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Simultaneous geomagnetic monitoring with multiple SQUIDs and fluxgate sensors across underground laboratories

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Abstract. For two periods of several weeks duration in spring and autumn 2014, we monitored fluctuations in the geomagnetic field using 3-axis SQUID magnetometers at three locations within the LSBB tunnel network. Measurements at the water flow point C, and the GAS gallery supplemented the measurements by the permanent [SQUID]^2 system in the Capsule. The frequency spectra of the magnetic fluctuations varied considerably between the three locations. These measurements have provided a unique data set to investigate the potential of underground SQUIDs to monitor the gradient of geomagnetic signals and thus investigate magnetotelluric effects and possible seasonal effects due to changes in the water content of the surrounding rock. We also compared the measurements of a SQUID and fluxgate system, and report on fluxgate measurements at the Boulby Underground Laboratory.

1. Introduction

The sources of time-varying geomagnetic fields include electrical currents in the ionosphere and telluric currents induced in the ground. Groundwater will influence the magnetic field as the water content of rock modifies its electrical properties. The flow of water through rock may also generate a magnetic field through the electrokinetic effect. The LSBB underground laboratory is an ideal site to study these processes, as the host of the permanent 3-axis magnetometer – [SQUID]^2 (SQUID in Shielding Qualified for Ionosphere Detection); as well as a network of seismometers and groundwater flow monitors [1].

SQUIDs (Superconducting Quantum Interference Devices) are precision magnetometers using a combination of superconducting loops and Josephson Junctions to track changes in the magnetic flux through a superconducting pick-up loop at a level equivalent to $\sim 10^{-15}$ T$\cdot$ Hz$^{-1/2}$ equivalent to $\sim$0.1 pT over a typical bandwidth of interest. However they are insensitive to the absolute value of the magnetic field and the length of time for which they can track the quasi-dc field is limited by flux jumps induced by electromagnetic interference and rapidly changing magnetic fields.

The Oxford University Department of Physics has developed new hardware and software techniques to monitor magnetic field fluctuations using SQUIDs, as part of a particle physics experiment [2, 3]. In collaboration with LSBB and UAPV we conceived a project to search for the magnetic signal from groundwater flow. We carried out a long term measurement in 2012 [4, 5]. This measurement gave a null result and set a lower limit of 0.2 nT on the magnetic field generated by groundwater flow at LSBB [6].

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The measurements showed that there is a significant magnetic field gradient across the underground laboratory due to telluric currents induced in the Earth's surface by the primary ionospheric signals. This is a limiting factor when searching for a local magnetic signal, but it also highlights a new opportunity. These currents are proportional to the electrical conductivity of the surrounding rock. Short term variations in the electrical conductivity are most likely caused by changes in the water content. Therefore we can in principle probe the water content by measuring the associated magnetic signals. Such magnetotelluric measurements with our SQUID technology could potentially allow higher resolution geophysics exploration.

Magnetotellurics (MT) is an electromagnetic technique for underground exploration using the natural fluctuations in the geomagnetic field as a probe signal. By monitoring the vector components of the magnetic field and the electric field on the surface, usually by simultaneous measurements in multiple locations, the impedance tensors and hence the electrical conductivity can be determined. The frequency measured, which ranges from mHz to kHz, determines the depth which can be probed [7, 8].

MT magnetic measurements are generally done using induction coils (at higher frequencies) and fluxgate probes (at lower frequencies). SQUIDs can achieve a resolution $\sim$1000 times better than fluxgates [9] over frequencies from quasi-dc to the top of the range of interest. After some preliminary studies [10], it appears they were abandoned as MT instruments. Their ability to probe low frequency signals is limited by interference induced artefacts. These can now be corrected using software techniques. With these new data analysis techniques it may now be feasible to use SQUIDs as magnetic sensors for MT measurements.

This paper reports further measurements carried out in 2014 and gives the results of a preliminary analysis. Simultaneous measurements were taken using three SQUID systems at the CAP, GAS and C points within the LSBB laboratory. In the following sections we discuss these measurements, as well as a comparison of SQUID and fluxgate measurements at the point C, and fluxgate measurements at the Boulby Underground Laboratory in the UK.

2. Variation in geomagnetic fluctuations across the LSBB complex

Frequency spectra of the geomagnetic signals recorded at the three points are shown in Fig. 1. As expected, the fluctuations are lowest in the Capsule, where the shielding of the metal walls reduce the geomagnetic field, and measures are taken to minimise the magnetic noise from power lines and other infrastructure. The CAP spectra does show some features in the range 3–30 Hz, likely to include a contribution from artefacts and perhaps the Schumann resonances. The origin of the sharp peak at 0.16 Hz is not clear.

The GAS and C spectra are distinctly different. It is not clear why the environment is different as there is a similar height of rock above each location. The fluctuations recorded at GAS show the highest level between 0.1 and 5 Hz, above this the spectrum drops down. The C spectra shows a series of peaks at the Schumann resonances at 8, 14, 21 and 28 Hz. These are much clearer than previous reports of the Schumann resonances in data recorded by the [SQUID]^2 system [11]. It appears these resonances are attenuated by the shielding around the Capsule, but the rock above point C has minimal effect on magnetic signals at these frequencies.

To compare the amplitude of the quasi-dc fluctuations at the different locations, we used a fitting algorithm to rescale the time domain signals recorded by the [SQUID]^2 system to give the best fit to one-hour segments of data recorded at the other stations, using the procedure described in Ref. [5]. This showed the amplitude of fluctuations recorded at C

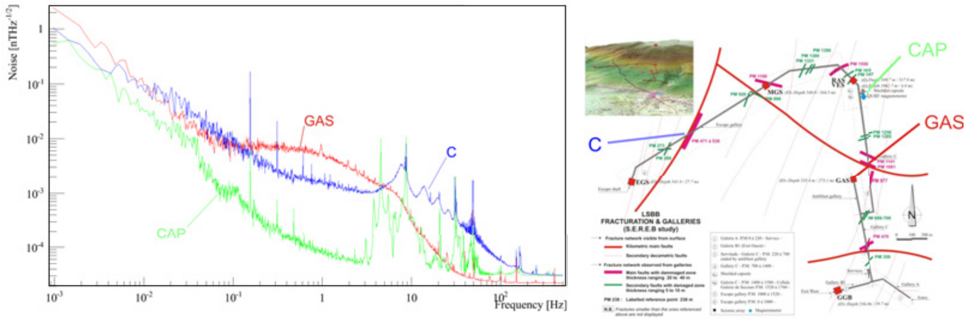


Figure 1. Left: frequency spectra of geomagnetic fluctuations recorded at different locations across the LSBB tunnel network: the shielded capsule (CAP), the GAS tunnel, and water flow point C. Right: a map of the LSBB laboratory showing the locations of the three measurement points.

Table 1. Scaling factors to convert the signal recorded by the [SQUID]^2 system to fit that recorded by the other SQUID systems.

Magnetometer and Location	Amplitude relative to [SQUID]^2
SQUID #1 C	1.57±0.16
SQUID #1 CAP	1.14±0.07
SQUID #2 GAS	1.61±0.14
SQUID #2 CAP	1.15±0.06

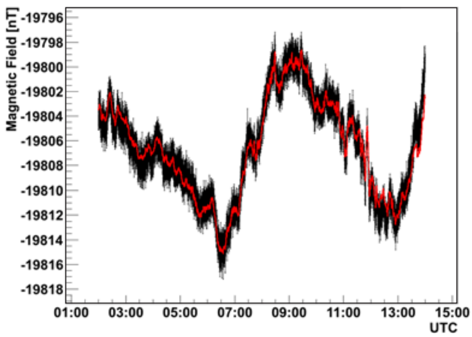
and GAS was 1.6 times that in the Capsule. When the SQUIDs used for these measurements were tested in the Capsule they recorded a 15% higher signal, which could be due to an error on the calibration, or the strong field gradients inside the metal capsule. We conclude there is no significant difference between the GAS and C, but the additional shielding at the Capsule reduced the amplitude of quasi-dc fluctuations by 40%. This is compatible with earlier measurements [4].

3. Tracking magnetic fields: SQUIDs versus fluxgates

The field at point C was monitored both with a SQUID system and a 3-axis fluxgate magnetometer. This provided an opportunity to compare the two instruments. The fluxgate sensor used was a Bartington Instrument *Mag03MSL100* low noise sensor (in April) and a *Mag661* sensor (in October). These sensors output three voltages proportional to the absolute value of the three magnetic field components. To monitor the field to the full (sub-nT) resolution, this was amplified by a factor of 100 (after subtracting the DC offset) before digitization using electronics build in-house and integrated with the SQUID readout.

Comparing the SQUID and fluxgate signals allowed us to check for drift of the fluxgate signals. It was seen that when initially turned on the signal sometimes showed some drift for the following hours, but after this, it was stable for long periods and followed the same pattern as the SQUID signal as shown in Fig. 2 (left).

Figure 2 (right) shows the frequency spectra of the signals recorded by the two sensors. The SQUIDs can achieve a reduction in the noise level typically ∼10 (depending on frequency), revealing phenomena such as the Schumann resonances. The two lines in come together at very low frequencies. For long term tracking, the fluxgates are perfectly adequate as the magnitude of geomagnetic fluctuations is much greater than the instrument noise.



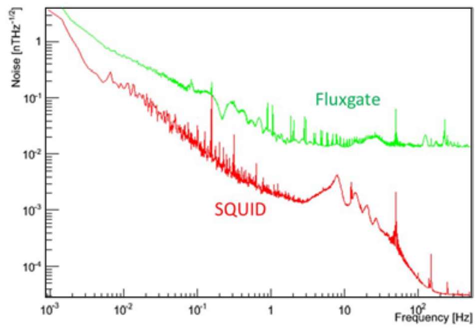
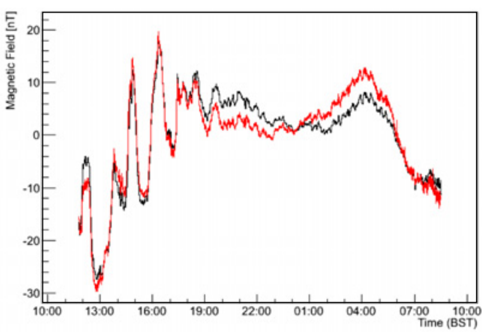


Figure 2. Left: magnetic signals recorded by the fluxgate (black line) and SQUID (red line) over a fourteen hour period. The 3-axis SQUID data has been transformed to fit this channel of the fluxgate to correct for difference in alignment of the two sensors. Right: frequency spectra of geomagnetic fluctuations recorded at point C using the SQUID (red) and fluxgate (green).



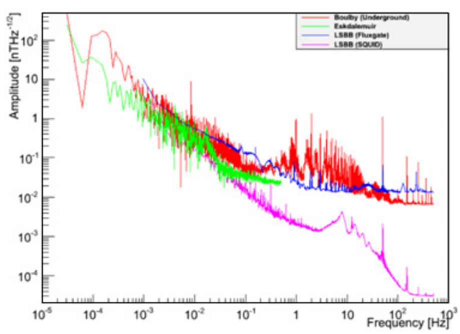


Figure 3. Left: magnetic signals recorded by fluxgate sensors at the Boulby Underground Laboratory (black line) and the INTERMAGNET data from the Eskdalemuir geomagnetic observatory, scaled to fit the Boulby data (red line). Right: frequency spectra of magnetic signals recorded at the Boulby Underground Laboratory (red), at LSBB using SQUIDs (pink) and fluxgates (blue). The data was not recorded synchronously. The spectrum of fluctuations recorded at Eskdalemuir is also shown (green).

Fluxgates have the advantage that they do not suffer from flux jumps and track the absolute field.

This study raises the possibility of combining the data sets from the two sensors. SQUID flux jumps could be more accurately identified and corrected by using the fluxgate data. Thus we could (in principle) produce a data set combining the resolution of the SQUID with the long term stability and absolute measurement provided by the fluxgate.

4. Comparisons with Boulby Underground Laboratory

The Boulby Underground Laboratory is a research facility 1.1 km underground in a potash mine in Yorkshire, England. Originally used for astroparticle physics experiments, it is now a general purpose underground laboratory.

We carried out a series of short term tests at Boulby using *Mag03MSL* fluxgate sensors to assess the suitability of the laboratory for geomagnetic measurements and the potential of magnetotelluric measurements in such a location. To our knowledge, this is the first publication of geomagnetic signals recorded in such a location.

Figure 3 shows that with this setup we could monitor the geomagnetic fluctuations to a similar resolution (although not as accurately) as the Eskdalemuir geomagnetic observatory.

We carried out simultaneous measurements on the surface with the aim of studying the attenuation of these at the underground location. Unfortunately the magnetic noise from human activities around the surface site (such as road traffic) was much greater than the geomagnetic fluctuations.

Figure 3 (right) shows the frequency spectrum of this data. The noise level recorded at Boulby is the same order of magnitude as that recorded using fluxgates at low noise locations. This suggests that Boulby is a potentially good site for geomagnetic monitoring. Further tests using a SQUID system would help assess this. Unlike LSBB, Boulby was not set up for low electromagnetic noise, therefore it may be this could be further improved.

5. Conclusions

This paper outlines the motivation for, and details of magnetic field measurements carried out using three separate SQUID magnetometers tracking geomagnetic fluctuations at different locations within the LSBB laboratory in a simultaneous operation.

We monitored the quasi-dc magnetic fluctuations at the C and GAS points and compared this to the data recorded by the [SQUID]^2 system in the capsule. Frequency spectra show that the Schumann resonances are clearly visible at point C.

These studies have demonstrated the potential of using multiple SQUID stations spread across LSBB to study magnetotelluric effects, search for local signals beneath the geomagnetic background, and investigate other phenomena.

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