OBSERVATORY MAGNETOMETER IN-SITU CALIBRATION

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ABSTRACT

An experimental validation of the in-situ calibration procedure, which allows estimating parameters of observatory magnetometers (scale factors, sensor misalignment) without its operation interruption, is presented. In order to control the validity of the procedure, the records provided by two magnetometers calibrated independantly in a coil system, have been processed. The in-situ estimations of the parameters are in very good agreement with the values provided by the coil system calibration.

Keywords: Flux-gate, Magnetometer, Calibration, Coil, Least-square, Estimator

1 INTRODUCTION

Magnetic observatories are continuously striving to improve the accuracy of the magnetic field measurements. A renewed interest arose recently in instruments using a scalar sensor placed into the center of a coil system. These instruments are able to achieve very high accuracy but at the expense of relatively high background noise (Schott, Boulard, Pérès, Cantin, & Bitterly, 2001; Vershovskiy, 2007). So far, the majority of the observatories are still equipped with flux-gate or even photoelectric variometers. The baselines of these types of variometers are estimated using well-known absolute measurements, whereas the scale factors and orientation of the sensor reference frame, which are implicitly involved into the computation of the absolutes values of the field, usually are poorly known and in almost every case are not regularly calibrated, as should be required. The lack of periodic calibrations can be partly explained by the fact that the metrological certification of the instruments must be carried out in a special laboratory by means of calibration coils. This check requires interrupting the measurements, transporting the instrument to and from the calibration site and reinstalling it in the observatory. This method is absolutely unacceptable, especially for remote observatories, because the time taken by the whole procedure can be very long, resulting in large gaps in the records. For these reasons, in-situ calibrations are much more advisable. One well-known method is based upon magnetometer rotation in the approximately constant Earth's magnetic field. However, whereas this method gives acceptable precision for, e.g., satellite magnetometers, it is not applicable to observatory magnetometers due to the actual limited range of field variation, large relative errors, and possibly unequal scale factors. In addition, the issue of the in-situ orientation of the triaxial magnetometer remains unsolved if we are seeking high accuracy.

In this paper we continue to discuss the possibility of calibrating *in-situ* the observatory instrument by means of the comparison of its records with the field recorded simultaneously by a reference magnetometer. The certified reference instrument has to be installed close to the tested one, its sensitivity axes properly oriented with respect to the geomagnetic reference frame, and the records made as synchronous as possible. There were attempts (Heilig, 2006) to use natural geomagnetic variations as a calibrating signal. However, to our knowledge, no experiments using independently calibrated instruments have been conducted for validating *in-situ* calibration procedure. This is the goal of the present study.

2 DESCRIPTION OF THE EXPERIMENTS

The improved version of the observatory magnetometer LEMI-025 has been specially designed as a reference instrument. In order to check practical aspects of the proposed *in-situ* calibration procedure, two such magnetometers have been installed in the Strasbourg University geophysical station Welschbruch for intercalibration, and the records acquired from 28.05 till 01.06.2010 are analyzed hereafter (Figure 1). On September 06-07, 2010 these two instruments were calibrated in the Accredited Magnetic Calibration and Test Laboratory (Nurmijarvi Geophysical Observatory, Finland). Just after calibration the magnetometers were installed in the variometer hut of the observatory, and two days' records (Figure 2) were acquired and processed.

The Coil calibration results were also applied to the Welschbruch records *a posteriori*, so we expected that the processing of synchronous records from both sites would provide the same estimations of the scale factors ratios (Kxt/Kxr=0.9996±0.0004; Kyt/Kyr=1.0004±0.0004; Kzt/Kzr=1.0004±0.0004) and non-orthogonality angles (Table 1) as the coil calibration procedure (t stands for test instrument and r for reference one).

Table 1. Non-orthogonality of the magnetometers LEMI-025 #04 and #06 after coil calibration in Nurmijarvi Geophysical Observatory (decimal degrees of arc)

	#04	#06	#04 - #06
X <=> Y	0.00° ± 0.02°	-0.01° ± 0.02°	0.01° ± 0.03°
X <=> Z	0.01° ± 0.02°	0.01° ± 0.02°	0° ± 0.03°
Y <=> Z	0.01° ± 0.02°	-0.01° ± 0.02°	0.02° ± 0.03°

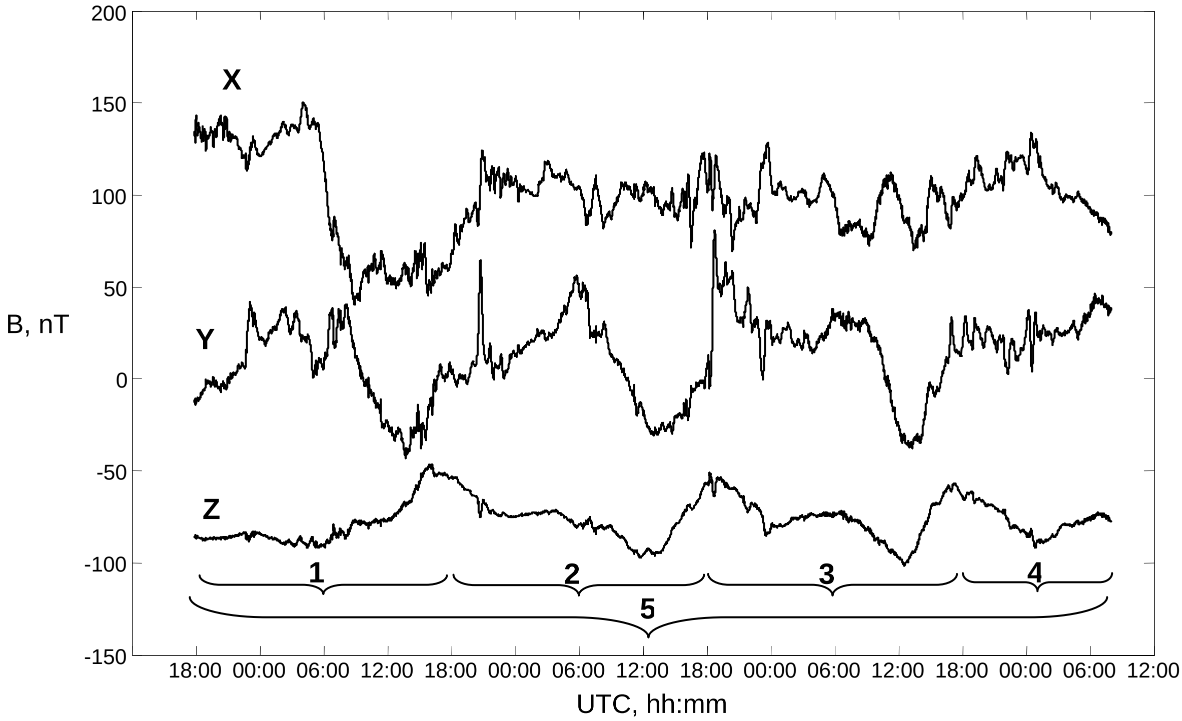

Figure 1. Records provided by magnetometer LEMI-025 #06 at Welschbruch Geophysical Station (28.05 – 01.06.2010)

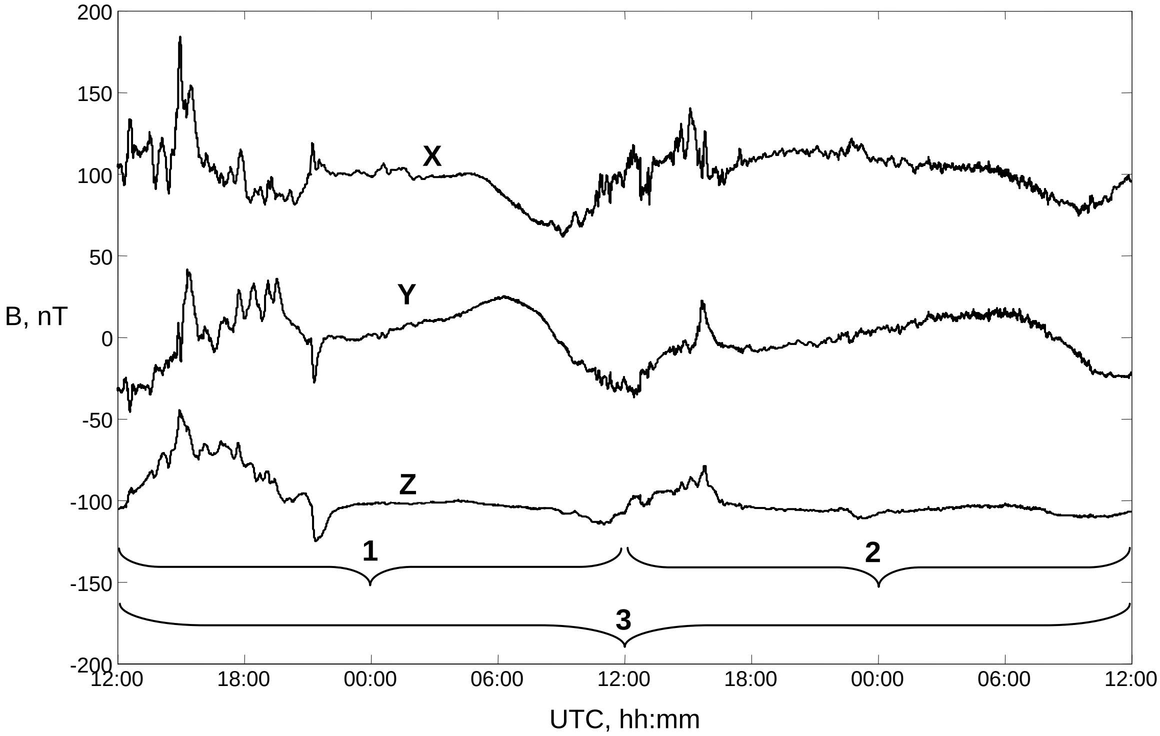

Figure 2. Records provided by the magnetometer LEMI-025 #06 at Nurmijarvi Geophysical Observatory (08.09 – 10.09.2010)

3 DATA PROCESSING ALGORITHM AND RESULTS OF INTERCALIBRATION

The magnetometers recorded data with a 10 Hz sampling rate and synchronization accuracy better than 10 ms. During the pre-processing step, disturbances, such as man-made magnetic disturbances, periodic signals from the scalar magnetic sensor, and spikes generated by the temperature regulator were partly corrected. In addition, the Welschbruch data are corrupted by magnetic signals from vehicles passing on the road nearby. This type of magnetic disturbances was not corrected. The cleaned data were filtered by means of a digital Gaussian FIR filter and decimated to 1 Hz sampling rate. These 1 Hz data were used for magnetometer parameter estimation. The LEMI-025 #06 was used as a reference instrument during all estimations and the LEMI-025 #04 as a test instrument.

The magnetometer readings are shaped into N x 3 matrixes **T** and **R** and incorporated into the following linear regression equation:

$$\mathbf{T} = (\mathbf{R} - \mathbf{d_r}) \cdot \mathbf{n} + \mathbf{d_t} \ , \tag{1}$$

where **n** is the 3 x 3 matrix mapping the reference signal onto the tested one and $\mathbf{d_r}$ and $\mathbf{d_t}$ the reference and tested instrumental noise respectively. The further decomposition of **n** provides the scale factors ratios and the angles of non-orthogonality.

A semi-parametric frequency domain weighted least squares estimator (FD WLSE) was employed for the estimation of the parameters. This method was proposed by Nielsen (2005) for finding the multilinear regression estimates when both errors and regressors are random variables with long-range autocorrelation, which is the case of synchronous measurements of geomagnetic variations. According to FD WLSE, estimation of regression parameters matrix may be found by the multivariate extension of the formula given by Nielsen (2005):

$$\mathbf{n}_{\gamma,m}^{\text{est}} = \left(\frac{1}{m} \cdot \sum_{j=1}^{m} \lambda_j^{\gamma} \cdot \mathrm{Re}\left(\mathbf{I}_{\mathbf{RR}}(\lambda_j)\right) \right)^{-1} \cdot \frac{1}{m} \cdot \sum_{j=1}^{m} \lambda_j^{\gamma} \cdot \mathrm{Re}\left(\mathbf{I}_{\mathbf{RT}}(\lambda_j)\right), \tag{2}$$

where $I_{RR,kl}(\lambda_j) = w_{R(\bullet,k)}(\lambda_j) \cdot w_{R(\bullet,l)}^{*}(\lambda_j) \in \mathbb{C}$ unless $k = l, \dim(\mathbf{I}_{\mathbf{RR}}) = 3 \times 3$ – elements of the cross-periodogram matrix $\mathbf{I}_{\mathbf{RR}}$ between time series measured by the reference magnetometer;

$I_{RT,kl}(\lambda_j) = w_{R(\bullet,k)}(\lambda_j) \cdot w_{T(\bullet,l)}^{*}(\lambda_j) \in \mathbb{C}$ unless $k = l, \dim(\mathbf{I}_{\mathbf{RT}}) = 3 \times 3$ – elements of the cross-periodogram matrix $\mathbf{I}_{\mathbf{RT}}$ between time series measured by the reference and tested magnetometers;

the asterisk (*) denotes complex conjugation;

$w_{R(\bullet,k)}(\lambda_j) = \frac{1}{\sqrt{2\pi N}} \cdot \sum_{t=1}^{N} R(t,k) \cdot e^{it\lambda_j}$ and $w_{T(\bullet,k)}(\lambda_j) = \frac{1}{\sqrt{2\pi N}} \cdot \sum_{t=1}^{N} T(t,k) \cdot e^{it\lambda_j}$ – discrete Fourier transforms of the time series recorded by the reference and tested magnetometers accordingly;

$\lambda_j = 2\pi j/N$ – normalized frequency of discrete Fourier transform;

$m = m(N)$ – a bandwidth parameter;

γ – parameter, which takes into account the power law dependence of spectral density of regression errors.

According to *a priori* information about spectral characteristics of the magnetometers noise, the parameter γ was set to 1 for all calculations. As follows from Eq. (2), the estimator uses a limited band of the whole spectrum of signals. The harmonics of discrete Fourier transform with numbers above *m* are not used in calculations. For all estimations, the parameter *m* was selected in such a way that the upper limit of the frequency band did not exceed 0.01 Hz. The records at Welschbruch station revealed a noticeable baseline instability on all components, and in addition, the trends of X and Z components looked strongly correlated (Figure 3). These correlated drifts (observed also in Nurmijarvi data (Figure 4), however, with an order of magnitude less) were obviously caused by tiny tilts of the sensors occurring during the recording time span. To avoid the influence of this effect on parameter estimations, the first harmonics of the Fourier spectra were excluded from calculations. This was performed by modifying Eq. (2) in order to sum up in the range [m_0, m], the value of m_0 corresponding to a lower limit of the frequency band approximately equal to 0.0002 Hz. In order to take into account a possible zero drift the column of a linear trend was also added to the data of the reference magnetometer.

The Welschbruch records were subdivided into four intervals as shown in Figure 1. The parameter matrix was estimated using data from each of these intervals as well as from the full-length record. The scale factors, non-orthogonality angles, and mutual orientation of the sensors were then derived from the matrix decomposition (Figure 5). The Nurmijarvi records were processed likewise, apart from the total number of intervals, which was equal to three - two 24-hours intervals and whole record - (Figure 2). The estimations obtained are presented in Figure 6. In both cases the estimations are given with a 95% confidence interval (depicted by error bars in Figures 5 and 6). The middle rows of plots in Figures 5 and 6 represent the differences of angles (X,Y), etc. between the tested and the reference magnetometer (compare to column 3 of Table 1). They would display the misalignment of the sensors of tested magnetometer if the reference magnetometer would be perfectly aligned. This is not strictly the case, but the misalignment of the reference magnetometer is small, according to column 2 of Table 1 (actually, the misalignment of the tested magnetometer is small too). The bottom rows of plots in these figures show the positions of the tested magnetometer axes with respect to the close to orthogonal reference instrument axes.

4 DISCUSSION OF THE IN-SITU CALIBRATION ESTIMATIONS

Figure 6 shows that the estimations based upon the Nurmijarvi records are mutually well consistent, with narrow confidence intervals, and are consistent too with the coil calibration outcomes. Indeed, all estimated parameters fall within the Coil calibration uncertainty. On the other hand, the parameters provided by the Welschbruch records are more scattered and have larger confidence intervals (Figure 5), especially for the parameters involving the Z component, i.e. scale factor ratio Kzt/Kzr and non-orthogonality angles between Z and X, Z and Y axes respectively. In addition, they are, on average, biased with respect to the expectation provided by the coil calibrations. Kxt/Kxr, Kyt/Kyr, Kzt/Kzr and the non-orthogonality angle Y - Z are biased by -0.04 % and 0.03° respectively.

The scattered distribution of estimations and their bias in the case of Welschbruch may be partly explained by a weaker strength of the vertical component of the geomagnetic variations in the frequency band used for processing as well as by the higher level of local magnetic disturbances and poorer baseline stability (compare Figures 3 and 4).

However, both Welschbruch and Nurmijarvi estimations of the mutual misalignment of the sensors' directions (the lowest plots in Figures 5 and 6) are well below 0.5 degrees of arc, an accuracy expected with the sensor platform levelling.

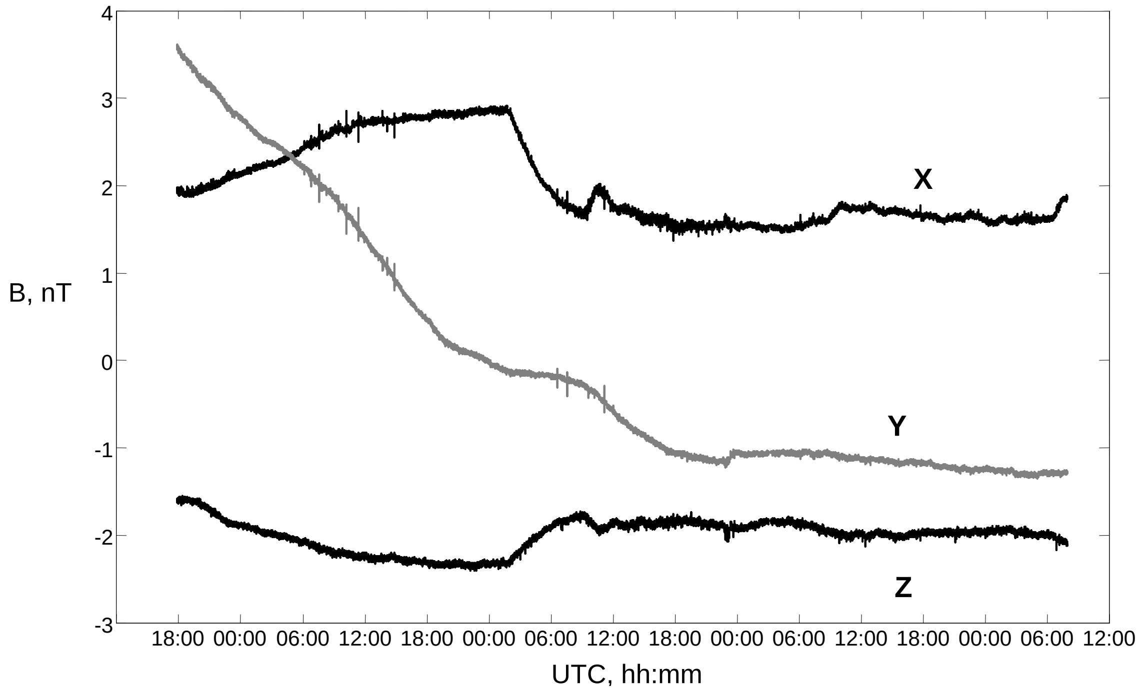

Figure 3. Signal differences between magnetometers LEMI-025 #04 and #06 at Welschbruch Geophysical Station (28.05 – 01.06.2010).

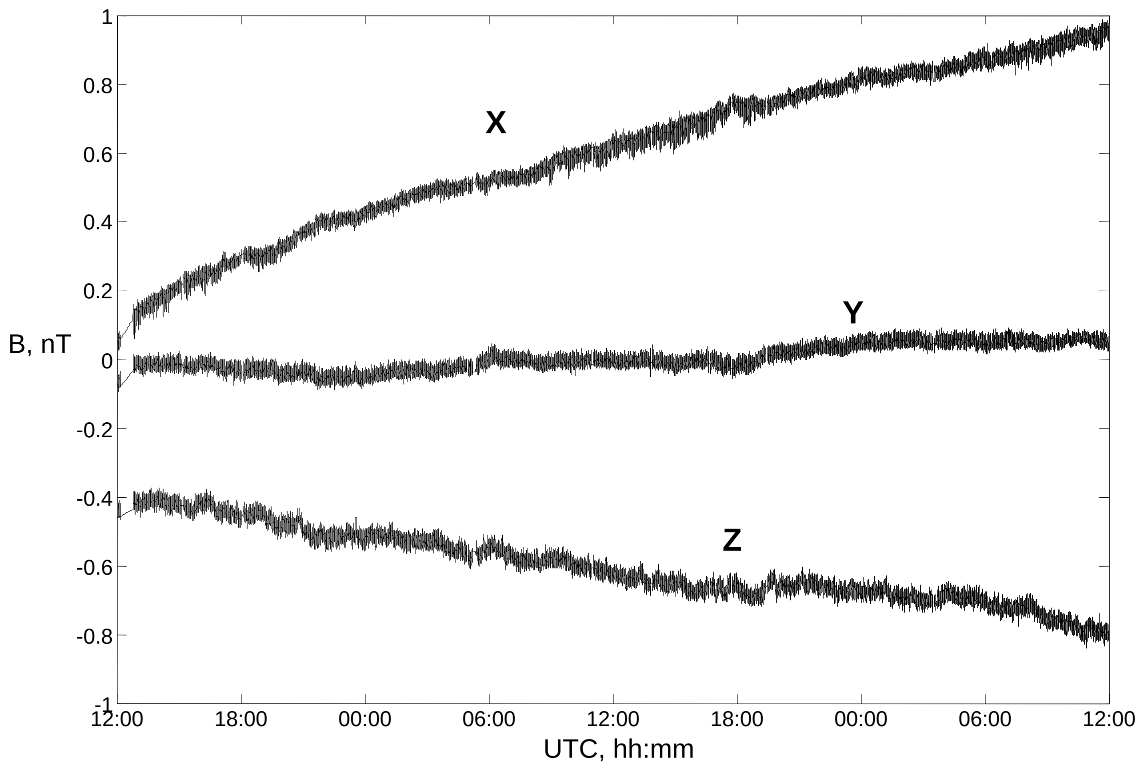

Figure 4. Same as Figure 3 at Nurmijarvi Geophysical Observatory (08.09 –10.09.2010).

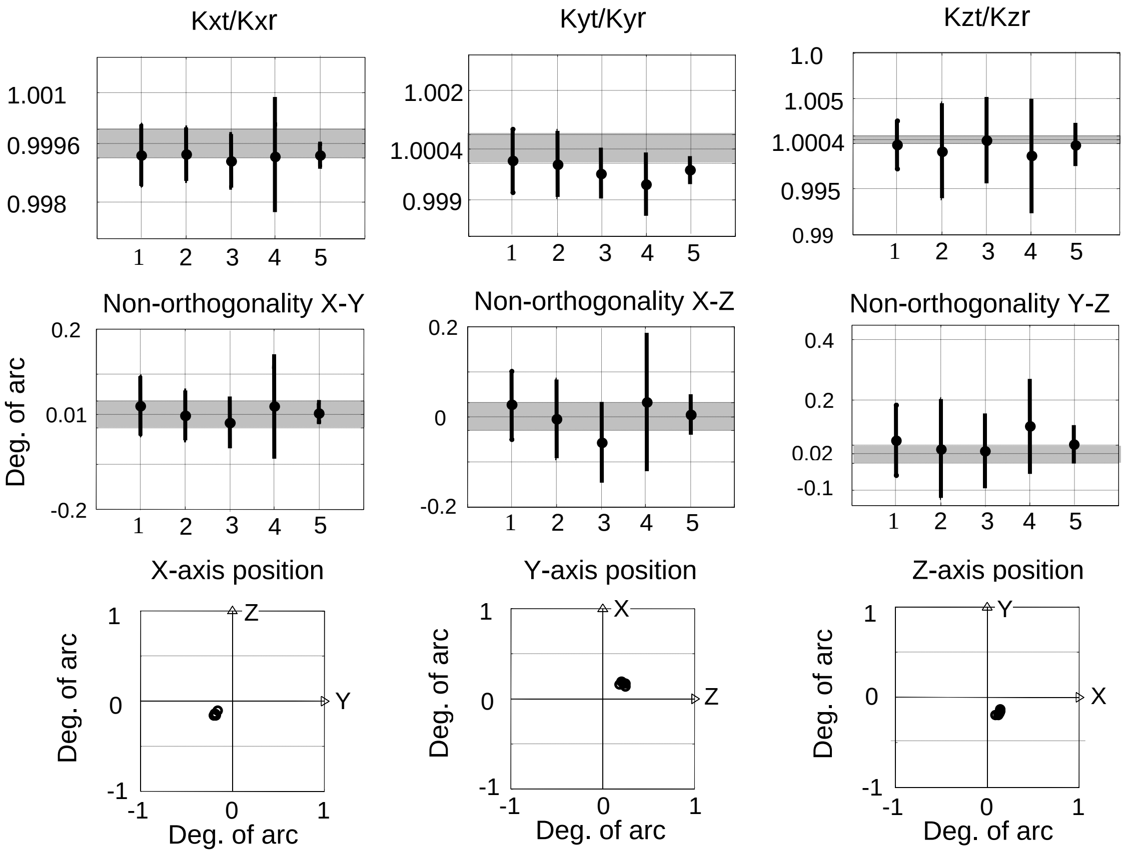

Figure 5. In-situ calibration of magnetometers LEMI-025 #04 and #06 at Welschbruch Geophysical Station (28.05 – 01.06.2010). The uncertainty of the Coil calibration results are depicted by grey zones.

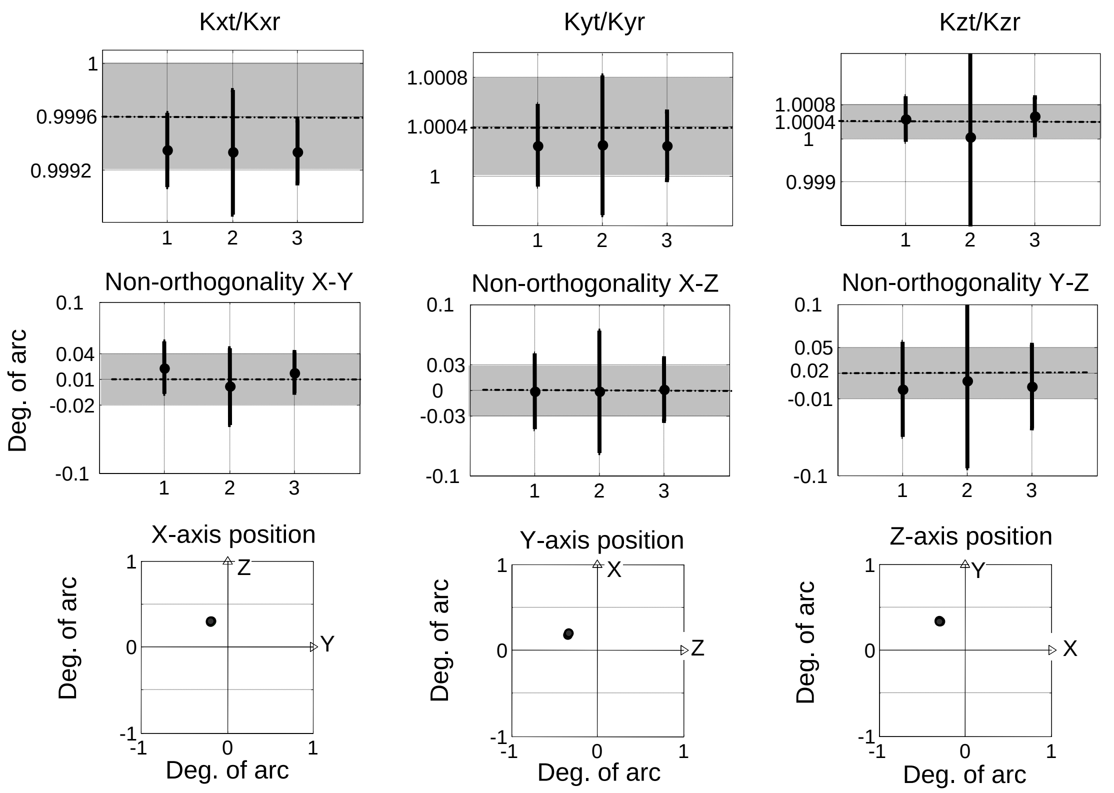

Figure 6. In-situ calibration of magnetometers LEMI-025 #04 and #06 at Nurmijarvi Geophysical Observatory (08 – 10.09.2010). The uncertainty of the Coil calibration results are depicted by grey zones.

5 CONCLUSION

The first tests of the *in-situ* calibration procedure we are currently working on have been performed at two sites with quite different magnetic environments, using two calibrated magnetometers. The magnetic environment, especially in the geophysical station of Welschbruch, and the behavior of the reference magnetometers were far from those assumed in the mathematical model implemented in the processing. Interferences produced by the proton magnetometer, the temperature stabilizing system, vehicles passing on the road nearby, and baseline drift made data processing more complicated than expected at the beginning of the tests. Inasmuch as such conditions could happen during actual application of the *in-situ* calibration procedure, the selection of appropriate pieces of records and processing using an algorithm with robust properties with respect to data not fulfilling the assumptions are recommended for successful implementation of the proposed calibration procedure.

But even in these far from ideal conditions, encouraging results were obtained. The low noise level of magnetometer LEMI-025 was experimentally confirmed; intercalibration errors of the order of 0.1% for scale factors and 0.1 degree of arc for non-orthogonality angles were obtained. This allows us to conclude that both the proposed *in-situ* calibration method and the reference 1-second LEMI-025 magnetometer have good perspectives for further applications.

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