Digital SQUID Magnetometer Development for Geophysics Applications Validated in Low-Noise Environment

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***Abstract*– A prototype digital version of the widely-used Superconducting Quantum Interference Device (SQUID) magnetometer has been tested in real conditions of operation in July 2007 in the low-noise underground facility of Rustrel France (Laboratoire Souterrain à Bas Bruit, LSBB). Geophysical studies that require a high-magnetic-field dynamic range can benefit from this digital device that makes use of the Rapid Single-Flux-Quantum (RSFQ) technique to achieve fast on-chip electronic feedback at cryogenic temperature. First measurements have shown that the on-chip digital processing of sensor signals, benefiting of all the advantages of digital technique, is a viable solution at cryogenic temperature.**

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I. CONTEXT OF DEVELOPMENT

During the 2002-2006 period, the 6th FrameWork Program of the European Community funded the project “High-T_c digital SQUID Sensor for NDE in Unshielded Environment” (“DigiSQUID”) under the “Competitive and Sustainable Growth” Programme. It advanced the development of second-order gradiometer digital SQUIDs making use of a high-critical temperature superconductor (HTS) technology and operating at the temperature of about 30 kelvin. In some fields of application where portability is required, such as the Non-destructive Evaluation (NDE) for example, a temperature of operation around 30 K is acceptable. Magnetometers and gradiometers fabricated in HTS technology at the University of Twente, Netherlands, have been studied and developed for use with custom-made cryocoolers.

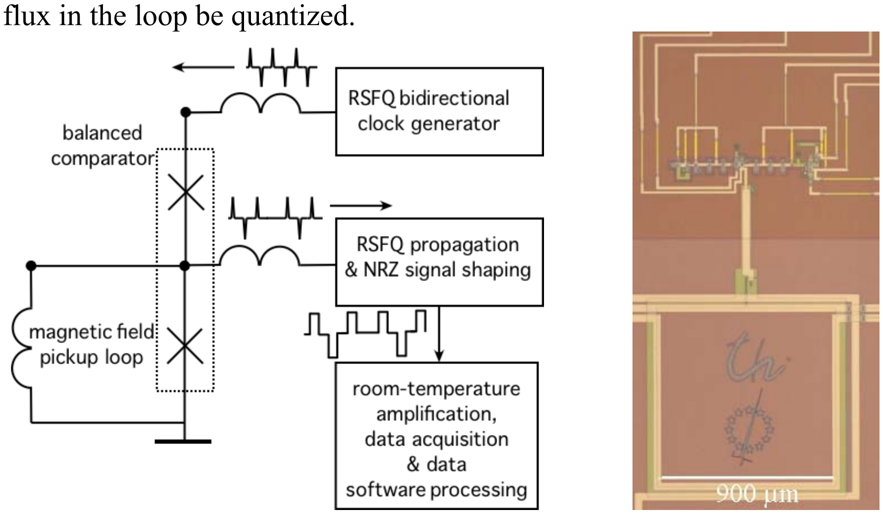
To validate the design of digital devices used, a low critical temperature (LTS) equivalent has been also studied at the University of Technology of Ilmenau (IUT) in Germany. This LTS version used the ISO9001-certified mature fabrication technology employing 1 kA/cm^2 current density niobium/aluminum oxide/niobium Josephson junctions available at the Fluxonics Foundry located at the Institute of Photonics Technology (IPHT) in Jena, Germany [1]. Several generations of devices were fabricated during the 2004-2007 period at the Fluxonics Foundry. Testing of these at the University of Savoie, France, resulted in step-by-step improvements aiming towards a viable magnetometer with a high-magnetic-field dynamic range. Ultimate tests have been performed in real conditions to identify all issues related to the operation of the digital device. For this purpose, we decided to operate the digital SQUID in the low-noise LSBB underground facility of Rustrel in French Provence [2]. This site, located in a remote place with low human activity (500 meters below the ground level - under the Plateau d'Albion), is the former French nuclear terrestrial launch control room. It has been refurbished for scientific purposes and is currently dedicated to miscellaneous scientific experiments in different fields of physics, ranging from the detection of dark matter in astroparticle physics, or detection of earthquakes in geophysics, to the tests of reliability of semiconductor field-programmable gate array (FPGA) circuits for industrial validation. This last research activity is crucial for the development of reconfigurable electronic circuits that are robust in the long term, especially for applications in space. The issues that are currently encountered in the semiconductor field will arise in the near future for superconductive electronics circuits as well, due to their ultimate speed performance and sensitivity, which also means sensitivity to unwanted perturbations.

In the present case, as the digital SQUID is mainly a magnetic field sensor, the LSBB environment offers three interesting testing features:

- there is no environmental magnetic noise at the level of sensitivity of the digital SQUID, since the ambient magnetic noise in the electromagnetically shielded 1250 m^3 chamber of LSBB has been measured not to exceed 3 $fTHz^{-1/2}$ above the 10 Hz frequency range;
- in the chamber, an analog SQUID system is installed for continuous monitoring of magnetic signatures of earthquakes; it can thus provide a direct comparison of digital and analog devices;
- higher magnetic field dynamic range, beyond the saturation of the analog SQUID sensor by external events, is needed to keep track of the absolute value of magnetic field in the case of magnetic field disturbances by phenomena of no interest. The continuous tracking of the absolute value of local magnetic field is of high scientific interest for geophysicists.

II. PRINCIPLE OF OPERATION

The pickup loop that detects the magnetic field is connected to a balanced current comparator made of two Josephson junctions, as shown in Figure 1. The comparator triggers when the sum of two currents, that of the clock Single-Flux-Quantum (SFQ) pulse and that induced by the detected magnetic field, exceeds a certain threshold, ΔI. When it happens, a new SFQ pulse is generated in the digital SQUID circuitry and transformed into a Non-Return-to-Zero (NRZ) signal by a RSFQ flip-flop cell. At the same time, an intrinsic feedback occurs in the pickup loop where the total flux is modified by one flux quantum, resetting the loop. Indeed, a fundamental property of a superconducting loop, due to the macroscopic quantum nature of superconductivity, requires that the magnetic flux in the loop be quantized.



(a) (b)

Fig 1. (a) Block diagram of the digital SQUID magnetometer. The balanced comparator is composed of two identical Josephson junctions; (b) photo of the device (courtesy of IPHT Jena): the pickup loop is seen at the bottom while the top central part connected to the loop is the balanced comparator. The top left part is the clock generator while the signal propagation and pulse shaping circuit is located to the right of the comparator.

The generated SFQ pulse is due to the switching of one Josephson junction of the balanced comparator. The pulse carries one magnetic flux quantum Φ_0 ($\Phi_0 = h/2e$ = 2.07 10^{-15} T.m^2 = 2.07 mV ps = 2.07 pH mA). Since it leaves the pickup loop, a current redistribution takes place in the loop to account for the loss of one magnetic flux quantum; this is due to the dynamics of the Josephson junction coupled to its environment. Hence, it plays naturally the role of a current feedback loop in semiconductor electronics.

The signal is then transmitted from the cryogenic to room-temperature stage and amplified before being processed. In the final step, a computer reconstructs the magnetic field waveform from the digital data. This digital SQUID type is a delta modulator and can either see positive changes of magnetic flux (it sends then positive SFQ pulses), or negative changes (negative SFQ pulses are sent in this case). The detailed explanation of the principle of operation and main properties of the digital SQUID can be found in [3]. The first experimental confirmation of simulations is described in [4].

The main asset of this rather simple digital SQUID, which only included 11 Josephson junctions, is its intrinsic very high quantized dynamic range, directly related to its slew-rate defined by the clock frequency driving the comparator sampling. The main drawback is the intrinsic flux resolution of one magnetic flux quantum Φ_0, resulting from the digital nature of its operation principle. It is several orders of magnitude lower than for the analog SQUIDs. A solution to overcome this drawback is to make use of a multi-stage version of the present design, which has been described in [5]. In this case, the price to pay is an increased complexity of the RSFQ processing unit, and a much larger number of Josephson junctions on the chip. An alternative is to combine one digital and one analog dc SQUID into a hybrid device - to take advantage of the ultimate sensitivity of analog SQUID in combination with the high dynamic range and speed of the digital SQUID. This solution has been studied in [6]. First experimental proof of principle has been validated in 2007 and is described in [7].

III. RECENT ACHIEVEMENTS

The SQUID characterization including sensitivity, dynamic range and the overnight stability was performed at the University of Savoie. A further step was the testing in real conditions at LSBB. For the last generation of devices, the detected peak-to-peak amplitude of 2810 Φ_0 has been achieved at 0.1 Hz - corresponding to a peak-to-peak field of 11.8 µT. The measured flux noise level was 220 mΦ_0.$Hz^{-1/2}$. The noise spectrum is shown in Figure 2.

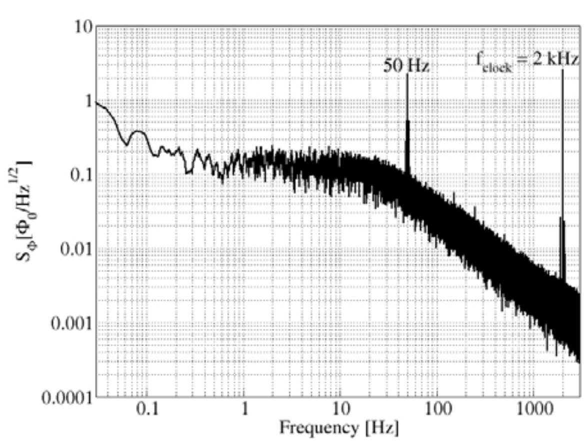


Fig 2. Measured flux noise spectral density of the digital SQUID magnetometer in unshielded conditions. No external field is applied (only the Earth's magnetic field is present). The clock frequency is 2 kHz. The duration of measurements is 128 seconds.

This performance corresponds to a dynamic range of 76 dB (around 12 bits) and to a field quantization step of 4.2 nT. Stability has been observed for several hours. All details can be found in [7]. This device has also been characterized as a current comparator by coupling inductively the pickup loop with another loop fed by a controlled current. In this case a much higher peak-to-peak amplitude of 14800 Φ_0 has been achieved, corresponding to a current resolution of 1.14 µA of the balanced comparator. The discrepancy between the performance of the digital SQUID as a magnetometer and in the presence of an inductively coupled magnetic field, localized only in the pickup loop region, is attributed to the perturbation of the digital RSFQ part of the device by the magnetic field applied in the magnetometer mode. We acted to solve this problem.

IV. MEASUREMENTS IN LSBB ENVIRONMENT

To reveal the potential problems occurring in real conditions of operation, the digital SQUID has been tested at the LSBB laboratory. Several versions have been examined during a two-week period. The cryostat with SQUID has been installed in the shielded chamber (called capsule), while the processing of data and control of the device were performed remotely from a room located just outside the chamber, about 15 meters away. Figure 3 shows both the analog and digital device setups within the chamber. Digital data were carried through USB shielded cables. In particular, we could verify that, in the case of electrical events generated by the electronics controlling the experiment (switches of power supplies, etc), some flux can be trapped in the device even if it is located far way and in an electromagnetically shielded room. That suggests that perturbations causing the flux trapping transmit through the wires connecting the superconducting device to the control electronics.

Several experiments have been performed as function of the magnetic field orientation, or with magnetic perturbations created artificially in the shielded chamber, as is shown in Figure 4, in order to ultimately correlate signals detected by both SQUID systems. In this experiment, a chair with parts made of a ferromagnetic material, has been moved in an oscillatory fashion at a distance of a few meters from the helium dewar of the digital SQUID. These oscillations have been performed in the top-down, East-West and North-South directions to generate differently oriented magnetic fields. The field seen by the digital SQUID corresponds to the component perpendicular to the device chip and is a linear combination of the East-West and North-South components. The oscillating magnetic field is clearly seen in Figure 4.

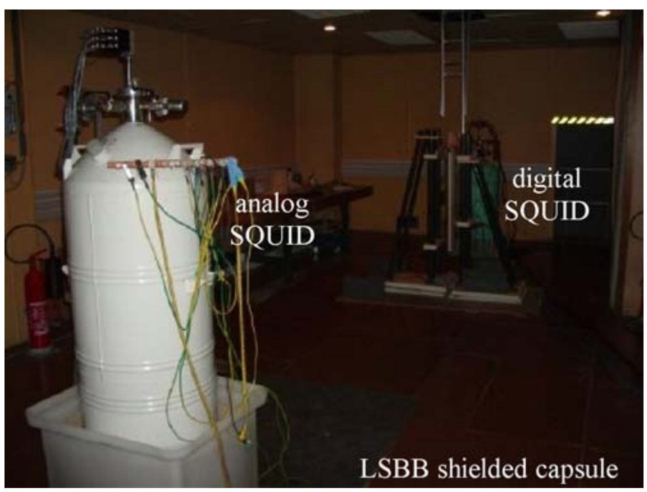


Fig 3. Setup of analog and digital SQUIDs in the shielded capsule at the low-noise facility of LSBB in Rustrel.

The different frequencies of oscillations correspond to the different directions of the magnetic field (first and third oscillation packets versus second and fourth packets) created by the chair oscillation, which was faster in one direction due to more available space for the movement. The different amplitudes of the second and fourth packets correspond to different amplitude and speed of the chair movement.

Although the sensitivity of the digital SQUID still needs to be increased by one to two orders of magnitude to be of real interest for the geophysics community, the device has proven to work with good long-term stability and was easy to operate.

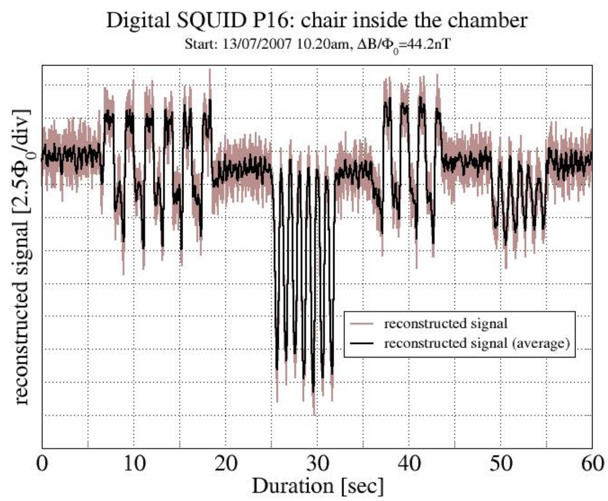


Fig 4. Reconstructed signal after post-processing of the digital SQUID data obtained in presence of a magnetic perturbation artificially created in the shielded room. The red curve corresponds to the measured signal while the black curve is obtained by doing a running average of the red curve to cancel most of the unwanted noise. The digital SQUID device used for these measurements had a sensitivity about 10 times lower that the optimized one, whose noise spectrum is given in Figure 2.

V. CURRENT STATUS AND PERSPECTIVES

At present, we already acquired a good knowledge of the design, fabrication and testing issues characteristic of this new kind of digital sensor. Hundreds of hours were spent in testing at least six different device versions corresponding to three generations of design. We solved most of the problems that have been encountered. In particular, a hybrid version of the digital SQUID, with analog dc SQUID coupled in series has been demonstrated [7]. We thus have high confidence the system can be improved to attain the specified goals. Resolution of the digital part can be improved easily as well, by increasing the size of the pickup loop; its area is currently 0.8 mm^2.

Our digital SQUID device is also intrinsically an analog-to-digital delta converter. As such, it can be used as well to monitor not only magnetic fields, but also currents or voltages, for example. This can be done up to about 1 GHz of clock frequency with the present design, but up to 30-40 GHz with a different design relying on the same technology. Complexity would remain low in any case, in the range of 10 to 50 Josephson junctions. From this point of view, our device opens the way to fast on-chip digital readout and processing of superconducting sensors needed for miscellaneous fields of applications, such as imagers for astronomy or security applications. Obviously, the eventual qualification of such devices for geophysics applications may open the way to small- to medium-scale networks for global Earth monitoring. The digital nature of the data allows one (due to its flexibility) to perform easily some complex post-processing tasks for cross-correlation purposes in particular. This flexibility, ultimately leading to lower fabrication costs, has contributed in part to the development of digital consumer electronics in the last twenty years.

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