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Geoscientific Instrumentation Methods and Data Systems Discussions

In-situ vectorial calibration of magnetic observatory

Alexandre Gonsette[1], Jean Rasson[1], François Humbled[1]

[1]Centre de Physique du Globe, Royal Meteorological, Dourbes, 5670, Belgium

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

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 they are primordial 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 a standardized or universally adopted scheme (Jankowski and Sucksdorff, 1996) including at least a set of 3 major instruments. The different data streams are combined to build a unique vector magnetic field data. The first device is a vector magnetometer, also called variometer, which records variations of the magnetic field components at regular interval (e.g. at 1Hz). 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. (unwanted) motion 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 realized by the two other instrument.

First, a scalar magnetometer, records the intensity of the field. Most of the time, a proton precession or an overhauser magnetometer is used for this task. They exploit the fact that protons precess at a frequency proportional to the magnetic field according to:

$$\omega_{precession} = \gamma \ \|\vec{B}\|, \quad (1)$$

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 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, 2011). 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:

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

Where X pointing the geographic North, Y eastward and Z downward are the three conventional Cartesian components of the field. The “0” index refers to the baseline while δ refers to the variometer data. Spherical and cylindrical configurations are also possible (Rasson, 2005). A baseline 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 guarantee. If the orthogonality errors are neglected, the problem of calibration can be expressed as followed:

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

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 in 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. This technique is exploited by satellites because vector reference field is not available but instruments are orbiting around the earth (Olsen et al., 2003). On the other hand, the vector calibration directly compares vector magnetometer measurements to reference vector value (Marusenkov et al., 2011). This requires a second variometer already calibrated. The method presented in this paper is relatively close to this last.

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 sufficient high frequency, particular errors can be highlighted.

2.1 Scale factor error

Let us consider an observatory working in Cartesian coordinate system variometer such as a LEMI-025. Each sensor converts a magnetic signal expressed in nanoTesla (nT) into a voltage itself digitized to give the signal in a convenient format. A scale factor in then used to convert true signal into digitized signal:

$$\delta X_{digital} = k_{\frac{nT}{V}} . \delta X_{voltage} . k_{\frac{V}{nT}} . \delta X_{real}, \tag{4}$$

Or, straightforward with:

$$k_X = k_{\frac{nT}{V}} . \delta X_{voltage} . k_{\frac{V}{nT}}, \tag{5}$$

Where k_X is a scale factor 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:

$$\begin{pmatrix} X_0^*(t) \\ Y_0^*(t) \\ Z_0^*(t) \end{pmatrix} = \begin{pmatrix} X(t) \\ Y(t) \\ Z(t) \end{pmatrix} - \begin{pmatrix} k_X \\ k_Y \\ k_Z \end{pmatrix} \begin{pmatrix} \delta X(t) \\ \delta Y(t) \\ \delta Z(t) \end{pmatrix}, \tag{6}$$

$$\begin{pmatrix} X_0^*(t) \\ Y_0^*(t) \\ Z_0^*(t) \end{pmatrix} = \begin{pmatrix} X_0(t) \\ Y_0(t) \\ Z_0(t) \end{pmatrix} + \begin{pmatrix} (1-k_X) \\ (1-k_Y) \\ (1-k_Z) \end{pmatrix} \begin{pmatrix} \delta X(t) \\ \delta Y(t) \\ \delta Z(t) \end{pmatrix}, \tag{7}$$

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The baseline varies then with respect to its corresponding variometer component value meaning that a correlation exists between both.

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 full magnetic observatory.

J.Rasson treated the simplified case of a rotation θ around the Z-axis (Rasson 2005). In that particular case, the relative real values are given by:

$$\begin{pmatrix} \delta X(t) \\ \delta Y(t) \\ \delta Z(t) \end{pmatrix} = \begin{pmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \delta U(t) \\ \delta V(t) \\ \delta W(t) \end{pmatrix}, \tag{8}$$

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

$$X_0 = X(t) - cos\,(\theta)\delta U(t) + \sin(\theta)\delta V(t), \tag{9}$$

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

$$X_0^* = X_0 + (1 - \cos(\theta))\,\delta U(t) - \sin(\theta)\delta V(t), \tag{10}$$

In this case, a correlation exists between the baseline and another relative component.

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. (10) may be interpreted ether as a scale factor error or as an orientation error.

3 Calibration process

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

General case, including orthogonality errors can be expressed by rewriting Eq. (3) as followed:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} \begin{bmatrix} U \\ V \\ W \end{bmatrix} + \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix}, \quad (11)$$

For each component, the problem simply consists of solving a linear system where a time series spot values and the synchronized three variometer components are the input. Equation (12) gives the system to solve for the X component (others are similar):

$$[X] = \begin{bmatrix} U & V & W & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \\ X_0 \end{bmatrix}, \quad (12)$$

Because each component is treated separately, scale factor, orientation and non-orthogonality are taken into account. The three coefficients can be injected in Eq. (11). Then, baselines and definitive data are computed according to conventional way.

4 Case study

A variometer LEMI-025 has been installed in Dourbes magnetic observatory. The device has voluntary 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 measurements because of its high frequency measurement capability. One measurement every 30 min have been made during four days

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, 2011) and could discard the concerned magnetic observatory. However, after solving the system for each components and applying transformation matrix to the variometer data, baseline computation gives more correct data. Finally, magnetic field vector can be reconstructed from the corrected baseline and transformed variometer values according to Eq. (2).

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 "case study" variometer and reference variometer. Notice that both are separated by 10 meters but the observatory environment should ensure minimal difference.

5 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 international standards. It also contributes to automatic installation and calibration of magnetic measurement systems. Future observatories 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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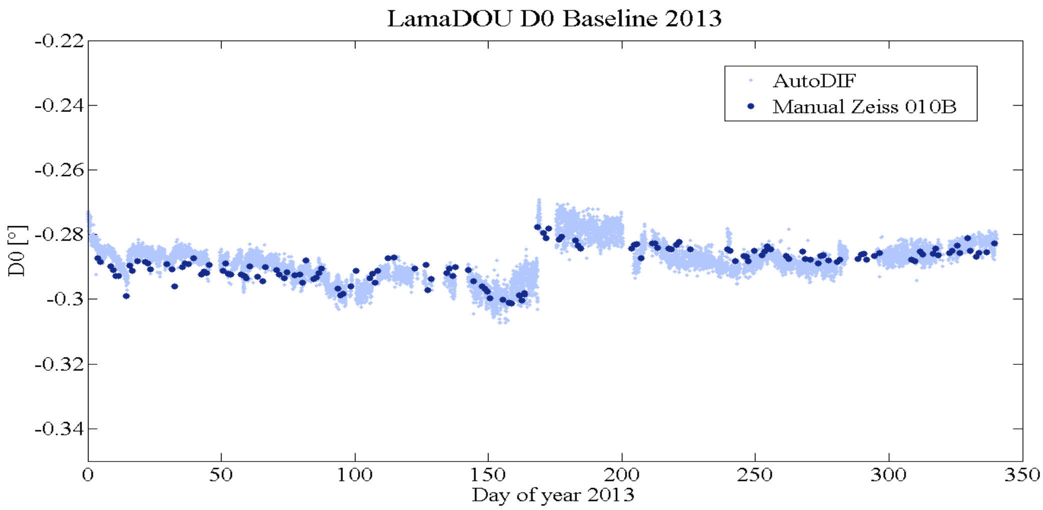

Figure 1: Baseline example computed from conventional manual measurement (Dark blue) and automatic system (light blue).In the middle of 2013, a baseline jump corresponding to an instrumental effect occurred proving that regular absolute measurement are crucial.

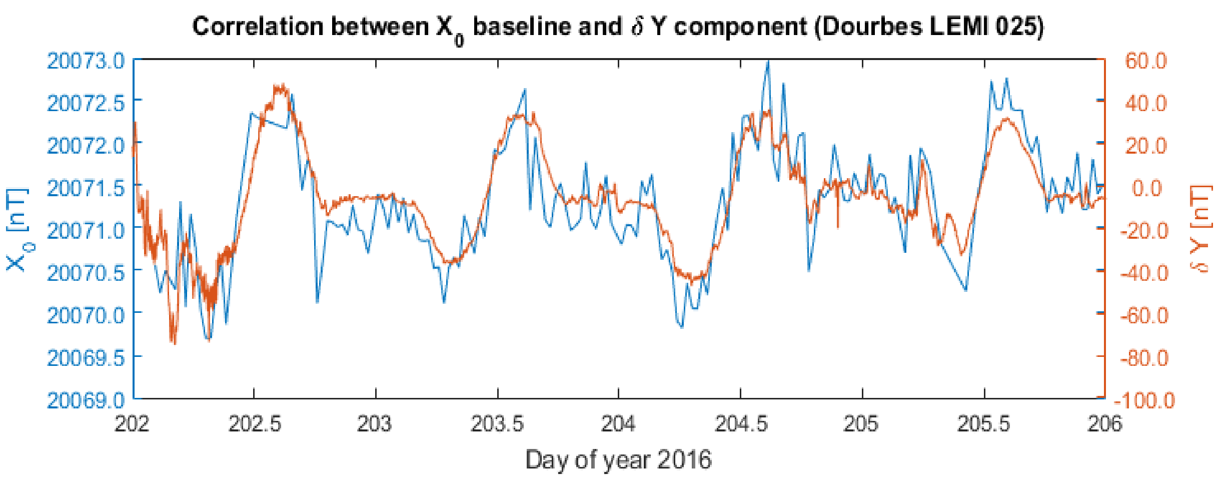

Figure 2: Blue: X_0 baseline computed from high frequency absolute measurements. Red: Variometer Y component from LEMI-025. Because the variometer is not properly oriented, a strong correlation appears between X_0 and δY.

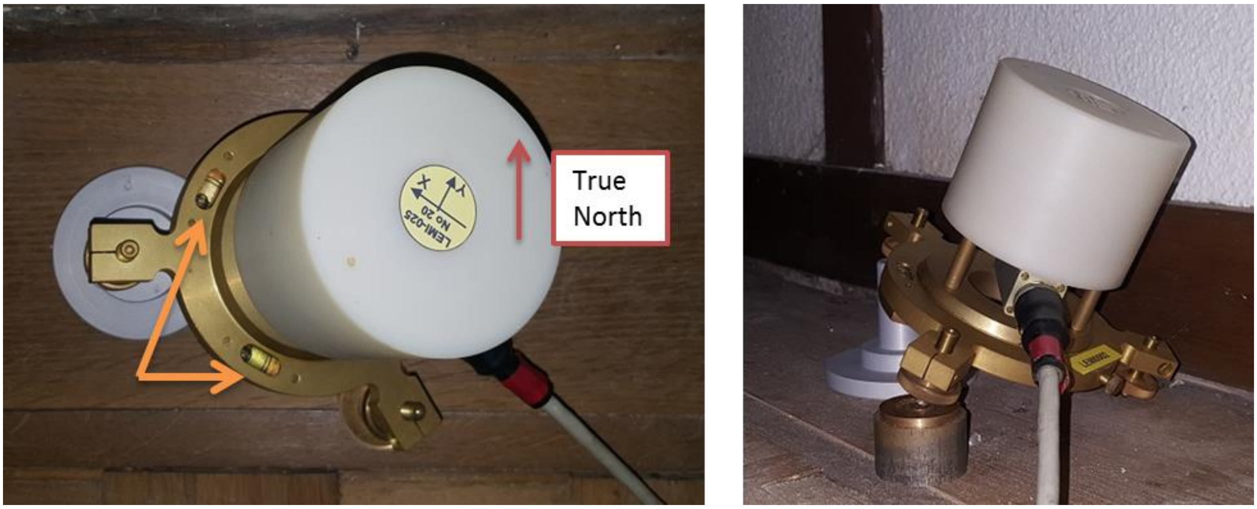

Figure 3: LEMi-025 installed in Dourbes magnetic observatory. The red arrow indicates the True-North direction. The orange arrows highlight the bubble levels saturation.

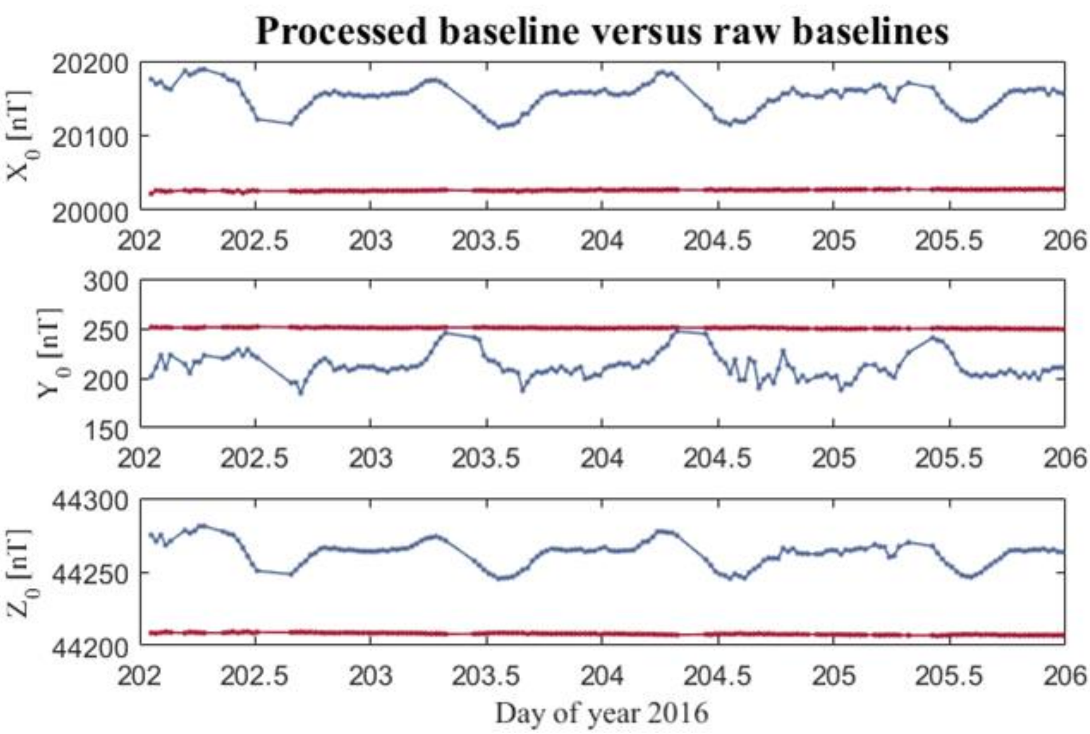

Figure 4: LEMi-025 baselines Blue: before processing. Red: after processing.

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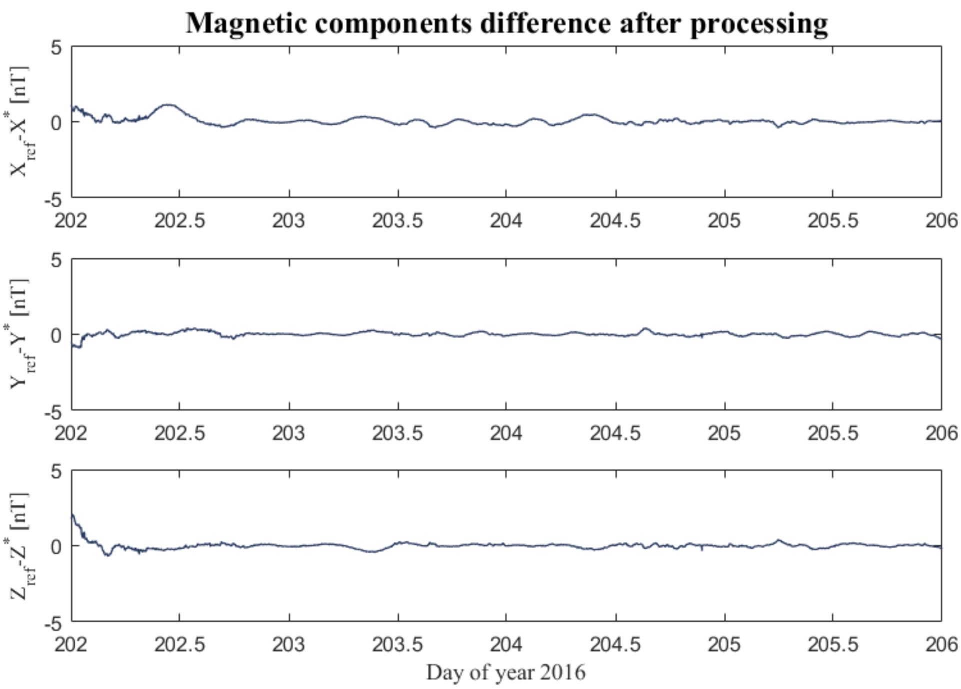

Figure 5: Variometer difference between reference variometer and "case study" variometer. The value are clearly within 1nT.