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EXPERIENCES WITH A NEW METHOD FOR THE ABSOLUTE COMPONENT DETERMINATION OF THE EARTH'S MAGNETIC FIELD

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1 INTRODUCTION

The expression "absolute measurement" is attributable to Gauss, who was the first to express magnetic intensity in units of length, time and mass. Gauss determined the horizontal intensity of the geomagnetic field in 1832 using two experiments. He determined M x H and M / H of a bar magnet, so that both the magnetic moment M of the magnet and the horizontal field intensity H could be deduced [1,2].

Even today, almost 200 years later, it is impossible to obtain absolute permanent recordings of the geomagnetic field components. The main problem is that the natural changes (variations) are very small in comparison to the total field intensity. It is difficult to guarantee a lasting orientation of the instrument, to observe the Nyquist- theorem, and to stabilize additional fields. Absolute permanent recordings are only possible for the scalar value (total intensity F) of the geomagnetic field vector. Several efforts have been done to develop magnetometers for the recording of components, but the success is small [3, 4, 5, 6, 7, 8, 9]. At the geomagnetic observatories the permanent measurements are so-called variation recordings. Those are relative measurements. The full magnitudes of the magnetic field components are obtained by adding the data of the variation recordings to the so called base line values obtained from absolute measurements, which are frequently carried out. Absolute measurement means, that the complete field vector (two angles, magnitude) is determined for a defined time.

The introduction of DI-fluxgate magnetometers in the 1980ies [10] provided a comparatively simple way for the absolute determination the two angles declination D and inclination I of the Earth's magnetic field for a defined time, and for a defined place. A DI-fluxgate consists of a theodolite and a one component fluxgate magnetometer. The theodolite has to be non magnetic. It is used to determine a very accurate orientation towards the geodetic coordinate system in the horizontal and in the vertical plane. The fluxgate is situated above the telescope axis of the theodolite. For the measurement, the theodolite is oriented in the direction where the magnetometer shows zero. Now the observer has to read and write down the angles, and the determination of declination and inclination can follow under consideration of the azimuth. Errors are eliminated by using all possible positions of the telescope. Such theodolites are expensive (special manufacturing) and difficult to operate with high precision so that good results are generally only obtained if the observer is skilful and experienced.

The method suggested by AUSTER[11] is an alternative to the DI-flux. This new instrument consists of a mechanical device to support a three-component fluxgate magnetometer (*basket* magnetometer). An additional scalar magnetometer is required for both methods to measure the total intensity F for the full description of the Earth field vector.

Both the physical principle and the prototype instrument are briefly described. The steps of measurement are outlined. Further, the results of three measurement campaigns are presented. Sources of errors are discussed as well.

2 FUNDAMENTALS OF THE NEW METHOD

Let our Cartesian coordinate system be V, W, and Z (black capitals) (Fig. 1). Z is identical with the vertical axis of our geodetic Cartesian coordinate system.

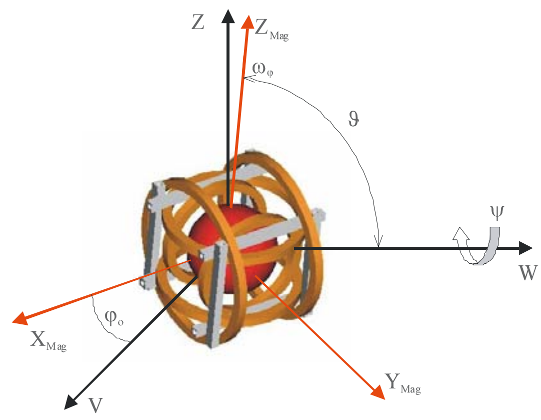

Fig. 1. Coordinate system

The *basket* magnetometer coordinate system may be X_{Mag}, Y_{Mag} and Z_{Mag} (red capitals). We measure $B_{Mag\ x}$, $B_{Mag\ y}$ and $B_{Mag\ z}$ – the magnetic field components in the magnetometer system. We get B_w by means of a coordinate transformation:

$$B_w = B_{MagX}\cdot\sin\phi_0\cdot\sin\delta_0 + B_{MagY}\cdot\cos\phi_0\cdot\sin\delta_0 + B_{MagZ}\cdot\cos\delta_0$$

Note that the field B_W in direction of the rotation axis W does not depend on the rotation angle ψ. If we rotate the sensor in three positions (ψ_1, ψ_2, ψ_3), we derive the

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following vector equation for the field component in W direction:

$$B_W \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} = \begin{bmatrix} B_{Mag\,x1} & B_{Mag\,y1} & B_{Mag\,z1} \\ B_{Mag\,x2} & B_{Mag\,y2} & B_{Mag\,z2} \\ B_{Mag\,x3} & B_{Mag\,y3} & B_{Mag\,z3} \end{bmatrix} \begin{pmatrix} \sin\varphi_0 \sin\vartheta_0 \\ \cos\varphi_0 \sin\vartheta_0 \\ \cos\vartheta_0 \end{pmatrix}$$

$$= \qquad \mathbf{MB}_{Mag} \qquad * \quad \hat{\mathbf{n}}(\varphi_0, \vartheta_0)$$

The matrix $\mathbf{MB}_{Mag}$ contains three measurement results of the fluxgate magnetometer. The vector $\hat{\mathbf{n}}$ contains the angles φ_0 and ϑ_0.. We rewrite the equation in the following form:

$$\mathbf{MB}_{Mag}{}^{-1} \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} = \frac{1}{B_W} \; \hat{\mathbf{n}}(\varphi_0, \vartheta_0)$$

If we take the absolute value of both sides of the equation the vector $\hat{\mathbf{n}}$ falls out because it is a unity vector. Therefore B_W can expressed as:

$$B_W = \left\| \mathbf{MB}_{Mag}{}^{-1} \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} \right\|^{-1}$$

The result shows that the field in the direction of the rotation axis *W* of our reference coordinate system is independent of all angles between both our coordinate systems. Thus, the field along the rotation axis can be derived directly from the measurement results of the three axis fluxgate *(basket)* magnetometer only. The knowledge of sensor orientation and rotation angles is not necessary. If we do the same procedure for the U axis we get:

the magnetic field strength along the W-axis
along the U-axis

and the scalar value from the second magnetometer. Consequently we have a complete data set to determine the field vector.

If the axes V and W are not the axes of our geodetic Cartesian coordinate system, a further coordinate transformation is required to get the desired information. Additionally we need the azimuth.

The calculation of the field along the rotation axis is based on the assumption of ideal magnetometer measurements. Unfortunately scale values, non-orthogonality and offsets of fluxgate magnetometers are not stable in time and vary with temperature.

Our measurement is based on the rotation about two well defined axes and the measurement of the scalar field strength. AUSTER [12] has shown that the rotation about two axes and the knowledge of the total field (measured by a scalar magnetometer) are sufficient to calibrate a magnetometer completely. So it is possible to use one set of our measurement results for both, first for the calibration of the magnetometer and second for the determination of the components. Consequently the calibration of the fluxgate magnetometer is always up to date.

3 THE INSTRUMENT

The instrument (Fig. 2) is made of aluminium and consists of a platform with three adjustable screws, and a turntable. Two orthogonal pairs of support prisms are mounted onto the turntable that can hold the magnetometer or a telescope. The magnetometer is placed in a small basket which is fitted at the centre of an aluminium bar. Using the two pairs of support prisms, the *basket* magnetometer can be rotated around the U and V axis, respectively.

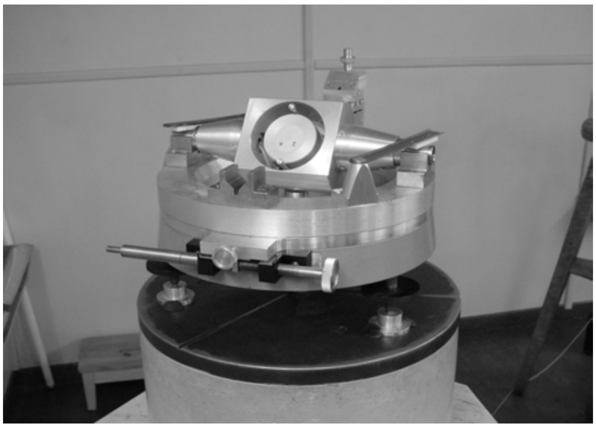


Fig. 2. The instrument together with the *basket* magnetometer

The turntable can be orientated horizontally using a spirit level. The defined geodetic direction is taken from a known azimuth mark using the telescope (Fig. 3). Naturally, such an instrument can never be built perfectly. Therefore we have tried to determine the mechanical deviations for the correction of our measurement results [6].

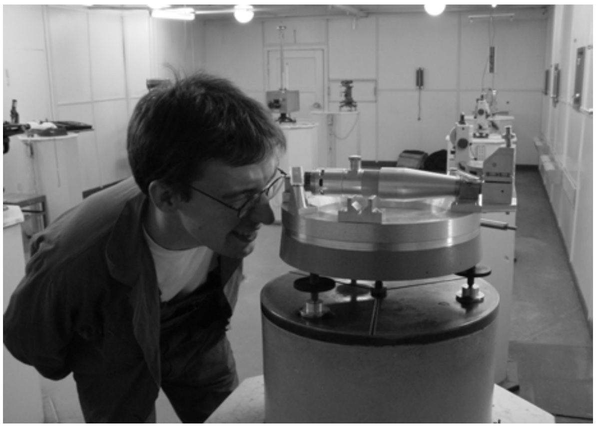


Fig. 3. The instrument together with tetelescope

Another problem of this prototype instrument is already known: it is impossible to adjust the telescope in the vertical direction. That means in many cases it is impossible to take an azimuth mark. This problem was solved by means of a pair of adjustable mirrors like a scissors telescope.

The *basket* magnetometer was made by the MAGSON company.

4 EXECUTION OF THE MEASUREMENT

First, the instrument is levelled. The orientation towards the geographic co-ordinate system is determined by taking an azimuth mark by means of the telescope. Then the measuring procedure is the following:

1 A scalar-measurement is made immediately above the instrument by means of a proton magnetometer.

2 The *basket* magnetometer is placed on support prisms P1 and P3. It is turned in steps of approximately 60 degrees, which means six positions for a full turn. Note, that we must ensure that a wide range of positions is covered, but it is not necessary to know the angles. In each position a measurement is taken computer controlled. (manual reading is not required!)

3 The measurements are repeated using the second set of support prisms. Again, the *basket* magnetometer is turned in six steps.

4 The turning procedure is repeated with the *basket* magnetometer being rotated in the x-y plane inside the basket; and by 180 degrees compared to the first and second position.

Three individual measurements are always analyzed to determine scaling factors, offsets, and non-orthogonality of the three components of the basket magnetometer. In total, we obtain 8 estimates.

The whole cycle of measurement takes less than 15 minutes. The operation is simple; it only involves rotating the instrument and pressing a button.

5 MODIFICATIONS SINCE LAST YEARS

At first we used a second three-component fluxgate magnetometer in addition to the three-component fluxgate (*basket*) magnetometer. Both readings were stored at the same time by a laptop. We used the recordings of the second fluxgate for the reduction of the variations.
Now we use the recordings of the observatory variometer. A routine has been written to provide the observatory data, both the vector variometer recordings and the total intensity F, for our readings.
A computer was integrated into the fluxgate electronic unit which replaces the laptop. The data transfer is done by means of a PC-card. The number of individual measurements was reduced from 48 to 24. The routine for evaluating the readings has been revised. The attention was focussed on the consideration of the variations. The result of the computation are the components H, D, Z or X,Y, Z respectively reduced to the start time of the measurement.

6 RESULTS OF THE TEST MEASUREMENTS AT NIEMEGK

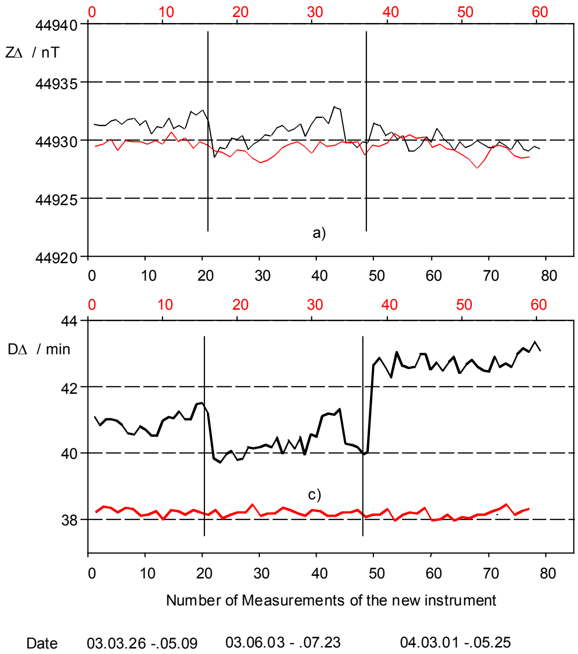
We have carried out three measurement campaigns started in 2003. The instrument was adjusted only once at the start of every campaign. The basket-fluxgate was in operation permanently to avoid thermal effects. As already mentioned, every data analysis starts by computing the characteristics of the basket magnetometer -the scale values, the offsets, and the orthogonality. From this results follows that the absolute accuracy of the *basket* magnetometer is within the range of 1 nT.

The comparison of the observatory recordings with our repeat measurements looks promising. Three variometers are permanently in operation at Niemegk observatory. The main system is the Danish fluxgate magnetometer FGE because this instruments has the best long-term stability. The base line of this instrument is determined by means of regular DI-flux measurements. The measurements of our new instrument should give the same results. Fig. 4a,b,c show the baseline of the FGE generated by the regular DI-flux measurements, and by measurements by means of the new device for the components H, D, and Z. The vertical lines indicate the end of each measurement campaign.

We observe in the H and Z-component that the agreement increased with every measurement campaign. In the Z-component it is nearly perfect now. The instrument was adjusted only at the beginning of every measurement campaign. The results show that the levelling faults have become smaller. There is a trend in the base line results of the first two measurement campaigns. The levelling of the prototype instrument was done in a different way in the third campaign, because a problem in the first campaigns causing this trend might have been that the oil under the turntable flowed. The individual measurements fluctuate considerably but no more than two times more than the values of the DI-flux. In contrast to H and Z, the results seem to be worse in D. The increasing offset means that the azimuth was not determined less well in the last campaigns. However, this would only be a question of perfect orientation. The fluctuations of the measurements are nearly 1min, which also is approximately two times more than for the DI-flux measurements.

7 DISCUSSION

The offset of the declination is only a question of determining the azimuth more accurately. We assume that it is a problem of the adjustment of the mirrors which are needed to view the azimuth mark through the telescope. They have to be adjusted or we remove them. An alternative would be to install a auxiliary azimuth mark which can be taken without using the mirrors. The perfect levelling of the last campaign in the H and Z component shows that the correction of mechanical faults is possible.



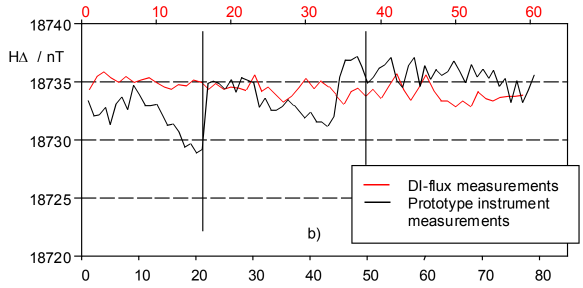


Fig. 4. The base line of FGE measured by DI-flux and the new instrument a.) Z-component b.) *H*-component c.) angle D

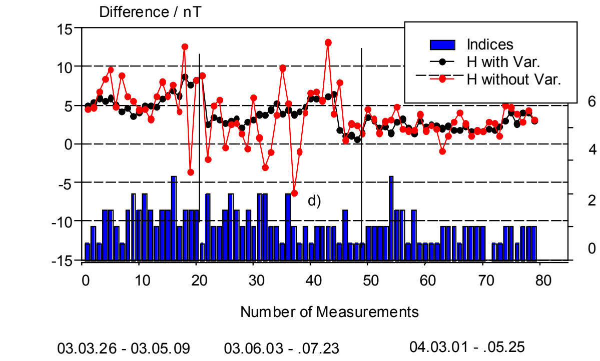


Fig. 5. Comparison of *H* with the Ngk recordings

Another question is the problem of fluctuations which are slightly too large for a good absolute vector magnetometer. The result of the absolute measurement is related to the time of the first measurement of the *basket* magnetometer. That means the magnetic variations have to be taken into account during the measurement process. Fig. 5 shows that this is achieved successfully. The Kp indices are displayed there as vertical bars to show the magnetic activity. We also carried out our measurements during high magnetic activity, in contrast to the observatory measurements with the DI flux which were carried out only at quiet days. We realize that the deviations to the Niemegk recordings are independent of the magnetic activity, confirming that the consideration of the variations is successful.

Since the computed scale values, the computed offsets and the computed non-orthogonality look good, the reason of the fluctuations is unclear. Two sources of errors might explain them: First, we have not yet studied temperature effects systematically. Second, strict linear behaviour of the *basket* magnetometer is a prerequisite to obtain accurate results. To check this also is one of our future tasks.

8 CONCLUSION

A new instrument for measuring the vector components of the Earth's magnetic field has been developed theoretically by H.-U. Auster, and was manufactured and tested at the geomagnetic Adolf-Schmidt-Observatory Niemegk of the GeoForschung Zentrum Potsdam. As a main advantage against existing instruments, the instrument can measure the absolute magnetic field without an iron-free theodolite. The accuracy of the results only depends on very accurate targeting of the azimuth mark, precise determination of mechanical tolerances, and linear response of the three-component fluxgate magnetometer. The first one only has to be done when setting up the instrument and the latter two ones depend on the manufacturing.

The handling for the actual measurements is so simple that untrained people can reliably operate it once the instrument is adjusted. The observatory work would be simplified by the application of this device. It would be particularly useful for stations which do not have trained staff.

We have carried out three measurement campaigns to test the comparability to standard methods. The results are promising but some further investigations are necessary to improve the accuracy of the results.

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