SQUID-based multichannel system for Magnetoencephalography

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Abstract. Here we present a multichannel system based on superconducting quantum interference devices (SQUIDs) for magnetoencephalography (MEG) measurements, developed and installed at Istituto di Cibernetica (ICIB) in Naples. This MEG system, consists of 163 full integrated SQUID magnetometers, 154 channels and 9 references, and has been designed to meet specifications concerning noise, dynamic range, slew rate and linearity through optimized design. The control electronics is located at room temperature and all the operations are performed inside a Magnetically Shielded Room (MSR). The system exhibits a magnetic white noise level of approximatively 5 fT/Hz\(^{1/2}\). This MEG system will be employed for both clinical and routine use.

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SQUIDs, Magnetoencephalography (MEG), superconductivity
1. Introduction

Magnetoencephalography (MEG) is a non-invasive functional imaging technique that measures the magnetic fields generated by neuronal activity of the brain using Superconducting Quantum Inference Devices (SQUIDs). Among the available brain imaging methods, MEG uniquely features both a good spatial and an excellent temporal resolution, thus allowing the investigation of key questions in neuroscience and neurophysiology [1], [2], [3], [4], [5].

MEG measurements reflect intracellular electric current flow in the brain and so they provide direct information about the dynamics of evoked and spontaneous neural activity. Unlike electroencephalogram (EEG), MEG is not subject to interferences due to the tissues and fluids lying between the cortex and the scalp [6], [7]. As magnetic fields are not distorted by the different conduction of the skull, MEG is an excellent localization tool for subcortical sources of brain activity. It is worth noting that measured magnetic fields are due exclusively to electric current components tangential to the skull surface. Therefore the measured signals are generated mainly in the cerebral sulci and there are only minimal contributions due to neurons that present a different orientation.

MEG is a useful tool to investigate both spontaneous and evoked activities. MEG can be employed to investigate the dynamic neuronal processes as well as to study cognitive processes such as language perception, memory encoding and retrieval and higher level tasks. Moreover concerning clinical applications, it has been proved that MEG is a useful diagnostic tool in the identification, prevention and treatment of numerous disease and illnesses as it allows to study various cerebral functions. So MEG has different applications, as for example stroke, epileptic spike localization, presurgical functional mapping, and Alzheimer disease.

2. Multichannel system

Multichannel MEG systems take advantage of improvements in SQUID technology, such as reproducibility, compact readout electronics, and coil configuration. The MEG system described in this paper has been developed at Istituto di Cibernetica in Naples in cooperation with the Advanced Technologies Biomagnetics (AtB) and it is located in our laboratory inside a clinic.

This MEG consists of 163 full integrated SQUID magnetometers. A helmet shaped array hosts 154 magnetometer SQUIDs, located in a suitable way to cover the whole head of the subject, and 3 vector magnetometers (consisting of 9 SQUIDs), located 6 cm above the helmet, and used as references (Fig.2). The reference magnetometers are perfectly orthogonal and oriented along the coordinate axes.
Figure 1. In the figure the whole MEG system, realized at Istituto di Cibernetica, inside the MSR is shown. In particular the dewar realized in fiberglass is visible.

Figure 2. Helmet shaped array consisting of 163 full integrated SQUID magnetometers, realized at ICIB-CNR. The three reference triplets (consisting of 9 SQUIDs), are visible.

2.1. SQUIDs

SQUID magnetometers are very sensitive low frequency magnetic field sensors and present a spectral density of magnetic noise of a few fT/Hz$^{1/2}$ \cite{8,9}. Due to their excellent performances, SQUID sensors are widely employed in several applications ranging from biomagnetism, to magnetic microscopy, quantum computing, nondestructive evaluation test and geophysics \cite{9}. For the MEG system described here SQUID sensors have been realized using a standard trilayer technology, that ensures good performances during time and a good signal to noise ratio, even at low frequencies. Each SQUID magnetometer includes an integrated superconducting flux transformer working as a magnetic flux pickup, to increase the magnetic field sensitivity \cite{10}. The design of the sensor is based on a Ketchen-type magnetometer \cite{11}. The SQUID loop is a square planar washer with an inductance of 260 pH, coupled to a 12-turn thin film input coil with 33 nH inductance connected in series with a square single turn pickup coil of 64 mm$^2$ area presenting an inductance of 27 nH. The Additional Positive Feedback (APF) \cite{12} circuit and the feedback coil for Flux-Locked-Loop (FLL) operation \cite{13} are fully integrated on chip to avoid any additional noise due to an external APF circuit. In order to obtain a high effective flux-capture area of 3 mm$^2$, corresponding to a flux-field conversion factor of 0.7 nT/$\Phi_0$, the mutual inductance between the input
coil and the SQUID has been increased by a much higher SQUID inductance \cite{14}.

In Fig.3 we report an experimental measurement of the voltage as a function of the magnetic flux (V-Φ) for a SQUID magnetometer and magnetic flux noise spectral density measured at $T = 4.2$ K.

![Figure 3. The voltage as a function of the magnetic flux (V-Φ) for a SQUID magnetometer and magnetic flux noise spectral density measured at $T = 4.2$ K are reported here.](image)

The SQUID sensors are arranged in close proximity to each other over the helmet shaped array reported in Fig.2. This geometry requires a particular care for both wire arrangement and design of the SQUID support to minimize cross-talk \cite{15}.

2.2. Dewar

For proper operation SQUIDs have to work at a temperature of 4.2 K, reached immersing them in liquid helium. The dewar enclosing the SQUIDs is an important component and must satisfy severe requirements \cite{3}. In our system the dewar has been realized in fibreglass as this material shows both excellent magnetic properties and optimal thickness. This choice has allowed to minimize the distance between head and SQUIDs, so that the sensors are located only 2 cm away from the scalp. Furthermore, to reduce the radiation losses, several layers of mylar have been enclosed inside the inner portion of the dewar.

The dewar has a capacity of 74 liters and a helium refill interval of 7 days, thanks also to a mold realized in foam that minimizes the heat transfer, as described in section 4.
2.3. Technical equipment

The readout electronics is placed at room temperature and is based on the FLL configuration [13] with direct coupling to the preamplifier and an APF circuit [12]. The contribution of electronic noise due to preamplifier has been limited by increasing the gain of the SQUIDs [12], [15]. Each SQUID is connected to the room temperature electronics through four shielded wires. Furthermore a suitable feedback coil integrated on the the SQUID magnetometer chip, prevents the cross-talk phenomenon between adjacent channels and allows the integration of a large number of channels [16]. In this configuration the SQUIDs are directly coupled to the amplifiers at room temperature and work in optimal conditions.

Continuous data can be acquired simultaneously from all channels in the bandwidth DC-400 Hz. The measured signals are then A/D converted at a sampling frequency of 8.2 kHz and sent to a group of digital signal processors (DSP). The DSP group is controlled through the console and is used to apply digital filters. Furthermore it guarantees that all SQUID channels are sampled simultaneously at 1.025 kHz with 22-bit ADCs (Analog to Digital Converter). SQUIDs’ parameters can be changed through the acquisition console by the operator.

A block diagram of our MEG system is shown in Fig.4. SCS is the Sensor Control System, PPS is the Pre Processing System, HRM and LRM are respectively the High Resolution Monitor and the Low Resolution Monitor, HOSTX indicates computers that contain DSP cards.

Using filters ensures that the digital signal processing is the same for each channel, so that there are no delays between different channels and that there are no jitters.

In Fig.5 a preliminary measurement of the spontaneous activity recorded by the MEG
2.4. EEG system

The MEG system is also equipped with a 32 integrated non-magnetic EEG-channels cap, with ultra-thin wires and low profile of electrodes, that is optimal for usage inside a MEG helmet \[17, 18\] and sintered Ag/AgCl electrodes guarantee an optimal EEG signal quality and do not need for re-chloriding. Data are transmitted at 24-bit resolution via optical cable to USB. This system allows to digital store the data and analyze them by using both commercial and open source programs.

![Figure 5](image.png)

**Figure 5.** Here a sketch of preliminary measurement of the spontaneous activity recorded by the MEG system on a healthy voluntary subject is shown.

There is also the possibility to record EOG and ECG using additional electrodes. Scalp EEG can be inspected visually in real time.

3. MSR

Since the magnetic signals emitted by the brain are about eight-nine orders of magnitude smaller than the magnetic disturbances arising from earth magnetic field and urban noise, it is necessary to shield from external magnetic signals. The most straightforward noise reduction method is to place the MEG system within a Magnetically Shielded Room (MSR), that allows to physically reduce the environmental noise.

A block diagram of the MEG system is illustrated in Fig.4 while a sketch of our system is reported in Fig.6.
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The MSR has been realized in aluminium and $\mu$-metal to reduce respectively high-frequency and low-frequency noise. Our MSR consists of three nested main layers: a pure aluminum layer (1.5 cm) and two $\mu$-metal layers (1.5 mm). Magnetic continuity is maintained by overlay strips. The external dimensions of our MRS are $3.7 \times 4.3 \times 3.4$ m$^3$ (l × w × h), and the inner dimensions are $2.9 \times 3.7 \times 2.9$ m$^3$. All the electric connections have been designed to not introduce any magnetic noise. The floor is independently suspended.

![Figure 6](image)

Figure 6. Here we report a sketch of the Magnetic Shielded Room containing MEG system.

The low noise dewar and the MRS have allowed us to obtain a white noise level of a white noise spectrum of approximately $5 \, \text{fT/Hz}^{1/2}$ that is good if compared to the average intrinsic noise of SQUIDs realized at ICIB-CNR, that is around $2 \, \text{fT/Hz}^{1/2}$ (Fig.3).

3.1. MSR attenuation

Here we report the measurements made to characterize the performance of the shielded chamber. We have measured the response of MSR to an external applied field produced by a pair of coils for the x and y component, in the frequency range 0.01 Hz-20 Hz (Fig.7). Passive shielding factors of 17266 and 2200 at 0.1 Hz and 1 Hz respectively.
have been reported. Results are summarized in Table 1.

We have observed that when a triangular waveform is injected inside the coils, the output of SQUIDs is a sinusoidal waveform. This behaviour is explained considering that MSR filters high frequency components. It has been observed also that the attenuation in the $y$ direction is slightly lower than in $x$ direction, probably due to the presence of the door.

| Frequency (Hz) | Amplitude (pT) | Attenuation x (dB) | Attenuation y (dB) |
|---------------|----------------|--------------------|--------------------|
| 0.01          | 18700          | -34.56             | -32.80             |
| 0.02          | 18900          | -34.47             | -32.99             |
| 0.04          | 18533          | -34.64             | -33.17             |
| 0.08          | 17900          | -34.94             | -33.96             |
| 0.1           | 17266          | -35.26             | -34.56             |
| 0.2           | 14000          | -37.08             | -38.20             |
| 0.4           | 9500           | -40.45             | -44.46             |
| 0.8           | 3300           | -49.63             | -53.19             |
| 1             | 2200           | -53.15             | -56.29             |
| 2             | 650            | -63.74             | -67.34             |
| 4             | 180            | -74.89             | -79.48             |
| 8             | 48             | -86.38             | -92.55             |
| 10            | 34             | -89.37             | -95.47             |
| 15            | 20             | -93.98             | -103.43            |
| 20            | 14             | -97.08             | -107.51            |

Table 1. Measured attenuation of the MSR to an external applied field in the frequency range 0.01 Hz - 20 Hz, for the $x$ and $y$ components. The amplitude is peak to peak.

4. System thermogram

We have used a thermal imaging camera to detect radiation in the infrared range of the electromagnetic spectrum and produce thermal images (thermograms) of the MEG system. In fact, as infrared radiation is emitted by all objects above absolute zero according to the black body radiation law, thermography allows to see and to measure variations in temperature [19], [20].

From the thermograms shown in Fig.8 it is evident that this system has an excellent thermal resistance. Major variations are observed on the joints and in the proximity of the helmet, due to the reduced thickness of the dewar at those points. It is worth noting that the temperature variations are within 1°C.

As a consequence of these measures a mold in foam has been realized. When the system
Figure 7. The magnetic shielding factor of the Magnetically Shielded Room as a function of the frequency for x (black line) and y (red line) direction.

Figure 8. Thermograms (thermal images) of the MEG system taken using a thermal imaging camera to monitor the thermal losses around the dewar. The values displayed have been evaluated through a thermal analysis of IR images.

is not performing measurements, it is placed inside the dewar, where usually the head of the subject is placed, it allows to minimize the thermal swapping.
5. Spectral And Seismic Noise Analysis

We have studied the Power Spectral Density (PSD) in the MEG laboratory environment by the means of seismic noise analysis techniques [21]. Seismic instrumentation has been used to measure the effective motion inside the MEG laboratory. In fact before installing a MEG system is also necessary to perform a careful analysis of seismic noise as large mechanical vibrations can induce a low-frequency noise that affect the proper functioning of the SQUIDs.

Data were collected along 4 days, including a week-end, to study the noise in different conditions [21]. Data analysis has shown that noise inside the MEG laboratory is present especially at really low frequencies, as shown in Fig.9. We plan to introduce antivibration pads below the MSR to avoid undesired mechanical oscillations and to use noise reduction techniques, as for example active compensation and off-line software methods.

![Figure 9](image.png)

Figure 9. Power Spectral Density (PSD) of the MEG laboratory environment is shown. Unit for the spectral amplitude is $(\mu m/s)/Hz$. 
6. Conclusion

We showed main characteristics, the technical equipment and the performance of our MEG system, consisting of 163 full integrated SQUIDs developed at Istituto di Cibernetica and located in a clinical environment.

The presented MEG system presents good characteristics for clinical and routine use. The noise floor is about 5 fT/Hz$^{1/2}$ and sensor performances are stable during operation. This guarantees that high-quality MEG recordings are possible with this system.

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