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DETERMINATION OF THE OVERHAUSER MAGNETOMETER UNCERTAINTY

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Overhauser magnetometers are the basic instruments for scalar measurements; however, their accuracy is determined at the time of manufacture only. Because of various effects affecting the gyromagnetic ratio of the used fluid or the stability of the oscillators in the circuitry, their accuracy should be verified during the instrument lifetime. Specific methodology of data processing and determination of the Overhauser magnetometer uncertainty is described in this paper.

Keywords: Overhauser magnetometer, Earth’s magnetic field, comparison, uncertainty

1 INTRODUCTION

The international comparison APMP.EM-S14 [1] was a great opportunity, how to determine the accuracy (the uncertainty) of the Overhauser magnetometer by metrology institutes and geomagnetic observatories. Czech Metrology Institute (CMI) participated on this comparison with Faculty of Electrical Engineering of Czech Technical University in Prague (CTU) and Institute of Geophysics of the Academy of Sciences of the Czech Republic (IG) collaboration in the field of Earth magnetic field measurement. The transfer standard - a modified Overhauser magnetometer type MMPG-1 - was supplied by the pilot laboratory VNIIM, Russia. Its accuracy has been determined with an uncertainty of 0.054 nT [2]. CTU-CMI and IG dispose of a commercial portable quantum magnetometer type GSM-19 based on the Overhauser effect.

Various methods can be used for the comparison. The usual methodology exploits a calibrated coil system, where the magnetometers are compared in an artificial magnetic field generated by the coil. This method is more convenient when the testing of the magnetometers should be carried out in their whole measurement range. However, the coil system, that mostly also cancels the Earth's magnetic field, is very complicated equipment and it brings further uncertainties which have to be considered.

Therefore, we decided to simplify the comparison method and have performed the magnetometer calibration in a very quiet Earth's magnetic field in the nonmagnetic building of Budkov geomagnetic observatory (member of the INTERMAGNET network). The short-time variation of the magnetic field is below 0.1 nT at this place.

2 THEORY

The transfer standard and the compared magnetometer were placed at two distant pillars (designation B and D) to avoid mutual influences (see Fig 1 and Fig. 2). The magnetometers were oriented in the same correct position with respect to the magnetic field vector. The magnetic flux density (MFD) was measured with a repeating time interval of 3 s and later the values were transfered to PC. Unfortunately, the magnetometers could not be perfectly synchronized and so a stable time difference of 1 s occurred, but this was not significant from the statistical point of view.

As a first step, we measured values $B_{F(A)i}$ with CTU-CMI magnetometer (designation F) in position A at time t_i and also the values $B_{V(B)i}$ with VNIIM magnetometer (designation V) in position B at almost the same time t_i . The mutual position of the magnetometers was swapped after about five minutes, so that we obtained values $B_{F(B)j}$ measured with magnetometer CTU-CMI in position B at time t_j and also values $B_{V(A)j}$ measured with magnetometer VNIIM in position A at almost the same time t_j. Measurement (swapping) was repeated by this way several times.

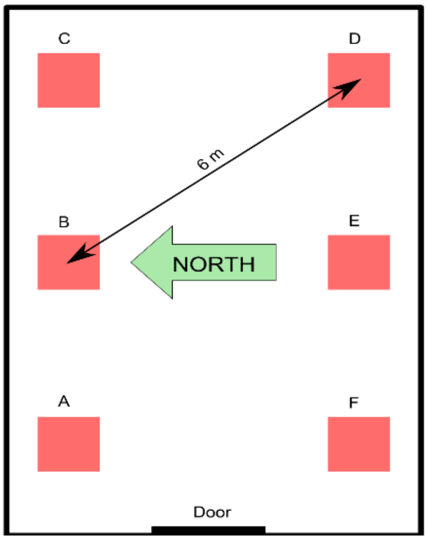

Fig. 1. Position of marble pillars (B and D) in Budkov absolute pavilion

Because of an existing, non-zero gradient between the two pillars A and B (approx. 6 nT) and because of the Earth’s field variations, specific methodology for data processing has been used. Differences $B_{F(A)i}$ - $B_{V(B)I}$ at time t_i

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were calculated together with differences $B_{F(B)j}$ - $B_{V(A)j}$ of opposite series at time t_j . By subtracting these differences we have got a double value of B difference between the two points A and B due to the MFD gradient. If the differences were summed and the result was divided by 2, the difference of the two compared magnetometers was obtained. Let us select n values of $B_{F(A)i}$ - $B_{V(B)i}$ and the same number of values of $B_{F(B)j}$ - $B_{V(A)j}$ that we have assigned randomly to the previous $B_{F(A)i}$ - $B_{V(B)i}$.

Fig. 2. Actual test setup with the compared magnetometers at the pillars B and D

The described calculation corresponds to an equation

$$\Delta_{FVi} = \frac{\left[\left(B_{F(A)i} - B_{V(B)i}\right) + \left(B_{F(B)j} - B_{V(A)j}\right)\right]}{2}, \qquad (1)$$

which is a result of one measurement of difference between the CTU-CMI and VNIIM magnetometers. The MFD gradient between the pillars was obtained during the comparison of the magnetometers according to

$$grad_i B_{FV} = \frac{\left[\left(B_{F(A)i} - B_{V(B)i}\right) - \left(B_{F(B)j} - B_{V(A)j}\right)\right]}{2}. \qquad (2)$$

The IG magnetometer (designation G) and VNIIM magnetometer were compared by the same way and in the same positions (difference Δ_{GV}). Also CTU-CMI and IG magnetometers were compared by the same way (difference Δ_{FG}), but this comparison was carried out three weeks later. These differences and relevant gradients can be calculated from

$$\Delta_{GVi} = \frac{\left[\left(B_{G(A)i} - B_{V(B)i}\right) + \left(B_{G(B)j} - B_{V(A)j}\right)\right]}{2}, \qquad (3)$$

$$\Delta_{FGi} = \frac{\left[\left(B_{F(A)i} - B_{G(B)i}\right) + \left(B_{F(B)j} - B_{G(A)j}\right)\right]}{2}, \qquad (4)$$

$$\mathrm{grad}_i B_{GV} = \frac{\left[\left(B_{G(A)i} - B_{V(B)i}\right) - \left(B_{G(B)j} - B_{V(A)j}\right)\right]}{2}, \qquad (5)$$

$$\mathrm{grad}_i B_{FG} = \frac{\left[\left(B_{F(A)i} - B_{G(B)i}\right) - \left(B_{F(B)j} - B_{G(A)j}\right)\right]}{2}. \qquad (6)$$

We decided to use linear regression (application of method of the least squares) to offset these differences. If the known measured differences are marked as $y_1 = \Delta_{FV}$, $y_2 = \Delta_{VG}$ and $y_3 = \Delta_{GF}$ then

$$y_1 + y_2 + y_3 = k\,, \qquad (7)$$

$$(A_1 + b_1) + (A_2 + b_2) + (A_3 + b_3) = k\,, \qquad (8)$$

where $\underline{A}_1$, A_2, A_3 are the correct values of differences, for which following condition is valid where u_γ is the coefficient γ_p of MFD conversion to frequency, u_{grad} is the uncertainty of the influence of vertical and horizontal gradients upon measured difference of B, u_{sysV} is the uncertainty of the influence of systematic uncertainty of measurement with magnetometer VNIIM, u_{sys} is the systematic uncertainty of measurement with magnetometer CTU-CMI or IG, u_{h} is the uncertainty of the influence of inhomogeneity of B upon measurement of B, u_{t} is the uncertainty of the influence of non-identical time of measurement of B, and u_{m} is the uncertainty of the influence of materials of

$$A_1 + A_2 + A_3 = 0\,, \qquad (9)$$

and b_1, b_2, b_3 are the parameters, for which is the following equation valid

$$b_1^2 + b_2^2 + b_3^2 = \min\,. \qquad (10)$$

Equation (10) is valid for following values of b_{i}

$$b_1 = b_2 = b_3 = \frac{k}{3}\,. \qquad (11)$$

For the measured differences we get from (7) and (8)

$$y_1 = A_1 + b_1, y_2 = A_2 + b_2, y_3 = A_3 + b_3 \qquad (12)$$

and by substituting the formula (11) we obtain the correct values A_1, A_2, A_3 as follows

$$A_1 = y_1 - \frac{k}{3}, \qquad (13)$$

$$A_2 = y_2 - \frac{k}{3}, \qquad (14)$$

$$A_3 = y_3 - \frac{k}{3}\,. \qquad (15)$$

The equations (15,16,17) can be also expressed as

$$A = \frac{2y_1 - y_2 - y_3}{3}, \qquad (16)$$

$$B = \frac{2y_2 - y_1 - y_3}{3}, \qquad (17)$$

$$C = \frac{2y_3 - y_1 - y_2}{3}\,. \qquad (18)$$

Table 1. Uncertainty budget

Source of uncertainty	Type of uncertainty	Sensitivity coefficient	Standard uncertainty value (nT)
u_{γ}	B	1	0.015
u_{grad}	B	1	0.100
u_{sysV}	B	1	0.025
u_{sys}	B	1	0.100
u_{h}	B	1	0.050
u_{t}	B	1	0.050
u_{m}	B	1	0.075
Standard deviation of measurement	A	1	0.026
Combined uncertainty	-	-	0.18
Expanded uncertainty (k=2)	-	-	0.36

Table 2. Mean gradient results

	Δ	<MFD> (nT)	σ, k=2 (nT/m)	<Δ_{T}> (nT/m/h)
CTU-CMI vs. VNIIM	Δ_{FV}	48582	0.887 ± 0.010	-0.035
IG vs. VNIIM	Δ_{GV}	48587	0.927 ± 0.014	+0.040
CTU-CMI vs. IG	Δ_{FG}	48577	0.784 ± 0.012	+0.060

Table 3. Measurement results (before linear regression)

	Δ (nT)	σ_{EXP}(nT)
$\boldsymbol{\Delta_{FV}}$	-0.144	0.020
$\boldsymbol{\Delta_{GV}}$	-0.496	0.012
$\boldsymbol{_{FG}}$	0.274	0.022

3 UNCERTAINTY ANALYSIS

The A-type uncertainty of the measurement is calculated from

$$u_{sA} = \sqrt{\frac{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2}{n\cdot\left(n-1\right)}}\ , \tag{19}$$

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i\ , \tag{20}$$

where *n* is the total number of measurements and is the arithmetic mean of the individual measured values x_{i}.

The B-type uncertainty of the Overhauser magnetometer measurements has several components, as follows

$$u_{sB} = \sqrt{u_{\gamma}^2 + u_{grad}^2 + u_{sysV}^2 + u_{sys}^2 + u_h^2 + u_t^2 + u_m^2}\ , \tag{21}$$

where u_{γ} is the coefficient γ_{P} of MFD conversion to frequency, u_{grad} is the uncertainty of the influence of vertical and horizontal gradients upon measured difference of *B*, u_{sysV} is the uncertainty of the influence of systematic uncertainty of measurement with magneto-meter VNIIM, u_{sys} is the systematic uncertainty of measurement with magnetometer CTU-CMI or IG, u_{h} is the uncertainty of the influence of inhomogeneity of *B* upon measurement of *B*, u_{t} is the uncertainty of the influence of non-identical time of measurement of *B*, and u_{m} is the uncertainty of the influence of materials of marble blocks.

The values of all type uncertainties including the expanded uncertainty are presented in Tab. 1.

Magnetometer comparison of the Mean value of < MFD> the Mean gradient of the MDF and its expanded standard deviation σ at *k* =2, and the Mean time change of gradient during measurement <Δ_{T}> - are in Table 2.

4 COMPARISON RESULTS

The arithmetic mean values Δ_{FV}, Δ_{GV}, Δ_{FG} and experimental standard deviations s_{FV} , s_{GV} , s_{FG} for evaluation of type A uncertainty were calculated from *n* measurement values by chosing several section of measurement (about two hundreds from each section, disregarding the values when the magnetometers were moved). These results of measured differences are presented in Table 3.

Mean values of measured gradients during the comparison are presented in Table 2. The least squares method described above was applied on the results from Table 3 and then the final comparison results were determined as

$$\Delta_{FV} = (-0.17 \pm 0.36)\,\mathrm{nT},$$
$$\Delta_{GV} = (-0.47 \pm 0.36)\,\mathrm{nT},$$
$$\Delta_{FG} = (0.30 \pm 0.36)\,\mathrm{nT}.$$

The final international comparison APMP.EM-S14 results of all participants who used different methods (Overhauser magnetometer, NMR magnetometer and AMR magnetometer) are in Fig. 3

5 CONCLUSIONS

A specific methodology of data processing for the international comparison of MMPG-1 Overhauser magnetometer was described. Also the uncertainty and uncertainty sources analysis of the Overhauser magnetometer measurements were determined during this comparison.

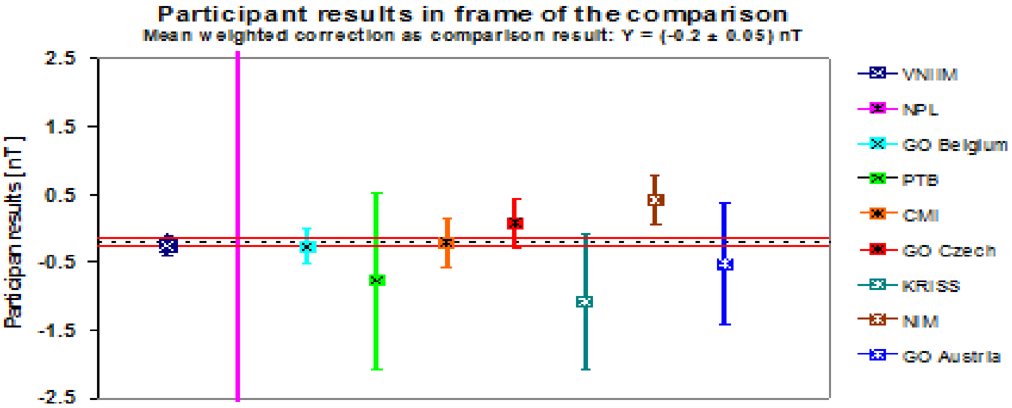

Fig. 3. Final results of APMP.EM-S14 international comparison for nominal value of 50 μT. GO Czech: IG magnetometer results and CMI: CTU-CMI magnetometer results

The final comparison results show that the proposed method was successful – after processing the final comparision results from all participants by the pilot laboratory, the required corrections of our results were only -0.02 nT (F) or 0.28 nT (G), respectively.

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