Exploration Geophysics (1984) **15**, 75-77

Paper

A Total Field Fluxgate Magnetometer

Sayyadul Arafin*
School of Physics
Universiti Sains Malaysia
Penang
Malaysia

Key words: total field, fluxgate, three components, magnetometry

Abstract

A fluxgate magnetometer capable of giving a continuous total-field profile has been developed using a three-axis instrument which does not involve moving parts. A simple method is presented for measuring the three relative angles of the fluxgates when they are not mutually orthogonal, and a procedure is described for transforming the outputs of the fluxgates into orthogonal components and into a value for the total magnetic field.

Introduction

Commercially available modern electronic magnetometers such as fluxgate, proton and optically-pumped instruments have advantages and disadvantages when compared to each other. For example, the fluxgate magnetometer is the cheapest of all, and is capable of providing a continuous record of data; whereas the proton-precession magnetometer has a maximum sampling rate of approximately 1 sample per second. The fluxgate magnetometer measures basically some component of the Earth's magnetic field, whereas the proton and optically-pumped magnetometers measure basically the total field. One commercially available fluxgate magnetometer, the three-axis Develco Model 9200C, weighs only six ounces and is very small. Such small physical dimension is an added advantage for easy field operation.

The fluxgate magnetometer commonly used in prospecting work measures only the component of the Earth's magnetic field in the direction of its sensor axis. For vertical field measurement within an accuracy of 1 nT, it is necessary to align the sensor to within 11 seconds of arc of the vertical (Dobrin 1960). Such an accuracy is virtually unattainable in a moving platform such as an aeroplane or a land vehicle, unless automatic and complicated orientation mechanisms are used.

It is therefore evident that it may be useful to construct a cheaper magnetometer which is easy to operate in the field from a moving vehicle, and which is efficient for ground level magnetic survey work. This paper describes such a total-field fluxgate magnetometer, constructed on the basis of a commercially available three-axis fluxgate magnetometer (Model Develco 9200C). Figure 1 shows the arrangement in block diagram of the electronic circuitry developed. The total-field value is obtained by electronically taking the square-root of the sum of the squares of the outputs of the three fluxgates. A major problem arises from misalignment of the sensor axes (understood to possibly be as great as 1°) as a misalignment of this magnitude would introduce a significant error in the total field measurement.

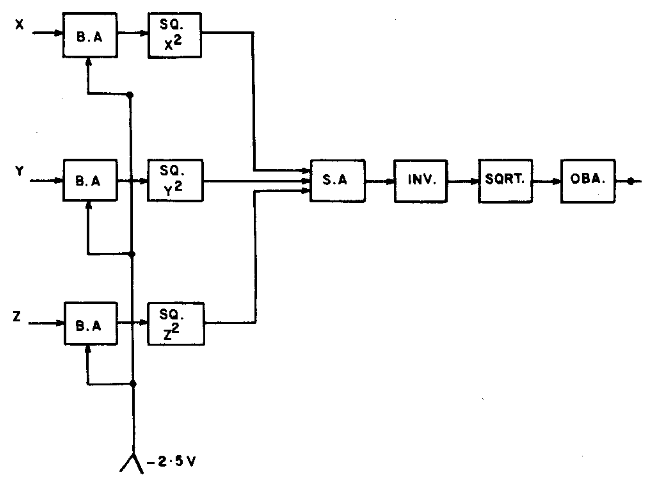

FIGURE 1
Block diagram of the electronic circuits used to build the total field fluxgate magnetometer. BA buffer amplifier, SQ squarer, SA summing amplifier, INV inverter, SQRT square rooter, OBA output BA, MOP magnetometer output, BOP buffer output, SU summer output. Magnetometer output, W_1, W_2, W_3 = 5/20,000 (±60,000 field), buffer output = −4.0(MOP −2.5), squarer output = $BOP^2/10$, summer output = −5(SQ), inverter output = −3(SU), square rooter output = 10 $\sqrt{INV}$, output of the buffer amplifier no. 2 = −1 (SQRT).

Unfortunately there is little published information concerning the problem of misalignment of sensor axes. McPherron and Snare's (1978) method appears to be the only technique to overcome this problem. These authors simultaneously determine the orientations of the sensors of a vector magnetometer, and the three coils necessary for its calibration, by using an optical cube and two theodolites.

Part of the work described in the paper was done while the author was at the University of New England, Armidale, Australia.

Further, starting with an initial model based on the assumption that the axis orientations are known to roughly one-half degree by construction, they are able to measure the orientations of the axes to an accuracy of 5 arc seconds using a computer simulation method.

We describe here a procedure to determine the angles of the fluxgates to the desired accuracy of 5 arc seconds. Also described is a matrix transformation for the conversion of the fluxgate outputs into orthogonal components which can be electronically squared, summed and 'square-rooted' to give a measure of the Earth's total magnetic field.

Instrumentation and data acquisition

The basic instrument employed is a Develco Model 9200C three-axis fluxgate magnetometer. The small size (1.25 in x 1.4 in x 4.5 in) and weight (6 oz) of this instrument make it convenient for use in applications where space and weight are at a premium. The miniature ring core fluxgate magnetometer uses integrated circuits to combine high reliability with high performance in a small package. The sensors and the related electronics are housed in a single package for ease of installation. Power consumption is minimal. Because of its low output impedance, long cables can be attached to the magnetometer without affecting its performance.

Let the sensor axes be denoted by 1,2,3 and let α,β,γ be the angles between the sensor axes (1 and 2), (2 and 3) and (3 and 1), respectively. The three angles can be measured by rotating the magnetometer three times in such a way that the Earth's magnetic field (T) each time lies exactly on a plane of the sensor axes. Then by measuring the outputs of the fluxgates, w_1, w_2 and w_3 we can show that

$$\alpha = \text{arc cos}(w_1/T) + \text{arc cos}(w_2/T)$$
$$\beta = \text{arc cos}(w_2/T) + \text{arc cos}(w_3/T)$$
$$\gamma = \text{arc cos}(w_3/T) + \text{arc cos}(w_1/T)$$

However, in practice it would be extremely difficult to align the field with the planes of the sensor axes. If δ is the angle between the Earth's field and a plane, then it can be shown that for values of δ as large as 0.42° the corresponding errors in the measurements of the angles would not exceed 5 arc seconds. An error of this magnitude in the angle measurements would incur an uncertainty of 1 nT in the total field measurement, which is the required accuracy in most prospecting work. This accuracy is attainable with the use of a high resolution digital voltmeter which can read up to five decimal places.

However, like any fluxgate instrument, the total field magnetometer described is also sensitive to temperature. This problem has been discussed by several authors, including Gordon *et al.* (1968), Primdahl (1970) and Trigg *et al.* (1971). The most common procedure to minimize the temperature drift is by temperature compensation.

Transformation to orthogonal components

Once the angles α, β and γ are known within the required accuracy of 5 arc seconds, the transformation of the outputs of the fluxgates into orthogonal components is simple and straightforward. A hypothetical orthogonal coordinate system (X,Y,Z) is established on the magnetometer head by nominating the direction of fluxgate 1 as X, the line perpendicular to axis 1 and lying in the plane of axes 1 and 2 as Y and the line perpendicular to the plane of fluxgates 1 and 2 at the origin 0 as Z (Fig. 2). The outputs of the fluxgates may be expressed in terms of the direction cosines between the fluxgates and the directions of the cartesian coordinates X, Y and Z. Let us introduce the following: m_{ij}, the direction cosine between fluxgate 'i' and the 'j' direction of the orthogonal set of coordinates X, Y and Z; w_i, the individual outputs of the three fluxgates; t_i, the components (East, North and Vertical) of the Earth's total magnetic field, T; $A=(a_{ij})$, the rotation (change in orientation) of the Earth's magnetic field, T with respect to the reference coordinates on the magnetometer head (i.e. the coordinates X, Y and Z).

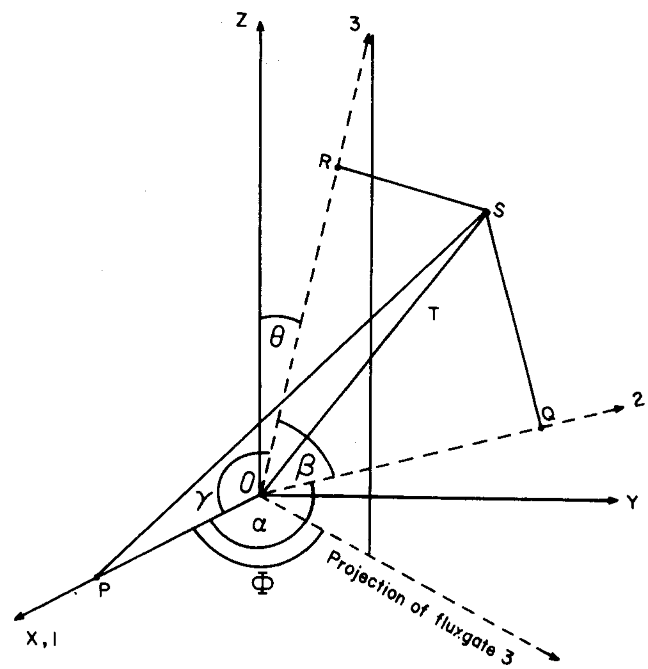

FIGURE 2

Diagram for converting the three axis fluxgate magnetometer outputs orthogonal components. OP = W_1, OQ - W_2, OR = W_3. W_1, W_2 and W_3 are the outputs of the three fluxgates. 1, 2 and 3 are the directions of the fluxgates. α, β and γ are the angles of the fluxgates. ϕ is the angle between fluxgate 1 and the projection of fluxgate 3 on the OXY plane. θ is the angle between Z and fluxgate 3. Note fluxgates 1 and 2 lie on the plane OXY. T is the total magnetic field.

The fluxgate outputs can be expressed in a matrix form as

$$W = MAT \qquad (1)$$

where W and T are 3 x 1 column vectors and M = m_{ij} and A = a_{ij} are 3 x 3 matrices. The linear equations (1) can be solved exactly for the unknowns (i.e. the orthogonal components with respect to X, Y and Z coordinates) provided an inverse of the matrix M exists. In terms of the angles α, β and γ, M may be written as

$$M = \begin{bmatrix} 1 & 0 & 0 \\ \cos\alpha & \sin\alpha & 0 \\ \sin\theta\cos\phi & \sin\theta\sin\phi & \cos\theta \end{bmatrix} \qquad (2)$$

where

$$\phi = \text{arc tan}\left(\frac{\cos\beta}{\cos\gamma\ \sin\alpha} - \cos\alpha\right)$$

is the angle between X axis and the line of projection of the fluxgate axis 3 on XY plane.

θ = arc sin(cosγ/cosϕ) is the angle between the Z axis and the direction of fluxgate 3. The value of the determinant of the square matrix M, sinα cosθ can never be zero because the values of α and θ can deviate from their proper values, $\pi/2$ and 0, respectively, by 1° at the most (according to the manufacturer). Therefore the inverse of the matrix M exists and the solution of equation (1) is unique. Hence

$$\begin{aligned} M^{-1} W &= M^{-1} MAT \\ &= AT \end{aligned} \qquad (3)$$

Let us refer to the vector AT as F = (f_i), whose components are those of the vector T rotated through an arbitrary angle. Hence the total scalar field, $\mathscr{F} = [\Sigma(f_i)^2]^{1/2}$. The scalar should be constant as the magnetometer is turned. The inverse of M is given by

$$M^{-1} = \begin{bmatrix} 1 & 0 & 0 \\ -\cot\alpha & \operatorname{cosec}\alpha & 0 \\ \cot\alpha\tan\theta\sin\phi \\ -\tan\theta\cos\phi & -\operatorname{cosec}\alpha\tan\theta\sin\phi & \sec\theta \end{bmatrix} \qquad (4)$$

The matrix A is equivalent to the three-dimensional rotation matrix which may be obtained by making three independent rotations in turn about the axes of a cartesian coordinate system through the three Euler angles. However, it is unnecessary to attempt to determine this matrix since we are presently interested only in the measurement of the total scalar field, and not the east, north and the vertical components.

Discussion

The chief advantage of the total field fluxgate magnetometer described here is that the instrument is small and may be operated from a moving vehicle, such as a Land Rover, without employing a mechanical orientation mechanism. The magnetometer is thus capable of providing a continuous record of the Earth's total magnetic field, at a lesser cost than that of other commonly used vehicle-borne magnetometers, such as the caesium vapour magnetometer system. The experimental method described for measuring the three angles is simple. A high resolution digital voltmeter would enhance the overall accuracy to 1 nT in the total field measurement. The outputs of the fluxgates need to be transformed into orthogonal components before connecting them to the buffer amplifiers (Fig. 1). The small temperature drift inherent with the instruments of this type may be kept to a minimum by temperature compensation.

Acknowledgments

The author wishes to express sincere gratitude to Associate Professor Ronald Green, Dr John M. Stanley, Mr F. C. Ludbey and Mr N. Taman for their help while he was at the University of New England, Armidale, Australia and to thank Dr Mohammad Ilyas, School of Physics, Universiti Sains Malaysia, for reading the manuscript.

References

Dobrin, M. B. (1960), *'Introduction to Geophysical Prospecting'* (2nd edn), McGraw-Hill, New York.

Gordon, D. I., Lundsten, R. H., Chiarodo, R. A. & Helm, H. J. Jr (1968), 'A fluxgate sensor of high stability for low field magnetometry', *IEEE Trans. Mag.* **4**, 397-401.

McPherron, R. L. & Snare, R. C. (1978), 'A procedure for accurate calibration of the orientation of the three sensors in a vector magnetometer', *IEEE Trans. Geosci. Electron.* **16**, 134-7.

Primdahl, F. (1970), 'Temperature compensation of fluxgate magnetometers', *IEEE Trans. Mag.* **6**, 819-22.

Trigg, D. F., Serson, P. H. & Camfield, P. A. (1971), 'A solid state electrical recording magnetometer', Publ. Earth Phys. Branch, Dept. Energy, Mines and Resources (U.S.A.), No. 41, pp. 66-80.

(Received 17 May 1982; accepted 3 January 1984)