PUBLS. INST. GEOPHYS. POL. ACAD. SC., C-99 (398), 2007

GAUSS: Geomagnetic Automated System

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Abstract

During the XIIth IAGA workshop on geomagnetic observatory instruments in Belsk we presented an instrument measuring the geomagnetic field automatically and absolutely, which was developed by Technical University Braunschweig and GeoForschungsZentrum Potsdam. This paper deals with the instrument basics, the design of the prototype and the measurement results obtained in Belsk. The method 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 qualified for automation because it only requires exact knowledge of the axes orientations. Apart from this, requirements on mechanical precision are moderate.

1. Introduction

Fully automated geomagnetic 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 2007, this volume) and a proton vector magnetometer (Auster *et al*. 2007, this volume) 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 2 years at the Niemegk observatory (Pulz *et al*. 2004). In section 3 we describe the solutions we found for automation of the manual operation steps. Setup in Belsk, steps of data processing as well as measurement results obtained during the workshop are given in Sections 4 and 5.

2. Basics of Applied Method of Absolute Measurement

We take advantage of a new method to determine the absolute magnetic field components by using a three axis fluxgate magnetometer which is turned around a well-defined axis (see Fig. 1). If measurements are taken at three positions the field strength in the direction of the axis can be calculated by Eq. (1).

$$B_{axis\_z}\begin{pmatrix}1\\1\\1\end{pmatrix} = \begin{bmatrix} B_{mx1} & B_{my1} & B_{mz1} \\ B_{mx2} & B_{my2} & B_{mz2} \\ B_{mx3} & B_{my3} & B_{mz3} \end{bmatrix} \begin{pmatrix}\sin(\varphi)\sin(\upsilon)\\ \cos(\varphi)\sin(\upsilon)\\ \cos(\upsilon)\end{pmatrix} = \mathbf{M}_m\, \mathbf{n}(\varphi,\upsilon)\,. \qquad (1)$$

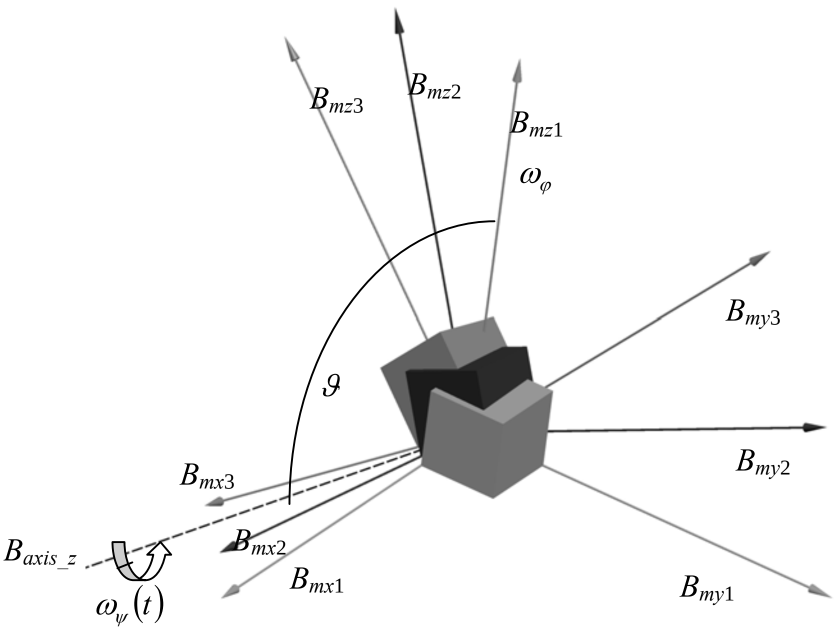

Fig. 1. We have to consider two coordinate systems, the magnetometer system B_m and the reference system B_{axis} which are related by Euler transformation about the angles (φ, ϑ, ψ). If the arbitrarily oriented three axes (x, y, z) fluxgate magnetometer is rotated by three angles ψ_1, ψ_2, ψ_3, the magnetic field B_{axis_z} along the rotation axis can be determined from the values B_{mx1} to B_{mz3}.

Due to the fact that **n**(φ, ϑ) is a unity vector, the field magnitude in direction of the rotation axis can be derived by a set of three measurements completely independently from sensor orientation and rotation angle, see Eq. (2).

$$\left|B_{axis\_z}\right| = Det\left[\mathbf{B}_m\right]\begin{pmatrix} \left(B_{mx3}(B_{my2}-B_{my1})+B_{mx2}(B_{my1}-B_{my3})+B_{mx1}(B_{my3}-B_{my2})\right)^2 \\ \left(+B_{mx3}(B_{mz2}-B_{mz1})+B_{mx2}(B_{mz1}-B_{mz3})+B_{mx1}(B_{mz3}-B_{mz2})\right)^2 \\ \left(+B_{my3}(B_{mz2}-B_{mz1})+B_{my2}(B_{mz1}-B_{mz3})+B_{my1}(B_{mz3}-B_{mz2})\right)^2 \end{pmatrix}^{-\frac{1}{2}} . \quad (2)$$

Measurements have to be done for two orientations of the rotation axis in order to measure the field vector completely, if additional scalar absolute intensity data are given. Systematic errors have to be eliminated during the measurement procedure to make the measurement method 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.

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 from 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. The Automation

The previous, manually operated system is shown in Fig. 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 leveled 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. 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 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 measurements, all the manual operation steps have to be performed by motors, as there are

- the rotation around the measurement axis (axis A),
- the turning of the sensor inside the basket (rotation around axis B),
- the change of orientation of the measurement axis (rotation around axis C).

Moreover, the orientation of the measurement axis with respect to the horizontal plane and a geodetic reference frame shall be measured by a laser-optical system.

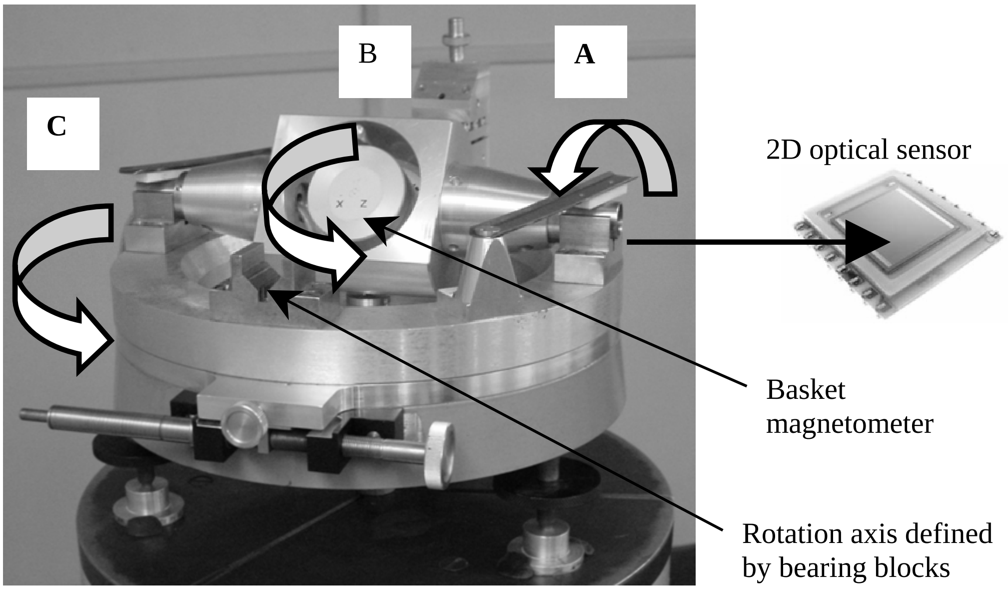

Fig. 2. Instrument which has been operated manually in Niemegk over more than two years. The arrows indicate the three rotations which are necessary to perform the absolute measurement.

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. Unfortunately the maximum push/pull force of the commercial available piezo motors is with 1N low. Considering gear loss and aging of friction properties a gear reduction of 20 for the sensor rotation (rotation B) and 40 for the basket rotation (rotation A) was realized. The sensor rotation is performed by a gear mechanism inside the basket. To decouple the basket rotation mechanically from the base part 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 is high enough to keep the weight permanently on the bottom side like a ship's keel (see Fig. 4 later in the text). In this way the angular position of the basket can be controlled by rotating the keel versus the rotation axis.

Turning the whole system into a second measurement direction and back requires a rotation around axis C in Fig. 2. 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, the requirement on stability during one measurement sequence is extremely high. 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, which is pressed in a notch of the steady part of the table by a vertically mounted spring. 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. 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 Fig. 3.

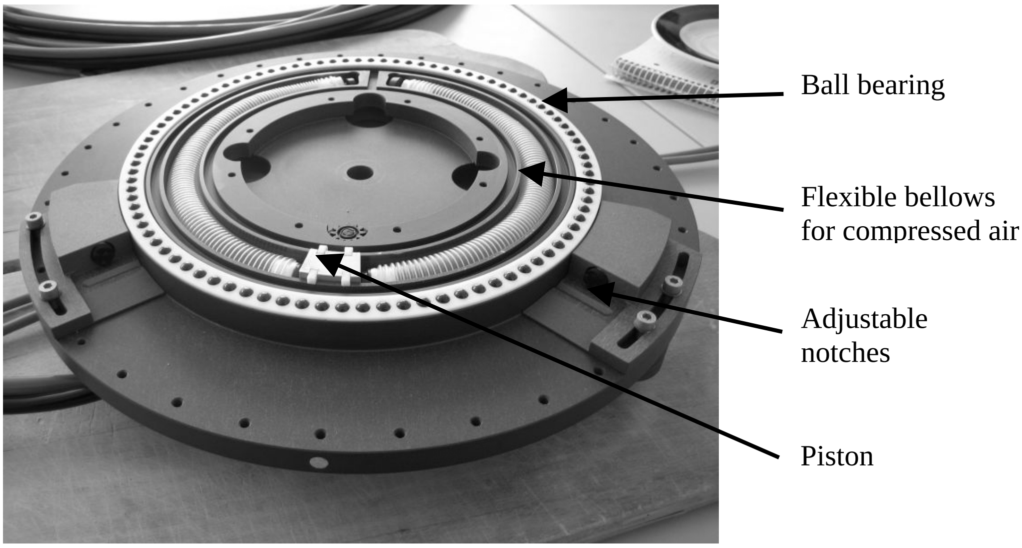

Fig. 3. Steady part of the turn table. The tappet is moved by switching compressed air alternating into the left or right tube. The rotatable part is pushed by the piston into its end positions defined by the notches.

The orientation of the measurement axes 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 optical axis has to be installed inside the rotating basket to determine the direction of the measurement axis. We used a distantly placed laser coupled in by glass fiber. The glass fiber 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 20×20 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.

To keep the laser spot within the measured and modeled PSD range 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 arc seconds (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+/–20°C per year for central Europe we need a pillar material with a linear expansion coefficient of 1 ppm/°C. Fused silica rollers with an thermal expansion coefficient of 0.5 – 0.9 ppm/°C are selected for the PSD mounting.

A more detailed description of the automation approach is given by Auster *et al*. (2007).

4. Setup in Belsk

Figure 4 shows the turn-table with basket, basket magnetometer and laser optics. A proton magnetometer (see Fig. 5, left) is necessary for calibration and to provide the third vector component. Two PSDs are mounted on pillars in a distance of about 15 m (one is visible in the background of Fig. 5 left). The automatic instrument performs discrete measurements, so this setup has to be complemented by a fluxgate variometer continuously recording the field variations (see Fig. 5, right). All instruments have separate control electronics and a GPS receiver for the exact time signal completes the

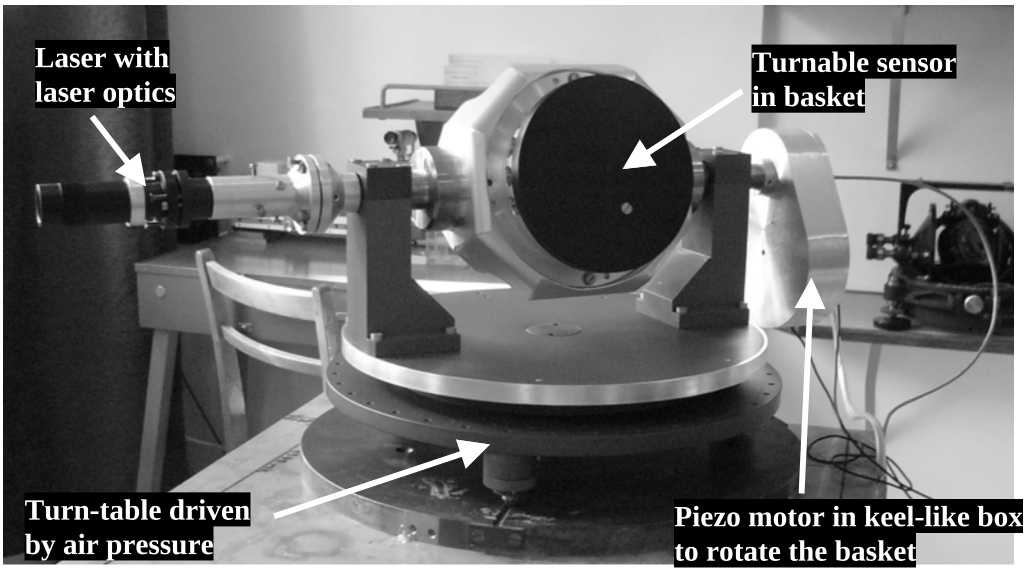

Fig. 4. The automatic absolute instrument with basket, basket magnetometer and laser optics on the turn-table.

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 circles in the setup drawing (Fig. 6) indicate the necessary clearance to guarantee disturbances of less than 0.2 nT.

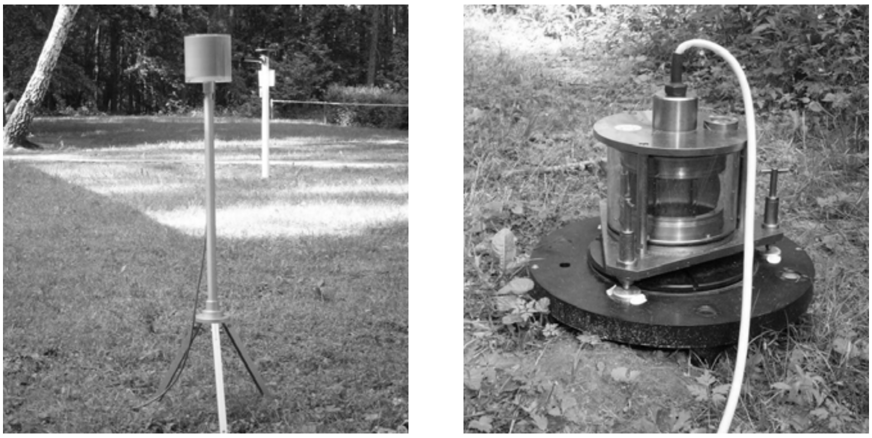

Fig. 5. Proton magnetometer for calibration and determination of third vector component (left panel), three component fluxgate magnetometer for reduction of variation (right panel). The resolution of both magnetometers is 10 pT. Both are provided by Magson GmbH.

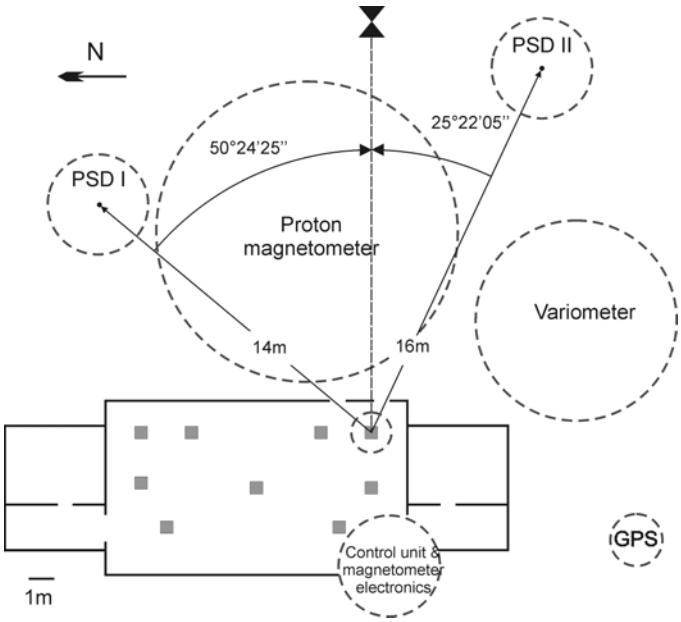

Fig. 6. Setup of all components of the automated observatory in and around the absolute house in Belsk, circles mark the necessary distances around each component to avoid interferences and disturbances.

First, all three rotation parts are brought in their initial positions. 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 approximately 60° steps forward and backward in each of the four possible 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 data processing.

The first 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 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 are determined. Measurement results show that the three angles of non-orthogonality are constant within the measurement accuracy of 10^{-6}. The offset stability was better than 0.5 nT during the measurement campaign in Belsk which corresponds to the offset stability of better than 1 nT/year specified in Niemegk before. The scale values depend strongly on the thermal expansion coefficient of copper (about 20 ppm/°C). These 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.

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. Thus, the variometer measurements have to be transformed into the coordinate system of the basket magnetometer, in order to reduce the field measured by the basket magnetometer. The calculation of the field in axis direction can subsequently be repeated by Eq. (1).

Finally, the direction of the measurement axis has to be determined. The crosses in Fig. 7 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. In a distance of 10-15 m (PSD I) a typical displacement error is about 0.05 mm. This corresponds to an angle error of 1 arcsec which is also clearly less than the design goal of 4 arcsec.

5. Results of Belsk Measurement and Outlook

The instrument was operated automatically during the workshop in Belsk. Measurement results compared with the observatory data are plotted in Fig. 8. Measurements (two per hour) were done during the Friday lecture fully automatically. The standard deviation of the difference between the measurements with the automated system and the Belsk observatory data are 1.9 nT in the X-component, 1.3 nT in the Y-component and 0.7 nT in the Z-component.

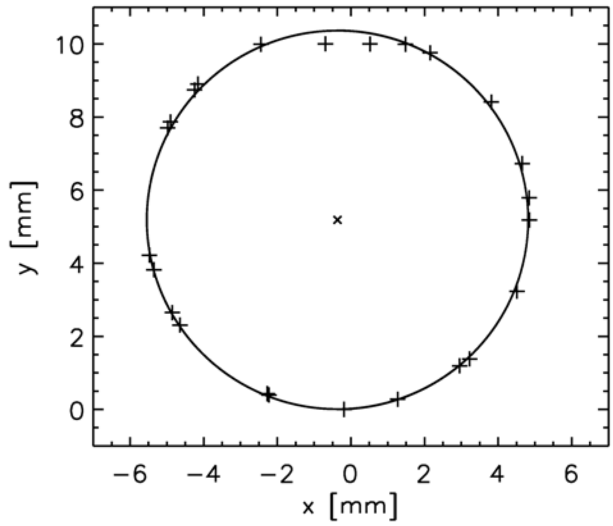

Fig. 7. Laser beam position on the PSD at each measurement of the basket magnetometer (crosses). The measurement axis orientation is determined by fitting a circle to the readings. The center [x_0 = –0.36, y_0 = 5.18] indicates the axis direction, the radius specifies the misalignment between rotation axis and axis of the laser beam.

These results and the 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 automation of absolute measurements has several advantages. Fully automated observatories can be set up at remote locations, where frequent access or the presence of trained personnel can be problematic. The quality of the measurements becomes independent from the qualification of the personnel. Absolute measurements can be performed more frequently, relaxing the requirements on stability of variometers. A very detailed description of instrument development, data processing software and measurements performed in Belsk and Niemegk can be found in Hemshorn (2007).

So far our prototype instrument has been operating fully automatically for short time intervals only. The next step will be to prove the instrument robustness for unattended long term measurements at Niemegk Observatory.

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.

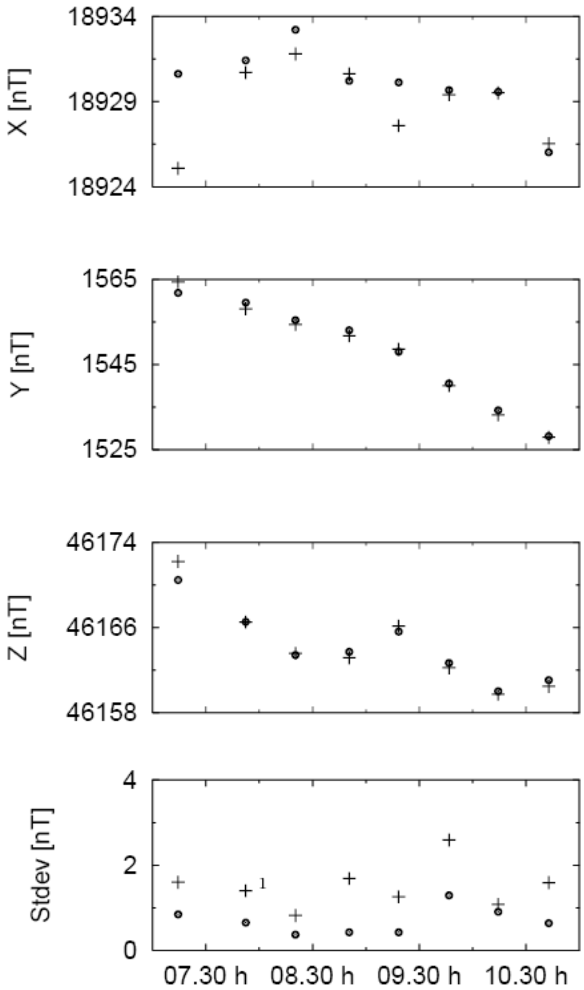

Fig. 8. X, Y and Z components measured by the automated system (dots) and values of Belsk observatory (crosses) are plotted in the upper three panels. In the bottom panel the standard deviation of redundant measurements before (crosses) and after (dots) variation reduction are shown. The values before variation reduction give us an estimate about the field variations during the measurement. After variation reduction the standard deviation provides an uncertainty estimate on the final result.

Acknowledgements. For the design and manufacturing of the mechanics we thank Carsten Müller, Bernd Chares, Markus Thiel, Roland Paul, Jörg Wummel, Bernd Stoll and Katrin Gebauer. For providing the excellent magnetometers and for software development and hardware installation many thanks to Volker Auster, Olaf Hillenmaier, Ronald Kroth, Markus Wiedemann and Edita Georgescu. Finally we wish to thank Anne Neska, Jan Reda and colleagues for support in the Geomagnetic Observatory Belsk.

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Accepted February 5, 2007