U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

MAGNETOMETER CALIBRATION DEVICE

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Open File Report 91-351

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INTRODUCTION

This paper describes a simple fixture which was developed to calibrate self-biasing, three component, ring core fluxgate magnetometers. The calibration process determines bias increments, zero field offsets, and relative non-orthogonality angles of the axes. These calibrations have previously been carried out in a large triaxial coil facility using optical surveying instruments and highly precise coil current measurements. Equally accurate determinations can be made using only this fixture, an auxiliary proton magnetometer, and the Earth's magnetic field.

The fixture consists of a holder for a ring core magnetometer which is capable of making course and fine rotations about two axes which are mutually perpendicular to the Earth's magnetic field. Operation of the fixture and the calculations required to determine the calibration constants are detailed in Appendix A.

Operation of the fixture with a ring core magnetometer is depicted in Figure 1. The fixture is shown in more detail in Figure 2. The fixture is constructed of wood, aluminum and brass. The hinge permits the holder plate to be tilted for alignment with the inclination angle of the Earth's magnetic field. Course and fine rotations about perpendicular axes are accomplished with brass screws. Tension is maintained by elastic bands. The fixture was designed and constructed by the author.

Figure 1

Appendix A

Physics of the Earth and Planetary Interiors, 59 (1990) 119–122
Elsevier Science Publishers B.V., Amsterdam – Printed in The Netherlands

Determination of the accuracy and operating constants in a digitally biased ring core magnetometer

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(Received April 7, 1984; revision accepted June 28, 1989)

Green, A.W.Jr., 1990. Determination of the accuracy and operating constants in a digitally biased ring core magnetometer. Phys. Earth Planet. Inter., 59: 119–122.

By using a very stable voltage reference and a high precision digital-to-analog converter to set bias in digital increments, the inherently high stability and accuracy of a ring core magnetometer can be significantly enhanced. In this case it becomes possible to measure not only variations about the bias level, but to measure the entire value of the field along each magnetometer sensing axis in a nearly absolute sense. To accomplish this, one must accurately determine the value of the digital bias increment for each axis, the zero field offset value for each axis, the scale values, and the transfer coefficients (or nonorthogonality angles) for pairs of axes. This determination can be carried out very simply, using only the Earth's field, a proton magnetometer, and a tripod-mounted fixture which is capable of rotations about two axes that are mutually perpendicular to the Earth's magnetic field vector.

1. Introduction

The self-biasing ring core magnetometer employs a comparator, an up-down counter, and a digital-to-analog converter to set the bias level in discrete increments on each magnetometer sensing axis. The increments are precisely controlled by the 16 bit digital-to-analog converter which uses a very stable heated zener diode as a reference. The bias level is tested 10 times per second. The bias increment for the instrument described here is about 340 gammas (nanoteslas); should the magnetic field being sensed change more than about 90% of 340 gammas, the bias level will be incremented up or down. The magnetometer has both digital and analog outputs.

The digital output consists of three nine bit words, N_x, N_y, N_z, which give the number of bias increments on the three sensing axes x, y, z, respectively.

The analog output consists of three values, X_i, Y_i, Z_i, which represent ordinate values for each axis (in gammas) above or below their respective bias levels. We define the bias increments, C_x, C_y, C_z, and note that

$$-C_x \leq X_i \leq C_x \tag{1}$$

$$-C_y \leq Y_i \leq C_y \tag{2}$$

$$-C_z \leq Z_i \leq Z_z \tag{3}$$

In other words, the absolute value of the analog output never exceeds the value of the bias increment.

We also note that the magnetometer may have zero field offsets. These are defined as E_x, E_y and E_z.

Thus, the 'actual' fields, X_a, Y_a, Z_a, along the sensing axes are:

$$X_a = N_x C_x + X_i - E_x \tag{4}$$

$$Y_a = N_y C_y + Y_i - E_y \tag{5}$$

$$Z_a = N_z C_z + Z_i - E_z \tag{6}$$

0031-9201/90/$03.50

2. Determination of bias increments and offsets

The bias increments and zero field offsets are determined separately for each axis by the same procedure. The procedure, using the x axis as an example, is outlined below.

The x sensor of the magnetometer is aligned (in the positive sense) along the Earth's field vector, so that the measured field (sum of bias field plus analog output) on each of the other two axes is less than 100 gammas (γ). This alignment is carried out using a tripod mounted fixture which is capable of making course and fine rotations about two axes which are mutually perpendicular to the Earth's magnetic field vector. For convenience, one of the rotation axes is chosen to be perpendicular to the local magnetic meridian plane. The field along the y and z axes are reduced to less than 100 γ by first making rotational adjustments to bring both N_y and N_z to zero, and then making fine adjustments that reduce the absolute values of Y_t and Z_t to less than 100 γ. When alignment has been achieved, N_x and X_t are recorded. At the same time, a measurement of the magnitude of the Earth's field F is made with a proton magnetometer at a nearby location. (The 'pier difference' in gammas between the locations of the proton magnetometer and the ring core magnetometer should be established in advance.)

The x sensor is then rotated through 180° so that it is now antiparallel to F. Again, the fields on the other two axes are reduced to less than 100 gammas; N_x, X_t and F are again recorded.

The data from the parallel and antiparallel alignments are used with eq. (4) to produce a set of simultaneous equations which can be solved for C_x and E_x. A sample calculation is given below.

Sample data:

$N_x = 163 \qquad X_t = 135.7\ \gamma$

$F = 55\,081\ \gamma$ (parallel alignment)

$N_x = -163 \qquad X_t = 18.2\ \gamma$

$F = -55\,080\ \gamma$ (antiparallel alignment)

For the x sensor aligned along F, we obtain from eqn. (4)

$$F = X_a = N_x C_x + X_t - E_x \tag{7}$$

Sample calculation:
Using the above data and eqn. (7), we can write

$$55\,081 = 163C_x + 135.7 - E_x \quad \text{(parallel alignment)} \tag{8}$$

$$-55\,080 = -163C_x + 18.2 - E_x \quad \text{(antiparallel alignment)} \tag{9}$$

From these, we obtain

$C_x = 337.56 \qquad E_x = 76.45\ \gamma$

The same procedure may be used to determine the bias increments and offset values for the other two axes.

It should be noted, that by reducing the fields on the other two orthogonal axes to less than 100 γ, we have reduced the error in determining the field along the Earth's field aligned axis to less than 0.2 γ (for $F = 50\,000\ \gamma$). Since the orthogonal axes were used in a nulling procedure to obtain alignment of the sensing axis with F, nonorthogonality would also produce an alignment error. It can be show that, if the nonorthogonality is less than 20 min of arc ($F = 50\,000\ \gamma$), the error in determining the projection of F along the aligned axis will be less than 1.0 γ. The resultant errors from either of the above in determining C_x and E_x will be quite negligible.

3. Determination of nonorthogonality

Nonorthogonality of sensor axes has the effect of producing cross-talk between the axes. If, for example, the z sensor makes an angle of less than 90° with the x sensor, the z sensor will measure not only the z field, but part of the x field. (The misalignment will also produce a decrease in the measured z field. However, for small angles and an x field comparable in size to the z field, the decrease in the measured z field is negligible and much smaller than the erroneous contribution from the x field.)

The nonorthogonality or misalignment of sensor axes can be determined by placing the sensor in a large triaxial coil facility and introducing carefully measured test fields. To minimize errors produced by field gradients, the coils must be several meters in diameter. Because the coils themselves are not orthogonal, the calibration procedure must determine the coil misalignments as well as the sensor misalignments. Methods of determining sensor and coil misalignments relative to an optically surveyed coordinate system in a large coil facility (such as that at the NASA Goddard Space Flight Center) are described by Acuna (1981) and by McPherron and Snare (1978).

The method described here does not require the use of a coil facility; one needs only the previously described fixture, the Earth's field, and a proton magnetometer. The calculations can be carried out on a hand calculator.

4. Mathematical relationships

With reference to Fig. 1

$$Z_a = Z_r \cos\alpha + X_r \sin\alpha \tag{10}$$

where X_r and Z_r are Earth magnetic field components in an orthogonal coordinate system, X_a and Z_a are the projections of X_r and Z_r in a nonorthogonal system, and α is the angle of nonorthogonality or misalignment. For the moment we assume Y_r is zero. Since X_a and X_r were chosen to be colinear, we obtain

$$X_a = X_r \tag{11}$$

For small α, we obtain

$$\cos\alpha \approx 1 \tag{12}$$

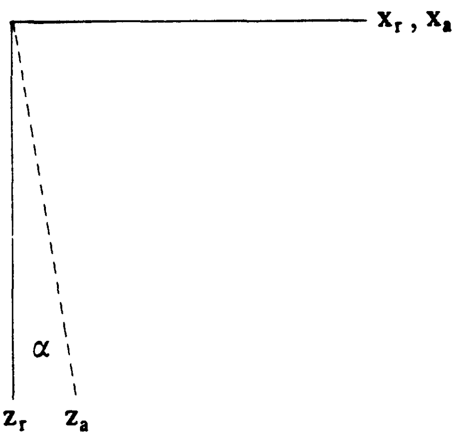

Fig. 1. Projections of the Earth's field components X_r and Z_r on nonorthogonal axes.

$$\sin\alpha \approx \alpha = C_{xz} \tag{13}$$

where C_{xz} is the 'transfer coefficient' between the x and z axes.

From eqns. (11), (12) and (13), eqn. (10) becomes

$$Z_a = Z_r + C_{xz} X_a \tag{14}$$

For nonzero Y_r and Y_a, it is easily shown that there will be an additional contribution to Z_a from the y field, so that

$$Z_a = Z_r + C_{xz} X_a + C_{yz} Y_a \tag{15}$$

Transposing eqn. (15) and writing similar equations for X_r and Y_r we obtain

$$X_r = X_a - C_{xy} Y_a - C_{xz} Z_a \tag{16}$$

$$Y_r = Y_a - C_{xy} X_a - C_{yz} Z_a \tag{17}$$

$$Z_r = Z_a - C_{xz} X_a - C_{yz} Y_a \tag{18}$$

5. Determination of C_{xz}

To experimentally determine C_{xz}, we orient the magnetometer so that the Earth's field vector **F** lies in the plane formed by the axes X_a and Z_a. This is accomplished by setting the axis of Y_a perpendicular to **F**. In practice, we null the output of the Y sensor so that $Y_a = 0$. (If Y_a is less than 100 γ, then the error along **F** will be less than 0.1γ for $F = 50\ 000\ \gamma$.) For computational ease, the fixture is rotated until X_a and Z_a are approximately equal.

When null is achieved, we record X_a, Z_a and F. F is measured with a proton magnetometer.

For $Y_a = 0$, eqns. (16) and (18) become

$$X_r = X_a - C_{xz} Z_a \tag{19}$$

$$Z_r = Z_a - C_{xz} X_a \tag{20}$$

We also note that for $Y_r = Y_a = 0$,

$$F^2 = X_r^2 + Z_r^2 \tag{21}$$

From eqns. (19), (20) and (21) we obtain

$$F_a^2 C_{xz}^2 - 4 X_a Z_a C_{xz} + F_a^2 - F^2 = 0 \tag{22}$$

where $F_a^2 = X_a^2 + Z_a^2$.

Solving eqn. (22) for C_{xz} we obtain

$$C_{xz} = P \pm (P^2 - d)^{1/2}$$

where

$$P = \frac{2X_a Z_a}{F_a^2} \quad \text{and } d = 1 - \frac{F^2}{F_a^2}$$

In the same fashion, C_{xy} and C_{yz} can be determined.

A sample calculation for C_{xz} is given below.
Sample data:

$N_x = 110$ $X_i = 90.80\ \gamma$ $C_x = 337.56$
$E_x = 76.45\ \gamma$ $N_z = 120$ $Z_i = 62.10\ \gamma$
$C_z = 338.58$ $E_z = 49.10\ \gamma$ $N_y = 0$
$Y_i = 4.20\ \gamma$ $F = 55072$

Sample calculation:

$X_a = N_x C_x + X_i - E_x = 37\,145.62\ \gamma$

$Z_a = 40\,642.72\ \gamma$

$d = -4.28 \times 10^{-4}$

$P = 0.995966$

$C_{xz} = -2.15 \times 10^{-4}$ radians $= -0.739'$

The negative sign means that the angle between X_a and Z_a is greater than $90°$.

6. Conclusion

Accuracy in operation of a triaxial ring core fluxgate magnetometer depends on knowledge of bias increments, offsets, and nonorthogonality of sensor axes. We have shown that these may be easily determined in the field using only a simple tripod-mounted fixture, the Earth's magnetic field, and a proton magnetometer.

References

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