Geosci. Instrum. Method. Data Syst., 6, 361–366, 2017
https://doi.org/10.5194/gi-6-361-2017


Geoscientific Instrumentation Methods and Data Systems
Open Access

# In situ vector calibration of magnetic observatories

**Alexandre Gonsette, Jean Rasson, and François Humbled**

Centre de Physique du Globe, Royal Meteorological Institute, 5670 Dourbes, Belgium

*Correspondence to:* Alexandre Gonsette (agonsett@meteo.be)

Received: 3 March 2017 – Discussion started: 27 March 2017
Revised: 29 June 2017 – Accepted: 13 July 2017 – Published: 25 September 2017

**Abstract.** The goal of magnetic observatories is to measure and provide a vector magnetic field in a geodetic coordinate system. For that purpose, instrument set-up and calibration are crucial. In particular, the scale factor and orientation of a vector magnetometer may affect the magnetic field measurement. Here, we highlight the baseline concept and demonstrate that it is essential for data quality control. We show how the baselines can highlight a possible calibration error. We also provide a calibration method based on high-frequency "absolute measurements". This method determines a transformation matrix for correcting variometer data suffering from scale factor and orientation errors. We finally present a practical case where recovered data have been successfully compared to those coming from a reference magnetometer.

## 1 Introduction

Most magnetic observatories are built according to a standardized or universally adopted scheme (Jankowski and Sucksdorff, 1996) including at least a set of three major instruments: a variometer, an absolute scalar magnetometer, and a declination and inclination flux instrument (DI-flux instrument). The different data streams are combined to build a unique vector of magnetic field data. The variometer is a vector magnetometer, which records variations of the magnetic field components at a regular interval (e.g. at 1 Hz). However, this is not an absolute instrument. In particular, reference directions, the vertical and geographical north, are not available. They usually work as near-zero sensors, so that an offset must be added to the relative value of each component in order to adjust it and therefore determine the complete vector. Those offsets or baselines should be as constant as possible but may drift more or less depending on the environment stability and device quality. For instance, thermal variations may affect the pillar stability. A baseline can also suffer from sudden variation due to an instrumental effect after a (unwanted) motion like a shock due to maintenance staff or a change in the surrounding environment (Fig. 1). A regular determination of the baselines is thus necessary to take their change into account. This is the main goal of the well-known "absolute measurements" that are carried out by the two other instruments.

First, a scalar magnetometer records the intensity of the field $|\boldsymbol{B}|$. Most of the time, a proton precession or an Overhauser magnetometer is used for this task. Overhauser magnetometer exploits the fact that protons perform precession at a frequency proportional to the magnetic field according to

$$\omega_{\text{precession}} = \gamma \, \|\boldsymbol{B}\|, \tag{1}$$

where $\gamma$, the gyromagnetic ratio, is a fundamental physical constant (Mohr et al., 2016). Therefore, this magnetometer can be considered an absolute instrument.

The last instrument serves to determine the magnetic field orientation according to reference direction. Magnetic declination is the angle between true north and the magnetic field in a horizontal plane, and the inclination is the angle between the horizontal plane and the field. In a conventional observatory, a DI-flux instrument (non-magnetic theodolite-embedding single-axis magnetic sensor) is manipulated by an observer according to a particular procedure (Kerridge, 1988) taking about 15 min per measurement. This instrument is also considered absolute because angles are measured according to geodetic reference directions. Due to this manpower dependency, the frequency of absolute measurements does not exceed once per day (St Louis, 2012). However, new automatic devices such as AutoDIF (automatic DI-flux instrument; Gonsette et al., 2012) close the loop by automa-

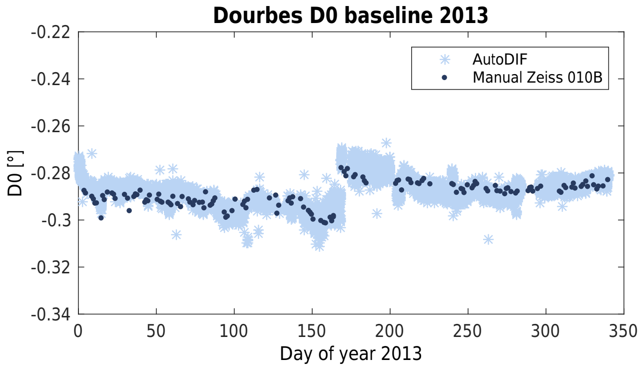


**Figure 1.** Baseline example computed from conventional manual measurements (dark blue) and the automatic system (light blue). In mid-2013, a baseline jump corresponding to an instrumental effect occurred, proving that regular absolute measurement are crucial.

tising the DI-flux measurements procedure. Moreover, AutoDIF is able to increase the frequency of baseline determination by performing several measurements per day.

After collecting synchronised data from the three instruments, baselines are computed by using the relation for the Cartesian coordinate system:

$$\begin{bmatrix} X_0(t) \\ Y_0(t) \\ Z_0(t) \end{bmatrix} = \begin{bmatrix} X(t) \\ Y(t) \\ Z(t) \end{bmatrix} - \begin{bmatrix} \delta X(t) \\ \delta Y(t) \\ \delta Z(t) \end{bmatrix}, \tag{2}$$

where $X(t)$, $Y(t)$ and $Z(t)$ are, at the time $t$, the tree conventional components of the field, pointing to the geographic north, eastward and downward respectively. The "0" index refers to the baseline spot measurements, while $\delta$ refers to the variometer data. The full baseline measurement protocol including a set of four absolute declinations and four absolute inclinations (even if only two are required for determining all the unknowns) can be found in the literature; this can also be found for spherical and cylindrical configurations (Rasson, 2005). The need for eight (at least six) measurements is justified by the DI-flux sensor offset and misalignment. A baseline function is then applied on these measurements using various methods such as a least-squares polynomial or spline approximation. Finally, the vector field is constructed by adding the variometer values to the adopted baselines.

Equation (2) assumes a variometer properly set up with the $Z$ axis vertical and the $X$ axis pointing toward the geographic north. The scale factor of each component is also assumed to be perfect.

A correct orientation is usually ensured by paying attention during the set-up step, but its stability in time is not always evident. Permafrost areas are examples of drifting regions (Eckstaller et al., 2007) where variometer orientation is not guaranteed. If the orthogonality errors are neglected, the problem of calibration can be expressed as follows:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \mathbf{R}_z(\gamma)\mathbf{R}_y(\beta)\mathbf{R}_x(\alpha) \begin{bmatrix} k_1 & 0 & 0 \\ 0 & k_2 & 0 \\ 0 & 0 & k_3 \end{bmatrix} \begin{bmatrix} \delta U \\ \delta V \\ \delta W \end{bmatrix} + \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix}, \tag{3}$$

where the $\mathbf{R}_{x,y,z}$ are an elementary rotation matrix and the $k_i$ variables are the scale factors for each component. $U$, $V$ and $W$ are the three variometers output into the sensors reference frame. Calibration procedures can be divided into two categories. On one hand, the scalar calibration compares scalar values computed from the vector magnetometer to absolute scalar values. This technique is exploited by satellites because the vector reference field is not available. Nevertheless, instruments are orbiting around the Earth (Olsen et al., 2003). The different scalar measurements from the scalar instrument can therefore be compared to the scalar values computed from the vector instrument. On the other hand, the vector calibration directly compares vector magnetometer measurements to the reference vector value. Marusenkov et al. (2011) used a second variometer already calibrated as the reference. Previously, Jankowski and Sucksdorff (1996) proposed a comparison between the variometer data and the absolute measurements performed during disturbed days in order to calibrate the observatory. The development was made for small angle errors (no more than 1–2°), but Jankowski and Sucksdorff (1996) suggested that the method could remain valid for any angle. Jankowski and Sucksdorff (1996) also pointed out the difficulty in getting sufficiently strong magnetic activity at low latitudes. The method presented in this paper is relatively close to the latter, except for the fact that the automatic DI-flux instrument can generate a large number of absolute measurements within a short time (e.g. 48 absolute measurements every 24 h), leading to a fast automatic calibration process also at low latitude or during significantly magnetic periods.

The method presented in this document is related to a variometer in XYZ configuration. However, other configurations may also be considered. For instance, many observatories set up their magnetometers in an HDZ configuration, where $H$ is the direction of the magnetic north, $D$ the declination and $Z$ the vertical component. Working directly with the $D$ component would lead to non-linear equations. Nevertheless, most modern variometers are based on fluxgate sensor technology. Thus, the recorded signal is the orthogonal projection of the field along the fluxgate sensitive axis. The residue ($\delta E$) expressed in nT (nanotesla) can be used like any geographic component and converted afterward into a declination value according to

$$\delta D = \frac{180}{\pi} \operatorname{asin}\left(\frac{\delta E}{H}\right). \tag{4}$$

The same approach can be used for a DFI magnetometer. However, the reader should keep in mind that not all variometer axes might have a compensating coil allowing them to work in the entire field. Indeed, recording the $D$ and $I$ variations is similar to a DI-flux process. The sensor is quasi-perpendicular to the field so that the residues are close to zero. The recorded signal could rapidly saturate.

## 2 Calibration error detection

Before solving the calibration problem, it could be useful to give some clues for detecting required adjustments. Indeed, it is difficult, when only examining definitive data, to detect a few nanotesla errors in daily amplitude. Direct comparison with other observatories requires them to be close enough while many observatories cannot afford to buy an auxiliary variometer. Fortunately, baselines are useful tools for checking data. As described below, they are affected by calibration errors, and, if they are measured with a sufficiently high frequency, particular errors can be highlighted.

### 2.1 Scale factor error

Let us consider an observatory working with a variometer, such as a LEMI-025, in a Cartesian coordinate system. Each sensor converts a real magnetic signal expressed in nanotesla into a more suitable format (usually a voltage). This converted signal passes through an ADC providing, in turn, a digital representation of the initial signal. A scale factor is then used to convert the true signal into a digitised signal. Consider the $X$ component:

$$\delta X_{\text{voltage}} = k_1\, \delta X_{\text{real}}, \tag{5}$$

$$\delta X_{\text{digital}} = k_2 \delta X_{\text{voltage}} = k\, \delta X_{\text{real}}, \tag{6}$$

where $\delta X_{\text{real}}$ is the real magnetic variation in nT toward the $X$ direction, $k_1$ is a scale factor in volt/nT converting the magnetic field signal into an electrical signal, $\delta X_{\text{voltage}}$ is the image of the field signal expressed in volts, $k_2$ is a scale factor in nT/volt converting the electric signal into a digital value, $k = k_2 k_1$ is the dimensionless scale factor converting the real magnetic signal into its digital representation. $k$ should be as close to 1 as possible.

Supposing now a difference between the digital and real variation of a component resulting from a badly calibrated scale factor, the baseline measurement will be affected by this error:

$$\begin{bmatrix} X_0^*(t) \\ Y_0^*(t) \\ Z_0^*(t) \end{bmatrix} = \begin{bmatrix} X(t) \\ Y(t) \\ Z(t) \end{bmatrix} - \begin{bmatrix} k_x & 0 & 0 \\ 0 & k_y & 0 \\ 0 & 0 & k_z \end{bmatrix} \begin{bmatrix} \delta X(t) \\ \delta Y(t) \\ \delta Z(t) \end{bmatrix}, \tag{7}$$

$$\begin{bmatrix} X_0^*(t) \\ Y_0^*(t) \\ Z_0^*(t) \end{bmatrix} = \begin{bmatrix} X_0(t) \\ Y_0(t) \\ Z_0(t) \end{bmatrix} + \begin{bmatrix} (1-k_X) & 0 & 0 \\ 0 & (1-k_Y) & 0 \\ 0 & 0 & (1-k_Z) \end{bmatrix} \begin{bmatrix} \delta X(t) \\ \delta Y(t) \\ \delta Z(t) \end{bmatrix}. \tag{8}$$

The (*) symbol denotes the erroneous baseline affected by a scale factor error. The baseline then varies with respect to its corresponding variometer component value, meaning that a correlation exists between both.

The scale factor is usually factory calibrated and should be stable over time. It is certainly true but there are many situations for which the scale factor is not known exactly (e.g. a homemade instrument) or differs from its factory value (e.g. a repair after a lightning strike may affect the instrument parameters). The impact of a scale factor error also depends on the magnitude of the magnetic activity. A 1 % error for the $H$ component scale factor at mid-latitude would lead to no more than 0.5 nT during quiet days. On the other hand, the same percent error at high latitude during a stormy day may affect the data by several nT.

### 2.2 Orientation error

Now, let us consider once again the same XYZ variometer but this time presenting an orientation error. That could be due, for instance, to a levelling error caused by a bad set-up or an unstable basement and/or an $X$ axis pointing to any other direction than the conventional one. The given components are affected by this orientation error and do not correspond to the expected ones. This is the reason why instruments such as ASMO (Alldregde, 1960) or any other three-axis magnetometers will never be considered as a full magnetic observatory.

Rasson (2005) treated the simplified case of a rotation $\theta$ around the $Z$ axis. The orthogonality between components was assumed to be perfect. In that particular case, the relative real values at time $t$ are given by

$$\begin{bmatrix} \delta X(t) \\ \delta Y(t) \\ \delta Z(t) \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \delta U(t) \\ \delta V(t) \\ \delta W(t) \end{bmatrix}. \tag{9}$$

The $X_0$ baseline, for instance, should be computed as

$$X_0 = X(t) - \cos(\theta)\, \delta U(t) + \sin(\theta)\, \delta V(t). \tag{10}$$

If no correction is applied, the observed baseline gives the following form:

$$X_0^* = X_0 - (1 - \cos(\theta))\, \delta U(t) - \sin(\theta)\, \delta V(t). \tag{11}$$

In this case, a correlation exists between the baseline and another relative component. Figure 2 shows an example of a variometer rotated around its vertical axis by 1.7°. The high-resolution baseline (blue) computed by means of an automatic DI-flux instrument presents the same trend as the $\delta Y$ (red) component. The peak–peak amplitude is more than 2 nT.

The general case is much more complex in particular if the orientation error is combined with a significant scale factor error. Indeed, the term $(1-\cos(\theta))$ in Eq. (11) may be interpreted either as a scale factor error or as an orientation error.

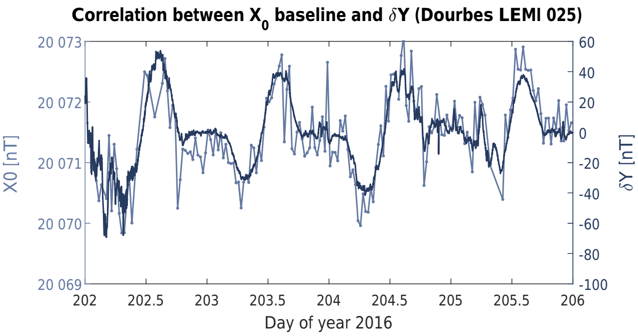


**Figure 2.** Light blue: $\mathbf{X}_0$ baseline computed from high-frequency absolute measurements. Dark blue: variometer $Y$ component from the LEMI-025. Because the variometer is not properly oriented, a strong correlation appears between $\mathbf{X}_0$ and $\mathbf{Y}$.

## 3 Calibration process

Absolute measurements, before giving baselines, provide absolute or spot values of the magnetic field. When performed with a sufficiently high frequency (e.g. once per hour), the generated magnetogram can be compared to the variometer value. Therefore, a vector calibration can be done as if a reference variometer was available.

A DI-flux instrument, either a manual system such as a Zeiss 010-B or an automatic system like the AutoDIF, is affected by the sensor offset and misalignments errors. A single spot measurement is therefore computed from a set of four declination (index 1 to 4) and four inclination (index 5 to 8) records. The eight synchronised variometer values as well as the eight scalar measurements are averaged. Thus, each spot value and corresponding variometer value is computed as follows:

$$X_m = \frac{\sum F_i}{8}\cos\left(\frac{I_5+I_6+I_7+I_8}{4}\right)\cos\left(\frac{D_1+D_2+D_3+D_4}{4}\right), \quad (12)$$

$$Y_m = \frac{\sum F_i}{8}\cos\left(\frac{I_5+I_6+I_7+I_8}{4}\right)\sin\left(\frac{D_1+D_2+D_3+D_4}{4}\right), \quad (13)$$

$$Z_m = \frac{\sum F_i}{8}\sin\left(\frac{I_5+I_6+I_7+I_8}{4}\right), \quad (14)$$

$$\begin{bmatrix} \delta U_m \\ \delta V_m \\ \delta W_m \end{bmatrix} = \frac{1}{8}\begin{bmatrix} \sum \delta U_i \\ \sum \delta V_i \\ \sum \delta W_i \end{bmatrix}, \quad (15)$$

where, the "$i$" index refers to the records 1 to 8 synchronised with the four declinations and the four inclinations.

Let us consider a series of $n$ samples built from Eqs. (12)–(15). The general case, including orthogonality errors, can be expressed by rewriting Eq. (3) as follows:

$$\begin{bmatrix} \boldsymbol{X}_m \\ \boldsymbol{Y}_m \\ \boldsymbol{Z}_m \end{bmatrix}^{\mathbf{T}} = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix}\begin{bmatrix} \delta\boldsymbol{U}_m \\ \delta\boldsymbol{V}_m \\ \delta\boldsymbol{W}_m \end{bmatrix}^{\mathbf{T}} + \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix}, \quad (16)$$

where $X_m = [X_{m1}, \ldots, X_{mn}]^T$, $Y = [Y_{m1}, \ldots, Y_{mn}]^T$, $Z = [Z_{m1}, \ldots, Z_{mn}]^T$ are the time series of $X$, $Y$ and $Z$ spot values recorded by means of the absolute instruments and $\delta U = [\delta U_{m1}, \ldots, \delta U_{mn}]^T$, $\delta V = [\delta V_{m1}, \ldots, \delta V_{mn}]^T$, $\delta W = [\delta W_{m1}, \ldots, \delta W_{mn}]^T$ are the three component time series of the variometer. Because the period of acquisition is relatively small (a few days is enough), the baseline values $X_0$, $Y_0$, $Z_0$ are assumed to be constant. For each component $X$, $Y$ and $Z$, the problem consists of solving a linear system, where a time series of spot values and the quasi-synchronised three variometer components are the input. Assuming the system to be overdetermined, the latter is solved in the least-squares sense. Equation (17) gives the coefficients corresponding to the $X$ component (others are similar):

$$\begin{bmatrix} a \\ b \\ c \\ X_0 \end{bmatrix} = \left(\mathbf{A}^{\mathbf{T}}\mathbf{A}\right)^{-1}\mathbf{A}^{\mathbf{T}}\mathbf{X}, \quad (17)$$

where $\mathbf{A} = \begin{bmatrix} \delta\mathbf{U} & \delta\mathbf{V} & \delta\mathbf{W} & \mathbf{1}\end{bmatrix}$. Once the whole coefficients matrix is determined, the variometer data are redressed:

$$\begin{bmatrix} \delta\boldsymbol{X} \\ \delta\boldsymbol{Y} \\ \delta\boldsymbol{Z} \end{bmatrix}^{T} = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix}\begin{bmatrix} \delta\boldsymbol{U} \\ \delta\boldsymbol{V} \\ \delta\boldsymbol{W} \end{bmatrix}^{T}. \quad (18)$$

Equation (18) refers to all variometer data and not only the averaged data obtained from Eq. (15). For each set of absolute measurements, the three corrected baselines can be processed in a conventional way. Considering an XYZ variometer, the $Z_0$ baseline is first computed and then $X_0$ and $Y_0$ are computed:

$$Z_0 = \frac{F_5+F_6+F_7+F_8}{4}\sin\left(\frac{I_5+I_6+I_7+I_8}{4}\right) - \frac{\delta Z_5+\delta Z_6+\delta Z_7+\delta Z_8}{4}, \quad (19)$$

$$H_i = \sqrt{F_i^2-(Z_0+\delta Z_i)^2}, \quad (20)$$

$$X_0 = \frac{H_1+H_2+H_3+H_4}{4}\cos\left(\frac{D_1+D_2+D_3+D_4}{4}\right) - \frac{\delta X_1+\delta X_2+\delta X_3+\delta X_4}{4}, \quad (21)$$

$$Y_0 = \frac{H_1+H_2+H_3+H_4}{4}\sin\left(\frac{D_1+D_2+D_3+D_4}{4}\right) - \frac{\delta Y_1+\delta Y_2+\delta Y_3+\delta Y_4}{4}. \quad (22)$$

A function (polynomial, cubic-spline, etc.) is then fitted on them. Finally, the magnetic vector is built according to Eq. (2).

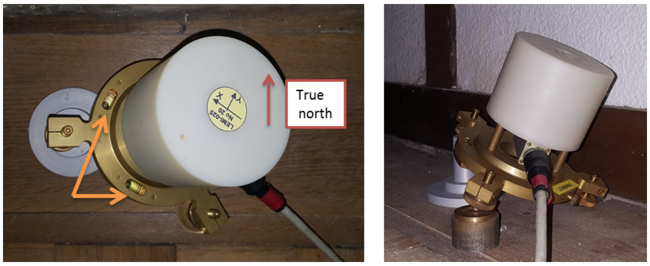


**Figure 3.** LEMI-025 installed in the Dourbes magnetic observatory. The red arrow indicates the true north direction. The orange arrows highlight the bubble-levels saturation.

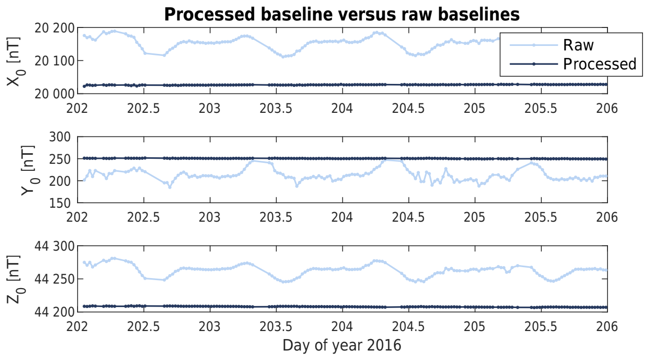


**Figure 4.** LEMi-025 baselines. Light blue: before processing. Dark blue: after processing.

## 4 Case study

A LEMI-025 variometer has been installed in the Dourbes magnetic observatory. The device has deliberately been set up in a non-conventional orientation as shown in Fig. 3. The levelling and orientation error have been strongly exaggerated compared to those encountered in conventional observatories, but, if we consider a possible future automatic deployment using systems such as a GyroDIF (Gonsette et al., 2017), the orientation could be completely random. An AutoDIF installed in the Dourbes absolute house has been used for performing absolute declination and inclination measurements because of its high-frequency measurement capability. An Overhauser magnetometer recorded the magnetic field intensity at the same time. One measurement every 30 min has been made during 4 days from 20 to 24 July 2016. The mean Kp index over this period is 2 while the maximum is 5 (only three periods of 3 h reached level 5 of the Kp index).

Before processing, the baseline computation clearly highlights the set-up error as shown in Fig. 4. Actually, such big variations do not meet the international standards (St Louis, 2012) and could discard the concerned magnetic observatory. Indeed, most observatories perform absolute $D$ and $I$ measurements no more than once a day, introducing an aliasing in the baseline computations. The amplitude of the baseline variations in Fig. 4 is such that the 5 nT tolerated errors are not met anymore. However, after solving the system for each components and applying the transformation matrix to the variometer data, the baseline computation gives more correct data. In this case, a cubic-spline function has been used for fitting to the baseline measurements.

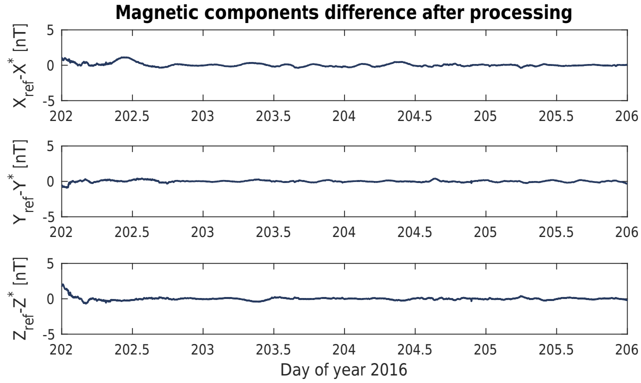


**Figure 5.** Variometer difference between a reference variometer and the case study variometer. The value are clearly within 1 nT.

A second LEMI-025 is installed in the variometer house of the Dourbes observatory. This one is correctly set up, so it could be used for a posteriori comparison. Figure 5 shows the difference between vector components built from the case study variometer and the reference variometer. Notice that, even if both are separated by as much as 10 m, the observatory environment should ensure minimal difference. If we exclude the borders for which the cubic-spline baselines are badly defined, the three curves meet the INTERMAGNET 1 s standards requiring an absolute accuracy not worse than $\pm 2.5$ nT. The $Y$ and $Z$ curves remain within $\pm 0.44$ nT. The $X$ component is slightly more noisy, with the upper and lower borders being $+1.11$ and $-0.38$ nT respectively. The mean differences are 0.06, 0.009 and 0.002 nT for $X$, $Y$ and $Z$ curves respectively, and the corresponding standard deviations ($1\sigma$) are 0.26, 0.15 and 0.23 nT respectively.

## 5 Discussion

In this paper, the measurement errors have not been taken into account. In particular, absolute measurements were performed sequentially so that the magnetic field could be changed between the first and the last measurement. Equations (12)–(14) do not take the variations between the mean declination time and the mean inclination time into account. Indeed, using Eqs. (19)–(22) with the badly set up variometer for compensating the magnetic activity would lead to a nonlinear system. Nevertheless, AutoDIF achieves a complete protocol of absolute measurement within less than 5 min including the geographic north measurement at the beginning. Because of the high number of measurements during a few days, the error due to this delay can be considered as random. Assuming that the measurement errors are a random noise, their effects are therefore cancelled according to the Gauss–Markov theorem.

Jankowski and Sucksdorff (1996) suggested taking advantage of a disturbed day in order to maximise the effect of a set-up error. However, the global measurement noise may increase, in particular at high latitude. Indeed, the synchronisation between instruments may become critical. Additionally, a rapid change in the magnetic field may induce soil current that could affect both the DI-flux instrument and the variometer. Fortunately, as the noise is random and this is even truer during chaotic magnetic activity, it has no effect on the final results.

Equation (16) supposes a constant baseline so that a small variation will contribute to the residues. However, the use of an automatic DI-flux instrument provides a large number of measurements within a short time period. The case study has been performed during only 4 days, within which the baseline variations are reasonably considered small. Their contribution to the error can therefore be considered negligible compared to the possible scale factor and orientation parameter effects. Nevertheless, INTERMAGNET recommends performing absolute measurements with an interval ranging from daily to weekly (St Louis, 2012).

## 6 Conclusions

The baselines and absolute measurements are powerful tools for checking data quality and for highlighting possible gross errors. The present paper has demonstrated that even with a strong set-up error, it is possible to recover good magnetic data meeting the international standards. It also contributes to automatic installation and calibration of magnetic measurement systems. Future observatory deployments will be more and more complex, with automatic dropped systems in unstable environments. The challenges of tomorrow are in Antarctica, the Earth's seafloor or even Mars (Dehant et al., 2012). The application of theses methods will contribute to reaching those objectives. They will require not only automatic instruments but also regular and automatic control.

*Data availability.* Data are available upon request from the corresponding author at agonsett@meteo.be.

*Competing interests.* The authors declare that they have no conflict of interest.

*Special issue statement.* This article is part of the special issue "The Earth's magnetic field: measurements, data, and applications from ground observations (ANGEO/GI inter-journal SI)". It is a result of the XVIIth IAGA Workshop on Geomagnetic Observatory Instruments, Data Acquisition and Processing, Dourbes, Belgium, 4–10 September 2016.

*Acknowledgements.* We would like to acknowledge the Royal Meteorological Institute of Belgium, which allowed this research. We also acknowledge the editor and the reviewers who contributed to the improvement of this article.

Edited by: Arnaud Chulliat
Reviewed by: Santiago Marsal and one anonymous referee

## References

Alldregde, L. R.: A proposed Automatic Standard Magnetic Observatory, J. Geophys. Res., 65, https://doi.org/10.1029/JZ065i011p03777, 1960.

Dehant, V., Banerdt, B. Lognonné, P., Grott, M., Asmar, S., Biele, J., Breuer, D., Forget, F., Jaumann, R., Johnson, C., Knapmeyer, M., Langlais, B., Le Feuvre, M., Mimoun, D., Mocquet, A., Read, P., Rivoldini, A., Romberg, O., Schubert, G., Smrekar, S., Spohn, T., Tortora, P., Ulamec, S., and Vennerstrom, S.: Future Mars geophysical observatories for understanding its internal structure, rotation and evolution, Planet. Space Sci., 68, 123–145, 2012.

Eckstaller, A., Müller, C., Ceranna, L., and Hartmann, G.: The geophysics observatory at Neumayer stations (GvN and NM-II) Antarctica, Polarforschung, 76, 3–24, 2007.

Gonsette, A., Rasson, J., and Marin, J.-L.: Autodif: Automatic Absolute DI Measurements, Proceeding of the XVth IAGA Workshop on Geomagnetic Observatory Instruments, data Acquisition and Processing, 2012.

Gonsette, A., Rasson, J., Bracke, S., Poncelet, A., Hendrickx, O., and Humbled, F.: Automatic True North detection during absolute magnetic declination measurement, Geosci. Instrum. Method. Data Syst. Discuss., https://doi.org/10.5194/gi-2017-18, in review, 2017.

Jankowski, J. and Sucksdorff, C.: Guide for magnetic measurements and observatory practice, Warsaw, IAGA, 1996.

Kerridge, D. J.: Theory of the Fluxgate-Theodolite, Geomagnetic Research Group Report 88/14, Edimburgh, British Geological Survey, 1988.

Marusenkov, A., Chambodut, A., Schott, J.-J., and Korepanov, V.: Observatory magnetometer in-situ calibration, Data Science Journal, 10, https://doi.org/10.2481/dsj.IAGA-17, 2011.

Mohr, P. J., Newell, D. B., and Taylor, B. N.: CODATA recommended values of the fundamental physical constants: 2014, Review of Modern Physics, 88, https://doi.org/10.1103/RevModPhys.88.035009, 2016.

Olsen, N., Toffner-Clausen, L., Sabaka, T. J., Brauer, P., Merayo, J. M. G., Jörgensen, J. L., Leger, J.-M., Nielsen, O. V., Primdahl, F., and Risbo, T.: Calibration of the Orsted vector magnetometer, Earth Planet. Space, 55, 11–18, 2003.

Rasson, J. L.: About Absolute Geomagnetic Measurements in the Observatory and in the Field, Publication scientifique et technique no 40, Institut Royal Météorologique, 2005.

St Louis, B. (Ed.): INTERMAGNET technical reference manual: Version 4.6, 92 pp., available at: http://intermagnet.org/publications/intermag_4-6.pdf (last access: 7 February 2017), 2012.