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Automation of Absolute Measurement of the Geomagnetic Field

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In this paper a device is presented to measure the geomagnetic field vector absolutely and automatically. In contrast to the standard DI-Flux measurement procedure our automation approach is based on the rotation of a three -component fluxgate magnetometer about precisely monitored axes without using a non-magnetic theodolite. This method is particularly suitable for automation because it only requires exact knowledge of the axes orientations. Apart from this, requirements on mechanical precision are moderate. The design of the facility is presented, and mechanical, optical and magnetic limitations are discussed. First promising results of measuring the Earth's magnetic field absolutely and automatically with the new device at Niemegk observatory are discussed.

Key words: Automation of absolute measurement, Geomagnetic field

1. Introduction

A network of about 170 geomagnetic observatories worldwide is continuously monitoring the geomagnetic field. This network, however, has significant gaps in remote and inhospitable areas and over the oceans. This is mainly due to the fact that it is not possible to operate a fully automated observatory, for the reasons outlined below.

The absolute vector data of the Earth's magnetic field have to be recorded continuously with a time resolution of one minute or less at a geomagnetic observatory (Jankowski and Sucksdorff, 1996). The measurements currently are divided into two parts: continuous relative variation recordings and distinct absolute measurements for calibration of these recordings. Field variations are continuously measured and digitally recorded, commonly by three-component fluxgate magnetometers (Aschenbrenner and Goubau, 1936) or magnetometers based on sensors which measure field components by a scalar sensor equipped with coil systems. Examples are proton vector magnetometer (Serson, 1962) or vector magnetometer using optical pumped magnetometers (Stuart, 1972). The elements of the geomagnetic field vector are recorded in instrument related coordinate systems. Variometers are subject to drifts arising both within the instrument (e.g. temperature effects) and the stability of the instrument mounting. Such measurements cannot be considered as absolute: Absolute measurements have to provide magnetic field data in terms of absolute physical basic units or universal physical constants and in a geographical reference frame. All systematic instrument errors have to be eliminated by the measurement procedure. This was achieved first by measurement of the horizontal intensity by Gauss (Kertz, 1992) and later on by sophisticated types of non magnetic theodolites (Fanselau, 1960). Today, the absolute measurements for calibration are generally done by the DI-flux method (Kring Lauridsen, 1985). A single axis fluxgate magnetometer mounted on a non-magnetic theodolite is used to measure the direction of the geomagnetic field in a reference system given by the vertical and one azimuthal direction. The field magnitude is measured by a proton magnetometer. Modern DI-flux measurements still have to be carried out manually. The method requires well trained personnel and one measurement takes about 30 min. Absolute measurements are typically performed on a weekly basis.

Current quality standards for geomagnetic observatory data ask for an accuracy better than ± 5 nT, including a long-term stability of variation recordings better than 5 nT/yr (St.-Louis, 2004). An accuracy of 1 nT can be achieved for absolute measurements by well-trained observatory staff. This corresponds to an angle error of 4 arcsec perpendicular to a total force of 50,000 nT, which we regard as design goal for any new instrument.

Fully automated observatories, which do not require manual operation of any instruments, are necessary to fill the gaps in the global network in remote areas, where access and presence of trained personnel are a problem. Here, we present a device which can perform discrete absolute measurements automatically and thus may replace the DI-flux theodolite in geomagnetic observatories. This does not remedy the need for separate variation and absolute measurements, but all the data can be recorded automatically and transferred to another location for processing. Attempts to automate a DI-theodolite (van Loo and Rasson, 2006) and a proton vector magnetometer (Auster et al., 2006) for discrete absolute measurements are pursued by other groups. Our approach is based on the method of rotating a three-axis fluxgate magnetometer about a defined axis, in order to determine the field component along that axis (Auster and Auster, 2003). The method, outlined in section 2, has been tested with a manually operated prototype instrument for the past two years at the Niemegk observatory (Pulz et al, 2004). In section 3 we

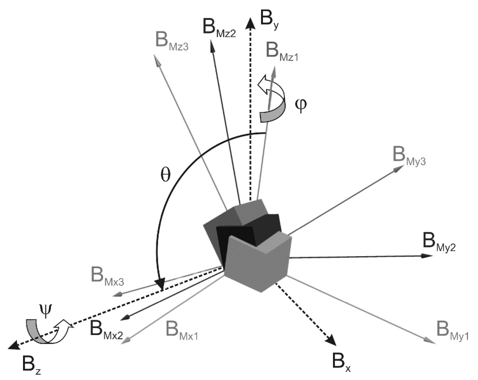

Fig. 1. Two coordinate systems are considered, the magnetometer system B_M and the reference system B_{axis} which are related by Euler transformation about the angles $(\varphi, \vartheta, \psi)$ with the following set of rotations: first, the magnetometer is rotated about its $B_{Mz} - axis$ until B_{Mx} becomes identical with the node line of the $B_{axis,x}$-$B_{axis,y}$ and B_{Mx}-B_{My} planes, next about this node line until B_{Mz} coincides with $B_{axis,z}$ and finally about $B_{axis,z}$ until the two coordinate systems overlap.

describe the solutions we found for automation of the manual operation steps. Data processing results from the first test runs as well as some error discussion are given in section 4 and 5.

2. *Absolute Measurement Method*

We take advantage of a new method to determine the absolute magnetic field components by using a three-axis fluxgate magnetometer which is turned about a well-defined axis (here: the Z-axis of a geographic reference system $(B_{axis,x}, B_{axis,y}, B_{axis,z})$). The magnetic field components in the magnetometer system (B_{Mx}, B_{My}, B_{Mz}) are related to a geographic reference system by an Euler transformation (cf. figure 1):

$$\begin{bmatrix} \cos\varphi\cos\psi - \sin\varphi\sin\psi\cos\vartheta & \sin\varphi\cos\psi + \cos\varphi\sin\psi\cos\vartheta & \sin\psi\sin\vartheta \\ -\cos\varphi\sin\psi - \sin\varphi\cos\psi\cos\vartheta & -\sin\varphi\sin\psi + \cos\varphi\cos\psi\cos\vartheta & \cos\psi\sin\vartheta \\ \sin\varphi\sin\vartheta & -\cos\varphi\sin\vartheta & \cos\vartheta \end{bmatrix}$$

$$\times \begin{pmatrix} B_{Mx} \\ B_{My} \\ B_{Mz} \end{pmatrix} = \begin{pmatrix} B_{axis,x} \\ B_{axis,y} \\ B_{axis,z} \end{pmatrix} \qquad (1)$$

If $(B_{Mxi}, B_{Myi}, B_{Mzi})$ are recorded at three different positions ($i = 1, 2, 3$, $\varphi = \varphi_0 = const$, $\vartheta = \vartheta_0 = const$, $\psi = \psi_i$) during one rotation, the field strength along the rotation axis can be calculated using the following equation:

$$B_{axis,z} \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} = \underbrace{\begin{bmatrix} B_{Mx1} & B_{My1} & B_{Mz1} \\ B_{Mx2} & B_{My2} & B_{Mz2} \\ B_{Mx3} & B_{My3} & B_{Mz3} \end{bmatrix}}_{\mathbf{B_m}} \cdot \underbrace{\begin{pmatrix} \sin\varphi\sin\vartheta \\ -\cos\varphi\sin\vartheta \\ \cos\vartheta \end{pmatrix}}_{\vec{n}(\varphi,\vartheta)} \qquad (2)$$

(for further mathematical derivation cf. Auster and Auster 2003). Due to the fact that $\vec{n}(\vartheta, \varphi)$ is a unit vector, equation 2 can be resolved by inverting the matrix $\mathbf{B_m}$ and calculating the modulus. Thus, the field magnitude in direction of the rotation axis becomes independent of the sensor orientation and can be expressed by:

$$|B_{axis,z}| = \left\| \mathbf{B_m^{-1}} \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} \right\|^{-1}$$

$$\begin{aligned} \det(\mathbf{B_m}) \times [(&B_{Mx1}(B_{My3} - B_{My2}) + B_{Mx2}(B_{My1} - B_{My3}) \\ &+ B_{Mx3}(B_{My2} - B_{My1}))^2 \\ &+ (B_{Mx1}(B_{Mz3} - B_{Mz2}) + B_{Mx2}(B_{Mz1} - B_{Mz3}) \\ &+ B_{Mx3}(B_{Mz2} - B_{Mz1}))^2 \\ &+ (B_{My1}(B_{Mz3} - B_{Mz2}) + B_{My2}(B_{Mz1} - B_{Mz3}) \\ &+ B_{My3}(B_{Mz2} - B_{Mz1}))^2]^{-\frac{1}{2}} \end{aligned} \qquad (3)$$

Although all angles fall out while calculating $B_{axis,z}$, it is still possible to determine φ, ϑ and ψ approximately in order to use them for a later variation reduction. If measurements are done for two orientations of the rotation axis and if additional scalar absolute intensity data are given, the field vector can be determined completely. Systematic errors have to be eliminated during the measurement to make the measurement absolute. A scalar calibration of the fluxgate magnetometer is obtained by comparison of proton magnetometer readings with the field magnitude derived from measurements of the fluxgate magnetometer at various orientations with respect to the Earth field vector. To increase the diversity of sensor orientations with respect to the geomagnetic field for calibration purposes and to increase the redundancy of measurements, the procedure should be repeated after a 90° rotation of the sensor perpendicular to the measurement axis (later called sensor orientation I & II).

An automation of this method is promising because the precision requirements of mechanical operations are low compared to those of the DI-flux method. The rotation of the sensor can be done with arbitrary angles because the field determination along the rotation axes is independent of the sensor orientation. Only the directions of the two rotation axes have to be determined precisely in order to allow for an accurate transformation of the data into a geographical reference frame. In the following section we describe in detail the steps of automation.

3. *Automation of the instrument*

The previous, manually operated system is shown in Figure 2. The three-component magnetometer is situated in a rotatable basket. Four bearing blocks, in which the basket can be rotated, define the two measurement directions. The bearing blocks have to be levelled by means of a level tube, and one set of bearing block have to be aligned to the azimuth mark using a telescope before measurements can be taken. Here, the error of the level tube is averaged out by interchanging its ends, and the misalignment between optical axis of telescope and direction given by the bearing blocks is compensated by turning the telescope inside the bearing blocks. The absolute measurement itself is performed by rotating the basket in both sets of bearing blocks. Magnetometer readings are taken at various rotation angles. At the same time the total field is measured by a scalar magnetometer. The orientation of the three-axes fluxgate sensor inside the basket can be altered for calibration of the measurements by unfastening, turning and fastening of the sensor. With data

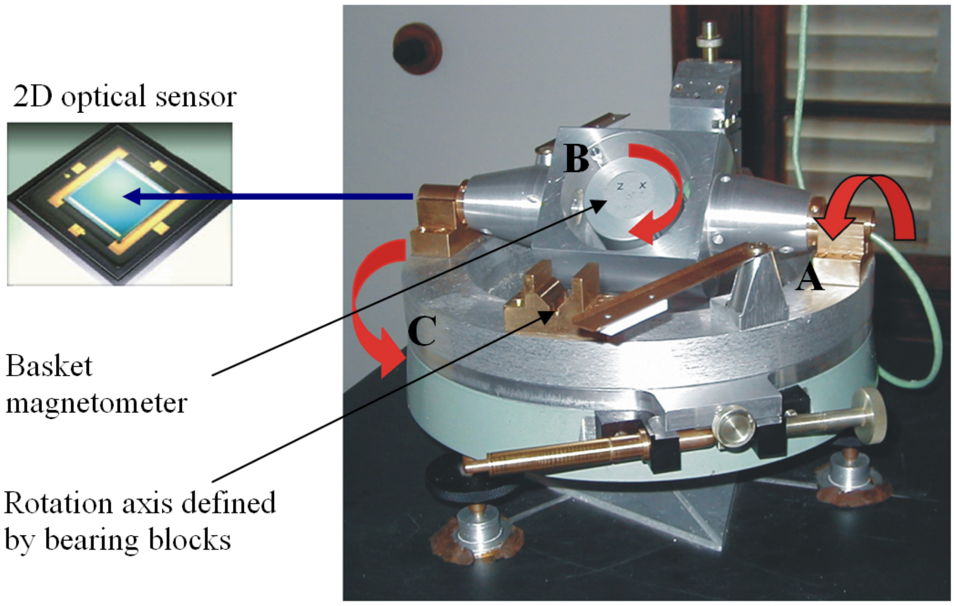

Fig. 2. Instrument, which has been operated manually in Niemegk over more than two years. The red arrows indicate the three rotations which are necessary to perform the absolute measurement. The blue arrow symbolizes the measurement axis which has to be determined by an optical system with a precision of 4 arcsec.

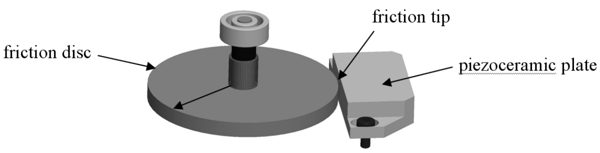

Fig. 3. Piezo ceramic drive unit: The friction tip drives the friction bar, shaped as a disc of radius 20 mm

from all the different orientations, the magnetometer can be fully calibrated and the magnetic field in direction of both rotation axes can be calculated.
To automate the measurement, all the manually operated steps have to be performed by motors, as there are

1) the rotation around the measurement axis (axis A), that should contain 360°forward and backward with six measurement stops in each direction;

2) the turning of the sensor inside the basket (rotation around axis B), where the rotation angle should be around 90°, but does not have to be very precise;

3) the change of orientation of the measurement axis (rotation around axis C), where the rotation angle should also be in the order of 90°and does not have to be very well known;

Moreover, the orientation of the measurement axis with respect to the horizontal plane and a geographic reference frame shall be measured by a laser-optical system.
All the automated movements have to be achieved without influencing the geomagnetic field. This can be done by non-magnetic motors or by transmission of forces from distant drive units. The only non-magnetic motor solutions we found are based on piezoelectric actuators. The heart of a piezoelectric actuator is a piezoceramic plate, which is excited in a high frequency resonant eigenmode. A friction tip affixed to the plate follows a linear path. It acts upon a friction bar which is attached to the moving part. All necessary elements like piezoceramics, friction tip and friction bar are available from non-magnetic material. Unfortunately, the maximum push/pull force of the commercially available piezo motors is with 1 N low. To maintain a proper distance between friction tip and friction bar the friction bar was designed as disc made of ceramics (see Figure 3). The disc has a radius of 20 mm which leads us to a piezo motor torque of 0.02 Nm.
The torque can be increased by a gear mechanism or if necessary torques have to be transmitted by pneumatic or hydraulic solutions. To select the appropriate drive unit and gear for each rotation an estimate of necessary drive moments has been made. The detailed constructions of the three types of rotation are described in the appendix.

3.1 Determination of measurement axis versus reference system

The orientation of the measurement axes in horizontal and vertical has to be known exactly to transform the measured data from the instrument coordinate system into the geographic coordinate system. This can be achieved by a laser beam and optical sensors mounted to known azimuth marks. The laser beam has to be installed inside the rotating basket to determine the direction of the measurement axis (see Figure 2). We investigated a distantly placed laser coupled in by fiber optics as well as a laser diode placed directly inside the basket. Both options work well. If the laser diode

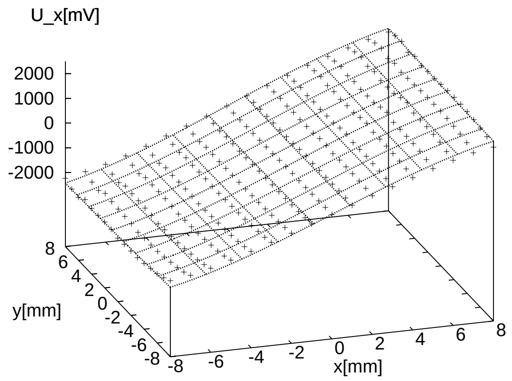

Fig. 4. Measurement results for a typical PSD sensor. The non-linearity of the relation between spot position and output voltage has been determined and modeled. Crosses are the measurement results, the grid represents the result of a polynomial fit

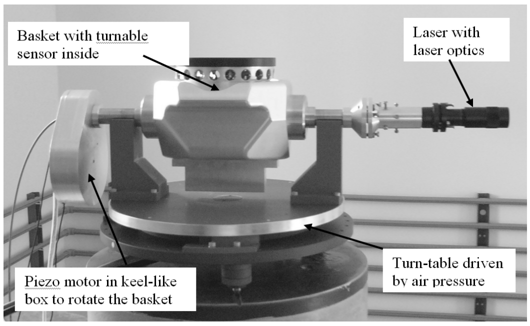

Fig. 5. The automatic absolute instrument with basket, basket magnetometer and laser optics on the turn-table.

is placed inside the basket it has to be accommodated in a distance of more than 100 mm from the fluxgate sensor to bring the influence of the remaining magnetic field below a 0.1 nT threshold. Independently of the kind of source it has to be equipped with an optics which focuses the laser beam at the position of the optical sensor. Several 2D optical sensors have been tested for applicability. The dimensions of the optical array should be as large as possible, the data processing simple and the costs reasonable. Finally, PSD (Position Sensing Detector) sensors with a sensitive area of 20 mm $\times$ 20 mm were selected. The measurement axis of the instrument now only has to be oriented within an accuracy given by the dimensions of the optical sensor. The analogue output voltages U_x, U_y of the sensor are proportional to the position X, Y of a light spot on the detector active area. Linearity errors (see Figure 4) are measured and corrected. To keep the laser spot within the measured and modelled PSD range of 16 mm $\times$ 16 mm we accept a displacement of 10 mm for the adjustment of measurement axis and a deviation of the laser axis from the rotation axis which results in a circle diameter of also 10 mm. This corresponds to a maximum misalignment error of 2 arcmin in a PSD distance of less than 20 m. Note again that this is the only alignment requirement we have on all three mechanical manipulations.

The geographical reference system, given by the PSD mounting, has to guarantee the full accuracy of 4 arcsec (0.4 mm in a distance of 20 m). Both tilting and expansion in vertical direction have to be avoided. With a pillar of two meters height and a temperature gradient of 10°C $\pm$ 20° C per year for central Europe we need a pillar material with a linear expansion coefficient of 1ppm/° C. Fused silica rollers with an thermal expansion coefficient of 0.5 - 0.9 ppm/°C are selected for the PSD mounting.

4. *Setup and data processing*

4.1 Setup of an automated observatory

The first automated system was installed in the absolute house of the Geomagnetic Observatory Niemegk, Germany. The system consists of the turn-table with basket, basket magnetometer and laser optics (see Figure 5) and two PSDs in a distance of 11 and 17 m (Figure 6). PSD I is mounted on a silica roller grounded in concrete outside the absolute house, PSD II is mounted inside the absolute house. For defining the direction towards the azimuth marks, the instrument is replaced by a theodolite. The identical positioning of the instrument and the theodolite are well defined by heading nutches in the pillar. After levelling of the instrument, an inital rotation fixes the horizontal reference on the PSD. This procedure can be repeated for verification of azimuth mark stiffness. As mentioned before, a proton magnetometer is necessary for calibration and to provide the third vector component. The automatic instrument performs discrete measurements, so this setup has to be complemented by a fluxgate variometer continuously recording the field variations. All instruments have separate control electronics, and a GPS receiver for the exact time signal completes the setup. To avoid interferences between the single elements, each of them was checked for its magnetic properties. Sources of self-generated magnetic fields are the polarization field of the proton magnetometer, the feedback field of the fluxgate magnetometers and remanent fields of electronics and mechanical parts. The dashed circles in the setup drawing (Figure 6) indicate the necessary clearance to guarantee disturbances of less than 0.2 nT.

The measurements start at each full hour. First, all three rotation parts are brought in their initial positions (measurement axis toward PSD I, sensor in position I, basket orientation horizontal). To avoid mechanical end stops and to compensate for unequal backwards and forwards velocity of the piezo motor, the sensor and basket rotation are controlled by the magnetic field vector measured by the basket magnetometer. Mean magnetic main field components for the location can be used for orientation control because a rough adjustment is sufficient. The basket is rotated in 60° steps forward and backward in each of the four combinations, PSD I & II, sensor orientation I & II. At every stop position measurements are taken for all three basket magnetometer components and the analogue voltages of the PSD outputs are digitized. The raw data from all 24 values per direction together with simultaneous readings from the additional variometer and proton magnetometer are the basis for the following data processing.

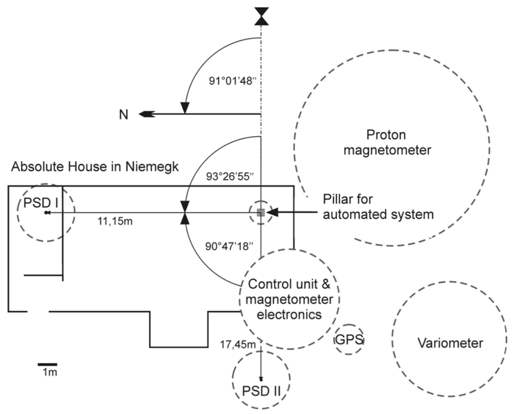

Fig. 6. Setup of all components of the automated observatory in and around the absolute house in Niemegk, circles mark the necessary distances around each component to avoid interferences and disturbances.

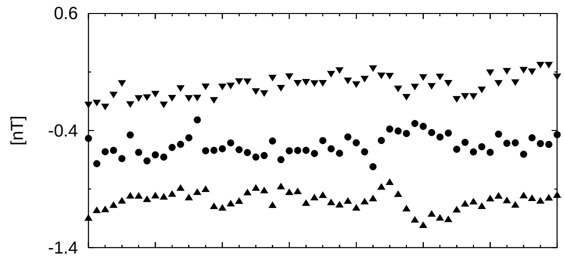

Fig. 7. Remaining output at zero field, the so-called offset of the basket magnetometer determined by scalar calibration at each absolute measurement.

4.2 Variation reduction

An absolute measurement with the automated system takes up to half an hour, similar to the DI-Flux procedure. Consequently, field variations during this period cannot be neglected and all individual data have to be reduced to the same time, e.g. the beginning of the measurement. To transform the variometer measurements into the coordinate system of the basket magnetometer, its orientation has to be recovered by the magnetic field measurements inside the basket. In a first step we rotate the variometer data into a coordinate system which is defined by the rotation axis ($B_{axis,z}$) and the vertical axis ($B_{axis,x}$). Field variations (typically less than 50 nT/30 min) are small compared to the Earth's main field. Therefore, the nominal orientation of the variometer and the orientation of the rotation axes with respect to the Earth's field is sufficient to determine the basket orientation. Reassembling equation 2 we can express the angles ϑ and φ by:

$$\vartheta = \arccos\Big\{-\frac{B_{axis,z}}{\det(\mathbf{B_m})}\cdot(B_{Mx1}(B_{My3}-B_{My2})+ +B_{Mx2}(B_{My1}-B_{My3})+B_{Mx3}(B_{My2}-B_{My1}))\Big\} \quad (4)$$

$$\varphi = \arcsin\Big\{-\frac{B_{axis,z}}{\sin\vartheta\ \det(\mathbf{B_M})}\cdot(B_{My1}(B_{Mz3}-B_{Mz2})+ +B_{My2}(B_{Mz1}-B_{Mz3})+B_{My3}(B_{Mz2}-B_{Mz1}))\Big\} \quad (5)$$

Finally, each rotation angle ψ_i can be determined by:

$$\psi_i = \arccos\Big\{B_{axis,x}(B_{Mxi}\cos\varphi+B_{Myi}\sin\varphi))+ +B_{axis,y}(B_{Myi}\cos\vartheta\cos\varphi-B_{Mxi}\cos\vartheta\sin\varphi+B_{Mzi}\sin\vartheta) \big(B_{Myi}\cos\vartheta\cos\varphi-B_{Mxi}\cos\vartheta\sin\varphi+B_{Mzi}\sin\vartheta)^2+ +(B_{Mxi}\cos\varphi+B_{Myi}\sin\varphi)^2\big)^{-1}\Big\} \quad (6)$$

After transformation of the field variations into the axis system this has to be rotated into the basket system using the angles determined by equation 4-6. The field measured by the basket magnetometer can now be reduced by variation values and the calculation of the field in axis direction by equation 3 can be repeated.

4.3 Calibration of the basket magnetometer

The next step of data processing is the calibration of the basket magnetometer. Assuming a linear transfer function between field and magnetometer output, the rotation of the sensor about two magnetometer axes is sufficient to perform a scalar calibration (Auster et al., 2002). The field magnitude on top of the pillar is known from absolute proton magnetometer readings reduced by the previously determined, constant field difference between location of the proton magnetometer sensor and measurement pillar. Thus we can fit each of the magnitudes derived by the basket magnetometer to the true scalar field value. Nine parameters (offset, scale factor and nonorthogonality in each of the three fluxgate-components) are determined. Measurement results show that the three angles of non-orthogonality are constant within the measurement accuracy of 10^{-5}. The scale values depend strongly on the thermal expansion coefficient of copper (about 20ppm/°C). Both results are in accordance with the properties we expect from a vector compensated fluxgate sensor which was designed for a large temperature range, especially for space applications. The offset behavior is plotted in Figure 7. The standard deviation of all 60 calibration results, which gives us a hint about the total accuracy of the calibration, is in the order of 0.1 nT. This is much better than the accuracy goal of 1 nT.

4.4 Transformation to geographic reference frame

Finally, the direction of the measurement axis has to be determined. The crosses in Figure 8 represent the typical output from the laser beam position (x_i, y_i) on the PSD. The axis direction (x_0, y_0) is determined by the center of a circle fitted to the measurement values. The error J is estimated by

$$J = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(d_i-r)^2} \quad (7)$$

$$d_i = \sqrt{(x_i-x_{center})^2+(y_i-y_{center})^2} \quad (8)$$

$$r = \frac{\sum_{i=1}^{N} d_i}{n} \quad (9)$$

In a distance of 11m (PSD I) a typical displacement error is about 0.05mm. This corresponds to an angle error of 1arcsec which is also clearly less than the design goal of 4arcsec.

5. *First results and error estimates*

The instrument was operated automatically at the Niemegk observatory and results were compared to the standard observatory data. Figure 9 shows the comparison for one day. Automatic absolute measurements were taken once

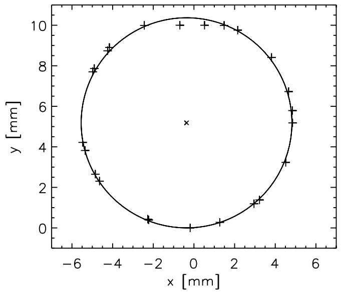

Fig. 8. Laser beam position on the PSD at each measurement of the basket magnetometer (crosses). The measurement axis orientation is determined by fitting a circle to the readings. The center [$x = -0.36$, $y = 5.18$] indicates the axis direction, the radius specifies the misalignment between rotation axis and axis of the laser beam.

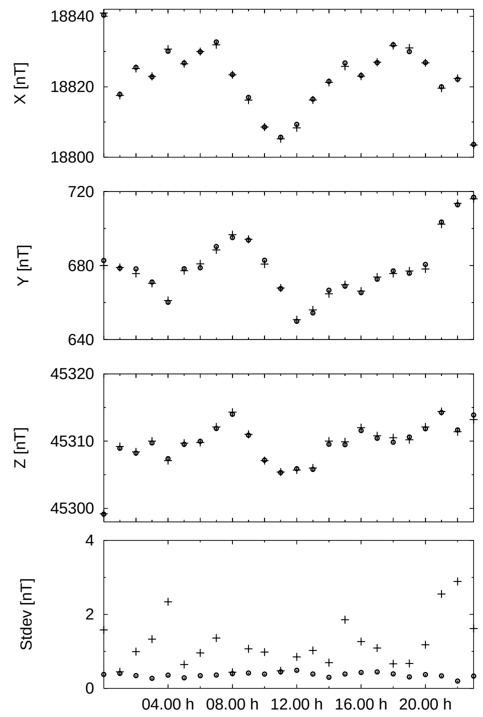

Fig. 9. Upper three panels: X, Y and Z component measured by the automated system (crosses) and values of Niemegk observatory data (circles) Bottom panel: standard deviation of redundant measurements before (crosses) and after (circles) variation reduction

an hour. The agreement for all three components is very good. The differences do not exceed 2.5 nT and result in a standard deviation of 0.5 nT in X, 1.5 nT in Y and 0.3 nT in Z for the whole day (24 measurements). The repeat accuracy in the vertical can be considered as more or less stable and is better than in the horizontal. Here, the rotation axis is switched twice at each measurement and its determination is deeply based on the PSD readings. Thus, the standard deviation for Z is lower than in the other components. Error estimates can alternatively be obtained from the redundancy in the automatic absolute measurement procedure. We have 24 measurement values in both axis directions, respectively, but only three are needed to calculate the field in axis direction (see equation 3). Consequently, we get eight independent results for each axis. The final value for the field component is derived by averaging of those eight results. The standard deviation of these values before variation reduction gives us an estimate about the field variations during the measurement. After variation reduction the standard deviation provides an uncertainty estimate on the final result, which includes all the sources of error mentioned in the previous section except for the final orientation. The comparison of standard deviation before and after variation correction is shown in Fig. 9. Apparently, the uncertainty of the results is independent of magnetic activity during the measurement, at least for the recorded period and only lies in the order of 0.4 nT. Based on our experience with the predecessing, manually operated instrument, we can assume the accuracy is truly independent of magnetic activity also over the long term.

6. *Summary and Outlook*

We have presented a device to perform automatically the absolute measurements for calibration of the variation recordings at geomagnetic observatories. The instrument is based on the method of rotating a three-axis fluxgate sensor around an axis to determine the field component in direction of that axis. The automatic instrument was developed from a manually operated device, which had been successfully tested at Niemegk geomagnetic observatory for more than two years. First results and error estimations show that the automated system can provide data well within the accuracy requirements for geomagnetic observatories, and comparable to carefully performed DI-Flux measurements. The standard deviation of the difference between the measurements with the automated system and the Niemegk observatory data is less than 1.5 nT in each component.

The automation of absolute measurements has several advantages:

1) Fully automated observatories can be set up at remote locations, where frequent access or the presence of trained personnel can be problematic.

2) The quality of the measurements becomes independent of the qualification of the personnel.

3) Absolute measurements can be performed more frequently, relaxing the requirements on stability of variometers.

So far, our prototype instrument has been operating fully automatically for short time intervals only. The next step will be to prove the instrument's robustness for unattended long term measurements. We are currently working on some improvements to overcome a few potential problems for long-term operation, which we noted during the test runs. Then the instrument will be operated in Geomagnetic Observatory Niemegk continuously.

Up to now, the prototype is adapted to the existing local conditions to the absolute house in Niemegk. For a new automated observatory in a remote region, the whole system including the azimuth marks could be situated underneath the surface, and power requirements could be lowered, so that all components could operate with battery supply only.

The current instrument design is suitable for use at mid

and high latitudes, but not for low latitudes, because the measurement axes should be not parallel to the total force. A future task will be to develop a re-designed version of the device for use at low latitudes.
The fully automated absolute instrument remedies the need for manual operation of a DI-Flux theodolite at geomagnetic observatories. Thus, it paves the way towards fully automated observatories, which are needed to fill gaps in remote areas of the global geomagnetic observatory network.

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Appendix

In all figures concerning the design of the three rotations (figures 10 – 13), normal forces are labelled with (n), forces in rotation direction with (r).

Rotation about the measurement axis (Rotation A)

The torque to rotate the basket depends on the friction of the bearing and the unbalance of the basket with respect to its rotation

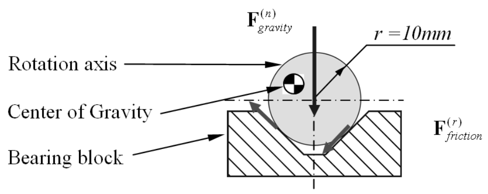

Fig. 10. Bearing of basket. The following forces and moments have to be considered: $F^{(n)}_{gravity} = 100$ N, $F^{(r)}_{friction} = 0.1 \cdot F^{(n)}_{gravity}$, $M_{friction} = F^{(nr)}_{friction} \cdot r$, $M_{unbalance} \leq M_{friction}$

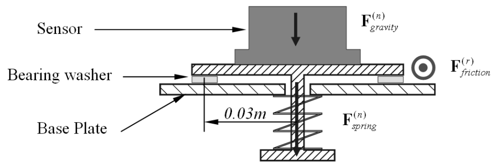

Fig. 11. Bearing of sensor: The friction force determined by friction coefficient μ and the normal forces

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axis. No lock mechanism is necessary because the position after rotation has to be stable only for the sampling time of a fluxgate magnetometer reading. The stiffness of the basket must be high, therefore the mass is in the order of 10 kg. On the other side the radius of the axis is 0.01 m only and materials with low friction coefficient (about 0.1) are selected for axis and bearing blocks. The gravity force of the unbalance can be minimized by balance weights in a way that friction is higher than the unbalance at any point. This corresponds with a displacement of the center of gravity of less than 1mm. The necessary torque M_B to rotate the basket can be calculated by:

$$M_B \geq \ 2 \cdot 0.1 \cdot 100 \,\mathrm{N} \cdot 0.01 \,\mathrm{m} = 0.2 \,\mathrm{Nm} \qquad (10)$$

The required torque is ten times higher than the torque provided by the piezo motor. Therefore, a gear mechanism is necessary. Considering gear loss and aging of friction properties a gear reduction of 40 was realized for the basket rotation. To decouple the basket rotation mechanically from the turn table an additional weight of 500 g is turned by the piezo motor around the rotation axis of the basket. The weight is accommodated in a distance of 70 mm perpendicular to the rotation axis. The torque of 0.35 Nm is high enough (see equation 10) to keep the unbalanced weight of motor and gear permanently on the bottom side like a ship's keel (see Figure 5). In this way the angular position of the basket can be controlled by rotating the keel versus the rotation axis.

Rotation of the sensor inside the basket (Rotation B)

The sensor accommodation is shown in Figure 11.
The sensor is pressed against a base plate by a spring. To rotate the sensor the friction between surface materials (aluminum) and washer (reinforced plastics) has to be overcome. The torque is given as the product of friction coefficient μ (in this case about 0.33), the normal force and the radius of the friction bearing ($r_{b,B}$). To guarantee a stable sensor accommodation at arbitrary sensor orientation, the spring force has to be much higher than the gravity force. Assuming a safety factor of 4, a sensor mass of 200 g and the worst case assumption that the normal force is the sum of gravity and spring force, the torque MS of the drive unit can be estimated as follow:

$$M_S \geq F^{(r)}_{friction} \cdot r = 0.33 \cdot (2 \,\mathrm{N} + 8 \,\mathrm{N}) \cdot 0.03 \,\mathrm{m} = 0.1 \,\mathrm{Nm} \quad (11)$$

To perform this rotation by a second piezo motor, a gear reduction of 20 is necessary to overcome the required torque.

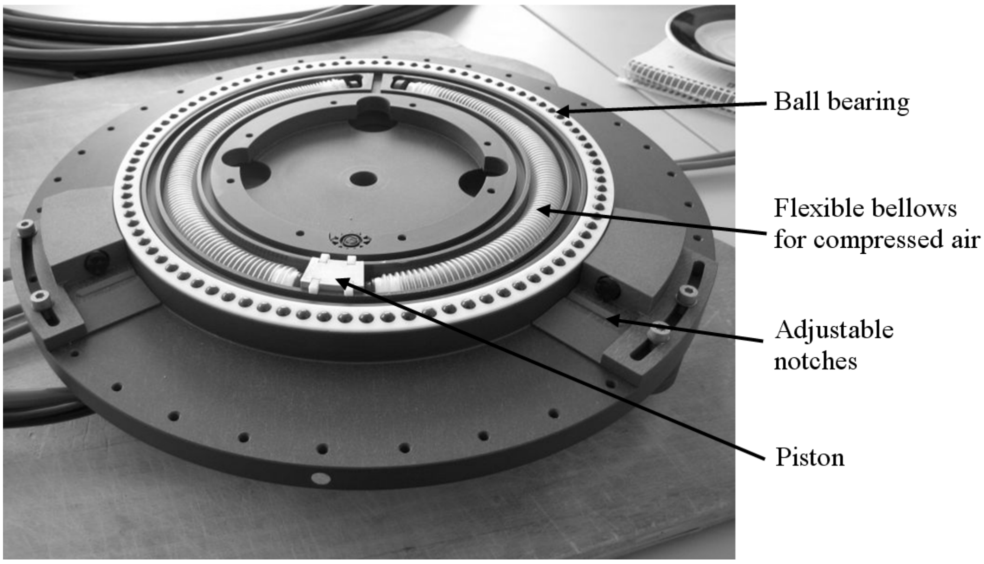

Fig. 12. Steady part of the turn table. The piston is moved by switching compressed air alternating into the left or right tube. The rotatable part is pushed by the piston into its end positions defined by the notches.

Change of orientation of the measurement axis (Rotation C)

Turning the whole system into a second measurement direction and back requires a rotation around axis C in Fig.1. Therefore, the system is placed on a turn-table. Although the requirement on absolute accuracy of the adjustment of the measurement axes is relaxed by the measurement range of the optical system (see next section), the requirement on stability during one measurement sequence is extremely high. It corresponds to an accuracy of an absolute measurement which is in the order of 4 arcsec. For a table with a lock mechanism on the outer radius of r_l of 200 mm this corresponds to a stability of 4 μm. Consequently the table has to be firmly locked in well defined end positions to keep the measurement axis steady during the rotation of sensor and basket. This is achieved by locking the rotating part of the table by means of a ball of a diameter of 5 mm, which is pressed in a notch of the steady part of the table by a vertically mounted spring (see Figure 13). Both, the force to rotate the table and the force to bring the system into and out of the locking mechanism have to be considered for estimating the necessary drive torque. Using a bearing based on silicon nitride balls (radius of bearing $r_{b,C}$= 164 mm, friction coefficient μ=0.02) the friction force of the 15 kg rotating part could be reduced to 3 N. The lock force has to be significantly higher, and therefore a safety factor of 4 has been considered. Assuming a friction free lock mechanism and a ramp angle of 45° the necessary spring force has to be equal to the lock force. The torque M_T which is necessary to bring the turn table in the other end position can be estimated as follow:

$$M_T \geq F_{lock}^{(r)} \cdot r_l + F_{friction}^{(r)} \cdot r_{b,C} \cong 3 \text{ Nm} \qquad (12)$$

Due to the high torque requirements of the turn-table we investigated pneumatic and hydraulic solutions for this rotation. Our current solution, based on a pneumatic drive unit, is shown in Figure 12. The force depends on effective area A and air pressure P. With a bellows diameter of 12 mm the torque for a pressure of 2 bar can be calculated as follows:

$$M_T = P \cdot A \cdot r = 2 \text{ bar} \cdot 113 \text{ mm}^2 \cdot 0.164 \text{ m} = 3.71 \text{ Nm} \quad (13)$$

This is more than required to overcome friction and locking as calculated in equation 13. Furthermore, a damping mechanism was added to limit the angular velocity and to avoid bouncing due to too much kinetic energy in the system.

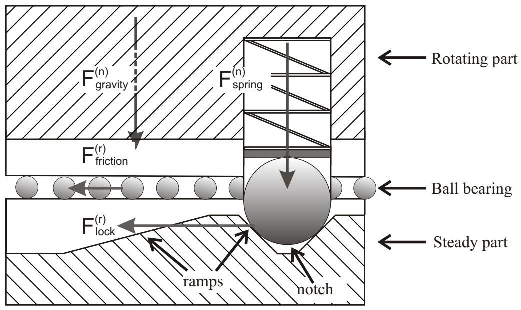

Fig. 13. Mechanism to lock the rotating part of the turn-table in the two measurement directions, respectively, by means of a ball that is pressed into a notch by a spring. The friction force can be derived by the mass of the table and friction coefficient of the bearing $F^{(r)}_{friction} = 0.02 \cdot F^{(n)}_{gravity}$. The spring force which is equal to the lock force has to be significantly higher than the friction force $F^{(n)}_{spring} = F^{(r)}_{lock} \geq 4 \cdot F^{(n)}_{friction}$.

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