LA-UR-96-3051

Title: **Gravity Gradiometry Based on High-T_c
Superconducting Sensors**

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Submitted to: **DOE Office of Scientific and Technical Information
(OSTI)**

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Form No. 836 R5
ST 2629 10/91

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Gravity Gradiometry Based on High-T_c Superconducting Sensors

Robert Kraus*, Allen Cogbill, and Matthew Stettler

Abstract

This is the final report of a one-year, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). The gravitational field of the earth has minuscule local variations that, though universal, are difficult to observe with any but the most sensitive instruments. These variations in the gravitational field are caused by local variations in the density of the earth's crust such as a voids or concentrations of high density material. Such anomalies can be observed directly by mapping the magnitude of the gravitational field (gravimetry) or by measuring the gradient of the gravitational field (gradiometry). We believe gradiometry is potentially superior to gravimetry because the measurement and interpretation of the results is generally simpler and gradiometry is less susceptible to masking by other effects (e.g., accelerations). This method introduces absolutely no energy or radiation into the region of interest. Furthermore, we believe this method can be adapted to moving platforms and the capability to take real-time data over large areas is certainly feasible. The scope of this work was to examine the feasibility and performance of a fieldable gradiometer using high-T_c materials.

1. Background and Research Objectives

The focus of this LDRD work was to complete a literature search of the current state-of-the-art for gravity gradiometry and investigate certain technical challenges associated with the fabrication of a fieldable (fieldable is defined as a device one can transport by hand, ground vehicle, and/or aircraft) superconducting gravity gradiometer. An extensive search of the literature in the field was completed and a design concept chosen on the basis of the simplicity and adaptability to the requirements of the intended customer.

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The specific technical challenges addressed by this LDRD effort have been 1) conceptual design and modeling of a vibration damping scheme for a superconducting gravity gradiometer, 2) conceptual design of a 3-component (dG_x/dx , dG_x/dy , dG_y/dx , dG_y/dy ; only three of which are unique) superconducting gravity gradiometer, and 3) conceptual design of a controllable high- T_c persistent current circuit.

The concept of a superconducting gravity gradiometer was proposed by numerous groups since the late 1970's. Our concept development began with the design originally proposed by Mapoles [1] because of the inherent simplicity over other designs and what we believe is the most easily adaptable configuration to a portable system. Simplicity of design is crucial for a system that is being designed for rapid data acquisition in the field. The basic concept uses a persistent current flowing in a coil located between two superconducting "proof masses." The persistent current is modulated by the relative motion of the masses resulting in a direct measure of the relative deflection of two suspended superconducting proof-masses relative to the central fixed coil. A SQUID (Superconducting QUantum Interference Device) is used to monitor the magnitude of the current. A change in the relative position of the two proof masses is a direct measure of the diagonal component of the gravity gradient tensor.

2. Importance to LANL'S Science and Technology Base and National R&D Needs

Our target application of a fieldable superconducting gravity gradiometer is to locate, characterize, and monitor underground structures at depths to approximately 100 m. Other studies have determined that gradiometric measurements of the gravity vector with a resolution between 1 and 10 Eötvös ($1 \text{ Eötvös} = 10^{-9} \text{ sec}^{-2}$) is potentially as effective as electromagnetic induction scattering (EMIS) methods for locating structures up to a depth of 100 m if the structure contains highly conductive scattering centers. Greater sensitivity is not required because models indicate that one can expect geologic "clutter" (unidentified density and topological variations in the vicinity of the measurement system) to contribute a 0.1 to 1 Eötvös noise level. Gravity gradiometry may be the only method for structures containing no high-conductivity scattering centers. Numerous other possible applications exist including underwater navigation, detection and monitoring of oil and gas reserves, and detection of underground waste sites.

3. Scientific Approach and Results

Numerous technical challenges must be addressed before a credible attempt to build a gravity gradiometer system for use in the field can be undertaken. These challenges have caused most potential customers, who might otherwise enthusiastically support the development of a superconducting gravity gradiometer system, to be skeptical about the practicability of such a system. We have made substantial progress in selecting a design concept for a fieldable superconducting gravity gradiometer and addressing three specific technical issues impeding successful fabrication of such a system. After an extensive literature search that pointed to more and more complex systems designed for high-precision (sub-Eötvös level) gradiometric measurements, we chose one of the simplest designs in the literature [1] because of the customer requirement that the ultimate system be man portable. As noted above, sub-Eötvös resolution is not required for an instrument to detect underground structures. We also felt that simplicity aided in building a realistic dynamical model for system vibration analysis.

Once the conceptual design was chosen, we selected three technical challenges that were express concerns of potential customers. First, show that a design constrained by the limitations of high-temperature superconducting (high- T_c) technology is feasible. Second, develop a concept to actively and rapidly damp vibrations in the system that would mask fluctuations in the gravitational gradient of interest. Finally, design a simple simultaneous multi-axis gradient measurement device that would greatly increase the reliability of locating underground structures and significantly enhance the ability to reconstruct images of the structure. We note that the first two technical challenges are tightly coupled.

To address the need for rapid active damping of vibrations in the system, we have conceived of a patentable design (because no test system was fabricated to prove the principle, we have not yet initiated the patent process). We have nominally identified a target gradiometric data acquisition rate of at least 1 Hz while the platform is in motion. Our superconducting gravity gradiometer design is a modified Mapoles [1] design where 95% of the mass of the proof masses are mechanically suspended (rather than 100% as per Mapoles). The remaining 5% of the mass is levitated with a persistent current in a superconducting loop beneath the mass. The current in this superconducting coil is precisely controlled by an active feedback loop to provide a time-varying force on the proof mass that damps vibrations of the system above the sampling frequency. This design concept has been modeled using the dynamical modeling capability of the MATLAB software package and shown to be effective in rapid vibration damping through an active feedback circuit. We found that while tremendous

mechanical resonances existed in a system damped only by the cryogen viscosity (the proof masses are suspended in the cryogen to maintain the superconducting state of the material), our design had significant damping at all frequencies below 1 kHz. A practical problem for implementing such a design with high- T_C materials is the creation and control of a persistent current. Such a scheme requires a superconducting "switch" that, to date, has never been fabricated. As part of a separately funded joint effort with the Superconducting Technology Center (STC) at Los Alamos, we have completed the design of a high- T_C switch and fabrication of the circuit is complete as of the writing of this report. We anticipate testing in the very near future.

Finally, we have extended the Mapoles design with relatively little added complexity to enable three-component measurement of the gravitational gradient tensor. This design adds a third proof mass to the Mapoles design and two more inductively coupled sense coils to monitor the relative motions of the proof masses. We recognize that, as a result of the added complexity of this system, a prudent approach to fabrication of a gravity gradiometer may be to focus on a single-axis gradiometer initially and assess the need to measure more components to unambiguously locate and characterize underground structures of interest.

References

- [1] Mapoles, E., "SQUID Applications to Geophysics," Proceedings of the Workshop held 2-4 June 1980, p 153 (1981).