USGS 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. The computations of the absolute and baseline values are presented with improved calculations, such as the exact conversion from nanoTeslas (nT) to degrees. Three years of testing were performed at College Magnetic Observatory (CMO) to compare the Residual method
10 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 is also being used at the Deadhorse Magnetic Observatory and will be implemented at the other USGS high latitude geomagnetic observatories in the summer of 2017.

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1 Introduction

Geomagnetic observatories are unique facilities. They measure the variation of the three vector components of the geomagnetic field at either one-minute and/or one-second time resolution and they also measure the absolute value of the
20 geomagnetic field (see, e.g. Rasson et al., 2007, Matzka et al, 2010, Love and Chulliat, 2013, Chulliat et al, 2016). 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 a continued development and improvement of
25 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 1970's the most common instruments employed are the proton precession magnetometer that measures the magnitude (F) of the geomagnetic vector, and since the 1980's, 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
30 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 nT, is 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,

5   for the Zeiss 020 theodolite discussed here, the angle is read to degrees, minutes of arc, and estimated to the 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. 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

10   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 nT, 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

15   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 E. Kring Lauridsen (1985), the

20   book by Jankowski and Sucksdorff (1996) and the study by Matzka and Hansen (2007). The computations shown in this paper have been updated to increase the accuracy and precision of the measurements.

This paper discusses the updated computational scheme adopted by the USGS and shows comparisons of the two methods employed at the USGS College Magnetic Observatory.

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2.0 Computations

For the sake of simplicity, all of the following equations will use angles in radians. For programing 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. Before going into

30   detail about the computations, the following definitions will be used.

nT = Value of magnetic field strength, 1 nT = 10^{-9} Teslas

H = Absolute value of the horizontal intensity, in nT.

D = Absolute value of the declination angle, in minutes.

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.

5   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.

10   f_i = the ith variation value for the total field, from the overhauser, in nT.

R_i = the ith residual value, in nT, i=1-4 for D readings, i=5-9, for I readings

AD_i = the ith measured declination angle in decimal degrees

A_1 = computed angle for West Down, in decimal degrees

15   A_2 = computed angle for East Down, in decimal degrees

A_3 = computed angle for West Up, in decimal degrees

A_4 = computed angle for East Up, in decimal degrees

HS = hemisphere, 1 for northern, -1 for southern

M = magnetic meridian angle, mean of A_1, A_2, A_3, and A_4

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AI_i = the ith measured inclination angle in decimal degrees

I_1 = computed angle for South Down, in decimal degrees

I_2 = computed angle for North Up, in decimal degrees

I_3 = computed angle for South Up, in decimal degrees

25   I_4 = computed angle for North Down, in decimal degrees

I_5 = computed calibration angle for South Up, in decimal degrees

H_b = baseline value for H, in nT

Z_b = baseline value for Z, in nT

30   D_b = baseline value for D, in minutes

F_{pc} = F pier correction, between the total field instrument and absolute pier, in nT

MU_1 = First Mark Up reading, in decimal degrees

MD_1 = First Mark Down reading, in decimal degrees

MU_2 = Second Mark Up reading, in decimal degrees

MD_2 = Second Mark Down reading, in decimal degrees

MA = mean value of the four Mark readings

AZ = True azimuth angle to the Azimuth mark, in decimal degrees

SV = Scale value of the fluxgate used on the DIM output

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2.1 Inclination Computations

The inclination angle computations are discussed first because the Horizontal baseline value, H_b, is needed for the computation

10 of D. For reference, using the null method, the computation of the Inclination angle is fairly simple,

$$\mathbf{I_N} = \frac{(AI_1 + AI_2) - (AI_3 + AI_4) + 360}{4}. \tag{1}$$

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.

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

$$I_1 = AI_1 + HS \ \sin^{-1}\left(\frac{R_5}{f_5}\right) - 180 \tag{2}$$

$$I_2 = AI_2 - HS \ \sin^{-1}\left(\frac{R_6}{f_6}\right) \tag{3}$$

$$I_3 = 180 - \left(AI_3 - HS \ \sin^{-1}\left(\frac{R_7}{f_7}\right)\right) \tag{4}$$

20

$$I_4 = 360 - \left(AI_4 + HS \ \sin^{-1}\left(\frac{R_8}{f_8}\right)\right) \tag{5}$$

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

$$\mathbf{I}_{mean} = \frac{(I_1 + I_2 + I_3 + I_4)}{4} \tag{6}$$

However, the computation can be further improved by making a correction to the individual F values in the computation of I_1 to I_4. The individual values for H, E, and Z are used to correct for changes in the orientation of F in the computation.

5 The individual F values f_5 through f_9 are corrected by

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

Where

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

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

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$$z_{mean} = \frac{(z_5 + z_6 + z_7 + z_8 + z_9)}{5}. \tag{10}$$

$$F_{mean} = \frac{(f_5 + f_6 + f_7 + f_8 + f_9)}{5}, \tag{11}$$

This correction introduces an iteration to the computation for I. After the various values of I are computed using equations 2 through 6, I_{mean} is used in equation 7 to correct the values for $f_5, f_6, f_7, f_8,$ and f_9. I is then computed again using equations 2
15 through 6. This iterative process is continued until the change in I_{mean} from one iteration to the next is less than 0.0001 degrees.

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, $F_{pc,}$

$$\mathbf{F} = F_{mean} + F_{pc} \tag{12}$$

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

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

5   and

$$\mathbf{Z} = \mathbf{F} \, \sin \mathbf{I} \tag{14}$$

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

$$\mathrm{H}_b = \sqrt{\mathbf{H}^2 - \mathrm{E}_{mean}^2} - H_{mean} \tag{15}$$

$$Z_b = \mathbf{Z} - Z_{mean} \tag{16}$$

10

An extra or fifth inclination measurement is performed to determine the scale value of the fluxgate magnetometer mounted on the DIM. This is used to verify the fluxgate's scale value. The angular difference of the telescope between the 4th and 5th I readings (elements 8 and 9, for h and z, respectively) is exactly 10.0 minutes, or 0.16667 degrees (for a theodolite that measures

15   in gradians (gon) one would use 0.2 gon). The angular change of the fluxgate with respect to the magnetic field (from perpendicular to slightly tilted) is denoted ΔB (Eqn. 17). The change in residuals is denoted as ΔR. Computation of the scale value thus follows:

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

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

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

Ideally the resulting scale value should be 1.000, indicating that the output of the DIM fluxgate is in fact nT. 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 a change in the scale value. Monitoring and tracking the scale value can help with diagnosing any problem that might develop with the instrument.

5

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

10   value for declination, using the Null method, can be described in simple terms as:

$\mathbf{D}_N$ = Magnetic meridian – average mark readings + the True Azimuth of the mark.

The baseline value is easily computed by taking the difference between $\mathbf{D}_N$ and the value for declination from the fluxgate.

15   However, this is complicated by the fact that the output of the fluxgate is in nT (E) and must be converted to an angular value. The conversion traditionally used is known as the small angle approximation. 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

20   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:

$$d_i = \tan^{-1}\left(\frac{e_i}{(h_i + H_b)}\right)$$

(20)

With advances in computing power the small angle approximation is no longer necessary and this exact formula is easily

25   computed. Using equation 20 can provide a more precise angular value for declination when converting the value from E.

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,

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$$A_1 = AD_1 - \sin^{-1}\left(\frac{R_1}{\sqrt{(h_1 + H_b)^2 + e_1^2}}\right) - d_1 \tag{21}$$

$$A_2 = AD_2 + \sin^{-1}\left(\frac{R_2}{\sqrt{(h_2 + H_b)^2 + e_2^2}}\right) - d_2 \tag{22}$$

$$A_3 = AD_3 - \sin^{-1}\left(\frac{R_3}{\sqrt{(h_3 + H_b)^2 + e_3^2}}\right) - d_3 \tag{23}$$

$$A_4 = AD_4 + \sin^{-1}\left(\frac{R_4}{\sqrt{(h_4 + H_b)^2 + e_4^2}}\right) - d_4 \tag{24}$$

5

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 equation 20.

The mean of the four angles A_i, termed the Magnetic Meridian, is next computed,

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

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

$$MA = \frac{(MU_1 + MU_2 + MD_1 + MD_2)}{4}. \tag{26}$$

20   The baseline value for Declination, in minutes, is computed, as follows,

$$D_b = (M - MA + AZ) \cdot 60 \tag{27}$$

Where AZ is the true azimuth angle to the Azimuth mark, in decimal degrees.

2.3 Final Absolute Values

5   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. These final absolute values are denoted with a subscripted **0** to avoid confusion. So the value for H would be determined by the following:

$$\mathbf{H_0} = \sqrt{(h_1 + H_b)^2 + e_1^2}. \tag{28}$$

10   The value for **D** is computed as:

$$\mathbf{D_0} = D_b + \tan^{-1}\left(\frac{e_1}{h_1 + H_b}\right)\frac{180}{\pi}. \tag{29}$$

The absolute value for **Z** would be,

$$\mathbf{Z_0} = Z_b + z_1. \tag{29}$$

15   **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 two angles, also known as the collimation error or misalignment angles, also termed the Sight Error and the Azimuth Error by Rasson (2005).

20   The Declination Sight Error, in seconds of arc, designated as ε_D is computed as follows:

$$\varepsilon_D = \frac{(A_4 + A_3 - A_2 - A_1)}{4\,\tan\mathbf{I}}\,3600\,. \tag{30}$$

The Azimuth Error, in seconds of arc, designated as δ, is computed as follows:

$$\delta = \frac{(A_4 - A_3 - A_2 + A_1)}{4}\,3600. \tag{31}$$

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 SO_D, is computed in nT,

$$SO_D = \mathbf{H}\left(\frac{\pi}{180}\right)\frac{(A_4 - A_3 + A_2 - A_1)}{4}. \tag{32}$$

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, in seconds of arc, designated as ε_I is computed as follows:

$$\varepsilon_I = \frac{(I_2 + I_1 - I_4 - I_3)}{4}\,3600. \tag{33}$$

The Inclination Sensor Magnetization Error, designated as SO_I, is also computed in nT,

$$SO_I = -\mathbf{F}\left(\frac{\pi}{180}\right)\frac{(I_2 - I_1 - I_4 + I_3)}{4}. \tag{34}$$

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. 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.

3.0 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 College Magnetic Observatory (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 absolutes 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 six 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-2012 and still continues. Baseline results of these tests are shown in Figure 1.

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 doesn't have to null the sensor during active periods of magnetic activity. The

5   Null method uses the traditional small angle computation to convert nT to minutes. The Residual method uses the exact conversion from nT to minutes. Also, some of the larger differences could be attributed to observer error or a higher level of magnetic activity.

Differences in the Horizontal component (H) baselines can be attributed to the weakness in the strength of the Horizontal field.

10   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

15   noticeable differences and 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.

The 14 months of baseline data, 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

20   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 2017 and in all observatories by 2019.

4.0 Discussion and Conclusions

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From the data presented above, it is evident that Absolute measurements using the Residual method are comparable to measurements with the Null method. With well-trained observers, both methods should yield similar results. When processing data from a high latitude observatory such as College, 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

30   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 nT to minutes of arc, 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.

5   The Residual method also makes it possible to move the observer away from the fluxgate sensor on the DIM to avoid contamination. For example at Brorfelde Observatory (BFE), the observer is 1-2 meters away from the instrument. Personnel from DTU, GFZ, and USGS have learned that when training new observers it is easier to teach the Residual method than the null method and the observers can get consistent results sooner.

10   The results suggest that those observatory programs, who have not done so before, to explore using the Residual method. In addition, the small angle approximation can be replaced with the exact computation for conversions from nT to angles of arc in order to derive more precise baseline results.

Acknowledgements

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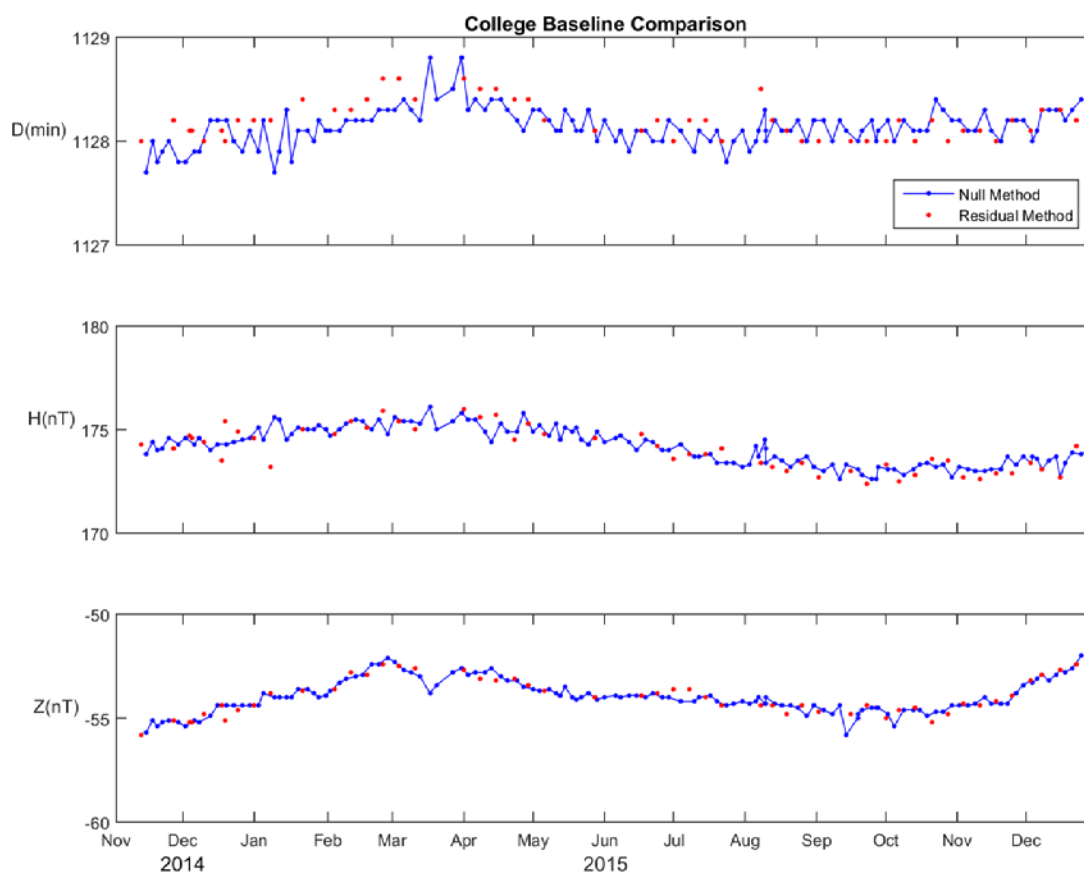
Figure 1: Comparison of baseline measurements using the Null and Residual methods at College Observatory in 2014 and 2015.