Two methods for a first order hardware gradiometer using two HTS SQUIDs

M. A. Espy, E. R. Flynn, R. H. Kraus, Jr., and A. N. Matlashov
Los Alamos National Laboratory, Los Alamos, New Mexico, 87545

***Abstract*—Two types of first order electronic gradiometers have been developed using high temperature superconducting (HTS) SQUIDs. Gradiometry is accomplished in hardware by either 1) subtracting the output of the signal and background SQUIDs in a summing amplifier (parallel technique) or 2) converting the inverted background SQUID output to a magnetic field at the sensor SQUID (series technique). Balance levels achieved are 2000 and 1000 at 20 Hz for the parallel and series methods respectively. Balance level as a function of frequency is presented. Balance level for hardware gradiometry is limited by time delays from the electronics and how well the signal amplitudes are matched. A simple algorithm that allows one to estimate the limit on balance level from these factors is presented and compared with data.**

I. INTRODUCTION

This paper presents two systems for first order electronic gradiometry in hardware using two similar HTS SQUID magnetometers. The first technique, parallel gradiometry, subtracts the output of a background SQUID and a signal SQUID in a summing amplifier. In the second technique, series gradiometry, the background SQUID output is converted to a magnetic field at the signal SQUID, preserving the signal-SQUID's dynamic range.

We discuss two factors that limit the balance level in gradiometers: how well matched the amplitudes of the signals being subtracted are and any time delays between them. In the discussion of these two gradiometers this paper explores crucial differences between electronic and wire-wound gradiometers. In wire-wound gradiometers the signal amplitudes depend on geometry (one can in principle have mechanical adjustment mechanisms but they are complicated and time consuming) and there is no time delay between the signals. In electronic gradiometers the signal amplitudes can be easily adjusted to very high precision but the signals may be out of phase from time delays caused by the electronics.

Balance level is defined as the ratio of the amplitudes of a uniform field measured by the signal SQUID without and with gradiometry. We present the theoretical "best" balance level one may attain, considering the limitations of time delays in the electronics and the matching of signal amplitudes. The behavior of both devices is that of a first order gradiometer with balance level limited by these two factors. A more complete discussion of the ideas put forth in this paper can be found in [1].

Manuscript submitted September 15, 1998.
This work was supported by the United States Department of Energy

II. DESCRIPTION

Both gradiometers used two Conductus HTS SQUID magnetometers with Conductus pcSQUID™ electronics [2], controlled via a personal computer. The SQUIDs were mounted in an axial gradiometer configuration, with their central axes aligned along a common axis. Both SQUIDs fit snugly inside a fiberglass tube placed vertically inside a fiberglass dewar. The distance between the two SQUIDs was 1 cm.

For parallel gradiometry, the output of both the background and signal SQUID went to a summing amplifier where the gains were adjusted and the difference was taken. For series gradiometry, the output of the background SQUID was sent to the amplifier for gain adjustment and then summed with the feedback current of the signal SQUID. This effectively "nulled" the background field at that SQUID. The series technique realizes the goal of eliminating most of the background fields seen by the signal SQUID and preserving the dynamic range.

III. TIME (τ_{DELAY}) AND PHASE (θ) DIFFERENCE: IN THEORY

Two main factors limit the balance achievable in any multi-SQUID gradiometer: differing signal amplitudes at the time of subtraction and time delays in each SQUID system. Signal amplitudes depend on geometrical considerations for a wire-wound gradiometer: the two SQUID pickup loops should be identical in area. With an electronic gradiometer there are two individual signals to be scaled. The requirements for proper alignment are the same for both wire-wound and electronic gradiometers. The time delays in the SQUID systems are a problem unique to electronic gradiometers.

A finite amount of time is required for the source magnetic field detected by a SQUID to be converted to a voltage output at the SQUID electronics. The time delay causes a phase difference between the source signal and the SQUID response that is a function of the signal frequency (discussed below). In the case of the parallel gradiometer the existence of these time delays is not problematic, however they must be *identical* for the two SQUIDs in order for the signals to be in phase (resulting in maximum cancellation) at the amplifier when subtracted. As the frequencies increase, a fixed difference in the time delay results in an increasing phase difference, causing balance level to deteriorate. For the series gradiometer any time delays in the electronics degrade gradiometer performance because the output of the background SQUID has to propagate through the electronics to the signal SQUID to cancel the real-time background field. This causes an inherently out-of-phase background cancellation. Thus the goals for the SQUID electronics time delay tuning are

1) that the time delays be identical for the parallel gradiometer and 2) minimized in the case of a series gradiometer.

To estimate time delays and resulting phase differences consider the small-signal closed-loop frequency response, $A(f)$, for a flux-locked loop circuit with signal-lock feedback and a one-pole integrator [3]

$$A(f) = \frac{G_f}{(1+G_f)}, \tag{1}$$

where G_f is the open loop gain defined as the complex number

$$G_f = \frac{V_\Phi G_I(f) M_{fb}}{R_{fb}} = \frac{f_1}{if}. \tag{2}$$

V_Φ is the SQUID transfer function at the working point of operation, $G_I(f) = 1/(i2\pi fRC)$ is the gain of an ideal one-pole integrator with resistance R and capacitance C, $i = \sqrt{-1}$, R_{fb} is the feedback resistance and M_{fb} is the feedback coil coupling. Using (2) f_1, the unity-gain frequency of the feedback loop, can be written as

$$f_1 = \frac{V_\Phi M_{fb}}{(2\pi RCR_{fb})}. \tag{3}$$

In this case, the closed loop frequency response $A(f)$ with the one-pole integrator is identical to that of a first-order low pass filter with a 3-dB cutoff frequency, f_c, and $f_1 = f_c$.

Using (1) and (2), the small signal phase shift, θ, is

$$\theta = \arctan\left\{\frac{\mathrm{Im}[A(f)]}{\mathrm{Re}[A(f)]}\right\} = \arctan\left[\frac{f}{f_1}\right] \approx \frac{f}{f_1} \tag{4}$$

at low frequencies.

The phase, θ, is related to time delays by

$$t_{delay} = \frac{\theta}{(2\pi f)} = \frac{1}{(2\pi f_1)}. \tag{5}$$

IV. Measured θ and T$_{DELAY}$

From (4) and (5) in the preceding section one can see that for any time delay in the system there is a corresponding phase difference that increases with increasing frequency. Thus, as noted above, the parallel and series two-SQUID gradiometers are generally optimized by both matching and minimizing time delays for both SQUID electronics. Matching the time delays is achieved by matching the small-signal cutoff frequency, f_1, for both background and sensor SQUID electronics. Minimizing the delays is achieved by making f_1 as large as possible.

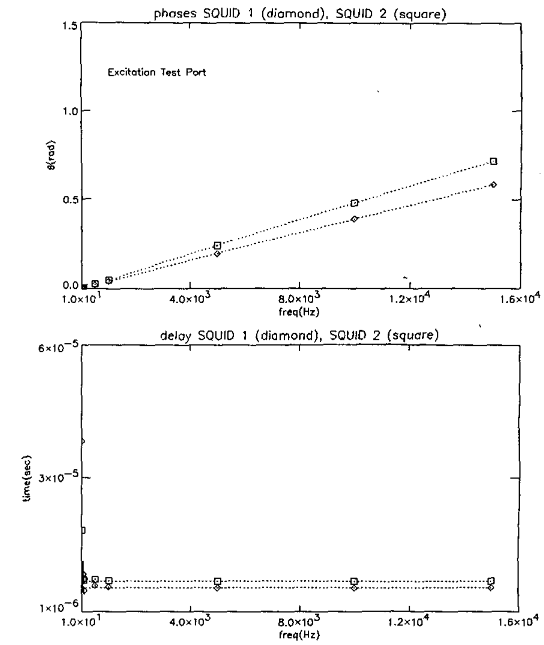

Fig. 1. Upper panel: Data points are measured phase difference, θ, between function generator signal and the SQUID response. The dotted line is a best fit to the data. Lower panel: Data points are the calculated t_{delay} for each θ. Dotted lines are the t_{delay} predicted from the best fit.

The two HTS SQUIDs used were similar in their feedback coil coupling, and the peak-to-peak amplitudes of their V-Φ curves. Eqn. (3) illustrates that this similarity means the f_1 of the two SQUIDs will be as alike as possible. Both SQUID magnetometers also had similar effective areas of ~0.08 mm^2, and white noise levels $<2\times10^{-13}$ T/√Hz.

The time delay was measured experimentally in a shielded can using a function generator to supply a test signal (~0.25 Φ_0 amplitude) to the feedback coil. The phase difference between the test signal and the SQUID's response were measured as a function of frequency by a lock-in amplifier. The results are plotted in Fig. 1.

In the upper panel of Fig. 1 the phase data are shown along with the polynomial fits to the data (dotted lines). The low frequency approximation of (4) predicts the phase vs. frequency behavior should be a linear function of the frequency, and the slope should be equal to $1/f_1$. The best fits to the data give f_1 of 25.8 kHz and 21.0 kHz for the background and signal SQUIDs respectively. f_1 is clearly linear with frequency and the measured f_1 are consistent with 20 kHz, which we measured previously. The lower panel of Fig. 1 shows the time delays corresponding to the phase data and the f_1 obtained from the fits. The data and best fit predictions are in good agreement. The measured time delays for the background and sensor SQUIDs are ~6.2 μs and ~7.6 μs respectively.

V. Theoretical Limit to Balance

If we use the measured time delay for either SQUID, t_{delay1} = 6.2 μs and t_{delay2} = 7.6 μs, then we can predict the balance level limit due to these time delays. Assuming a sine wave signal of amplitude, K, one can predict the balance level, $\gamma(t_{delay})$ as

$$\gamma(t_{delay}) = \frac{|\Sigma|}{|\Delta|}, \tag{6}$$

where

$$\Delta = K_1 \sin(\omega t - \omega t_{delay1}) - K_2 \sin(\omega t - \omega t_{delay2}) \tag{7}$$

and

$$\Sigma = K_2 \sin(\omega t - \omega t_{delay2}), \tag{8}$$

In the above equations, $\omega = 2\pi f$, where f is the frequency of interest. t_{delay} is the delay time.

If we assume that $K_1 = K_2$, and use the small angle approximations

$$\cos(\omega t_{delay}) \approx 1, \tag{9}$$

$$\sin(\omega t_{delay}) \approx \omega t_{delay}, \tag{10}$$

we can write

$$\gamma(t_{delay}) = \frac{1}{\omega\left|t_{delay1} - t_{delay2}\right|} = \frac{1}{\omega \delta t_{delay}}. \tag{11}$$

To estimate the effects of not matching the signal amplitudes, let us assume that $|K_1| = a\ |K_2|$, where a is a scaling factor close to 1. As with wire-wound gradiometers the difference in signal amplitude may arise from having pick-up coils with different area or alignment. But unlike wire-wound gradiometers there are now two (or more) separate SQUID signals, which can be electronically scaled with very high accuracy (about one part-per-million). In this case, again using the small angle approximation, we find the balance level to be

$$\gamma(t_{delay}, a) = \frac{1}{\sqrt{(1-a)^2 + \omega^2 \delta t_{delay}^2}}. \tag{12}$$

VI. Operation in a Shielded Environment

The balance levels for both techniques were measured with the SQUIDs inside a shielded can using an external test coil driven by a sine wave signal from a function generator. The magnetic signal was about 0.25 Φ_0 at each SQUID. The measured balance level for both gradiometers are presented in Fig. 2 as data points. The balance levels predicted by a best fit to (11) are shown as dotted lines, with δt_{delay} allowed to vary. The balance levels predicted by a best fit to (12) are shown as dashed lines, where both a and δt_{delay} were allowed to vary. There is no feasible way, a priori, to determine a. It depends somewhat on how well the SQUIDs are aligned and oriented. However, because we can use the gains on the amplifier to account for most of the effects of mismatch (something one cannot do with a wire-wound gradiometer), one qualitatively expects that a will not be more than 1±0.10.

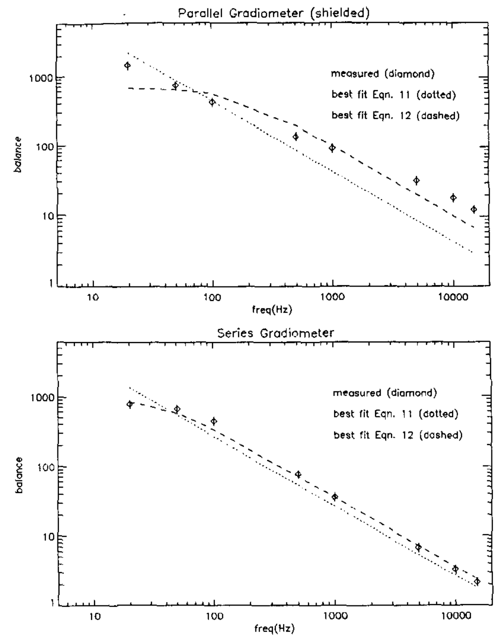

Fig. 2. Upper panel: Measured and predicted balance levels for parallel noise cancellation. Lower panel: Measured and predicted balance levels for series noise cancellation. Measurements were performed with the SQUIDs inside a magnetically shielded can.

For the parallel method the fit to (11) (dotted line in the upper panel) we found δt_{delay} = 3.64±0.21 µs. The best fit of the data to (12) (dashed line) gave a = 1.0015±0.0002 and δt_{delay} = 1.55±0.11 µs. The latter is in good agreement with that expected from our phase measurements, δt_{delay} = (7.6 - 6.2) µs = 1.4 µs.

For the series method the fit to (11) (dotted line in the lower panel) we found δt_{delay} = 5.95± 0.32 µs. The best fit of the data to (12) (dashed line) gave a = 1.0011±0.0002 and δt_{delay} = 4.45±0.26 µs. The upper limit on δt_{delay} can be estimated by assuming δt_{delay2} will be less than the sum of the delays for the background and signal SQUIDs. From this we expect $\delta t_{delay} \leq$ 13.8 µs - 6.2 µs, or $\delta t_{delay} \leq$ 7.6 µs. This is true for both fits.

Fig. 2 clearly shows that both the parallel and series gradiometers behave as devices with a balance level limited by the phase shifts in the electronics. Therefore, reducing time delays in the electronics will allow even better balance levels than we report here. We also see that even small differences in the values of K_1 and K_2 (a not quite 1) can result in a large difference in the achievable balance level, especially at low frequencies. This reinforces the need for great care in matching SQUID signal amplitudes.

VII. Operation in an Unshielded Environment

The SQUID gradiometers were also characterized in the unshielded laboratory. The SQUIDs were dominated by 60 Hz and harmonics caused by the power lines. The white noise floor at 4.5 kHz for the background and signal

SQUIDs were 1.75×10^{-13} T/√Hz and 1.25×10^{-13} T/√Hz, respectively. The white noise level using parallel and series noise cancellation were 1.9×10^{-13} T/√Hz and 2.3×10^{-13} T/√Hz, respectively.

The parallel method performed better, reducing the 60 Hz peak by a factor of ~25 compared to the case with no gradiometry. The series method reduced the 60 Hz peak by ~9 [1]. The reduction is small because of large gradients in the power line noise in our laboratory.

Even with exceptionally high balance level, first order gradiometry is only effective for unshielded applications where the gradient of the ambient field noise is small [4]. Power line noise in many cases cannot be assumed to be uniform and therefore first order gradiometry may not be adequate. A second order gradiometer will likely be more suitable, however this is a more difficult device to realize with HTS SQUIDs and beyond the scope of this paper [5].

The balance level for the unshielded environment was measured using a uniform field from a Helmholtz coil providing a similar amplitude signal as in the shielded case. In this case, a large ambient noise signal was superposed on the signal from the Helmholtz coil. We were interested in measuring the balance levels in the unshielded case because it has been shown that the phase shift of the SQUIDs can change as a function of signal amplitude [6]. Such an additional phase shift would reduce the balance level observed in the shielded can. These levels are plotted in Fig. 3 along with the predicted balance levels (dotted, and dashed lines, same as Fig. 2). It can be seen that the balance levels are similar to those in the shielded case and very well fit by the theoretical predictions of (11) and (12). We conclude that the additional phase shift is negligible.

For the parallel method the fit to (11) (dotted line in the upper panel) gave $\delta t_{delay} = 3.29 \pm 0.22$ μs. The best fit of the data to (12) (dashed line) gave $a = 1.0008 \pm 0.0001$ and $\delta t_{delay} = 0.95 \pm 0.07$ μs. We expect from our phase measurements that $\delta t_{delay} \sim 1.4$ μs.

The series method fit to (11) (dotted line in the lower panel) gave $\delta t_{delay} = 9.24 \pm 0.39$ μs. The best fit of the data to (12) (dashed line) gave $a = 1.0011 \pm 0.0002$ and $\delta t_{delay} = 4.85 \pm 0.28$ μs. We expect δt_{delay} to be $\leq$ 7.6 μs. The balance levels and best fit parameters between the shielded and unshielded case are indistinguishable.

VIII. Discussion

We designed two first order HTS SQUID gradiometers. Both the parallel and series techniques were implemented with commercial magnetometers and electronics.

Unlike conventional wire-wound gradiometers, time delays in the SQUID electronics affect the balance level by introducing different phases between the SQUID signals. Balance level can be optimized by maximizing the small-signal cut-off frequency, f_l, or minimizing the time delays (series method) and tuning f_l to be as similar as possible (parallel and conventional electronic methods) for the two SQUIDs. These steps are crucial to obtaining a high balance level and maintaining it as frequencies increase. Time delay was a limiting factor to the balance level of our gradiometers and led to the balance level deteriorating with increasing frequency.

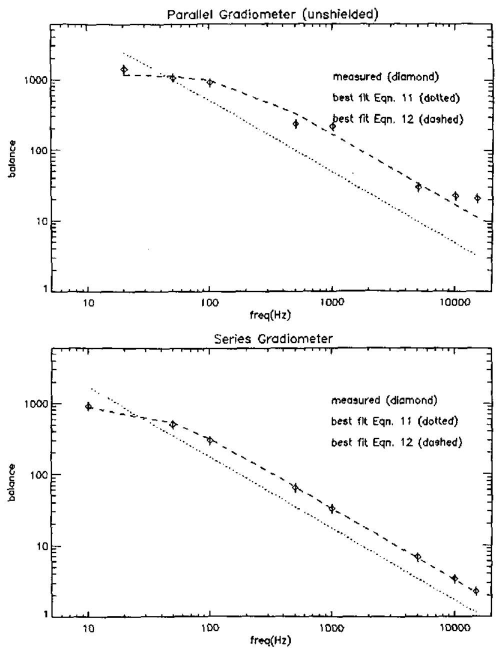

Fig. 2. Unner nanel: Measured and nredicted balance levels for narallel
Fig. 3. Upper panel: Measured and predicted balance levels for parallel noise cancellation. Lower panel: Measured and predicted balance levels for series noise cancellation. Measurements were performed with the SQUIDs in the unshielded laboratory.

An advantage of electronic gradiometry is that one can adjust the signal amplitudes in real time, and reduce the need for matching the pick-up coil geometries to high precision.

The series gradiometer has the further advantage of the noise being "nulled" at the sensor, preserving much of the dynamic range of the sensor device. Excellent balance levels of 10^3 can be achieved at 20Hz with off-the-shelf commercial devices, and better results could be expected with better matched electronics and reduced time delays in the electronics. One possible approach to further noise reduction is to design a simple second order electronic HTS gradiometer.

Matching the signal amplitudes and minimizing electronic time delays is critical to optimizing the performance of any order gradiometer using more than one SQUID.

References

[1] M. A. Espy, R. H. Kraus, Jr., E. R. Flynn and A. Matlashov, Rev. Sci. Instrum. **69**, No. 1 (1998).

[2] Conductus, Inc. 969 W. Maude Ave. Sunnyvale, CA. 94086

[3] Dietmar Drung, *SQUID Sensors:Fundamentals, Fabrication and Applications*, edited by H. Weinstock (Kluwer, Dordrecht, 1996).

[4] P. Carelli, I. Modena, and G. L. Romani, Proceedings of the NATO Advanced Study Institute on Biomagnetism, 1-12 Sept., 1982 (Plenum, New York, 1983).

[5] Y. Tavrin, Y. Zhang, W. Wolf, and A. I. Braginski, Supercon. Sci. Technol. 7, 265 (1994).

[6] A. Matlashov, A. Garachtchenko, V. Vinetskiy, and R. Cantor, Proceedings of the Sixth International Superconductive Electronics Conference, Berlin, Germany (1997).