Versatile High Performance Digital SQUID Electronics

C. Ludwig, C. Kessler, A.J. Steinfort, W. Ludwig

***Abstract*—The digital SQUID Electronics DSE32 has been developed to perform software gradiometry with SQUID magnetometers in multi-channel systems using both High-T_c and Low-T_c SQUIDs. A low-noise preamplifier is followed by a fast hybrid feedback-loop, combining the bandwidth of an analog feedback-loop with the accuracy of a digital loop. By resetting and counting of flux quanta in the SQUID, the dynamic range has been substantially increased. All parameters of SQUID and electronics are firmware controlled and allow for auto-setup and tuning. Data are transferred with a rate of 20 Mbit/s by means of a noise-minimizing, bi-directional optical fiber. Low power consumption allows the use of a battery, further reducing external noise pick-up. The electronics layout is designed for multi-channel applications, as needed in biomagnetic systems.**

***Index Terms*—hybrid digital SQUID electronics, low noise amplifier, software gradiometry, high dynamic range.**

I. MOTIVATION

MEASURING small magnetic fields in the presence of high disturbing environmental fields is the main challenge in various applications of SQUID systems requiring both a large dynamic range and a high slewrate.

A. Biomagnetism

Magnetic field measurements in unshielded environment require high slewrates. Sine wave amplitudes at 50 or 150 Hz of significantly more than 1 μT are not at all exotic in an industrial or a hospital environment. Hence, slewrates of 1 mT/s are the challenge to be met. High-T_c SQUIDs with white noise of less than 10 fT/√Hz are available, raising the question to what extent software gradiometry is able to reduce environmental noise. In order to take full advantage of the SQUID's sensitivity, a dynamic range of about 160 dB/√Hz is required, as well as a trigger jitter of less than 10 ps/√Hz.

B. Airborne MAD

Magnetic anomaly detection using a moving platform poses stringent requirements on slewrate and dynamic range of the SQUIDs and its electronics. It needs at least a dynamic range of 175 dB to recover e.g. a 100 fT target signal hidden in the earth's magnetic field in a non-stabilized towed body. To make use of the rotational invariance of the total magnetic field, the corresponding high dynamic range has to be transferred with a linearity of at least 10^7 into the computer where adequate algorithms might correct for the system's imperfections like misalignment, cross-talk, transfer factor etc...

Manuscript received September 20, 2000. This work was supported in part by the German BMBF under grant No. 13N7328. All authors are with STL Systemtechnik Ludwig GmbH, Max-Stromeyerstr. 116, D-78467 Konstanz, Germany

II. ELECTRONICS

A. Concept

Digital SQUID electronics with digitally controlled flux locked loop have been introduced by CTF with reported slew rates of 33 kΦ_0/s [1]. The digital SQUID electronics uses the SQUID itself as an integral part of the analog-to-digital conversion. The SQUID's transfer function, being exactly periodic in the physical constant Φ_0, allows to increase the significant number of bits compared to conventional ADCs without increasing the noise. Within one Φ_0-period of the transfer function the point of operation of the electronics is stabilized by an analog flux-locked loop (FLL). Conventional ADCs are used to digitize the feed-back voltage to the relevant bits inside the Φ_0-period. Controlled phase slips between different points of operation together with up or down counting of the Φ_0-steps yield the additional theoretically error free bits. The combination of both bit sections forms the digital output signal which is valid up to 32 bits. The linearity, however, strongly depends on the SQUID.

B. Implementation

Large bandwidth paired with high sensitivity was the principle design goal. Hence, the preamplifier forming the first stage of a combined analog and digital flux-locked-loop (FLL) features a bandwidth of 5 MHz and an input noise of approximately 360 pV/√Hz as shown in Fig. 1.

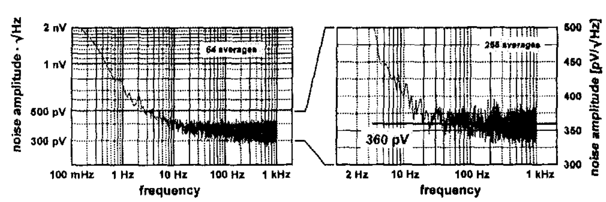

Fig. 1. Preamplifier noise with shorted inputs @ 2 kHz sample rate.

While the analog preamplifier exhibits a transition time as fast as 20 ns, the use of complex programmable logic devices (CPLD) together with a network of fast ADCs and DACs results in a very short digital loop delay of ≈ 200 ns. Additionally, the CPLD solution does consume significantly less power than any solution around digital signal processors.

Every time when the flux fed back to the SQUID exceeds 1 Φ_0, the FLL is opened for a short moment to permit the point of operation to slip one or more Φ_0-periods. This happens extremely fast and allows for a slewrate of more than 20 million Φ_0/sec.

Special care has been taken to handle the voltage span of nearly 10 decades arising between the digital section (3.3 V) and the analog input (400 pV) by separately shielding both sections as seen in Fig. 2. Additionally, the coupling between signals has been minimized by consequently following rf design rules within the multilayer boards. Temperature drifts are minimized by firmware controlled temperature compensation based on temperature measurement of the housing.

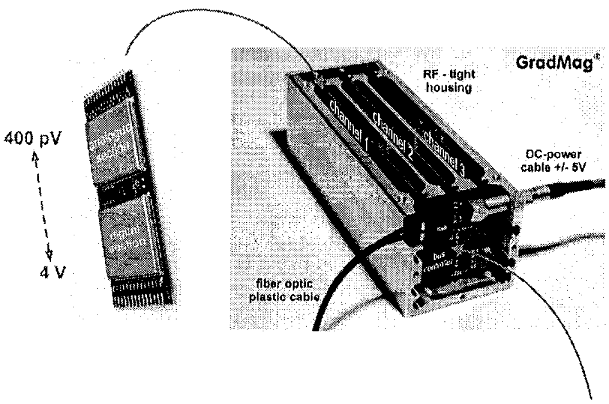

Fig. 2 Single channel board with analog and digital sections separately shielded and the implementation in its rf housing

As ground loops are often the reason for noise interference, a fiber-optic data transmission link (BiFOC) has been implemented based on PMMA plastic fibers. To avoid the fiber-optic link to become a noise generator, a sophisticated transfer protocol has been chosen which is inactive in the frequency band below 2 MHz. Currents of the power supply or LED used for the fiber-optic data link are critical with respect to magnetic coupling with the SQUID. Therefore the power consumption has been minimized to less than 1W per channel, thus minimizing magnetic noise and making battery operation a reasonable option.

A baud rate of 20 MHz is used to get the data rate of 2 MBytes/s. Multi-channel systems can easily be set up using a cascaded network of fiber-optically coupled routers which also handle the data decimation if required. Exactly simultaneous triggering is implemented by using the phase synchronized fiber-optic network to derive the 20 MHz clock signal.

The DSE32 SQUID electronics may be used with High-T_c or Low-T_c SQUIDs. Both the typical High-T_c bias-reversal and the Low-T_c modulation mode are implemented and can even be used simultaneously. The built-in auto-calibration mode finds most of the important parameters of the SQUIDs automatically: the noise optimized bias current and bias voltage, the phase shift in the bias-reversal mode and the reverse-gain-error. The latter describes the scaling error between the physical Φ_0–scale and the electronically defined flux scale within the Φ_0–period.

III. Performance

The SQUID electronics DSE32 has been tested with High-T_c and Low-T_c SQUID systems under various environmental conditions. In the following part, experimental results are presented showing the electronics and SQUID limits concerning the dynamic range, slewrate, and noise for both High-T_c and Low-T_c SQUIDs.

A. *High-T_c dc SQUIDs*

(M. Faley, FZ Jülich, Jülich, Germany)

The performance of the SQUID electronics has been demonstrated with measurements inside the magnetically shielded rooms of PTB, Berlin. Bicrystal SQUIDs in Flip-Chip design [2] were used.

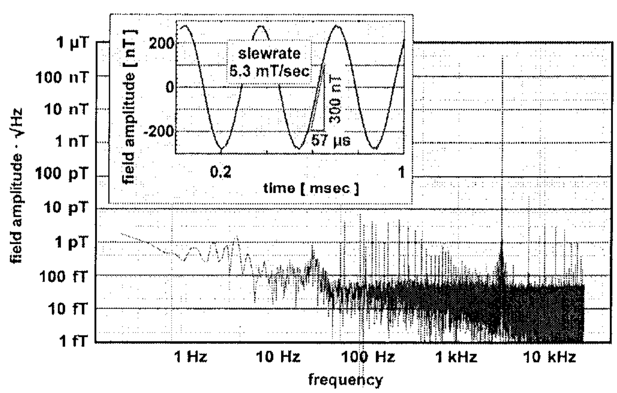

Fig. 3. Slewrate measurement in the BMSR in Berlin with 8 x 8 mm² High-T_c SQUIDs of FZ Jülich (M. Faley). White noise level: 20 fT/√Hz.

Two SQUID types were tested with pick-up loops of 8 x 8 mm² (type A) or 16 x 16 mm² (type B), respectively. In a first experiment shown in Fig. 3, the slewrate of the A-type SQUIDs was measured and exhibited 5 million Φ_0/sec, generated by a low noise sine-wave generator with 270 Φ_0 amplitude @ 3 kHz. Sample rate and bias reversal frequency were chosen to 50 kHz and 100 kHz, respectively. The same plot demonstrates also a dynamic range of 130 dB as the noise of the SQUID is still visible with 15 $\mu\Phi_0/\sqrt{Hz}$. This noise remained unchanged whether the 3 kHz signal was applied or not.

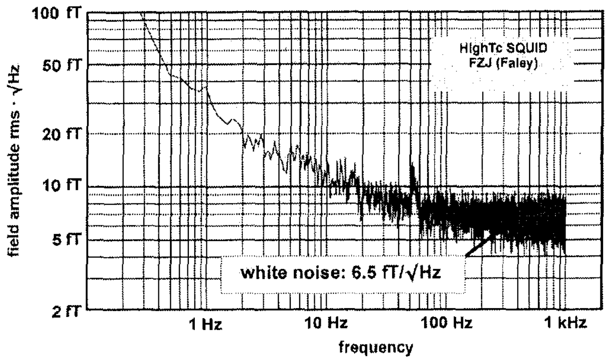

Fig. 4. Noise measurement in the new APMSR in Berlin with 16 x 16 mm² High-T_c SQUIDs of FZ Jülich (M. Faley)

The B-type SQUIDs had been measured in the new Active and Passive Magnetically Shielded Room (APMSR) of PTB in Berlin. As the electronics is intrinsically calibrated in Φ_0, the field factor of the SQUID was established to be 0.47 nT/Φ_0 using a Helmholtz-coil system of PTB inside the APMSR. The noise plot shown in Fig. 4 exhibits a 1/f character with noise levels of 6.5 fT/√Hz @ 1 kHz, 11 fT/√Hz @ 10 Hz and 30 fT/√Hz @ 1 Hz. Sample rate and bias reversal frequency were chosen to 2 kHz and 100 kHz, respectively. The cryostat was not wrapped in Al foil, as this increased the white noise to over 11 fT/√Hz. No interference between SQUID and electronics could be observed .

B. High-T_c rf SQUIDs

(Y. Zhang, FZ Jülich, Jülich, Germany)

Using the SQUID as an integral part of an A/D converter is not restricted to dc SQUIDs only. rf SQUIDs can also be used if special care is taken not to contribute noise into the SQUIDs. The rf SQUID electronics of the Research Center Juelich [3], operating at several hundred MHz had been prepared to interface the DSE32 electronics such that basically the internal low noise preamplifier of the DSE32 was substituted by the external rf electronics. The result was a very fast low noise digital SQUID system with a slewrate of 2.5 million Φ_0/sec and a white noise level of ≈ 40 fT/√Hz . The noise level was not increased compared to the noise of the rf SQUID system alone, thus suggesting that the digital electronics did not spoil the SQUID performance. As the bandwidth of the rf SQUID is basically limited by the tank circuit, the noise problem is expected to be less severe as compared to dc SQUIDs. The measurements demonstrated that the rf SQUIDs of Y. Zhang (FZ Jülich) are "field proof" to a high extent. It was possible to apply fields of more than the earth's magnetic field and still track the output signal.

C. Low-T_c dc SQUIDs

(Zakosarenko, Stolz, Institute for Physical High Technology, Jena, Germany)

While the flux noise limit of High-Tc SQUIDs is substantially higher than that of Low-T_c SQUIDs, the modulation depth is comparable (≈50 μV/Φ_0 with High-Tc Faley's SQUIDs, ≈80 μV/Φ_0 with Low-T_c Jena SQUIDs). As a result, the SQUID electronics is challenged the most by Low-T_c SQUIDs:

- in order to measure flux noise of 2 μΦ_0/√Hz, a very low noise preamplifier is required
- the low energy noise level favors rf interference

The noise measurement shown in Fig. 5 was performed inside the IPHT magnetically shielded room (IMSR), with small rf interference present, reducing the modulation depth by more than 30% to 50 μV/Φ_0. The leakage was identified and removed.

Fig. 5 displays a typical noise spectrum obtained from a Nb-SQUID in the IMSR. Using a sample rate of 20 kHz and a bias reversal frequency of 100 kHz a white noise level of less than 3.5 μΦ_0/√Hz was measured. The SQUID sensitivity was found to be ≈1nT/ Φ_0.

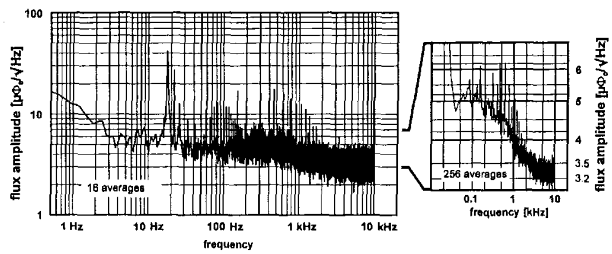

Fig. 5. Noise measurement of Low-Tc SQUID of IPHT Jena inside the IPHT magnetically shielded room

The slewrate was measured outside the IMSR using a Helmholtz-coil system in a laboratory environment. Sine-wave signals with an amplitude of 16900 Φ_0 , corresponding to ≈17 μT, could be tracked @ 400 Hz, resulting in a slewrate of 21 million Φ_0/sec or ≈21 mT/sec. In this experiment, the sample rate was chosen to be 200 kHz and no bias reversal was used. The result is displayed in Fig. 6.

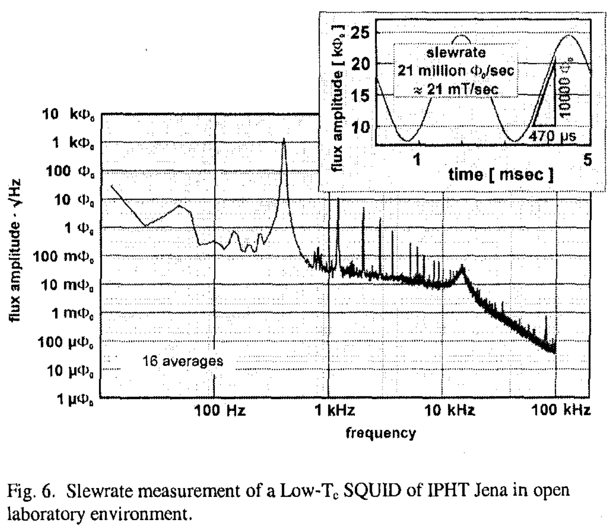

Fig. 6. Slewrate measurement of a Low-T_c SQUID of IPHT Jena in open laboratory environment.

D. Performance overview

The synopsis of the various measurements is shown in Fig. 7. Characteristic are 5 types of limiting factors:

1) SQUID limit

Above 10 kΦ_0 we find a SQUID limit which is defined by the non-linear and hysteretic effects SQUIDs undergo at higher fields. This limit is very much dependent on the SQUID's layout and varies quite significantly.

2) Slewrate limit

The slewrates measured are limiting the field amplitudes in the higher frequency regime. The amplitudes tracked are inverse to the frequency.

3) Bandwidth limit.

The bandwidth of ≈5 MHz is limiting the frequency range and is affected by the wiring to the SQUID.

4) BiFOC limit

The 2 MB/s data transfer rate of the fiber-optic interface "BiFOC" limits the usable total sample rate (actual sample rate times number of channels used) at present to 500 kHz and hence the frequency to 250 kHz, when a 4 byte data representation is used. This limit can be set to higher frequencies by changing the data representation or running the interface with higher data rates.

5) Preamplifier noise

The preamplifier noise limits the SQUID performance if either the modulation depth is small or the energy resolution is high. With Low-T_c SQUIDs, less then 2 $\mu\Phi_0$ are possible, with modulation depths beyond 80 $\mu V/\Phi_0$.

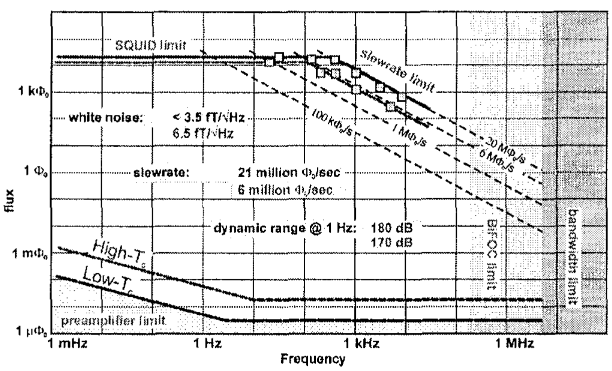

Fig. 7. Synopsis of the SQUID electronics performance and its limiting factors.

It was not possible to demonstrate the dynamic range of the SQUID electronics in one single experiment because of the experimental conditions and/or the SQUID limitations.

The huge dynamic range of 180 dB, however, can be perceived in the synopsis comparing the noise limit of 3.3 $\mu\Phi_0/\sqrt{Hz}$ and the 17 kΦ_0 amplitude of the sine-wave generator in the slewrate experiment (1% percentile). Finally, one should keep in mind that only the SQUID is the limiting factor for low frequency signals since the 32 bit resolution is rather a data format than a principal limitation.

IV. Summary

In a hybrid A/D conversion process, the SQUID intrinsically contributes its periodic transfer function, thus significantly increasing the dynamic range of the A/D converter.

The CPLD based implementation combines the performance of the best analog SQUID electronics available with the digital power of 32 Bit dynamic and the speed of more than 20 million Φ_0/sec without increasing the SQUID noise.

The electronics is now commercially available and matches a variety of present SQUID designs in the Low-T_c and High-T_c regime demonstrated so far with directly coupled SQUIDs. The results underline its importance for software gradiometry in unshielded environment or measurements on moving platforms.

Acknowledgment

The authors like to thank M. Faley (Forschungszentrum Jülich) for providing his highly sensitive dc SQUID and for his support during various measurements, V. Zakosarenko, R. Stolz and H.G. Meyer (Institute for Physical High Technologies, Jena) for supporting us with the Low-T_c SQUID and the measurement facilities, and the Berlin SQUID group of PTB for offering us the opportunity to measure in the APMSR.

References

[1] J Vrba, V Angus, K Betts, M B Burbank, T Cheung, A A Fife, G Haid, P R Kubik, S Lee, W Ludwig, J McCubbin, J McKay, D McKenzie, S E Robinson, M Smith, P Spear, B Taylor, M Tillotson, D Cheyne, H Weinberg, "143 channel whole cortex MEG system", in C. Aine, Y. Okada, G. Stroink, S. Swithenby and C. Wood (Eds.) Biomag96, Proceedings of the Tenth International Conference on Biomagnetism, Springer-Verlag, pp. 1079-1082 (2000)

[2] M.I. Faley, U. Poppe, K. Urban, D.N. Paulsen, T. Starr, R.L. Fagaly, "Low noise HTS dc-SQUID flip-chip magnetometers and gradiometers" , Submitted for publication in Proceedings ASC 2000, IEEE Transactions on Applied Superconductivity

[3] Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany, www.fz-juelich.de