Geophysical Exploration using Magnetic Gradiometry based on HTS SQUIDs

C.P. Foley, D.L. Tilbrook, K.E. Leslie, R.A. Binks, G.B. Donaldson, J. Du, S.K. Lam, P.W. Schmidt and D.A. Clark

***Abstract*— Magnetic tensor gradiometry provides gradient components of true potential fields which enables unique depth estimates and improves analytic signal methods as well as providing a number of other advantages. A high temperature SQUID (HTS) gradiometer can provide measurements of the components of the earth's field tensor creating a new tool for mineral exploration. A successful comparison between a HTS SQUID gradiometer and a Cs-vapour gradiometer under survey conditions has been conducted. Both instruments were configured vertically. The HTS gradiometer measured the B_{zz} component of the gradient tensor, while the Cs-vapor gradiometer measured the vertical gradient of the total magnetic intensity. The HTS gradient measurement was the difference in output between two coaxial SQUID sensors. Effective noise levels achieved were 0.16-0.3 nT/m RMS, compared with 0.1-0.5 nT/m RMS for the Cs-vapor system. The SQUID noise was dominated by vibration with additional contributions from the multiplexed sampling between the SQUIDs. This paper reports on the system development, design issues, trial results and the implications for geophysical exploration.**

***Index Terms*— HTS, gradiometer, geophysics, mineral exploration, SQUIDs**

I. INTRODUCTION

During the early stages of mineral exploration for targets with a remanent magnetic field such as kimberlite pipes and iron ore, it is mandatory to carry out magnetic surveys. The acquisition and processing of magnetic surveys using total magnetic intensity (TMI) data from airborne cesium vapour magnetometers have improved remarkably over the past decade. It is now possible to collect high quality images.

Nevertheless, there remains much information in the magnetic data that is not accessed, largely due to time constraints and the lack of appropriate technologies to measure the magnetic field vectors directly. For instance, while the magnetic field is a vector quantity, the processed TMI data is treated as a scalar and the resulting images are similar to topographic maps. It is possible to derive vector components from suitably processed TMI data, however a more faithful representation of the vector field would be obtained by direct measurement [1]. The accuracy of direct measurements of the field vector is largely governed by orientation errors, which for airborne platforms are so large that the theoretical derivation of the components from the TMI data is actually preferable. For this reason, it is desirable to measure the field gradients rather than field vectors.

Gradient measurements are relatively insensitive to orientation. This is because gradients arise largely from anomalous sources, and the background gradient is low. This contrasts with the field vector which is dominated by the background field arising from the Earth's core. Gradient measurements are therefore most appropriate for airborne applications. Another advantage is they obviate the need for base stations and corrections for diurnal variations. They also greatly reduce the need for regional corrections which are required by TMI surveys because of deeper crustal fields that are not of exploration interest or the normal latitudinal intensity variation of the earth's magnetic field. More information on the advantages of measuring the gradients is given in ref. [2].

CSIRO is undertaking a major project to develop an airborne magnetic gradiometer. This report describes the initial ground based trial at Tallawang, Australia, where a single axis software SQUID gradiometer measured the B_{zz} component of the earth's magnetic field gradient tensor and compared this to two Cs vapor magnetometers operating as a gradiometer with the sensors positioned 1 m apart.

II. Initial Comparison of SQUIDs and Vapour Magnetometers

A comparison of a 3 axis SQUID magnetometer with metal vapour vector magnetometers was undertaken to investigate the use of differential vector magnetometers to overcome non-uniqueness problems in magnetics. This is reported in detail in ref. [3]. This comparison measured the noise levels of potassium (GEM K) and cesium (Cs2) vapour magnetometers with an early version CSIRO SQUID magnetometer. A summary of the different systems' operating parameters is given in Table I.

The conclusion of this comparison was that SQUID systems have superior noise characteristics, can measure vector components directly and have lower power consumption. This favors their use in magnetic gradiometry in survey applications. However they are affected by low

Manuscript received September 16, 2000.

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TABLE I
COMPARISON OF OPERATING PARAMETERS OF SENSORS AS MAGNETOMETERS

Sensor	Noise at 1 Hz	Power Consumption	Drift
GEM K	15-35 pT/√Hz	30 V, 450 mA	?
Cs2	40-78 pT/√Hz	30 V, 450 mA	Yes
SQUID	15-21 pT/√Hz	12 V, 150 mA	Yes

frequency drift, an issue that would require further device and system improvement.

III. ISSUES RELATING TO THE SQUID GRADIOMETER SYSTEM DESIGN

SQUID gradiometers consist of two discrete spatially separated superconducting sensors in either an axial or planar configuration. The axial gradiometer can be two separate SQUIDs with the output either electronically or mathematically subtracted. While the planar gradiometer can be a single chip gradiometer [4], we used the former, in which the SQUIDs had a 300 mm vertical separation. The difference was obtained by a software subtraction. This option was decided on as the simplest method to achieve an initial survey system.

Determination of the required parallelism of the SQUIDs in the gradiometer was calculated using the assumption that $\delta B_x/\delta z(x)$ is of the order of the estimated field gradient (300 nT/m) at the trial site in Tallawang. By considering the two SQUIDs mounted ideally with respect to the z axis and assuming a 1% error in the calculated gradient, the maximum gain/mismatch error for a 300 mm base line was calculated as: $\Delta B(SQUID_1\text{-}SQUID_2) = 300\ nTm^{-1} \div 0.3\ m = 90\ nT$. For a 1% gradient error, $\delta B_x/\delta z(x)$ must be accurate to 0.9 nT/0.3 m = 3 nT/m.

Assuming that the SQUIDs are perfectly matched and aligned and given the components of the gradient tensor, we can calculate the error in the measured vertical gradient due to deflection of the z axis of the whole assembly away from the vertical through an angle θ. For the 2D case, the apparent vertical gradient of vertical field in the rotated SQUID reference frame is: $\delta B_z/\delta z \cos^2\theta + 2\delta B_z/\delta x \cos\theta \sin\theta + \delta B_x/\delta x \sin^2\theta$. Because the divergence of the field is zero, $\delta B_z/\delta x = -\delta B_x/\delta x = \delta B_z/\delta z$, so that a 1 % error in $\delta B_z/\delta z$ occurs when $\theta = 0.3°$. However, when B_x, B_y and B_z are approximately 50 μT, a misalignment θ_2 of one SQUID produces an error in the measured ΔB of 50 μT $\sin\theta_2$. For the same gradient (300 nT/m = 90 nT/300 mm) as above, a 1% error (0.9 nT/300 mm) due to misalignment corresponds to $\theta_2 = 3.7$ seconds of arc. This means that the flexure of the rigid rod supporting the two SQUIDs must be less than ~5 μm to obtain a 1 % error.

The single-axis SQUID-based gradiometer developed for this trial consisted of a pair of rf SQUIDs mounted on a Pyrex rod. The SQUID assembly was operated in a glass dewar containing the liquid nitrogen. Shielding against interference from external rf noise was achieved by the application of a non-magnetic rf shield to the external wall of the dewar.

The sensitive axes of the SQUIDs were aligned by facing the Pyrex rod to ensure that the end surfaces were parallel to an accuracy of approximately 1 arc minute. The SQUIDs were oriented to align the flux focusers and clamped to the Pyrex rod by a header assembly which also contained the feedback coil, rf excitation coil and tank circuit. The SQUIDs were operated in individually controlled flux-locked loops employing custom-built CSIRO electronics to form two independent single-axis magnetometers. When mounted in the dewar described above, the magnetometers sensed the vertical component of the magnetic field. An additional pair of coils was fixed rigidly to the Pyrex rod to facilitate calibration of the SQUIDs against thermal drift. Unfortunately these coils were found to act as an rf antenna and were disconnected. Calibration was undertaken using an external coil which proved to work adequately although not as convenient.

Data from the two magnetometers were collected independently using a National Instruments DAQCard -4350 24 bit ADC interfaced to a Pentium 266 Notebook computer. The difference calculation to yield gradiometer data was carried out separately during the data analysis phase.

At the Tallawang test site, peak magnetic field gradients were about 500 nT/m. Assuming a total magnetic field of about 50,000 nT, misalignment of the SQUIDs of the order of 1 minute of arc corresponds to a fixed error of 15 nT. To enable removal of this fixed error signal, the gradiometer was calibrated in Helmholtz coils and the fixed error removed during the data analysis phase. Subsequent field testing proved that the gradiometer was stable to better than +/-0.1 nT.

III. SYSTEM PERFORMANCE AND TRIAL RESULTS

Two rf HTS SQUIDs were used for this trial. The SQUID characteristics are given in the Table II below.

The parameters of "field removed" and "field reapplied" are an indication of how well a SQUID will operate in a magnetically unshielded environment with a changing magnetic field. If creep (indicated by the change in the SQUID output without any changes to the input) is slow and the SQUID is stable with fields reapplied, then the SQUID is suitable for unshielded operation.

Fig. 1 shows the data collected in a pre-trial test where the magnetometer data of both SQUIDs follow identical paths. The software-determined gradient was found to have a sensitivity better than 0.1 nT. Fig. 1 also shows a magnet brought close to the gradiometer creating an artificial gradient, rotated and then removed. No drift was observed and the SQUIDs remained in lock. The system could be

TABLE II
SQUID CHARACTERISTICS USED IN THE GRADIOMETER

Device	Type	Noise at 1 Hz fT/√Hz	1 kHz fT/√Hz	Field Removed	Field Reapplied
A	6mm full washer	1229	496	Slow creep	Stable
B	6mm full washer	1537	344	Creeping	Stable

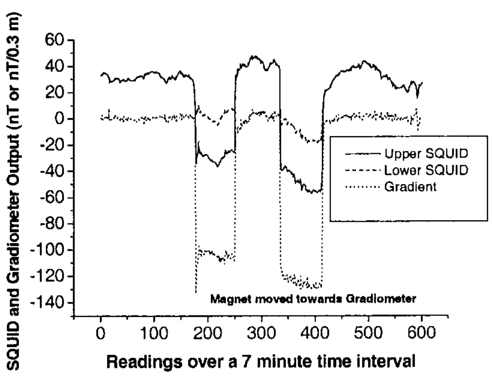

Fig. 1. Data collected in a pre-trial test over 7 minutes. The SQUIDs follow each other closely. The introduction of an external magnet close to the system shows an increase in the gradient.

moved without loss of lock or flux jumps.

Situated 17 km north of Gulgong, Australia, the Tallawang magnetite deposit occurs as a skarn along the western margin of the Gulgong granite. The body is tabular, striking north by north by north-east and dipping steeply to the west. The northern end of the skarn is currently mined by Commercial Minerals, a Normandy subsidiary, for magnetite which is used in coal washeries. The body has a pronounced magnetic anomaly and has been used by CSIRO as a test site previously.

The HTS SQUID and Cs vapor gradiometers were trialed at Tallawang on 10/9/99 over a 140 m (for the SQUID) and 200 m (for the Cs) traverse.

The trial was considered a success. The SQUID systems remained in lock, their noise performance did not vary during the day and there were no problems encountered during the trial. Over a period of 5.5 hours, the change in the ratio of the SQUID gains was no more than 1.25%.

Modeling of the anticipated gradient measured by the Cs and SQUID gradiometers at ground level is shown in Fig. 2. This calculation used a simple 2D dipping sheet or tabular geological model of the magnetite deposit.

A. Cs Vapor Gradiometer Results

The Cs vapor gradiometer measures the difference in total magnetic field intensity over 1 m separation with a vertical orientation (dF/dz). The z axis measurements are shown in Fig. 4. The data show a maximum gradient of about 500 nT/m compared with the model, which gave a figure of 350 nT/m. The Cs gradient trial data show an additional maximum at about 50 m which is due to a separate magnetic source that was not included in the model.

B. SQUID Gradiometer Results

Dc measurements were made over a 2.5 minute sample time to determine the extent of the environmental noise and are shown in Fig. 3. Wind noise was effectively removed by an arrangement of wind shields. Noise spectra with and without the wind shields showed that this arrangement was effective. Signals below 20 Hz appear to be caused by motion of the SQUID in the background earth's magnetic field. The peaks at approximately 1.5 , 4 and 15 Hz are thought to be due to vibrations due to machinery operating at a distance of about 1 km from the measurement site. The peak at 50 Hz is due to magnetic fields associated with distant power lines. The upper SQUID A of the pair showed a very similar spectrum. Laboratory noise measurements showed the potential for a reduction in the noise limit of the gradiometer over the 0.2 to 20 Hz range if a better suspension system is devised. The SQUIDs were found to follow each other closely and the gradient resolution was an order of magnitude better at Tallawang which is a more remote location than in the region outside the CSIRO TIP laboratories where the pre-trial testing occurred which is located in a big city. The SQUID gradiometer data and the Cs z axis data along the Tallawang traverse are shown in Fig. 4. It is interesting to note that the B_{zz} data (x=50 m) has a secondary minimum at about the

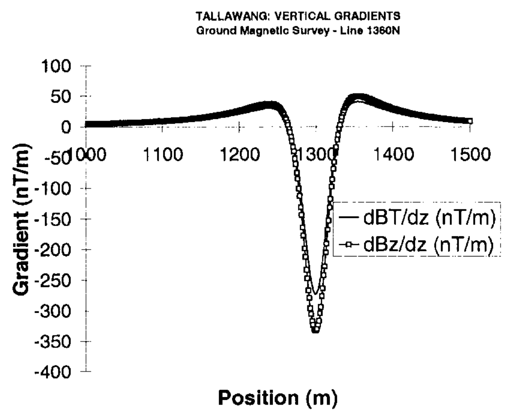

Fig.2. Comparison of the predicted vertical gradient of the total field (B_zT) and the vertical gradient of the vertical field (B_{zz}) anomalies for the Tallawang magnetite deposit.

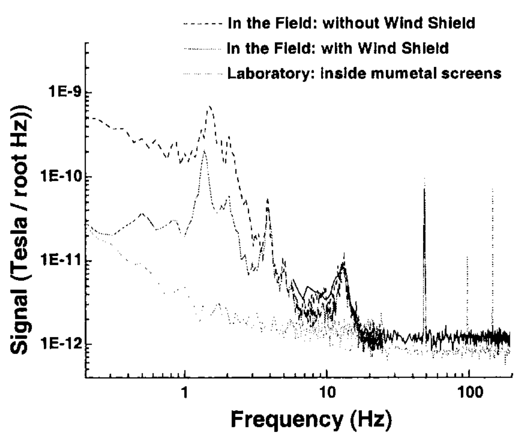

Fig. 3. Vertical magnetic field strengths measured by the lower SQUID B of a pair forming an axial gradiometer in magnetic shielding and in the field with and without wind shields.

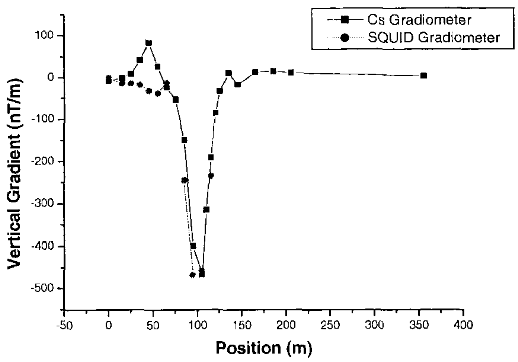

Fig. 4. Comparison of the Cs and SQUID vertical gradient data. It must be remembered that the Cs data is a total field measurement while the SQUID data is the B_{zz} vector component only. This shows there are some differences in the vector data compared to the total field data.

same position that the Cs total field data shows a maximum. The SQUID data also shows a broader minimum about the 100 m station.

IV. Discussion of the Results

The SQUID system observed a geophysical signal from a known magnetite deposit. The noise comparison of the Cs vapour gradiometer was in the range of 0.1-0.5 nT/m while the SQUID gradiometer noise was in a narrower range of 0.16-0.3 nT/m rms. The SQUID noise was lowest over the gradient maximum (100 m position) when the Cs system was experiencing its highest noise value. It was clear that the SQUID system showed less modulation due to motion within the magnetic gradient compared to the Cs system. The SQUID noise was dominated by vibration with additional contributions from the multiplexed sampling. These SQUID results are on an experimental system and we anticipate that the noise levels can be improved significantly. For the next generation system, currently under development, improvements are being made based on the understanding of the SQUID gradiometer design requirements ascertained by undertaking both the trial and the system modeling and testing.

V. Issues Relating to a Future 3 Axis Airborne SQUID Gradiometer

The noise floors of the independent rf SQUID magnetometers were of the order of 1 pT at 1 Hz, although in the final 3 axis gradiometer the use of significantly quieter SQUIDs is envisioned (up to 2 orders of magnitude improvement). CSIRO has developed a 90 fT/√Hz (1 kHz) rf system currently used in a Spinning Rock Magnetometer. Although the sensitivity of the apparatus is ultimately limited by these noise floors, this theoretical limit is difficult to realise in practice. Any relative vibrational motion of one SQUID with respect to the other, produces significant error signals which are likely to dominate over the noise floors of the individual SQUID systems. In the earth's field vibrationally induced rotation of the sensitive directions of the SQUIDs of the order of only 20 nRad will increase the noise floor of the system to around 1 pT. In the single axis gradiometer, the collinearity of the sensitive directions of the SQUIDs determines the common mode rejection performance of the overall gradiometer and hence also determines the sensitivity of the gradiometer system. It should be noted that the problem of collinearity of the SQUIDs will be reduced considerably in a full three-axis design. In this case, provided that the three-axis SQUIDs assemblies are mounted rigidly with respect to each other, the problem of non-collinearity of the sensitive directions of the SQUIDs may be removed by applying rotation matrices prior to calculating the difference data. In this trial, however, there is insufficient data to facilitate use of rotation matrices in this way.

VI. Conclusions

A successful comparison between a high-temperature SQUID (HTS) gradiometer survey and a Cs-vapour gradiometer survey has been conducted. Both instruments were configured vertically. The HTS gradiometer measured the B_{zz} component of the gradient tensor, while the Cs-vapour gradiometer measured the vertical gradient of the total magnetic intensity (TMI). The total anomalous magnetization of the test site is also close to vertical which is optimal for the comparison between the measurements of the B_{zz} gradient component and the vertical gradient of the TMI. There are some differences between these parameters. The measurements compare well with the modelling.

The HTS gradient measurement was the difference in output between two coaxial SQUID sensors. Effective noise levels achieved were 0.16-0.3 nT/m RMS, compared with 0.1-0.5 nT/m RMS for the Cs-vapour system.

The SQUID noise was dominated by vibration with additional contributions from the multiplexed sampling. This trial was an experiment and we anticipate that the SQUID system noise levels will improve significantly for the next generation system currently under development.

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