Precise Scalar Calibration of a Tri-Axial Braunbek Coil System

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A calibration of the well-defined Braunbek coil system was carried out using the scalar method. The whole measuring setup was designed to minimize the uncertainty of the scalar calibration procedure. The measurement time as well as the sampling ratio were adjusted to reduce the influence of the ambient magnetic field variation. We calibrated the coil sensitivity with the uncertainty of 30 ppm and orthogonality with the uncertainty <0.01°. The results were compared with a different technique.

***Index Terms*—Angle, Braunbek system, calibration, coils.**

I. INTRODUCTION

AN ANGULAR precision of tri-axial magnetic sensors is required below 0.05° and thereby their calibration technique has to correspond to this required precision. The tri-axial magnetic sensor can be calibrated using the scalar principle [1] or a coil system can be used as the reference magnetic system according to [2].

If we exploit the coil system, its parameters (sensitivities and orthogonality) have to be known to precisely evaluate the parameters to the calibrated magnetometer.

The most commonly used method for calibration of the coils system is based on the tri-axial magnetometer and a theodolite. It utilizes the similar method to declination inclination flux measurement [3], but the method is dependent on the tri-axial magnetometer whose parameter verification has to be done with respect to superior standard and so it carries other unwanted uncertainty. Since the theodolite has to be perfectly leveled or aligned to the coil system, the weakness of this method is obvious. Moreover, the theodolite has limited range of position in the vertical direction, which can decrease the accuracy of the calibration principle.

We introduced the scalar method for the calibration of 3-D coil system [4]. The main idea is based on the directionally independent scalar measurement of the magnetic field. The scalar magnetometer is inside the homogenous space of the calibrated coil system and the current sequence excites the coils. Then, the parameters of the system are calculated from the total magnetic field measurement and current measurement by an analytical way (sensitivity) and a non-linear optimization method (orthogonality), respectively.

The scalar technique has two main sources of the uncertainty: 1) an ambient magnetic field variation and 2) current measurement uncertainty. In [5], we analyzed the impact of the input measurand on the results. It is the first experiment the method was mainly loaded by the current determination error. As we recommended, the uncertainty of the both input measurements has to be as low as possible. In fact, the current measurement uncertainty should be at least at same level as the variations of the ambient magnetic field.

Fig. 1. Braunbek coil system in PTB Braunschweig.

The motivation was to test the minimal achievable uncertainty with which the coil parameters can be calibrated. In this paper, we present the results of dramatically improved measurement setup which gives the best published accuracy. We also show a new way to express the measurement uncertainty.

II. COIL SYSTEM

To avoid problems concerning to a magnetic field gradient caused by a small coil size, we wanted to choose the sufficient coil system.

We were able to calibrate the 4 m Braunbek coil system [6] in Physikalisch-Technische Bundesanstalt (PTB), Braunschweig (Fig. 1). This system is characterized by the excellent homogeneity and symmetrical axes. The facility is placed out of the city center; therefore, the magnetic field disturbance is as low as $\pm 2 \sim n$T within a time interval of ∼300 s, which is illustrated by an ambient magnetic field record shown in Fig. 2. This variation is further considered as an uncertainty of the magnetic field measurement, which give us, by considering of range 30–110 μT, relative uncertainty of 66 ppm.

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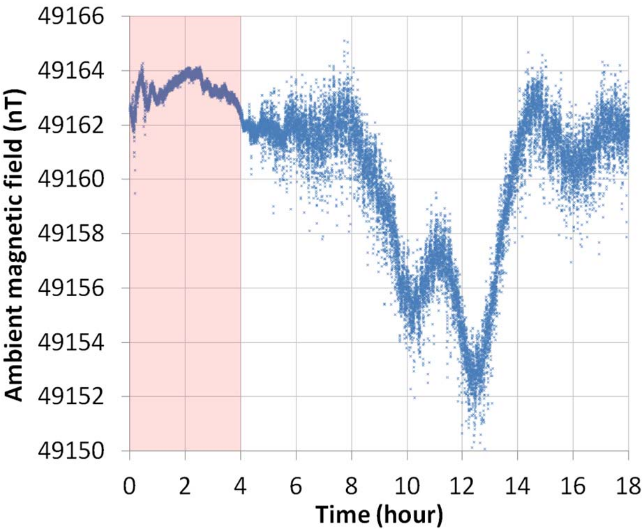

Fig. 2. Ambient magnetic field record—PTB non-magnetic facility.

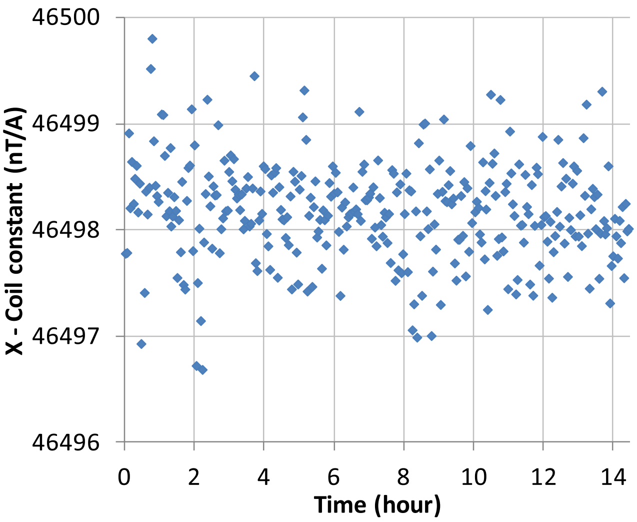

Fig. 3. Calculated constant of *x*-axis—long time period.

TABLE I
DEVICE PRECISION

Quantity	Value, Range	Precision
Total magnetic field	30μT-110μT	2nT (70 ppm-15 ppm)
Resistors	1 Ω	5 μΩ (5 ppm)
Voltmeter	1V	10 μV (10 ppm)

TABLE II
CALIBRATION OF COIL SENSITIVITY–SCALAR METHOD

Axis	Sensitivity	Uncertainty
X – North-South	46498.16	24 ppm
Y– East-West	48143.03	25 ppm
Z – Vertical	49848.24	26 ppm

The vector of the Earth's magnetic field does not change only size, but also orientation (inclination and declination angles). We monitored the vectorial components of the Earth's field during calibration by auxiliary tri-axial fluxgate sensor and calculate the variation of these two angles. The variation was <0.0005° (within a measurement time of 300 s) that has a negligible impact of 5 ppm. We therefore ignored the changes of Earth's field direction.

III. INSTRUMENTATION

Based on [5], the precision of current measurement should be similar or better than variations of the magnetic field. Therefore, we measured the current flowing into the coil as a voltage drop on the very precise resistors and the voltage was measured with very precise 8(1/2)—digit voltmeter Agilent 3458 A. All devices precisions are shown in Table I. The magnetic field was measured by the Overhauser magnetometer because its reading is independent on the magnetic field vector direction and its precision is 0.2 nT.

To be able to calibrate the coil system in long time interval, the devices were connected by the general purpose interface bus and were controlled by a LabView software. A current sequence needed for calibration was also controlled by the computer program. Both current and magnetic field readings were synchronously sampled.

From the recorded data, we could conclude the statistical behavior of the calculated coil parameter.

IV. SENSITIVITY CALIBRATION

We knew roughly the coil sensitivities so we adapted the current sequence applied to the individual coil to keep the magnetic field inside the coil system, within the dynamic range of the magnetometer.

The Y-coil axis was oriented in East–West direction so the positive and negative current could have the same amplitude because the total magnetic field was almost the same for both current polarities.

Nevertheless, the situations of the X-coil pointed to North and the vertical coil are more complicated. There should be in this case the vectorial sum of the Earth's and coil magnetic field vectors should be considered. The currents had different amplitudes for positive and negative steps due to the Earth's field components.

When we measured, the huge magnetic steps were applied to keep low uncertainty. The steps of the magnetic field affected the Overhauser magnetometer because it is not able to track these steep changes. We were forced to spread the steps and divide them to consequent smaller changes. This way the magnetometer was able to follow the signal, by retuning. This feature of course extended the measurement time.

The measurement was carried out for long time period (Fig. 3) and the measurement set was used for the calculation of the A-type uncertainty as a standard deviation of the measured values. The B-type uncertainty was estimated according to [5] from the known sources.

The sensitivities as well as their uncertainty are shown in Table II. We were able to reduce the uncertainty of the sensitivity down to 30 ppm.

The sensitivity of all axes was also calibrated with a different technique which is a standard method of PTB. They measure with proton magnetometer utilizing free precession and they actively cancel the Earth's magnetic field

TABLE III
CALIBRATION OF COIL ORTHOGONALITY—PTB METHOD

Axis	Sensitivity	Uncertainty
X – North-South	46499.14	30 ppm
Y– East-West	48143.59	31 ppm
Z – Vertical	49848.21	32 ppm

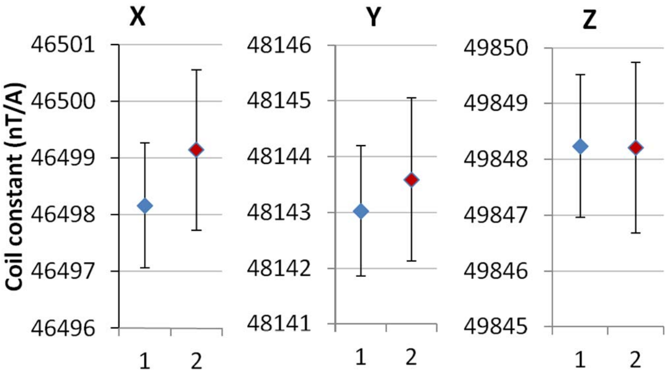

Fig. 4. Comparison of the calibration methods for sensitivity (1: the scalar calibration and 2: PTB calibration principle).

during measurement. They measured with the same voltmeters, shunt resistors, and current sources as we used for scalar calibration.

The proton magnetometer sensor head is oriented perpendicularly to a calibrated axis inside the homogenous area of the Braunbek system. The calibrated coil of the cancelation system is substituted by the extra 1 m Helmholtz coil, which replaces the axis in the cancelation system. That means that cancelation system is still able to compensate the Earth's magnetic field but one axis (replaced by Helmholtz coil) can by calibrated. During the measurement the Earth's field is suppressed to very low values (maximum of 10 *n*T due to gradient field variations) and the proton magnetometer measures only the field generated by the calibrated Braunbek coil. To decrease also the influence of residual magnetic field (after compensation) both polarities of current are applied into the calibrated axis and the average value is taken as a right one. For calibrating other axis, the setup has to be rotated to other coil—direction of the extra Helmholtz coil and proton magnetometer.

The results are shown in Table III. As it can be observable from Fig. 4, both calibrating techniques have the same results with regards to their uncertainty band (their tolerance bands have an overlap).

V. ORTHOGONALITY CALIBRATION

If the sensitivities were calculated, the orthogonality can be calibrated. Planning of a current sequence for the coil orthogonality estimation had to be done in advance. The situation is a little easier (than at the sensitivity calibration) because two coils are excited at the same time and thus the combination of the currents can be adjusted so that the total magnetic field was in the range of the magnetometer and the current measurement comply the uncertainty requirements.

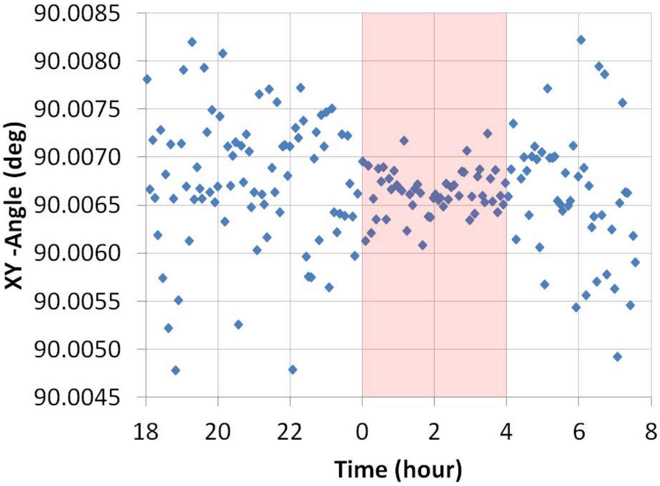

Fig. 5. Calculated orthogonal angle between *x*-axis and *y*-axis—long time period.

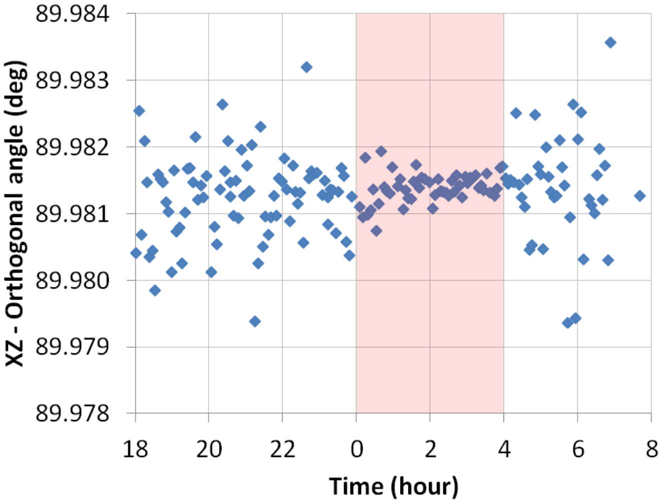

Fig. 6. Calculated orthogonal angle between *x*-axis and *z*-axis—long time period.

For example, if the vertical axis is excited in the opposite direction to the Earth's field, the total magnetic field will be very low and below the range of magnetometer. However, we can apply sufficient current into the second coil to increase the total field and so precisely measure the magnetic field.

Since the current sequence (needed for calculation of orthogonality) contains at least four current combinations, the sequence takes more time. This can bring troubles because one of the requirements of scalar calibration is the stability of the ambient magnetic field. While the excitation is running, the ambient magnetic field, which is measured at the beginning of the sequence, can drift and it causes the error in the calculation.

To improve this measurement, the approximation of that drift can be implemented. The ambient magnetic field is measured at the beginning and also at the end of the sequence and the approximated value of the ambient magnetic field is substituted into individual part of the sequence, into the equations.

We also calibrated the orthogonal angle between all coils during a long period (Figs. 5 and 6) to express the uncertainty

TABLE IV

CALIBRATION OF COIL ORTHOGONALITY—SCALAR METHOD

Axes	Angle	Uncertainty
X – Y	90.0067	0.0036 deg
X – Z	89.9813	0.0037 deg
Y – Z	89.9963	0.004 deg

by the standard deviation. The results are shown in Table IV and we got the precision <0.01°.

The calibration of the orthogonal angle by the PTB method is theoretically possible but very complicated. We plan to implement this method in the near future.

VI. DISCUSSION

One can observe a different behavior of the variation of calibrated parameters during the long period testing. The variation of the calculated sensitivity (example in Fig. 3) has the similar distribution through the whole period whereas the variation of the orthogonal angle (Figs. 5 and 6) behaves differently because the variation was decreased during the time interval from midnight to 4 A.M.

If we compare the ambient magnetic field record (Fig. 2) and the record of the resulted orthogonality (Figs. 5 and 6), we find correlation that is presented as a transparent red band in each figure. At that time, a decline of the ambient field variation caused the variation of the calculated orthogonal angle.

The reason, why the sensitivity calibration is resistant against time of calibration, is that the time sequence is shorter than the orthogonal angle calibration and the ambient field variation has no significant influence.

VII. CONCLUSION

Even though the PTB location was not ideal in terms of the stability of the ambient magnetic field during day time, we achieved very precise results. Based on this calibration, we can conclude that this Braunbek coil system has excellent orthogonality and if we need to calibrate the magnetic sensor within the 0.05° precision, we do not need to compensate such small coil misalignments. For higher precision, the correction has to be applied.

From the measurement experience, it is more suitable to measure at night time between 0 and 4 A.M., when the ambient field is most stable.

For coil sensitivity, we successfully compared our results with PTB traditional method.

We would also like to verify the orthogonal angle by a different method to have a comparison with our procedure. In the future, we will try to design the method, which would be able to calibrate orthogonality using the proton magnetometer.

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