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CONSIDERATIONS ABOUT INFRASTRUCTURE, DEVICES AND PHYSICAL PRINCIPLES IN GEOMAGNETIC FIELD METROLOGY

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Abstract. The continuous development of data acquisition and processing techniques in planetary geomagnetic observatories allows at this time to extract as complete information about the morphology and evolution over time of the terrestrial geomagnetic field. In the evolution of the acquisition of geomagnetic data, different physical phenomena were used for the realization of magnetic sensors for both absolute and triaxial variometric measurements. These magnetic sensors communicate through specialized software programs with acquisition systems and process computers. This whole chain together with the underground labs where the sensors are located make up the infrastructure of a geomagnetic observer. The paper describes the physical phenomena underlying the geomagnetic field metrology, the equipment used and the software programs for communication and data transmission. We made a breakdown of equipment and infrastructure at the Surlari National Geomagnetic Observatory (located in an area without magnetic anomalies, about 30 km North of Bucharest), as well as the way we performed the transfer functions of different devices to improve data quality to the standards accepted by IAGA (International Association for Geomagnetism and Aeronomy) and used in all observatories from INTERMAGNET network. The main research objectives are also presented, along with the applicative importance of measurements in the geomagnetic observatories.

Keywords: geomagnetic field, declination, inclination, magnetic sensors, INTERMAGNET network.

Rezumat. Considerații privind infrastructura, dispozitivele și principiile fizice în metrologia câmpului geomagnetic. Dezvoltarea continuă a tehnicilor de achiziție si procesare a datelor în observatoarele geomagnetice planetare permite în acest moment extragerea unor informații cât mai complete despre morfologia și evoluția în timp a câmpului geomagnetic terestru. În evoluția achizițiilor datelor geomagnetice au fost folosite diferite fenomene fizice pentru realizarea de senzori magnetici atât pentru măsurătorile absolute cât și pentru măsurătorile variometrice triaxiale. Acești senzori magnetici comunică prin programe software specializate cu sistemele de achiziție și calculatoarele de proces. Tot acest lanț împreună cu laboratoarele subterane în care sunt amplasați senzorii alcștuiesc infrastructura unui observator geomagnetic. În lucrare sunt descrise fenomenele fizice care stau la baza metrologiei câmpului geomagnetic, aparatura folosită și programele software de comunicare și de transmitere a datelor. Am făcut o detaliere a aparaturii și infrastructurii de la Observatorul Geomagnetic Național Șurlari (situat într-o zonă fără anomalii magnetice, la cca. 30 km nord de București), precum și a modului în care am realizat funcțiile de transfer pentru diferite echipamente pentru îmbunătățirea calității datelor la standardele acceptate de IAGA (Asociația Internațională pentru Geomagnetism și Aeronomie) și utilizate în toate observatoarele afiliate rețelei INTERMAGNET. Sunt prezentate și principalele obiective de cercetare precum și importanța aplicativă a măsurătorilor din observatoarele geomagnetice.

Cuvinte cheie: câmpul geomagnetic, declinație, înclinație, senzori magnetici, rețeaua INTERMAGNET.

INTRODUCTION

The main research and development objectives of a geomagnetic observatory (BENOIT, 2012) are:

– permanent knowledge of the structure and evolution of transitional geomagnetic field during several solar cycles;
– providing highly accurate absolute values of the magnetic field direction and intensity;
– characterization of the planetary and local "magnetic state" by the regular computing of geomagnetic activity indices;
– regular comparison of the base levels of geomagnetic records (national magnetic standards) to other planetary observatories;
– study of various temporal geomagnetic variations with periods in a very wide range in time from seconds to hundreds of years;
– determining the spatial distribution of the geomagnetic field, mainly at national level and integrate these images into continental or planetary maps. These distributions are obtained by repeated measurements in a network of points evenly distributed across the country. Determined values are used to obtain the secular variation of the normal geomagnetic field and building of magnetic maps made in different times;
– contribution to establish periodic coefficients of the IGRF (International Geomagnetic Reference Field) in the IAGA (International Association of Geomagnetism and Aeronomy) with shaping local peculiarities reported in our country.

Important applications are related to the appropriate dimensioning of the energy networks, in communications, aviation transport and oil pipeline transport due to additional induced currents. Other application of measurements of geomagnetic field are in environmental domain in wastewater treatment (ZGAVAROGEA et al., 2016).

Metrological elements of the geomagnetic field at a point on the Earth's surface can be characterized by the following items:

- the horizontal geomagnetic field intensity (H) representing the horizontal projection of the total magnetic field vector;

- the vertical geomagnetic field intensity (Z) denotes the projection onto the downward vertical of the total magnetic field vector with positive value in the northern hemisphere and negative in southern hemisphere;
- the intensity of the geomagnetic field direction N (X) denotes the projection onto the direction of geographic North vector horizontal geomagnetic field intensity;
- the direction of the geomagnetic field intensity E (Y) denotes the projection onto the direction east of the geographical location of the vector horizontal geomagnetic field intensity;
- the declination is the angle between the North geographic direction and North magnetic direction, determining the orientation of the horizontal geomagnetic field;
- the inclination (in degrees) is the angle between the horizontal and total geomagnetic field.

A schematic diagram of the contribution of physical processes to the geomagnetic field is presented in Fig. 1.

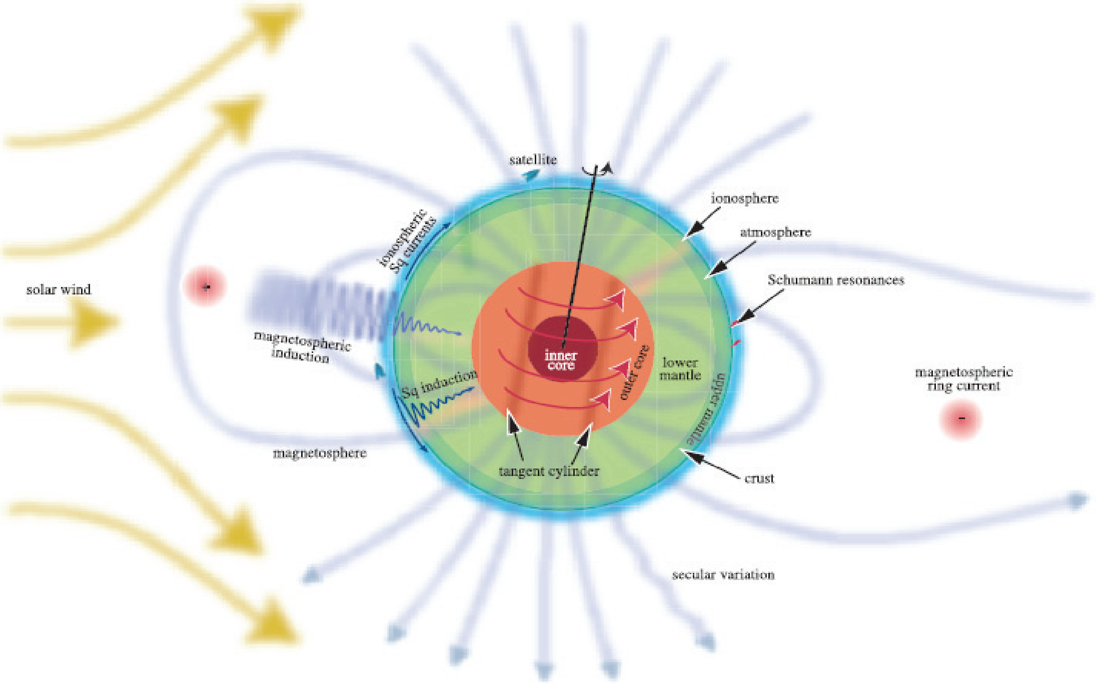


Figure 1. Scheme with the contribution of physical processes to the geomagnetic field (CONSTABLE, 2005).

A schematic representation of the frequency spectrum of the geomagnetic field is shown in Fig. 2.

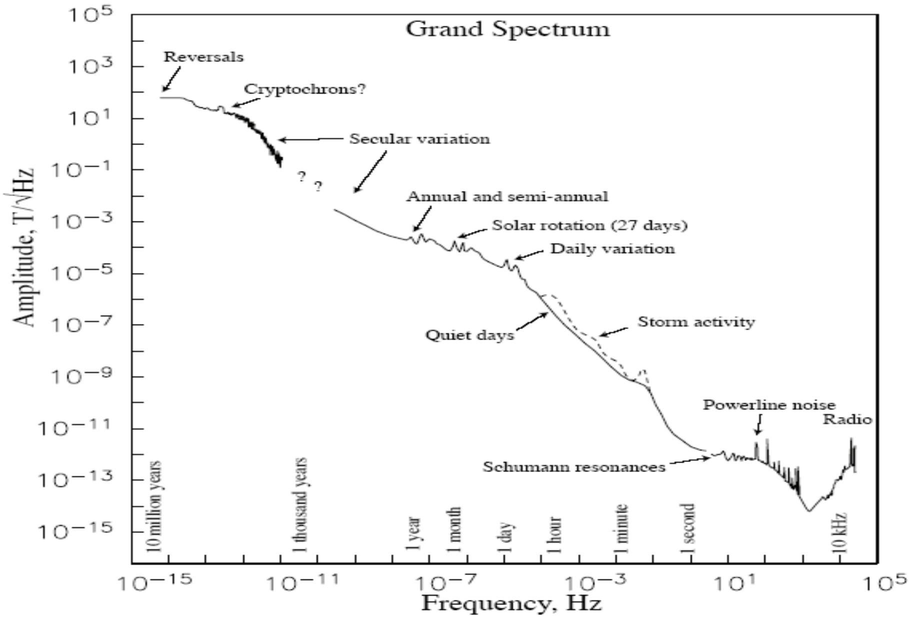


Figure 2. Broad amplitude spectrum for geomagnetic variations
according to frequency and causality (internal or external) (CONSTABLE C.- 2005).

PHENOMENA USED IN GEOMAGNETIC FIELD METROLOGY

More physical phenomena have been used over time for the quantitative determination of the geomagnetic field as absolute values and its variations in space or time, based on traditional measurements of geomagnetism and magnetic prospecting.

The first phenomenon uses the tracking of the position of equilibrium of a permanent magnet under the exclusive action of the geomagnetic field or the action of a torque generated by it and determining the period of oscillation for quantitative assessment of the direction and intensity of the geomagnetic field. The action of the geomagnetic field on a magnet leads to a determined orientation, which coincides with the geomagnetic field orientation only when the magnet is not subject to any foreign constraints.

The magnetization of materials with high susceptibility, i.e. the phenomenon of magnetic induction led to the construction of devices and the development of appropriate measurement techniques has played an important role in the development of geomagnetic metrology, terrestrial and air, and even in measurements made with artificial satellites of Earth. The directional distribution of the magnetic induction represents the cumulative effects through the relative parts of the magnetic sensor by materials, magnetization and amplification of each of these effects. All of these have provided excellent conditions for a highly accurate quantitative determination of the geomagnetic field, in terms of direction and size, in its evolution in time and space distribution (GEBBINS & HERRERO-BERVERA, 2007).

The phenomenon of electromagnetic induction has contributed to the metrological technique. Rotating coils have been used since the first half of the nineteenth century for measuring the intensity of the geomagnetic components, or to track their space orientation. The axis of rotation of the coil must be orthogonal on the field direction and measure the induced current in these conditions, which means the parallelism between the rotation axis and field direction.

Characteristic for the traditional geomagnetic measurements, based on the use of the phenomena mentioned, is the fact that they lead to the knowledge of the geomagnetic field through angles that define its direction and the intensity of its components after certain directions. These parameters vary depending on the location of the observation point on Earth. Reported to a local reference system, defined by the horizontal and the north direction, i.e. to the tri-rectangular axis system oriented in the directions north, east and vertical (downward), the geomagnetic field is determined without ambiguity, if are known three geomagnetic elements: either two angles and the total intensity (or the intensity of a component of it), or two components of the intensity and an angle, or the intensity of three components.

The first way of defining was the first used and is in use today for absolute determinations.

The geomagnetic elements measured in this way are: 1) magnetic declination D, represented by the angle between projection on the horizontal of the field and the north direction, 2) magnetic inclination I, i.e. the angle between the total field direction and its projection on the horizontal plane and 3) horizontal component H, the projection of the total magnetic field F on the horizontal plane.

The second way is used in particular for the geomagnetic observatory records, where the following are tracked: declination changes ΔD, variations of the horizontal and vertical component, ΔH and ΔZ.

Determining the field by the third method (north component (X), east component (Y) and vertical component downward (Z) is performed by means of a device, based on magnetic induction, with the magnetized bars oriented properly.

Two phenomena able to highlight the existence of the geomagnetic field, and to serve, ensuring the required accuracy, for quantitative assessment, began to be taken into account for geomagnetic metrology purposes around 1960. Later on they were effectively introduced and used on a larger scale in the measurements: nuclear precession and optical pumping.

Intra-atomic processes occur in both phenomena, governed by the laws of quantum mechanics.

They were used for indirect measurement of the geomagnetic field intensity, led to the construction of devices and the development of methods of modern geomagnetic metrology, designated through the term of quantum magnetometry.

The case of nuclear precession, by applying an intense auxiliary magnetic field, with about two orders of magnitude stronger than that of the Earth , and with a transversal direction thereon on it, nuclei possessing a magnetic moment of some atoms – hydrogen is currently used in geomagnetic metrology, whose nucleus is an even proton, resulting in the term of proton precession (or resonance), commonly used in this area – are oriented with their magnetic axes by this direction required by the auxiliary field (polarizing field).

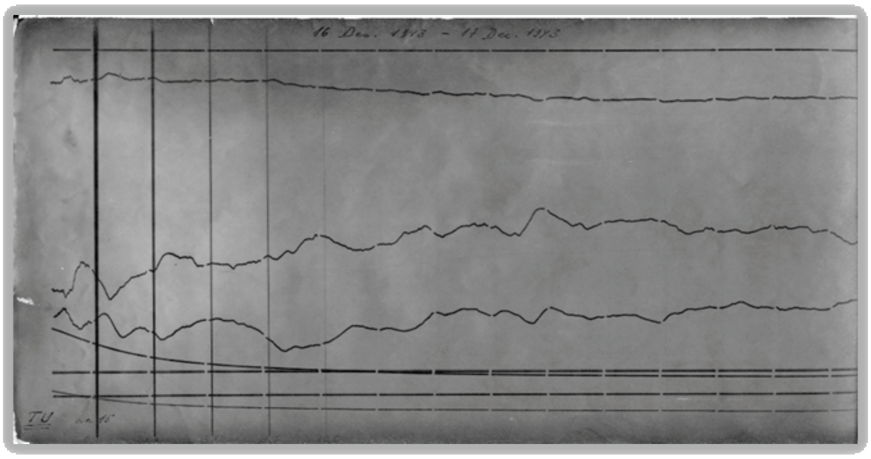
When this field is suppressed, small magnets represented by nuclei with magnetic moment (for hydrogen: protons) remain under the exclusive influence of the geomagnetic field, whose orientation tends to return from the polarization magnetic field direction to that of the geomagnetic field. This takes place through a precession motion, whose frequency is proportional to its intensity. Thus, the knowledge of frequency of precession and the proportionality constant will be determining the total geomagnetic field intensity.

Optical pumping is an excitation process of atoms or ions in an environment through irradiation with electromagnetic radiation. Radiation and intensity spectrum, passing from higher energy levels on lower level, result in a population inversion between two energy levels. The Zeeman effect indirect method, because of the very low magnitude of the geomagnetic field, cannot be used directly to determine its intensity by measuring the "splitting" of spectral lines emitted by the atoms subjected to his influence. The redistribution of electrons between two levels can be achieved by excitation with radiation of lower frequency corresponding to the energy difference between them.

In both these determinations, through proton precession or optical pumping, frequency is directly measured - a measure that requires complicated electronic devices but can be made with great precision - and resulting in a total geomagnetic field value.

THE GEOMAGNETIC EQUIPMENT USED IN THE SURLARI OBSERVATORY

An analog recording system for the D, H and Z components of geomagnetic field was installed at the Surlari geomagnetic Observatory in 1943. This system is composed of a counterbalanced clockwork mechanism and 3 wire-twisting magnetometers. This mechanism ensures that the photographic paper advances speeds of 20, 60 and 120 mm/h. The magnetometers consist of permanent magnets attached to non-magnetic material provided with mirror and snap at the end of the quartz wire (for sensors D and H). The Z component sensor consists of a permanent magnet located on two quartz slides which allow vertical movement. The whole mechanism is enclosed in a box so as not to be disturbed by possible air currents produced in the room. The temporary resolution in continuous shooting mode (speed 20 mm / h) obtained with this device is 3 minutes (1mm). The first daily magnetogram recorded in this format is shown in Fig. 3.



Maximum recording limit of the analog system

The field in Vertical direction

The field in North direction

The field in East direction

Parameters related to functionality of the analog recording system on thermosensitive paper.

Figure 3. First magnetogram recorded at Surlari Geomagnetic Observatory.
Registered physical parameters are explained in the column on the right side of the figure).

In addition to this system, an analog recording system consists of 3 Bobrov variometers and a clockwork mechanism Matting Weissenberg were brought to our observatory in 1959. Unlike Askania variometers, the Bobrov variometers have better stability in time, a reduced sensitivity to temperature changes and are less sensitive to shocks. The clockwork mechanism has four gears: 20, 60, 120, 240 mm / h which is used for the permanent records that of 20mm / h. In 1972 a fourth variometer is attached to this system,whose magnet is oriented in the total magnetic field vector plane.

An important operation in the functioning of these magnetometers is the calibration for establishing the sensitivity of each component records (nT/mm). This is done by means of DC powered coils placed in the directions perpendicular to the axis sensors. The DC power has a known intensity. The two systems have operated continuously until 2003, producing analogue records on photographic paper.

It is also very important to obtain a base level of records with absolute measurements made with theodolite Matting Weissenberg, ground inductor and oscillations box in a first phase and then theodolite Matting Weissenberg and quartz horizontal magnetometer for the H component QHM. In addition to these device, a Varian proton precession magnetometer was brought in 1968, measuring the scalar value of the total field.

The triaxial magnetometer MAG-03MC allows simultaneous recording of the components Hx (North direction), Hy (on the East) and Hz (vertical direction down) of the geomagnetic field. The sensors of this magnetometer are magnetic inductive type and are made of coils with a large number of turns and a magnetic core with high permeability (Permalloy).

The characteristic response (floor type) of this magnetic sensor shows a very good functionality for a band of frequencies between 1Hz and 2000 Hz.

The MAG 03 DAM logger has two connectors for analog input signal from two flux gate magnetometers and a RS-232 connector with 25 pins for output signal. The logger is controlled by software developed in FORTRAN that allows selecting the number of channels to be recorded (from 1-6), the choice of sampling rate (between one second and 10 seconds) and the measuring range. The sampling rate refers to the frequency of purchase and not the storage, it is 10 times lower.

MAG-01h DI Fluxgate Magnetometer produced by Bartington Instruments Ltd., England, with THEO 010b nonmagnetic theodolite, measuring declination and inclination of the geomagnetic field in absolute terms. These measurements are used to establish the base level of permanent records.

Measurements with DI Fluxgate are run at regular intervals, especially during periods of magnetic calm, and are national magnetic standards for the geomagnetic mapping work of the national territory. With their help, the magnetometers of other research or industrial companies are calibrated. The MAG-01h DI Fluxgate is recommended by the International Association of Geomagnetism and Aeronomy (IAGA) for use in observatories and to achieve precision of 0.1 nT for magnetic field values and ± 1 seconds for declination and inclination.

This type of magnetometer can be used mounted on a Wild T1 theodolite nonmagnetic. It can measure both declination and inclination of the geomagnetic field with an accuracy of ± one second sexagesimal degree.

Typically, this device works with the zero method (when the magnetic sensor is positioned perfectly horizontal) and the declination of the magnetic field can be determined. When placed in a perpendicular plane to the horizontal component of geomagnetic field, the inclination of the magnetic field can be determined. Also, when the sensor is placed in a vertical plane, perpendicular to the horizontal geomagnetic field, the total field gradient can be determined.

Geometrics G-856 proton precession magnetometers are used for absolute measurements of total magnetic field. They have a very good thermal stability and resolution consistent with the standards of IAGA. Data can be stored in the internal memory of electronic units or by connecting it to a computer. G-856 can be used in differential version using two sensors, mounted on a particular tripod to obtain geomagnetic field variation with distance.

In early 2009 a new system was installed at OGNS for the continuous recording of variation of the magnetic field (Hx, Hy, Hz and F) with the support of German Research Centre for Geosciences (GFZ).

The acquisition system consists of:

- triaxial fluxgate magnetometer FGE;
- scalar Overhauser proton magnetometer GEM Systems GSM90;
- MAGDALOG data logger;

The FGE vector magnetometer was built by the Danish Meteorological Institute using three commercial fluxgate sensors, mounted in a block of marble 12x12x12cm^3 through the quartz tube. Offset coils ensure maximum stability or drift to 3 nT / year. The variation with temperature of recorded values due sensors is below 0.2 nT/°C and of the electronics, as 0.1 nT /°C.

For a good stability of the baseline, a suspended version of the cube of marble was adopted in most of geomagnetic observatories. In this way the baseline drift is less than 3.2 nT / year, the result obtained even where one classical fluxgate would have a drift over 100 nT / year. The alignment error of the three vector components is maximum 2mrad (7 min of arc.). And the shaft suspensions error is +/-0.5°. Sensitivity: 400 nT / V.

GSM90 Overhauser proton magnetometer is a scalar magnetometer designed for magnetic observatories and other applications (Volcanology), where stability and accuracy are absolutely necessary. With a resolution of 0.01 nT, 0.2 nT absolute accuracy and drift of 0.05 nT / year can be successfully used in calculating basic values for a magnetic observatory. With a resolution of 0.01 nT, an absolute accuracy of 0.2 nT and drift of 0.05 nT / year can be successfully used in calculating baseline values for a magnetic observatory.

The torsion photoelectric magnetometer PSM

The magnetometer is composed of a set of 3 torsion variometers. The variometers are connected to an electronic system based on the principle of compensation (feedback). The compensation current is proportional to the intensity of the geomagnetic field to be compensated by current injected in coils located on the variometer. The resolution of these variometers is 0.1 nT and the variation with temperature is below 0.01nT/°C. This magnetometer is connected to the Bartington MAG 03-DAM data logger. The technical specifications of the logger are presented above.

An alternative solution recommended by specialists of the Institute of Geophysics Polish Academy and Belsk Observatory is the multifunction logger NDL (Network Data Logger), that meets four very important functions:

- perform AD conversion on 24-bit, 6 channels, with variable sampling step;
- ensure universal time synchronization through GPS;
- store information on Compact Flash Card;
- provide direct connection to the Internet with a speed of 10 Mb / s through a specialized processor.

We compared different magnetometers within Surlari National Geomagnetic Observatory (SNGO). Differences between the results lead to interesting conclusions regarding the strengths and weak points of each magnetometer (ASIMOPOLOS L.et.al. - 2010, 2012a, 2012b).. By using different calibration methods, further exemplified, we obtained the transfer functions for the recorded values with each magnetometer. For each device we make a calibration and we calculate transfer functions. For example we show PSM transfer function (Hx channel) in correspondence with MAG03MC, transfer functions for geomagnetic components (Hx, Hy, Hz) for PSM magnetometer in correspondence with FGE magnetometer (Figs. 4-6) and correlation between PSM and FGE (Fig.7).

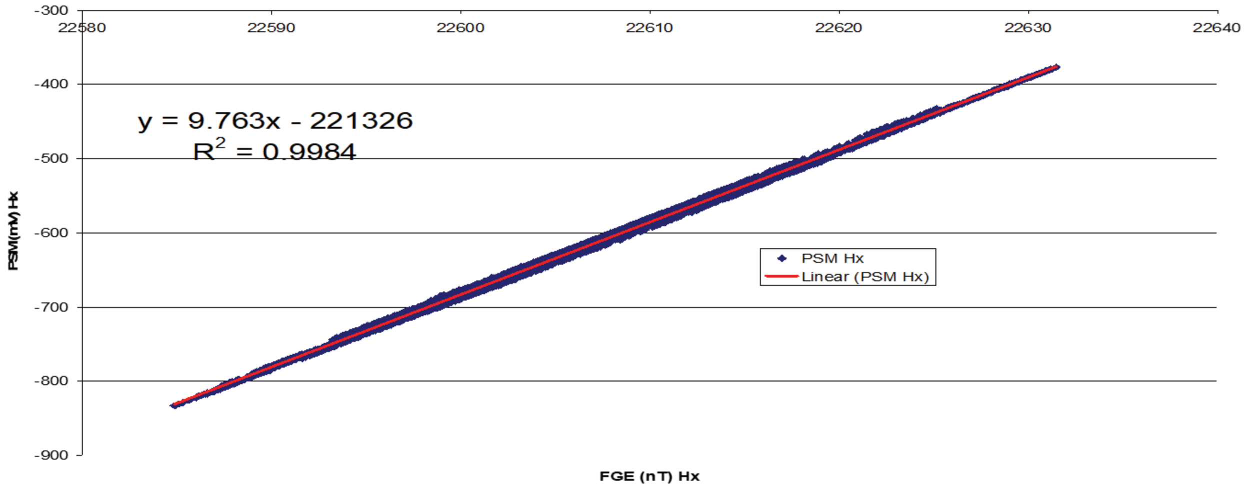


Figure 4. Transfer function for Hx (North geomagnetic component) (mV to nT);
PSM magnetic sensor and MAG03DAM logger.

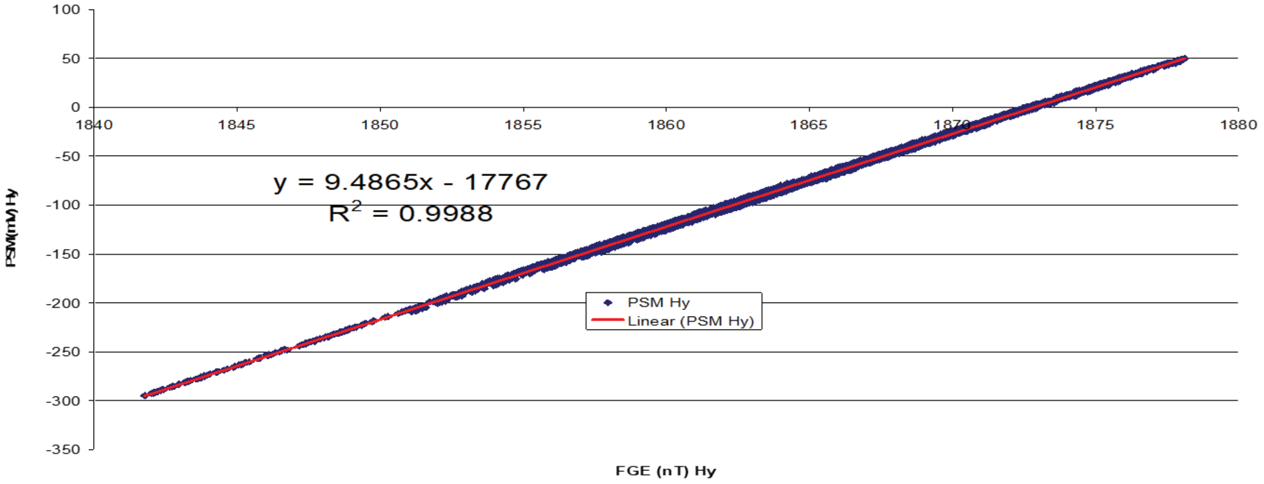


Figure 5. Transfer function for Hy (East geomagnetic component) (mV to nT);
PSM magnetic sensor and MAG03DAM logger.

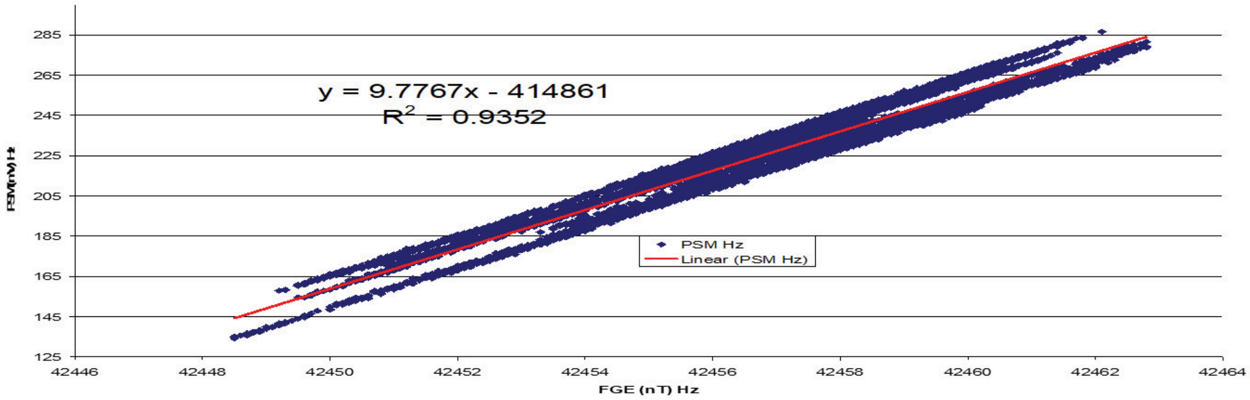


Figure 6. Transfer function for Hz (Vertical geomagnetic component (mV to nT);
PSM magnetic sensor and MAG03DAM logger.

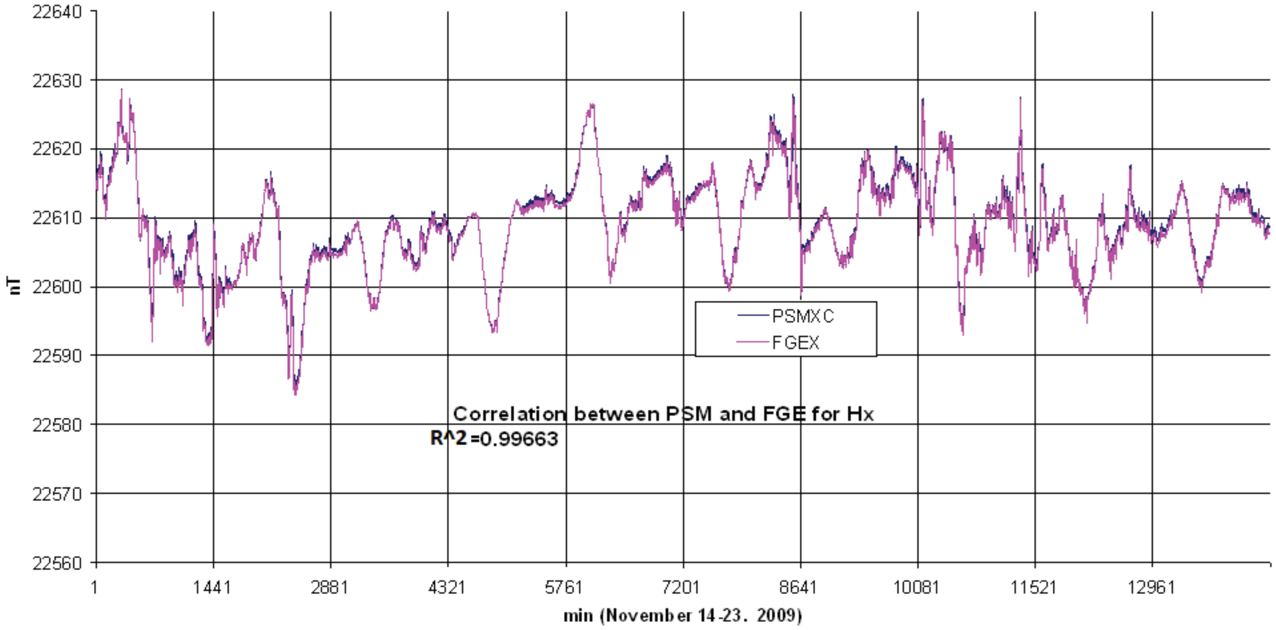


Figure 7. Correlation between Hx (North geomagnetic component) acquired with the PSM sensor, after applying the transfer function (PSMXC), and the FGE sensor (FGEX).

The differences between the two curves obtained after calibration are very small (maximum 0.5 nT) so they seem overlapped. The curve in blue colour is only visible in some points, while only the red curve can be seen otherwise.

This effect occurs because the red curve is in the front plane and the blue curve is in the back plane.

The calibration operation involves following steps:

- recording a time series of values with a non-calibrated magnetometer;
- introduction of a calibration pulse whose parameters are known (the value of current intensity introduced (mA) and instrumental characteristics of each component measured (nT / mA);
- calculating the pulse amplitude calibration;
- scale transformation of values from pixels recorded to the nT by comparing each registered value with the calculated calibration factor.

CONCLUSIONS

The observation of the geomagnetic field variation over time represents the basic activity of geomagnetic observatories and aims at collecting the necessary data for the elaboration of models and theories on the internal/external mechanisms about variation of the magnetic field. The geomagnetic field variation study provides information on the Earth's internal conductivity, their knowledge being also useful in magnetic prospecting works whose results need to be processed to extract the effects of diurnal variations, the value of the normal field at the date and location of the prospecting, and of secular variation when using panels measured in different epochs.

An important application of observer data is the determination of the magnetic declination (the angle between the geographic and magnetic north) used for the correction of navigational instruments on board aircraft during landing and take-off maneuvers, for GPS guidance systems used in civil aviation, and military, satellite trajectories, missiles and missiles, etc.

This parameter can be estimated with good accuracy for magnetically calm days. For agitated days, and even more so during magnetic storms, the variation of the declination parameter becomes significant. A geomagnetic storm is known to have different characteristics (amplitudes, gradient, geomagnetic coefficients) depending on the latitude at which it is measured. Thus, at the beginning of a geomagnetic storm, the data from the closest to ground (geomagnetic observation points) is needed on-line for the corrections of the guidance systems.

Another important application is related to the appropriate dimensioning of energy networks (transformers, transport cables, etc.), depending on the underground conductivity of the respective area, the local geomagnetic pattern as well as the on-line geomagnetic data on which certain energy protection systems can be coupled or decoupled during geomagnetic storms of varying degrees.

It is very important to calculate the additional currents induced in large pipelines used for the transport of petroleum products during geomagnetic storms to determine the necessary stresses to be applied to different segments of anticorrosive conduit.

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