Tracking geomagnetic fluctuations to picotesla accuracy using two SQUID vector magnetometers

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SQUIDs can be used to monitor the three vector components of the geomagnetic field to a high precision at very low frequencies, yet as they are susceptible to external interference, the accuracy to which they can track changes in the dc field over long periods has been unclear. We have carried out simultaneous measurements of the geomagnetic field recorded using two independent 3-axis SQUID magnetometers at the Laboratoire Souterrain à Bas Bruit (LSBB). We demonstrate a technique to take the difference between a linear transform of the three signals from one magnetometer, and a reference signal from the other, in order to account for any difference in alignment and calibration, and track local signals at a sub-nT level. We confirmed that both systems tracked the same signal with an RMS difference as low as 56pT over a period of 72 hours. To our knowledge this is the first such demonstration of the long term accuracy of SQUID magnetometers for monitoring geomagnetic fields.

I. INTRODUCTION

The monitoring of the Earth's magnetic field to a high precision is essential to achieve a full understanding of our planet, the ionosphere, and space weather.[1,2] This has important practical implications to better understand the risks associated with magnetic storms.[3,4] The potential for using SQUIDs for geomagnetic measurements was recognized early on[5], and they are routinely used for airborne magnetic surveys[6] and transient electromagnetic surveys[7].

The absolute value of the scalar magnetic field can be monitored to sub picotesla accuracy using atomic magnetometers, and such instruments have surpassed the performance of SQUIDs in many applications.[8] However measuring the three components of the magnetic field vector requires other sensors. Magnetic induction coils can make high precision measurements at higher frequencies, but, as these are only sensitive to the rate of change of magnetic field, at the low frequencies (below 1Hz) of particular interest to geomagnetic studies, performance is reduced, and to obtain a high sensitivity, coils must be very large.[9]

Fluxgates are the usual instruments for monitoring of the vector magnetic field by geomagnetic observatories.[1,10] There is now considerable interest in the use of the SQUID sensors to reach a much better resolution.[11] A possible future scenario could see geomagnetic observatories using a combination of an optical magnetometer (for absolute scalar measurements), and a three axis SQUID system to track changes in the vector components to picotesla precision.

The [SQUID]^2 system (SQUID in Shielding QUalified for Ionosphere Detection) is a permanent 3-axis SQUID system monitoring the field at LSBB, in order to study (for example) ultra-low frequency signals,[12,13] magnetic storms, transient luminous events,[14] and magnetic signals induced by seismic waves.[15,16]

The Laboratoire Souterrain à Bas Bruit is an ideal location to monitor magnetic field fluctuations. The [SQUID]^2 system is located in the LSBB Capsule – a former command center for the French ground based nuclear missile system. This is shielded by 2cm steel, 2m reinforced concrete, and over 518m of rock.[17] The room is supported by shock absorbers. The magnetometer is in continuous operation and the open access data is available from the LSBB server.[18]

SQUIDs can monitor magnetic field changes to a precision of <0.1pT.[19] They are not sensitive to the absolute magnetic field, but only track changes in the magnetic flux. To give a linear response over a wide dynamic range, they are operated in a flux-locked-loop, applying a feedback signal to stabilize their operating point. This makes the SQUID response linear over a very large range.[21]

If the external field changes faster than the slew rate of the feedback loop, the output will apparently jump by an integer number of flux quanta. These flux-jumps can also be triggered by external interference. Isolated flux jumps can be corrected by software,[19,20] but a series of jumps in quick succession will cause the system to lose track of the field. RF electromagnetic interference can also be demodulated by the SQUID causing the signal to drift.[21]

This limitation together with the need to cool to low temperatures, has restricted their application.[22-23]

These effects have the potential to limit the accuracy of a SQUID signal over long periods. Uncorrected flux jumps or other interference induced effects could throw the signal off track. The signal produced by an abrupt change in the magnetic field is sometimes indistinguishable from an artifact produced by a flux jump, and may be erroneously 'corrected' by software. Therefore to be sure that the signal recorded by a SQUID magnetometer is an accurate record of the drift in the magnetic field, this should be confirmed using a second instrument.

We believe in quiet conditions in the low noise environment at LSBB, the [SQUID]^2 system can accurately track magnetic field fluctuations at the sub-nT level, but until now this has not be confirmed by an independent magnetometer. In this study we have used a second system, temporarily installed in the LSBB Capsule with [SQUID]^2, to show that the SQUIDs can accurately track field changes over a period of 72 hours. Thus we demonstrate their potential in a suitable environment as a high precision instrument for geomagnetic monitoring.

The Oxford precision measurements group have developed a very similar SQUID system[19] to monitor magnetic fields in the cryoEDM neutron electric dipole moment (EDM) experiment.[24-26] The requirement here is to track any drift in the magnetic field between measurements of the neutron Larmor precession frequency, which could mimic an EDM signal.[27] Thus the technical challenge – using SQUIDs to accurately track changes in the quasi-static field – is the same as that faced by geomagnetic studies. In July 2011 we adapted this system to take measurements at LSBB. By monitoring the same signal with two separate systems, developed independently, we can confirm that in this environment both systems accurately track the external field and are not disrupted by flux jumps or other artifacts.

The cryoEDM magnetometer is required to measure the average magnetic field in a shielded environment to ~0.1pT precision over a ~130s neutron measurement period, and track any drift between measurements with different applied electric fields. The absolute magnetic field will be determined from the neutron precession frequency in zero electric field, and the SQUIDs used to track changes during EDM measurements. The system must be able to track changes over periods of several hours or longer. If the magnetometer loses track due to an interference burst, then it will be necessary to repeat an absolute field measurement, with a loss in EDM measurement time. We believe that the cryoEDM system will meet this requirement, but until now we have not monitored its long term accuracy using an independent magnetometer.

The Oxford SQUID system used at LSBB was a 3-axis magnetometer, consisting of Supracon SQUIDs connected to Nb wire pick-up loops. The readout electronics was a STAR-cryoelectronics PFL-800 preamplifier, connected directly to a control and 1kHz multichannel recorder developed in-house. This was connected to a PC using an optical link to minimize electromagnetic interference.

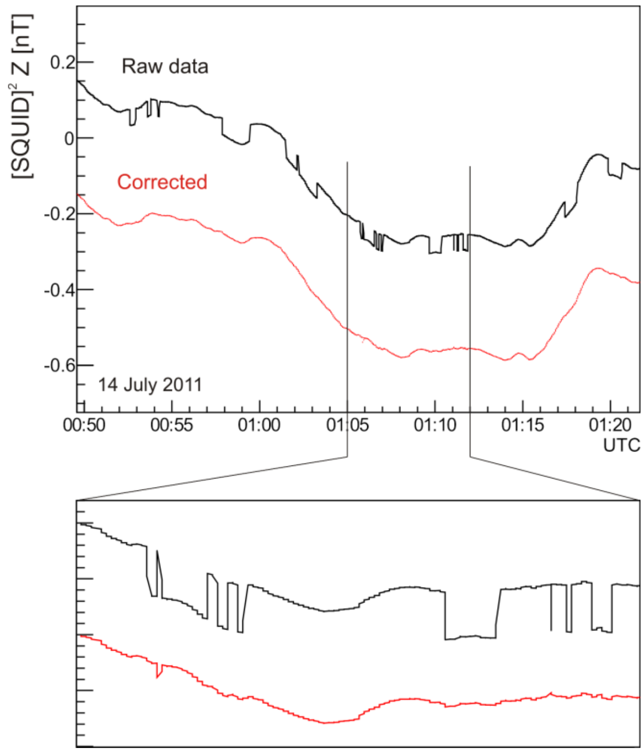

FIG. 1. The [SQUID]^2 Z signal over a 30 minute period showing the burst noise which was corrected by software. The lines have been offset for clarity.

II. DATA CORRECTION, CALIBRATION AND ANALYSIS

A. Data acquisition and jump correction

The two SQUID systems output a voltage as a function of time proportional to the magnetic field along each of the three axes, with an arbitrary offset. The first step in the analysis is to convert this to data sets giving the magnetic field. The [SQUID]^2 system uses an Agecodagis Kephren digitizer to record the output voltage to 32-bit resolution (9.3nV) over the full range (±20V)[28] (in the future this may be done using a digital SQUID system[29]). The output voltage is simply multiplied by a calibration factor to give a data point in nT. Close analysis of the data for the Z channel revealed a number of small (~0.04nT), abrupt jumps between two levels as shown in Fig. 1. This shows random switching between two separate flux levels, but the magnitude is too small to be explained by flux quantum jumps. This could be due to the hopping of superconducting vortices in the pick-up loops, or superconducting material close to the SQUIDs, as discussed as a source of 1/f noise in ref 21 (pages 201-208), and ref 30, or a similar effect. In this analysis these jumps were removed using a software algorithm. As this effect has only a minimal effect on the long term average, the correction had only a small impact on the results given in Table I, but it greatly improved the clarity of the plot in Fig. 2. No such correction was needed for the other channels.

The Oxford system used a 16-bit ADC. In order to monitor the field at full resolution, it was necessary to restrict the range. Therefore whenever the output voltage reached the range limits (±10V) it would reset the feedback loop, so the output would jump an integer number of flux quanta to bring it back to ~0V. These resets were detected and corrected during the analysis (as described in Ref. 17,18). The intrinsic noise of the SQUID has been measured as $2.6 \mathrm{fT \cdot Hz^{-1/2}}$ above 1Hz and $\left(3.2/\sqrt{f}\right) \mathrm{fT \cdot Hz^{-1/2}}$ below this.[19]

The $[\mathrm{SQUID}]^2$ data is recorded at 500Hz, and the Oxford system runs at 1kHz. The magnetic shielding provided by the Capsule attenuates any signals above 40Hz to below $3 \mathrm{fTHz^{-1/2}}$, allowing the study of magnetic signals in this range, without interference by high-frequency noise.

B. Calibration

The calibration of the Oxford system (to determine the V/nT conversion factor) was done in a magnetically shielded cryostat at Oxford using the procedure as described in Ref. 19. A calibration coil consisting of 200 turns on a 1mm diameter former was used to generate a magnetic field step of known magnitude. The magnetic flux change through each pick-up loop was calculated by modeling the coil as a magnetic dipole and numerically integrating the field across the area of each loop. The calibration measurements were repeated with the coil in four different positions relate to the loop. As a cross check, one channel was also calibrated using a Helmholtz coil mounted inside the cryostat; this gave a factor 18% less than that measured with the calibration coil. We take this as a measure of the absolute accuracy of the calibration, which is limited by the precision of the coil construction and the distortion of the field by the cryoperm shield around each SQUID.

The calibration of the $[\mathrm{SQUID}]^2$ system was normalized to the Oxford system using the scaling procedure explained in section II C. To confirm that the amplitude of the magnetic field fluctuations at the location of both magnetometers is the same, we carried out a separate measurement at a later date in which both systems were calibrated using a signal generated by a 0.9m diameter external coil. The field at the location of each pick-up loop was calculated using the Biot-Savart law. Both SQUIDs were then shown to track the same ionospheric fluctuations, within 12% - the expected accuracy of the calibration.

C. Transformation of magnetometry data

Taking the difference between the signals measured by each SQUID system could not be done by simply taking X_1 minus X_2, as this would be dominated by a number of systematic effects:

- The accuracy of the calibration of each system (see section II B)
- The relative alignment of the two systems. The axes were aligned, X=North-South, Y=East-West, Z=Vertical. We aimed to align the two systems in the same way, but some misalignment, especially for the horizontal axes is inevitable.
- The pick-up loops are not perfectly flat, so will pick-up a small contribution from the field component perpendicular to their axis.
- The magnetic field may be distorted by nearby material such as the cryoperm shield around the SQUID sensors.

These effects are all small, but due to the high sensitivity of the SQUIDs, significant. Fortunately, they can be corrected for (to first order), by applying a linear transformation to one data set to give the best fit to that measured at the same time by the other system. So, if the three signals measured by the $[\mathrm{SQUID}]^2$ system are given by X_{sq2}, Y_{sq2}, Z_{sq2}; and those measured by the Oxford system are given by X_{ox}, Y_{ox}, and Z_{ox}, then we can rescale the $[\mathrm{SQUID}]^2$ data to give the best fit to Oxford X-component as follows:

$$X'_{sq2} = AX_{sq2} + BY_{sq2} + CZ_{sq2} + D \qquad (1)$$

Where A, B, C and D are constants, calculated to minimize:

$$\sum_{\text{All data points}} \left(X'_{sq2} - X_{ox}\right)^2 \qquad (2)$$

It can be shown that this is given by:

$$\begin{pmatrix} A \\ B \\ C \\ D \end{pmatrix} = \begin{pmatrix} \sum X_{sq2}^2 & \sum X_{sq2}Y_{sq2} & \sum X_{sq2}Z_{sq2} & \sum X_{sq2} \\ \sum X_{sq2}Y_{sq2} & \sum Y_{sq2}^2 & \sum Y_{sq2}Z_{sq2} & \sum Y_{sq2} \\ \sum X_{sq2}Z_{sq2} & \sum Y_{sq2}Z_{sq2} & \sum Z_{sq2}^2 & \sum Z_{sq2} \\ \sum X_{sq2} & \sum Y_{sq2} & \sum Z_{sq2} & N \end{pmatrix}^{-1} \begin{pmatrix} \sum X_{ox}X_{sq2} \\ \sum X_{ox}Y_{sq2} \\ \sum X_{ox}Z_{sq2} \\ \sum X_{ox} \end{pmatrix} \qquad (3)$$

Where the summations are over *N* data points. For two well aligned systems measuring the same magnetic field, we expect A~1, B~0 and C~0. D takes account of the arbitrary offset between two signals (as SQUIDs do not measure the absolute magnetic field, but only the relative drift). This transformation method is similar to that reported in ref 31.

III. MAGNETOMETRY MEASUREMENTS INSIDE THE LSBB CAPSULE

Fig. 2 shows a measurement taken over 72 hours during a quiet period when there was no activity inside the laboratory. The RMS difference between the transformed and reference signal over this 72 hour period is 56pT (NS), 114pT (EW) and 110pT (Z). The RMS difference increases with the total measurement time; over shorter periods, it is much lower as shown in Table I. The correlation of the signals is a strong confirmation that both magnetometers accurately track magnetic field changes at this sensitivity for long periods.

Table II gives the transformation parameters which gave the best fit of the Oxford data to the $[SQUID]^2$ signal using the procedure described in section II C, for the 72 hour measurement plotted in Fig. 2. The calibration of the $[SQUID]^2$ system has been normalized such that $A^2+B^2+C^2=1$. We can estimate the angles between the axes by taking the arccosine of A, B and C. This suggests the angle between the two vertical axes is ~4° and slightly greater for the horizontal axes. This interpretation neglects the small calibration differences between channels.

From the intrinsic noise level of the SQUIDs alone we would expect a much lower RMS difference.[19] The small measured difference between the two signals is much larger than that expected due to the nonlinearity of the SQUIDs.[21] Temperature drift of the readout electronics is a possible cause, but the magnitude is larger than we would expect. The temperature in the underground tunnel did not vary significantly over the 72 hour period and the $[SQUID]^2$ electronics is housed in a temperature controlled enclosure.

The difference can be explained by a number of effects: a tiny movement of the dipstick supporting the SQUID pick-up loops, producing a change in the flux through the loops due to the static field; tiny movements of nearby ferromagnetic objects, such as the steel door to the Capsule; and the gradient of the field fluctuations over the short distance between the two magnetometers. As the dominant fluctuations are produced in the ionosphere ~100km away,[1,2] we would not expect a significant gradient in this field over this distance. The steel walls of the Capsule may distort this to produce a gradient over the small distance between the two magnetometers, but the time varying signals measured at the two positions will be proportional to one another (to first order), therefore this will be corrected by the transformation described in section II C. Secondary currents induced in the rock or the Capsule walls could give small effect.[1,32]

This method could in principle be applied to use two SQUID magnetometers as a gradiometer to subtract the dominant magnetic field fluctuations, and detect a local magnetic signal, such as that produced by the flow of water underground[33], or earthquake precursory phenomena. [34,35] It could also be used to study the currents induced within the Earth's crust by ionospheric currents.[32] The values in Table I give a measure of the sensitivity of this technique for measuring weak magnetic signals against the background field fluctuations inside the LSBB Capsule.

TABLE I. RMS difference between the transformed $[SQUID]^2$ data and the Oxford signal for the three channels. These values are the mean of the RMS difference for periods of the given duration within the 72 hour measurement shown in Fig. 2.

Duration of fit period [h]	X [pT]	Y [pT]	Z [pT]
72	56	144	110
24	54	60	41
8	41	44	25
1	28	28	18

TABLE II. Top: the scaling parameters which give the best fit of the three signals recorded by the $[SQUID]^2$ magnetometer, to a single signal recorded by the Oxford system, as described in section II C. Bottom: the angles between the axes of each magnetometer, determined from the arccosine of the scaling parameters.

Field component	Transformation parameters		
	A	B	C
X (NS)	0.973	-0.220	-0.068
Y (EW)	0.122	0.993	-0.008
Z (Vertical)	-0.043	-0.049	0.998

Field component	Angle [degrees]		
	acos(A)	acos(B)	acos(C)
X (NS)	13.3	102.7	93.9
Y (EW)	83.0	6.78	94.6
Z (Vertical)	92.5	92.8	3.62

IV. CONCLUSIONS

In this paper we present a comparison of the magnetic field signals recorded by two separate SQUID magnetometers. We have shown that the two systems track the same signal at a level of 56pT over 72 hours. This shows that in a suitable environment SQUIDs can accurately track changes in the geomagnetic field. Thus, we are confident the $[SQUID]^2$ system can be used to analyze geomagnetic signals over periods of this length; and the Oxford system can be used to track the magnetic field fluctuations in the cryoEDM experiment over long periods.

We have demonstrated a technique to transform the data from one magnetometer to allow a comparison with a second, accounting for the calibration differences, alignment, and local field distortion. This has many potential applications as a way to measure a weak local magnetic signal against a much larger background, such as that from ionospheric currents.

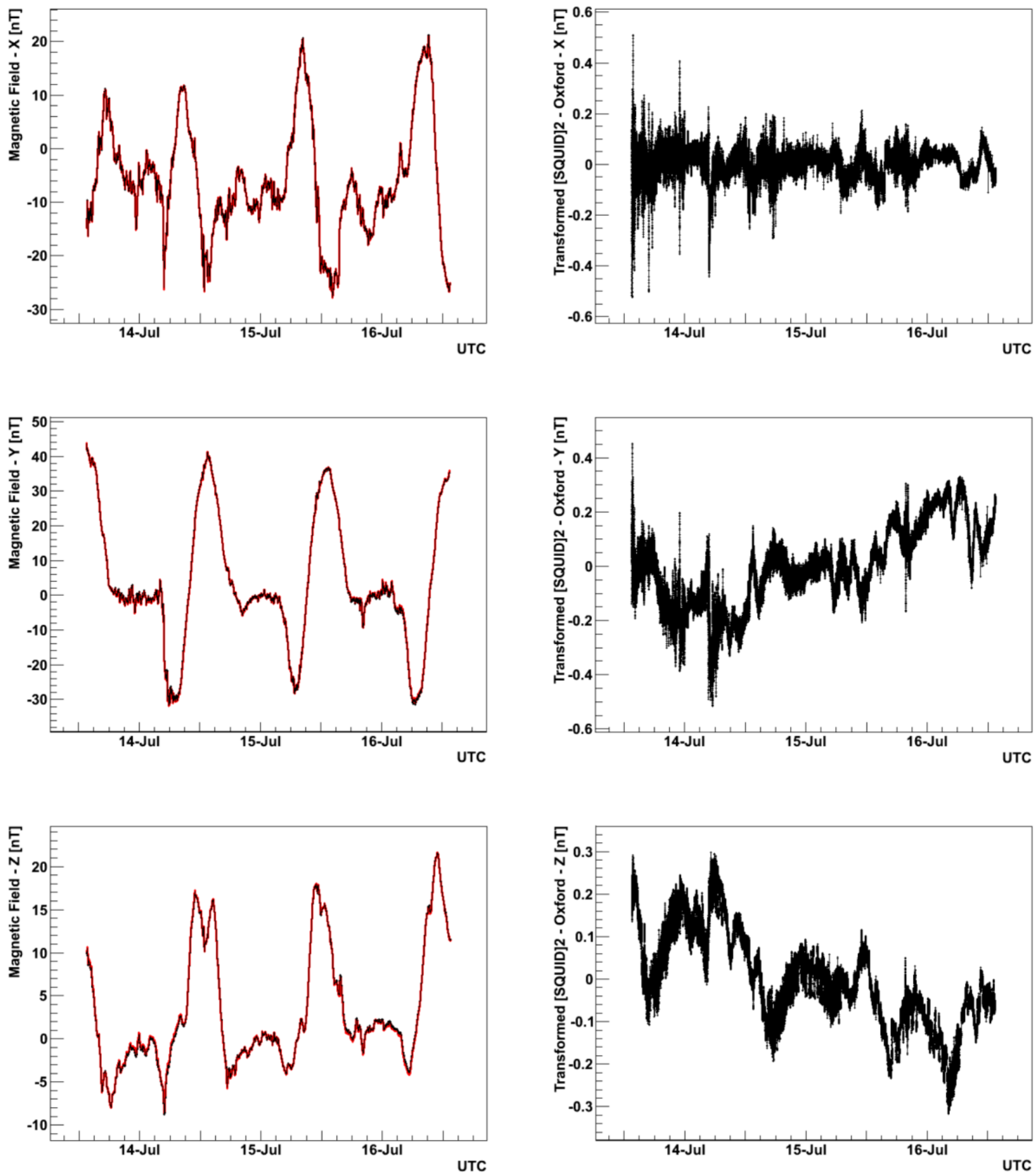

FIG 2. Magnetometry signals recorded in the LSBB Capsule (Top: NS, middle: EW, bottom: Z) over a 72 hour period during a public holiday in 2011, when there was no activity in the laboratory. The left hand plot shows the field measured by the Oxford system (in black); and the signal from $[SQUID]^2$ system after the linear transform (in red). The two lines overlap almost perfectly. The right hand plot shows the difference between the two lines.

ACKNOWLEDGEMENTS

This project has been possible thanks to the generous support of INRA-UAPV-EMMAH; the platform for fundamental and applied interdisciplinary research, LSBB, University of Nice, University of Avignon, CNRS, http://www.lsbb.eu; as well as Hertford College, Oxford; and the Science and Technology Facilities Council (through the cryoEDM experiment). We would like to thank all the staff at LSBB for their assistance, and Prof. Hans Kraus (Oxford) who designed the data acquisition hardware and software.

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