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U.S. Geological Survey experience with the residual absolutes method

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Abstract. The U.S. Geological Survey (USGS) Geomagnetism Program has developed and tested the residual method of absolutes, with the assistance of the Danish Technical University's (DTU) Geomagnetism Program. Three years of testing were performed at College Magnetic Observatory (CMO), Fairbanks, Alaska, to compare the residual method with the null method. Results show that the two methods compare very well with each other and both sets of baseline data were used to process the 2015 definitive data. The residual method will be implemented at the other USGS high-latitude geomagnetic observatories in the summer of 2017 and 2018.

1 Introduction

Geomagnetic observatories are unique facilities. They measure the variation of the three vector components of the geomagnetic field at 1 min or 1 s time resolution and they also measure the absolute value of the geomagnetic field (see, e.g., Rasson et al., 2017; Matzka et al., 2010; Love and Chulliat, 2013; Chulliat et al., 2017). The vector components are typically measured with a three-axis fluxgate magnetometer. The absolute measurements are used to generate baseline values, which are the difference between the absolute values and raw variation data, for each magnetic component. The baseline values are used to calibrate the variation data to produce final definitive data. Since the first systematic geomagnetic observations in the 16th century (Malin, 1987), there has been continued development and improvement of instruments to measure absolute values of the geomagnetic field. Some of these instruments measure the strength of a magnetic vector component, the magnitude of the entire vector, or the angles of the orientation of the geomagnetic vector. Beginning in the 1970s the most common instruments employed are the proton precession magnetometer that measures the magnitude (F) of the geomagnetic vector and, since the 1980s, the declination–inclination magnetometer (DIM), also known as the DI-fluxgate, which is used to measure the declination (D) and inclination (I) angles of the geomagnetic vector. These three measurements make it possible to compute all other components of the vector (Jankowski and Sucksdorff, 1996). The DIM is used to measure four declination angles, in four different orientations, and four inclination angles. This instrument is used as a null detector, where the output of the fluxgate sensor is zero when the magnetic field vector is perpendicular to the sensor. The so-called "null method" was the technique first developed for use with the DIM. This method requires the observer to rotate the instrument so the analog output of the fluxgate, in nanoteslas (nT), is zeroed or nulled and the time of the null reading and the angle are recorded. The null method works well and is still in use today. The angular readings are read through a microscope where, for the Zeiss 020 theodolite discussed here, the angle is read in degrees and arcminutes and estimated to a tenth of a minute. However, there are two drawbacks to the null method: (1) at high latitudes, where the geomagnetic field is more active, a good null can be difficult to obtain; and (2) the null method requires the observer to be within arm's reach of the DIM to constantly adjust the theodolite–sensor orientation to achieve a nulled output on the fluxgate. If the observer is not free of ferrous materials, such as watches, keys, tools, dental work, or small electronics, then the presence of these items can contaminate the measurements.

The point of the residual method is to allow readings of the horizontal or vertical circle for positions where the output of the fluxgate, termed the residual value in nanoteslas, is not exactly zero. This makes it easier to cope with rapid changes of the geomagnetic field. It also allows the observer to be farther away from the DIM, reducing the possibility of contaminated measurements. Additionally, as in the case for Zeiss 020 theodolite, the circle reading can be set exactly to a whole-minute value and the output of the DIM magnetometer can be used to mathematically compensate for the resulting small deviation in angle between the whole minutes as opposed to estimating tenths of minutes by eye. The residual method presented here was developed for the Danish geomagnetic observatories at Danish Technical University (DTU), originally part of the Danish Meteorological Institute. The method and computations are based on a document written by Kring Lauridsen (1985), a book by Jankowski and Sucksdorff (1996), and a study by Matzka and Hansen (2007).

This paper presents the updated computational scheme used by the U.S. Geological Survey (USGS) and shows comparisons of the two methods employed at the USGS College Magnetic Observatory (CMO), Fairbanks, Alaska.

2 Computations

For the sake of simplicity, all of the following equations will use angles in radians, unless indicated otherwise. For programming purposes, angles measured in degrees or gradians will need to be converted to radians as appropriate. Instrument orientations, such as west down, refer to the direction the telescope is pointing and the position of the fluxgate sensor mounted on the telescope. The definitions used can be found in the Appendix.

2.1 Inclination computations

The inclination angle computations are discussed first because the horizontal baseline value, H_b, is needed for the computation of D. For reference, using the null method, the computation of the inclination angle is fairly simple:

$$I_N = \frac{(\mathrm{AI}_1 + \mathrm{AI}_2) - (\mathrm{AI}_3 + \mathrm{AI}_4) + 2\pi}{4}. \quad (1)$$

AI_{1-4} refers to the south down orientation, the north up orientation, the south up orientation, and the north down orientation, respectively. This sequence is the USGS order for the four inclination measurements.

For the residual method, the computations involve some additional steps. Each inclination reading (AI_i) is first corrected using the corresponding residual value.

$$I_1 = \mathrm{AI}_1 + \mathrm{HS}\,\sin^{-1}\left(\frac{R_5}{f_5}\right) - \pi \quad (2)$$

$$I_2 = \mathrm{AI}_2 - \mathrm{HS}\,\sin^{-1}\left(\frac{R_6}{f_6}\right) \quad (3)$$

$$I_3 = \pi - \left(\mathrm{AI}_3 - \mathrm{HS}\,\sin^{-1}\left(\frac{R_7}{f_7}\right)\right) \quad (4)$$

$$I_4 = 2\pi - \left(\mathrm{AI}_4 + \mathrm{HS}\,\sin^{-1}\left(\frac{R_8}{f_8}\right)\right) \quad (5)$$

The inclination is computed by taking the mean of these four angles.

$$I_\mathrm{mean} = \frac{(I_1 + I_2 + I_3 + I_4)}{4} \quad (6)$$

However, the method can be further improved by making the timing of the individual F values independent of the timing of I_1 to I_4. This requires variometer data, which are typically available at observatories. Crucially, it allows using the same pillar for D, I, and F, as the DI-flux and the scalar magnetometer can be deployed sequentially on the observatory's main pillar.

The individual F values f_5 through f_9 are calculated by

$$f_i = F_\mathrm{mean} + (h_i - h_\mathrm{mean})\cos I_\mathrm{mean} + (z_i - z_\mathrm{mean})\sin I_\mathrm{mean} + \frac{\left(e_i^2 - e_\mathrm{mean}^2\right)}{2F_\mathrm{mean}}, \quad (7)$$

where AI_2 is used as a first guess for I_mean. F_mean, h_mean, z_mean, and e_mean are either mean values over the arbitrary time instances of the F measurements or, for the case of simultaneous I and F measurements, mean values over the time instances of the I measurements. The latter case is described in Eqs. (8) to (11):

$$h_\mathrm{mean} = \frac{(h_5 + h_6 + h_7 + h_8 + h_9)}{5}, \quad (8)$$

$$e_\mathrm{mean} = \frac{(e_5 + e_6 + e_7 + e_8 + e_9)}{5}, \quad (9)$$

$$z_\mathrm{mean} = \frac{(z_5 + z_6 + z_7 + z_8 + z_9)}{5}, \quad (10)$$

$$F_\mathrm{mean} = \frac{(f_5 + f_6 + f_7 + f_8 + f_9)}{5}. \quad (11)$$

Hence, this introduces an iteration to the computation for I. After values for f_5–f_9 are estimated using Eqs. (7) to (11) and the various values of I are computed using Eq. (2) through Eq. (6), I_mean is used in Eq. (7) to correct the values for f_5–f_9. I is then computed again using Eq. (2) through Eq. (6). This iterative process is continued until the change in I_mean from one iteration to the next is less than 0.0001°. This usually results in a very small change in I from one iteration to the next except in conditions of high activity.

The final inclination value I is used to compute the absolute values for the H and Z. To obtain a final value for F, it is necessary to add in the F pier correction, F_pc:

$$F = F_\mathrm{mean} + F_\mathrm{pc}. \quad (12)$$

Then H and Z, for the times of the four inclination measurements, can be computed using F and I:

$$H = F \cos I \tag{13}$$

and

$$Z = F \sin I. \tag{14}$$

These two absolute values can be used to compute the baseline values for H and Z.

$$H_\mathrm{b} = \sqrt{H^2 - E_\mathrm{mean}^2} - H_\mathrm{mean} \tag{15}$$

$$Z_\mathrm{b} = Z - Z_\mathrm{mean} \tag{16}$$

An extra or fifth inclination measurement is performed to determine the scale value of the fluxgate magnetometer mounted on the DIM. The angular difference of the telescope between the fourth and fifth I readings (elements 8 and 9, for h and z, respectively) is exactly 10.0 min, or 0.16667° (for a theodolite that measures in gradians (gon) one would use 0.2 gon instead). These angular changes are chosen such that the output of the fluxgate magnetometer is still on scale, between ±200 nT for a DTU model G fluxgate magnetometer, and also because they are very convenient to set for a Zeiss 020 theodolite. The angular change of the fluxgate with respect to the magnetic field (from perpendicular to slightly tilted) is denoted ΔB, in degrees (Eq. 17). The change in residuals is denoted as ΔR. Computation of the scale value thus follows:

$$\Delta B = 0.16667 + \left(-\sin I \cdot \frac{(h_9 - h_8)}{F} + \cos I \cdot \frac{(z_9 - z_8)}{F} \right) \frac{180}{\pi}, \tag{17}$$

$$\Delta R = R_9 - R_8, \tag{18}$$

$$\mathrm{SV} = F \frac{\Delta B}{\Delta R}. \tag{19}$$

Ideally, the resulting scale value should be 1.000, indicating that the output of the DIM fluxgate is in fact in nanoteslas. In practice, it can range from 0.99 to 1.01. As long as the measured residual values are within ±10.0 nT, there is no need to adjust for an error of 1 % in the scale value. Monitoring and tracking the scale value can help with diagnosing any problem that might develop with the instrument.

2.2 Declination computations

Computing the absolute value for declination, using the null method, from the declination measurements is fairly simple. The magnetic meridian is computed as the average of the four declination readings. The four mark readings, which are sightings on the true azimuth mark before and after the declination measurements, are also averaged. The computation of the absolute value for declination, using the null method, can be described in simple terms as

$$D_N = \text{magnetic meridian} - \text{average mark readings} + \text{the true azimuth of the mark.}$$

The baseline value is easily computed by taking the difference between D_N and the value for declination from the fluxgate. However, this is complicated by the fact that the output of the fluxgate is in nanoteslas (E) and must be converted to an angular value. The conversion traditionally used is known as the small angle approximation. While the small angle approximation has been useful, sometimes the value of H used in the approximation is a previous year's annual mean instead of a current value. More detail on this can be found in Jankowski and Sucksdorff (1996) and Wienert (1970).

The exact formula for the declination conversion uses the simple trigonometric relation that the declination angle can be computed from the inverse tangent of the value of E divided by the absolute value of H. Therefore, the calculations are more complex than those for the null method. The ordinate or magnetometer values, from the observatory fluxgate for e_{1-4}, are converted to an angle using the exact conversion as

$$d_i = \tan^{-1}\left(\frac{e_i}{(h_i + H_\mathrm{b})}\right). \tag{20}$$

Using Eq. (20) can provide a more precise angular value for declination when converting the value from E. This can be especially important at high latitudes, as shown in Fig. 1. The figure shows the difference between the computation of D using the small angle approximation and the exact computation for several high-latitude observatories, where the H component value is small, and one mid-latitude observatory. One could argue that at low latitudes the difference is negligible; however, if the exact computation is used at high latitudes, the same computation should be used everywhere for consistency. In addition, use of the exact computation makes it unnecessary to reorient the variometer when E gets large, which we regard as a significant advantage for observatory operations. With advances in computing power, the exact formula is now easily computed.

The USGS declination measurements are in the following order: west down, east down, west up, and east up, which correspond to AD_1 through AD_4, respectively. The angles for each reading are computed in the following fashion:

$$A_1 = \mathrm{AD}_1 - \sin^{-1}\left(\frac{R_1}{\sqrt{(h_1 + H_\mathrm{b})^2 + e_1^2}}\right) - d_1, \tag{21}$$

$$A_2 = \mathrm{AD}_2 + \sin^{-1}\left(\frac{R_2}{\sqrt{(h_2 + H_\mathrm{b})^2 + e_2^2}}\right) - d_2, \tag{22}$$

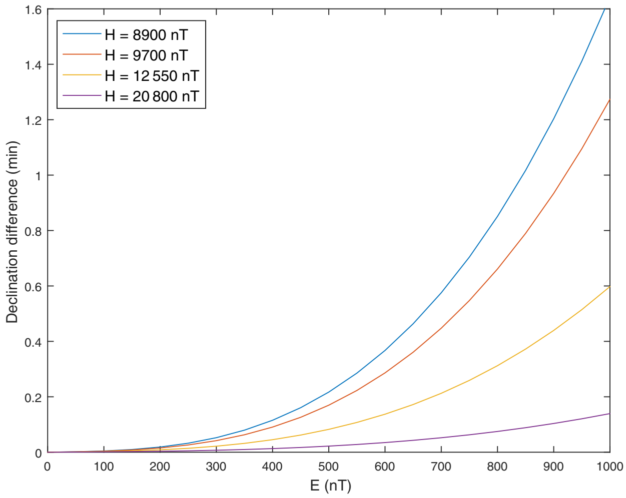

Figure 1. A comparison of the difference between the computation of declination from E using the small angle approximation and the exact formula. The difference is shown for three high-latitude observatories and one mid-latitude observatory.

$$A_3 = \mathrm{AD}_3 - \sin^{-1}\left(\frac{R_3}{\sqrt{(h_3 + H_\mathrm{b})^2 + e_3^2}}\right) - d_3, \quad (23)$$

$$A_4 = \mathrm{AD}_4 + \sin^{-1}\left(\frac{R_4}{\sqrt{(h_4 + H_\mathrm{b})^2 + e_4^2}}\right) - d_4. \quad (24)$$

Equations (21)–(24) are more complex than those used for the null method because they have two terms that add to the accuracy of the computations. The term inside the inverse sine function, the residual (R_i) divided by H, represents the interpolated value added to the angular measurement (AD_i). The interpolation value corrects for the H baseline value and the variation about the orientation axis (H) of the fluxgate sensor. The second term represents the value of e_i for each measurement, converted to an angle, as computed by Eq. (20).

The mean of the four angles A_i, termed the magnetic meridian, is computed next:

$$M = \frac{(A_1 + A_2 + A_3 + A_4)}{4}. \quad (25)$$

Similarly, the mean should be computed for the four mark angles:

$$\mathrm{MA} = \frac{(\mathrm{MU}_1 + \mathrm{MU}_2 + \mathrm{MD}_1 + \mathrm{MD}_2)}{4}. \quad (26)$$

The baseline value for declination, in degrees, is computed as follows:

$$D_\mathrm{b} = (M - \mathrm{MA} + \mathrm{AZ}), \quad (27)$$

where AZ is the true azimuth angle to the azimuth mark.

2.3 Final absolute values

In this method, the absolute values for H, D, and Z are computed for the starting time of the measurements, corresponding to the west down measurement, for use in data processing. So the value for H would be determined by the following:

$$H = \sqrt{(h_1 + H_\mathrm{b})^2 + e_1^2}. \quad (28)$$

The value for D, in degrees, is computed as

$$D = D_\mathrm{b} + \tan^{-1}\left(\frac{e_1}{h_1 + H_\mathrm{b}}\right)\frac{180}{\pi}. \quad (29)$$

The absolute value for Z would be

$$Z = Z_\mathrm{b} + z_1. \quad (30)$$

2.4 Diagnostic fluxgate parameters

There are five separate error parameters that can be computed from the measured declination and inclination angles that are useful for diagnosing the quality of measurements performed with the DIM.

For the D measurements, there are the angles, known as the collimation errors or misalignment angles, in the horizontal plane, also termed the sight error and the azimuth error by Rasson (2005).

The declination sight error, in arcseconds, designated as ε_D is computed as follows:

$$\varepsilon_\mathrm{D} = \frac{(A_4 + A_3 - A_2 - A_1)}{4 \tan I}\left(\frac{180}{\pi}\right)3600. \quad (31)$$

The azimuth error, in arcseconds, designated as δ, is computed as follows:

$$\delta = \frac{(A_4 - A_3 - A_2 + A_1)}{4}\left(\frac{180}{\pi}\right)3600. \quad (32)$$

The declination sensor offset, defined as the sensor reading in a true zero magnetic field, also called sensor magnetization error by Rasson (2005), designated as $\mathrm{SO_D}$, is computed in nanoteslas:

$$\mathrm{SO_D} = H\frac{(A_4 - A_3 + A_2 - A_1)}{4}. \quad (33)$$

The sight error and sensor offset can also be computed for the inclination readings, whereas the azimuth error cannot be determined for inclination.

The inclination sight error, also known as the misalignment in the vertical plane, in arcseconds, designated as ε_I is computed as follows:

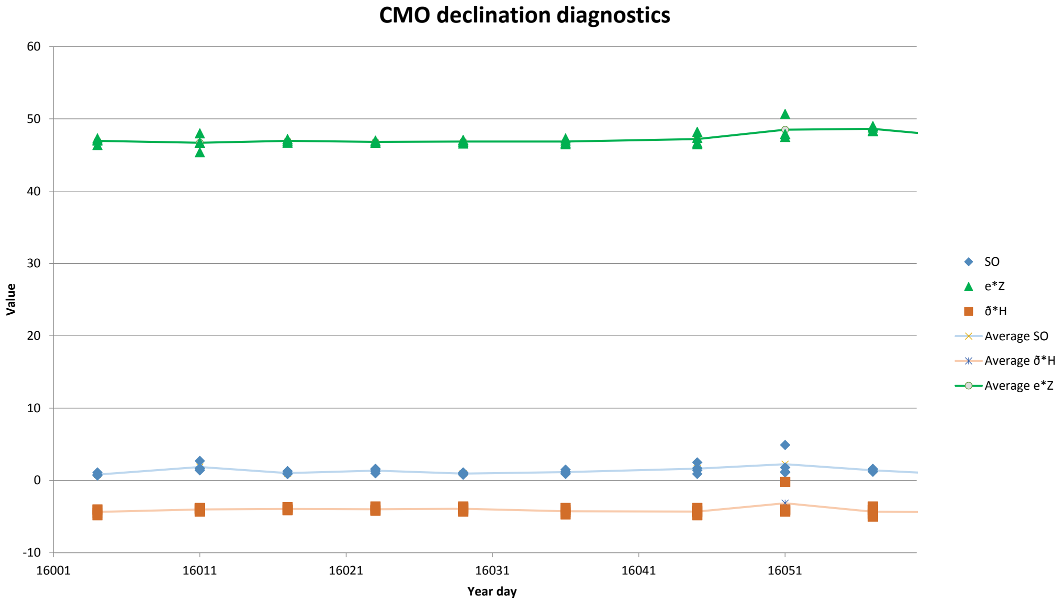

Figure 2. Declination diagnostic parameters from absolute observations for the first 2 months of 2016, plotted with an arbitrary vertical scale. The graph shows the four individual observations and their average. There is an outlier value observed on day 51 that is probably a bad measurement that should be eliminated before processing.

$$\varepsilon_{\mathrm{I}} = \frac{(I_2 + I_1 - I_4 - I_3)}{4}\left(\frac{180}{\pi}\right)3600. \quad (34)$$

The inclination sensor magnetization error, designated as $\mathrm{SO_I}$, is also computed in nanoteslas:

$$\mathrm{SO_I} = -F\frac{(I_2 - I_1 - I_4 + I_3)}{4}. \quad (35)$$

These error parameters have two uses. In the first case, these error values are computed for an individual set, and can be compared to the values of previous or following sets. The resulting values should be approximately the same. If one value is noticeably different, it usually indicates a bad set of observations as demonstrated in Fig. 2. Figure 2 shows the three declination parameters for 2 months of 2016. One of the individual observations on day 51 is probably a bad reading and should be eliminated from the baselines. In the second case, these error values can be tracked over longer periods to see if there are any drifts or changes in the results. Long-term changes can indicate developing problems with the instrument, including contamination, a loose sensor, or other mechanical problems with the theodolite.

3 Absolute measurement tests

The residual method was tested at most of the USGS observatories by USGS staff during site visits over the course of a year, and the agreement between the null and residual methods was satisfactory. More extensive testing was performed at the CMO. This was a logical choice because the observatory has good baseline stability and is located at high geomagnetic latitude, 65° N, allowing us to test the residual method at high latitude. In addition, there were two observers performing absolute measurements three times a week. One of the observers was trained to use the residual method once a week while the other observer continued using the null method twice a week. After 6 months, the second observer was trained to use the residual method so that both observers could alternate methods to eliminate the possibility of an observer bias, which could otherwise take months to identify. This overlap of techniques was started in mid-2013 and still continues. Baseline results of some of these tests are shown in Fig. 3.

In the comparison of the two sets of baselines, there are agreements and differences. The baselines for declination show differences that are mostly on the order of a tenth of a minute apart. These differences could be easily explained by round-off error, but it is also possible that it could be due to differences in computation schemes, with the residual method deriving more accurate baselines because the observer does not have to null the sensor during active periods of magnetic activity. The null method uses the traditional small angle computation to convert nanoteslas to minutes. The residual method uses the exact conversion from nanoteslas to minutes. Also, some of the larger differences could be attributed to observer error or a higher level of magnetic activity.

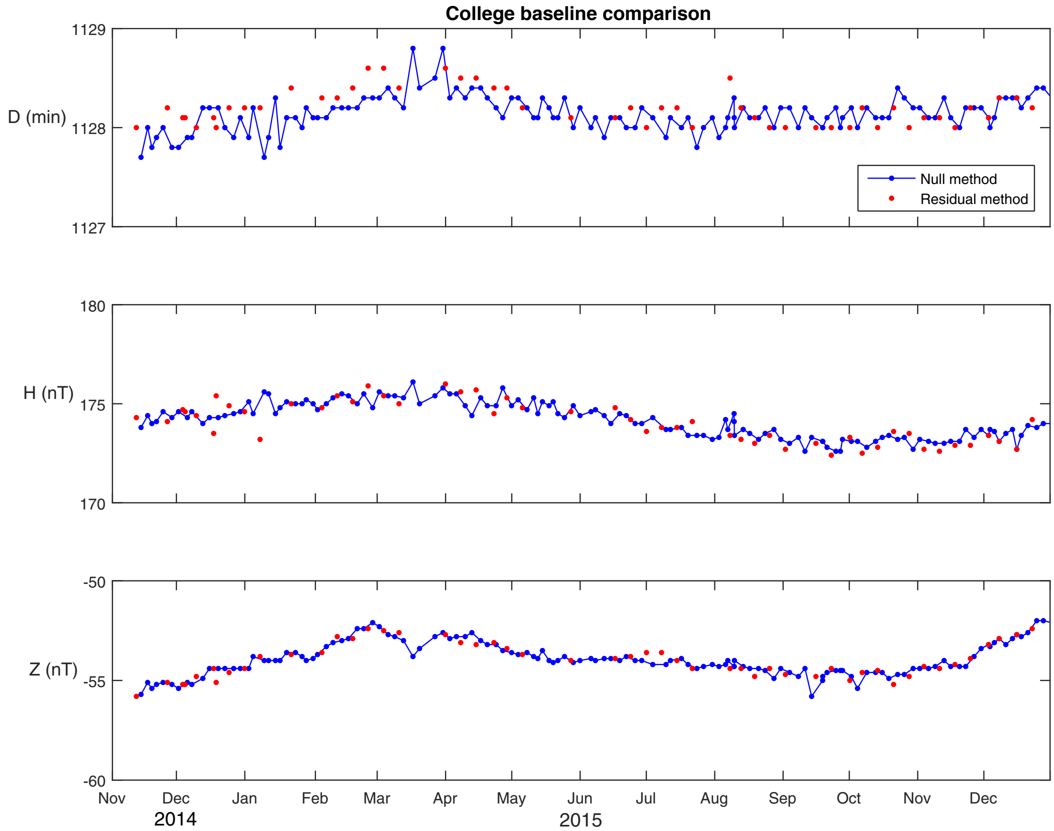

Figure 3. Comparison of baseline measurements using the null and residual methods at College Magnetic Observatory in 2014 and 2015. The three graphs show that there is considerable agreement between the null and residual methods. The D graph has a 2.0 min scale and the differences are only about 0.1 or 0.2 min.

Differences in the horizontal component (H) baselines can be attributed to the weakness in the strength of the horizontal field. At higher latitudes, the strength of H has a much smaller contribution to the total field compared to the vertical component. This makes it harder to get stable, repeatable measurements of the H component at high-latitude observatories. Some of the larger differences could also be due to observer error.

The vertical baselines (Z) show very good agreement between the two methods. There are only a few spots where there are noticeable differences, which could be ascribed to causes mentioned above. In some cases the baseline curve from the residual method looks to be a little more stable than the curve from the null method.

Since 1996, the USGS has usually performed absolute observations, using the null method, with four separate measurements or sets over about an hour. Four sets were also measured when using the residual method. Four separate measurements make it possible to evaluate the range or spread of the measurements. At CMO, the residual method showed a consistently smaller value in the range of the four measurements, especially in the H baselines.

The 14 months of baseline data shown, using the two measurement methods, were combined and used for the final processing of the definitive data for 2015. A few measurements using the null method were removed from the data set due to possible contamination; none of the data from the residual method were removed because of possible contamination. The residual method has been implemented at both College and Deadhorse observatories. The USGS plans to implement the residual method at the remaining USGS observatories in Alaska in 2018 and in all observatories by 2019.

4 Discussion and conclusions

From the data presented above, it is evident that absolute measurements using the residual method are comparable to measurements with the null method. While it is difficult to judge the absolute accuracy of the results, the residual method, with a smaller range in the four sets of observations, demonstrates more precise results, suggesting an increase in the accuracy of the baseline measurements. With well-trained observers, both methods should yield similar results. When processing data from a high-latitude observatory such as CMO, there are some baseline data values that are removed from the data measured using the null method when the magnetic activity is high. With the residual method, the amount of baseline data removed due to high magnetic activity is less than half than was removed from the data measured with the null method.

The residual method presented also offers the possibility of more precise results for the absolute and baseline measurements. The use of the exact computation, for the conversion from nanoteslas to arcminutes, does provide a more accurate calculation for the declination results because the small angle approximation is eliminated.

We have demonstrated that the residual method is at least as good as the null method. In some cases, it is better because the nature of the method makes it more accurate during higher levels of magnetic activity, typically seen at high magnetic latitudes. This provides for extra baseline data for the times when the null method would not be possible due to high magnetic activity. The residual method also makes it possible to move the observer away from the fluxgate sensor on the DIM to avoid contamination. This is especially helpful for observers who wear glasses. For example, at Brorfelde Observatory (BFE), Denmark, the observer is 1–2 m away from the instrument. Personnel from DTU, German Research Centre for Geosciences (GFZ), and USGS have learned that when training new observers it is easier to teach the residual method than the null method; that way, the observers can get consistent results sooner.

Data availability. The College Magnetic Observatory definitive data, for 2014 and 2015, have been published on the Intermagnet web site at http://www.intermagnet.org. Intermagnet has not yet assigned a DOI to the data.

Appendix A: Definitions

nT	value of magnetic field strength, $1\,\mathrm{nT} = 10^{-9}\,\mathrm{T}$
H	absolute value of the horizontal intensity, in nT
D	absolute value of the declination angle, in degrees
Z	absolute value of the vertical intensity, in nT
F	absolute magnitude of the magnetic field vector in nT, also known as the total field
I	absolute value of the inclination angle, in degrees
E	declination value in nT, recorded by the observatory fluxgate
h_i	the ith variation value for the horizontal field, H, from the fluxgate, in nT
e_i	the ith variation value for the declination field, E, from the fluxgate, in nT
z_i	the ith variation value for the vertical field, Z, from the fluxgate, in nT
f_i	the ith variation value for the total field, from the total field magnetometer, in nT
R_i	the ith residual value, in nT: $i = 1$–4 for D readings and $i = 5$–9 for I readings
AD_i	the ith measured declination angle
A_1	computed angle for west down
A_2	computed angle for east down
A_3	computed angle for west up
A_4	computed angle for east up
HS	hemisphere: 1 for Northern and −1 for Southern
M	magnetic meridian angle, mean of A_1–A_4
AI_i	the ith measured inclination angle
I_1	computed angle for south down
I_2	computed angle for north up
I_3	computed angle for south up
I_4	computed angle for north down
I_5	computed calibration angle for north down
H_b	baseline value for H, in nT
Z_b	baseline value for Z, in nT
D_b	baseline value for D, in min
F_pc	F pier correction, between the total field instrument and absolute pier, in nT
MU_1	first mark up reading
MD_1	first mark down reading
MU_2	second mark up reading
MD_2	second mark down reading
MA	mean value of the four mark readings
AZ	true azimuth angle to the azimuth mark
SV	sale value of the fluxgate used on the DIM output

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

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References

Chulliat, A., Matzka, J., Masson, A., and Milan, S. E.: Key Ground-Based and Space-Based Assets to Disentangle Magnetic Field Sources in the Earth's Environment, Space Sci. Rev., 206, 123–156, https://doi.org/10.1007/s11214-016-0291-y, 2017.

Jankowski, J. and Sucksdorff, C.: Guide for magnetic measurements and observatory practice, IAGA, Warsaw, p. 235, 1996.

Kring Lauridsen, E:, Experiences with the DI-Fluxgate magnetometer inclusive theory of the instrument and comparison with other methods, Danish Meteorological Institute Geophysical Paper R-71, Danish Meteorological Institute, Copenhagen, 1985.

Love, J. J. and Chulliat, A.: An international network of geomagnetic observatories EOS, 94, 373–374, https://doi.org/10.1002/2013EO420001, 2013.

Malin, S.: Historical Introduction to Geomagnetism, in: Geomagnetism, Vol. 1, edited by: Jacobs, J. A., Academic Press, London, 1987.

Matzka, J. and Hansen, T. L.: On the various published formulas to determine sensor offset and sensor misalignment for the DI-flux, Publs. Inst. Geophys. Pol. Acad. Sci., C-99, 298–303, 2007.

Matzka, J., Chulliat, A., Mandea, M., Finlay, C. C., and Qamili, E.: Geomagnetic observations for main field studies: From ground to space, Space Sci. Rev., 155, 29–64, https://doi.org/10.1007/s11214-010-9693-4, 2010.

Rasson, J. L.: About absolute geomagnetic measurements in the observatory and in the field, Scientific and Technical Publication No. 40, Royal Institute of Meteorology of Belgium, Brussels, 2005.

Rasson, J. L.: Observatories, Instrumentation, in: Encyclopedia of Geomagnetism and Paleomagnetism, edited by: Gubbins, D. and Herrero-Bervera, E., Springer, London, 711–713, 2007.

Rasson, J. L., Toh, H., and Yang, D.: The global geomagnetic observatory network, in: Geomagnetic Observations and Models, AGA Special Sopron Book Series, Vol. 5, edited by: Mandea, M. and Korte, M.., Springer, Heidelberg, 127–148, https://doi.org/10.1007/978-90-481-9858-0_6, 2017.

Wienert, K. A.: Notes on geomagnetic observatory and survey practice, UNESCO, Brussels, p. 217, 1970.