PUBLS. INST. GEOPHYS. POL. ACAD. SC., C-99 (398), 2007

On the Various Published Formulas to Determine Sensor Offset and Sensor Misalignment for the DI-flux

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A b s t r a c t

An inconsistency regarding the calculation of sensor offset and sensor misalignment for the fluxgate theodolite in the IAGA Guide for Magnetic Measurements and Observatory Practice (Jankowski and Sucksdorff 1996) is discussed and resolved by comparison of the given formulas and examples with the original literature (Kring Lauridsen 1985) and experimental data. An erroneous sign is found on page 99 in formula (5.7) for inclination collimation and formula (5.8) for sensor offset calculated from the declination measurement. Jankowski and Sucksdorff (1996) have the same formulas as Kring Lauridsen (1985), but a different sequence of theodolite positions for the declination measurement led to a confusion of input variables and consequently to the erroneous signs. An electronic version of Kring Lauridsen (1985) is now available on request.

1. Introduction

The absolute measurement of declination D by a fluxgate theodolite (DI-flux) as described by Kring Lauridsen (1985) and on page 87 to page 100 in Jankowski and Sucksdorff (1996) is not affected by the sensor offset of the fluxgate and the misalignment of the fluxgate sensor with the optical axis of the telescope, provided that the sensor offset and the misalignment are small and remain constant during the measurement. In the following, the reference to Kring Lauridsen (1985) will be abbreviated by KL and Jankowski and Sucksdorff (1996) by JS. The sensor offset S_0 is defined as the (small) fluxgate reading in zero field (KL, formula 5). The horizontal misalignment or declination collimation δ is the (small) angle between the sensor axis and the plane defined by the optical axis X' and the downward pointing axis Z' of the horizontal circle. For a north-pointing telescope, $\delta > 0$ if the sensor axis is misaligned towards a northeasterly/southwesterly direction. The vertical misalignment or inclination collimation ε is the (small) angle between the optical axis and the plane defined by the sensor axis and Y', which is the axis of the vertical circle. For a north-pointing telescope, $\varepsilon > 0$ for a sensor axis dipping to north (KL, formula 2). All three parameters are now referred to as theodolite parameters. When calculated from a declination measurement, they will be referred to as $S_{0,D}$, δ_D and ε_D. Likewise, the inclination measurement as described in KL and JS allows to calculate the sensor offset $S_{0,I}$ and the inclination collimation ε_I. The declination collimation δ cannot be calculated from the inclination measurement described in KL and JS.

For measurements of declination and inclination with the DI-flux we noticed opposite signs for $S_{0,D}$ and $S_{0,I}$ as well as for ε_D and ε_I when using the procedures and formulas given in JS. A further complication arose from the fact that this inconsistency apparently does not affect the example for a declination and an inclination measurement given there. For obvious reasons, this problem didn't receive much attention in the past. Firstly, the number of geomagnetic observatories that calculate theodolite parameters seems to be limited, and most of these base their calculation on the original publication by KL (leading to consistent results, see below). Secondly, theodolite parameters are usually adjusted to be close to zero and the discrepancy in sign can then be disguised by the noise level of the measurement. Thirdly, the main purpose of routinely calculating the theodolite parameters, namely to control their stability from one measurement to the other, is not adversely affected by an erroneous sign. It is nevertheless of advantage to know the correct signs of the misalignment angles, e.g. during any procedure of adjusting a sensor on a telescope. Whereas the IAGA guidebook (JS) is an important and valuable contemporary reference for geomagnetic observatory work and widely in use, the original publication by KL has been out of print, making it difficult for interested persons to work out the differences in theodolite parameters for KL and JS. In the following, the above described inconsistency is discussed and resolved. Additionally, an electronic copy of KL is available on request.

2. Results

2.1 Experimental results

Figure 1 shows sensor offset $S_{0,D}$ and $S_{0,I}$ and inclination collimation ε_D and ε_I for six DI-flux measurements at the Geophysical Observatory Fürstenfeldbruck (FUR). The theodolite is a Zeiss 10B and no particular care was taken to adjust the sensor axis to the optical axis. The absolute measurements were conducted with the zero-method and according to the procedure described in JS (their Tables 5.1, 5.2 on pages 90 to 93). The theodolite parameters were calculated according to JS (their formulas 5.6 to

5.10 on pages 99, 100). It is obvious from Fig. 1 (left panel) that both $S_{0,D}$ and $S_{0,I}$ as well as ε_D and ε_I are of opposite sign. The sensor offset S_0 is additionally dependent on temperature (right panel). We note that the change in ε_D and ε_I between measurements no. 3 and no. 4 in Fig. 4 is large compared to the variation of ε_D and ε_I usually observed from one absolute measurement to the next at FUR and that this coincides with an intentional transfer of the DI-flux from one pillar to another.

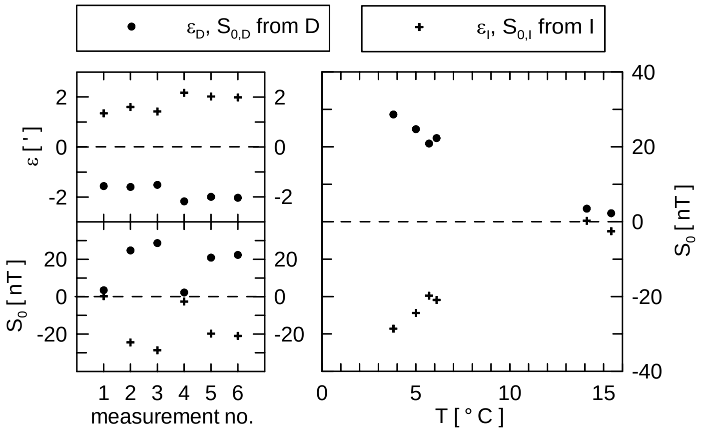

Fig. 1. Theodolite parameters inclination collimation ε_D and ε_I and sensor offset $S_{0,D}$ and $S_{0,I}$ determined according to JS for six DI-flux measurements at FUR (left panel). The strong variability of the sensor offset S_0 is controlled by temperature (right panel).

The sign for all theodolite parameters for the experimental data from Fig. 1 and the example calculated in JS (their Tables 5.1, 5.2) is given in the upper part of Table 1. For both data sets, the theodolite parameters were calculated according to the procedure outlined in JS and in KL. Within both data sets, the calculation after JS and after KL gives the same sign only for the parameters $S_{0,I}$, δ_D and ε_I. The experimental data from Fig. 1 gives consistent results for $S_{0,D}$ and $S_{0,I}$ as well as for ε_D and ε_I when calculated after KL, but opposite signs when calculated after JS. The data from JS (their Tables 5.1, 5.2) behaves exactly vice versa.

An experiment was performed, where the fluxgate sensor housing was deliberately misaligned by comparatively large angles. The tangents of the angles were determined with a ruler. Following the definition of the signs of the angles by KL as outlined in our introduction, the angles were approximately $\delta = +2.3°$ and $\varepsilon = +1.6°$. This substantial misalignment was chosen to be larger than any additional misalignment between the sensor axis and the sensor housing to make sure that the sign of the misalignment is well defined. The resulting theodolite parameters determined according to the procedures of JS and KL are shown in the lower left part of Table 1. Firstly, we recognise that the signs of individual parameters do show the same relationship between the result after JS and the result after KL as we already observed for the experimental data of Fig. 1. From that, a simplified scheme can be derived for the two experimental data sets. In this scheme, all theodolite parameters calculated after KL are set to be +1 and the parameters for JS are set +1 when the sign is the same as after KL, or –1 when the sign is opposite to KL. This derived scheme is shown in the lower right part of Table 2. Secondly, δ_D, ε_D and ε_I calculated after KL and δ_D and ε_I calculated after JS are in agreement with the deliberate misalignment. However, ε_D calculated after JS gives the opposite sign.

Table 1

Sign of theodolite parameters

	Experimental data from Figure 1, this paper		Example data from JS, their Table 5.1, 5.2	
Theodolite parameters …	… calculated after JS	… calculated after KL	… calculated after JS	… calculated after KL
$S_{0,D}$	+	–	–	+
$S_{0,I}$	–	–	–	–
δ_D	–	–	+	+
ε_D	–	+	+	–
ε_I	+	+	+	+
	Experimental data with $\delta \sim +2.3°$ and $\varepsilon \sim +1.6°$		Experimental data, derived scheme	
Theodolite parameters …	… calculated after JS	… calculated after KL	… calculated after JS	… calculated after KL
$S_{0,D}$	13 nT	–13 nT	–1	+1
$S_{0,I}$	–8 nT	–8 nT	+1	+1
δ_D	1.8°	1.8°	+1	+1
ε_D	–1.4°	+1.4°	–1	+1
ε_I	+1.4°	+1.4°	+1	+1

2.2 Comparison of formulas

The publication by KL was checked for possible errors in sign by one of us (TLH) without being able to find one. In the following, we will neglect any terms arising from temporal variations, or from the residual or close-to-zero-technique, or from imperfect telescope leveling. Then, the structures of the formulas given by JS are identical to those in KL, e.g. compare the formula for δ_D in JS (their formula 5.6) with the one in KL (his formula 13, his Table 1). A difficulty in comparing the formulas is that the circle readings for the DI-flux measurements are labeled sequentially with an index running from 1 to 4 both in KL (e.g. as φ_1, φ_2, φ_3, φ_4 in his formula 13) and in JS (e.g. as A'_1, A'_2, A'_3, A'_4, in their formulas 5.6 to 5.8). The index from 1 to 4 refers to one of four theodolite positions during either the declination or the inclination measurement.

Let us consider the 1. reading of the declination measurement, for which in JS the telescope is defined to be pointing to the west and the sensor is up, i.e. on top of the telescope (their Table 5.1). In KL, the first reading is done in a position where the telescope is not pointing to the west but pointing to the east and the sensor is up. Note that this information is not immediately obvious in KL, because the orientation of the alidade there is indicated by the position of the vertical circle, not of the telescope. The positions of the theodolite in KL can also be reconstructed from the scheme on his page 4, where clearly the 1. position is obtained by rotating the telescope by approximately $\pi/2 + D$ from north towards east. In Table 2 the sequence of all four positions for both the declination and inclination measurement after KL and JS are compared.

Table 2

Various sequences of the four positions for DI-flux measurements

Position no: Sequence:	1	2	3	4
Declination after JS	telescope: W sensor: up	E up	W down	E down
Declination after KL	telescope: E sensor: up	W up	E down	W down
Inclination JS and KL	telescope: N sensor: up	S down	N down	S up

3. Discussion

The internal consistency of the theodolite parameters calculated after KL and the internal inconsistency in sign for $S_{0,D}$ and $S_{0,I}$ as well as ε_D and ε_I calculated after JS already suggests some error in sign for the method described in JS (Table 1, upper left part). The validity of the calculation of ε_D, ε_I and δ_D after KL is independently confirmed by experimental results from a fluxgate with known misalignment (Table 1, lower left part). Also, the validity for δ_D and ε_I and the error in sign for ε_D calculated after JS are confirmed. Employing the experimentally derived scheme (Table 1, lower right part) suggests (but doesn't prove) that $S_{0,D}$ after JS is subject to an error in sign and that $S_{0,I}$ after JS is correct.

A comparison of the procedures and formulas shows that there is no difference for the inclination measurement between KL and JS. However, for the declination measurement the first and the second as well as the third and the fourth position are interchanged in JS compared to KL (Table 2). The circle readings of the first and second position as well as for the third and fourth reading are contributing to the formulas of $S_{0,D}$ and ε_D with different sign and the observed interchange of the positions leads to the opposite sign for this parameters (e.g. formula 5.7 and 5.8 on page 99. in JS).

However, in the formula for the calculation of δ_D (e.g. formula 5.6 on page 99 in JS), the readings of the third and second position as well as the for the third and fourth position are contributing with the same sign, and the observed interchange does not change the sign here.

In contrast to all experimental data that we have gathered, the measurement example shown and calculated in JS is in itself consistent. Also, it gives inconsistent signs for the theodolite parameters when calculated after KL (Table 1, upper right panel). Since the problem in JS is an interchange of measurement position which is not taken into account in their formulas, the actual values cited in their example must also have experienced an interchange in one way or another.

4. Conclusion

The experimental results and the comparison of the formulas in JS and KL lead to the conclusion, that either the sequence of positions as laid down in JS (their Table 5.1, starting with telescope pointing west and sensor up) has to be changed to the sequence described by KL (starting with telescope pointing east, sensor up) to fit the formulas 5.7 and 5.8 on page 99 in JS, or that the sign for $S_{0,D}$ and ε_D in formulas 5.7. and 5.8 on page 99 in JS has to be changed to fit the sequence described in Table 5.1 in JS. In order to make available new copies of KL, we have produced an electronic version that is available on request.

Acknowledgements. JM would like to thank Ole Rasmussen for initially sending him a copy of KL and time series of theodolite parameters. Martin Feller is thanked for many FUR absolute measurements.

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Accepted February 13, 2007