MEASURING THE ORTHOGONALITY ERROR OF COIL SYSTEMS

B. Heilig [(1)], A. Csontos [(1)], K. Pajunpää [(2)], D. Gouws [(3)], T. White [(4)], B. St-Louis [(5)], D. Calp [(5)]

[(1)] Geological and Geophysical Institute of Hungary, H-1143 Stefánia út 14, Budapest, Hungary, heilig.balazs@mfgi.hu,
[(2)] Finnish Meteorological Institute, Helsinki, Finland,
[(3)] South African National Space Agency, Hermanus, South-Africa,
[(4)] United States Geological Survey Geomagnetism Group, Golden, CO, USA
[(5)] Geological Survey of Canada, Ottawa, Canada

SUMMARY

Recently, a simple method was proposed for the determination of pitch angle between two coil axes by means of a total field magnetometer. The method is applicable when the homogeneous volume in the centre of the coil system is large enough to accommodate the total field sensor. Orthogonality of calibration coil systems used for calibrating vector magnetometers can be attained by this procedure. In addition, the method can be easily automated and applied to the calibration of delta inclination–delta declination (dIdD) magnetometers. The method was tested by several independent research groups, having a variety of test equipment, and located at differing geomagnetic observatories, including: Nurmijärvi, Finland; Hermanus, South Africa; Ottawa, Canada; Tihany, Hungary. This paper summarizes the test results, and discusses the advantages and limitations of the method.

1. INTRODUCTION

For the calibration of fluxgate magnetometers, mostly large room-sized coil systems are used. The precision of the calibration procedure depends on how accurately the orthogonality of the calibration coil system is known. The method considered to be the most reliable for the determination of the misalignment angles of the calibration coils is based on measurements made by a DI-flux magnetometer on a pillar in the centre of the coils (Pajunpää et al 2007). The coils should be large enough to have room for the instrument and the observer executing the measurements. The measurement is time-consuming. Here, a more time-efficient process is introduced which can be easily automated and can also be used with small-sized (15–20 cm in diameter) coils.

2. DESCRIPTION OF THE PROCEDURE

In this section the proposed method is summarized based on Heilig (2012). The procedure is based on a well-known method introduced by Alldredge and Saldukas (1964) to measure the magnitude of the magnetic field generated by a coil using a scalar magnetometer. Let $\boldsymbol{A}_{1+}$ and $\boldsymbol{A}_{1-}$ denote the bias fields created by positive and negative currents, respectively, in the coil C_1. These bias fields are collinear and equal in magnitude but oppositely directed. During a data acquisition sequence, the magnitude of the total field ($\boldsymbol{F}$) and the deflected fields ($\boldsymbol{F} + \boldsymbol{A}_{1+}$ and $\boldsymbol{F} + \boldsymbol{A}_{1-}$) are measured. The corresponding readings are F, F_{1+} and F_{1-}, respectively. Since the resulting vectors are coplanar, the magnitude of the bias field $A_1 = |\boldsymbol{A}_{1+}| = |\boldsymbol{A}_{1-}|$ can be easily obtained (Alldredge and Saldukas 1964) from the triangles formed by $\boldsymbol{F}$, $\boldsymbol{F}_{1+}$, $\boldsymbol{A}_{1+}$ and $\boldsymbol{F}$, $\boldsymbol{F}_{1-}$, $\boldsymbol{A}_{1-}$, respectively, by applying the law of cosines:

$$A_1 = \sqrt{\left(F_{1+}^2 + F_{1-}^2 - 2F^2\right)/2}\ , \tag{1}$$

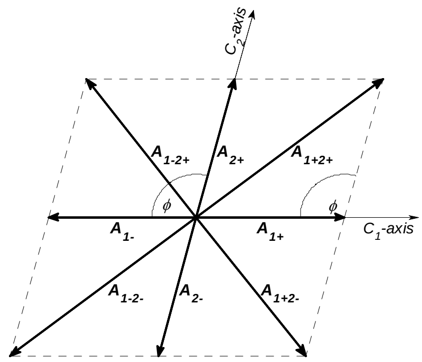

Figure 1 –Bias fields generated by the coils and their combinations (from Heilig, 2012)

If the current I_1 introduced in the coil is known, the coil constant can also be derived as A_1/ I_1.

Let C_1 and C_2 be two coils between which the pitch angle has to be determined. Let A_{2+}/A_{2-} denote the bias fields created by positive/negative currents in the C_2 coil. The corresponding magnetometer readings are F_{2+} and F_{2-}. The magnitude of the deflection field, A_2, in the coil C_2 can be calculated in the same way as A_1 in Equation (1). If A_{1+} and A_{2+} are applied simultaneously, a new combination bias field is created: the vector sum of A_{1+} and A_{2+}. Let us denote it by A_{1+2+} (Fig. 1). By changing the direction of the current in both coils, we get another bias field, A_{1-2-}. The two opposite bias fields are again of equal magnitude and coplanar, hence their magnitude (A_{12}) can be determined in the same way as in the single-coil case by Equation (1), namely

$$A_{12} = \sqrt{\left(F_{1+2+}^2 + F_{1-2-}^2 - 2F^2\right)/2}\,, \tag{2}$$

where $F_{1+2+} = |\boldsymbol{F} + \boldsymbol{A}_{1+2+}|$ and $F_{1-2-} = |\boldsymbol{F} + \boldsymbol{A}_{1-2-}|$. In Fig. 1, $A_1 = |\boldsymbol{A}_{1+}|$, $A_2 = |\boldsymbol{A}_{2+}|$ and $A_{12} = |\boldsymbol{A}_{1+2+}|$ form a triangle, and are related through the law of cosines as

$$A_{12}^2 = A_1^2 + A_2^2 - 2A_1A_2\cos\varphi\,, \tag{3}$$

from which φ can be easily calculated

$$\varphi = \arccos\left(\frac{A_{12}^2 - A_1^2 - A_2^2}{-2A_1A_2}\right), \tag{4}$$

Coils C_1 and C_2 are orthogonal if $\varphi = \pi/2$. Any deviation from this value is the degree to which the coil system is non-orthogonal. The orthogonality error is therefore defined as $\varepsilon = \varphi - \pi/2$. Applying the other combination of the bias fields, the angle φ' can be determined from

$$A_{21}^2 = A_1^2 + A_2^2 + 2A_1A_2\cos(\varphi') \tag{5}$$

where $A_{21} = |\boldsymbol{A}_{1+} + \boldsymbol{A}_{2-}| = |\boldsymbol{A}_{1-} + \boldsymbol{A}_{2+}|$ is the magnitude of the other combination of the bias fields. If all assumptions are valid, then $\varphi = \varphi'$ (or $\varepsilon = \varepsilon'$). Conversely, if $\varphi \neq \varphi'$, the symmetry of the system has been violated. Such cases are discussed in the following section.

3. TEST MEASUREMENTS AND RESULTS

The proposed method was tested by independent groups at different locations using different coil systems. The total field magnetometer applied for testing was a GEM System GSM-19 Overhauser magnetometer (using tuned mode at THY and using auto-tune mode elsewhere) in all locations, except for NUR, where a PMP-7 proton magnetometer was used. Here we summarize and discuss the most important test results.

Case 1: varying coil current (recorded): ELSEC Helmholtz coil pair at THY

A Helmholtz coil pair (C_V – vertical, C_H – horizontal) was driven by a current generator, and the current strength was recorded throughout the experiment. While the range of the current variation was about 1.8 mA (1.7 %), the magnitude of the opposite currents differed only a few tenths of a µA. Table 1 summarizes the observations. The bias fields computed using Eq. (1) were as follows: A_V = 15849.90 nT and A_H = 15636.78nT; the combined bias fields from Eq. (2): A_{VH} = 22330.28 nT and A_{HV} = 21810.56 nT. The difference between the two estimations of the orthogonality error, $|\varepsilon\text{-}\varepsilon'|$ was close to 2°. This large difference indicates that the measurements were contaminated, possibly by current strength variation. However, the temporal variation of the coil currents can be easily corrected by reducing all bias fields to the same current level according to $A_{xcorr} = A_x(I_{ref}/I)$, where I_{ref} is an arbitrarily chosen reference current strength (in our case 100 mA). The corrected values are: A_{Vcorr} = 15301.86 nT, A_{Hcorr} = 15353.28 nT, etc. With this simple correction the difference between the two estimations of the orthogonality error decreased below 0°01' (ε = 1°20'41", ε'=1°19'49") ! This example suggests that even slight current variations could corrupt the results if not taken into account.

***Table 1* – Example of a measurement cycle**

Comp.	[nT]	Current [mA]	Comp.	[nT]	Current [mA]
F	48158.34	0.000	F	48158.94	0.000
F_{V+}	62729.07	+103.582	F_{H+}	50789.71	+101.847
F_{V-}	34726.85	-103.582	F_{H-}	50477.62	-101.847
F	48159.13	0.000	F	48160.04	0.000
F_{V+H+}	64616.48	+101.828	F_{V+H-}	64191.42	+101.807
F_{V-H-}	38217.77	-101.828	F_{V-H+}	38335.9	-101.807

Case 2: varying, unknown coil current, semi-automated measurement, dIdD coil system at THY

With the same method, the orthogonality error of the *dIdD* coils can be measured directly, without any additional instrumentation. At the time of the test presented here, the magnitude of the ambient magnetic field, F, was about 48,200 nT, the inclination, $I \approx 63.5°$, and the declination, $D \approx 3.5°$. The applied bias field was about 11,800 nT (~ 25% of F). The absolute accuracy of the measurement of the bias fields is estimated to be better than 1 nT. At first, the instrument was run in the normal *dIdD* mode to derive A_d and A_i. In the second step, the current was introduced into both coils simultaneously. The C_D- and C_I-coils were connected in series to ensure the same current in both coils. From these measurement sequences the combination bias fields, A_{di} and A_{id} were then calculated. A full measurement sequence (10 readings) lasted less than 1 minute. Altogether 30 sequences were completed. The difference between the two estimations, $|\varepsilon\text{-}\varepsilon'|$ ranged between 0' and 5', likely again due to the variation of the current strength. GEM Systems' *dIdD* uses 10 mA current for generating the bias field in the coils. A 4 μA variation in the bias current could account for the observed differences. However, even if the current was not recorded during this experiment, the results can be corrected supposing that $I_D = I_I \neq I_{DI} = I_{ID}$ (which is reasonable if the current strength depends on the resistivity of the coils, since the resistivity of C_D- and C_I-coils are similar). If all four currents were equal, then the following equality (derived from the sum of Eqs. (3) and (5)) should be satisfied:

$$A_{di}^2 + A_{id}^2 = 2\left(A_i^2 + A_d^2\right), \tag{6}$$

Eq. (6) does not apply in the case of varying current. However, if the above assumptions on the bias currents ($I_D = I_I \neq I_{DI} = I_{ID}$) are valid, a constant γ (= I_{DI}/I_D) can be found that satisfies the following modified equation:

$$A_{di}^2 + A_{id}^2 = 2\gamma^2\left(A_i^2 + A_d^2\right), \tag{7}$$

This γ can then be used to correct the computed bias fields ($A_{xcorr} = \gamma A_x$).

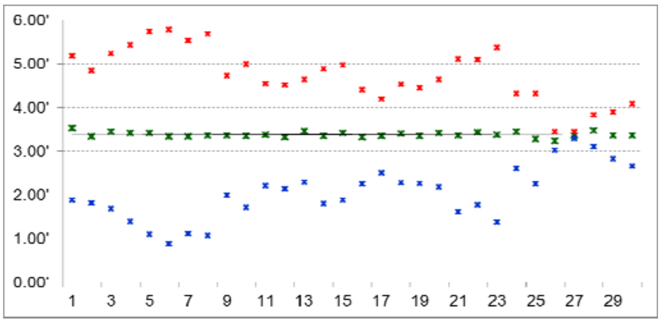

***Figure 2* –The results of the orthogonality error measurements of dIdD without (red and blue) and with (green) corrections**

Figure 2 shows the results of the test without corrections (red and blue x) and with corrections (green x) for current variations. Note that the corrected values are close to the arithmetic means of the uncorrected results. The mean of the 30 corrected observations is very stable, with a 0'04" standard deviation about 3'23".

Absolute accuracy

For practical applications, the most important consideration is absolute accuracy of the measurement. That is why the orthogonality error values obtained by the new method were compared to the values obtained by the well-proven FMI method. The FMI method is based on DIM absolute measurements carried out by an observer in the centre of the coil system (Pajunpää et al, 2007). At GSC, the FMI measurements were taken immediately before the new method was used. This ensures the highest level of consistency between the two methods. Table 2 summarizes the results of these comparisons, which were carried out by three different groups, FMI, SANSA, and USGS variously at the three locations, Nurmijärvi (Finland, NUR), Hermanus (South Africa, HER), Ottawa (Canada, OTT).

Table 2 **– Comparison of the results of the new method and the FMI method**

Coils	OTT FMI	USGS new	nr	HER FMI	SANSA new	nr	NUR FMI	FMI new	nr
HD (XY)	-2’07”±06”	-2’01”±01”	3*20	2’37”	2’42”±51”	6*1	0’04”±2”	0’10”±5”	3*1
HZ (XZ)	1’33”±06”	1’19”±02”	3*20	0’04”	n.a.	6*1			0
DZ (YZ)	1’48”±06”	1’34”±01”	3*20	0’04”	0’14”±31”	6*1			0

The difference was, in all cases, less than 10”-15”. However, the scatter of the results varies. At OTT, an extremely stable current generator was used, and the results published in Table 2 were achieved without any corrections. Also, during the three full tests, 20 magnetometer readings (‘nr’ in Table 2) were taken at each bias field applied. We therefore assume these two reasons as explanations for the lowest scatter in the results here

At HER, measurement sequences at two different current strengths were carried out for all dual combinations (HD, HZ, DZ) of the three calibration coils. Current strengths were recorded, and all measurements were later corrected for current changes. The angle between the HZ pair could not be determined because one of the deflected fields was too low (15-18 μT) to be measured accurately, since it is out of the measurement range of the Overhauser magnetometer. This failed test with the Hz coils occurred because the ambient field at HER is in the 25,700 nT range, being among the lowest of all observatories world-wide, and points to one of the limitations of the procedure. However, we think that the method could be modified for use in such circumstances simply by activating a third coil to increase the effective ambient field. But this modification has not yet been tested.

In NUR, only the XY coil pair was used for the test. Three measurement sequences were completed. Bias fields were corrected for the temporal variation of the coil currents. After the temporal variation correction, the mean result (0’06”±7”) was quite close to the reference value. However, we were not satisfied with large differences found between ε and ε'. In remediation, we corrected all magnetometer readings for the time variation of the geomagnetic field. The time series used for the correction, then, was calculated from the observed variations in the ambient field and from the corresponding constant bias fields. This correction resulted in the difference $|\varepsilon-\varepsilon'|$ decreasing from 3’-5’ to below 1’.

4. CONCLUSIONS

The tests show that the proposed method is suitable to measure the misalignment errors of coil systems. The procedure is much faster than the previous method based on DIM observations, and can be easily automated. With this method an accuracy close to 10” can be achieved for both the *dIdD* and the calibration coil system configurations.

However, there are limitations of the applicability of the method. The test results showed that the stability of the driving current is crucial. Only one of the tested current generators was stable enough to avoid having to apply a correction in the computed bias fields for current strength variation. At low magnetic latitudes, the low total field values of ambient field limit the applicability of the method. Also, in the low latitude zone measurements made in the meridional plane are critical. The procedure should be applied in quiet conditions. In moderately disturbed conditions the time variation of the geomagnetic field should be taken into account. In general, it is recommended to take many measurements and use the mean of all ε and ε' to arrive at the primary result. The method described here augments pre-existing practices but does not completely replace them. This method does not yield any information on the absolute orientation of the coils.

5. ACKNOWLEDGEMENT

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