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Коротке повідомлення

Short note

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# Measurement of the difference in the geomagnetic induction between the magnetometer pillars of the geomagnetic observatory of the Ukrainian Antarctic Akademik Vernadsky station

**Abstract.** The article describes the features of measurements of spatial inhomogeneities of the geomagnetic field between the pillars of magnetometers in the measuring pavilion, which were carried out at the geomagnetic observatory of the Ukrainian Antarctic Akademik Vernadsky station in 2015. Some preliminary results of these measurements are also given. The concept of the time-scaled value of the geomagnetic field induction is introduced, which is convenient for compensating for time changes of the real geomagnetic induction and bringing it to one reference level of induction. The differences in geomagnetic induction between pillars are obtained as the differences in time-scaled values of the geomagnetic induction on the pillars. The technique allows comparing long-term series of measurements of field inhomogeneities at important points in space. The main objectives are to increase the accuracy of measurements of local inhomogeneities of the geomagnetic field in the measuring pavilion of the geomagnetic observatory of the Ukrainian Antarctic Akademik Vernadsky station and to determine the differences in the geomagnetic induction between the pillars on which the magnetometer sensors are installed. Obtaining numerical values of the differences in the geomagnetic induction between the pillars as objective criteria needed to assess the accuracy of the data in the final processing of geomagnetic observatory data. The method of comparison of two series of data is used: one obtained by the scalar magnetometer installed in the observatory as a mandatory stationary device, and the other obtained during measurements with a mobile magnetometer at the desired points in space. Compensation of temporal changes of the geomagnetic field by time-scaling the measurement readings of the mobile magnetometer relative to one reference value and thus, bringing them to one selected and fixed time epoch. Special geometric scheme of mobile measurements in the space around the pillars with magnetometer sensors or at important points in space. A rough estimate of method errors. Based on the analysis of the obtained data, the efficiency of the method and its acceptable potential accuracy were confirmed. We obtained approximate numerical values of the differences in the geomagnetic field induction between the pillars on which the magnetometer sensors are installed. Further increase in the accuracy of determining these differences is possible using modern devices of high accuracy and GPS-synchronization of mobile measurements.

**Keywords:** geomagnetic field gradient, compensation of time changes of the field, time-scaled geomagnetic field induction, increase of accuracy of geomagnetic field measurements

## 1 Introduction

The need to determine and periodically re-check the overall accuracy of geomagnetic data is due to two factors: (1) the need to use a scalar magnetometer as a mandatory device in the equipment of a geomagnetic observatory and (2) the change of the format of data transmitted to the INTERMAGNET network from IMF V1.22 to IMF V1.23.

Generally speaking, evaluation of the observatory's geomagnetic data's accuracy should incorporate all possible errors on all the stages of the measuring process, starting with automatic and manual measurements and ending with calculations yielding the final results. In this paper, we did not evaluate the contribution of the errors of absolute observations to the overall accuracy of geomagnetic data but concentrated only on the accuracy of the part which consists in measuring the differences of the geomagnetic field induction between the pillars bearing magnetometer sensors or between separate points within the measurement pavilion.

As such differences can change with time, it is recommended to measure them at least once a year (Jankowski & Sucksdorff, 1996; INTERMAGNET Technical Reference Manual, 2012). One should bear in mind that the project of the measurement pavilion was developed to accommodate photographic registration of the field's components, while the sensitive digital magnetometers we have today do require qualitatively different conditions. Besides that, the limited amount of information necessary for urgent measurements to be made by winterers forced them to solve the problems using their own resources. The measurement of the differences of the field induction was somewhat similar to the method employed near the Akademik Vernadsky station during tectonomagnetic profiling and geomagnetic mapping (Orlyuk & Romenets, 2020; Korepanov et al., 2004; Maksymchuk et al., 2018). However, in contrast to the cited works, we focused on those operations (critical in terms of accuracy of measurements), which constitute the whole process of measuring the differences in geomagnetic induction between points. That is why the emphasis was also placed on the described technique, which aimed to ensure the maximum possible accuracy in determining the geomagnetic induction differences over long time intervals, regardless of the time changes of the geomagnetic field.

## 2 Methods

### 2.1 The approach to the measurement of the geomagnetic field induction differences between the magnetometers' pillars

We considered the factors that could affect the accuracy of determining the between-pillar differences in the induction of the geomagnetic field. First of all, this is the temporal variability of the field and the possible presence of a spatial field gradient where the magnetometer sensors are located.

We made following obvious assumptions:

1. The spatial image of the geomagnetic field's induction can be built for one and the same time $t_0$.
2. Temporal changes in each $F_{mi}$ reading taken at the time $t_i$ by the mobile magnetometer can be compensated by time-scaling of the $F_{mi}$ reading with respect to the selected and fixed reference value $F_{m0}$, which was recorded by the stationary scalar magnetometer at the time $t_0$.
3. Spatial uncertainty of the field's heterogeneity (caused by the presence of the spatial gradient) can be minimized by a choice of a geometric pattern of mobile measurements around the point of interest, e.g., the geomagnetic sensor on the pillar.

Let us consider these assumptions in more detail.

1. **Spatial image of the field:** For every point of the studied space, it is possible to simultaneously determine the induction of the geomagnetic field at the chosen and fixed time $t_0$ (and thus to the absolute value of the field induction $F_{s0}$, which is registered by the observatory's stationary scalar magnetometer at $t_0$). To do this, one should neutralize the field's temporal variability for the mobile measurements at $t_i$.

It should be noted that this tacitly postulates a linear approach. For every spatial point, the temporal changes of the geomagnetic field caused by secular and daily variations are taken as linear and proportional, discarding the non-linear effects of the field's distortion when it changes. Since the daily variations in the modulus of the field induction vector are small (no more than ~0.3% of the modulus), this assumption of linearity seems to be acceptable in the range of the considered time intervals.

2. **Compensation for time changes** of the geomagnetic field is that each $F_{mi}$ reading of mobile measurements made by the mobile scalar magnetometer at the desired point in space at any point in time $t_i$ has to be led (scaled) to a single selected and fixed time $t_0$.

Although, more precisely, this means scaling all mobile measurements of $F_{mi}$ relative to the fixed value of the field induction $F_{s0}$, recorded by the stationary scalar magnetometer of the observatory at $t_0$.

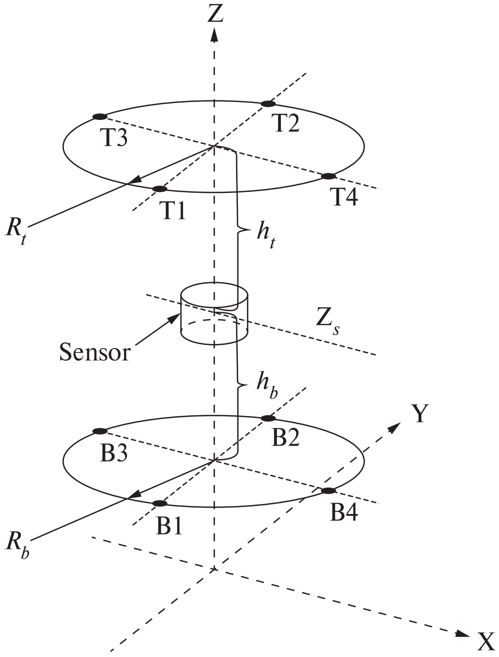

**Figure 1.** The geometry of the mobile measurements to obtain the field induction in the sensor placement point $Z_s$. Measurements are done above (points T1, T2, T3, and T4) at distance $R_t$ from the axis $Z$ at height $h_t$ over the sensor; below (B1, B2, B3, and B4) at distance $R_b$ from $Z$ at height $h_b$ lower than the sensor's center

For this purpose, two scalar measurement datasets are used:

- The data of measurements $F_{si}$, made using the stationary observatory scalar magnetometer, which is a mandatory piece of equipment of the magnetometer complex.
- The data of mobile measurements $F_{mi}$, made using the mobile magnetometer near the studied points.

The time-compensated values of $F_t$ are obtained from the equation

$$F_t = K_i \times F_{mi}, \qquad (1)$$

where $K_i = \frac{F_{s0}}{F_{si}}$ is the space-time-dependent coefficient of the variability of the geomagnetic field calculated from the readings $F_{s0}$ and $F_{si}$ of the stationary scalar magnetometer at the fixed moment $t_0$ and some arbitrary moment $t_i$ when the mobile-magnetometer measurement was done, and $F_{mi}$ is the reading of mobile measurement made by the mobile scalar magnetometer at $t_i$ in a studied point of space.

Let us name the values of the field induction $F_t$ calculated in this way at the desired points in space as time-scaled.

The difference of the field between the points of interest (the magnetometers' pillars) can be obtained as the difference between their time-scaled field induction.

The chosen value $F_{s0}$ is a constant relative to which one should compare the measurements done in different time epochs. Since such temporal scaling posits no special limitations as to the duration or the exact time of mobile measurements (and under the linearity assumption), it seems possible to suggest that the scaling can be done over large intervals of time, e.g., months or even years, if one bears in mind the estimated overall accuracy of the technique and the class of accuracy of the measuring devices.

3. **Error minimization given some spatial gradient of the field** to minimize the overall error of the calculations is done through a choice of measurements geometry (Fig. 1). For this purpose, mobile magnetometer readings are taken in more than the one point (the placement of the sensor $Z_s$ on the pillar) but in several points around the device.

We considered it sufficient (to detect the presence of a gradient) to choose 4 points above the location of the sensor $Z_s$ and, accordingly, 4 points below. At the presence of a noticeable spatial gradient of the field near the sensor, it is possible to increase the absolute accuracy if one conducts mobile measurements in more points around the sensor. The field induction in the sensor placement point $Z_s$, minimized with respect to spatial errors due to the gradient, is obtained as the mean of the time-scaled field induction $F_t$ around the sensor, measured with the mobile magnetometer as shown in Fig. 1.

## 2.2 The general components of errors of measurement of the field induction differences

For the following consideration, it is convenient to regard the geomagnetic field's temporal variations at two time scales: the slow drifts (over years or decades) and fast changes (seconds to hours). Then the momentary field induction $F(\vec{r}, t)$ at the Earth surface in any point $\vec{r}$ and at any time $t$ can be conditionally presented as a sum of two parts, one quasi-stable and the other changeable:

$$F(\vec{r},t) = F_0(\vec{r},t) + F_v(\vec{r},t) \qquad (2)$$

The first component $F_0(\vec{r}, t)$ is quasi-stable, not much dependent on time, and describes the so-called basic field vector believed to be generated by the outer layers of Earth core. Over very short geologic time intervals (day to month), the component shapes an almost time-stable spatial distribution of the geomagnetic field of the measurement pavilion, arising primarily from the magnetism of the rock and artificial objects located nearby. Thus we can neglect the temporal dependence of the component and consider only its spatial dependence. Then, this component can be presented as a function of only the spatial coordinates $F_0(\vec{r}, t) \approx F_0(\vec{r})$.

The second component $F_v(\vec{r}, t)$ represents the fast-changing field generated by sources in the outer Earth layers and the geospace. It's a function that incorporates the dependency of the field both on the spatial coordinates and on time. When this component is measured in point around the sensor with fixed space coordinates $\vec{r}$ over some time interval, it can be written as the function $F_v(\vec{r}, t) \approx F_v(t)$.

Under these assumptions, the overall evaluation of the errors of the calculation method can be done as the field differential $F_v(\vec{r}, t)$ in (2) depending on the variable variations in this way:

$$\Delta F(\vec{r},t) = \vec{\nabla} F_0(\vec{r}) \cdot \Delta \vec{r} + \frac{d}{dt} F_v(t) \cdot \Delta t \qquad (3)$$

At geomagnetically calm conditions (as the simplest and best case), the rate of change of the field is zero or near zero, and we have $\frac{d}{dt} F_v(t) \approx 0$. Then the overall method error $\Delta F(\vec{r}, t)$ is defined by only the field gradient $\vec{\nabla} F_0(\vec{r})$ near the point of the sensor placement $Z_s$ and the error of the mobile magnetometer positioning during the measurements around the sensor. But it is also possible that the pillar design or the gradient in the point $Z_s$ itself imposes the necessity of measurements in several points above the sensor and below it (Fig. 1).

Under geomagnetically disturbed conditions, when the rate of change of the field $\frac{d}{dt} F_v(t)$ is noticeable, the primary source of the method's error can be the mutual imprecision of time points $\Delta t$ between the times of measurement by the stationary and mobile magnetometers (their mutual dyssynchrony). The overall error $\Delta F(\vec{r}, t)$ will be proportional both to the value of the mutual dyssynchrony of the measurements by the magnetometers $\Delta t$ and to the rate $\frac{d}{dt} F_v(t)$ of the field change as a measure of its perturbation, giving $\Delta F(\vec{r}, t) \approx \frac{d}{dt} F_v(t) \cdot \Delta t$.

Evidently, GPS-synchronization of both the stationary and mobile measurements allows reducing the error to zero.

The linearity assumption means that the ratio of the field induction $F_{mi}$, measured by a mobile magnetometer at one point in space, to the field induction $F_{si}$, simultaneously measured by the stationary scalar magnetometer of the observatory, should be constant for all points in space at a fixed time instant $t$.

Using the formula (2) and taking $F_{s0}$ to be constant, one can roughly evaluate the relative error of the time-scaled field induction $F_t$ as

$$\frac{\Delta F_t}{F_t} = \frac{\Delta F_{mt}}{F_{mt}} + \frac{\Delta F_{st}}{F_{st}}. \qquad (4)$$

The first summand $\frac{\Delta F_{mt}}{F_{mt}}$ is the relative error of readings $F_{mt}$ of mobile magnetometer measurements. In our case, it arises mostly from two aspects. The first is the mutual asynchrony of the measurement times of the stationary and the mobile scalar magnetometers. The second is the relative error of measurements of the mobile scalar magnetometer (low accuracy grade magnetometer PMP-8). The operator's reaction time for manual registration of the measurement time can be neglected under geomagnetically calm conditions.

The second summand $\frac{\Delta F_{st}}{F_{st}}$ in the formula (4) is the relative error $F_{st}$ of the stationary scalar magnetometer, including the equipment's accuracy class.

## 3 Results

### 3.1 Measurements in 2015

On the Akademik Vernadsky station, the stationary scalar magnetometer since 2011 has been magnetometer

POS-1 based on the Overhauser effect. As the mobile scalar magnetometer, the proton magnetometer PMP-8 was used. This same magnetometer was always used for standard absolute observations in the observatory.

In 2015, during the 20th Ukrainian Antarctic Expedition, three series of measurements were carried out: in September, October and November.

The perturbation of the geomagnetic field in September — November 2015 gradually decreased, as one can see from the averaged modulus of field change rate $\frac{d}{dt}F(\vec{r}, t)$ (see Table). Thus, the measurements in October and November 2015 were done in favorable geomagnetic conditions. This is why in these series of measurements, the contribution of the error arising from manual time registration can be considered the least.

### 3.2 Measurement error

Rough estimates of measurement error were done using general considerations as outlined in the preceding sections.

In the expression (4), the relative error $\frac{\Delta F_{st}}{F_{st}}$ of the stationary scalar magnetometer was determined both by its technical characteristics (for POS-1 it can be around $\leq 2.5 \cdot 10^{-5}$ (Khomutov, 2017; Denisova et al., 2002)) and the specifics of its installation and exploitation. Due to noticeable POS-1 data noise, minimal filtering (arithmetic averaging or Gaussian filter) was applied.

**Table.** The conditions of measurements of the differences of geomagnetic field between pillars

| № | Month | Measurement between pillars | $\frac{d}{dt}F(\vec{r}, t)$ |
|---|---|---|---|
| 1 | September | LEMI-008 №16, POS-1 | ≤60 pT/sec |
| 2 | October | LEMI-008 №16, Abs. | ≤40 pT/sec |
| 3 | November | LEMI-008 №16, Abs. | ≤15 pT/sec |

Note: Pillar Abs. is the pillar of absolute measurements with the scalar magnetometer PMP-8 used for the regular absolute observations.

At field perturbation of ≤40 pT/sec, typical for measurement series of the mobile scalar magnetometer PMP-8 in October and November 2015, the relative error $\frac{\Delta F_{mt}}{F_{mt}}$ in the expression (4) could not exceed approximately $\sim 5 \cdot 10^{-6}$. Tentatively, the value of the overall relative error of the field differences could have reached $\sim 2 \cdot 10^{-5}$ (that is, about ~1 nT).

### 3.3 Results of measurements

It was known a priori that in the measurement pavilion near the magnetometer pillars, a field gradient can exist not specifically studied before.

While measuring the field induction for the pillars LEMI-008 and POS-1, we followed the layout depicted in Fig. 1. The distances $R_t$ and $R_b$ to the vertical axis were the same, c. ~75 cm. The heights $h_t$ and $h_b$ (above and below the sensor in question, respectively) were also almost the same, c. ~20 cm.

The layout was far simpler for the pillar of the absolute observations since the magnetometer PMP-8 was installed at its fixed position as always during absolute observations. To reduce the error, the measurements were taken from the PMP-8 magnetometer for a certain (~1–1.5 minutes) time. The results of these measurements are shown in Fig. 2.

For convenience, the value 38177.0 nT was chosen as a reference value of the field induction $F_0$ for the time-scaling of all measurements. It should be noted that for this constant, if necessary, you can also take another value, respectively, adjusting the previous results of calculations. This is relevant when comparing the differences over long time intervals (months or years).

It can be seen that measurements of the field differences near the pillar of absolute observations in the conditions of the least perturbation (October 11 and November 23, 2015) showed acceptable stability of results. The plot in Fig. 2 also illustrates the overall errors of converting data obtained from mobile measurements (marked as stars) to time-scaled and time-independent (black circles).

For the pillar of the scalar magnetometer PMP-8 (the pillar of absolute observations), we obtained the value

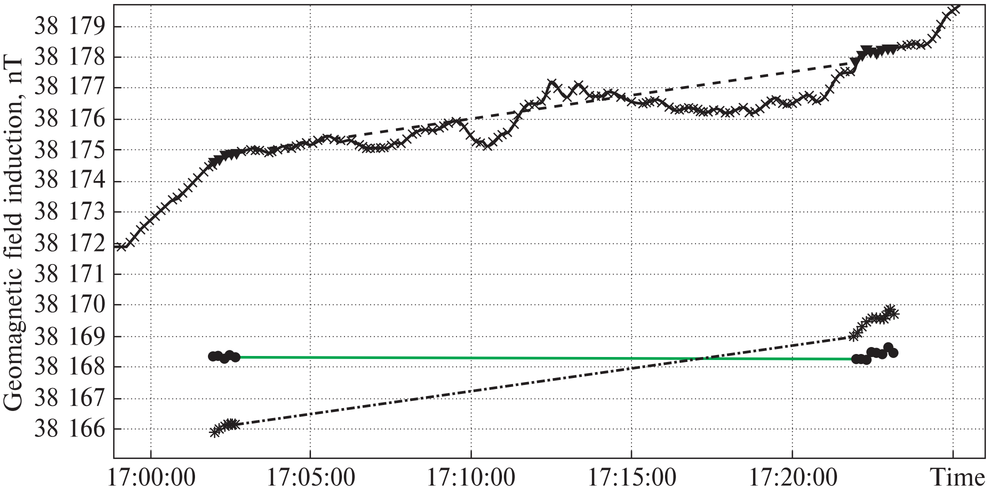

**Figure 2.** The measurements taken on October 11, 2015, around the pillar of absolute observations were done in two series (17 h 02 min 00 s — 17 h 02 min 40 s and 17 h 22 min 00 s — 17 h 23 min 10 s). The data of continuous measurements of the scalar magnetometer POS-1 are marked by "×" on the thin line above. Asterisks on the dash-dotted line indicate the mobile measurement readings. The black circles on the solid bottom line represent the time-scaled field induction. The POS-1 scalar measurement data at the moments of mobile measurements are marked with inverted black triangles on the upper dashed line

of the time-scaled field induction $F_{Abs}$ = 38168.5 nT with the error not above ~0.5 nT (Fig. 2).

For the time-scaled field induction on the pillars holding the sensors of other magnetometers, we obtained results of varying accuracy.

The measurements confirmed the presence of a gradient near the pillars POS-1 and LEMI-008 №16. The value of the time-scaled field induction for the pillar holding the LEMI-008 №16 sensor can be estimated as $F_{LEMI}$ = 38161.0 nT. The errors of calculations were caused by the imprecise positioning of the mobile magnetometer and the flawed manual fixation of time. In addition, at each of the 8 points around the sensor, only one measurement was made. That is, we cannot even use the Student's t-distribution. From this, it follows that we can only conclude about the presence or absence of a gradient. These results indicated the need for careful measurements of the field inhomogeneity around the pillars in the future.

Thus, a rough value of the difference in the field induction between the PMP-8 pillar and the LEMI-008 №16 pillar in 2015 could be estimated as $\Delta_{AbsLEMI} = F_{Abs} - F_{LEMI} = {\sim}8$ nT.

To obtain more precise results, it is necessary to conduct measurements using better equipment (e.g., a gradiometer with GPS-synchronization of mobile measurements). Expanding the dataset can greatly reduce the statistical error of measurements. All obtained data should be appropriately time-scaled.

## 4 Conclusions

The essence of the proposed method lies in the determination of the time-scaled field induction (tied to a fixed time epoch) for every single important point or pillar bearing measuring equipment sensors. The differences in geomagnetic induction between the pillars of the magnetometers are calculated as the differences in the corresponding values of time-scaled field induction.

During the measurements of the differences of the field induction between the magnetometers' pillars in 2015, we were able to obtain results of low precision because we used devices of low accuracy class. The measurements confirmed the presence of the gradient near the pillars of POS-1 and LEMI-008 №16. The method can potentially yield more accurate values of the field induction differences between pillars if the mobile measurements are GPS-synchronized and the mobile scalar magnetometer belongs to a higher accuracy class than PMP-8. In our opinion, continued research could contribute to the necessary objective basis for the treatment of the geomagnetic data of the Akademik Vernadsky observatory.

To employ the method, one needs two datasets of scalar measurements of the geomagnetic field induction tied to the accurate timestamp:

1. A dataset of continuous observatory measurements $F_s$ of the stationary scalar magnetometer, which is a mandatory piece of equipment of a geomagnetic observatory.

2. A dataset of mobile measurements $F_t$ using a mobile scalar magnetometer around the studied point (such as shown in Fig. 1).

The measurements are not required to be simultaneous since linear interpolation can be applied to any given point in time. It is necessary only to precisely synchronize the clocks of both scalar magnetometers since this impacts on the final accuracy of calculations.

When calculating the differences in the field induction between the pillars, it is necessary to indicate the time epoch and the value of the field induction $F_0$, taken as a reference value for time-scaling. At the station, the modulus of the field vector decreases approximately by ~100 nT over the year, which is why all mobile measurements a year or more apart should be time-scaled to the reference value $F_0$.

Measurements according to the described method can be one of the possible ways to implement the recommendations of INTERMAGNET on the need to control possible changes in the magnetic environment of the measuring pavilion of the observatory of the Akademik Vernadsky station.

*Author contributions*. ML: main idea, data analysis, writing of the article. YO: measurements at Akademik Vernadsky station.

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*Conflict of Interest*. The authors declare that they have no conflict of interest.

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## Вимірювання різниці геомагнітної індукції між тумбами магнітометрів геомагнітної обсерваторії Української антарктичної станції «Академік Вернадський»

**Реферат**. Описано особливості вимірювань просторових неоднорідностей поля між тумбами магнітометрів у вимірювальному павільйоні геомагнітної обсерваторії станції «Академік Вернадський» у 2015 році, а також деякі попередні результати цих вимірювань. Введено поняття масштабованої величини індукції геомагнітного поля для компенсації ча́сових змін реальної індукції геомагнітного поля та приведення його до одного опорного рівня індукції. Різниці індукції поля між тумбами отримуються як різниці масштабованих величин індукції геомагнітного поля на тумбах. Методика дозволяє порівнювати багаторічні ряди вимірювань неоднорідностей поля у важливих точках простору. Підвищення точності вимірювань локальних неоднорідностей геомагнітного поля у вимірювальному павільйоні геомагнітної обсерваторії станції «Академік Вернадський» та визначення різниць геомагнітної індукції між тумбами, на яких встановлено датчики магнітометрів, було метою даного дослідження. Отримання числових значень різниць індукції поля між тумбами як об'єктивних критеріїв, необхідних для оцінок точності даних, при кінцевій обробці даних геомагнітної обсерваторії. Використано метод порівняння двох рядів даних, один з яких отримано скалярним магнітометром, установленим в обсерваторії як обов'язковий стаціонарний прилад, а другий — під час вимірювань мобільним магнітометром у потрібних точках простору. Компенсація ча́сових змін геомагнітного поля шляхом масштабування даних вимірювань мобільного магнітометра відносно одного опорного рівня індукції й, отже, таким чином приведення їх до однієї вибраної й зафіксованої ча́сової епохи. Спеціальна геометрична схема мобільних вимірювань у просторі навколо тумб з датчиками магнітометрів або у важливих точках простору. Статистичний аналіз обчислених даних. Груба оцінка похибок методу. На основі аналізу отриманих даних було підтверджено працездатність методу та прийнятну його потенційну точність. Отримано приблизні числові величини різниць індукції геомагнітного поля між тумбами, на яких встановлено датчики магнітометрів. Подальше підвищення точності визначення цих різниць можливе при застосуванні сучасних приладів підвищеного класу точності та при застосуванні GPS-синхронізації мобільних вимірювань.

**Ключові слова**: градієнт геомагнітного поля, компенсація часових змін поля, масштабована індукція поля, підвищення точності вимірювань геомагнітного поля