Geosci. Instrum. Method. Data Syst., 6, 353–360, 2017
https://doi.org/10.5194/gi-6-353-2017

Geoscientific Instrumentation Methods and Data Systems
Open Access
EGU

Several years of experience with automatic DI-flux systems: theory, validation and results

Antoine Poncelet, Alexandre Gonsette, and Jean Rasson

Royal Meteorological Institute of Belgium, Rue du Centre de Physique 4, 5670 Dourbes, Belgium

Correspondence to: Antoine Poncelet (antoine.poncelet@meteo.be)

Received: 3 March 2017 – Discussion started: 13 March 2017
Revised: 7 June 2017 – Accepted: 18 June 2017 – Published: 25 September 2017

Abstract. The previous release of our automatic DI-flux instrument, called AutoDIF mk2.2, has now been running continuously since June 2012 in the absolute house of Dourbes magnetic observatory performing measurement every 30 min. A second one has been working in the tunnel of Conrad observatory (Austria) since December 2013. After this proof of concept, we improved the AutoDIF to version mk2.3, which was presented at the 16th IAGA workshop in Hyderabad. As of publication, we have successfully deployed six AutoDIFs in various environments: two in Dourbes (DOU), one in Manhay (MAB), one in Conrad (CON), one in Daejeon (South Korea) and one is used for tests. The latter was installed for 10 months in Chambon-la-Forêt (CLF) and, since 2016, has been in Kakioka (KAK). In this paper, we will compare the automatic to the human-made measurements and discuss the advantages and disadvantages of automatic measurements.

1 Introduction

After some years of development, our automatic DI-flux instrument (Van Loo and Rasson, 2007; Rasson et al., 2009; Rasson and Gonsette, 2011), called AutoDIF mk2.2, has been running continuously since June 2012 in the absolute house of Dourbes observatory (DOU). A second one has also been running in Conrad Observatory (WIC) since 2013. These two long time series give us feedback on the strengths and weaknesses of these instruments. This paper will present firstly the calibration or validation of the most important sensors (fluxgate, level and encoders) and, secondly, the baseline results of AutoDIF mk2.2 for observatories in Dourbes and Conrad. Based on these results and our experience, we show the improvement we have made to achieve the AutoDIF mk2.3. Then, we present some baseline results for this last version of AutoDIF.

2 Theory of automated DI flux

Lauridsen (Lauridsen, 1985) and Kerridge (Kerridge, 1988) established a DI-flux model by giving the magnetic sensor output value according to its orientation in space. In addition to the 2 degrees of freedom (DOF) related to the rotation axes, sensor offset and misalignment errors were taken into account, leading to a system with 5 DOF. We propose here to extend those models in order to include a possible levelling error consisting of two angular DOF, one toward the geographic north and the other toward the east. The vector magnetic field is then expressed in the sensor frame. The first term of Eq. (1) gives the magnetic sensor output according to its 7 DOF.

$$\boldsymbol{T} = \begin{bmatrix} 1 & \gamma & \epsilon \\ -\gamma & 1 & 0 \\ -\epsilon & 0 & 1 \end{bmatrix} R_y(\beta)\, R_z(\phi) \begin{bmatrix} 1 & 0 & -A \\ 0 & 1 & -B \\ A & B & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} + \begin{bmatrix} T_{0x} \\ T_{0y} \\ T_{0z} \end{bmatrix}, \tag{1}$$

where $[X, Y, Z]^t$ is the coordinate system, X is pointing north, Y is pointing east, Z is pointing down, A is the tilt angle in the geographic northern direction, B is the tilt angle in the eastern direction, T_0 is the sensor offset, ϕ is the rotation angle around vertical axis, β is the rotation angle around horizontal axis, ϵ is the collimation error in a vertical plane, γ is the collimation error in a horizontal plane, $\boldsymbol{T}$ is the magnetic field vector in the sensor frame, $R_y(\beta)$ is the rotation matrix

Published by Copernicus Publications on behalf of the European Geosciences Union.

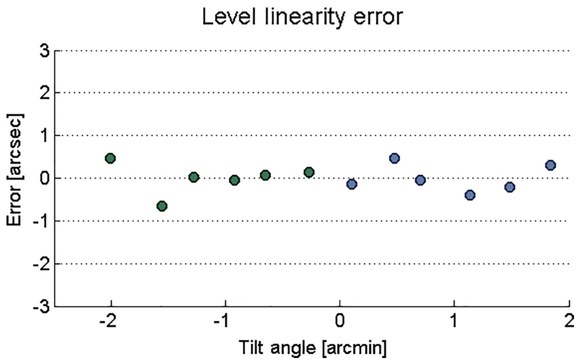

Figure 1. AutoDIF tilt sensor linearity error. The tilt range is $\pm 2'$.

around horizontal axis of the theodolite, and $\varphi R_z()$ is the rotation matrix around vertical axis of the theodolite. Considering the following transformation, $\begin{bmatrix} X \\ Y \end{bmatrix} = \begin{bmatrix} H\cos(D) \\ H\sin(D) \end{bmatrix}$, the development of the first term of Eq. (1) leads to the AutoDIF model (Eq. 2).

$$\begin{aligned}\varphi\varphi T_X &= H\cos(\phi - D)(\cos(\beta) - \epsilon\sin(\beta)) - \gamma \\ &\quad H\sin(\phi - D) - Z\ (\sin(\beta) - \epsilon\cos(\beta))\ - Z(\cos(\beta) \\ &\quad - \epsilon\sin(\beta)\ \ (A\cos(\phi) + B\sin(\phi)) + Z\gamma(A\sin(\phi)B\cos(\phi) \\ &\quad + -H(\sin(\beta) + \epsilon\cos(\beta))(A\cos(D) + B\sin(D)) \\ &\quad + T_{0x} \qquad (2)\end{aligned}$$

2.1 Declination

Declination measurement is performed by putting magnetic sensor perpendicular to the field in a horizontal plane. Therefore, four configurations are possible: $\beta = 0, \pi$ and $\varphi - D = \frac{\pi}{2}\frac{3\pi}{2}$ (where $\varphi - D$ is the angle of the magnetic azimuth). The four configurations are commonly designed according to the sensor pointing direction and its position relative to the horizontal axis. We thus have

- east-up: $\beta = 0$ and $\varphi - D = \frac{\pi}{2}$;
- west-down: $\beta = \pi$ and $\varphi - D = \frac{\pi}{2}$;
- east-down: $\beta = \pi$ and $\varphi - D = \frac{3\pi}{2}$;
- west-up: $\beta = 0$ and $\varphi - D = \frac{3\pi}{2}$.

Keeping small angles approximations and removing second-order terms such as $\epsilon A\ or\ \epsilon\beta_0$ (for readability), we obtain

$$\begin{aligned}T_{\mathrm{EU}} &\approx H(\phi - D) + \frac{\pi}{2} - \gamma H - Z(\beta_{\mathrm{EU}} - \epsilon \\ &\quad + (A\cos(\phi) + B\sin(\phi))) + T_{0x}, \qquad (3)\\ T_{\mathrm{WD}} &\approx -H(\phi - D) - \frac{\pi}{2} - \gamma H - Z(\beta_{\mathrm{WD}} + \epsilon \\ &\quad - (A\cos(\phi) + B\sin(\phi))) + T_{0x}, \qquad (4)\\ T_{\mathrm{ED}} &\approx H(\phi - D) + \frac{\pi}{2} + \gamma H - Z(\beta_{\mathrm{ED}} + \epsilon \\ &\quad + (A\cos(\phi) + B\sin(\phi))) + T_{0x}, \qquad (5)\\ T_{\mathrm{WU}} &\approx -H(\phi - D) - \frac{\pi}{2} + \gamma H - Z(\beta_{\mathrm{WU}} - \epsilon \\ &\quad - (A\cos(\phi) + B\sin(\phi))) + T_{0x}. \qquad (6)\end{aligned}$$

Or, if ϕ is isolated,

$$\begin{aligned}\phi_{\mathrm{EU}} &\approx \frac{T_{\mathrm{EU}} - T_{0x}}{H} + D + \frac{\pi}{2} + \gamma + \tan(I) \\ &\quad (\beta_{\mathrm{EU}} - \epsilon + (A\cos(\phi) + B\sin(\phi))), \qquad (7)\\ \phi_{\mathrm{WD}} &\approx -\frac{T_{\mathrm{WD}} - T_{0x}}{H} + D + \frac{\pi}{2} - \gamma - \tan(I) \\ &\quad (\beta_{\mathrm{WD}} + \epsilon - (A\cos(\phi) + B\sin(\phi))), \qquad (8)\\ \phi_{\mathrm{ED}} &\approx \frac{T_{\mathrm{ED}} - T_{0x}}{H} + D + \frac{\pi}{2} - \gamma + \tan(I) \\ &\quad (\beta_{\mathrm{ED}} + \epsilon + (A\cos(\phi) + B\sin(\phi))), \qquad (9)\\ \phi_{\mathrm{WU}} &\approx -\frac{T_{\mathrm{WU}} - T_{0x}}{H} + D + \frac{\pi}{2} + \gamma - \tan(I) \\ &\quad (\beta_{\mathrm{WU}} - \epsilon - (A\cos(\phi) + B\sin(\phi))). \qquad (10)\end{aligned}$$

If we consider the zero method, sensor output is zero. The average of Eqs. (7)–(10) leads to

$$\begin{aligned}\frac{\phi_{\mathrm{EU}} + \phi_{\mathrm{WD}} + \phi_{\mathrm{ED}} + \phi_{\mathrm{WU}}}{4} &\approx D + \frac{\pi}{2} \\ &\quad + \tan(I)(\frac{\sum \beta_i}{4} + A\cos(\phi) + B\sin(\phi)). \qquad (11)\end{aligned}$$

Only the 2 initial degrees of freedom and levelling terms remain.

2.2 Inclination

Inclination computations are similar to declination with $\phi = D + k\pi$. The resulting equation (similar to Eq. 11) is given by

$$\begin{aligned}&\frac{\beta_{\mathrm{NU}} + (\beta_{\mathrm{SD}} - \pi) + (2\pi - \beta_{\mathrm{ND}}) + (\pi - \beta_{\mathrm{NU}})}{4} \\ &\quad \approx I + (A\cos(D) + B\sin(D)). \qquad (12)\end{aligned}$$

3 Validation

Equations (11)–(12) demonstrate the importance of angular reading accuracy and tilt measurement accuracy in the case of magnetic declination/inclination measurement. Moreover, ϕ is related to the true north while angle reading is related to the circle index. The way the true north is determined is also critical for declination measurement. Usually, an azimuth mark is pointed. Those three points are investigated here.

3.1 Level calibration

A magnetic field is a powerful natural signal that can be used for many purposes. In particular, its stability, ensured by the

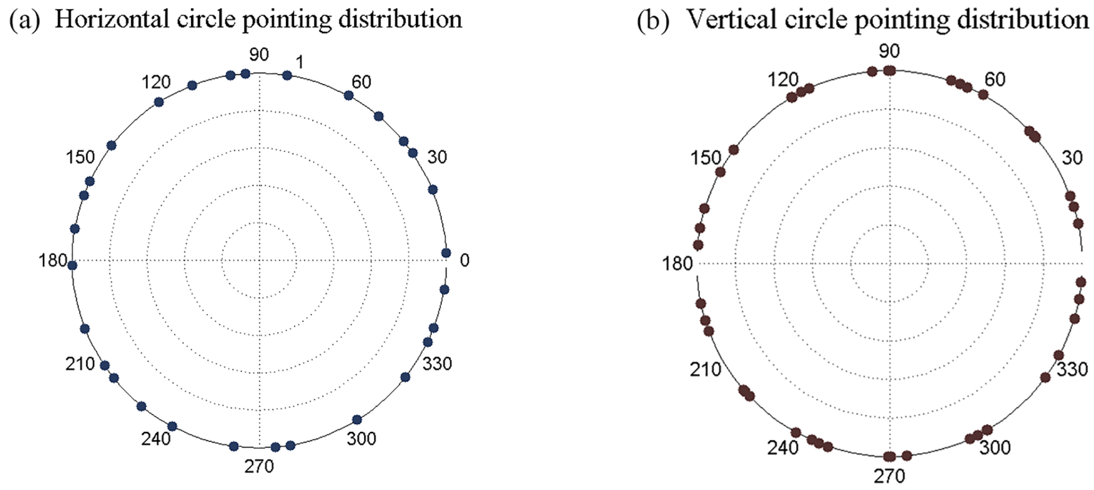

Figure 2. Distribution of pointed direction during ISO-17123 norm validation procedure.

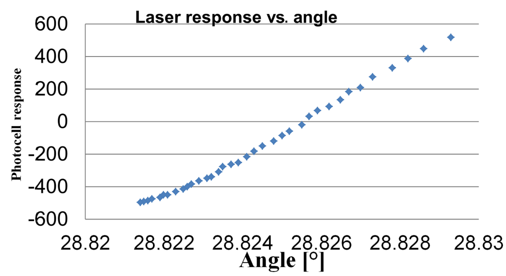

Figure 3. Photocell response when the laser points at the reflector from left to right.

coupling of DI flux with a variometer, provides a useful way to calibrate the AutoDIF tilt sensor. A foot screw is placed in the magnetic meridian while the instrument is set up in inclination measurement, i.e. $\phi = D$ and $T \approx 0$. The "actuated" angle is therefore $A\cos(D) + B\sin(D)$. The field projection onto the magnetic sensor is given by

$$T = \boldsymbol{F}\sin(\alpha), \tag{13}$$

where α is the complementary angle between sensor axis and magnetic field $\boldsymbol{F}$. When turning the foot screw, the instrument gets tilted in the magnetic meridian. A series of recording allows the calibration of the level sensor scale factor and its linearity. The magnetic sensor has 0.1 nT resolution, corresponding to 0.5″, so Fig. 1 does not highlight any linearity error.

Figure 4. AutoDIF mk2.2 on pillar DO2 in Dourbes absolute house.

3.2 Angle reading

It is evident that angle reading accuracy is critical when working with a theodolite. Fortunately, ISO-17123 norm provides a validation protocol for determining the angle reading uncertainty associated with both horizontal and vertical circles. The principle consists of pointing five different directions roughly distributed over a circle (once with the sensor up and a second time with the sensor down), then turning the instrument by 120° and pointing the fluxgate sensors up and down. The angular differences between measurements for same pointing directions are computed. Finally, a stan-

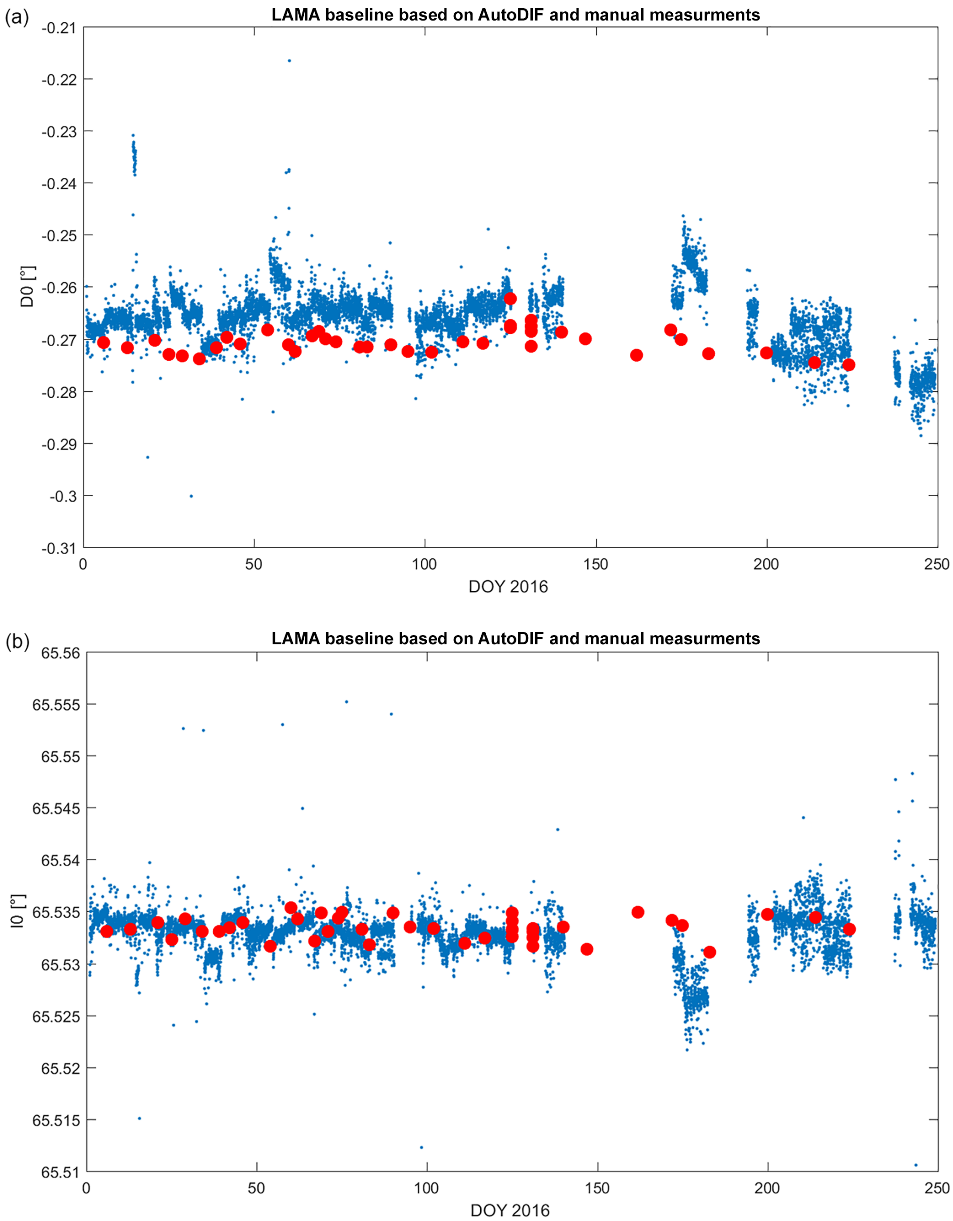

Figure 5. LAMADOU intercomparison baselines for 2016 of AutoDIF measurements (blue dot) and manual measurements with Zeiss 010B.

dard deviation of these differences is established. This norm has been directly applied to determine the AutoDIF horizontal circle, leading to $1\sigma = 5''$. Comparatively, a Zeiss 010B has been tested and gave $1\sigma = 4''$.

ISO-17123 is not suitable for validating the vertical circle. First, this norm only checks a small part of the circle and must point at different targets in a vertical plan. Nevertheless, it has been demonstrated above that a magnetic sensor in an inclination configuration has enough resolution to allow an adaptation of this norm. The inclination measurement set consists of four pointing directions driven by the magnetic sensor. By turning this one around the horizontal axis, a new set of four positions can be made but now using another part of the circle. However, angles between each position should be the same. A variometer can be used to take magnetic field variation into account. The standard deviation using this modified method has been determined ($1\sigma = 3''$). Figure 2 shows the circle positions covered by the validation procedure.

3.3 Azimuth mark

The AutoDIF true north determination system is based on the azimuth mark pointing principle. A laser points at a retroreflector. The returning beam spot strikes the embedded photocells located on both the left and right side of the laser. When

Figure 6. AutoDIF mk2.2 with its Plexiglas cloche on pillar A16 in the tunnel of Conrad observatory (WIC).

the spot is balanced between photocells, the difference signal is zero. Figure 3 shows the photocell response while the laser travels to the reflector from the left to the right.

4 Experiences

AutoDIF mk2.2 was first presented during the 14th IAGA Workshop 2010 in Changchun (China) (Rasson and Gonsette, 2011). Two years later a more reliable version was put to the test during the 15th IAGA Workshop in San Fernando (Spain) (Gonsette and Rasson, 2013). This system is now running for about 5 years in the Dourbes magnetic observatory.

Experience acquired allowed to identify some weaknesses or possible improvements (Fig. 5). For instance, mechanical improvement or better electronic level allowed better magnetic measurement. The software has also evolved giving a real-time computation of the absolute measurement or spot values (declination, inclination and azimuth). A MQTT data transfer protocol has also been implemented for nearly real-time data transfer (Bracke et al., 2016).

We present a few measurement results here. It is more convenient to show instrument baselines rather than vector measurement because this quantity is free of magnetic variation and thus more suitable for DI-flux comparison.

4.1 Dourbes

Just after the 15th IAGA workshop, the AutoDIF was installed on the pillar DO2 in the absolute house of Dourbes magnetic observatory (Fig. 4). The azimuth mark is located at about 100 m. This pillar is almost always dedicated to this AutoDIF so it can perform absolute measurement every 30 min so that we obtained 48 measurements per day (See Fig. 5). We only move it twice a week to perform manual absolute measurement for comparison. Because the instrument is also dedicated to experiment and improvement tests, big gaps correspond to immobilisation times.

Figure 5 show comparison baseline of LAMADOU variometer between automatic and manual measurements since beginning of 2016. We can see that for declination, AutoDIF is just over the manual measurement but the variation along the year is the same. The difference is less than 0.005°. For inclination, the difference is less than 0.002°. These differences may arise from the differing instruments (errors on angle readings; see Sect. 3.2) and/or from target azimuth determination.

4.2 Conrad

At the end of 2012, we installed an AutoDIF in the tunnel of the WIC on the pillar A16 with an azimuth mark at 50 m. At the beginning, a moisture problem did not permit the device to work properly (95 % relative humidity). This was solved by heating the instrument in a Plexiglas enclosure (See Fig. 6)

In Fig. 7, we can see that baselines computed on the AutoDIF measurement are very close to the manual one, except in the last set of data. The gap of automatic data is due to bad contact of the wire of the fluxgate and the laser of the AutoDIF. The last dataset is recorded after a quick in situ repair. After that event, the AutoDIF was sent back to Dourbes for repair and an upgrade. The red line is the adopted baseline based on the official pillar A16 where manual measurements are performed.

4.3 Choutuppal

An AutoDIF participated to intercomparison session during the 16th IAGA Workshop in Choutuppal. It performed a measurement set every 30 min during 1 week. Figure 8 shows the baseline results of the intercomparison session. The gap during the night of the first day is due to an unexpected power failure.

The drop of declination baseline, D0, at the beginning and at the end comes from a drift of the target, which was mounted on a tripod. Figure 9 (left) shows D0 and the trace measurement during the week, which can explain the D0 variation. This drop can also explain low D0 values for AutoDIF compared to the manual measurements performed on the pillars P1 to P7. This mishap confirms that both pillars (for the instrument and for the target azimuth marked) need to be very stable. In this case the azimuth mark was at 100 m. We can also observe diurnal variation of the baseline (see Fig. 8). That can be explained by the variometer variation (see Fig. 9, right) probably due to a bad evaluation of the scale factor or misalignment of the variometer. These kinds

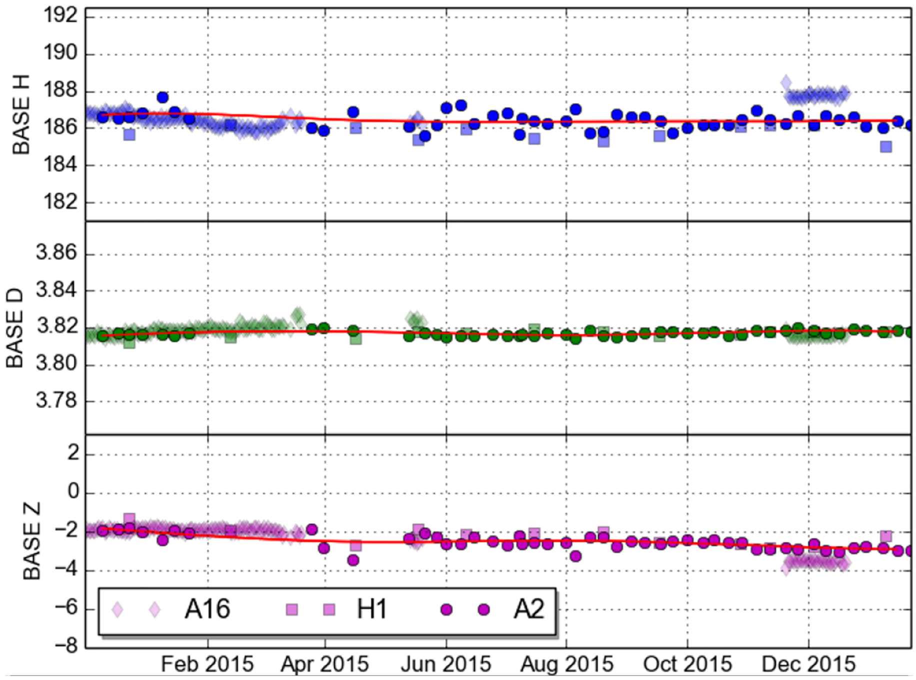

Figure 7. Baseline value for FGE variometer, A16 AutoDIF, H1, and A2 manual measurements (H and Z in nT and D in degrees) (Leonhardt et al., 2015).

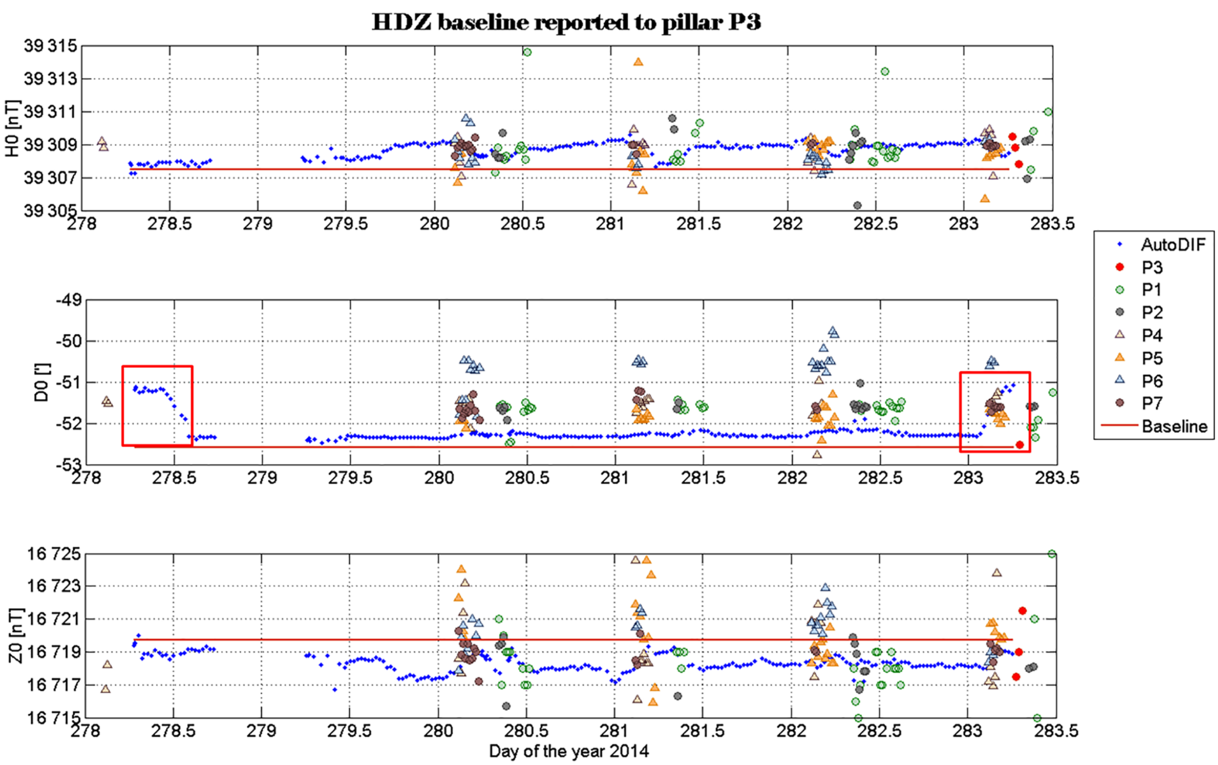

Figure 8. AutoDIF on its pillar during the 16th IAGA Workshop in Choutuppal.

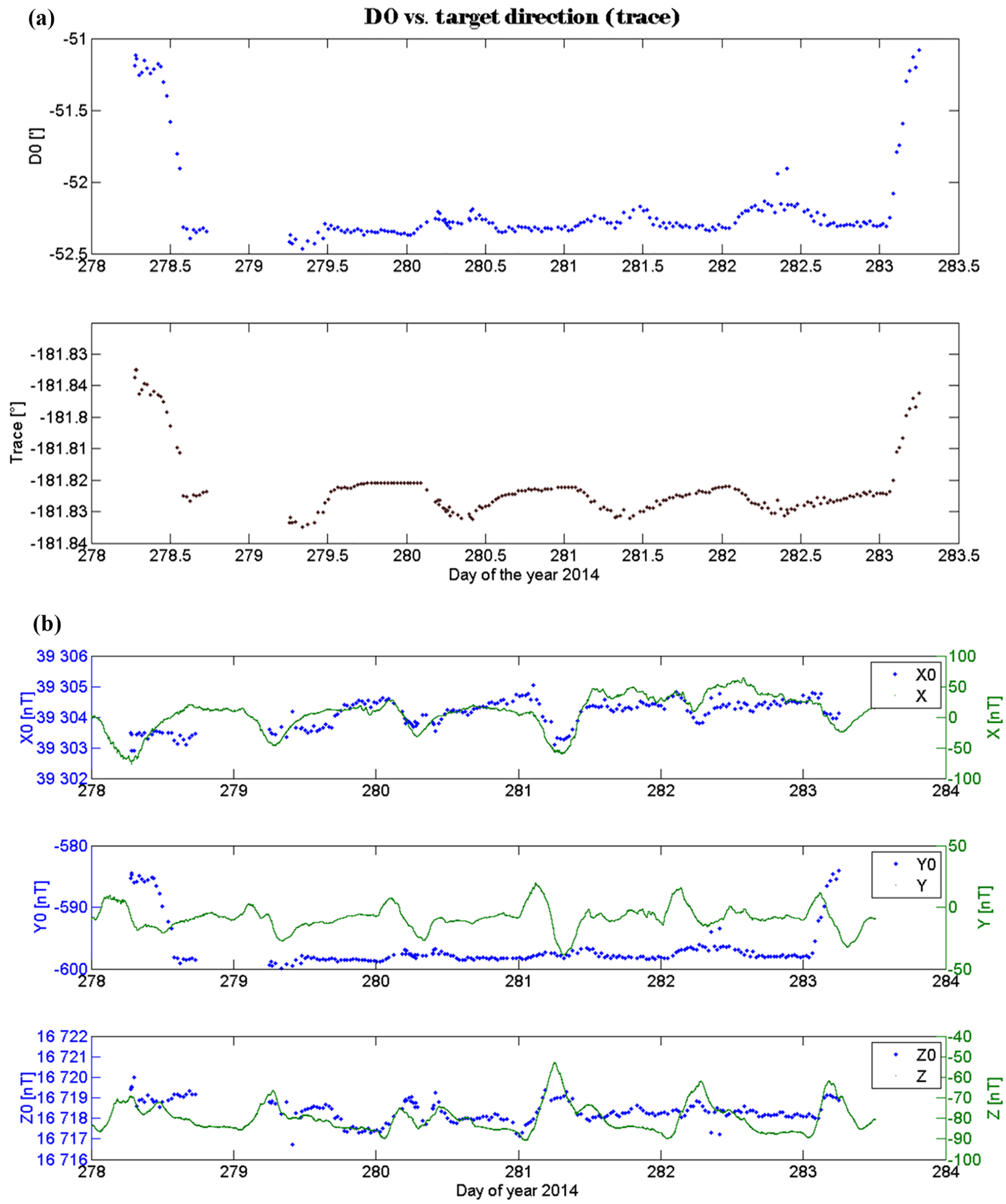

Figure 9. **(a)** Drift of the target in front of D0 variation. **(b)** Variometer diurnal variation (green curve) due to bad scale factor or misalignment of the sensor.

of results are only visible when you perform a lot of absolute measurements like with the AutoDIF.

5 Conclusions

After 7 years of development, we can now say that AutoDIF has reached a level of maturity which allows us to envisage its commercialisation in observatories. The benefits that they could offer are multiple:

– control manual absolute measurement;

– reduce the number of occurrences of the manual measurement (particularly interesting for unmanned observatory where a manual measurement can be performed every year or 2 years when you visit the observatory);

– with the possibility of measurements that are well distributed throughout the day and at high frequency, they can check the correct orientation of their variometer and/or other defects in the installation of these.

Data availability. Data are available at www.intermagnet.org.

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 17th IAGA Workshop on Geomagnetic Observatory Instruments, Data Acquisition and Processing, Dourbes, Belgium, 4–10 September 2016.

Edited by: Arnaud Chulliat
Reviewed by: Lészló Hegymegi and Bill Worthington

References

Bracke, S., Gonsette, A., Rasson, J.-L., Poncelet, A., and Hendrickx, O.: Automated observatory in Antarctica: Real-Time data transfer on constrained networks in practice, XVIIth IAGA Workshop on Geomagnetic Observatory Instruments, Data acquisition and Processing, Dourbes, Belgium, 2016.

Gonsette, A. and Rasson, J.: Autodif: Automatic Absolute DI Measurements, in: proceedings of the XVth IAGA Workshop on Geomagnetic Observatory Instruments, Data Acquisition and Processing, Boletin ROA No. 03/13, 16–19, 2013.

Kerridge, D. J.: Theory of the fluxgate-theodolite, Report WM/88/14, British Geological Survey, 1988.

Lauridsen, E. K.: Experience with the declination-inclination (DI) fluxgate magnetometer including theory of the instrument and comparison with other methods, Danish meteorological institute, 1985.

Leonhardt, R., Egli, R., Leichter, B., Herzog, I., Kornfeld, R., Bailey, R., Kompein, N., Arneitz, P., Draxler, A., Mandl, R., and Steiner, R.: Conrad Observatory: magnetic Results 2015, in: GMO Bulletin 2, Zentralanstal für Meteorologie und Geodynamik, Vienna, 2015.

Rasson, J.-L. and Gonsette, A.: The MarkII Automatic DIFlux, in: Data Science Journal, CODATA, vol. 10, 30 August 2011.

Rasson, J. L., van Loo, S., and Berrami, N.: Automatic DIflux Measurements with AUTODIF, in: Proceedings of the XIIIth IAGA Workshop on geomagnetic observatory instruments, data acquisition, and processing, U.S. Geological Survey Open-File Report 2009-1226, 220–224, 2009.

Van Loo, S. A. and Rasson, J. L.: Presentation of the prototype of an automated DIFlux, Publs. Inst. Geophys. Pol. Acad. Sc., C-99 (398), 77–86, 2007.