In situ Vector Calibration of Magnetic Observatory

I would like to thank Dr. Chuliat as associated editor, Dr Marsal and Anonymous for they reviewer work.

The corrected manuscript is just after the reply to the reviewer 2. The corrections related to reviewer 1 appear in blue while those related to the reviewer 2 are in red.

Answer to Reviewer 1:

The manuscript deals with the calibration of variometers by use of previously calibrated observatory variometers or, especially, by use of automatic absolute instruments which are capable of providing the full magnetic vector in a geographic reference frame with a sufficiently high sampling rate. This is especially relevant for the authors, who manufacture the mentioned absolute magnetometers.

Even if new science is not specifically dealt with in the manuscript, the authors expound procedures beyond baseline determination that are often disregarded in the daily observatory practice, e.g., checking the scale factors or the orthogonality errors of triaxial magnetometers. In my opinion, this makes the manuscript suitable for publication in this special issue.

However, there are minor points that should be treated before publication. In particular, the manuscript is very concise, and some aspects need a somewhat more extended explanation to be useful for the potential reader.

The English is not bad, though it can be improved. The authors can find some hints at the end of this document, though they should note that I'm not a native English speaker.

Minor points:

- In equation (2) (and indeed throughout the manuscript) the authors assume that a geographic reference frame is used for the variometer. However, a number of observatories legitimately use a local geomagnetic reference frame instead. In order not to exclude those observatories, please, include a comment on how the subsequent equations would be modified in that case.

This method can be used only for scalar components otherwise the equations would not be linear anymore. Fortunately, many variometers are based on a three-axes fluxgate sensor (or a combination of 3 single-axes) so that they actually record a scalar product of the magnetic field with his sensitive axes. This projection is a scalar component that can be treated like a geographic component. For instance, when a variometer is setup in HDZ configuration, the sensor used for measuring the declination variations (δD) is put perpendicular to the field in the horizontal plane and record the orthogonal projection (δE) of the H component onto its sensitive axis.

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

The same approach can be used for a DFI magnetometer. However, a magnetometer especially developed for measuring HDF or DFI may have a limited range for the D and I components. Indeed, the principle is based on a zero (or near zero) method. Thus, a compensating coil is not necessary in case of correct setup.

- Paragraph above equation (3). I think most observers (including myself) assume the scale factors are those given by the variometer manufacturers, thus disregarding future changes. Do authors suggest that the given scale factors might change in the long term or even be incorrect? If so, and in order for the article to alert the potential reader, could the authors give an order of magnitude of the error that those observers are making with this assumption? Extend this discussion to the orthogonality errors given by the manufacturers.

The purpose of this text is not to contest the quality of the variometers available in the market. We did not perform a long terms study of their parameters. However, the scale factor is a major parameter affecting the measurement. We think that it is logical to take it into account in this text.

Nevertheless, an observatory may wish to develop its own variometer. Also, if a failure occurs (e.g., due to a lightning), it may be necessary to change some parts of the instruments, in particular in the electronic. The scale factor as well as other parameters may change. If the repair is performed onsite, the variometer re-calibration could be inaccurate.

Concerning the magnitude of errors, it will depend on the magnitude of the daily variations. At high latitude, 1% error on the scale factor may be critical.

- Equation (4) – (5). Please, clarify this notation: define clearly what are the different k's and δX's, and what are their units. Notation has been adapted

- Equations (8) – (10) use δU, δV, δW while equations (3), (11) and (12) use U, V, W, whereas I think they refer to the same variables. If so, please unify the notation. The notation has been unified.

- Eq. (10): The plus sign in the right hand side should be a minus. You are entirely right.

- Eq. (12): Please, give some more details on how to solve this system. For example, is it solved using least-squares? If so, this method assumes that the baselines (X_0, Y_0, Z_0) are constant, so one cannot extend for too many days (otherwise, the baseline conditions may have changed). The use of automatic absolute measurements for the variometer calibration probably gives better results if one catches disturbed rather than quiet (e.g., Sq) conditions, so that the range of variation is greater and somewhat unpredictable. Please, discuss about these points and give some useful hints to the reader.
Indeed, assuming the system to be overdetermined, it is solved in the least-square sense. The real baseline is supposed relatively constant so that a small variation will contribute to the residues. Therefore, the baseline variation amplitude will limit the method. For the case study, only 4 days have been used. Even if, the red X0 baseline in the figure 4 is slightly increasing, the results in Figure 5 are satisfactory. Please remember that the method does not aim to determine this baseline but only the parameters.

The use of an automatic DIFlux provides a lot of samples within a short time. The more the field is active, the stronger the effect is on the baselines. However, the absolute measurements during a high K period should be considered with caution. The synchronization between instruments may become critical. Also, a rapid field variation may induce soil currents. So, the global measurement noise may increase, in particular at high latitude.

- Figure 2 is not referred in the main body of the manuscript. Corrected

- Others: Done
    - In the title, I've not been able to find the word "vectorial" in the English dictionary. I think the correct adjective is "vector".
    - P. 1, l. 8: I suggest replacing "they are primordial" with "it is essential".
    - P. 1, l. 13: Most magnetic observatories are built according **to** a

- standardized …
- P. 1, l. 13-14: Please, just mention the three instruments at the end of this
- sentence.
- P. 1, l. 16: … at **a** regular interval.
- P. 1, l. 16: Space between 1 and Hz.
- P. 1, l. 16: However**,** ...
- P. 1, l. 17: … near zero sensors**,** ….
- P. 1, l. 21: … e.g.**,**
- P. 1, l. 21: What kind of motion do authors refer to?
- P. 1, l. 23: Replace “realized” with “carried out”.
- P. 1, l. 24: Instrument**s**
- P. 1, l. 25: First, a scalar magnetometer record**ing** the intensity of the field ||□ □ ||.
- P. 1, l. 26: Replace “precess” with “perform precession”.
- P. 2, l.1: Therefore**,** …
- P. 2, l. 7: according **to**
- P. 2, l. 18-19: **w**here X, Y and Z are the three conventional Cartesian
- components of the field, **pointing to the geographic North, eastward and**
- **downward, respectively**.
- P. 2, l. 27: guarantee**d**
- P. 2, l. 28: follow**s**
- P. 2, l. 31: Replace the last “in” with “into”.
- P. 3, l. 2: Is this what you really mean? Or: is not available **by** instruments. I mean that absolute DI measurements are not available but they can take advantage of the different scalar recording due to the orbital motion. Text has been clarified.
- orbiting around the **E**arth.
- P. 3, l. 5: Replace “this last” with “the latter”.
- P. 3, l. 11: Sufficient**ly**.
- P. 3, l. 12-13: Let us consider an observatory working **w i t h a variometer**
- **such as a LEMI-025**, in **a** Cartesian coordinate system.
- P. 3, l. 14: nano**t**esla.
- P. 4, l. 8: as **a** full …
- P. 4, l. 10: Rasson (2005) treated …
- P. 4, l. 23: e**i**ther
- P. 4, l. 23: value**s**
- P. 4, l. 23: sufficient**ly**
- P. 4, l. 27: Therefore**,** a **vector** calibration
- P. 4, l. 28: **The** general case, including orthogonality errors**,** can be expressed
- by rewriting Eq. (3) as follow**s**
- P. 5, l. 2: system**,** where
- P. 5, l. 7: according to **the** …
- P. 5, l. 7: replace “voluntary” with “deliberately”.
- P. 5, l. 12: observatories**,** …
- P. 5, l. 12: 30 min **has** been made during four days**.**
- P. 5, l. 18: Please, be more specific in what particular standards are not met. The baselines stability may affect the definitive data. The resulting error may therefore be bigger than the 5nT tolerated by INTERMAGNET. Text has been adapted.
- P. 5, l. 20: Finally, **the** magnetic field …
- P. 5, l. 23: setup**,** …
- P. 5, l. 24: from **the** “case study” variometer and **the** reference variometer.
- P. 5, l. 25: 10 **m**

- P. 5, l. 25: Is this what you mean?: “Notice that, even if both are separated by as much as 10 , the observatory environment ensures a minimal difference.” Indeed, this is what I mean
- P. 6, l. 4: … **the** international standards.
- P. 6, l. 5: future observator**y** deployments will be more and more complex**,**
- with …
- Figure 1 caption: **d**ark, and comma after occurred.
- Figure 4 caption: LEMi-025 baselines**.** Blue: before processing**;** **r**ed: after processing.
- Figure 5: Variometer difference between **a** reference variometer and **the** “case study” variometer. The value**s** are clearly within 1 nT. (Leave a space between 1 and nT).

Answer to Reviewer 2:

The manuscript describes the new aspect of in-situ calibration of geomagnetic observatory variometers, which uses as a reference records the absolute values of the Earth magnetic field components measured in the automatic mode. The recently developed equipment performs the automatic absolute measurements with a sample rate much higher (20-40 times) than that of manually operated instruments. This enhancement of the sample rate opens new possibilities of the absolute measurements, traditionally exploited for baselines estimation, for calibration of the scale factors, the orthogonality and orientation errors of magnetometers. This application of the absolute measurements is particularly important for deploying and operating unmanned geomagnetic observatories. So, the manuscript addresses the relevant topic within the scope of GI.

Authors show (both theoretically and experimentally), that the baselines are sensitive to the errors in scale factors and the variometer components misalignment in respect to the geographic frame axes. Applying some data processing procedure to the record of the arbitrary oriented variometer and the set of the absolute values of the magnetic field the transformation matrix is estimated. As a result, the corrected variometer data coincide well with that of the properly installed reference instrument. Unfortunately, authors had not provided the details of the data processing procedure. Further developing this calibration method it would be useful also to answer the following questions:

What is theoretical backgrounds of the selected data processing procedure?
The procedure consists of solving an overdetermined linear system in the least-square sense. The method has been more developed in the manuscript.

What is the calibration uncertainty of the proposed method?
Is it possible, for instance, to achieve the scale factors and the orientation errors accuracy, which is sufficient to meet the requirements to INTERMAGNET one-second data?
The uncertainty and the accuracy are detailed in the case study section. I show that the $\pm 2.5nT$ requirement for the 1 sec data is met.

What factors are most important for achieving better accuracy?
I don’t think that a factor is more important than another but I give some examples and magnitudes for both scale factor and orientation in section 2.

If the records of the badly calibrated variometer are used in the absolute measurements protocol, how accurate will be the results of this instrument calibration?

I am not sure to understand your last question. The absolute measurements are supposed to be correct. So if a completely wrong variometer data is used in the absolute protocol without any correction, the amplitude of the error could be, in the worst case, the amplitude of the expected daily variation plus the amplitude of the wrong variometer component.

In my opinion, the manuscript could be published after correcting some drawbacks and unclear points, the list of which are given below.

p. 3, l. 3-4.

A comparison of two records for variometer calibration purposes was used by 1 different authors. Please, add more references on this topic. I suggest to mention the book

J. Jankowski and C. Sucksdorff, *IAGA guide for magnetic measurements and observatory practice*. Warsaw: IAGA, 1996, where a reference record obtained from absolute measurements was proposed to use for the variometers calibration (subsection 8.2, p. 160, 161):

"The method is easily used if there is a standard recording station with well known characteristics nearby. It will be more elaborate to collect the needed data from absolute measurements made during a magnetically active day. The method is based on a comparison of recorded natural variations of the magnetic field with simultaneously measured or recorded data which have no systematic errors.

...

The necessary data for the computation of quantities Δx_1, ... , Δx_n can be obtained from absolute measurements made during a disturbed day or disturbed days. It is a rather laborious and time consuming way, but has the advantage that it can be accomplished after the installation of the variometer. And every observatory has the facilities for these measurements."

The reference has been added and the paragraph has been adapted.

p. 3 Eq. (4) and (5)

What is $\delta X_{voltage}$? If this is a voltage proportional to a measured signal δX_{real}, as it follows from the text in the lines 13-14, then $\delta X_{digital}$ is proportional to δX_{real} squared. From other side, $\delta X_{voltage}$ should not depend on δX_{real}, in order to keep k_x close to 1, if other terms in Eq. (5) are also constant. What are units of the terms in Eq. (4) and (5)?

I apologize, the notation was entirely wrong. The idea is simply to describe the acquisition chain. A real signal δX_{real} in nT is converted in an electrical signal $\delta X_{voltage}$ in Volts. Then, this signal passes through an ADC and converted in digital value $\delta X_{digital}$.

p. 3 Eq. (6) and (7)

Probably, the vectors in these equations should be multiplied by element-wise manner, yielding the Hadamard product (also known as the Schur product or the entrywise product). However, in the given notation it looks like an attempt to obtain a matrix product of two column vectors, which is not defined. I suggest to rewrite Eq. (6) and (7) using a special symbol for the entry-wise product or representing the column vector of the scale factors in the form of a square matrix (similarly to Eq. (3)).
Meaning of the symbol “*” is not described in the text. This symbol often denotes a complex conjugate of a matrix, so it would be better to explain directly its meaning in these equations.
The notation has been adapted and the star symbol described.

p. 4, Eq. (8)
In my opinion, this equation is valid only for perfectly orthogonal components.
It is true. A comment has been added

p. 5, Eq. (11) and (12)
Random components of measurement uncertainty, which are inevitably appeared in absolute values as well as variometer data due to instrumental noises or magnetic interferences, do not included in Eq. (11), (12). Does it mean that the method used for solving these equations is not influenced by this kind of disturbances? Please, provide some basic description of the data processing procedure used to estimate the calibration coefficients.
The system is solved in the least-square sense. So, a random error has no effect according to the Gauss-Markov theorem. The chapters 3 and 4 have been completed with more descriptions as well as more equations. In particular, the way of preprocessing the sets of absolute measurements has been explained. The random errors, in particular those due to the absolute measurements time-stamp are now discussed in a new chapter 5.

As it follows from the text (p. 5, l. 2-4), the variables *X, Y, Z, U, V, W* represent series of values. Then, in Eq. (11) these variables should be in the form of row vectors, but in Eq. (12) the same variables have to be in the form of column vectors. Is it correct?
It is correct. They represent series of values. The notation has been adapted.
Are the variables X_0, Y_0, Z_0 scalars or vectors? They are considered as constant in this equation. So they are scalar values.

What is the reason of using the two notations for matrices and vectors: “[]” in Eq. (3), (11), (12) and “()” in other equations? Notation corrected
In accordance with the journal rules vectors are identified in bold italic font and matrices — in bold roman font. Please, correct all equations in order to meet these requirements.
There is Intermagnet Technical Reference Manual, version 4.6 (2012). Is it necessary to refer to the previous version of the document? The reference has been adapted.

In-situ vector calibration of magnetic observatory

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

1 Introduction

Most of magnetic observatories are built according to a standardized or universally adopted scheme (Jankowski and Sucksdorff, 1996) including at least a set of 3 major instruments: a variometer, an absolute scalar magnetometer and a DIFlux. The different data streams are combined to build a unique vector 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, 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 them 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 instrumental effect after, e.g., a (unwanted) motion like a shock due to a maintenance staff or 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, recording the intensity of the field $|\vec{B}|$. Most of the time, a proton precession or an overhauser magnetometer is used for this task. They exploit the fact that protons perform precession at a frequency proportional to the magnetic field according to:

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

Where γ, the gyromagnetic ratio, is a fundamental physical constant(Mohr et al., 2014). Therefore, this magnetometer can be considered as 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 magnetic field in a horizontal plane and inclination is the angle between the horizontal plane and the field. In a conventional observatory, a DIFlux (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 as absolute because angles are measured according to geodetic reference directions. Due to this manpower dependency, the frequency of absolute measurements does not exceed once a day (St Louis, 2012). However, new automatic devices such as AutoDIF (Gonsette et al., 2012) close the loop by automatizing the DIFlux measurements procedure. Moreover, AutoDIF is able to increase the frequency of baseline determination by performing several measurements per day.

After collecting synchronized data from the three instruments, baselines are computed by using the relation, e.g. for Cartesian coordinate system:

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

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 δ refers to the variometer data. The full baselines measurement protocol including a set of 4 absolute declinations and 4 absolute inclinations (even if only 2 are required for determining all the unknowns) can be found in the literature, also for spherical and cylindrical configurations (Rasson, 2005). The need for 8 (at last 6) measurements is justified by the DIFlux sensor offset and misalignment. A baseline function is then applied on these measurements using various methods such as least-squared polynomial or spline approximation. Finally, the vector field is constructed by adding the variometer values to the adopted baselines.

Equation (2) supposes a variometer properly setup with Z axis vertical and X axis pointing toward geographic north. The scale factor of each component is also supposed perfect.

A correct orientation is usually ensured by paying attention during the setup 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:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = R_z(\gamma) R_y(\beta) R_x(\alpha) \begin{bmatrix} k_1 & 0 & 0 \\ 0 & k_2 & 0 \\ 0 & 0 & k_3 \end{bmatrix} \begin{bmatrix} \delta U \\ \delta V \\ \delta W \end{bmatrix} + \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix}, \qquad (3)$$

Where the $R_{x,y,z}$are an elementary rotation matrix and the k_i are the scale factors for each component. U, V and W are the three variometer output into the sensors reference frame. Calibration procedures can be divided in two categories. On one hand, the scalar calibration compares scalar values computed from vector magnetometer to absolute scalar values. technique is exploited by satellites because 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 reference vector value. (Marusenkov et al., 2011) used a second variometer already calibrated as reference. Previously, (Jankowski & 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 angles errors (no more than 1°-2°) but they suggested that the method could remain valid for any angle. They also pointed out the difficulty to get sufficient strong magnetic activity at low latitude. The method presented in this paper is relatively close to the latter except that the automatic DIFlux can generate a lot of absolute measurement within a short time (e.g. 48 absolute measurements each 24h) leading to a fast automatic calibration process also at low latitude or during quite magnetic period.

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 setup their magnetometers in 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 nonlinear equations. Nevertheless, most of modern variometers are based on fluxgate sensors technology. Thus, the recorded signal is the orthogonal projection of the field along the fluxgate sensitive axis. The residue (δE) expressed in nT 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 all variometer axes may not have a compensating coil allowing them to work in full-field. Indeed, recording the D and I variations is similar to a DIFlux process. The sensor is quasi-perpendicular to the field so that the residues is 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 (nT) 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 in then used to convert true signal into digitized signal. Considering the X component:

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

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

Where $\delta X_{real}$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, $\delta X_{voltage}$ 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. It should be as close to 1 as possible.

Supposing now a difference between 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 varies then with respect to its corresponding variometer component value meaning that a correlation exists between both.

The scale factor is usually factory calibrated and supposed to be stable over the time. It is certainly true but there are many situations for which the scale factor is not known exactly (e.g., homemade instrument) or differs from its factory value (e.g. a repair after a lightning may affect the instrument parameters). The impact of a scale factor error also depends on the magnitude of the magnetic activity. One percent error for the H component scale factor at mid latitude would lead to no more than 0.5nT during quite day. 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 a default in orientation. That could be due, for instance, to a levelling error caused by a bad setup 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 3-axes magnetometers will never be considered as a full magnetic observatory.

Rasson (2005) treated the simplified case of a rotation θ around the Z-axis. The orthogonality between components was supposed 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 get 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 variometer rotated around its vertical by 1.7°. The high resolution baseline (blue) computed by means of an automatic DIFlux (AutoDIF) presents the same trend as the δY (red) component. The peak-peak amplitude is more than 2nT.

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.

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 DIFlux, either manual 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 4 declination (index 1 to 4) and 4 inclination (index 5 to 8) records. The 8 synchronized variometer values as well as the 8 scalar measurements are averaged. Thus, each spot value and corresponding variometer values are computed as follows:

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

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

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

$$\begin{bmatrix} \delta \mathrm{U_m} \\ \delta \mathrm{V_m} \\ \delta \mathrm{W_m} \end{bmatrix} = \begin{bmatrix} \sum \delta U_i \\ \sum \delta V_i \\ \sum \delta W_i \end{bmatrix} \tag{15}$$

Where, the “i” index refers to the records 1 to 8 synchronized with the 4 declinations and the 4 inclinations.

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

$$\begin{bmatrix} \boldsymbol{X_m} \\ \boldsymbol{Y_m} \\ \boldsymbol{Z_m} \end{bmatrix}^{\boldsymbol{T}} = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} \begin{bmatrix} \boldsymbol{\delta U_m} \\ \boldsymbol{\delta V_m} \\ \boldsymbol{\delta W_m} \end{bmatrix}^{\boldsymbol{T}} + \begin{bmatrix} \mathrm{X}_0 \\ \mathrm{Y}_0 \\ \mathrm{Z}_0 \end{bmatrix}, \tag{16}$$

where $X_m = [X_{m1}, \dots, X_{mn}]^T, Y = [Y_{m1}, \dots, Y_{mn}]^T, Z = [Z_{m1}, \dots, Z_{mn}]^T$ are the time series of X, Y and Z spot values recorded by means of the absolute instruments and $\delta U = [\delta U_{m1}, \dots, \delta U_{mn}]^T, \delta V = [\delta V_{m1}, \dots, \delta V_{mn}]^T$, $\delta W = [\delta W_{m1}, \dots, \delta W_{mn}]^T$ are the three components 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 supposed 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-synchronized three variometer components are the input. Assuming the system to be overdetermined, the latter is solved in the least-square sense. Equation (17) gives the coefficients corresponding to the X component (others are similar):

$$\begin{bmatrix} a \\ b \\ c \\ X_0 \end{bmatrix} = (\mathbf{A^T A})^{-1}\mathbf{A^T}\boldsymbol{X} \tag{17}$$

where $\mathbf{A} = [\boldsymbol{\delta U} \quad \boldsymbol{\delta V} \quad \boldsymbol{\delta W} \quad \mathbf{1}]$. Once the whole coefficients matrix determined, the variometer data are redressed:

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

Equation (18) refers to all variometer data and not only the “averaged” data obtained from Eq. (15). For each set of absolute measurements, the 3 corrected baselines can be processed in a conventional way. Considering a XYZ variometer, the Z_0 baseline is first computed then X_0 and Y_0:

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

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

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

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

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

4 Case study

A variometer LEMI-025 has been installed in Dourbes magnetic observatory. The device has deliberately been setup in a non-conventional orientation as shown in Fig. 3. The levelling and orientation default have been strongly exaggerated compared to those encountered in conventional observatories, but if we consider possible future automatic deployment using systems such as 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-stamp. One measurement every 30 min has been made during four days from July 20th to July 24th 2016. The mean Kp over this period is 2 while the maximum is 5 (only 3 periods of 3 hours reached the level 5).

Before processing, the baseline computation clearly highlights the setup 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 absolutes D&I measurements no more than once a day introducing an aliasing in the baselines computations. The amplitude of the baselines variations in Fig. 4 is such that the 5nT tolerated errors are not met anymore. However, after solving the system for each components and applying transformation matrix to the variometer data, baseline computation gives more correct data. In this case, a cubic-spline has been used for fitting to the baseline measurements.

A second LEMI-025 is installed in the variometer house of Dourbes observatory. This one is correctly setup, 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 splines baselines are badly defined, the three curves meet the INTERMAGNET 1-second standards requiring an absolute accuracy not worse than $\pm 2.5nT$. Y and Z curves remain within$\pm 0.44nT$. The X component is slightly more noisy with an upper and lower borders being $+1.11nT$ and $-0.38nT$ respectively. The mean differences are 0.06nT, 0.009nT and 0.002nT for X, Y and Z curves respectively and the corresponding standard deviations (1σ) are 0.26nT, 0.15nT and 0.23nT respectively.

5 Discussion

In this paper, the measurement errors have not been taken into account. In particular, absolute measurements are performed sequentially so that the magnetic field could have 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 Eq. (19-22) with the badly setup variometer for compensating the magnetic activity would lead to a non-linear system. Nevertheless, and AutoDIF achieves a complete protocol of absolute measurement is performed within less than 5 minutes 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 also the measurement errors as a random noise, theirs effect are therefore cancelled according to the Gauss-Markov theorem.

(Jankowski and Sucksdorff, 1996) suggested to take advantage of a disturbed day in order to maximize the effect of a setup error. However, the global measurement noise may increase, in particular at high latitude. Indeed, the synchronization between instruments may become critical. Also, a rapid change in the magnetic field may induce soil current that could affect both the DIFlux and the variometer. Fortunately, as the noise is random, and it 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 DIFlux provides a lot of measurements within a short time period. The case study has been performed during only 4 days within which the baselines variations are reasonably considered small. Their contribution to the error can therefore be considered negligible compared to the possible scale factor and orientation parameters effects. Anyway, INTERMAGNET recommends performing absolute measurements with an interval ranging from daily to weekly (St Louis, 2012).

6 Conclusion

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 setup 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. Antarctic, seafloor or even Mars (Dehant et al., 2012) are the challenges of Tomorrow. They will require not only automatic instruments but also regular and automatic control.

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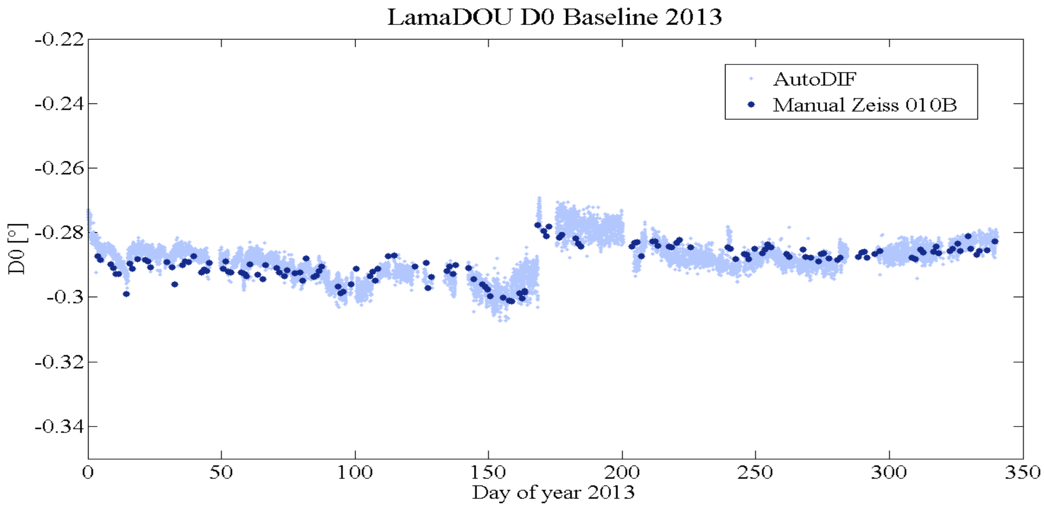

Figure 1: Baseline example computed from conventional manual measurement (dark blue) and automatic system (light blue).In the middle of 2013, a baseline jump corresponding to an instrumental effect occurred, proving that regular absolute measurement are crucial.

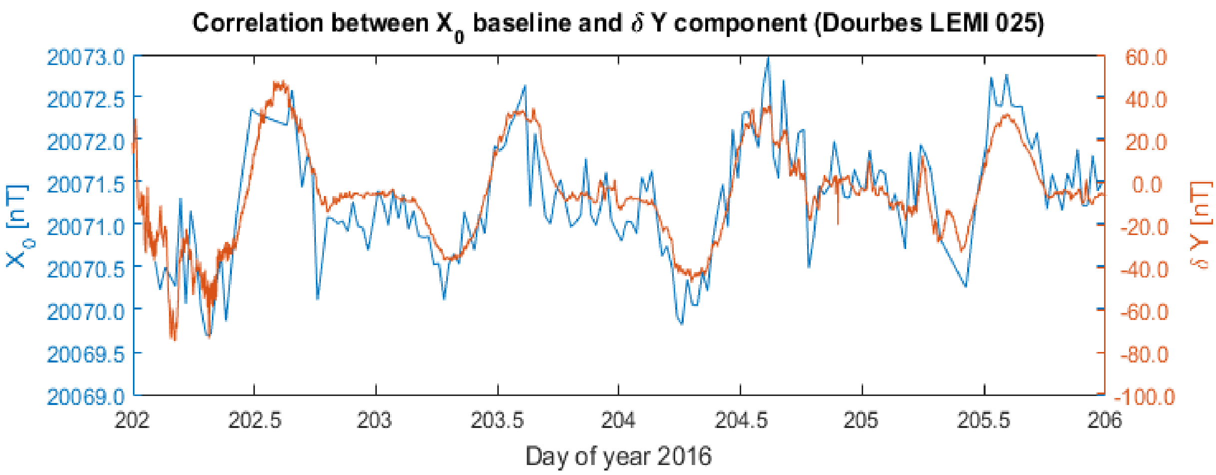

Figure 2: Blue: X_0 baseline computed from high frequency absolute measurements. Red: Variometer Y component from LEMI-025. Because the variometer is not properly oriented, a strong correlation appears between X_0 and δY.

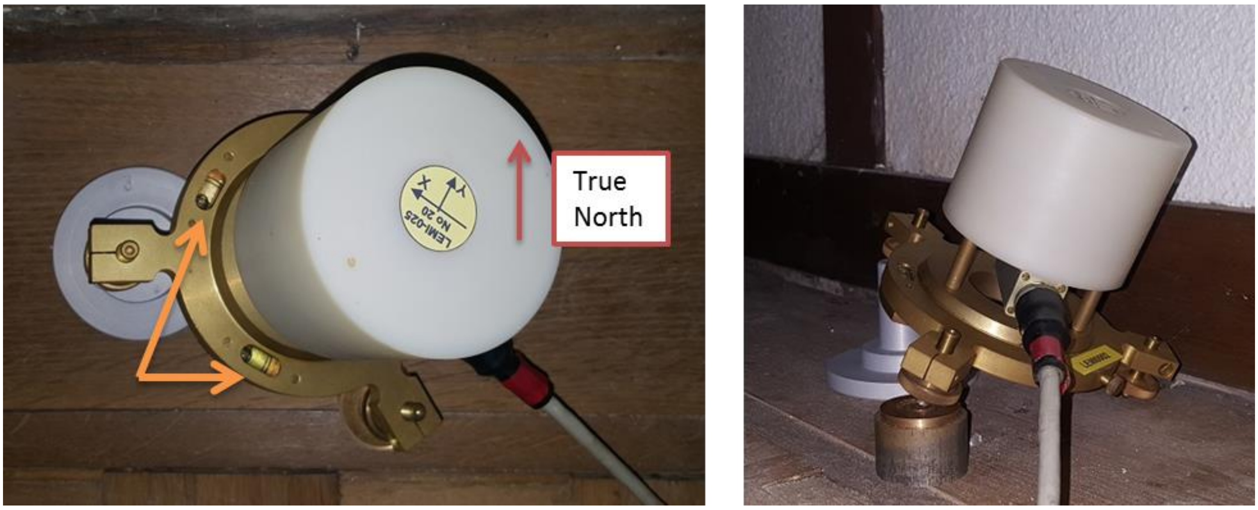

Figure 3: LEMi-025 installed in Dourbes magnetic observatory. The red arrow indicates the True-North direction. The orange arrows highlight the bubble levels saturation.

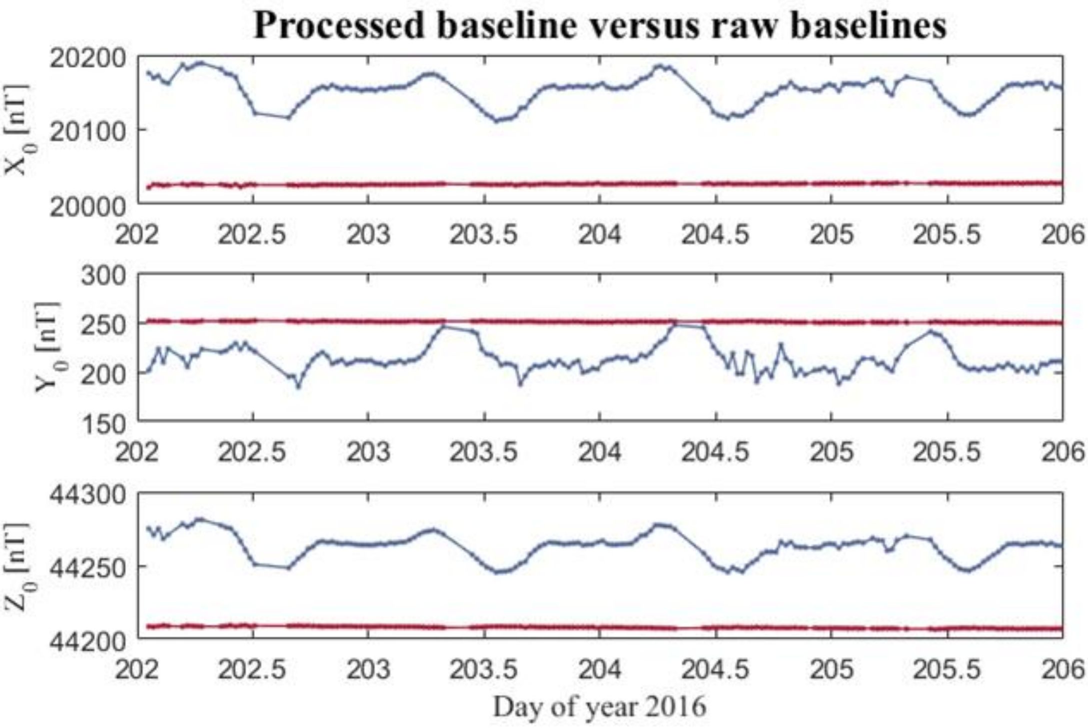

Figure 4: LEMi-025 baselines Blue: before processing. red: after processing.

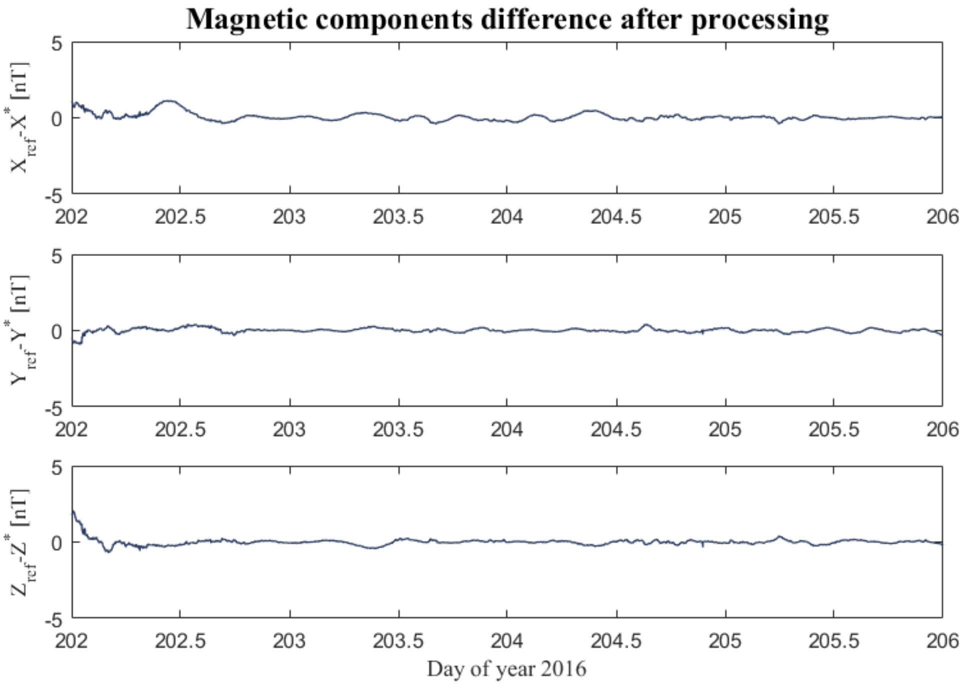

Figure 5: Variometer difference between a reference variometer and the “case study” variometer. The value are clearly within 1 nT.