Development of a high temperature superconducting magnetic tensor gradiometer for underwater UXO detection

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Abstract-**We are developing a magnetic tensor gradiometer for underwater unexploded ordnance (UXO) detection using high-T_c SQUID planar gradiometers. The system will use signals from six planar gradiometers, located on the faces of a hexagonal pyramid, to calculate the full gradient tensor. It will be towed underwater and will need to deal with noise caused by ocean waves, sensor motion and the measurement capsule itself. This paper presents our progress to date on this project including test results of gradiometer performance in laboratory conditions.**

I. INTRODUCTION

As many as one million acres of the marine environment are potentially contaminated by unexploded ordnance (UXO). Magnetometers are widely used for UXO detection with total magnetic intensity (TMI) measurements the most commonly used survey method. TMI data are successful at detecting magnetic anomalies but have difficulty in discriminating between military munitions and nonhazardous metallic debris. Measuring the magnetic gradient tensor improves the detection, localization and classification (DLC) of magnetic targets.

A detailed discussion of the benefits of magnetic gradient tensor measurements can be found in [1]. The gradient tensor can be calculated from TMI measurements but this requires low-noise measurements, dense spatial sampling, and extensive areal coverage. In contrast, direct measurement of the magnetic gradient tensor can provide the same information from a less densely sampled survey.

A review of the literature found magnetic tensor gradiometers that have been developed for UXO detection using various magnetic vector sensors: magnetoresistive (MR) [2], fluxgate [3], and superconducting quantum interference device (SQUID) sensors [4, 5]. SQUID sensors are the most sensitive of the three types. All of these systems use multiple sensors and calculate the gradients, either in software or electronically, which can be prone to error.

SQUIDs can be configured as highly balanced intrinsic gradiometers which measure the gradient directly. Reference [6] describes a full-tensor SQUID gradiometer system designed for airborne geophysical applications which uses intrinsic planar low temperature SQUID gradiometers. That system achieved a white noise level of 0.6 pT/m/Hz$^{1/2}$ with a corner frequency at 0.3 Hz, measured in a magnetically shielded room.

In comparison, we are developing a magnetic tensor gradiometer for underwater UXO detection using high-T_c SQUID planar gradiometers with an unshielded target gradient sensitivity of 2 pT/m/Hz$^{1/2}$ at 10 Hz. We chose high temperature rather than low temperature SQUIDs as they are easier to deploy, using liquid nitrogen rather than liquid helium for cooling.

The technical challenges for this project include: designing a high-T_c SQUID device that can achieve the required gradient sensitivity in motion; identification and removal of magnetic noise caused by ocean waves, sensor motion, and the measurement capsule itself; and developing a dipole-tracking algorithm for gradient tensor measurements that is both robust and computationally undemanding. This paper presents some of the progress to date on this project, including an evaluation of gradiometer performance in laboratory conditions.

II. PROPERTIES OF THE MAGNETIC GRADIENT TENSOR

In free space, the magnetic gradient tensor, $\mathbf{B} = \nabla\mathbf{b}$, where $\mathbf{b}$ is the magnetic field vector, is both traceless and symmetric, implying that only five of the nine gradient components, shown in (1), are independent (two diagonal and three off-diagonal).

$$\mathbf{B} = \begin{bmatrix} B_{xx} & B_{xy} & B_{xz} \\ B_{yx} & B_{yy} & B_{yz} \\ B_{zx} & B_{zy} & B_{zz} \end{bmatrix} = \begin{bmatrix} \frac{\partial b_x}{\partial x} & \frac{\partial b_y}{\partial x} & \frac{\partial b_z}{\partial x} \\ \frac{\partial b_x}{\partial y} & \frac{\partial b_y}{\partial y} & \frac{\partial b_z}{\partial y} \\ \frac{\partial b_x}{\partial z} & \frac{\partial b_y}{\partial z} & \frac{\partial b_z}{\partial z} \end{bmatrix} \tag{1}$$

However, in a conductive medium such as seawater, the gradient tensor is asymmetric. In underwater surveys, the magnetic sensors are located within a sealed capsule, within which the gradient tensor is symmetric. This raises the question of how the measurements within capsule relate to the magnetic

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field components and the asymmetric gradient tensor that existed in the surrounding medium prior to insertion of the instrument package.

To investigate this question, we modelled the effects of an ellipsoidal cavity within a conductive medium, which can be used to model a wide variety of capsule shapes [7, 8]. These results allow measurements by sensors that have been calibrated in air to be corrected for the effect of a conductive medium.

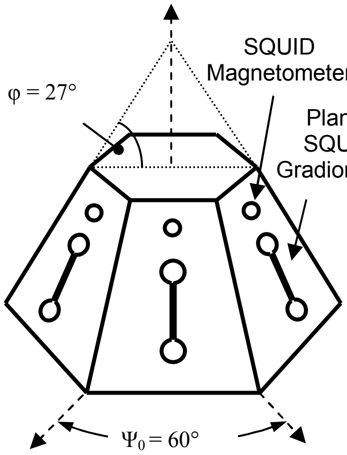

Figure 1. The magnetic gradient tensor system using six magnetometers and gradiometers mounted on the faces of a hexagonal pyramid with an inclination angle φ = 27°.

III. THE MAGNETIC TENSOR GRADIOMETER

Planar gradiometers can only measure the off-diagonal components of the gradient tensor (e.g., $\partial b_x/\partial y$). However, Eschner and Ludwig [9] showed that by using at least five planar gradiometers positioned on at least three non-parallel surfaces, one can calculate all components of the gradient tensor. Our design, shown in Fig.1, consists of an array of six planar SQUID gradiometers positioned on the slant faces of a hexagonal pyramid which provides data redundancy leading to an over-determined system of linear equations for calculating the tensor components. Each face also incorporates a SQUID magnetometer for determining the magnetic field perpendicular to the respective surface and to compensate for any residual gradiometer sensitivity to common mode signals.

IV. HIGH-T_C SQUID FLIP-CHIP GRADIOMETER DESIGN

To achieve the best gradient sensitivity and performance, we have chosen a long baseline high-T_c SQUID gradiometer based on a flip-chip design from [10]. This design uses a small gradiometer as the readout sensor, inductively coupled to a long baseline (l = 18.5 mm) gradiometric flux transformer via an S-shaped input coil. The schematic in Fig. 2 shows an electrical representation of the flip-chip gradiometer.

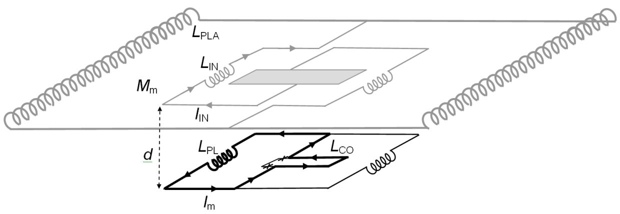

Figure 2. Electrical representation of the flip-chip gradiometer.

Figure 3. Picture of the two device designs A and B, with the larger gradiometric flux transformers on the left and the smaller readout gradiometers on the right.

In order to achieve the target gradient sensitivity, we have investigated the performance of three separate gradiometric transformer and readout device designs. The first two designs, which we have called Design A and B, are described in [11] and shown in Fig. 3. Design A had a gradient sensitivity of 6.7 pT/m/Hz$^{1/2}$ in the white noise region and 43.0 pT/m/Hz$^{1/2}$ at 10 Hz, measured unshielded in an open laboratory. Design B had similar outer dimensions to Design A, but the inner loop dimensions were varied to decrease the inductance and allow better inductance matching and coupling.

Fig. 4 shows the improvement in gradient sensitivity achieved using the flip-chip design over just the readout gradiometer. The improved gradiometer design used for Design B produced an increased gradient sensitivity, shown in Fig. 5, with an overall lowest gradient sensitivity of ~2.9 pT/m/Hz$^{1/2}$ in the white noise region and 17.0 pT/m/Hz$^{1/2}$ at 10 Hz, again measured in an open laboratory. Design C has not yet undergone testing but it is expected to have the best gradient sensitivity of the three designs due to its increased baseline (l = 22.5 mm) and area (15%). All of the flip-chip gradiometers fabricated thus far have exhibited excellent unshielded behaviour, remaining very stable even while operating in unshielded magnetically noisy environments.

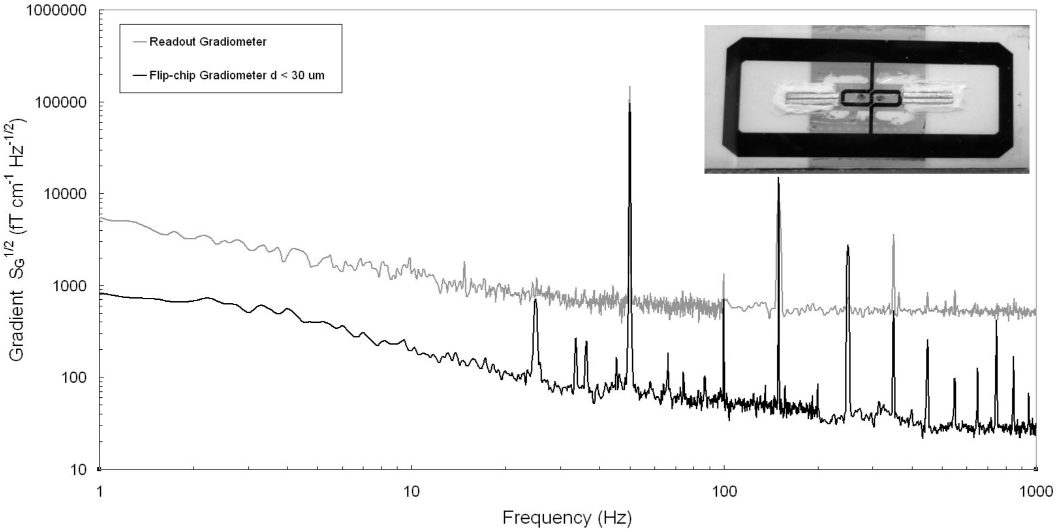

Figure 4. This graph shows the improvement in the unshielded gradient field sensitivity of the flip-chip gradiometer in comparison to the readout gradiometer for Design B. The noise spectrum was measured using dc biasing only. The inset photo shows the flip-chip coupled device.

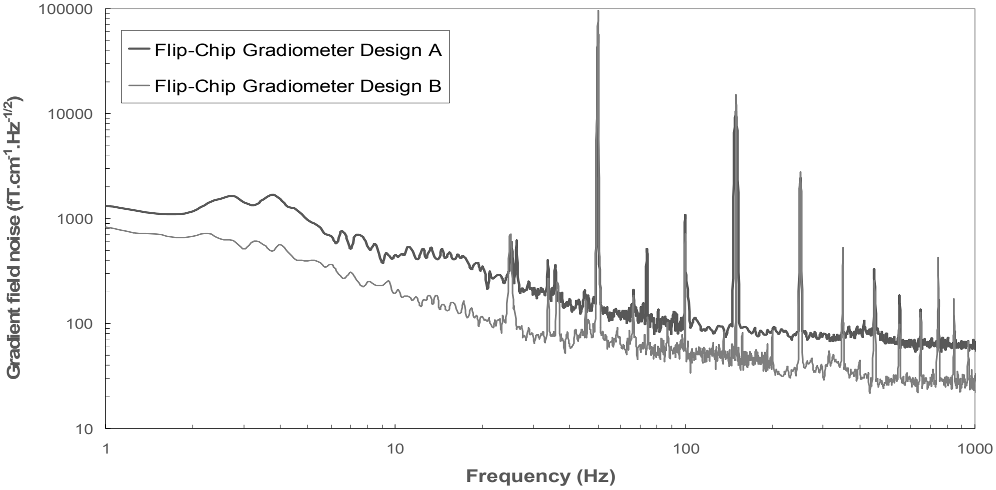

Figure 5. This graph shows the unshielded gradient noise spectra of Design A and B using dc biasing technique only. Gradiometer design B, despite having a slightly higher intrinsic flux noise, showed approximately 25% improvement in gradient field sensitivity due to its improved signal coupling.

V. ACTIVE FIELD COMPENSATION SYSTEM

We have started tilt testing of the planar gradiometers to determine their performance while in motion in the Earth's magnetic field. In-motion, these devices show large orientation error changes in the Earth's field due to the finite balance of the gradiometers; however, they remain highly stable even after strong motion.

A global feedback system is being developed to cancel the Earth's field at the sensors. This will not only reduce the dynamic range required by the SQUID devices but will also compensate for the in-motion orientation errors. We are using a 3-axis room temperature AMR sensor [12] as well as three single-axis high temperature SQUID magnetometers to use as reference magnetometers for the feedback system. We are currently comparing a number of feedback coil systems, looking at the uniformity that can be achieved with a compact system suitable for underwater towing.

VI. CONCLUSIONS

To achieve the required target gradient sensitivity of a high temperature superconducting magnetic tensor gradiometer for underwater UXO detection, we are using a long baseline flip-chip gradiometer. To allow stable operation while undergoing strong motion in the Earth's magnetic field, we plan to implement an active-field compensation system incorporating both AMR and SQUID magnetometers. In addition, we are developing a robust dipole-tracking algorithm for magnetic gradient tensor measurements as well as modelling the effects of the instrument capsule on magnetic field measurements in seawater.

We are currently in the process of assembling the full tensor gradiometer. Once that is complete, we will be carrying out a series of static and dynamic tests of the gradiometer in laboratory conditions.

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