Digitally controlled high-performance dc SQUID readout electronics for a 304-channel vector magnetometer

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Abstract. Recently, we have developed a family of dc superconducting quantum interference device (SQUID) readout electronics for several applications. These electronics comprise a low-noise preamplifier followed by an integrator, and an analog SQUID bias circuit. A highly-compact low-power version with a flux-locked loop bandwidth of 0.3 MHz and a white noise level of 1 nV/√Hz was specially designed for a 304-channel low-Tc dc SQUID vector magnetometer, intended to operate in the new Berlin Magnetically Shielded Room (BMSR-2). In order to minimize the space needed to mount the electronics on top of the dewar and to minimize the power consumption, we have integrated four electronics channels on one 3 cm x 10 cm sized board. Furthermore we embedded the analog components of these four channels into a digitally controlled system including an in-system programmable microcontroller. Four of these integrated boards were combined to one module with a size of 4 cm x 4 cm x 16 cm. 19 of these modules were implemented, resulting in a total power consumption of about 61 W. To initialize the 304 channels and to service the system we have developed software tools running on a laptop computer. By means of these software tools the microcontrollers are fed with all required data such as the working points, the characteristic parameters of the sensors (noise, voltage swing), or the sensor position inside of the vector magnetometer system. In this paper, the developed electronics including the software tools are described, and first results are presented.

1. Introduction
At the Physikalisch-Technische Bundesanstalt (PTB), a 304-channel low-Tc dc SQUID vector magnetometer has been developed for high-sensitive biomagnetic measurements which will be performed inside the new Berlin Magnetically Shielded Room (BMSR-2). This system had to be equipped with our W9-SQUIDs [1], and with read-out electronics characterized by a white noise level of 1 nV/√Hz and a moderate bandwidth of a few hundred kHz.

Additionally, systems with such a high number of channels make tremendous demands on power consumption, mounting area, and number of connecting cables. A low power consumption is required for lowering the heat dissipation. The mounting area, that is the space needed to mount the electronics on top of the dewar, commonly depends on the horizontal space between the corresponding SQUID sensors, or sensor modules. In our case, this space was predetermined to be of only 4 cm x 4 cm per 16 SQUIDs.
2. The read-out electronics for the 304-channel vector magnetometer

Basically, our dc SQUID readout electronics consist of a low-noise preamplifier followed by an integrator, and an analog SQUID bias circuit [1]. These analog circuits are embedded into a digitally-controlled system[2].

In order to meet the demands of a multi-channel system (described above), we had to design a highly-compact low-power version with a moderate flux-locked loop bandwidth and a white noise level of 1 nV/√Hz. To achieve the high compactness and to minimize the power consumption, we integrated the electronics of four channels on one 3 cm x 10 cm sized printed circuit board (PCB). Furthermore we embedded the analog components of these four channels into a combined digitally controlled circuit consisting of an in-system programmable microcontroller, digital-to-analog converters (DACs), and switches. Each device is a surface mounted device with a minimum package size. The flat passive components (resistors and capacitors in 0603 package) were mounted on the outer layer (visible on the right-hand side of Fig. 1.), while the active components were placed on the inner side.

![Image of electronics](image.png)

Fig. 1. The electronics of the 304-channel vector magnetometer of the PTB. On the right-hand side, the PCBs of one 16-channel electronics module are shown.

Four of these PCBs were combined to make modules with a size of 4 cm x 4 cm x 16 cm, which corresponds with vector magnetometer modules containing 16 low-Tc SQUIDs [3]. 19 of these modules were implemented (Fig. 1), resulting in a maximum power consumption of 61W.

3. Digital control

3.1. Communication

Each 16-channel module is connected via a 50-pole high density SCSI-connector with a so-called couple rack, that is located outside the magnetically shielded room and is attended to decouple the analog output signals. Each cable contains 16 lines for the analog output signals of the 16 channels, lines for power supply, and lines for the serial interface needed for the communication between user interface and electronics.

As serial interface we have chosen the RS-485, which is able to drive larger systems. Additionally, the RS-485 builds a half-duplex transmission system in a master-slave mode, i.e. at the same time only one device is allowed to send data whereas all the others are set to receive data. Because today the PCs are often equipped with the universal serial bus (USB) port only, we have employed an optically isolated USB to RS-485 adapter [4] without any loss in resolution.

The data transfer is based on a transport protocol that uses the readable American standard code for information interchange (ASCII) and a two digit check sum.
Some of the user instructions like “read the properties of the whole SQUID system” cause to a lot of data traffic in a 304-channel system. In order to reduce the time required to wait for the answers of such a complex instruction, the microcontroller answers to those with a data frame of a flexible length. For example: The basic instruction “set voltage bias to value xxx.xx μV” for bias adjustment is always completed with the subsequent instruction to read out the seven ADCs on board to obtain the updated values for a fast monitoring via front panel (see: user interface). This procedure takes a time of about 85 ms if a baud rate of 19200 bit/s is selected. That is fast enough to manage the 304-channel system.

3.2. Digital controlling on board
The key part in the electronics’ digital section is the microcontroller AT90LS8535 [5]. Using the content of the random access memory (RAM) of the microcontroller, this device controls the analog parts of the electronics via switches or DACs, which are also mounted on the PCB. Because the data of the RAM are lost after switching power off, the data set can be saved into the electrically erasable programmable read-only memory (EEPROM) after finishing the adjustments. The electronics always starts with the values stored in the EEPROMs. Thus, a completely adjusted SQUID system can also be operated without a PC.

Another useful feature is the capability to store properties of the SQUID in the corresponding EEPROM, such as the noise parameters determined during the SQUID characterization, or system specifics such as the position of the SQUID in the system. The first information can be used to detect changes in the SQUID parameters, while the last one helps to identify the measuring channel.

3.3. User interface
Generally, the parameters of low-Tc SQUIDs remain stable for a long time. Thus, usually the system operates with the predetermined values. However, a software tool is needed for the system initialization, and for managing the system in case of service, for instance after replacing a SQUID.
Therefore, we developed the software “SQUIDViewer” (Fig. 2.), based on LabView™. The SQUIDViewer starts with a routine, that scans the bus for the available electronics and performs a series of safety checks. In our case, the SQUIDViewer has to find the addresses of 76 operating boards. Afterwards the SQUIDViewer waits for user actions. In case hardware has been changed, the user starts with a tool allowing to assign the module name and the position of the SQUID inside the vector module to the electronics channel. After this, he opens a second tool which sorts these pre-initialized modules and gives him the opportunity to store the SQUID specific parameters in the corresponding microcontroller. Initially, these are the parameters predetermined during the SQUID characterization. For the fine adjustments, a third front panel can be used that displays and controls the electronics of the single SQUID. Finally, the user has the option to store the adjusted parameters of a single channel, a PCB, a module, or the whole system into a data file. This is helpful both for the documentation and to read back parameters into the electronics in case of a hardware replacement.

4. First results
For a system test, the vector magnetometer was characterized inside the BMSR-2 without proband. A typical white noise level of less than 2 fT/√Hz at 1 kHz the SQUID channels was measured (respectively of less than 3 fT/√Hz for the SQUIDs near the dewar bottom). At 0.01 Hz noise levels of 400 fT/√Hz for SQUIDs measuring the horizontal components, and 2-3 pT/√Hz for the z-components were detected. Applying an additional active shielding, the magnetic field noise in vertical direction was reduced by at least a factor of 5 at 0.01 Hz [6].

5. Summary
We briefly described the electronics hardware and software to control a 304-channel low-Tc vector magnetometer, which was designed at the PTB. The digital controlling allows one to initialize and to operate such a complex system very efficiently. In first measurements, we demonstrated that the combination of our vector magnetometer and magnetically shielded room form a powerful measurement system for biomagnetic signals.

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