INVITED PAPER *Special Section on Frontiers of Superconductive Electronics*

Superconductive Digital Magnetometers with Single-Flux-Quantum Electronics

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SUMMARY Superconducting Quantum Interference Devices (SQUIDs) are known to be the most sensitive magnetometers, used in a wide range of applications like biomagnetism, geomagnetism, Non Destructive Evaluation (NDE), metrology or fundamental science. For all these applications, the SQUID sensor is used in analog mode and associated with a carefully designed room-temperature control and/or feedback electronics. Nevertheless, the use of SQUID sensors in digital mode is of high interest for several applications due to their quantum accuracy associated to high linearity, and their potentially very high slew rate and dynamic range. The concept and performances of a low-Tc digital magnetometer based on Single-Flux-Quantum (SFQ) logic, fabricated at the FLUXONICS Foundry located at IPHT Jena, Germany, are given after a presentation of the context of development of superconductive digital magnetometers. The sensitivity, limited to one magnetic single flux quantum, and a dynamic range of 76 dB, that corresponds to an upper limit of the magnetic field amplitude higher than 5 μT, have been measured along with overnight stability. The dynamic range of about 2800 magnetic flux quanta Φ_0 has been experimentally observed with an external magnetic field. First signatures of magnetic fields have been observed simultaneously with the ones of analog SQUIDs in the low noise environment of the Laboratoire Souterrain à Bas Bruit (LSBB) located in Rustrel, Provence, France.

key words: *SQUID, SFQ, RSFQ, Single-Flux-Quantum, Rapid Single-Flux-Quantum, digital SQUID, magnetometer, superconducting electronics, superconducting digital electronics*

1. Introduction

Superconducting quantum interference devices are one of the most widely spread applications of Superconducting Electronics. They are used as magnetometers or gradiometers in biomagnetism, geomagnetic prospecting, magnetic microscopy, non destructive evaluation (NDE) or more recently in low field Nuclear Magnetic Resonance, as a few examples. So far, all the existing systems are based on analog devices, associated to sophisticated electronics. A review of SQUID applications can be found in [1], [2]. A recent review of the history of SQUIDs in Europe is given in [3], [4].

Today, the Single-Flux-Quantum technique [5], [6] allows to build digital electronics systems with unparallel performance [7]. These circuits are made of Josephson junctions, like SQUIDs, and are fully compatible with superconducting magnetic sensors since they rely on the same technology. Magnetic sensors combined on-chip with a superconductive digitization module present four particular features that are of interest for some of the above-mentioned application fields: (i) quantum accurate digitization, due to the flux quantization of superconducting loops, that is associated with very high linearity, (ii) high slew-rates that can allow to monitor fast variations of magnetic fields, or dc to low frequency magnetic fields in a fast changing magnetic environment, (iii) very high dynamic range connected to the principle of operation of the digital magnetometer and, (iv) possibilities of on-chip digital processing and/or multiplexing for multichannel systems or imaging arrays since, as in contemporary electronics, digital techniques are of high interest for systems requiring eventually many channels or specific signal processing.

The combination of magnetic detectors with digital electronics for signal processing is an attractive solution to provide simultaneously the ultimate sensitivity of SQUIDs magnetometers or gradiometers with the advantages of digital techniques which offer more flexibility and are eventually a more cost-effective solution.

2. From Conventional to Superconducting Digital Processing of SQUID Signals

Analog SQUIDs have proven to be the most sensitive magnetometers with sensitivities of the order of $1\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$ [8], [9] for low-T_c SQUIDs and below $40\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$ [1], [2], [10] for high-T_c SQUID magnetometers. SQUIDs gradiometers are also at the state-of-the-art in terms of sensitivity that can reach a few tens of $\mathrm{fT/cm}/\sqrt{\mathrm{Hz}}$ [10]–[12]. Though the sensitivity of analog SQUIDs is unsurpassed, a customized electronics is usually designed with a flux-locked loop [13] to obtain a stable point of operation. This task is usually achieved with a room-temperature electronics that can show some limitations in terms of bandwidth due to the maximum slew-rate of the electronics, though recent developments have enable to go above 100 MHz [14]. Also, the dynamic range can be limited by the maximum current allowed by the feedback electronics. An interesting synopsis of the SQUID electronics performance is given in Fig. 7 of [15].

A first step in the direction of SQUIDs with digital feedback has been reached by D. Drung [16] in 1986 where the dc SQUID, the pickup coil and the A/D converter were integrated on a single chip. Nevertheless, this was accomplished with room-temperature feedback digital electronics

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circuits. This can still ultimately limit the bandwidth. Besides, some problems related to crosstalk can appear if arrays of sensors are desired. Two years later, the first SQUID with on-chip superconducting digital feedback was demonstrated by N. Fujimaki [17]. In this case, the digital feedback is based on a superconducting storage loop and a write gate. The sensitivity was $70\,\mu\Phi_0/\sqrt{\mathrm{Hz}}$ with a slew-rate of the order of 200 Φ_0/s associated with the hysteretic behaviour of the Josephson junctions and a principle of operation using the threshold curve of the SQUID sensor. In 1993, a derived version based on latching logic with double write gates has been proposed and tested to increase the dynamic range [18]. This has led to a working device with a sensitivity of $20\,\mu\Phi_0/\sqrt{\mathrm{Hz}}$ with a slew-rate of the order of $5 \cdot 10^6 \Phi_0$/s at a clock frequency of 5 MHz [19]. In Europe, a close concept lead in 1999 to a device with a sensitivity of $4\,\mathrm{m}\Phi_0/\sqrt{\mathrm{Hz}}$ with a slew-rate of the order of $4{\cdot}10^5 \Phi_0$/s at a clock frequency of 80 MHz [20]. The next step to still increase the dynamic range and slew rates is to use Rapid Single-Flux-Quantum devices since they can easily operate at more than 10 GHz of clock frequency and can consequently lead to slew rates in the $10^9 \Phi_0$/s range. The concept was brought by Rylov as early as in 1990 [21]. A detailed review of the last features and devices based on this concept can be found in [22]. A derived version of this design with some SFQ cells, like the comparator, replaced by their latching logic counterparts, that was more suitable regarding the clock frequencies in the MHz range, was experimentally demonstrated in 1995 by Yuh et al. [23]. Another step in the direction of digital SQUIDs based on the SFQ technique was also made with a dual channel digital SQUID, demonstrated by Takeda et al in 1995 [24]. The experimental demonstration of the concept with SFQ cells has been partly demonstrated in 1997 [25].

Most of the work about digital SQUIDs with SFQ electronics requires the fabrication of circuits that can count a few tens of Josephson junctions or more. This corresponds to rather simple circuits for low-Tc superconducting technologies, but is already difficult to achieve with less mature high-Tc superconductors. Nevertheless, high-Tc digital SQUIDs are of very high interest because of reduced cryogenic constraints which implies better portability and lower cost. Portability is an essential requirement for most of the applications envisioned for digital SQUIDs mentioned in the introduction.

3. Development of Digital SQUIDs in Europe

As a result, a project entitled “Digi-SQUID: Digital High-Tc Squid sensors for Non-Destructive Evaluation in Unshielded Environment” has been funded by the European Union fifth Framework Programme between 2002 and 2006. The major goal was to design and validate experimentally a magnetic digital sensor for NDE with high dynamic range and a reasonable sensitivity better than 1 $\mathrm{pT}/\sqrt{\mathrm{Hz}}$ that can operate in an unshielded environment [27]. In order to insure portability, the project included the development of a 2-stage cooler with a cooling power of 3 W at 70 K and 0.5 W at 30 K, associated with a digital SQUID gradiometer based on an already-proven high-Tc technology [28]. A constraint was to build a demonstrator from a digital circuit counting only a few tens of Josephson junctions to account for the moderate maturity of high-Tc superconducting digital devices. Indeed, digital circuits based on high-Tc technologies have progressed in terms of complexity and speed during the last years [29] and operational circuits with about 100 Josephson junctions have been proven. Nevertheless, their maturity is not yet at the state of low-Tc digital circuits that can count thousands of Josephson junctions [7]. As a consequence, it is often of interest to develop low-Tc circuits to prove a concept, validate the design and set up the experimental test environment when some applications are still possible with the stronger constraint of cryogeny at liquid helium temperature. For the Digi-SQUID project, the design implied circuits with a minimum number of Josephson junctions, to enable the implementation with high-Tc superconductors. A version has also been designed for low-Tc superconductors. This last version is indeed interesting for specific applications that require simultaneously a high sensitivity and a high dynamic range to record signals in presence of unwanted magnetic perturbations. The digital SQUID concept based on the SFQ technique, without latching logic device, and with 11 non-hysteretic Josephson junctions has been developed at the University of Technology Ilmenau and published in [26]. A design with only 8 Josephson junctions is also possible. The low degree of complexity, associated with non-hysteretic junctions, is compatible with several kinds of superconducting thin film technologies, including high-T_c materials, which will be of importance in the future when portable systems are required. The principle of the concept is described in Fig. 1. The pickup loop is directly connected to one of the junction of the Josephson comparator. Consequently, the flux in the pickup loop is maintained at a constant value within the limit of one flux quantum since one flux quantum enters the loop whenever the bottom junction

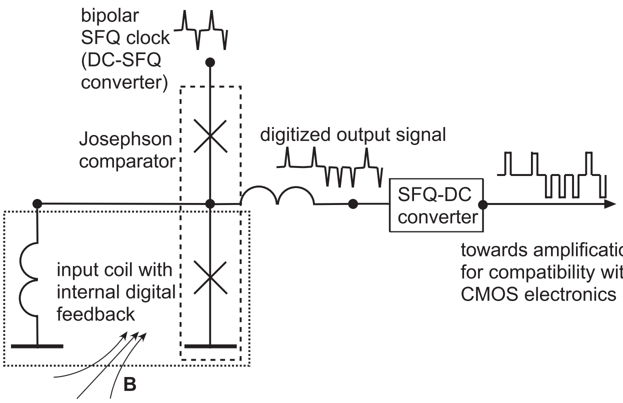

Fig. 1 Concept of digital SQUID with bipolar SFQ clock and SFQ conversion to a Non-Return-to-Zero signal compatible with CMOS standards. The feedback of one magnetic flux quantum is internal to the device, associated with the switching of the bottom junction of the comparator at the clock instants [26].

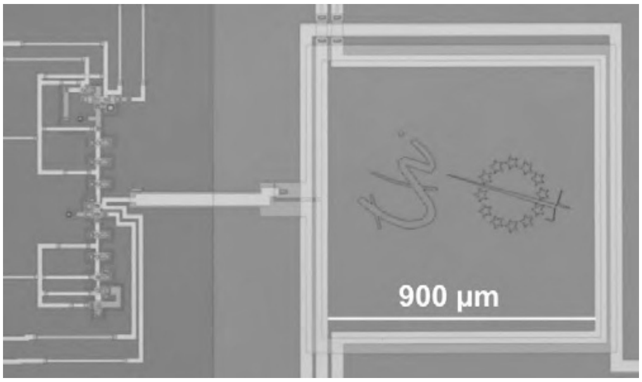

Fig. 2 Picture of a digital magnetometer with its pickup loop of $0.9 \times 0.9\,\mathrm{mm}^2$. The SFQ processing part is located to the left, the pickup loop to the right. An inductively coupled line is also present to apply locally a magnetic field in the pickup loop. This device has been fabricated with shunted Nb/Al-AlOx/Nb Josephson junctions at the European FLUXONICS Foundry [30].

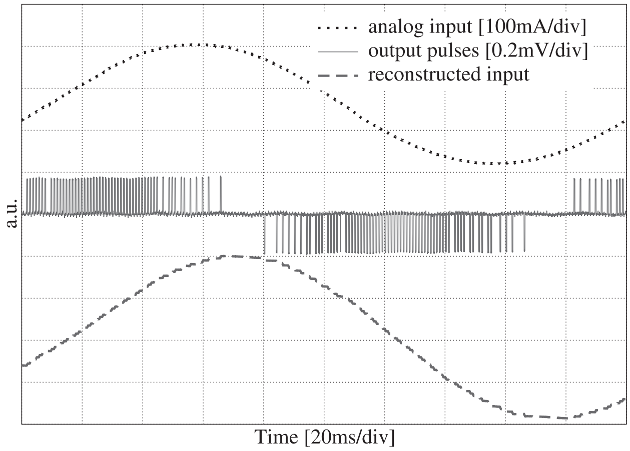

Fig. 3 Experimental analysis of the digital SQUID concept with low-Tc superconducting technology showing a reconstructed sinusoidal signal at 5 Hz along with the pulsed digitized signal (from [33]).

of the comparator switches. For this reason, such a device can exhibit a high dynamic range as long as the magnetic field does not perturb the behavior of the SFQ part of the device. In order to keep low the number of junctions of the device, the concept was chosen with a bipolar ac bias and a bipolar SFQ clock to keep only one output channel with negative pulses for negative slope of the input signal, and positive pulses for positive slopes. The digital SQUIDs is a delta type analog-to-digital converter. The bipolar clock is achieved through an ac-biased DC-SFQ converter that allows, when the bias is going back from positive to zero voltage, to reset the SFQ cell and makes it ready for the next set of biasing at negative values. Consequently one positive pulse, followed by one negative SFQ pulse, are generated by the clock for each period of the ac bias voltage. The ac bias mode is also used for the SFQ-DC converter that transforms the output pulses to a Non-Return-to-Zero output signal that is further amplified with a 80 dB gain low-noise amplifier placed at room temperature. The device has been fabricated, based on low-Tc shunted Nb/Al-AlOx/Nb Josephson junctions, at the Institute of Photonic Technology (IPHT) in Jena (Germany) that runs the European FLUXONICS Foundry [30]. Figure 2 shows the magnetometer with a pickup loop of $0.9 \times 0.9\,\mathrm{mm}^2$. The concept has been verified experimentally in a third step in 2004 [31]. In this case the magnetic field was simulated by a current running in a line inductively coupled to a small pickup loop. Figure 3 shows the reconstruction of a low frequency sinusoidal signal after digitization by the SFQ digital SQUID. One can clearly see the output negative and positive pulses in the center trace. Their amplitude is about 0.2 mV which corresponds roughly to the $R_N I_c$ product of $256\,\mu\mathrm{V}$ of the FLUXONICS Foundry process. Their width is not the one of a quantized pulse that is much too short to be recorded, but the width of rectangular pulses obtained at the output of the SFQ-DC converter with a rising edge triggered by the SFQ pulse and the falling edge associated with the bias reset to zero, due to ac biasing.

4. From the Proven Concept to Digital Magnetometers

The next step was to perform magnetic field measurements by replacing the inductively coupled current line by the direct sensing of the magnetic field. This has been done by designing a new set of digital SQUID magnetometers with different loop areas and comparator sensitivities. An extensive study has been performed to verify possible drifts, long-term stability, influence of external parasitics, maximum slew-rate and dynamic range [32]. A stable operation of the magnetometer in unshielded conditions has been observed for more than 10 hours. The best intrinsic magnetic field resolution with a pickup loop of $0.9 \times 0.9\,\mathrm{mm}^2$, has been found to be about 4.2 nT, corresponding to one magnetic flux quantum. This resolution corresponds to a floor noise $0.22\Phi_0/\sqrt{\mathrm{Hz}}$ at 0.1 Hz [32]. In all cases the quantization step corresponds to one magnetic flux quantum Φ_0.

4.1 Dynamic Range

A dynamic range of 14800 magnetic flux quanta Φ_0 could be demonstrated for an inductively coupled current [32]. With a magnetic field input, the dynamic range was experimentally lower, of the order of 2810 single flux quanta Φ_0. The difference between both observed values is due to the fact that in the later case the magnetic field is not only focused on the pickup loop, but on the entire chip, since it is applied with a set of Helmholtz superconducting coils placed around the chip holder inside the dipstick (see Fig. 4). The external magnetic field of the Earth was screened with a Vitrovac film taped around the dipstick. As a consequence the entire SFQ circuit was under the influence of the magnetic field produced by the coils. Naturally, whenever a part of a superconducting loop of the SFQ circuitry is exposed to the magnetic field to detect, its operation point is shifted which reduces the margins of operation of the SFQ circuit since each part of the circuit cannot be controlled indepen-

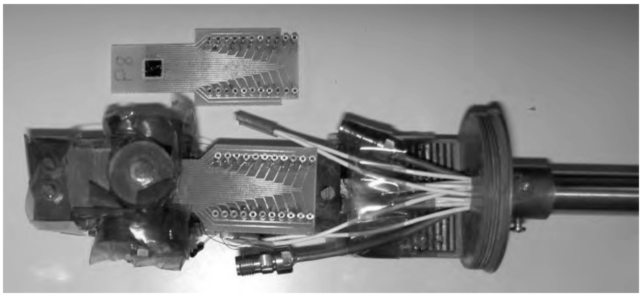

Fig. 4 Cold part of the dipstick that is plunged into liquid helium. One can see two sets of Helmoltz superconducting coils used to apply a controlled external magnetic field, as well as the low-Tc digital SQUID chip installed on an epoxy carrier.

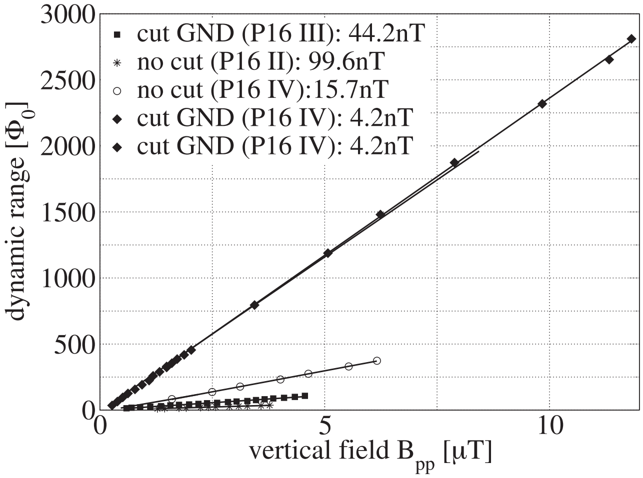

Fig. 5 Dynamic range expressed in quanta of magnetic field Φ_0 for different digital magnetometers, as a function of the peak-to-peak magnetic field applied in a direction perpendicular to the plane of the magnetometer chip. The magnetic field value indicated in the legend is the resolution of the magnetometer comparator.

dently. The main cell that was influenced by this effect was the SFQ-DC converter. Figure 5 shows the dynamic range of several digital magnetometers that have been tested in the course of the year 2007. One can notice that, for device P16IV, two resolutions of 15.7 nT and 4.2 nT have been respectively measured. In the second case, a ground loop that was mistakenly surrounding the chip of the digital magnetometer has been cut in order to avoid the quantization of the magnetic flux on the chip. This resulted in a direct improvement of the sensitivity by a factor of 4, in much better agreement with the values predicted by simulations. The associated dynamic range is 76 dB [32]. We also did experiments in the Earth's magnetic field to validate the behavior in real conditions, since it is of interest for many applications.

4.2 Slew Rate

The slew rate is another feature that is in favor of digital SQUIDs for several applications. In some cases associated with operation in unshielded conditions, the device should be able to follow the change of magnetic field induced by the movement of the device or by external perturbations, without loosing its sensitivity and its reference level. The dynamic range is naturally a key parameter to insure that the sensor will not be saturated. Another parameter is the slew rate of the device that should be high enough to stand up to fast changes of the magnetic field. From this perspective, the use of full SFQ processing for the magnetometer signal is of high interest since the SFQ technique is intrinsically fast with clock frequencies that stand in the tens of GHz range. With the present device with bipolar biasing the ultimate speed is reduced but can still reach the 1 GHz range which is much above what all other kinds of magnetic sensors can produce. Another interesting feature is due to the quantizing nature of the pickup loop integrated with the Josephson comparator: the device does not loose the magnetic field reference value even if an event causes a magnetic field variation faster than the slew rate of the digital SQUID. The magnetic field being sampled at every clock pulse, if the magnetic field has changed by more than one flux quantum between two clock pulses — this rate corresponds to the slew rate- only one flux quantum is read and measured while the additional ones remain stored in the loop and can be read during the next clock pulses. Consequently the reconstructed output signal does not follow the real variation of the field versus time. Nevertheless, as long as the magnetic field is not strong enough to trigger the Josephson comparator in absence of clock pulse, the magnetic field that is reconstructed after the fast external magnetic event is faithful to the external applied value: the reference level is kept and there is no unlocking of the digital magnetometer. To illustrate this fact, Fig. 6 shows on its top trace a square magnetic signal applied with a slope that is about 1500 times the slew rate of the digital magnetometer. The bottom trace is the reconstructed signal after digitization. The slopes of the rising and falling edges of this trace give the slew rate of the device, corresponding to one magnetic flux quantum detected at the output of the comparator for every clock pulse, at the sampling frequency of 2 kHz. Nevertheless, once the fast change is over, the absolute value of the reconstructed field is in perfect agreement with the expected one, showing that there is no unlocking of the device and that it keeps the absolute value of the field in memory even through events that vary 1500 times faster than the device slew rate.

4.3 Comparative Tests in Low Noise Environment

After a full characterization in the laboratory, the digital magnetometers have been carried out in the low noise LSBB laboratory in a remote area in the south of France [34]. Among other experiments, this laboratory is running, on a permanent basis, sismometers and commercial analog SQUIDs to study seismo-ionospheric signals [35], or fundamental Physics phenomena [36]. The sensitivity of the commercial SQUID system is of the order of $1\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$. The instruments are located under the plateau d'Albion in the Rustrel village, in a capsule that is a Faraday cage but not

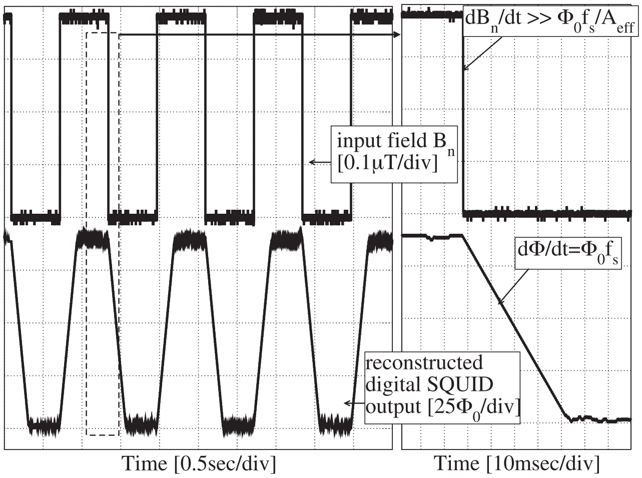

Fig. 6 Applied magnetic field and reconstructed pattern after digitization. The slopes of the magnetic field rising and falling edges of the square signal are about 1500 times the slew rate $\Phi_0 f_s$ of the digital magnetometer, where f_s is the sampling frequency of 2 kHz. One can notice that the absolute value of the magnetic field is memorized, even if the magnetometer cannot follow the fast changes of the applied field.

Fig. 7 Capsule located at a depth of 500 meters in the LSBB underground laboratory in which SQUIDs are installed.

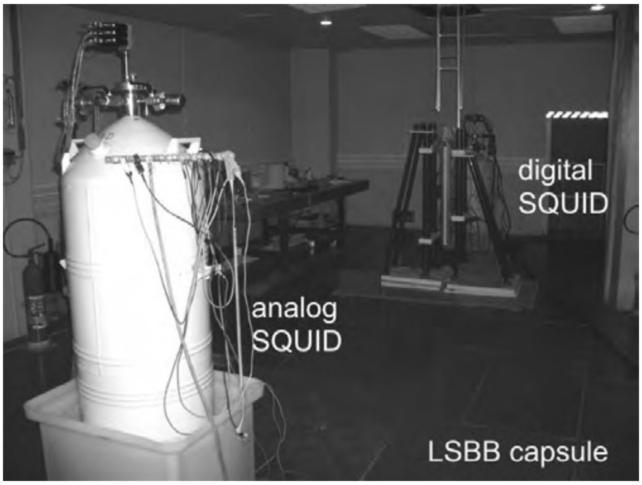

Fig. 8 The two liquid helium dewars installed in the capsule of LSBB. The 3-axis analog SQUID system is installed in the front dewar while the one-axis digital magnetometer is at about 10 meters from the first dewar.

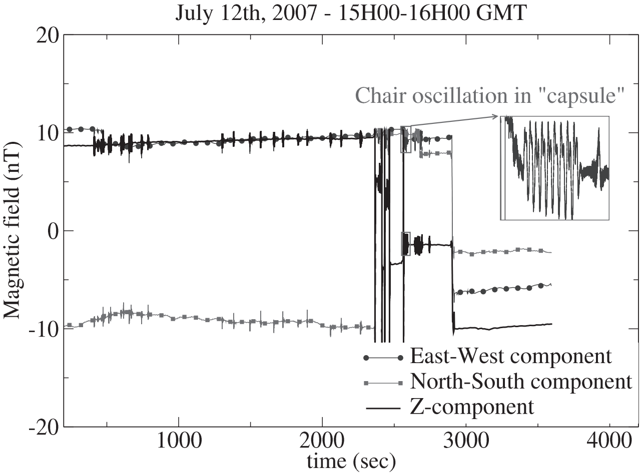

Fig. 9 Signals of the commercial analog SQUID system recorded during one hour. The inset shows a close-up view of the variation of the magnetic field when a ferromagnetic chair is moved at a few meters from the SQUID dewar in a oscillatory way during a few seconds. The strong variations of the field before and after the chair oscillations are due to the closing and opening of the capsule door.

a zero gauss chamber. Consequently, it is a low frequency filter for magnetic signals, and is mechanically decoupled from the mountain (see Fig. 7). The capsule is at about 500 meters under the ground level and 1.5 km from the side of the mountain. The digital SQUID magnetometer has been installed in the capsule in a separate liquid helium dewar located at about 10 meters from the dewar containing the commercial 3-axis analog SQUID system (see Fig. 8). For these measurements, there was no magnetic shielding of the device so it can directly sense the Earth's magnetic field. A chair with ferromagnetic parts has been used to generate a variable magnetic field. It was located closer to the digital SQUID in order to take into account its lower sensitivity. The signals from the two SQUID systems were recorded simultaneously for several types of magnetic signals. The digital SQUID signal was amplified at room temperature with an 80 dB gain amplifier, and reconstructed on the fly by the PC software associated with a LabView data acquisition board. The digital SQUID electronics, e.g. control electronics, bias supply and output signal amplification was located outside the capsule, at about 20 meters from the device.

Figure 9 shows the signals of the three axis of the analog SQUID system recorded during one hour. A close-up view in the inset allows to see the variation of the East-West component of the magnetic field when the chair was moved with oscillations at a few meters from the SQUID system. One can clearly see the oscillatory behavior on the SQUID signals. Several experiments have been performed for two days. The digital SQUID that was used was the device P16III that has rather a low sensitivity of about 44 nT/Φ_0 (see Fig. 5). Nevertheless it was sufficient to clearly see the

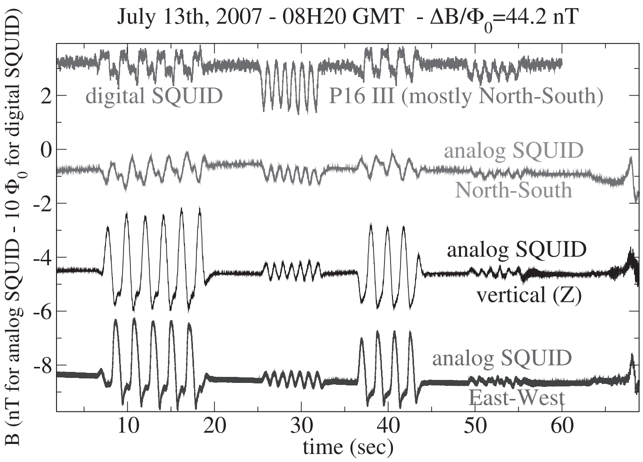

Fig. 10 Comparison of the signals obtained by an analog SQUID system with the reconstructed signal of the digital magnetometer. A ferromagnetic chair has been used to generate the oscillatory magnetic field. It was placed at a few meters from the SQUID sensors.

signal variations and correlate them to the signals provided by the analog SQUIDs. Figure 10 shows the signals of the three axis of the analog SQUIDs, along with the signal of the digital SQUID after reconstruction. We see a very good correlation between the digital SQUID signal, for which the detected component was mostly the North-South one, with the three signals of the analog SQUID system. As expected, the pattern of the digital magnetometer signal is closer to the North-South component of the analog SQUID. This experiment has allowed us to verify that the full system could operate properly, even with a control electronics located at 20 meters from the device. The overnight stability was proven to be very good without any noticeable drift in absence of overwhelming perturbation.

5. Conclusion

The digital magnetometer that has been developed and tested in real conditions of operation is a first step towards digital magnetic sensors. Presently the sensitivity is low with respect to other sorts of magnetometers, since we are limited by the intrinsic magnetic flux quantum Φ_0, according to the principle described above. But the main features that are of interest for this kind of device, e.g. dynamic range and slew rate, are promising and in good agreement with expectations. The possibility to digitize on-chip the signal of a superconducting sensor that has been proven, will allow in the medium term the construction of more complex systems, like imagers. Consequently, the potentialities of low-Tc SFQ electronics in terms of speed, low consumption, quantum accuracy and complexity, regarding multiplexing possibilities for instance, will likely boost the development of superconducting electronics by opening the range of applications. Indeed, we should note that the work conducted with magnetometers can be transfered to other transducers for which the physical quantity is transformed in a current, since the first digitization stage of the SFQ signal processing circuit is based on a current comparator. For magnetometers, the additional requirement connected to the need to work in non magnetically shielded environment is more difficult to achieve but foreseeable solutions exist to bypass this issue. Also several solutions can be investigated to increase the sensitivity. The first one consists of designing a more sophisticated SFQ digitization circuit, at the price of a higher complexity [37]. Nevertheless this complexity is compatible with the state-of-the-art of SFQ technology for low-Tc superconductors. Another solution consists of designing an hybrid device that includes an analog dc SQUID in order to take simultaneously advantage of the high dynamic range of the digital SQUID and the high sensitivity of the analog SQUID [38]. The proof of concept of such a design has been experimentally brought in the course of the work described in this paper [32]. The field of digital superconducting sensors is still in its infancy but many opportunities are now reachable with the state-of-the-art technology of low-Tc superconductors. One can also expect high-Tc superconductors to be able to reach some of the challenges of this field, at least for the devices associated to reasonably low complexity.

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