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SCALAR CALIBRATION OF 3-D COIL SYSTEM

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The scalar method was used for calibration of the 3-D coil system. The method is based on obtaining set of non-linear equations by using a sequence of the calibration current steps into the individual coils or into the combination of coils. The coil sensitivities and angle between the magnetic coils axes were calculated by numerical method. The estimated achievable uncertainty is 0.02 degrees for angle and 0.01% for coil constant. The developed method was tested during the calibration of the 2-meter coil system in Průhonice.

Keywords: calibration, 3D coil system, scalar magnetometer

1 INTRODUCTION

Three-dimensional coil systems are important for calibration of magnetic sensors [1]. Even if the coil support structure is precisely fabricated and the winding position is well defined it is necessary to periodically calibrate the 6 coil parameters which are: 3 coil sensitivities and three angles α_{12}, α_{13}, α_{23} between axes of the coil system. The mentioned 6 parameters can be used in correction matrix to calculate the coil current necessary for the generation of the testing field with required amplitude and direction which is used for the calibration of magnetic sensors.

There are different techniques to find these parameters. Measurement of the coil geometry and calculation is usually not enough precise even if the laser scanner is used because the coil winding is not precisely aligned with the support. Therefore the precise calibration should be based on magnetic measurements.

When using 3-D vectorial sensor head for the calibration of 3-D coil system, [2] the problem becomes more complicated, as we have to consider sensitivities and offsets of individual sensors (another 6 parameters), their mutual angular deviations (another 3 angles) and also the misalignment between the coil and sensor reference system (another 3 angles).

A method is known using a single-axis fluxgate sensor mounted on top of non-magnetic theodolite (so called DI-flux). The coil constants are calculated from a series of measurements using precise rotation of the sensor. This procedure was developed for the absolute measurement of the Earth's field at geomagnetic observatories [3]. It is still made manually, although there is a possibility to perform it automatically on remote observatories [4]. Using three-axial fluxgate sensor for DI-flux was described in [5].

In this paper we describe a calibration method which uses scalar magnetometer in the middle of the coil system. This method is principally different from scalar calibration of magnetic sensor, which is based on rotating the sensor in the homogenous field with constant scalar value [6].

All mentioned magnetic calibration methods are influenced by the Earth's magnetic field variations. It is not possible to use magnetic shielding, as the presence of ferromagnetic material would significantly change the coil properties. Averaging helps to reduce the uncertainty and it is useful to monitor the field to avoid magnetic storms. Ideal solution is to perform the calibration in magnetic vacuum created by active compensation system; such compensation coils should be significantly larger than the coils under test.

2 THEORY

The scalar magnetometer precisely measures

$$B_{TOT} = \sqrt{B_X^2 + B_Y^2 + B_Z^2} \qquad (1)$$

in a limited range (typically 10 000 to 100 000 nT), but with high precision (typically 0.1 to 1 nT). By applying well a proper sequence of current steps with changing polarity and amplitude into the individual coils and simultaneously to all combinations of the coil pairs, we can make a series of measurements which gives enough equations to calculate coil system parameters.

2.1 Single coil

In this case the calibration current is applied into the individual coil to establish its sensitivity. The resulting field is

$$B_{TOT}^2 = \left(I_L S + B_E \sin(\varepsilon)\right)^2 + \left(B_E \cos(\varepsilon)\right)^2 \qquad (2)$$

where S is sensitivity of the coil,
I_L is the coil current,
B_E is the Earth's magnetic field
and ε is the angle between the coil and Earth's magnetic vector.

There are only three unknown variables (S, ε, and B_E) in this equation and thus only three different calibration currents are needed to obtain them.

The simplest choice ($-I_L$, 0, + I_L) is not always optimum to minimize the uncertainty.

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2.2 Double coils

In order to calculate the angle between two coils we apply suitable currents into both of them and measure the resulting field. Supposing that the coil sensitivities are already calibrated in the previous step, we can write for the resulting field

$$B_{TOT}^2 = \left(B_{L1} + B_{L2}\cos(\alpha) + B_E\cos(\delta)\cos(\gamma)\right)^2 + \left(B_{L2}\sin(\alpha) + B_E\cos(\delta)\sin(\gamma)\right)^2 + \left(B_E\sin(\delta)\right)^2 \quad (3)$$

where B_{TOT} is magnetic field measured by scalar magnetometer,

B_{L1} is magnetic field generated by the first reference coil

and B_{L2} is magnetic field of second coil.

α is the desired angle between the coils.

δ and γ describe the direction of the Earth's field

It means that 3 variables in the equation are unknown and so the 3 different combinations of calibration currents have to be applied into both coils to calculate the angle α.

2.3 Triple coil

The second possibility of calculation of the angles in the triple coil system is to apply the combined currents into the all three coils.

But this case the calculation is very difficult because the equations contain 7 unknown parameters and therefore seven different combinations of the calibration currents should be generated to achieve these parameters.

Instead of this we applied double coil calibration procedure to all 3 combinations (*xy*, *xz* and *yz*) of coil pairs and calculated all 3 unknown angles.

2.4 Calculation

The equation 3 is non-linear with respect to establishing the angles hence we have to use least square method for calculating these parameters. Concretely, we used the Gauss-Newton algorithm in the Matlab. In fact, we have to use the least square method to establish coil sensitivities too even thought the analytical solution exists because the analytical solution does not give results due to variation of the Earth's magnetic field.

3 EXPERIMENTS

To verify this method the experimental measurement was perform at the triaxial 2-meter coil system in Pruhonice. This system serves primary to cancelation of the Earth's magnetic field. The coils system consists of different coils and the arrangement is similar to Fig. 1. The biggest coil *H* is placed in the North-South direction, the second coil h has axis parallel to the West-East and it is the smallest. The third axis is vertical.

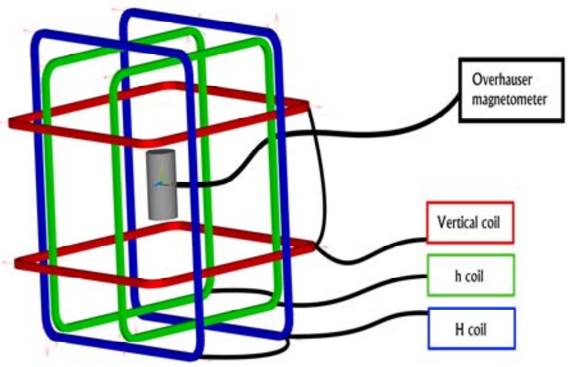

Fig. 1. Measurement setup for scalar calibration of triple coils.

As a precise scalar magnetometer, the Overhauser magnetometer GSM-19 (from GEM Systems, Inc.) with dynamic range from 15 µT to 120 µT, was used.

The currents had to be properly chosen to avoid overrange and to minimize the uncertainty. The head of the magnetometer was put into the middle of the coil system and the coil currents were measured by 6.5-digit Agilent 34401A multi-meter. 100 PLC integration time was used to suppress AC interferences. The measurement setup is shown in Fig. 1.

The measurements were carried out with step sequences analogously to Fig. 2. Every sequence contains an active part and passive part. In the active part, a combination of the calibration currents is applied into the selected coils and the generated magnetic field together with Earth's magnetic field is measured by the scalar magnetometer. In the second passive part, only the Earth's magnetic field is measured.

The time of each active and passive part is about 20 seconds to avoid heating of coil, to obtain more measured values for averaging and to allow stabilizing of the magnetic field after switching the current.

During this sequence the currents and magnetic field are acquired from devices to the personal computer in 5 seconds intervals and subsequently the data are averaged and the coil system parameters are calculated.

This sequence was used both for each single coil and for each combination of coil pairs. In both cases the selected current combination is repeated twice to check correct measurement.

As it was mentioned three equations are required to get the angle between coil axes, but we generated four combination of calibration sequence for checking calculation of angle from different generated values.

4 RESULTS

Since the extra measurement for double coil case was done we could make comparison between calculated angles. As the Table 1 shows that the *H* and *h* coils are almost perpendicular but we have found 1 degree angular misalignment between *z* and *h* axis.

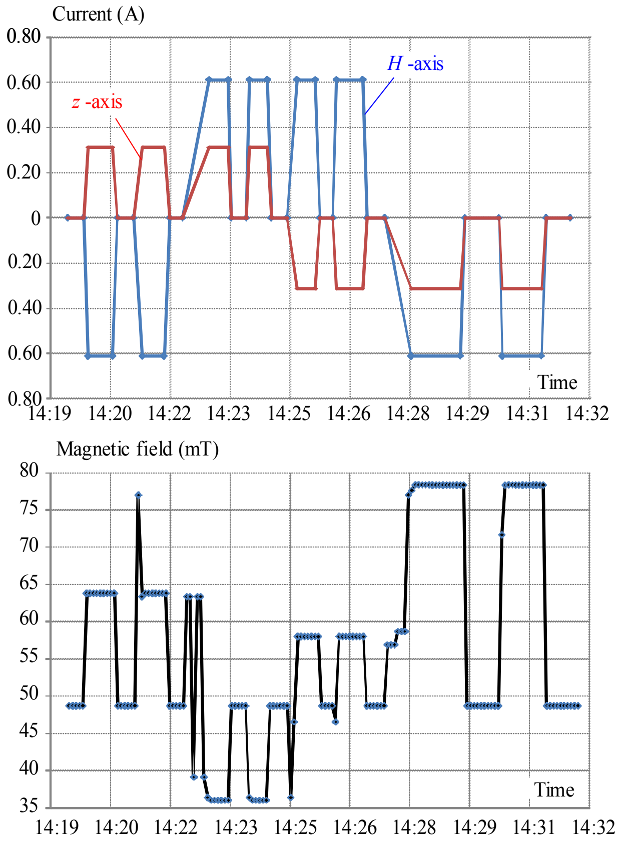

Fig. 2. Calibration sequence for double coils case - *H*-*z* coils

Table 1. Results obtained after Matlab calculation

axis	Sensitivity (nT/A)	N-S (*H*)	W-E (*h*)	Vertical (*z*)
N-S (*H*)	56929.32	-	89.96°	89.96°
W-E (*h*)	19311.16	89.96°	-	91.16°
Vertical (*z*)	37121.03	89.96°	91.16°	-

Estimation of the uncertainty of the described scalar method is difficult because the least square method is used for calculation. The simulated values respecting the devices error und Earth's magnetic field non-stability were used as an input of the non-linear least square method algorithm and the results were compared with the ideal case. In this way, we calculated the worst-case errors declared as our uncertainty.

5 CONCLUSION

The main novel aspect of this method consists in using only one scalar magnetometer to measure and calculate the properties of 3-D coil system with sufficient uncertainty. Classical measurement using fluxgate vector sensor on non-magnetic theodolite is time consuming and cannot be automated.

Provided that the current was measured by ammeter with precision of 0.01% and the Earth magnetic field variation during measurement is 5 nT, the achievable angular uncertainty is 0.02 degrees. This uncertainty can be further reduced by inter-calibration of ammeters and averaging. The self-heating of the coils should be kept under control by using predetermined measuring sequence.

REFERENCES

[1] RIPKA, P.(ed): Magnetic sensors and magnetometers, Artech 2001

[2] LASAHN, M.P. – TRENKER, G.: Vectorial Calibration of 3D Magnetic Field Sensor Arrays, IEEE Transactions on Instrumentation and Measurement No. 44 (1995), 360–362

[3] JANKOWSKI, J. – SUCKSDORF, C.: Guide for Magnetic Measurements and Observatory Practice (Warsaw: International Association of Geomagnetism and Aeronomy) (1996).

[4] AUSTER, H. U. – MANDEA, M. – GEESE A. – PULZ, E. – KORTE, M.: Automation of absolute measurements of the geomagnetic field, Earth Planets and Space, 59, 9, (2007) 1007-1014.

[5] Hemshorn, A. – Auster, H. U. – Fredow, M: DI-flux measurement of the geomagnetic field using a three-axial fluxgate sensor, Meas. Sci. Technol. 20 (2009) 027004

[6] MERAYO, J.M.G. – BRAUER, P. – PRIMDAHL, F. – PETERSEN, J. R. – NIELSEN, O. V: Scalar Calibration of Vector Magnetometers, Meas. Sci. Technol., Vol 11, No 2, (2000) 120-132.

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