945–2024 and Related Parameters.htm];
- the results of measurements of module $\boldsymbol{B}$ in the magnetic observatories “Kyiv”, “Lviv” and “Odesa” [Orlyuk et al., 2012], at the repeat stations (RS) (58 points) [Tregubenko et al., 2008, 2013] and reference magnetic points (RMP) of the II class at the rate of 1 point per sheet of scale 1:200 000 (114 points) [Kanyuka et al., 2012];
- maps of the anomalous magnetic field with a scale of 1: 500 000–1: 1 000 000 [Map…, 1977; Nechaeva et al., 2002; Orlyuk et al., 2018];
- a map of the Earth's surface relief [Entin et al., 2015].

## Methods of the induction module B maps construction

The formula for calculating the induction module $\boldsymbol{B}$ for an arbitrary point and (*x, y, z*) for an arbitrary year $\boldsymbol{p}$ can be written as follows:

$$\boldsymbol{B}_{i,y} = \boldsymbol{B}_{0,i,p} + \Delta\boldsymbol{B}_{i.y.} + \Delta\Delta\boldsymbol{B}_{i.y.}, \quad (1)$$

where $\boldsymbol{i}$ is a point with coordinates $\boldsymbol{(x, y, z); y}$ – year of field calculation; $\boldsymbol{B}_{0,i,y}$ is the induction value of the Earth's normal magnetic field; $\Delta\boldsymbol{B}_{i.y.}$ – anomaly of the induction module; $\Delta\Delta\boldsymbol{B}_{i.y.}$ – change in anomalies of the induction module due to variations in the external field $\boldsymbol{B}_{0,i,y}$ (magnetizing effect). The calculation of the magnetizing effect is due to the fact that in the case of conditioning of the total magnetization of the rock by the inductive component $\boldsymbol{Ii}$, the magnitude of the anomaly depends on the magnetizing field $\boldsymbol{B}_{0,i,y}$. According to [Orlyuk, Romenets, 2005], the ratio $\Delta\boldsymbol{D}=\Delta\boldsymbol{B}_{i.y.} / \boldsymbol{B}_{0,i,y}$ is constant for this type of source and can be used to calculate $\Delta\Delta\boldsymbol{B}_{i.y.}$

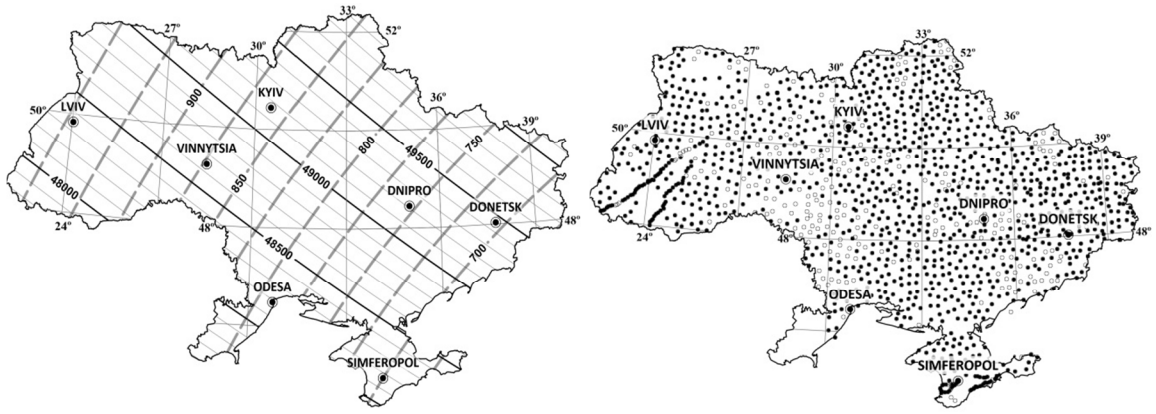
The analytical model IGRF-DGRF was used as the Earth's normal magnetic field. The current IGRF-13 model was derived from geomagnetic data recorded by satellites, magnetic observatories, and aerial, ground, and marine magnetic surveys.

IGRF-13 provides a DGRF model for the epoch 2015.0, an IGRF model for the epoch 2020.0, and a forecast model of IGRF age variation for the 5-year time interval from 2020.0 to 2025.0. For the epochs from 1900.0 to 2010.0, the coefficients of the IGRF-13 model do not change compared to IGRF-12. Fig. 1, *a* shows maps of the $\boldsymbol{B}_{IGRF}$ geomagnetic field induction module for the territory of Ukraine in 1969.5 epoch and its dynamics $\boldsymbol{B}_{IGRF2005.5\text{-}1969.5}$ for 36 years.

On the territory of Ukraine, the $\boldsymbol{B}_{IGRF}$ field of 1969.5 changes from 47.400 nT in the west-southwest to 50.200 nT in the east. The $\boldsymbol{B}_{IGRF}$ field in the epoch of 2005.5 has a similar character and varies in the range of 48.400–51.000 nT. During the specified time interval, the $\boldsymbol{B}_{IGRF}$ geomagnetic field induction module has uneven dynamics within our country. In particular, the $\boldsymbol{B}_{IGRF}$ experienced the greatest changes in the west of Ukraine, where the value of $\boldsymbol{B}_{IGRF2005.5\text{-}1969.5}$ is 960 nT. The induction module of the Earth's normal geomagnetic field changed the least in the east of its territory and the eastern part of Crimea and is 660 nT.

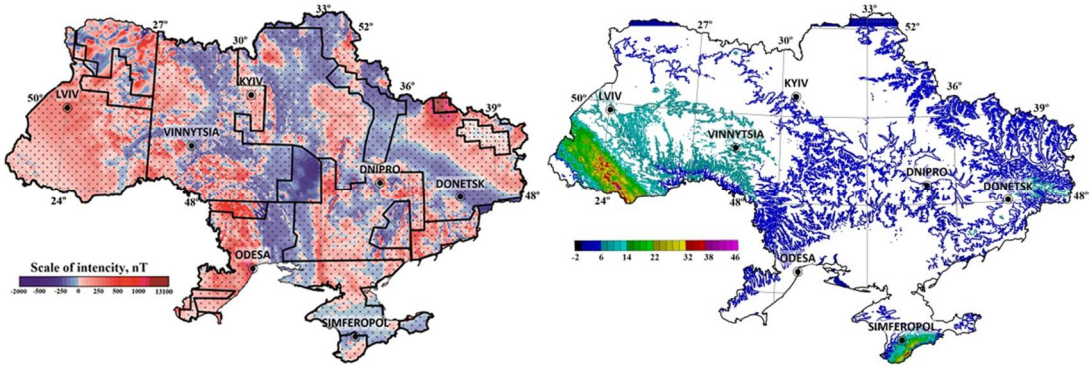
To calculate the module of induction of geomagnetic field $\boldsymbol{B}_{i,y,}$ the module values of the field in the epoch of 1969.5 with a number of 1,460 points, a digital map of the anomalous magnetic field with scale 1: 1 000 000 (surveying height 200 m relative to the Earth's surface relief) with discretization of a 1x1 km field sample (about 602.000 points) (Fig. 2, *a, b*). In connection with different height levels of observation points, the value of $\boldsymbol{B}_{0,i,y}$ was calculated taking into account the topography of the Earth's surface (Fig. 2, *b*).

For a significant part of the territory of Ukraine, this value does not exceed 5–6 nT. Slightly larger corrections for the terrain are observed in the central part of Donbas and the Podilsk Highland, while reaching their maximum values within the Crimean (34 nT) and Carpathian (46 nT) mountains.




a b

**Fig. 1.** The module of induction of the geomagnetic field $\boldsymbol{B}_{IGRF}$ for the territory of Ukraine for the epoch 1969.5 and its dynamics $\boldsymbol{B}_{IGRF2005.5–1969.5}$ for 36 years (a) and the measurement points of the induction module $\boldsymbol{B}$ for the epoch 1969.5 y (b).




a b

**Fig. 2.** Visualization of a digital map of the anomalous magnetic field scale 1: 1 000 000 (a) and the value of the correction when calculating the $\boldsymbol{B}_{IGRF}$ due to the change in the topography of the Earth's surface (b). Black contours and hatching show the areas of magnetic surveys. Intensity of anomalies in nanoteslas.

The first stage of the geomagnetic field induction module map development was the creation of the $\Delta \boldsymbol{B}_{i.y}$ map to the same level in the epoch of 1969.5. First, the points of the absolute reference network were plotted on the original map with a sampling network of 1×1 km. The absolute values of the induction vector of geomagnetic field $\boldsymbol{B}$ were obtained there. The anomalous magnetic field map [Nechaeva et al., 2002] was developed based on various scales (from 1: 10 000 to 1:200 000) aero-, ground-, and hydromagnetic surveys, performed over a long period. The technology used to bring the map to the same level is not specified. However, in most cases, standard methods were applied to construct maps of the anomalous magnetic field of individual areas. These methods involved using the normal magnetic field of the Earth from LO IZMIRAN at the time of the survey [Pochtarev, 1986].The induction module $\boldsymbol{B}$ values observed can be compared with their corresponding calculated values. The induction module of the geomagnetic field in the 1969.5 epoch was calculated as the sum of the normal and anomalous magnetic field: $\boldsymbol{B}_{i.1969.5} = \boldsymbol{B}_{0,1969,5} + \Delta \boldsymbol{B}_a$. These were then quantitatively compared to the absolute values at the observation points in 1969.5 using the analytical model IGRF-DGRF [https://ccmc.gsfc.nasa.gov/modelweb/models/igrf_vitmo.php] for the Earth's normal magnetic field. This allowed for obtaining the correction value needed to bring the map of the induction module $\boldsymbol{B}$ to the epoch of 1969.5. For this, it was taken into account that in a number of points located in areas with high gradient anomalies there were significant discrepancies between the observed and calculated values of $\boldsymbol{B}_{1969.5}$ ($\sigma = \boldsymbol{B}_{1969.5,obs} - \mathbf{B}_{1969.5,calc}$). They were, however, not considered when introducing the amendment. Based on the results of the analysis, the value $\sigma$ was calculated in 1.200 points spread over the territory of Ukraine on a 1×1 km grid by interpolation. The resulting amendment was added to the induction module map $\boldsymbol{B}_{1969.5,calc.}$ resolution at the epoch of 1969.5. This digital map is the basis for designing the

induction module maps of the geomagnetic field $\boldsymbol{B_{i,y}}$ for an arbitrary epoch.

In order to develop maps of the geomagnetic field's induction module for any given year, it is necessary to consider the dynamic nature of its normal component module and the impact of its anomalies' magnetization. $\boldsymbol{B_{i,y}} = \boldsymbol{B_{0i,y}} + \boldsymbol{\Delta\Delta B_{i.y.}}$ The secular variations of the geomagnetic field were estimated using the dynamics of the $\boldsymbol{B_{IGRF}}$ field, which is closest to the secular variations calculated from observatory data. In particular, for the "Kyiv" observatory, the value of the secular variations $\boldsymbol{B}$ is 884 nT, according to the calculated average annual values for the period from 1969.5 to 2005.5. It is 870 nT, based on the $\boldsymbol{B_{IGRF}}$ field. For the "Lviv" observatory, the values are 952 nT and 951.5 nT respectively.

According to [Orlyuk, Romenets 2005], the ratio $\boldsymbol{\Delta D = \Delta B_{i.y.} / B_{0,i,y}}$ is constant and can be used to calculate $\boldsymbol{\Delta\Delta B_{i.y}}$. Based on this statement it is possible to calculate the magnitude of the magnetizing effect for any epoch. For example, the expression for estimating this parameter for the time interval 1969.5–2005.5 is written:

$$\Delta D = \frac{\Delta B_{i,1969}}{B_{0,i,1969}} = \frac{\Delta B_{i,2005}}{B_{0,i,2005}} = \text{const}. \quad (2)$$

In this case, the value $\boldsymbol{\Delta B_{i.2005}}$ which can be obtained from the ratio is unknown

$$\Delta B_{i,2005} = \frac{\Delta B_{i,1969}}{B_{0,i,1969}} B_{0,i,2005}. \quad (3)$$

The magnitude of magnetizing effect $\boldsymbol{\Delta\Delta B_{i.}}$ is defined as the difference between anomalies of the induction module $\Delta B_{i.y.}$ for the epoch of 1969.5 and 2005.5 year

$$\Delta\Delta B_{i,2005} = \Delta B_{i,2005} - \Delta B_{i,1969}. \quad (4)$$

Note that using observations of the induction module $\boldsymbol{B}$ in observatories and RS, the ΔD parameter can be used to correct the level of the Earth's normal magnetic field, which will be discussed in the next publication.

## Research results

The proposed method aims to construct the induction module maps of geomagnetic field and the possibility of developing a map of the induction module anomalies for 1969.5. This allows for obtaining a map of the anomalous magnetic field for this epoch [Nechaeva et al., 2002]. First, the analysis was conducted to find the difference between the original and the anomalous magnetic field map $\boldsymbol{\Delta B_{1969,5}} = \boldsymbol{= B_{1969,5} - B_{IGRF1969,5}}$, [Nechaeva et al., 2002]. Fig. 3 shows the profiles comparing the anomalous field values of these two maps.

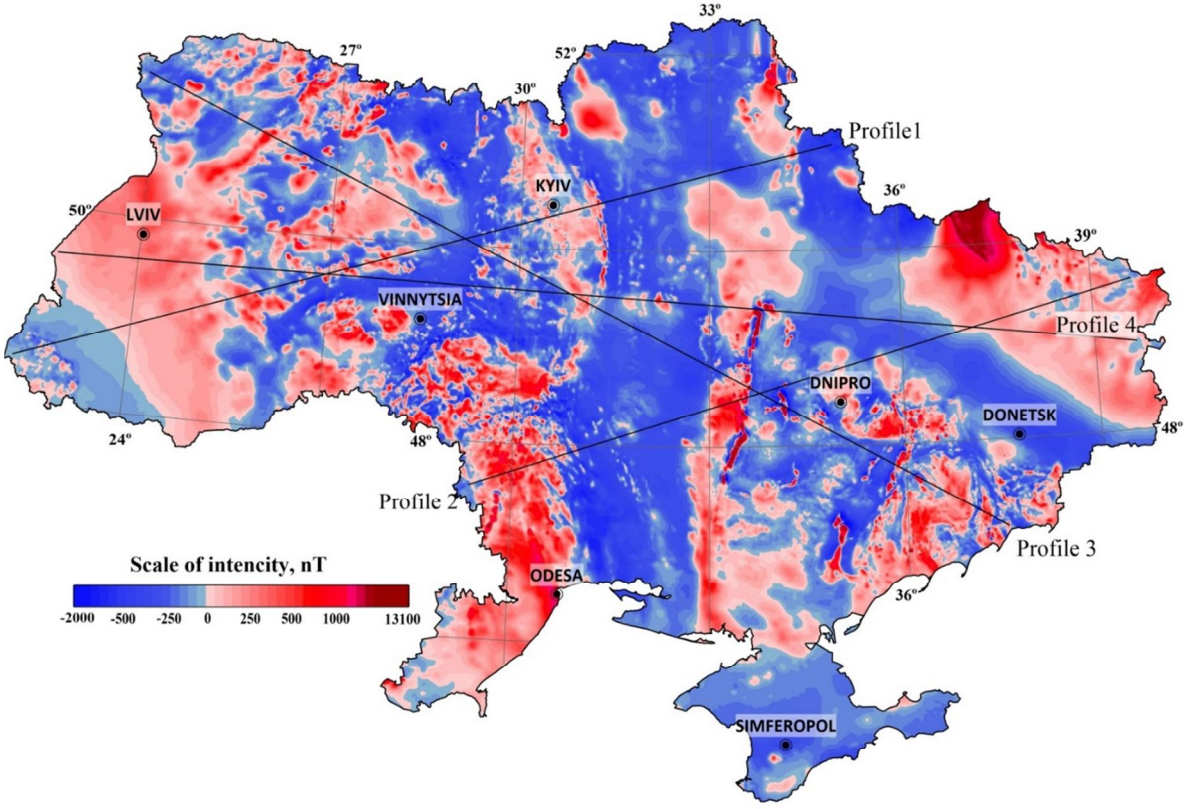
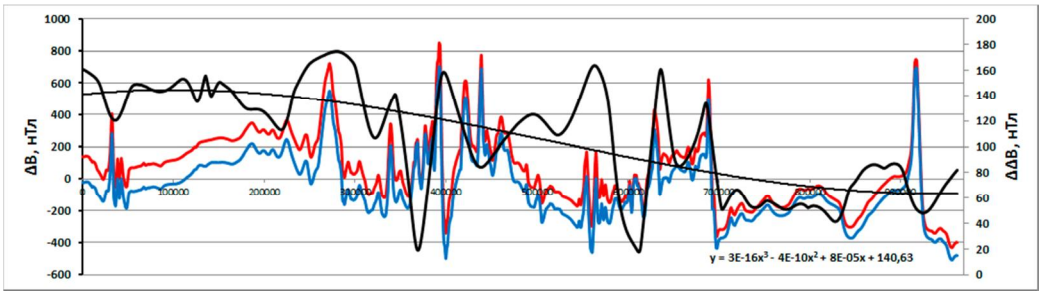
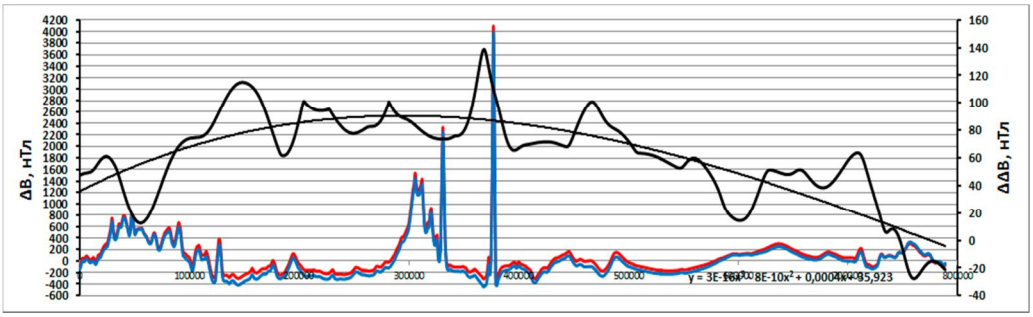



**Fig. 3.** Map of the anomalous magnetic field in the 1969.5 epoch $\boldsymbol{\Delta B = B_{1969,5} - B_{IGRF1969,5}}$ with plotted profiles along which the anomalous field values were compared with the original map of the anomalous magnetic field [Nechaeva et al., 2002].

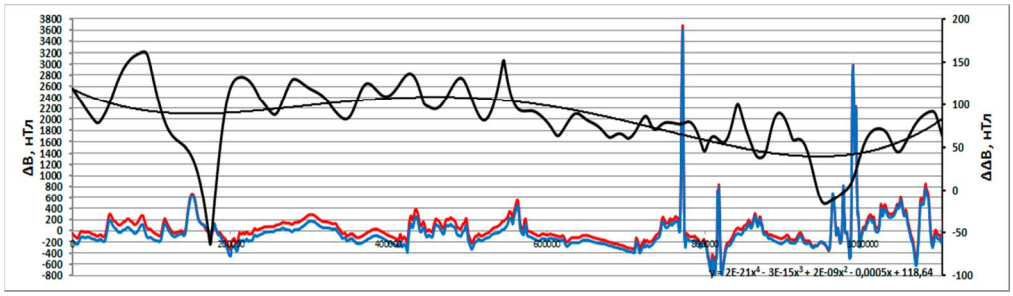
Profile1




Profile2




Profile3




Profile4

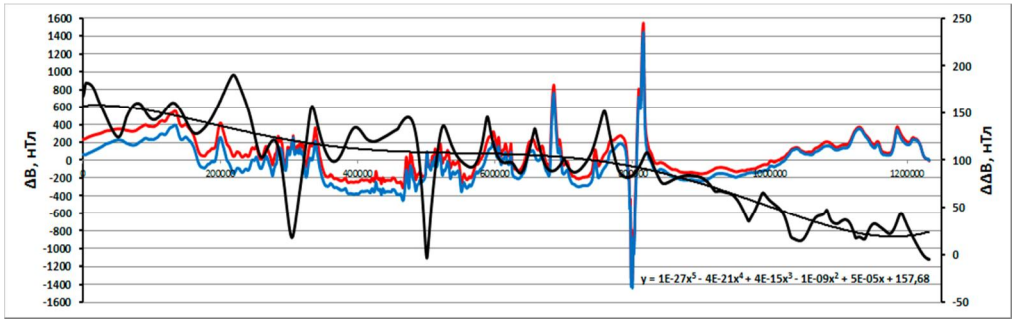



**Fig. 4.** Graphs of the anomalous magnetic field along the profiles: the original map [Nechaeva et al., 2002] (left scale, red color), the developed map $\Delta B_{1969.5}$ (left scale blue color), and the difference curve (black color bold line – trend right scale).

According to our analysis of the anomalous magnetic field along 4 profiles, we observed significant differences in the field level between our developed map and the original map of the anomalous magnetic field. Different anomalies have a "regional" character and vary from the first tens to 100–250 nT. This may be because the original magnetic map was compiled based on different time magnetic surveys and using the normal magnetic field of alternative models.

Profile 1 extends in the north-eastern direction (see Fig. 5). The difference curve is well approximated by a polynomial of the 3rd degree and varies from 60 nT in the east to 140 nT in the west (Fig. 5). Concerning the trend component "regional-local" deviations with an intensity of up to ±(20–60 nT) are distinguished. Therefore minimal differences (up to ±20 nT) are observed in the southwestern and northeastern parts of the profile. Maximum differences of up to ±60 nT are observed in the central part of the profile.

The trend component along profile 2 is approximated by a polynomial of the 2nd-degree typical field values. They range from 0–30 nT on the edges to 80–90nT in the central part. Field deviations of ±20 nT are characteristic against this background. The profile 3 difference curve is characterized by close values of the trend and regional components. In profile 4, the trend component changes from 150 nT in the west of the profile to 25 nT in its east. Therefore, local deviations are typical for the western part of the profile reaching ±40–80 nT. Considering the analysis of the difference graphs of the original map of the anomalous magnetic field and the map of the anomalous magnetic field reduced to the epoch of 1969.5 using the $\boldsymbol{B}_{IGRF}$ field we can talk about their significant difference in both regional and local manifestations. Based on this, the calculated average value of the anomalous magnetic field of the developed map is close to 0 nT. This indicates the correctness of the level of the Earth's normal magnetic field.

Fig. 5 shows the results of the map of the geomagnetic field induction module for the territory of Ukraine. As can be seen from Fig. 5, *a* the correction for bringing modular values to the level of 1969.5 changes from $\sigma$=–200 nT in the west territory to $\sigma$=150 nT in its east but for the most part it is within the range of –100–0 nT. As a rule, $\sigma$ has a regional component, but it also has a local character in certain places. The induction module of geomagnetic field $\boldsymbol{B}_{i,1969.5}$ varies within 46.500–62.000 nT increasing from the southwest to the northeast (Fig. 5, *b*). Against the regional background of 48.000–50.000 nT regional and local magnetic anomalies stand out the most intense of which correspond to the Kryvorizko-Kremenchutska and Kurska anomalies.

The induction module of the geomagnetic field $\boldsymbol{B}_{i,2005.5}$ has the same character but varies within 47.000–63.000 nT. The dynamics of the $\boldsymbol{B}_{IGRF}$ field and the magnitude of the magnetizing effect are shown in Fig. 5, *c*. The magnitude of $\boldsymbol{B}_{IGRF2005.5–1969.5}$ is characterized by values from 700 nT in the east territory of Ukraine to 950 nT in its west.

During the period from 1969.5 to 2005.5 the magnitude of magnetizing effect $\Delta\Delta\boldsymbol{B}_{i.2005.5–1969.5}$ varies within ±10 nT, reaching maximum values (up to 100–190 nT) in areas of intense anomalies. The difference between values of the geomagnetic field induction modulus calculated and measured on RS in the epoch of 2005.5 and 2010.5 does not exceed the first tens of nanoteslas.

The developed technique and created digital maps of the geomagnetic field induction module and its anomalies for an arbitrary epoch are in full accordance with modern trends in the creation of anomalous magnetic fields of various scales and details [Korhonen, 2007; Maus, 2010; Maus et al., 2009; Meyer et al., 2017; Olsen et al., 2017; Liu et.al., 2023] and modular values of geomagnetic field components [Chulliat et.al., 2015; Enhanced..., 2015; Enhanced…, 2017] for the planet as a whole.

To assess the accuracy of calculated values of $\boldsymbol{B}_{i,2005}$, we compared the obtained values with results of surveying on RS of I$^{st}$ and II$^{nd}$ classes (114 points) [Kanyuka et al., 2012; Tregubenko et al., 2008, 2013; Maksymchuk et.al., 2015, 2013]. As can be seen from Fig. 4, *a*, the RS points, which are plotted on the created map of the anomalous magnetic field at the epoch of 1969.5 ($\Delta\boldsymbol{B}_{1969.5} = \boldsymbol{B}_{1969.5} - \boldsymbol{B}_{IGRF1969.5}$), are located mainly in places with weak magnetic anomalies, but some of them are located in areas with a strongly differentiated magnetic field, which causes significant differences between the measured and calculated field values. With this in mind, an estimate of the mean square deviation was performed with the "elimination" of points with significant differences between the calculated and measured values of the module $\boldsymbol{B}$. According to calculations, for 114 RS the difference values are within (–150–1073) nT, and the mean square deviation is $\sigma$=15.1 nT, for 98 RS – ((–50–112) nT, $\sigma$=5.2 nT ), and for 54 RS – ((–45–41) nT, $\sigma$=3.0 nT), respectively. Considering the absolute values of the $\boldsymbol{B}_{IGRF}$ field (49.000–50.500 nT) and its secular variations (700–900 nT), the obtained accuracy of module $\boldsymbol{B}$ calculation can be considered more than satisfactory. Fig. 4, *b* shows a map of the difference between measured $B_{i,2005,meas.}$ and calculated $B_{i,2005,calc.}$ values of the geomagnetic field induction module at RS..

Fig. 6 shows a map of the difference between measured $\boldsymbol{B}_{i,2005.5,meas.}$and calculated $\boldsymbol{B}_{i,2005.5,calc.}$ values of the geomagnetic field induction module on RS.

According to the analysis, this value varies from –20 to +40 nT for most Ukraine`s territory. The character of error spread of calculated values relative to the measured values has a regional character. For the central and eastern parts of the territory, the difference between $\boldsymbol{B}_{i,2005,5,meas}$ $\boldsymbol{B}_{i,2005,5,calc}$ is 20–60 nT. In the western part, anomalies from –20 to +40 nT are characteristic for most of the territory. Such a distribution of $\boldsymbol{B}_{i,2005,5,meas} - \boldsymbol{B}_{i,2005,5,calc}$ distinction may indicate that this value is not taken into account in the secular variations of the normal field of the IGRF model. But it is worth noting that changes in the regional background divide Ukraine into western and eastern parts. They also differ in a number of geological and geophysical parameters of the lithosphere. For instance, the speed of longitudinal waves in the upper mantle and different structural plans of lineaments and fault zones vary between the two regions. Although the differences between calculated and observed values of $\boldsymbol{B}$ are insignificant, they still require an explanation. From our point of view, these differences could be related to modern geodynamic and fluid processes occurring in the upper mantle and deep fault zones that are currently active in the development of Ukraine's lithosphere. Firstly, in fact, the western part of the territory of Ukraine is characterized by reduced speeds

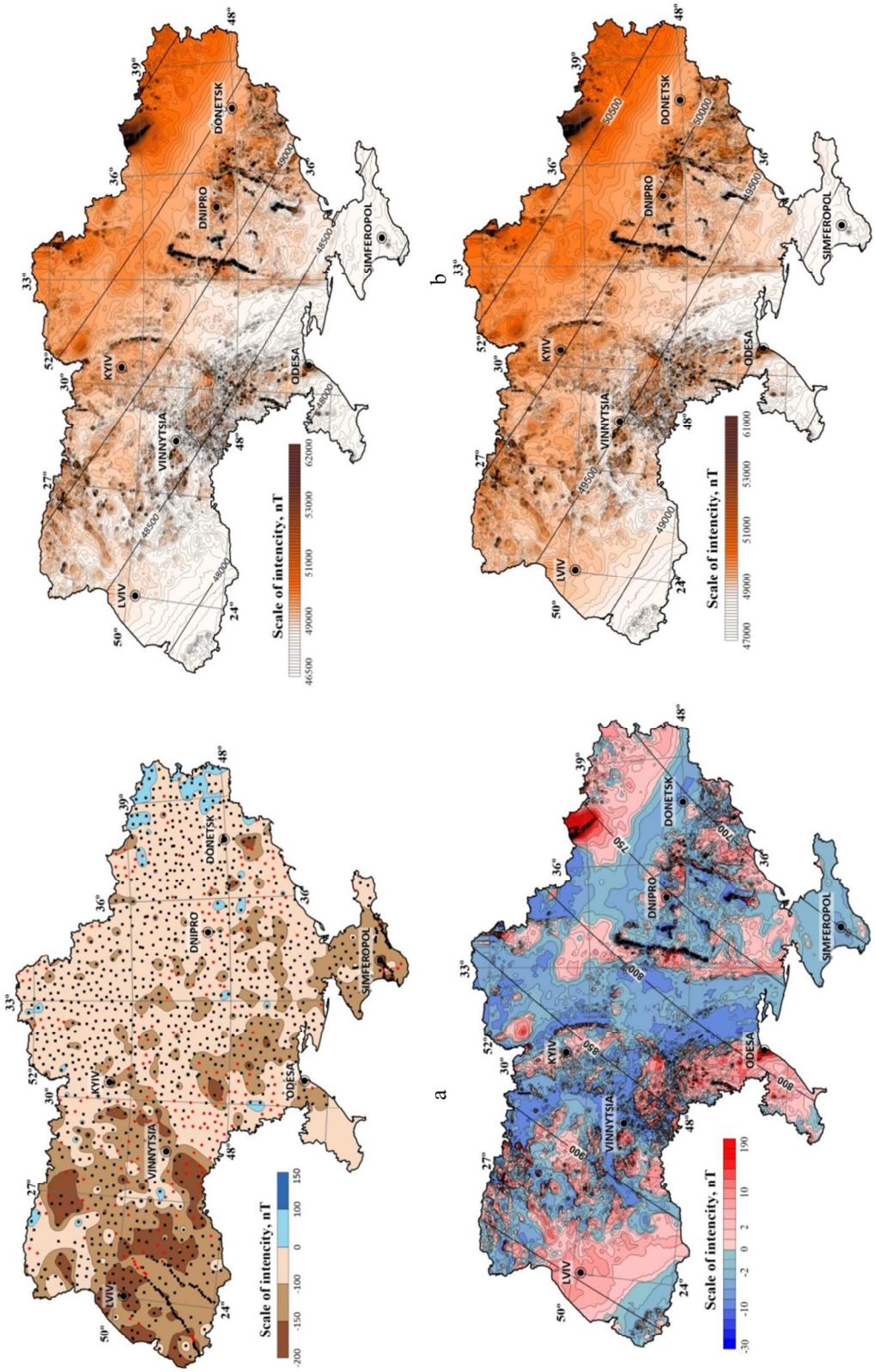



**Fig. 5.** Digital map of the induction module of geomagnetic field for the territory of Ukraine: location diagram of the points (black and red dots) of measurement of the module values of field in the epoch of 1969.5 and the value of correction to bring data to the same level (5a); map of the calculated values of induction module $\boldsymbol{B}_{1969,calc.}$, resolution (5b); dynamics of the $\boldsymbol{B}_{IGRF2005,5\text{-}1969,5}$ field for the interval 1969–2005 and the magnitude of magnetizing effect $\Delta\Delta\boldsymbol{B}_{i,2005,5\text{-}1969,5}$ (5c); map of module $\boldsymbol{B}_{i,2005,5}$ in the epoch of 2005.5 (5d).

of longitudinal waves, while the eastern part by their increased values [Geiko et al., 1998]. This may indicate a different composition of the mantle in relation to the fluid component, possibly caused by the development and formation of the West European platform [Kutas et al., 2018]. The significant differences between calculated and measured values of module ***B*** are observed in areas of recent geological activity in Ukraine. These areas often contain ancient and recent faults and fault zones, such as the Carpathian region, the southwestern and southern edges of the East European platform, the Kherson-Smolensk trans-regional tectonic suture zone, and the nearby Shchors-Mykolaiv and Novgorod-Sivers'k – Novokakhovka one lineament zones, reflecting the latest activation of the Earth's crust [Kutas et al., 2018; Verkhovtsev, 2008; Tretyak et al., 2015]. Finally, it is worth paying attention to a certain t maximum difference values of ***B*** with electrical conductivity anomalies in the Earth's crust and upper mantle, particularly in the Carpathian and Kirovohrad zones [Tretyak et al., 2015; Burakhovich, Kulyk, 2007; Burakhovich, Kushnir, 2023]. Based on the above, the proposed technology makes it possible to obtain reliable values of module ***B*** for an arbitrary epoch and perform analysis of differences, which are extremely informative about the characteristics of modern geodynamic processes.

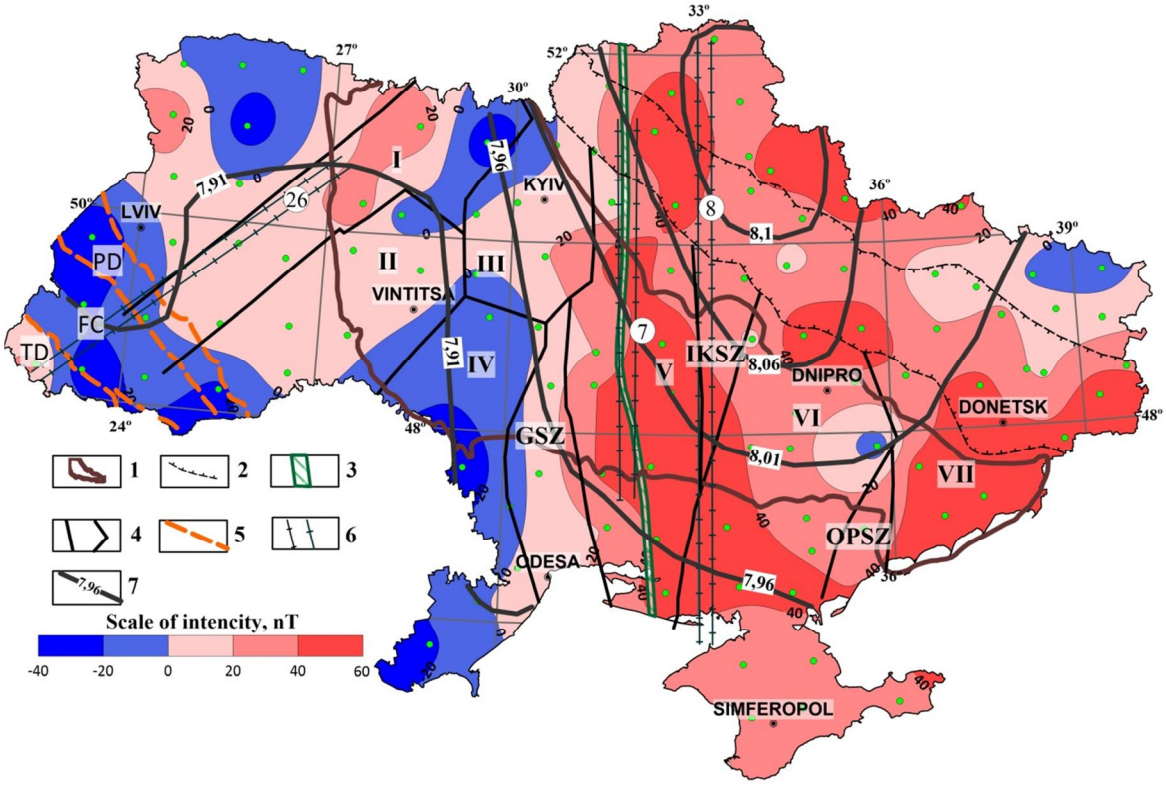



**Fig. 6.** Map of difference of the observed $B_{i,2005.5,obs.}$ and calculated $B_{i,2005.5,calc.}$ values of induction modulus of geomagnetic field on RS (dots in green):

1 – edge of Ukrainian shield; 2 – the boundary of Dnipro-Donetsk avlakogen; 3 – Kherson–Smolensk transregional tectonic suture zone; 4 – zones of between-megablock faults; 5 – boundaries of tectonic units of the Ukrainian Carpathians: PD – Pre-Carpathian Depression, FC – Folded Carpathians, TD – Transcarpathian Depression; 6 – lineament zones (author's numbering preserved [Verkhovtsev, 2008.]): 7 – Shchors-Mykolaiv one, 8 – Novgorod-Sivers'k – Novokakhovka one, 26 – Khust-Korets one; 7 – velocity of longitudinal waves at a depth of 50 km [Geiko et al., 1998]. Megablocks of Ukrainian Shield: I – Volyn one; II – Podillia one; II – Ros'-Tikich one; IV – Buh one; V – Ingul one; VI – Central Dnieper'; VII – Periazovian; Suture zones: GSZ – Golovanivs'k one; IKSZ – Ingulets-Kryvyi Rih one; OPSZ – Orihovo-Pavlograd one.

Note that the developed technology for calculating the induction module of a geomagnetic field can be used not only for forecasting its values for future epochs, but also for obtaining information about the corresponding maps in the past. For this purpose, we calculated the $B_Z$ component of the geomagnetic field and anomalies $\Delta B_Z$ in the 1935 epoch. For this purpose the map of anomalies of the geomagnetic field vertical component was constructed for the central and eastern parts of the territory of Ukraine [Rose, 1937]. Considering the

accuracy of this map (±120 nT), the field isolines at 500 nT are drawn with extreme precision. This verifies the calculated values of the geomagnetic field, especially between the 0 nT-500 nT and 500 nT isolines.

## Conclusions

A digital map of the geomagnetic field induction module $\boldsymbol{B}$ and its anomalies $\Delta\boldsymbol{B}$ (scale 1: 1 000 000) for the epoch of 1969.5 for the territory of Ukraine was created for the first time, using IGRF-13 as the Earth`s normal field. Additionally, the construction of appropriate maps for an arbitrary epoch was proposed, particularly, for the epoch of 2005.5.

To create the map of geomagnetic field induction module $\boldsymbol{B}$ we used the results of the absolute ground magnetic survey of 1969–1972, the analytical model of the main geomagnetic field $\boldsymbol{B}_{IGRF}$, as well as the map of anomalous magnetic field on a scale of 1: 1 000 000.

We obtained the digital modulus and anomaly map of geomagnetic field induction module $\boldsymbol{B}$ for the 1969.5 epoch. Correction was calculated based on their difference values at the points of the absolute reference network. This information was then spread across the entire territory of Ukraine using a1x1km network. The spatial distribution of the correction, which varies within –200–150 nT, characterizes the difference between the LO IZMIRAN and IGRF field models.

The geomagnetic field induction module $\boldsymbol{B}$ for an arbitrary epoch was calculated by adding the calculated values of the field's dynamics $\boldsymbol{B}_{IGRF}$ and the "magnetizing" effect of induction modulus $\Delta\Delta\boldsymbol{B}$ anomalies to its values for the epoch 1969.5.

The digital map of the geomagnetic field induction module created in 2005.5 was verified by measuring the values of its module on magnetic observatories of *Kyiv*, *Lviv,* and *Odesa*, as well as in the points of secular variations and RS of the II$^{nd}$ class. The verification demonstrated their differences within –20–40 nT.

The most significant differences between the calculated and measured values of module $\boldsymbol{B}$ align with the areas of recent activity in Ukraine. These areas often inherit ancient and recent faults and fault zones, as well as exhibit electrical conductivity anomalies in the Earth's crust and upper mantle. The most notable of these are the Carpathian and Kirovograd zones.

## References


Burakhovich, T. K., & Kulyk, S. N. (2007). Quasi-three-dimensional geoelectrical model of the Kirovohrad anomaly of electrical conductivity, *Geofizicheskiy Zhurnal*., 29, 1, 45–55. (in Russian). http://www.igph.kiev.ua/ukr/journal.html#

Burakhovich, T. K., & Kushnir, A. M. (2023). History, current state and directions of development of geoelectromagnetic research in Ukraine. *Bulletin of Taras Shevchenko Kyiv National University. Geology*, 1(100), 58–66. (in Ukrainian). https://geology.bulletin.knu.ua/article/view/844/676

Chulliat, A., S. Macmillan, P. Alken, C. Beggan, M. Nair, B. Hamilton, A. Woods, V. Ridley, S. Maus and A. Thomson, (2015). The US/UK World Magnetic Model for 2015–2020: Technical Report, National Geophysical Data Center, NOAA. http://doi.org/10.7289/V5TB14V7

DGRF/IGRF [Electronic Resource]. Mode of access: URL: DGRF/IGRF Geomagnetic Field Model 1945–2024 and Related Parameters.htm). https://ccmc.gsfc.nasa.gov/modelweb/models/igrf_vitmo.php).

Entin, V. A., Guskov, S. I., Orlyuk, M. I., Gintov, O. B., & Osmak, R. V. (2015). Map of the absolute values of the gravity field of Ukraine and some aspects of its possible interpretation. *Geofizicheskiy Zhurnal*,.37(1), 58–65. (in Russian)

Enhanced Magnetic Model (EMM) 2015. https://www.ncei.noaa.gov/products/enhanced-magnetic-model

Enhanced Magnetic Model (EMM) 2017. https://www.ncei.noaa.gov/products/enhanced-magnetic-model

Geiko, V. S., Tsvetkova, T. A., Sannikova, N. G., Lyvanova, L. P., & Geiko K. V. (1998). Regional 3-D P-velocity structure of the mantle of northwestern Eurasia. *Geofizicheskiy Zhurnal*., Vol. 2, No. 3. P. 67–91. (in Russian)

Kanyuka, A., Chuyko, L., Lozovyi, A., & Mendriy, Ya. (2015). Creation of a network of reference geomagnetic (T) points on the territory of Ukraine. Report on geophysical study of the subsurface. Funds of DGE "Dniprogeofizika", DGE "Ukrgeofizika". (in Ukrainian).

Korhonen, J. V., Fairhead, J. D., Hamoudi, M., Hemant, K., Lesur, V., Mandea, M., Maus, S., Purucker, M., & Thébault, E. (2007). Magnetic Anomaly Map of the World, 1st edition. GTK, Helsinki. Map published by Commission for Geological Map of the World, supported by UNESCO.

Krutykhovska, Z. O., Pashkevich, I. K., Rusakov, O. M., & Solovyov, V. D. (1973). Terrestrial absolute magnetic survey of the territory of the Ukrainian SSR. *Visnyk. Academy of Sciences of the Ukrainian SSR*, 9, 101–102. (in Ukrainian).

Kutas R. Y., Orlyuk M. I., Pashkevich I. K., Burakhovich T. K., Makarenko I. B., & Bugaenko I. V. (2018). Deep structure of the territory of Ukraine according to modern geophysical data. General information. In the book: Essays on geodynamics of Ukraine. Ed. V.I. Starostenko, O.B. Gintov. Kyiv: BI EN EY, P. 17–24

Liu, P. F., Jiang, Y., Yan, Q., and Hirt, A. M. (2023). The behavior of a lithospheric magnetization and

magnetic field model. *Earth Planet. Phys.*, 7(1), 66–73. http://doi.org/10.26464/epp2023025

Map of the anomalous magnetic field of the Ukrainian shield m-ba 1: 500 000. (1977). Explanatory note (edited by Yu. B. Kravchenko, Z. A. Krutikhovskaya). Kyiv, Kyivgeologiya. 100 p.

Maksymchuk, V., Orlyuk, M., & Tregubenko, V. (2015). Repeat stations measurements in Ukraine 2014–2015. *In MagNetE 2015*, Budapest 16–18 september: abstracts. Budapest: Geological and Geophysical Institute of Hungary, 2015, p.24.

Maksymchuk, V, Orlyuk, M, Tregybenko, V, Horodyskyy, Y, & Marchenko, D. (2013). Ukrainian geomagnetic repeat station network and results of the field work reduced to the epoch 2005.5. Ann. Geophys. [Internet]. 2013 Mar.7; 55(6). Available from: https://www.annalsofgeophysics.eu/index.php/annals/article/view/5406

Maus, S. (2010). An ellipsoidal harmonic representation of Earth's lithospheric magnetic field to degree and order 720. *Geochem. Geophys. Geosyst*., 11(6), Q06015. https://doi.org/10.1029/2010GC003026

Maus, S., Barckhausen, U., Berkenbosch, H., Bournas, N., Brozena, J …Tontini, F. C. (2009). EMAG2: A 2-arc min resolution Earth Magnetic Anomaly Grid compiled from satellite, airborne, and marine magnetic measurements. *Geochem. Geophys. Geosyst.*, 10(8), Q08005. https://doi.org/10.1029/2009GC002471

Meyer, B., Saltus, R., and Chulliat, A. (2017). EMAG2v3: Earth Magnetic Anomaly Grid (2-arc-minute resolution). Version 3. NOAA National Centers for Environmental Information. https://doi.org/10.7289/V5H70CVX.

Nechaeva, T. S., Shimkiv, L M., Horkavko, V. M., & Yentin, V. A. (2002). Map of the anomalous magnetic field (ΔT) a of Ukraine scale 1:1 000 000. Kyiv. (in Ukrainian).

Olsen, O., Ravat, D., Finlay, Ch. C., & Kother, L. K. (2017). LCS-1: a high-resolution global model of the lithospheric magnetic field derived from CHAMP and Swarm satellite observations. *Geophysical Journal International*, 211(3), 1461–1477. https://doi.org/10.1093/gji/ggx 381.

Orlyuk, M., Marchenko, A., Romenets, A., & Bakarjieva, M. (2018). Ukrainian Regional Magnetic Map: the results of calculations of the geomagnetic field components for the Epoch 2015. COBS Journal, 5, 40.

Orlyuk, M. Y., & Romenets A. A. (2005). A new criterion for estimating of spatial-temporal perturbation of the Earth's magnetic field and some aspects of its use. *Geofizicheskiy Zhurnal*., 27(6), 1012–1023. http://www.igph.kiev.ua/ukr/journal.html# (in Russian).

Orlyuk, M. I., Romenets, A. A., Sumaruk, P. V., Sumaruk, Yu. P., & Sumaruk, T. P. (2012). Spatial-temporal structure of the Earth's magnetic field of the territory of Ukraine: evaluation of the contribution of internal and external sources. *Geofizicheskiy Zhurnal*, 34, 3, 137–145. (in Russian). ttps://journals.uran.ua/geofizicheskiy/article/view/116651/110688

Pashkevich, I. K., & Solovyov, V. D. (1971). The results of the work on the creation of a ground support magnetic network on the territory of the Ukrainian SSR. Report on the work of the geophysical party 93/68-71 for the period 1968-1071. Part I. Text. 1971. IGF funds of the National Academy of Sciences of Ukraine. (in Russian).

Pochtarev, V. I. Normal magnetic field of the Earth. M.: Nauka, 1980. 268 p.

Rose, T. N. (1937). Regional magnetic anomalies of Ukraine and their connection with geotectonics. *Uchen. zap Leningrad University, Ser. Phys*., 3, 123–133. (in Russian).

Tregubenko, V. I., Maksymchuk, V. Yu., Orlyuk, M. I., Marchenko, D. O., Myasoedov, V. P., & Romenets, A. O. (2008). Conducting a component magnetic survey on the reference network and building maps of the normal geomagnetic field and the age course of the 2005 era for the territory of Ukraine. Funds of UTGF, UkrDGRI;

Tregubenko, V. I., Maksymchuk, V. Yu., Orlyuk, M. I., Marchenko, D. O., Myasoedov, V. P., & Romenets, A. O. (2013). Components of the Earth's magnetic field on the territory of Ukraine for the epoch of 2010. according to the results of measurements at the Repeat Station points. *Mineral resources of Ukraine*, 3, 37–40.

Tretyak, K. R., Maksymchuk, V. Yu., & Kutas R. I. (2015). Modern geodynamics and geophysical fields of the Carpathians and adjacent territories. Lviv Polytechnic Publishing, 420 p.

Verkhovtsev, V. G. (2008). Latest platform geostructures of Ukraine and the dynamics of their development. Auth.-t dis.d.geol.Sc. Kyiv, Institute of Geological Sciences of the National Academy of Sciences of Ukraine. 36 p. (in Ukrainian).

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# РОЗРОБКА ЦИФРОВИХ КАРТ МОДУЛЯ ІНДУКЦІЇ ГЕОМАГНІТНОГО ПОЛЯ ДЛЯ ТЕРИТОРІЇ УКРАЇНИ

Знання про геомагнітне поле території України базуються на магнітних зйомках модуля індукції геомагнітного поля **B** та його силових і кутових компонент, а також спостережень або розрахунку їх аномальних величин. У статті викладено методику та розроблено цифрову карту модуля індукції геомагнітного поля на епоху 1969,5 року, яка є базовою для розробки карт модуля **B** та його аномалій Δ**B** для довільної епохи. Для побудови карти модуля індукції геомагнітного поля **B** використано результати наземної абсолютної магнітної зйомки 1969–1972 рр, аналітичну модель головного геомагнітного поля $B_{IGRF}$, а також карту аномального магнітного поля м-бу 1: 1 000 000. Цифрова карта модуля та аномалій модуля індукції геомагнітного поля B на епоху 1969,5р отримана шляхом розрахунку поправки за їх різницевими значеннями в пунктах абсолютної опорної мережі, яку шляхом інтерполяції було поширено за матрицею 1х1км на весь масив даних для території України. Модуль індукції геомагнітного поля **B** на епоху 2005,5 р. розраховано шляхом додавання до його значень на епоху 1969,5р розрахованих величин динаміки поля $B_{IGRF}$ та "підмагнічуючого" ефекту аномалій модуля індукції **ΔΔB**. Розроблена карта $\mathbf{B_{i,p}}$ є наближеним представленням модуля магнітного поля, оскільки при розрахунку не враховувалася величина залишкової намагніченості,що може зумовлювати незначні відхилення розрахованих та спостережених значень поля. Модуль індукції геомагнітного поля **B** на епоху 1969,5 р. змінюється в інтервалі 46500–62000 нТл, а на епоху 2005,5 р − 47000–63000 нТл, зростаючи з південного заходу на північний схід території України. Максимальні його значення спостерігаються в районах регіональних та локальних магнітних аномалій, зокрема в районі Криворізько-Кременчуцької аномальної смуги та південно-східного краю Курської аномалії. Динаміка поля $\mathbf{B}_{IGRF}$ за період 1969,5–2005,5 рр. характеризується величинами від 700 нТл на сході території України до 950 нТл на її заході, а величина підмагнічую чого ефекту **ΔΔB** змінюється в межах ±10 нТл, досягаючи максимальних величин (до 100-190 нТл) в областях інтенсивних магнітних аномалій. Верифікація розробленої на епоху 2005,5р цифрової карти модуля індукції геомагнітного поля **B** замірами значень його модуля в магнітних обсерваторіях "Київ", "Львів" та "Одеса", а також у пунктах вікового ходу та опорних магнітних пунктах II класу засвідчила незначні (-20–40 нТл) розходження розрахованих та заміряних величин модуля **B.** Найзначніші їх відмінності просторово корелюються із областями сучасної активізації земної кори території України та аномаліями електропровідності.

*Ключові слова*: модуль індукції геомагнітного поля **B**, магнітна зйомка, магнітні карти**,** аналітична модель поля IGRF-DGRF, пункти вікового ходу.

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