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***Abstract*—The fluxgate magnetometer has long been the standard instrument of magnetic observatories due to its ease of use and sensitivity in the nanotesla range. Recently more sensitive magnetic sensors have become a requirement to study in particular the interaction between earthquakes and the ionosphere. The Superconducting QUantum Interference Device (SQUID) is capable of detecting magnetic flux in the femtotesla range and is well suited for detecting these interactions. Traditionally however, these devices have not been used to study the ionosphere due to shielding requirements. The Laboratoire Souterrain à Bas Bruit (LSBB) in France employs a low critical temperature (Low-Tc) SQUID for geomagnetic research, but it is placed in a unique low noise environment, 500 meters underground, that makes it impractical for other observatories to replicate. In this work, we implemented a completely unshielded high-Tc SQUID system at a magnetic observatory to complement fluxgate measurements. Here we discuss the implementation of the 3-axis SQUID magnetometer from an engineering perspective, including hut and rig design, placement, data acquisition, noise measurements, and possible future developments.**

***Index Terms*—geomagnetism, magnetic observatory, SQUID magnetometer, unshielded SQUIDs**

I. Introduction

FLUXGATE magnetometers are used extensively by magnetic observatories for geomagnetic measurements because they are easy to install and operate, provide very good sensitivity for most research purposes, and measure the components of the magnetic field directly [1].

Manuscript received February 28, 2013. This work was supported in part by the South African National Research Foundation, grant number 69006.

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Superconducting Quantum Interference Device (SQUID) magnetometers measure the magnetic flux, from which one can also derive the field components (unlike proton precession or optically pumped magnetometers), but have better sensitivity and lower noise levels than fluxgates. SQUID magnetometer drawbacks are cryogenic cooling, as well as measurements that are relative to a starting value, rather than absolute field strength measurements.

Solar activity influences the Earth's ionosphere, which accounts for a large part of geomagnetic field fluctuations. However, seismic activity creates pressure waves that also disturb the ionosphere and cause magnetic field fluctuations. Recently, experiments with an ultra-low noise underground (SQUID) sensor yielded interesting observations of earth-ionosphere coupling [2]. This sensor at the Laboratoire Souterrain à Bas Bruit (LSBB) near Rustrel, France, also detects aquifer oscillation in response to seismic excitation [3].

Due to these measurement results, which so far represent a single node in a near-field configuration, a French-South African collaborative project was initiated to extend the SQUID sensor system to include a second node in the Southern Hemisphere as a first step towards constructing a global instrument with interconnected nodes. In this paper, we describe the construction of a SQUID sensor node at the Space Science Directorate of the South African National Space Agency (SANSA) in Hermanus, South Africa. We also detail design choices made, and how knowledge gained from the LSBB instrument guided the design.

II. SQUID Magnetometers

SQUID magnetometers (for a review, see [4]) are very sensitive, and can measure variations in magnetic field strength perpendicular to a superconducting loop in the femtotesla range. Three-axis SQUID magnetometers, as with fluxgates, are constructed by placing three SQUID magnetometers perpendicular to one another so that the three axial directions are covered.

SQUID magnetometers have high bandwidth compared to fluxgates (from dc to the low megahertz range, limited mostly by feedback and control electronics), but have drawbacks: they have limited dynamic range, they measure field strength variations relative to a startup or reset value (and are therefore not well suited to absolute measurements), and require cryogenic cooling. Low-Tc SQUIDs are the most sensitive, but operate at 4.2 Kelvin in liquid helium, while high-Tc SQUIDs operate at 77 Kelvin in liquid nitrogen at the cost of lowered sensitivity and increased noise (by about one order of magnitude).

SQUID magnetometers and gradiometers (magnetometers with two flux pickup loops that measure the gradient of a magnetic field) find application in magnetoencephalography [5], nondestructive evaluation [6], geomagnetic prospection [7], archaeological mapping [8] and more.

Another geophysical application of SQUIDs, although long ignored due to the drawbacks of operating SQUID magnetometers in an unshielded environment, is in the long term monitoring of the geomagnetic field for the study of magneto-ionospheric and magneto-seismic interactions. The Laboratoire Souterrain à Bas Bruit (LSBB) in Rustrel, France, is at present the only facility that has explored this. LSBB houses a low-Tc 3 axis SQUID in a shielded capsule below 518 m of karstic rock and a broadband underground seismic array spread along the galleries in a unique low noise environment.

With the SQUID magnetometer, scientists at LSBB observed a link between earthquakes and disturbances in the ionosphere [2]. When an earthquake occurs, two types of seismic waves are released. P-waves oscillate radially from the point of origin, while S-waves oscillate in at right angles to the direction of propagation. P-waves are weakly coupled to the atmosphere and the ionosphere, but cause enough of a disturbance in the motion of the ions to be picked up nearly instantaneously by a SQUID thousands of kilometers away [2], [3]. Analysis of the power spectrum obtained during quiet days in terms of seismic and magnetic activities allows the identification of more than 20 normal modes in the millihertz range [9] with a deviation of less than 1% from the calculated frequencies given by the Preliminary Reference Earth Model (PREM) model [10].

III. SQUID System

For practical reasons the SQUID system to be installed at SANSA Space Science in Hermanus had to be selected before a site noise profile and hut were available. Engineering decisions were thus made, as detailed below.

A. SQUID selection

The low-Tc SQUID magnetometers at LSBB in France are low temperature devices from Star Cryoelectronics [11], of which the best have field noise characteristics below 3 fT/Hz$^{1/2}$ above 10 Hz. As shown in Fig. 1, below 1Hz, noise measured at positions of various depths inside the LSBB galeries (GAS and GGB) corresponds to the geomagnetic field contribution, which is around 1nT/Hz$^{1/2}$ at 1 mHz and drops to 1pT/Hz$^{1/2}$ at 1 Hz [12]. Above 1 Hz, until the LSBB capsule and mountain shielding starts to dominate above 40 Hz, the magnetic field noise spectral density is between 500 fT/Hz$^{1/2}$ and 1 pT/Hz$^{1/2}$.

We expected the field noise at Hermanus, which is more exposed to human and tidal disturbances, to be worse than that at the shielded facility of LSBB, which allowed us to select a

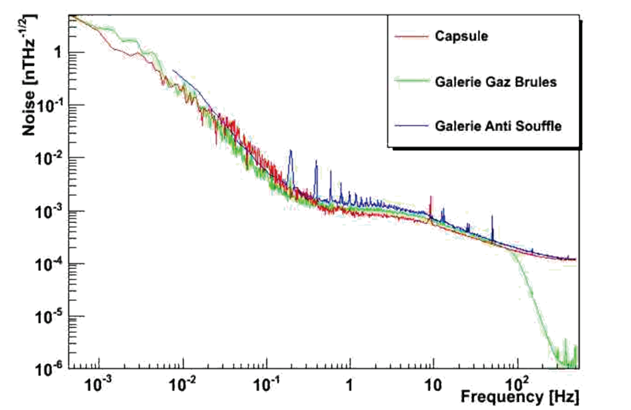

Figure 1: Magnetic noise spectral density at three different locations within LSBB.

less expensive high-Tc SQUID magnetometer. Star Cryoelectronics [11] offers the less sensitive M1000 and M2700 YBCO-based SQUID magnetometers, with field noise characteristics at 10 Hz of 100 fT/Hz$^{1/2}$ and 300 fT/Hz$^{1/2}$ respectively. Both of these are more than adequate for our purposes, and only require liquid nitrogen cooling (as opposed to liquid helium cooling for the system at LSBB). We thus opted for the low cost M2700 magnetometers for the first proof-of-concept system.

B. Cryogenic Cooling

The M2700 SQUID magnetometers operate at 77 Kelvin, which is maintained by keeping the magnetometers immersed in liquid nitrogen. Currently the cost of liquid nitrogen at Stellenbosch University, excluding transport to Hermanus, is about US$ 2 per liter. Liquid helium is more than ten times as expensive.

The Bio-34 dewar from Statebourne Cryogenics was chosen for its long rated static holding time of 189 days (at an evaporation rate of 0.18 litres/day) and because it contains only aluminium; a non-magnetic metal. The dewar has a capacity of 34 liters, and the current system setup results in 0.72 liters of evaporation per day.

The SQUIDs must remain immersed during operation and the system can thus not be operated until the dewar is empty, but only until the liquid nitrogen level drops to about 10 cm from the bottom of the dewar. With the heat introduced by the probes (causing an evaporation rate of almost a litre per day) we currently only get 28 days of continuous operation between refills. Our goal is to improve this to over 30 days with changes to the setup.

The system currently uses one cryogenic probe per sensor, with the SQUID magnetometer attached to the immersed lower end and the feedback and control electronics attached to the other end at room temperature. The neck of the dewar is capped with a plastic lid with rubber seals to prevent air leaks and heat losses through the neck or the probe inserts, while evaporated gas is vented through a 5 metre long flexible plastic hose. We thus do not expect any significant gain in liquid nitrogen holding time through improvements to the neck seals, but rather by replacing the individual cryogenic probes with a single probe that has mounting support for all three magnetometers.

The cryogenic setup is by no means perfect. In the short term a refill mechanism is needed to allow dewar refill without removing the magnetometers from the liquid nitrogen (operation is currently interrupted for a few minutes when dewars are changed). This is not only to ensure continuity of measurements, but also to prevent a degradation of the noise characteristics of the SQUIDs when they are heated. An automatic liquid nitrogen level meter is also planned, as we currently use a lowered meter ruler to probe the liquid level – a procedure that shows up as a disturbance in the measurement data. In the long term, the aluminium dewars might be replaced with all-fibreglass or glass dewars to prevent eddy currents on the dewars from influencing measurements, although we have yet to see clear evidence of eddy current interference on our data.

C. Rig

A rig (see Fig. 2) was designed to hold the SQUID magnetometers and probes securely in place inside the dewar during operation, allow lift-out during dewar exchange, smooth insertion during immersion cooling, and rotation to adjust magnetometer orientation in the *x*-*y* plane. The rig is made of non-magnetic corrosion resistant metals (we used only aluminium and brass) for sturdiness without compromising the magnetic cleanliness of the SQUID hut. The aluminium parts were anodized to increase strength, improve corrosion resistance (the sea breeze along the southern Atlantic coast of South Africa is notoriously corrosive) and to give it a non-conductive surface.

The probe-lift was designed to achieve optimal maneuverability while using minimal floor space. The probes were given 3 degrees of freedom, capable of moving up and down, rotating around the support pillar and rotating around the centre axis of the dewar to adjust orientation to true north. The rig design incorporates common manufacturing techniques and equipment, with minimal high precision dimensions. To ensure smooth operation, Vesconite self-lubricating plain bearings and Teflon washers and spacers were used at important functional interfaces.

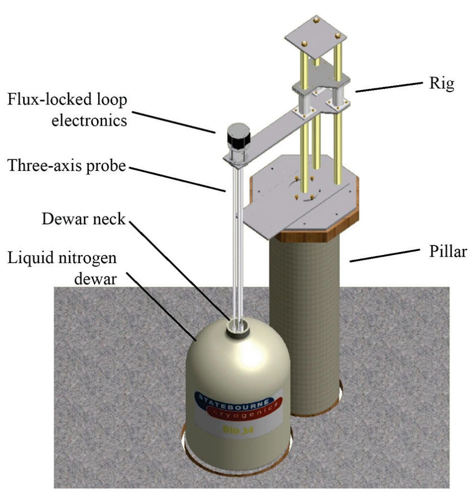

Figure 2: Illustration of rig and dewar setup.

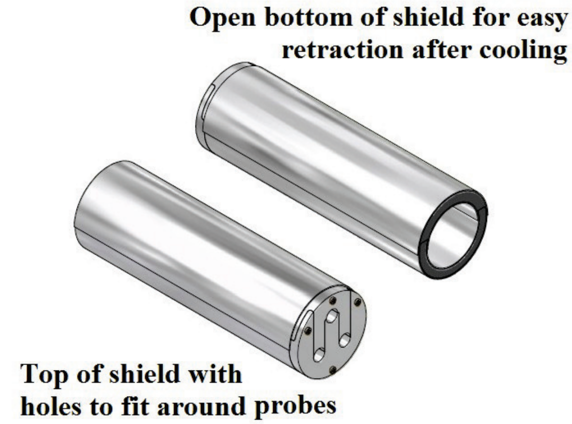

Figure 3: Double-walled mu-metal magnetic shield

D. Magnetic Shielding

As magnetometers to measure geomagnetic field, the SQUIDs must operate unshielded. However, cooling a high-Tc SQUID in a static magnetic field such as that of the Earth results in trapped flux and increased 1/*f* noise [4]. Therefore, to reduce 1/*f* noise, a magnetic shield was designed that would allow the SQUIDs to be cooled while largely shielded from the Earth's field, but can be removed after cooling to allow unshielded operation.

Shield dimensions were kept small enough to fit through the neck of the dewar through the use of high permeability CoNetic AA with μ_r > 100 000 from Magnetic Shield Corporation [13]. A double-wall cylinder was designed to improve shielding efficiency, and the shield can be retracted and disassembled from the probes and rig while the SQUIDs are cooled and in operation (see Fig. 3). The shield provides a shielding factor (at its centre) of greater than 100 in the radial direction (horizontal as mounted), and somewhat less than 100 in the axial direction (vertical as mounted). At 300 K in a shielded room, we measure less than 100 nT field strength due to remanent magnetization of the shield in all directions at the centre of the shield. In the Earth's field, we measure about 100 nT in the radial and 250 nT in the axial directions.

While this shield is largely effective, cooling it results in a large amount of boil-off of liquid nitrogen, while removing the shield during SQUID operation, even though possible, is cumbersome due to significant icing and disrupts measurements. In future, an active field cancellation system with Helmholtz coils and fluxgate as feedback will be implemented to zero the static field at the position of the SQUIDs during cool-down.

E. Hut Design

The SQUID setup is not open to the elements. A dedicated hut was built to house and shield the SQUIDs from the elements in a magnetically clean area of the SANSA Space Science facility in Hermanus.

In order to minimize vibrations of the SQUID setup due to local disturbances such as human activity, the SQUID rig is clamped to a concrete pillar and a similar pillar holds the dewar. Both pillars are built on compressed sand and decoupled from each other and from the floor and foundations of the hut. Although the SQUID hut is sufficiently decoupled from the rig and dewar pillars, there is still concern about pressure fluctuations when wind buffets the door. In the near future, a sealed, reinforced door will be investigated.

The control room, which houses the SQUID control electronics, data acquisition system and network interface is 20 metres away from the SQUID hut.

IV. Environment

A. Site Description

The SQUID magnetometer presented here has been installed at the South African National Space Agency (SANSA): Directorate Space Science , formerly known as the Hermanus Magnetic Observatory (HMO), in Hermanus, South Africa. The location was not chosen for seismic stability, low magnetic noise or the absence of human activity (all factors that contribute to the unique suitability of the LSBB site in France for SQUID magnetometry), but purely because it is an INTERMAGNET participant observatory, with calibrated 3-axis fluxgate measurements. Although the site is surrounded by small industries and in close proximity to the littoral zone of the nearby Atlantic Ocean, it comprises 16 hectares of mostly magnetically clean environment, and the town of Hermanus does not have any electrical trains. The area is close to the South Atlantic Magnetic Anomaly and has a low total geomagnetic field component (which makes ionospheric disturbances more pronounced).

B. Magnetic Noise Profile

The noise characteristics of the M2700 SQUID magnetometers were discussed in section 3.A. We measured the magnetic noise profile of the Hermanus site with the SQUID magnetometers, and results of the magnetic noise spectral density for the East-West field component are shown in Fig. 4 and Fig. 5. The data were filtered with an active filter with a fourth order Butterworth characteristic an a cutoff frequency of 10 Hz to reduce 50 Hz power line interference and remove aliasing from the 128 kHz bias reversal frequency of the SQUIDs. The sampling frequency is 125 Hz. The noise profile plots were split in two to reduce computer memory requirements. In this first, filtered test, we found a field noise of 20 nT/Hz$^{1/2}$ at 1 mHz, which decreases to 3 pT/Hz$^{1/2}$ at 10 Hz. Above 10 Hz, the filter attenuates the measurements, but with current data acquisition unit's resolution of 2 pT, quantization noise determines the measured noised floor.

The magnetic noise spectrum displays a classic 1/*f* profile. We will further investigate filtering and cut-off frequency to best minimize aliasing [14].

V. Data Acquisition and Dissemination

Accurate time stamping of measured data is required in order to compare magnetic disturbances measured at both Hermanus and LSBB for the purpose of triangulating the origin of a disturbance. To do this, a GPS receiver was added to the measurement system to obtain UTC time with accuracy better than 100 ns (RMS). LSBB also time stamps data with the aid of a GPS receiver.

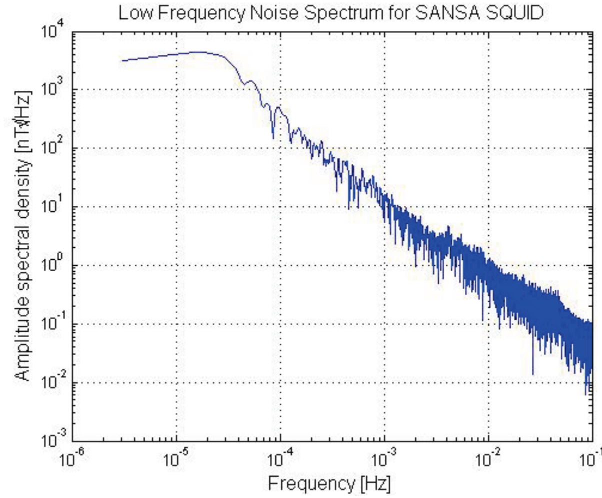

Figure 4: Low frequency magnetic noise spectral density for the East-West component at SANSA Space Science, Hermanus.

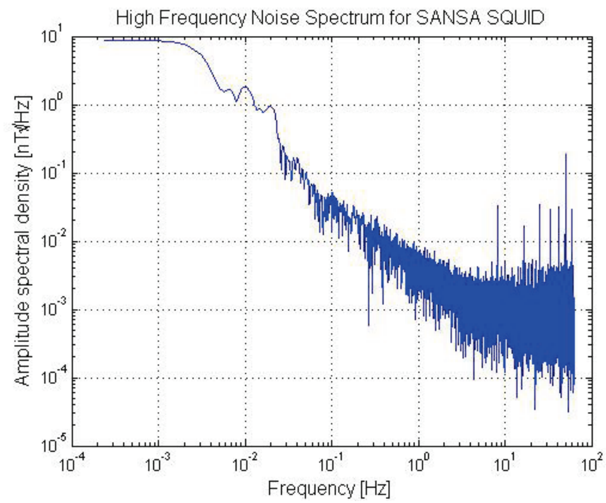

Figure 5: High frequency magnetic noise spectral density for the East-West component at SANSA Space Science, Hermanus

For three-axis measurements, the three analogue voltage outputs of the Star Cryoelectronics Programmable Feedback Loops (that control the SQUIDs) are digitized over their entire range from -10 V to 10 V. Depending on the fine tuning of the SQUID modulation parameters, we obtain a sensitivity of around 25 nT/V in high sensitivity mode, for a full-scale dynamic range of 500 nT. In order to measure the amplitude of the magnetic field strength to 5 pT (the original goal), we need a 17 bit analogue to digital converter. We therefore selected a National Instruments data acquisition unit (NI-DAQ USB-6281) with 18-bits resolution and external triggering for synchronizing with the GPS time stamping system. The DAQ can be sampled at up to 500 kHz for high frequency measurements, but currently we use a sampling rate of 125 Hz to limit the data rate. Fourth order Butterworth active analogue filters with cutoff frequencies at 50 Hz between the Programmable Feedback Loops and the DAQ remove high frequency components from the measured signals to prevent aliasing.

All measured data are stored on-site in the control room at SANSA Space Science in Hermanus, as well as on a server at the Department of Electrical and Electronic Engineering at Stellenbosch University, Stellenbosch, South Africa. The measured data are open for research purposes, and the server in Stellenbosch is directly accessible from the internet.

VI. SQUID Tests

Fig. 6 shows the observatory fluxgate data and SQUID data (*z* component, unfiltered) recorded at SANSA Space Science in Hermanus over a 60-hour period starting on the 5th February 2013. As can be seen, the SQUID data tracks the fluxgate data very well, and the Solar Quiet (SQ) variation is clearly visible. The SQUID measurements are relative to zero at cool-down, and were shifted to have the same average as the fluxgate data for this comparison. For this data set the SQUID was cooled unshielded and operated unshielded and unfiltered.

The sharp transition near the 4 hour mark in the SQUID data is caused by a jump in the SQUID output brought on by a sharp transient that the control electronics cannot follow. This is typical for SQUID magnetometers, and can be caused by human interference, lightning or a power transient in our setup. We will do more detailed experiments in future to isolate the cause of jumps, but with access to the fluxgate measurements we can simply shift the SQUID data after a jump by the amplitude offset.

VII. Conclusion

We have deployed SQUID sensors for measuring small variations in the geomagnetic field at the South African National Space Agency's Space Science Directorate in Hermanus, South Africa. This SQUID geomagnetic sensor forms the second node in a proposed global network of SQUID sensors. The site was selected because it is magnetically clean and also serves as an INTERMAGNET observatory. With engineering decisions guided by cost considerations, we managed to obtain stable and near-continuous operation (interrupted only by liquid nitrogen refills) and a very good noise profile. This enables us to add data to the LSBB measurements for correlation purposes. All measured data is open for public access (http://geomagnet.ee.sun.ac.za/). In the short term we will incrementally improve aspects such as the resolution of the data acquisition system, filter response, sampling frequency and the sensitivity of the SQUIDs. We also plan to include a seismograph in the instrument setup. In the long term, we intend to use the experience gathered in the construction of this SQUID node to deploy more isolated nodes far from human activity, such as in the vast and arid Karoo which also houses the bulk of the Square Kilometre Array and in Antarctica.

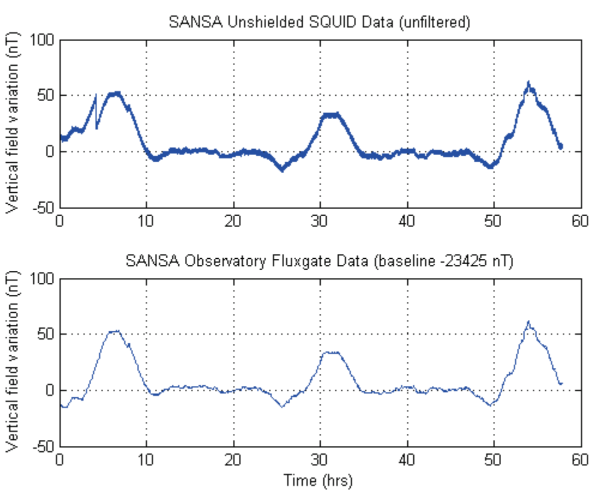

Figure 6: Comparison between SQUID and fluxgate *z*-component data during the 5-7 February 2013 period.

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