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Author(s): A. N. Matlashov, R. H. Kraus, Jr., M. A. Espy, E. D. Best, M. C. Briles, E. Y. Raby, and E. R. Flynn

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Design and Performance of the LANL 158-channel Magnetoencephalography System

A. N. Matlashov, R. H. Kraus, Jr., M. A. Espy, E. D. Best, M. C. Briles, E. Y. Raby, and E. R. Flynn [a]
Biophysics Group, Los Alamos National Laboratory, Los Alamos NM 87545, USA
[a] Senior Scientific, Albuquerque NM 87201, USA

Abstract

Design and performance for a recently completed whole-head magnetoencephalography (MEG) system using a superconducting imaging-surface (SIS) surrounding an array of SQUID magnetometers is reported. The helmet-like SIS is hemispherical in shape with a brim. The SIS images nearby sources while shields sensors from ambient magnetic noise. The shielding factor depends on magnetometer position and orientation. Typical shielding values of 200 in central sulcus area have been observed. Nine reference channels form three vector magnetometers, which are placed outside SIS. Signal channels consist of 149 SQUID magnetometers with 0.84nT/Φ_0 field sensitivity and less then 3 fT/√Hz noise. Typical SQUID – room temperature separations are about 20mm in the cooled state. Twelve 16-channel flux-lock loop units are connected to two 96-channel control units allowing up to 192 total SQUID channels. The control unit includes signal conditioning circuits as well as system test and control circuits. After conditioning all signals are fed to 192-channel, 24-bit data acquisition system capable of sampling up to 48kSa/sec/channel. The SIS-MEG system enables high-quality human functional brain data to be recorded in a one-layer magnetically shielded room.

1 Introduction

In order to provide biomagnetic measurements in typical urban environments, very effective magnetic noise cancellation methods must be used. Such methods include spatial filtration of magnetic field based on gradiometer configuration of input coils, various forms of electronic noise suppression systems, large size ferromagnetic shields or magnetically shielded rooms (MSR) and superconducting shields. The most popular method at present days is a combination of a magnetically shielded room with a gradiometer configuration of input coils. Most modern large scale MEG measuring systems include a MSR and gradiometric input coils of one form or another. MSRs, however, have several inherent limitations and usually result in significant inconvenience for users. Consequently, MEG system designs that can provide biomagnetic measurements without using a MSR remain an important and valuable pursuit.

A five-channel system with electronic noise subtraction in addition to highly balanced input gradiometer coils was designed by SHE (later BTi) in the mid-1980's [1]. Similar ideas are still in use by CardioMag Imaging in their very efficient multi channel magnetocardiogram (MCG) systems [2]. The first large scale MEG systems that can work without a MSR were designed by CTF. Those systems were based on simple first-order input gradiometers combined with very sophisticated electronic methods of ambient noise suppression [3]. All of these approaches for noise reduction are based on evolutionary improvements of previously proposed "classical" ideas.

A few "non-classical" approaches were proposed over the same timeframe, however these ideas were not implemented due to a lack of necessary technology or theoretical framework to predict the effects. For example, it has been suggested that electronic noise cancellation methods similar to what have been developed by CTF could be realized with almost ideal accuracy by using modern digital so called RSFQ (rapid single-flux-quantum) SQUIDs with practically unlimited (for biomagnetic signals) dynamic and frequency range [4]. Unfortunately practical RSFQ SQUIDs exist even today primarily in concept and theory similar to DC SQUIDs in the beginning of the 1970's.

There have also been passive noise reduction methods suggested using are new technologies and approaches. For instance, discovery of high-temperature superconductivity (HTS) in 1986 led to the design of an absolutely new kind of large-scale shield for biomagnetism – a large size HTS superconductive shield with 77K working temperature [5]. Although this shield has extremely high shielding factor, the unit severely impacts convenience for practical applications and is extremely expensive.

Our system is based on the concept of incorporating a low temperature superconductive shield (Superconducting Imaging Surface, SIS) that is small enough to be placed inside a helium dewar together with LTS

SQUID array [6]. Our experimental results demonstrate the efficiency of such shielding performs as well as gradiometer coils. Combining our SIS system with a single-layer MSR gives similar result to using expensive gradiometers inside a moderate MSR. At the same time our design has some advantages and greater potential for further improvements than conventional gradiometer-based systems. The SIS decreases both uniform magnetic field and also all its spatial gradients. Additionally, the shielding factor of the SIS is frequency independent because of the nature of superconductors.

A computational modeling code to model the forward physics of the SIS for our MEG system was developed [7]. This code is now being used to design new superconductive shield geometries that enable significantly greater shielding factors using either LTS or HTS materials. This approach can lead to building a large scale MEG systems that can function without using any MSR.

2 Superconducting Imaging Surface and SQUID Array

The system consists of hemispherical superconductive shield and a DC SQUID magnetometer array placed inside the hemisphere. Magnetic sources within the hemispherical superconductive shield cause Meissner currents on the superconductor surface resulting in a distorted magnetic image of the source, consequently the name 'superconducting imaging surface' or SIS. Typical shielding values of 200 in central sulcus area have been observed, independent of noise source or frequency. The shielding decreases smoothly by about a factor of ten at the sensors nearest the brim area.

The sensor array consists of 149 SQUID magnetometers. Each SQUID magnetometer measures the superposed magnetic field from a magnetic source and it's image. We have designed and experimentally tested a computational model that completely describes the effect of the SIS on any given magnetic source field distribution [8]. The spatial accuracy of source localization has been experimentally measured using our 63-coil phantom. The phantom consists of 21 small triplet coil sets placed at different distances and orientations from SQUID magnetometer array. Each set consists of three mutually orthogonal coils one of which is orthogonal to a common phantom radius. Source localization was performed using a simple minimum norm inverse solution approach. We demonstrated an average phantom source localization accuracy of about 0.2 mm, and worst case localization accuracy of 0.4 mm. These results demonstrate that the SIS forward physics are completely described in our computational model and solving the inverse problem is no more difficult than other conventional multi channel MEG systems.

The SIS is about 140mm radius hemisphere made from lead with 50mm brim around its edge. All SQUID sensors are orthogonal to SIS radius and placed at different distances to the SIS (minimizing the head-sensor spacing) in the range from about 10 to 30 mm. Each SQUID sensor is placed in a button-shaped package that is 19mm diameter and 4mm thick [9, 10]. The SQUID sensor is built using one-chip niobium SQUID magnetometer with about 8×8 mm^2 pick-up coil glued to 0.5 mm thick printed circuit board (PCB) and protected using glued fiberglass cover. Each SQUID chip is bonded to PCB pads that are connected through vias to external wires. Each magnetometer uses six contacts – two contacts for SQUID output, two for feedback and modulation signals, and two for a heater. The field sensitivity is 0.84 nT/Φ_0 and the field resolution is better than 3 fT/√Hz.

In addition to 149 signal channels there are 9 reference channels. The reference channels consist of three separated vector magnetometers. All reference channels are placed outside of the SIS. System performance for source localization and shielding factors did not use the reference sensors.

One copper and two phosphor bronze twisted wire pairs are used per SQUID magnetometer to connect it to room temperature connectors. Wires for 32 SQUID magnetometers are placed inside one 6.5 mm diameter helical stainless steel tube. There are six such tubes in the system soldered to the lead brim of the SIS. Room temperature ends of the tubes go to aluminum connector boxes, one box for every 32 channels. There are two 68-pin SCSI connectors per box, each connector provides connections for 16 SQUID magnetometers. A separate 68-pin connector is used to connect groups of 32 SQUID magnetometers heater control signals.

The sensors and SIS are placed inside a fibreglass whole-head dewar with typical SQUID – room temperature separation is about 20mm in the cooled state. The dewar holding time is about three days.

3 Electronics Architecture

Sixteen channels of feedback flux-lock (FFL) electronics are housed per enclosure and all signals are carried in a single 68-pin shielded SCSI connector/cable. Each 16-channel FFL unit provides all necessary signals and communication for 16 SQUID magnetometers and provides 16 differential outputs and 16 differential inputs. The bias current, course and fine offset adjustment, run/tune mode, reset command, etc. can be remotely controlled. The electronics are entirely self contained and controlled by serial communication with a dedicated PC or the MEG system operator interface computer. The FLL units have dimensions W260×D250×H90mm^3 and placed 2m apart from SQUID connectors.

Six FLL units are connected to one 96-channel control unit using standard 15m SCSI cables. The differential inputs can be connected to an electronic noise suppression system (ENSS, currently under development) using standard 50-wire SCSI cables. There are two hardware independent control units allowing up to 192 total SQUID channels (primary and reference). The control unit includes signal conditioning circuits, internal software controlled signal test generator, multiplexers to control all output signals using both BNC and DB25 connectors and a digital communication interface. The input digital control signal comes using standard RS232 interface. Each SQUID electronics channel provides about 80kHz small signal frequency range and slew rate more than 10^5 Φ_0/sec. The electronics have been designed in cooperation with Cryoton Ltd. and built by Cryoton Ltd [11].

After conditioning all differential outputs of the SQUID electronics are fed to 192-channel, 24-bit data acquisition system ICS-110B capable of sampling up to 48 kSA/sec/channel continuously [12].

4 Conclusion

We built and tested the first biomagnetic measuring system using the superconducting image surface approach. The SIS-MEG system enables high-quality human function brain data to be recorded inside a moderate magnetically shielded room. We are currently pursuing further development of the SIS design that will lead to ability to build a large scale MEG system that can produce SQUID-noise limited data without any MSR.

5 Literature

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