

Title: On Cross-Axis Effect of the Anisotropic Magnetoresistive Sensors

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Abstract

Cross-axis effect error of typical AMR sensor is ± 1100 nT in the Earth's field, which in worst case may cause ± 2.4 deg error in azimuth reading of tri-axial AMR compass. In systems which cannot use flipping or feedback, crossfield error can be numerically corrected if we know the sensitivity and field scale constant (anisotropy field) of the particular sensor. Three new methods to measure this constant are presented: the field steps using Helmholtz coils, the sensor rotation in geomagnetic field and four point calibration in geomagnetic field. The measurements performed for Honeywell HMC1002 sensor show that the last method gives lowest uncertainty. The correction iteration algorithm using measured constant reduces crossfield azimuth error below ± 0.05 deg.

Keywords: magnetoresistor, AMR, cross-axis.

Introduction

Anisotropic magnetoresistive sensors (AMR) can be used for sensing weak magnetic fields such as the Earth's field ($\sim 48 \mu\text{T}$, horizontal component $\sim 19.5 \mu\text{T}$ in the Central Europe). The theory of AMR sensors is discussed in [1] and [2]. The measured AMR sensor HMC1002 manufactured by Honeywell consists of two sets of magnetoresistors forming two Wheatstone bridges for sensing magnetic field in two mutually perpendicular directions. Each magnetoresistor contains permalloy strip with barber-pole structure of conductor on top.

The unwanted sensitivity to a field perpendicular to the sensitivity axis - cross-axis effect - appears also at other types of magnetic sensors, such as fluxgates. The cross-axis effect in case of fluxgate sensors is of the order of 5 to 50 nT when measuring the Earth's field [3]. In case of AMR sensors, this error can be much larger (up to 1100 nT for Honeywell HMC1002 when measuring the Earth's field) which may cause azimuth error up to ± 2.4 deg in case of compass application. The cross-axis field in AMR sensor is situated in the plane of the permalloy strip, but perpendicular to the sensitivity axis. The cross-axis effect can be suppressed by using the sensor in the feedback mode or by periodical flipping and averaging the reading for "set" and "reset" state [4]. These techniques cannot be used in low-power applications. According to [5], cross-axis effect in AMR can be characterised by the field scale constant B_S (sum of shape and induced anisotropy). In order to perform numerical correction of the readings affected by cross-axis effect [5], B_S should be precisely known. Three methods to measure and quantify the field scale constant are compared and the results are presented in this paper: the field steps using Helmholtz coils [6], the sensor rotation in geomagnetic field and four-point calibration in geomagnetic field.

Cross-axis model. According to [5] the cross-axis effect can be modelled by equation for the output voltage V of the sensor:

$$V = \frac{a.B}{B_S + B_C} \quad (1)$$

where a is the constant proportional to the anisotropic magnetoresistance $\Delta\rho/\rho$, B is the external field applied in the sensitivity axis (i.e. in the plane of permalloy thin film strips and perpendicular to them), B_S is the field scale constant (sum of shape and induced anisotropy) and B_C is the applied field in the cross-axis direction (i.e. parallel to the permalloy thin film strips).

Cross-axis error influence. According to the manufacturer, the Honeywell HMC1002 sensors have the $B_S = 0.8$ mT. The influence of cross-axis effect on the azimuth reading in compass application (without sensor flipping and feedback) was modelled with the use of geomagnetic field magnitude of 48000 nT and inclination of 66 deg (corresponding to geomagnetic field in the central Europe). For compass in horizontal position the resulting azimuth error reached maximum value of 1 deg (see Fig. 1). This error increases when one of the sensors is closer to the Earth's field vector: the worst-case maximum error is 2.4 deg for compass pitch equal to local inclination. This situation occurs in horizontal position at the equator. When the cross-axis effect is numerically corrected, the B_S constant should be precisely known. The uncertainty in the determination of B_S constant causes residual error in azimuth (see Fig. 2).

1st method: Perpendicular field steps. The sensor was placed horizontally in the north direction thus the measured field B_X was the horizontal component of the geomagnetic field and the Helmholtz coils were used to generate the perpendicular field B_C in the east and west

directions. Three output values were then measured: without B_C (2) and for both polarities of B_C (3) and (4).

$$V_1 = \frac{a.B_x \cos\Delta\varphi}{B_s + B_x \sin\Delta\varphi} \quad (2)$$

$$V_2 = \frac{a.B_x \cos\Delta\varphi + a.B_C \sin\Delta\psi}{B_s + B_x \sin\Delta\varphi + B_C \cos\Delta\psi} \quad (3)$$

$$V_2 = \frac{a.B_x \cos\Delta\varphi - a.B_C \sin\Delta\psi}{B_s + B_x \sin\Delta\varphi - B_C \cos\Delta\psi} \quad (4)$$

The $\Delta\psi$ angle represents the deviation of the Helmholtz coils from the cross-axis direction, 1 deg alignment is easily achievable. Then the $B_C \cos\Delta\psi \approx B_C$. The $\Delta\varphi$ angle represents deviation of the sensor sensitivity axis from the geomagnetic field, 1 deg value is again achievable. Then $B_x \cdot \sin\Delta\varphi$ is much smaller than expected value of B_s and the equations result in the simplified formula for B_s independent of the geomagnetic field horizontal component B_x and constant a . :

$$B_s = B_C \frac{V_3 - V_2}{V_3 + V_2 - 2V_1} \quad (5)$$

The experiment setup was arranged with Honeywell HMC1002 sensor aligned with sensitive axis heading to the north and Helmholtz coils generating field in east and west directions. The applied cross-axis field magnitude was 50 μ T, the output from the sensor was amplified and then measured by integrating 6,5 digit voltmeter (the integration time was 200 NPLC). The results were acquired in the unshielded laboratory in the magnetically most silent part of the day (0:00 A.M. to 3:30 A.M.). However, the results from these measurements (see Fig. 3) show huge variations of B_s (up to 20%), which can result in azimuth uncertainty after cross-axis compensation up to 0.15 deg. The overall average value from this measurement is $B_s =$

0.797 mT. We believe that the uncertainty is the result of numerical instability of the formula, where mutually close values V_1, V_2 and V_3 form small value in the fraction's denominator so every small uncertainty in one of the V -values leads to high uncertainty in B_S value.

2nd method: Rotation with corrected deviations. The idea was to use components of geomagnetic field both as the measured field and cross-axis field. The model indicates that cross-axis effect can be expressed as a change in sensitivity of the sensor dependent on the magnitude of the cross-axis field. Thus when the measured field is small the cross-axis effect is also of small magnitude. The measurement setup was arranged so that measured sensor mounted on non-magnetic theodolite can be rotated around its nominal sensitive axis ('roll'). First, the sensor was heading to the east or to the west and while measuring the sensor output, the setup was rotated in roll. In ideal case, the sensed field magnitude is zero as the sensitivity axis is perpendicular to the geomagnetic field. However, the real sensor orientation shows $\Delta\varphi$ deviation in azimuth and $\Delta\delta$ deviation in pitch which result in sinewave-shape error during roll. Also when the rotation axis is not pointing exactly to the east, stable reading offset O appears during roll. But still the cross-axis effect is much lower (~ 50 nT) compared to other effects (deviations cause typically ~ 1000 nT change of the sensor output) as the measured field magnitude is low. The sensor output $B_{XE}(\rho)$ (X stands for x-axis, E stands for east) can be expressed by (6) using ρ as roll and I as total field B_{TOT} inclination angle:

$$B_{XE}(\rho) = O - B_{TOT} \sin\Delta\varphi \cdot \cos(\rho + I) - B_{TOT} \sin\Delta\delta \cdot \sin(\rho + I) \quad (6)$$

The unknown parameters O , $\Delta\varphi$, $\Delta\delta$ can be calculated using the best fit of sine over the measured values in roll (7):

$$B_{XE}(\rho) = a_1 + b_1 \sin(\rho + c_1) \quad (7)$$

Then the resulting values of $\Delta\varphi$ and $\Delta\delta$ are (8) and (9), the sign selection has to be made according to the proof.

$$\Delta\varphi = \pm \arcsin \left(\frac{b_1}{B_{TOT}} \frac{\tan c_1 - \tan I}{\sqrt{\tan^2 c_1 \cdot \tan^2 I + \tan^2 c_1 + \tan^2 I + 1}} \right) \quad (8)$$

$$\Delta\delta = \pm \arcsin \left(\frac{b_1}{B_{TOT}} \frac{\tan c_1 \cdot \tan I + 1}{\sqrt{\tan^2 c_1 \cdot \tan^2 I + \tan^2 c_1 + \tan^2 I + 1}} \right) \quad (9)$$

The next step was to measure sensor response $B_{XN}(\rho)$ while rotating in roll with sensor sensitive axis heading to the north or to the south. The situation is described in (10), where $A \cdot \sin \rho$ is a sine approximation of cross-axis effect during roll when heading to the north. The other terms represent horizontal component of the geomagnetic field and projections of vertical component of the geomagnetic field into the sensitivity axis due to azimuth and pitch deviations of the sensor.

$$B_{XN}(\rho) = B_{TOT} \cos I - B_{TOT} \sin I \cdot \sin \Delta\delta \cdot \cos \rho + B_{TOT} \sin I \cdot \sin \Delta\varphi \cdot \sin \rho - A \sin \rho \quad (10)$$

With $\Delta\delta$ and $\Delta\varphi$ already known, the unknown parameter A approximating the influence of cross-axis effect over roll by a sine wave can be calculated by fitting the $B_{XN}(\rho)$ with sine function (11).

$$B_{XN}(\rho) = a_2 + b_2 \sin(\rho + c_2) \quad (11)$$

The resulting A value calculated from the amplitude of the sine wave is then (12) (the cross-axis amplitude can be also calculated from the phase of this B_{XN} signal).

$$A = -B_{TOT} \sin I \cdot \sin \Delta\varphi \pm \sqrt{b_2^2 - B_{TOT}^2 \sin^2 I \cdot \sin^2 \Delta\delta} \quad (12)$$

The field scale constant was then calculated from (13) representing the difference between reading with and without cross-axis effect.

$$A = B_{TOT} \cos I - \frac{B_{TOT} \cos I}{1 + \frac{B_{TOT} \cos I}{B_S}} \quad (13)$$

The data reading from heading to the west can be found in Fig. 4, while data measured when heading to the north and to the south can be found in Fig. 5. The resulting values of $B_S = 0,88$ mT show high variation of 20% among the measurements. This variation could cause residual azimuth error up to 0.15 deg.

3rd method: Four-point calibration. This method proposes easy and fast field scale constant measurement which requires only four readings. The measured and cross-axis field are both represented by geomagnetic field components. The main idea is that the readings of the sensor when heading to north and south show results influenced both by sensor deviations and cross-axis effect. However, these two impacts can be separated from each other. When rolling the sensor in the direction to the north and south, deviations show the same phase and amplitude of a sine-wave superimposed to the measured horizontal component of the geomagnetic field, while cross-axis effect shows opposite values at the same roll values when comparing north to south. The readings are taken for sensor heading to the north (B_{XN}) and then to the south (B_{XS}) with sensor in the roll of 90 and 270 deg (horizontal component of the geomagnetic field in the sensitive axis while vertical component is aligned with the cross-axis direction). The data taken can be expressed for north direction as (14) and for south direction as (15), where $B_C(\rho)$ is the influence of cross-axis effect and $B_{TOT} \cdot \sin(\rho + \mu)$ represents the influence of sensor deviations.

$$B_{XN}(\rho) = B_{TOT} \sin(\rho + \mu) + B_{TOT} \cos I + B_C(\rho) \quad (14)$$

$$B_{XS}(\rho) = B_{TOT} \sin(\rho + \mu) - B_{TOT} \cos I - B_C(\rho) \quad (15)$$

By subtracting (15) from (14) we receive (16).

$$\frac{B_{XN}(\rho) - B_{XS}(\rho)}{2} = B_{TOT} \cos I + B_C(\rho) \quad (16)$$

The right side of the equation (16) for $\rho=90, 270$ deg can be expressed as (17) and (18).

$$B_{TOT} \cos I + B_C(90) = \frac{B_{TOT} \cos I}{1 - \frac{B_{TOT} \sin I}{B_S}} \quad (17)$$

$$B_{TOT} \cos I + B_C(270) = \frac{B_{TOT} \cos I}{1 + \frac{B_{TOT} \sin I}{B_S}} \quad (18)$$

Combining (16), (17) and (18) we get (19).

$$B_S = B_{TOT} \sin I \frac{B_{XN}(90) - B_{XS}(90) + B_{XN}(270) - B_{XS}(270)}{B_{XN}(90) - B_{XS}(90) - B_{XN}(270) + B_{XS}(270)} \quad (19)$$

The resulting equation (19) is independent of sensor sensitivity, offset and deviations from rotation axis. This modified method gives the field scale constant with uncertainty better than 2 % (816 μ T for HMC1002 sensor). After the correction the resulting azimuth uncertainty due to the cross-axis effect is below 0.04 deg.

Conclusion

The uncompensated cross-axis error in anisotropic magnetoresistors can lead to significant errors when sensing geomagnetic field (up to 2.4 deg error in azimuth in compass application). This error can be suppressed by periodical flipping or by magnetic feedback, which is not always possible when working in low-power applications. The numerical compensation of this error is viable in triaxial sensor configuration. However, a field scale constant for given sensor must be known. The use of inaccurate field scale constant leads to residual error in sensor reading (20 % lower field scale constant leads to 0.15 deg of residual azimuth error). This article dealt with three alternative methods of field scale constant

measurements. The methods were theoretically described and the measurement results for Honeywell HMC1002 sensor were presented. The perpendicular field steps method produces results with high dispersion (20 % of the mean value), however with proper averaging, the results are usable ($B_S = 0.797$ mT). The sensor rotation in geomagnetic field results a high variation values of field scale constant (the resulting value was $B_S = 0.88$ mT), the averaging in this case is complicated due to the need of setting exactly the same position in roll for many times. The four-point calibration method offers precise results with relatively small amount of measured data ($B_S = 0.816$ mT).

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Figure captions

Fig. 1: A simulation of azimuth error in HMC1002 AMR sensor compass resulting from cross-axis effect in the whole azimuth range for horizontal position, 60 deg field inclination. The maximum error of 1 deg is in the north-east and south-west directions.

Fig. 2: A simulation of azimuth residual error of HMC1002 AMR sensor compass after numerical correction of cross-axis effect for wrong values of B_S ranging from 0.64 to 0.88 mT (i.e. -20 % to +10 % of the correct value 0.8 mT). The residual error when correct B_S values are applied is below 0.001 deg.

Fig. 3: Results from perpendicular field steps method. V_1 denotes amplified sensor output without perpendicular field, V_2 and V_3 denote amplified sensor output with cross-axis field of 50 μ T in both polarities. The resulting B_S value shows variations of ± 20 %.

Fig. 4: The sensor readings while rotating along its axis of sensitivity heading to the west and the best-fit sine curve of measured data. The sine shape of the sensor reading is the result of sensor deviations from rotation axis.

Fig. 5: The sensor readings while rotating along its sensitivity axis heading to the north and south with respective sine best fit curves (the horizontal component of geomagnetic field reading removed). The different amplitude and phase of the curves is a result of cross-axis effect which affects north and south readings with opposite polarity errors.

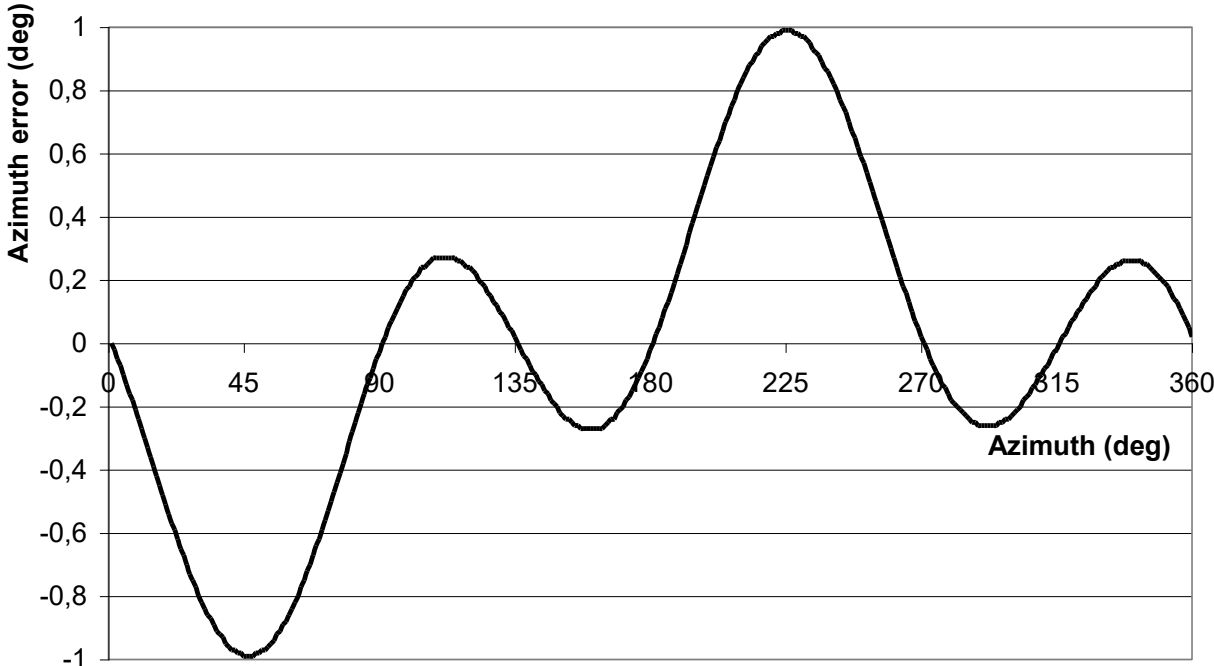


Fig. 1

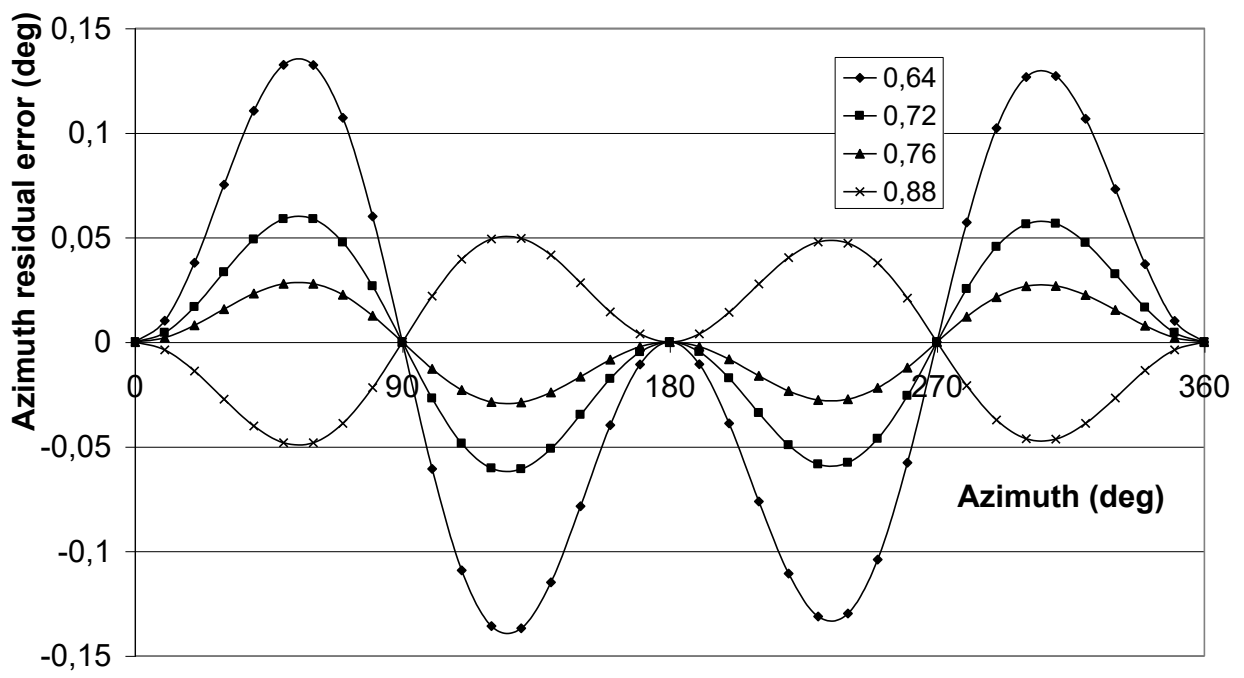


Fig. 2

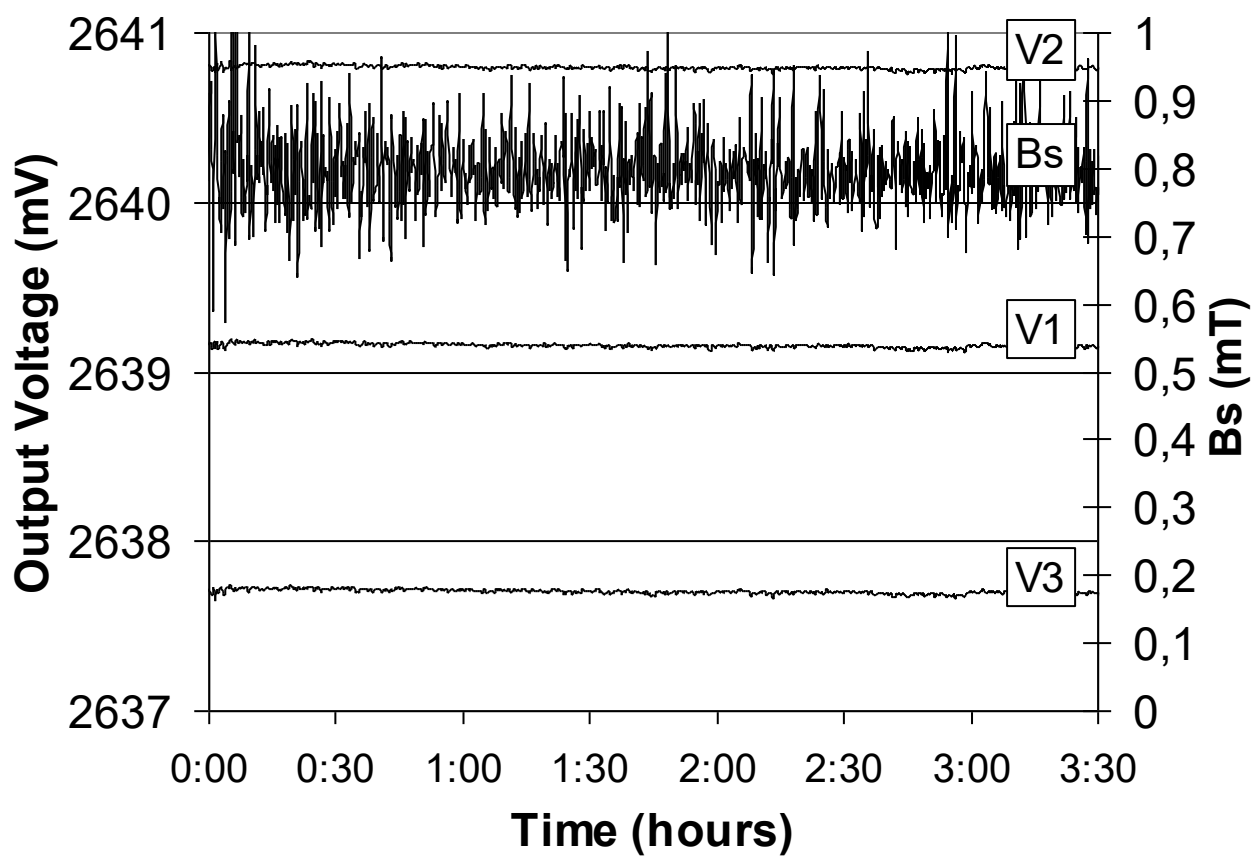


Fig. 3

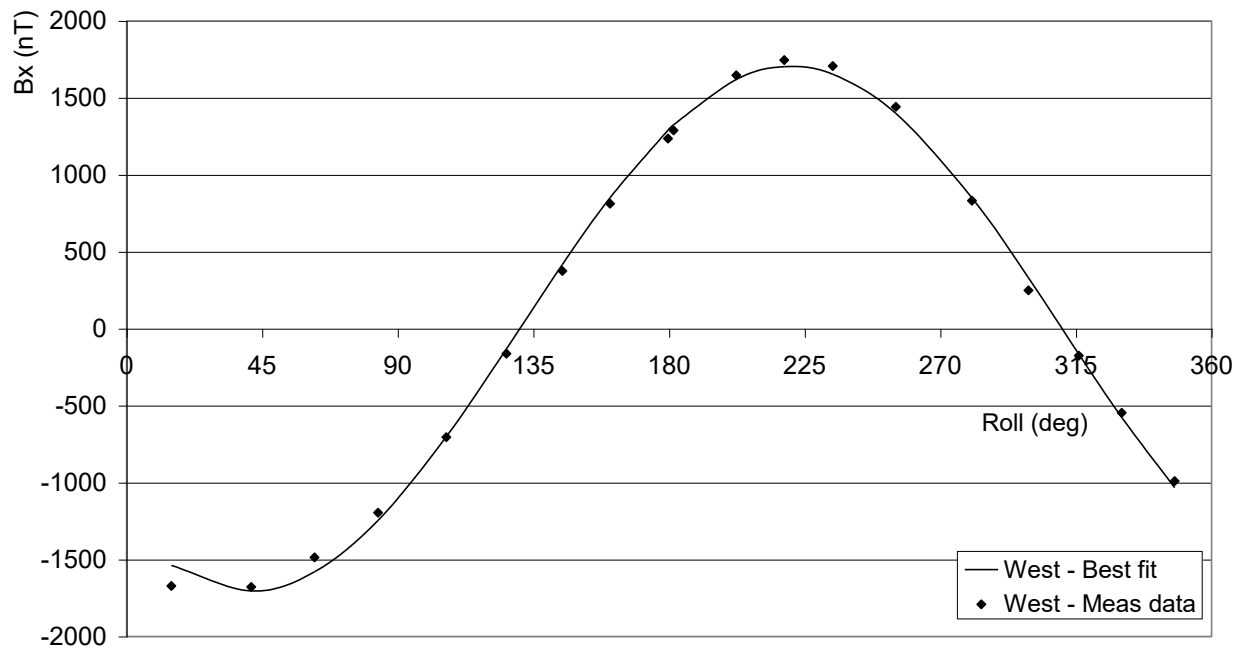


Fig. 4

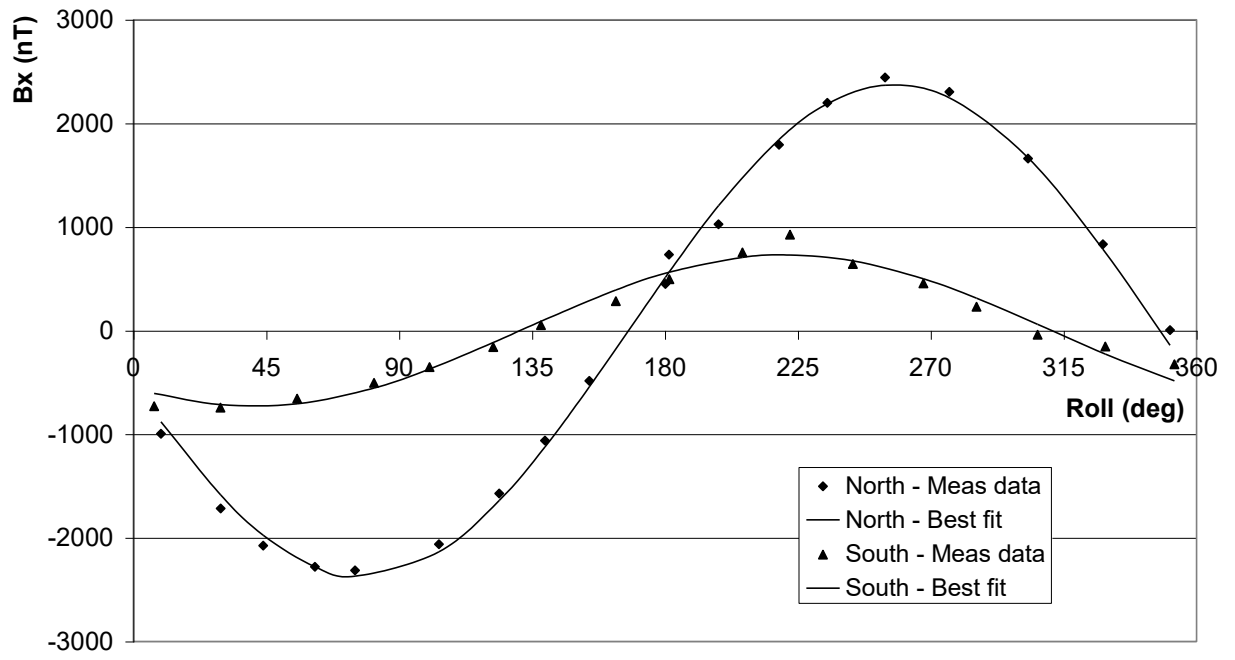


Fig. 5

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