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# Development and Application of Differential Vector Magnetometers

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## Abstract

Vector magnetometers may be used to determine the *in situ* magnetic properties of magnetic anomaly sources. The adaptation of caesium-vapour magnetometers to vector measurements has been challenging but rewarding. We describe the considerations that we have taken into account and summarise our success to date.

Key words: magnetometer, vector, differential, in situ Q, pulsation, diurnal

## Introduction

The amplification of micropulsations in the vicinity of ferromagnetic rock masses has been detected by Ward and Ruddock (1962). In their experiment they used a pair of alkali-vapour scalar magnetometers, one over the source and one removed from the source. Later, Goldstein and Ward (1966) showed that it was possible to distinguish the contributions of induced and remanent magnetisation to a magnetic anomaly and, so, infer an approximate Koenigsberger Ratio (Q) for the source, assuming that the induced and remanent magnetizations are coaxial. Micropulsation amplification was detected only over anomalies whose sources were shallow and had low Q values. The larger amplitude diurnal variation was required to detect such changes for deeply-buried sources and those of relatively low susceptibility. The Q values, determined in this way using scalar magnetometers, are only nominal since, in general, the induced and remanent magnetisations are not parallel. It follows that their relative contributions to the anomaly are not simply proportional to their intensities, but depend on orientation and geometry.

Parkinson and Barnes (1985) developed a more general method using simultaneous vector measurements. They demonstrated their method over an intense anomaly using three-component fluxgate magnetometers. An appendix by Clark, in Parkinson and Barnes (1985), showed that vector measurements can be used to test for parallellism of the induced and remanent magnetizations, and confirmed the assumption of those authors that the massive magnetite deposit at Savage River, Tasmania, carries a substantial remanence that is directed approximately parallel to the present field and is characterized by a Koenigsberger ratio of ~0.5. Furthermore, it can be shown that measurements of three-component anomalies on, and off, an anomaly allow the Q and the directions of the total and remanent magnetisations to be determined. For a compact source, it is possible to locate the centre of the source.

Apart from the above application, there are several advantages of vector magnetometer surveys: (i) they provide information on the strike extent of geological features, (ii) they enable strike directions of linear features to be determined from individual profiles, and (iii) they define the direction to off-profile sources. These advantages equate to better data for any given line-kilometre or, alternatively, data at lower cost. Moreover, magnetic components, being directional gradients of the potential, are non-solenoidal, obey Laplace's equation and the principle of superposition, and are therefore potential fields. The total field anomaly is a non-linear combination of components that depends on the local geomagnetic field (direction and intensity) and does not obey Laplace's equation or the principle of superposition. Standard filtering procedures for upward and downward continuation, calculation of vertical derivatives and reduction to the pole are strictly valid only for potential fields. Component anomalies are also simpler to interpret since their form is independent of the local geomagnetic field direction.

## Caesium-vapour Vector Magnetometers

The great practical difficulty with high-resolution vector component surveys is the extreme sensitivity of components to sensor orientation. Absolute orientation accuracy to the second of arc level is necessary to achieve noise levels comparable to those of conventional total field surveys. In the following discussion, we use the generic term fluctuation for high frequency geomagnetic temporal variations (periods of less than a few seconds).

In collaboration with the Geophysical Research Institute of the University of New England, we have built two vector instruments based on caesium-vapour magnetometers. Although caesium-vapour magnetometers are fundamentally scalar instruments, by using forward and reversed bias fields it is possible to determine component fields. For mutually perpendicular coil axes, the orthogonal components are easily found from the following.

$$\mathbf{T} = X\mathbf{i} + Y\mathbf{j} + Z\mathbf{k}$$

$$\left|\mathbf{T}^2\right| = X^2 + Y^2 + Z^2$$

$$\left|\mathbf{T}_1^2\right| = (X + \Delta X)^2 + Y^2 + Z^2$$

$$\left|\mathbf{T}_2^2\right| = (X - \Delta X)^2 + Y^2 + Z^2$$

$$\left|\mathbf{T}_1^2\right| + \left|\mathbf{T}_2^2\right| = 2\left|\mathbf{T}^2\right| + 2(\Delta X)^2$$

$$\left|\mathbf{T}_1^2\right| - \left|\mathbf{T}_2^2\right| = 4X\Delta X$$

$$X = \left(\left|\mathbf{T}_1^2\right| - \left|\mathbf{T}_2^2\right|\right) / 4\Delta X$$

$$\Delta X = \left\{\left(\left|\mathbf{T}_1^2\right| + \left|\mathbf{T}_2^2\right| - 2\left|\mathbf{T}^2\right|\right) / 2\right\}^{\frac{1}{2}}$$

where T is the local geomagnetic field, with orthogonal components $X\mathbf{i}$, $Y\mathbf{j}$ and $Z\mathbf{k}$; $|\mathbf{T}_1^2|$ is the total field intensity with a forward bias field, $\Delta X$, in the **i** direction, and $|\mathbf{T}_2^2|$ is the total field intensity with a reversed bias field in the **i** direction. Thus, $X\mathbf{i}$, the component of the ambient field aligned with the X-coil, is determined. Likewise, $Y\mathbf{j}$ and $Z\mathbf{k}$ are determined.

Table 1 shows the sensitivities of the vector measurements required for a meaningful assessment for different conditions, such as Q value of source and magnitude of the particular geomagnetic fluctuation being used. Clearly a widely applicable system must have sub-nanotesla sensitivity. While the caesium-vapour sensor has an intrinsic sensitivity of 0.01 nT, it has proved difficult to achieve consistent sub-nanotesla vector measurements. Some of the problems we have encountered include: (i) the requirement for high precision bias field reversibility, (ii) geomagnetic field fluctuations during single vector measurement, and (iii) mechanically rigid coil mounts. Clearly the forward and reversed $\Delta X$ must be made equal, as far as is practical, to determine $X\mathbf{i}$ precisely. In addition, (ii) above will affect the determination of $X\mathbf{i}$ in a similar fashion, so the time for the entire measurement procedure must be kept as short as possible. For the differential mode of operation, the alignment of the two magnetometers is also crucial. The required accuracy of the alignment depends on the size of the anomaly, the magnitude of fluctuations and the Q.

**TABLE 1**
**Required Sensitivity**

| Anomaly (nT) | ΔB(t) (nT) | Magnetometer Sensitivity (nT) | | |
|---|---|---|---|---|
| | | Q = 0 | Q = 1 | Q = 9 |
| 10,000 | 100 | 20 | 10 | 1 |
| | 10 | 2 | 1 | 0.1 |
| | 1 | 0.2 | 0.1 | 0.01 |
| 1,000 | 100 | 2 | 1 | 0.1 |
| | 10 | 0.2 | 0.1 | 0.01 |
| 100 | 100 | 0.2 | 0.1 | 0.01 |
| | 10 | 0.02 | 0.01 | 0.001 |

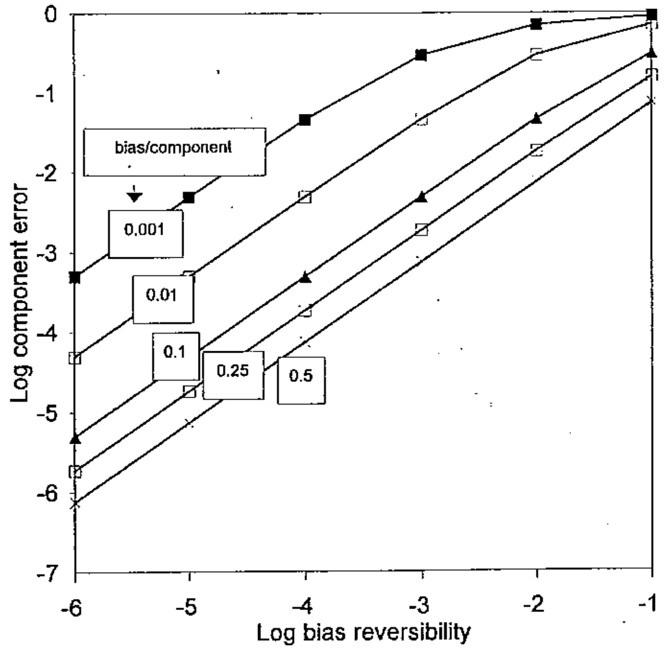

FIGURE 1
**Log-log plot of bias field reversibility versus component error, for different bias field magnitudes, expressed as a fraction of the component magnitude. A component error of one part in 300 000 (0.1 nT in 30 000 nT or $\log_{10}$ of −5.5), requires a bias field of somewhere between 10% and 25% of the component magnitude (say 3000 nT — 7500 nT) and a reversibility of about 1 ppm (a few pT). By the same argument, a fluctuation of the ambient field by a few pT during measurement will lead to an error of comparable magnitude.**

To determine how sensitive this method is to the above factors, we have simulated measurements while varying the bias field reversibility. The bias field reversibility is defined as the difference divided by the average value of the forward and reversed bias field, or:

$$2\,(\Delta X_f - \Delta X_r) \,/\, (\Delta X_f + \Delta X_r)$$

A reversibility of zero implies exact equality of the forward and reversed bias fields. Figure 1 shows a log-log plot of bias field reversibly versus error in the component for different bias fields. The bias fields are expressed as fractions of the component magnitude from 0.001 to 0.5. For a given bias field reversibility, the larger the bias field, the smaller the error. For a component magnitude of 30 000 nT, an accuracy of 0.1 nT equates to one part in 300 000. This requires a bias field of somewhere between 10% and 25% of the component magnitude (say 3000 — 7500 nT) and a reversibility of about 1 ppm (or a few pico Tesla, pT). With the present coil set, this corresponds to a current stability of better than 0.1 μA. So far, we have managed to achieve 0.3 μA stability.

The problem of the component varying in magnitude while the measurement is in progress is more insidious, but has a similar effect as current stability on degrading the signal. For a bias field equal to 10% of the component, i.e. 3000 nT, a fluctuation of only 3 pT in the component during measurement (say 100 ms) will produce an error of more than 0.1 nT in the calculated intensity of the component. The magnetometer behaves as a differentiator and changes of the field are amplified. We have simulated this effect on a computer and have also observed it in real data. In Fig. 2 we compare a record of a few minutes duration of measured total magnetic intensities (TMI) and intensities of the components recorded in nearby Ku-ring-gai Chase National Park. The Z data mirror changes in TMI in an exaggerated manner. In addition, there is an off-set between the two data sets that is partly caused by non-orthogonality, but also by a design problem which we have only recently isolated. The noise level of the components, for intervals when the TMI is fairly constant, appears to be <1 nT. After eliminating the remaining problems, we expect to be able to record vector field measurement with noise levels well below the nT level when the field is not changing rapidly.

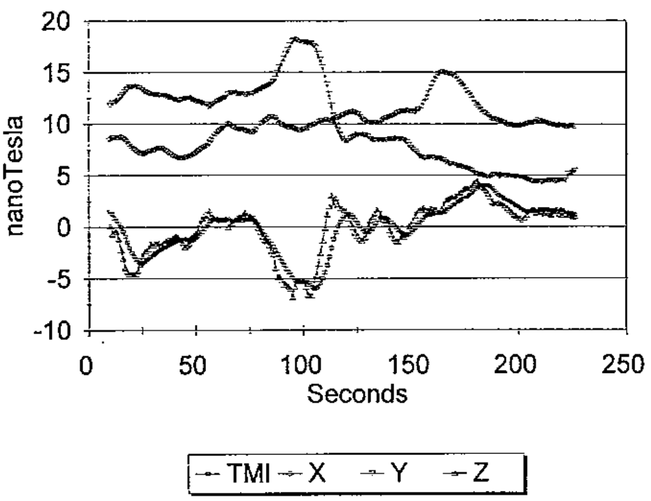

**FIGURE 2**
**Comparison of variations measured in total magnetic intensities and intensities of components. TMI and Z are plotted about 0 while X and Y are plotted about the 10 nT ordinate.**

## Conclusions

To reduce errors of the type discussed above it is clearly advisable to use as large a bias field as possible. However, there are two constraints on the magnitude of the bias fields, (i) they must not be so large that the orientation of the total field is deflected into the dead-zone of the caesium-vapour sensor, and (ii) power consumption. The first problem could be largely overcome by using the latest caesium-vapour sensors that are less affected by orientation. The latter problem could be off-set by using more turns for the coils, but this increases inductance effects causing an increase in measurement time (there is a wait-time between current switching that depends on the rate of decay). However, it is prudent to make measurements as quickly as possible to reduce the effect of geomagnetic fluctuations. The optimisation of this system is therefore a trade-off between competing effects requiring the rapid acquisition of individual vector measurements.

SQUID magnetometer systems offer several advantages since they are intrinsically vector instruments and, in effect, make measurements instantaneously. However, the requirement of liquid helium has precluded their use as field instruments. High temperature (liquid nitrogen temperature) SQUID magnetometers have just become available commercially and promise to overcome this. Since a complete vector measurement requires three sensors, there may be calibration difficulties, and it is not clear how stable and robust high temperature SQUIDs are as field instruments. Nevertheless, it will be of interest to compare the systems when an opportunity arises.

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