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A second-order SQUID gradiometer operating at 77 K

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Abstract. We describe a portable second-order electronic SQUID gradiometer cooled with liquid nitrogen and capable of operating in unshielded space. The measured magnetic-field resolution is <300 fT $Hz^{-1/2}$ and <170 fT $Hz^{-1/2}$ when operating in the first-order mode. The gradiometer was successfully used for the recording of screening magnetocardiograms of over 200 human subjects at four different geographic locations.

1. Introduction

We reported earlier on a first-order, electronic SQUID gradiometer cooled by liquid nitrogen, i.e. operating at 77 K, and also sensitive enough to measure biomagnetic signals in the absence of any magnetic shielding [1, 2]. Recently, we extended the same system concept to a portable second-order gradiometer. Here, we present a preliminary description of its construction and performance. We also discuss some details of the adopted approach. All other background information can be found in references [1] and [2]. As is customary in SQUIDs, for biomagnetic measurements the gradiometer is used to measure magnetic fields of a localized source, rather than gradients. The gradiometric configuration permits us to reject the common mode and gradients due to other, undesired sources. Consequently, to define the sensitivity of interest to the user, we indicate the magnetic field resolution (B_N in fT $Hz^{-1/2}$) rather than the gradient resolution (in fT m^{-2} $Hz^{-1/2}$).

2. SQUID sensors and flux concentrators

Three epitaxial $YBa_2Cu_3O_7$ (YBCO) thin-film washer RF SQUIDs with step-edge junctions were positioned in parallel planes 2, 3 and 4 as shown in figure 1. The planes were separated by the same vertical base distance of 6 cm. When measured in a magnetic shield, the three SQUIDs had similar properties, summarized in table 1. Their field resolution and symmetry were improved by sandwiching each washer with a bulk YBCO semiconical flux concentrator disc having an outer diameter of 25 mm and a hole of 5 mm, in which the tank circuit coil was positioned. A much smaller hole would significantly reduce the coupling between the tank coil and the SQUID loop. Each disc was cut along its diameter, to prevent a short-circuit loop, and the two parts were glued together, with the glue serving as an insulator. The resulting magnetic field/flux transformation coefficient was $\partial B/\partial F \simeq 0.5$ nT/Φ_0 in all three SQUIDs, an improvement by a factor of three (compared with data of table 1) [3].

The bulk flux concentrators not only increased $\partial B/\partial F$, but also dramatically improved the magnetic symmetry of our washers. In the absence of concentrators, the first-order gradiometer slowly oscillated in the earth field, as described in [2], and could not be balanced to better than $\simeq 2 \times 10^{-2}$, while with concentrators $\simeq 3 \times 10^{-4}$ could be attained. We speculate that the near-edge regions of our thin-film washers could have been quite non-uniform. Shielding by bulk concentrators may have improved the effective uniformity.

3. Cardanic suspension fixture, shielding and electronics

The SQUIDs were mounted in a non-magnetic fixture with two cardanic ring suspensions. This was an extension of that described in [2]. All fixture parts, except for the springs, were machined from 25% fibreglass-

Table 1. Shielded washer SQUID properties, $f_T = 150$ MHz, $\beta_L = 2\pi I_c L_s/\Phi_0 \simeq 1$.

Parameter	Value
SQUID hole area (μm^2)	200 × 200
Washer area (mm^2)	8 × 8
Inductance, L_s (pH)	300
Transfer function, $\partial V/\partial\Phi$ ($\mu V/\Phi_0$)	60
Spectral density of flux noise at 1 Hz (Φ_0 $Hz^{-1/2}$)	1×10^{-4}
Energy resolution 1 Hz, ε (J/Hz)	$<7 \times 10^{-29}$
Field/flux transformation coefficient, $\partial B/\partial\Phi$ (nT/Φ_0)	1.5
Field resolution, B_N ($fT/Hz^{-1/2}$)	150

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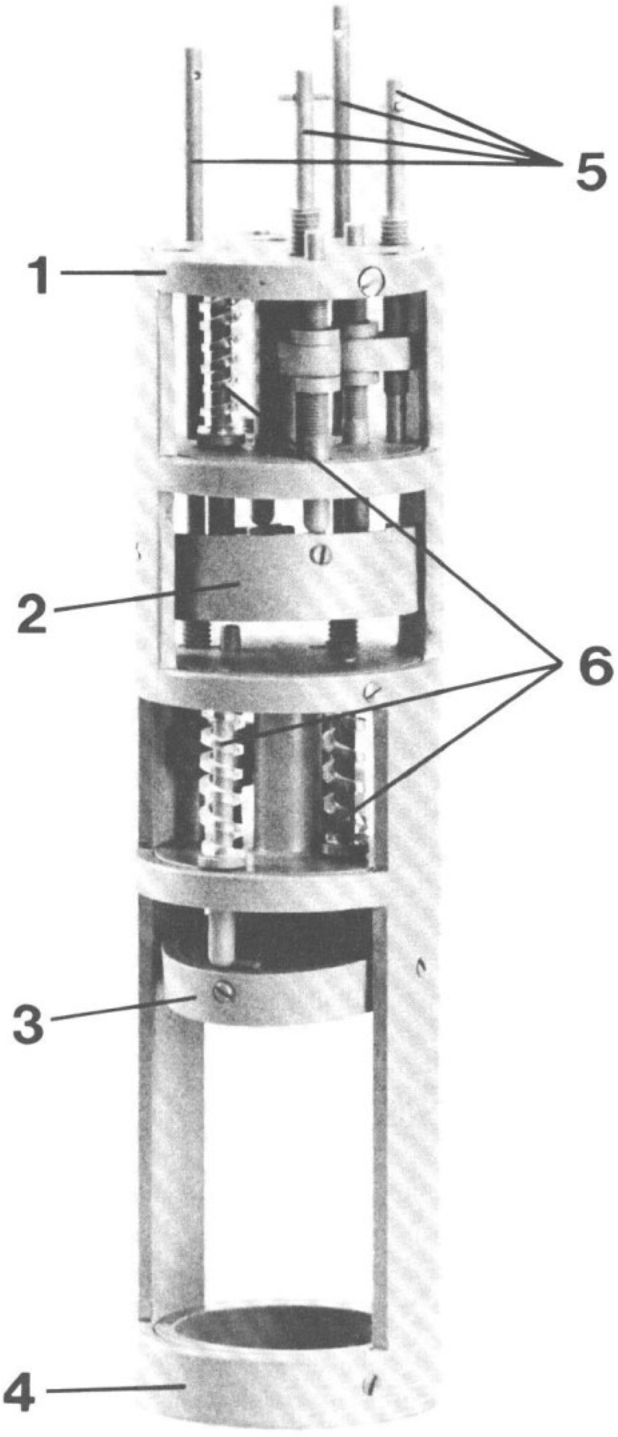

Figure 1. Photograph of the gradiometric fixture (right). Labelled are: 1, tubular support; 2, 3 and 4, planes with suspension rings holding washers and flux concentrators; 5, control rods; 6, spring-loaded bolts.

reinforced Teflon. Springs were made from plexiglass. A photo of the present, improved fixture is shown in figure 1. In contrast to [1, 2], differential thread controls were used for fine-tuning (balancing) of suspension rings. Additional advantages of these controls were to eliminate the rotation of pushing rods (which in [1, 2] resulted in some ambiguity of optimum balance position), and the possibility of shifting the control rods for the cardanic ring in plane 3 to outside the upper flux concentrator in plane 2. The fixture and the surrounding RF shield were rigidly mounted in a low-self-noise fibreglass cryostat filled with liquid N_2, and suitable for biomagnetic measurements [2].

The RF shield consisted of a perforated lead cylinder. The low normal conductivity of lead prevents additional noise due to induced currents, which was always observed, especially in SQUID A, when using a highly conductive copper shield. The perforation permitted the gaseous N_2 to freely escape from the inside of the fixture without bubble formation in the liquid, which may also cause additional noise.

The SQUID tank frequency was $f_T = 82$ MHz. Three RF SQUID electronics sets with low-noise preamplifiers (1.5 nV $\mathrm{Hz}^{-1/2}$ noise voltage, referred to the input) were identical with those of [1, 2] and formed three SQUID channels: A (SQUID in plane 4), B (plane 3) and C (plane 2). Outputs of these channels could be electronically subtracted and balanced while the simultaneous direct read-out was also possible. The outputs were filtered by bandpass filters, usually set for a bandwidth of 0.3 or 2 to 30 Hz in order to additionally suppress the 50 Hz line frequency signal and its harmonics. The slew rate measured for each of the three channels was $1 \pm 0.3 \times 10^5\ \Phi_0\ \mathrm{sec}^{-1}$.

4. Balancing procedure

The gradiometer was balanced, in an unshielded laboratory space. First, the lower first-order gradiometer set (A − B) was balanced by adjusting the B plane (3 in figure 1) with respect to A (4) as described in [2], i.e. by slowly oscillating the whole cryostat in the earth field. Subsequently, the upper set (B − C) was balanced in the same way with plane B fixed and C (2) adjusted. Alternatively, the second-order output A − 2B + C was balanced by adjusting plane C (2) to minimize the field gradient due, e.g., to a $\simeq 4$ m distant Sm–Co magnet rotated around its axis at two positions orthogonal with respect to the axis of the cryostat and to each other. As already mentioned, a first-order imbalance (A − B)/B of only 3×10^{-4} could be attained. The best gradient rejection was >100. This made it possible to operate the second-order gradiometer also in the presence of mobile nearby magnetic objects such as office furniture and cars. The duration of the whole balancing procedure was no more than 30 minutes. After balancing, multiple thermal cycling of the system between 77 and $\simeq 300$ K hardly perturbed the balance, so that (A − B)/B of 5×10^{-4} could be maintained without any readjustments. The balance was also insensitive to car transportation over large distances. After travelling over 2000 km, no adjustment was necessary. System portability was thus ensured.

5. System performance

After a proper balancing, the field resolution of the whole system in the flux-locked loop (FLL) mode was

$B_N < 300$ fT Hz$^{-1/2}$ between 1 and 30 Hz, and was limited by a relatively high $1/f$ noise in channel C. The first-order A − B gradiometer resolution was $B_N \simeq 170$ fT Hz$^{-1/2}$, as can be seen in the noise spectrum shown in figure 2. This shows that the $1/f$ noise contribution of the bulk YBCO flux concentrators is relatively low. Table 2 summarizes the system performance in the absence of any magnetic shield.

We should note that the performance given in table 2 could only be attained with selected SQUID washers having a step-edge junction uniformity such that no parasitic quantization periods appeared, and no resulting modulation of the SQUID signal occurred in stronger external fields. Unfortunately, only a very small fraction of the washers fabricated to date, fewer than 3%, exhibited the requisite uniformity and stability of operation in the absence of magnetic shielding. Consequently, selecting three washers with sufficiently similar characteristics has been difficult.

The effectiveness of gradient rejection in the second-order gradiometer configuration is illustrated in figure 3(*a*) and (*b*). The effect of a passenger car, passing by at a distance of 15 m, on the first-order is shown in the lower trace of figure 3(*a*). The upper trace shows a magnetocardiogram (MCG) of a male subject, simultaneously recorded as the second-order gradiometer output. A signal distortion attributable to the event can hardly be noticed. The lower trace in figure 3(*b*) is the first-order output in the presence of external quasi-periodic field caused by on/off switching of a nearly resistive load by a bimetal switch, and by a metallic chair diplacement. The upper trace is the MCG recorded simultanously at the second-order output. The trace is, again, almost unaffected. Indeed, figure 3 demonstrates visually the superior performance of the second-order gradiometer and its suitability for measurements in unshielded space. In the FLL mode, the system can tolerate AC ambient fields below 200 nT. It is, however, unable to operate in the presence of transient fields of up to and in excess of 1 μT amplitude, which are typical of an urban clinical environment, with many other diagnostic and therapeutic systems operating nearby, and with electric trolleys in the vicinity [4]. For such an operation, the development of an additional, active compensation of strong external fields would be necessary.

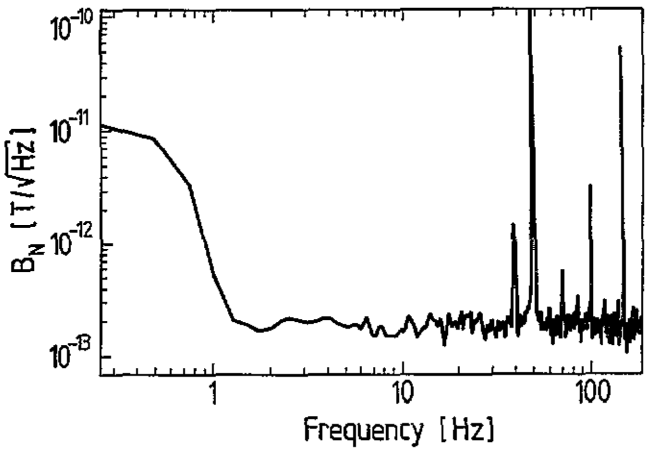

Figure 2. Noise spectrum of the first-order gradiometer (A − B), measured without any shielding and bandpass filtering.

Table 2. Performance of second-order gradiometer in unshielded space.

Parameter	Value
Field/flux coefficient, $\partial B/\partial\Phi$ (T/Φ_0)	5×10^{-10}
Noise amplitude (peak-to-peak) (T)	2×10^{-2}
Spectral field resolution, B_N (fT Hz$^{-1/2}$)	
first-order gradiometer (A − B)	<170
second-order gradiometer (A − 2B + C)	<300
Bandwidth, Δf (Hz)	0.3 to 30 or 2 to 30
Slewing rate, $\partial\Phi/\partial t$ (Φ_0 sec^{-1})	1×10^5
Dynamic range (dB)	150 ($\simeq 1000\ \Phi_0$)
Common-mode rejection	>3000
Gradient rejection	>100

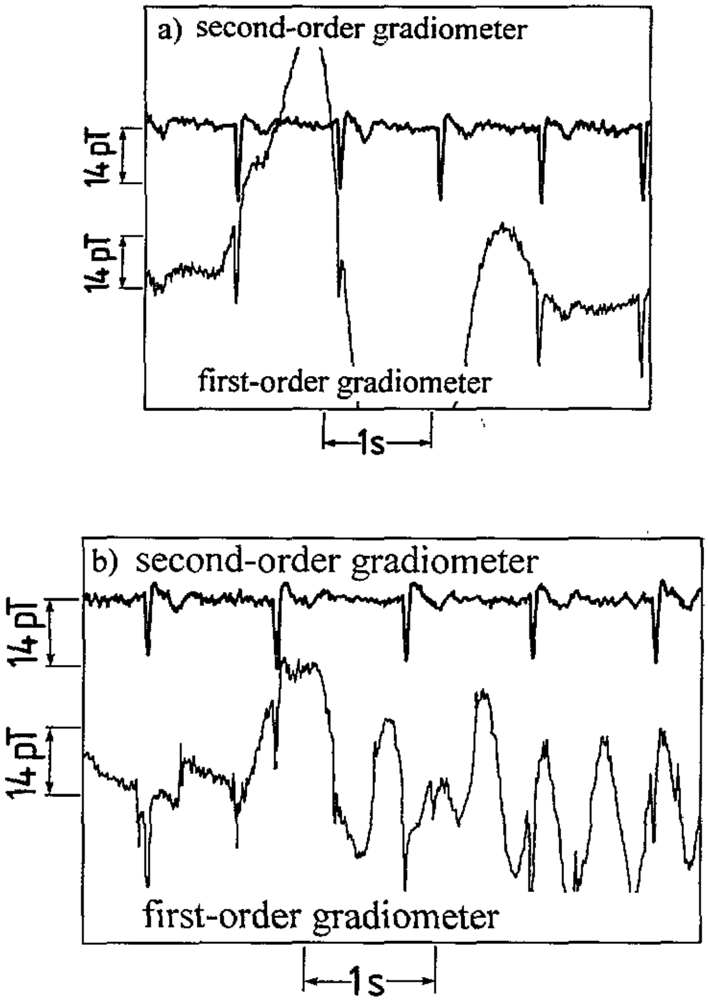

Figure 3. Comparison of first- and second-order gradiometer outputs during a real-time MCG measurement (see text for description).

6. System applications

The system was used for screening MCG measurement of over 200 human subjects at four different urban locations in three European countries. About 10% of the subjects exhibited clear MCG abnormalities, which in almost all cases could be correlated with previously diagnosed heart disease. In a shielded room, the first-order system was also used for magnetoencephalography of evoked responses of human cortex [5]. One study of biomagnetic responses of animals was also conducted [6]. Usefulness for several non-destructive material evaluation (NDE) applications was verified.

7. Outlook

With the present type of YBCO RF SQUID washers, the system sensitivity can be increased electronically, by more than a factor of two, through the increase of the tank frequency. We are now developing SQUID electronics with f_T between 300 and 500 MHz, and project the resulting B_N to be <100 fT Hz$^{-1/2}$ above 1 Hz. We also expect to extend the bandwidth up to several hundred Hz through the implementation of digital electronics with comb filters, presently under development. Investigation of active compensation schemes is pending.

Further sensitivity improvements are attainable through optimization of SQUID washers and flux concentrators, including washers with current-injection pick-up loops [7] and, eventually, through the use of sensors integrated with low-noise HTS flux transformers [7, 8]. We believe that a system having a B_N of 10 to 30 fT Hz$^{-1/2}$ is feasible and could, eventually, replace most of the present liquid-helium-cooled biomagnetic systems. Obviously, the concept of an electronically and mechanically balanced gradiometer described here can be equally well exploited with RF and DC HTS SQUID sensors. However, this concept may not be very attractive for multi-sensor systems, since it has three times the number of electronic channels and a complicated mechanical construction.

Acknowledgments

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