Correlation between fluxgate and SQUID data for space weather events

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Abstract. The Superconducting QUantum Interference Devices (SQUIDs), are fairly recent types of magnetometers, that use flux quantization combined with Josephson tunneling to detect very faint ($< 10^{-15}T$) magnetic fields. A correlative study between SQUID and Fluxgate data-sets was conducted during 2012, at SANSA Space Science, with the aim of validating the use of SQUID as a reliable instrument for Space Weather observations. In this study, SQUID data, obtained from the Low Noise Laboratory (LSBB) in France was compared to fluxgate data sets from three closest observatories to LSBB; all further than 500 km from LSBB. As a follow-up study, our aim is to correlate SANSA Space Science SQUID data recorded at Hermanus, Western Cape, with fluxgate data obtained on-site in Hermanus. The LSBB SQUID, which was used in the previous study, is a low-Tc 3-axis (XYZ) device and it is shielded from most human interference. The SQUID magnetometer operated at Hermanus for the duration of this study is a high-Tc two-axis (XZ) device and is completely unshielded. The advantage of the current study is that the SQUIDs are operated within 50m from the observatory fluxgates, thus we expect a far better correlation than what was obtained in the previous study. This should improve the isolation of signals detected by the SQUID over and above those detected by the fluxgates.

1. Introduction

Space weather is a study of the interaction between the Sun-Earth system and the effects it has on technology (space and ground based) and society (human health) [1]. The understanding and future predictions of different events, like geomagnetic storms, associated with this Sun-Earth interaction form the basis of space weather. Over the years magnetic observations have produced rich information to better our space weather understanding and helped in developing models that predict future space weather events, by monitoring the geomagnetic field variations using magnetometers. These observations are mainly done by fluxgate magnetometers [2], which measure the absolute strength and the direction of the magnetic field. Since fluxgate magnetometers have been successfully used for space weather research for many years, a comparative study between new magnetometers and fluxgates can be sufficient to validate the use of a given magnetometer in space weather research.

Such a study was conducted at South African National Space Agency (SANSA) Space Science in Hermanus, Western Cape, in 2012 [3]. A comparative study between fluxgate and SQUID magnetometers was performed to validate the use of SQUID magnetometers for space weather research, using data for geomagnetic storms during 2011. The study was performed using SQUID data acquired from a unique Low Noise Underground Laboratory, Laboratoire Souterrain á Bas Bruit (LSBB) in France, correlated to fluxgate data-sets from the three closest magnetic observatories, namely: Chambon la Forêt (France), Ebro (Spain) and Fürstenfeldbruck (Germany). The use of SQUID magnetometers for space weather research was successfully validated, with the SQUID and fluxgate measurements exhibiting good correlation. At the very least the correlation of peaks in amplitude spectral density between the SQUID data and that of the fluxgate measurements was 59%. With the fluxgates used for this study all being more than 500 km away from the SQUID, the correlation was not as high as it would be if the fluxgate and SQUID were located in the same location, as geomagnetic field is position dependent.

This paper present a follow-up study of the aforementioned study. In our study, the correlation was done between SQUID and fluxgate data-sets both obtained from the South African National Space Agency (SANSA) Space Science in Hermanus (South Africa), where SQUID and fluxgate magnetometers operated within 50 m from each other. The SQUID used in the previous study is a 3-axis low-T_c SQUID operated in liquid helium (4.2 K) in a low noise underground laboratory shielded from most human disturbances [4]. The SANSA SQUID is a 2-axis (for this study) high-T_c SQUID operated in a liquid nitrogen (77 K), completely unshielded in the field of about 26 μT. The environment is magnetically clean to observatory standards, but experiences more human interference than that at LSBB. The high-Tc SQUIDs also experience $1/f$ noise at low frequencies which the low-Tc SQUIDs do not suffer from [5]. Cooling the SQUID magnetometer in a virtually zero ambient fields significantly reduce $1/f$ noise [6], however, the system to create a zero-field for colling is still under development [7] for the SANSA SQUID. Since the SQUID and fluxgate used for this study are in such close proximity (within 50 m), we expect correlation to be better than what was obtained in the previous study. This improved correlation should aid in better isolating signals detected by SQUID magnetometer over and above those detected by the fluxgate.

2. Materials

Data used for this study, as mentioned above, was obtained from the SQUID and the fluxgate magnetometers both located at the South African National Space Agency (SANSA) Space Science, formerly known as the Hermanus Magnetic Observatory (HMO). The observatory is part of the world-wide network of magnetic observatories: International Real-time Magnetic Observatory Network (INTERMAGNET). SANSA is situated in the small coastal town of Hermanus, and is in close proximity to the Atlantic Ocean and a small industrial area. However, the SANSA facility is magnetically clean to magnetic observatory standards.

2.1. Fluxgate

The Fluxgate magnetometer is located in a magnetically clean hut within 50 m meters from the SQUID magnetometer, thus they virtually measure the same field. This FGE fluxgate magnetometer was manufactured by the Danish Meteorological Institute, in Denmark. It is a 3-axis magnetometer, with a band-width ranging from DC to 1 Hz, monitoring the HDZ geomagnetic components. The x-component can be mathematically derived from the H- and D-components as [8],

$$X = H\cos(D). \tag{1}$$

The fluxgate records data every second, with the data sampled every 5 seconds. A numerical filter is then applied to produce 1 minute data according to INTERMAGNET specifications. SANSA fluxgate data are available at (`http://intermagnet.org/`).

2.2. SQUID

The SQUID at SANSA is a high-T_c M2700 SQUID magnetometer from Star Cryoelectronics, with field noise characteristics of 300 fT/$\sqrt{\text{Hz}}$ at 10 Hz (calibarated field noise is 186 fT/$\sqrt{\text{Hz}}$ at 10 Hz for the x axis, and 168 fT/$\sqrt{\text{Hz}}$ at 10 Hz for the z axis). The SQUID is operated at 77 K with the SQUID sensors immersed in liquid nitrogen contained in a non-magnetic dewar, as shown in Figure 1. The SQUID sensors are held by a non-magnetic rig which is used to lift the sensors in and out of the dewar during liquid nitrogen refills and to orientate the sensor in the $x - y$ plane. The dewar and the rig are both clamped to concrete pillars which are built on compressed sand and decoupled from each other, to minimize vibrations due to local disturbances. The SQUID is housed in a non-magnetic hut, with its floor and foundations also decoupled from the SQUID's dewar and rig pillars. For this study, the SQUID magnetometer was set up to measure only the x and z geomagnetic components. The magnetic field strength in Hermanus is about 23.6 μT in the vertical direction and 9.6 μT in the horizontal direction (x component). For further information about the SANSA SQUID refer to [7].

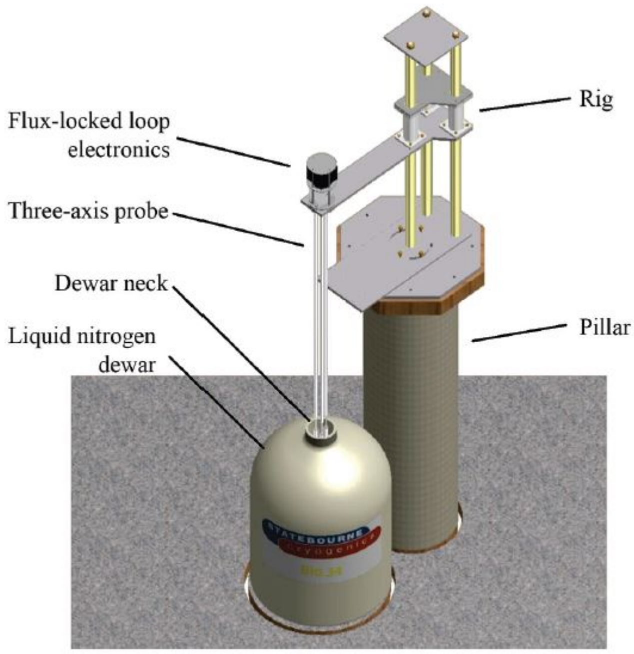

Figure 1. Schematic of SQUID dewar and rig (Image: courtesy of [7])

2.3. SQUID calibration

Currently the SANSA SQUID is set up to measure magnetic variations in the geographical north to south direction (geomagnetic x component) and in the vertical downward direction (geomagnetic z component). The SQUID sensor measuring the geomagnetic z component is set up to be vertically aligned in the mechanical rig, but the x component SQUID must be orientated to align it with the geomagnetic x component. To align the SQUID sensor with the geomagnetic x component, fluxgate data is used to determine the declination D, which is the angle between the geomagnetic h and x components, and using a very accurate magnetic compass (B3 Landing compass with an accuracy of 0.1 degrees); the SQUID sensor is orientated from magnetic to true North by D.

2.4. SQUID data acquisition
The voltage output of SQUID sensors are recorded using a National Instruments data acquisition unit (NI-DAQ USB-6281) with 18 bit analogue to digital converters and external triggering for synchronizing with the GPS time stamping system [7]. The DAQ is currently sampled at 125 Hz, but for high frequency measurements it can be sampled up to 500 kHz. To prevent aliasing from high frequency components, the SQUID sensor outputs are filtered by fourth order Butterworth active analogue filters with cutoff frequencies at 50 Hz, before being fed to the DAQ. With this data acquisition system, the SANSA SQUID setup can currently measure the amplitude of the field strength as low as 5 pT. SQUID data are stored on-site in a control room at SANSA Space Science and are also open for research purposes on a server at the Department of Electrical and Electronic Engineering at Stellenbosch University. The server is accessed via (`http://geomagnet.ee.sun.ac.za/`).

3. Methods
The correlation was done both in the *time domain* and the *frequency domain.* For the frequency-domain correlation, the spectra of both the SQUID and Fluxgate data sets were obtained using Fast Fourier Transforms (FFTs). FFTs are a computationally faster version of Discrete Fourier Transforms (DFTs). Given a discrete data-set, $\{x_n\}$, in the time-domain, its spectrum, $\{X_k\}$, can be obtained using a DFT algorithm [9],

$$X_k = \sum_{n=0}^{N-1} x_n e^{-j2\pi kn/N}, \quad k = 1, 2, \ldots, N, \tag{2}$$

where $j = \sqrt{-1}$ and k represents discrete instances in frequency. The highest frequency, f_{max}, the can be observed without *aliasing* is given by

$$f_{max} < \frac{1}{2\,\triangle} = f_N, \tag{3}$$

where $\triangle$ is the sampling frequency and f_N is the *Nyquist frequency.* Aliasing is the effect of high frequency components in a Fourier spectrum to appear as ghost (spurious) frequency components at a low frequency part of the spectrum. The Nyquist frequency is the highest frequency component that can be observed in data sampled at $\triangle$ intervals, without any aliasing. There are different types of Fourier spectra that can be computed to obtain the desired information from a given data-set. In this case, an *Amplitude Spectral Density* (ASD) was computed to obtain frequency components with their equivalent amplitudes, contained in the both the SQUID and fluxgate data-sets. The ASD is given by,

$$|X_k| \times \sqrt{T}, \tag{4}$$

where T is the time interval, and the ASD has units of [nT/$\sqrt{\text{Hz}}$].

4. Data Analysis
The data used for this study was recorded on the 25th of May 2013, which was a geomagnetically disturbed day with the K index recored at Hermanus reaching values as high as 5. The fluxgate and SQUID data-sets were both compared in the time-domain and frequency domain. For the correlation in the time domain, the SQUID data had to be down-sampled from 125 Hz to match the sampling rate of the fluxgate data - 1/60 Hz - , using the MATLAB function *decimate.* Decimate filters data with a Chebyshev low-pass filter before re-sampling it to achieved the desired sampling rate (lower). As seen from Figure 2, the time domain signals from the x and z components of the SQUID and fluxgate had a very good correlation, with the correlation of the

x at 99.78% and the z components at 99.99%. In the frequency domain, the frequency range at which the SQUID and fluxgate data-sets could be compared, was limited by two factors. Since the sampling rate of the fluxgate data is 60 seconds, the fluxgate Nyquist frequency is 8.3 mHz. Due to the fluxgate Nyquist frequency and high $1/f$ noise below 1 mHz on the SQUID, the SQUID and fluxgate spectra were correlated from 1 mHz to 8 mHz. This frequency range is of most interest in Space weather as resonances in this range are often due to Earth- Ionosphere-Magnetosphere coupling [10].

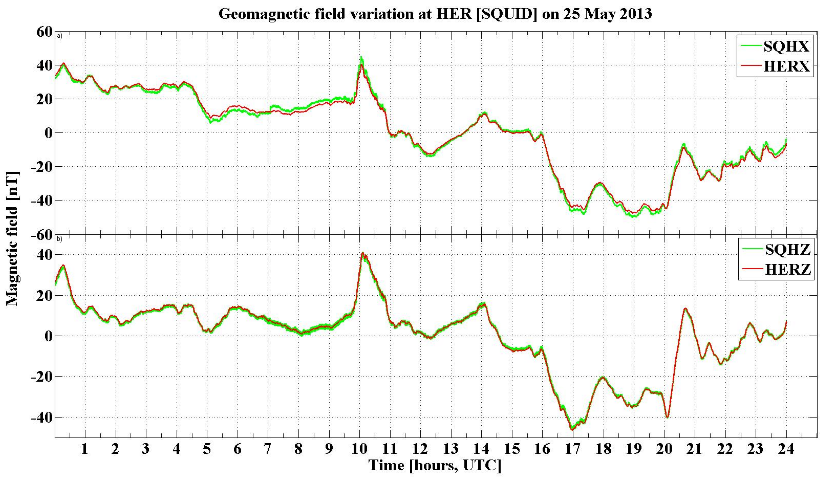

Figure 2. SQUID x (SQHX) and z (SQHZ) channels, plotted with their corresponding fluxgate x (HERX) and z (HERZ) channels for calculation of the correlation of SQUID and fluxgate data-sets in the time domain.

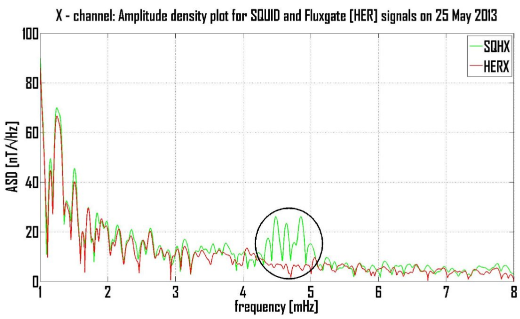

Figure 3. SQUID and Fluxgate x-channels spectra compared to check for correlation of frequency components contained in fluxgate and SQUID data-sets.

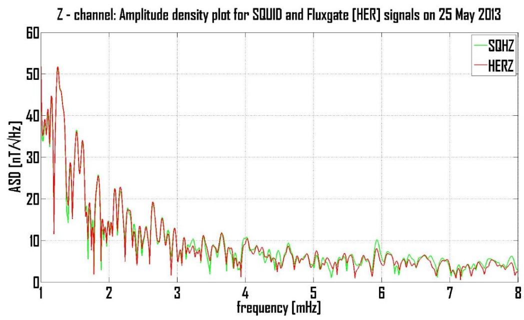

Figure 4. SQUID and Fluxgate z-channels spectra compared to check for correlation of frequency components contained in fluxgate and SQUID data-sets.

Figures 3 and 4 respectively show the Amplitude Spectral Density of x and z components for both the SQUID and fluxgate data-sets. The x and y spectra of the SQUID exhibited excellent correlation with the respective fluxgate spectra: all frequency components present in the x and z spectrum were present in the respective SQUID spectrum. As seen from Figure 3, at frequency components, 3.554, 3.740, 4.224, 4.366, 4.642, 4.850 and 4.992 mHz (all circled in black on Figure 3), present in the SQUID x channel spectrum were not observed in the fluxgate spectrum. These frequency components are possibly due to near-field sources, i.e., sources that only affect the SQUID but not the fluxgate, like fluctuations of air pressure inside the SQUID hut as the wind buffets the door, or possibly some other effect localised to the SQUID measurement system, control electronics or interface cables that respond to interference that does not affect the fluxgate. Frequency components at, 1.15, **1.24**, 1.51, 1.62, 1.71, **1.84**, **1.89**, 1.98, 2.13, 2.34, **2.63**, **2.77**, 2.88, 3.13, 3.83 and **4.02** mHz were all observed in both the x and z spectra of both the SQUID and fluxgate data, with the bold frequencies representing frequencies components that lie within ± 0.1 mHz of the so called "magic" frequencies (see [11] for more about magic frequencies).

5. Conclusion

The correlation between the fluxgate and SQUID datasets is as high as we expected, since our instruments are in such proximity that they virtually measure the same field. Moreover, great care was also taken in the alignment of the sensors. Due to the high correlation, we conclude that the SQUID can be used a valid space weather research magnetometer as suggested by [3]. However, the results can still be improved by analyzing more data recored on geomagnetic stormy days with varying intensity. The SQUID's high sensitivity enables it to detect very faint magnetic fluctuations caused by variety of sources including, lightnings, tidal motions and earthquakes. The SANSA SQUID is aimed at being part of a long-term global instruments with interconnected nodes to study magnetic fluctuations caused by seismic activities. To our knowledge LSBB is currently the only facility that have extensively studied geomagnetic fluctuations due to seismic activities.

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