

Slow variations of the Earth's magnetic field: technical, methodological and organizational features of measurements

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Abstract. Variations of the Earth's magnetic field with times of several years or more reflect the processes within the planet and cause great scientific interest. Over the past 100 years the regular observations at magnetic observatories (MOs) and repeat stations are the only experimental basis for studying such variations. In recent decades, satellite measurements have complemented ground-based measurements, thus partially solving the problems of spatially highly heterogeneous global network of magnetic observatories. Absolute observations are made at MOs to get the total field intensity vector. Until now, these measurements are performed manually, they are labor intensity and subject to many factors, that are often poorly controlled and reduce the reliability of the results, especially over long periods of time (years and decades), including (1) systematic errors of used magnetometers; (2) magnetic pollution of the absolute pavilion and its surroundings (at a distance of the first hundred meters); (3) instability of the pillars and remote target required to determine magnetic declination; (4) changes of observers and their weak qualification. Significant methodological problems arise if MO is moved to new location without special activity or infrastructure of MO (pavilions or pillars) is changed without careful control. For long-term stability and reliability of measurements, magnetic observatories were joined in IAGA network and then INTERMAGNET. Within these networks, requirements and standards have been defined, absolute magnetometers are compared every two years and observers are being trained. Modern hardware technologies allow to solve partially problems the automation of absolute observations, the self-calibration of the magnetometers, the checking of the MO's magnetic environment, etc. Fully automated measurement systems help to expand the MO network.

1 Introduction

The basis for the study of long-term variations of the Earth's magnetic field are absolute magnetic observations at stationary points – at magnetic observatories and repeat stations. In the last century the repeat stations are significantly improved situation with low spatial density of observatories, but observations at the repeat stations were limited to land and areas of accessibility [1–3]. Satellite measurements in recent decades have largely solved the problem

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of spatial heterogeneity in the location of observatories. However, the temporal homogeneity of the satellite data sets is limited by the lifetime of the satellite at orbit, and onboard magnetometers require calibration using groundbase magnetometer data [4, 5].

Thus, in the last century and to now, the quality of information on magnetic field long-term variations is determined by ground-based absolute observations at observatories. The term "absolute observations" means that the elements of the magnetic field are defined in the absolute sense - as elements of the total magnetic intensity vector. Traditionally, special magnetometers are used for such measurements, these measurements are performed in pavilions that are maximally protected from magnetic pollution under the longest possible unchanged magnetic environment [6, 7]. The standard set of instruments usually includes a scalar magnetometer for measuring the total field F and a DIflux magnetometer for measuring the magnetic declination D and inclination I , see Figure 1 [8].

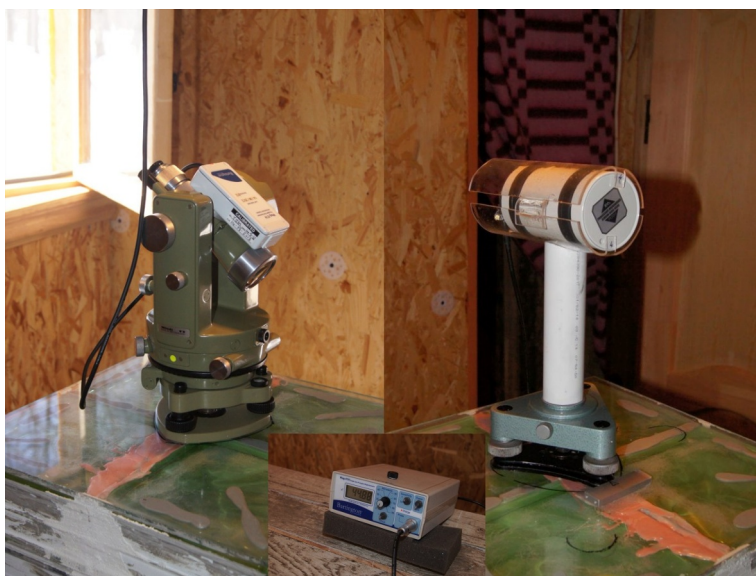


Figure 1. Absolute magnetometers: DIflux Mag-01H (left) with electronics (in frame) and Overhauser scalar magnetometer POS-1 (right) at Geophysical Observatory Paratunka (PET).

2 Errors of the observers

The random errors that observers make during absolute observations such as errors in the readings and timestamps, the mistakes during writing to the observation log or the typing into computer etc., do not have a noticeable impact to long-term variations. When errors are large, they are detected during the processing and analysis of the results, usually in baseline values. If the magnitude of this error is small, the contribution to the final results is also insignificant. It may also be noted that scalar magnetometers are independent of the observer.

The method of measurement using DIflux is more hard and is associated with the active interaction of the observer and the device. A DIflux is a high-precision non-magnetic theodolite with a fluxgate sensor at the telescope. During the measurement, the observer takes readings from the scales of the vertical and horizontal circles. The source of errors here can be two factors:

1) *problems with vision of the observer.* In ordinary life, these problems are solved, for example, by glasses, or ignored. However, during magnetic observations glasses usually can not be used because of their magnetism, so the observer with limited sharpness control of microscopes sees the reference system of theodolite scales is not confident enough;

2) *problems with the quality of reading microscopes of theodolite scales.* Non-magnetic theodolites, which are commonly used in DIFluxes, are often standard theodolites in which magnetic elements are replaced by non-magnetic ones. After this alteration, the quality of many units is reduced, including it can occur with the optical elements of reading devices (microscopes, scales, etc.). Observers even with good eyesight can take readings in different ways, depending on the illumination of the scale, the angle of view, etc.

The above problems can lead to systematic errors in the readings of circle scales - to overestimate or understate of readings. Thus, the error of the vertical circle readings can give an error in the inclination of a few arc seconds and the corresponding errors in the absolute values of the vertical or horizontal component up to 1 nT. At the XVI IAGA Workshop on geomagnetic observatory instruments, data acquisition and processing in Hyderabad in 2014, the main result of the measurement session was the estimation of personal errors of observers. The observers were issued special certificates. The final report of the Workshop shows the errors of observers in declination and inclination (Figure 2). The results of three observers were removed because the deviations exceeded the limit of 3σ (Figure 2, not shown). As can be seen, systematic errors reach 15-20", which at the latitude of Hyderabad gives an error in the horizontal and vertical components up to 3 nT. It is necessary to take into account that absolute observations were made on DIFlux used for comparison, then the obtained results are the summary effect of instrumental and personal errors.

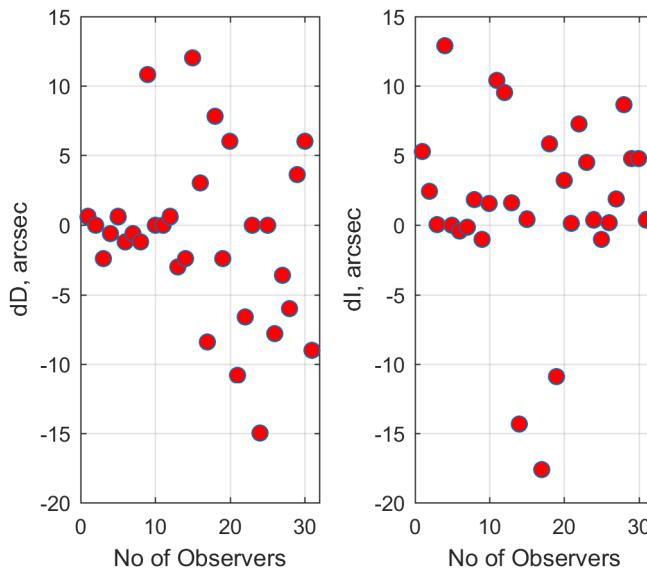


Figure 2. Errors of absolute values of declination **D** and inclination **I** obtained by 31 observers during the intercomparison of magnetometers at the IAGA Workshop in Hyderabad in 2014.

Figure 3 shows the results of absolute observations at the Observatory Paratunka (PET) in 2018-2019 - the baseline values of H_0 and Z_0 of the fluxgate magnetometer FGE-DTU, ob-

tained from observations by five observers using the DIFLUX LEMI-203 (non-magnetic theodolite 3T2KP). Two observers Obs1 and Obs2 clearly show systematic deviations from the average of the other three observers, reaching 1-2 nT for H0. Histograms of deviations H0 and Z0 on the bottom panel also demonstrate the presence of a systematic component in the results: systematic errors Obs1 and Obs2 have different signs, the ratio of deviations H0 and Z0 indicates that this is a result of problems with absolute measurements of inclination I . Special experiments have shown that observers Obs1 and Obs2 get the readings of the vertical circle differently.

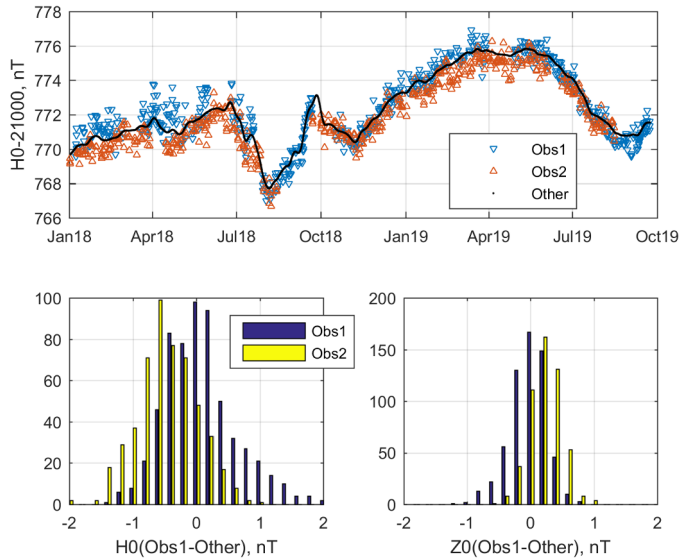


Figure 3. Personal differences of observers according to the results of absolute measurements at the Observatory Paratunka (PET) in 2018-2019. Upper panel — the baseline values of H0 for two observers and the average value for the other three observers (approximation for each hour). Bottom panel: on the left — the distribution of deviations of individual values of H0 of two observers from the system of other observers, on the right—the same for the component Z0.

The above examples are partial, but they show that systematic errors in determining the absolute values of the magnetic field vector due to personal errors of observers can reach several nT. If there is only single observer at the observatory, these errors will remain unknown, and the change of observers can lead to fictitious changes in the results of measurements that are not related to the real variations of the magnetic field. There are cases when observations are made by every observers during week, then there are weekly unreal fluctuations in the baseline values, and hence in the absolute values of the field elements.

3 Absolute magnetometer problems

The problem of systematic instrument errors (accuracy) is well known, it is actively discussed by both developers and users. Within the scope of this report, the main interest is this problem with respect to absolute magnetometers — scalar and DIFLUX. The standard metrological way is calibration of the device with rate determined by the developer/manufacturer,

and obtain a certificate with important parameters, including its systematic errors. Difficulties arise when there are no certified metrological services with appropriate calibration facilities. For example, in Russia, the calibration of scalar magnetometers can be performed in the Laboratory of National Standards in the Field of Magnetic Measurements (VNIIM, <http://www.vniim.ru/lab-magnit.en.html>), however, DIFlux verification is a significant problem. In addition, a significant factor is the cost of such calibration.

Understanding this problem led to that IAGA (and INTERMAGNET) began to hold special workshops every two years, on the basis of existing magnetic observatories with a well-developed infrastructure and having the required hardware. The last such Workshop (XVIII) was held in 2018 at the Conrad Observatory, Vienna, Austria (www.iaga-workshop.org), some proceedings are presented in [9]. As part of the Workshop measurement session, absolute observations are made on DIFlux, which were brought by magnetologists. After processing the results of observations, estimates of the systematic errors of every magnetometers are given. Unfortunately, at the last Workshops the results of such processing are not published. But as an example Figure 4 a presents the results of a intercomparison of nineteen DIFluxes at an earlier XI Workshop-2004 at Kakioka Observatory, Japan (data from [10]).

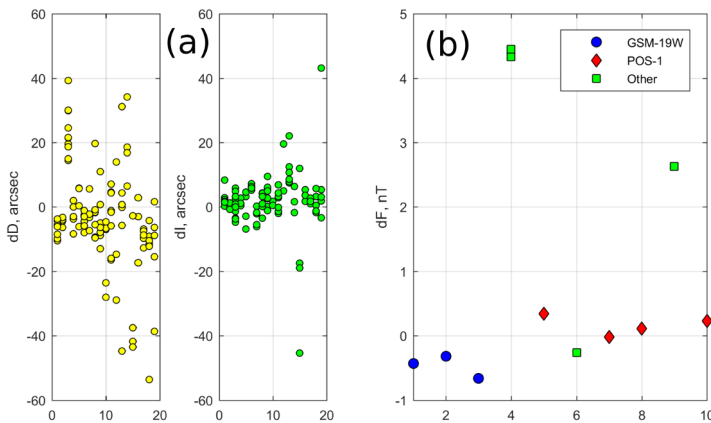


Figure 4. The results of intercomparison of absolute magnetometers. (a) deviations of absolute values of \mathbf{D} and \mathbf{I} of compared DIFluxes from reference DIFlux, Observatory Kakioka, Japan (2004). (b) deviations of total field intensity values \mathbf{F} of compared scalar magnetometers from reference device obtained during intercomparison at Observatory Arti, 2017. Numbers at abscissa are presented conditional number of magnetometer.

It can be seen that in addition to the dispersion of individual values, there are significant systematic deviations in results of individual DIFlux. For example, DIFlux No.03 gives dD up to +20", No.15 - up to -30", DIFluxes No.12 and No.13 have a deviation of dI more than 10" (values of dD and dI with deviations greater than 60" were considered as errors of observations and are not presented at Figure 4a). It should be noted that the observers are an essential part of the DIFlux magnetometer, so the results may also include personal systematic errors of inexperienced or novice observers.

Unlike DIFlux, scalar magnetometers can be calibrated in specialized metrological centers, but their verification is also carried out during measurement session of IAGA Workshop. The relative simplicity of the procedure allows to compare scalar magnetometers in conditions not very close to the perfect. An example would be the intercomparison of scalar instru-

ments at the Geophysical Observatory Arti in 2017 [11]. Three GSM-19W, four POS-1 and single POS-4, Scintrex SM-5 and Geometrix G-859 were presented. The Overhauser magnetometer POS-1 N11 from Laboratory of Quantum magnetometry of UrFU (Yekaterinburg), certified in VNIIM was used as reference. The deviations dF of compared magnetometers from reference device are shown in Figure 4b. As can be seen, Overhauser magnetometers have a systematic error of less than 1 nT, while quantum magnetometers showed deviations up to 3-4 nT.

In general, special metrologically correct calibrations and more simpler intercomparisons show that modern absolute magnetometers, when operating in the normal conditions, provide the determination of the magnetic field elements with an error up to a few nT. These estimates coincide with the requirements of the INTERMAGNET standards for magnetic observatories [8]: "An IMO must try to meet the following recommendations: Definitive Data Accuracy: ± 5 nT" (page 5). At the same time, changes in the parameters of absolute instruments are possible, which can lead to more significant systematic measurement errors. Detection of these changes is possible if the absolute observations at the observatory are performed often enough, there are at least two variometers and their baseline values do not change very quickly. Otherwise, it is quite difficult to distinguish the problems of absolute magnetometers from the problems of variational measurements.

Another element of absolute observations, which can be conditionally attributed to the instruments is a remote azimuthal reference mark (target), which is necessary to determine the magnetic declination. Azimuth of this reference mark should be known, because it is directly used in the calculation of declination from absolute observations. The target should be stable and clearly visible from main pillar in absolute pavilion. In general, it is recommended to install remote mark at the maximal long distance from pillar to minimize the angular errors of possible movements. At distance of about 300 m, perpendicular shift of mark (or pillar) of 1 cm leads to error in azimuth and declination up to 7". In practice, this recommendation is limited to the real conditions around the absolute pavilion (buildings, trees) and visibility of remote mark during bad weather.

In concerning to the accuracy of measuring the slow variations of the magnetic field, two points can be noted: the accuracy and frequency of determination of the reference point azimuth and its stability between these observations. The standard methods of azimuth determination are astronomical observations of the Sun or Polar [12] and currently geodetic GPS measurements [13]. Figure 5 presents the results of the determination of the remote mark azimuth by astronomical observations of the Sun at the Geophysical Observatory Paratunka in 2013-2018. Observations were made using non-magnetic theodolite 3T2KP (Diflux LEMI-203) directly from the main pillar in the absolute pavilion. The remote mark at the Observatory "Paratunka" is a pipe mounted on the wall of a residential 4-storey building at a distance of about 300 m. Simultaneous visibility of the Sun and the mark through the window is available during one week on spring and autumn. Usually observations were carried out during 2-3 consecutive days with 5-10 independent measurements per day.

As seen at Figure 5 the scatter between individual measurements is about 10-15", the scatter between the results in neighbouring days is up to 5-10". This scatter is mainly determined by the bad visibility of the Sun due to trees and air turbulence. The results show that during 6 years the azimuth of the reference mark has no systematic drift, which is important for long-term accuracy of the magnetic declination. Since the azimuth of the remote target also depends on the stability of the pillar for absolute observations, the obtained estimations also indicate that the pillar in the absolute pavilion is stable.

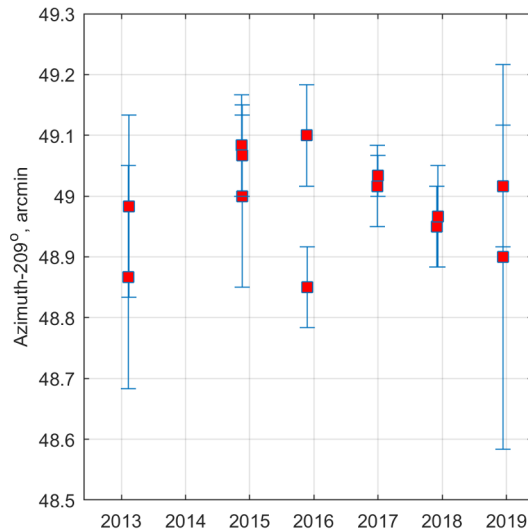


Figure 5. The results of astronomical observations of remote target at Observatory Paratunka. Squares ■ define the mean values of the azimuth, vertical bars are standard deviations for results of the daily measurements.

4 Methodical and organizational problems

One of the main problems of magnetic observatories is the effect of anthropogenic interference on the measurement results. Usually observatories are organized in magnetically quiet places. However, the development of cities and settlements (industry, infrastructure), highways, etc. for decades leads to that the noise level becomes unacceptably high. Moreover, increasing the precision of magnetic measurements makes visible the noise that was previously below the level of sensitivity of the magnetometers. The result is the decision to move the magnetic observatory to a new place.

The moving of the observatory is a very hard event that requires significant financial costs, huge organizational and methodological efforts. The moving can cover a time period of months or more. During this time absolute magnetic observations are performed at the old and new locations, the effects of underlying terrestrial rocks are studied, the stability of pillars, the reliability of the infrastructure, etc. are checked. Observatories with the longest history can be moved to a new location several times. An example is the oldest Observatory in Russia: the modern Observatory "Arti" (Institute of Geophysics UrB RAS) was founded in 1836 in Yekaterinburg, in 1932 due to noise from trams, it was moved with the new place named "Vysokaya Dubrava", in 1969 it was moved to current place "Arti". All these transfers were carried out very carefully, which ensured the continuity of long-term magnetic measurements [14]]. Similar multi- transfers were in the history of the magnetic Observatory "Irkutsk" since 1886 (see [http://en.iszf.irk.ru/Irkutsk_Geomagnetic_Observatory_\(IRT\)](http://en.iszf.irk.ru/Irkutsk_Geomagnetic_Observatory_(IRT))). Changes in the elements of the magnetic field during such transfers can reach hundreds of nT, see Figure 6 (http://www.geomag.bgs.ac.uk/data_service/data/annual_means.shtml).

More frequent events are *the transfer of absolute observations to another pavilion* on the observatory area or the construction of a new pavilion at the old place because old pavilion became useless due to some reasons. Compared with the moving of the observatory to new locations, this process is much easier organizationally and methodically and less costly. Ex-

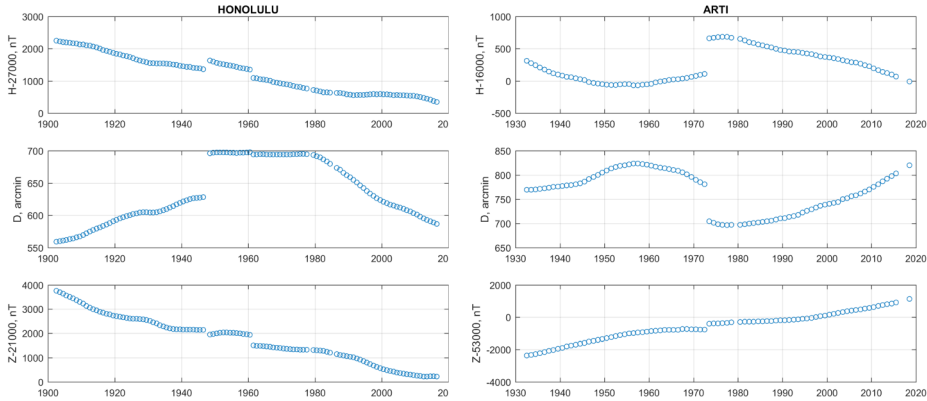


Figure 6. Examples of jumps in yearmean data records at magnetic observatories Honolulu and Arti due to moving to new locations.

pected changes of the magnetic field can reach tens of nT. More simpler procedure is *the transfer of absolute observations to another pillar* in the same pavilion. Usually, the spatial distribution of the magnetic field inside of the absolute pavilion is known and sufficiently uniform, so possible jumps in magnetic measurements are expected to be no more than a few nT.

As an illustration, the yearmean value files prepared by INTERMAGNET observatories in 2017 were considered. The data sets in these files are usually more shorter than those available in the World Data Centers because observatories with a long history are presented only more up-to-date data, often after the IGY. However, in relation to our task, they are quite informative. Total data from 113 observatories were prepared and checked in 2016, including files with yearmean values. 43 of them have information about jumps (marked with a special flag "J"). Table 1 provides summary statistics for different reasons.

Table 1. Variation magnetometers at Observatory Paratunka, 2017

Reason	Moving of Observatory	Change of pavilion	Change of pillar	Change of magnetometer	Methodical	Magnetic pollution	Unknown
Number of jumps	10	10	25	11	14	6	9

Jumps due to the moving of absolute magnetometers given in the table are mainly connected with transition of observatories from old quartz H-magnetometers and declinometers with unknown systematic errors to modern DIFLUX. Methodological errors have a large number of possible reasons. For example, many observatories have ceased to take into account the "historical" reductions introduced in earlier periods and reaching several tens of nT. There are cases of errors in the calculation of the total field elements of the magnetic field, the cases of re-observation of the remote target azimuth and so on. Magnetic pollution is the presence in the absolute pavilion or its surroundings of structural elements, devices, etc., which influ-

enced the magnetic field on the main pillar, were detected and eliminated. The magnitude of the jumps reached a few nT. In nine cases the cause of the jumps was not established, and their value reached several nT.

5 Conclusions

1. There are many factors that can affect the accuracy of annual and/or monthly mean values of the total field vector, presented by magnetic observatories.
2. Many of these reasons cannot be effectively controlled. Meta-information about them is often not available to users.
3. In general, annual and monthly values of magnetic elements can be obtained with accuracy up to a few nT. This is in agreement with INTERMAGNET Manual. If the user needs more confidence in the quality of data, he must check it more carefully.
4. In some cases undetectable errors can be reach tens of nT.

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