A novel combined gravity & magnetic gradiometer system for mobile applications

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Summary

This paper is based on completing three years of a development programme and provides an overview of the next phase of this programme, which is to develop a combined gravity and magnetic gradiometer system for mobile applications. The system is designed to measure two gravity (T_{XZ}, T_{YZ}) and two magnetic (B_{XZ}, B_{YZ}) gradients at the same time. All readings are taken in absolute units and referred to the same local coordinate frame. The sensor hardware occupies a cylindrical volume of about 12 cm in diameter and 30 cm in length. Its total weight does not exceed 12 kg. It can sustain horizontal accelerations of up to 0.1g, and it is entirely immune to vertical accelerations of up to a few g. In principle, the magnetic gradient measuring counterpart of the sensor hardware is immune to any kind of mechanical movements.

Introduction

Gravity and magnetic gradiometry are powerful tools for many geophysical applications including direct search to locate oil, gas, water and mineral resources. Over the past decade a number of different gradiometers have been developed using sophisticated techniques including the use of low temperature technologies. In the controlled environment of the laboratory this has enabled enormous progress to be made in improving measurement accuracy but there remain fundamental problems in achieving the same accuracy in motion.

Three years ago, a development programme commenced in New Zealand targeted at achieving absolute measurements of gravity gradients from a mobile platform, with an instrumental noise envelope of less than +/- 1 Eötvös per 10 sec measurement interval. The programme is based on a new approach to gravity gradient measurements and combines the advantages of cryoelectronics with a modulation technique (not a rotational one) enabling the effective separation of gravity gradient signals from their parasitic counterparts. This approach also created the opportunity to construct a sensor with a radically different configuration to traditional gradiometers and one which as a result, was significantly smaller and lighter.

More recently the same principle and almost the same sensor hardware have been applied to the direct measurement of magnetic gradients. Multiple laboratory testing has proven that the accuracy of measurements, which can be obtained with this new type of instrument, is sufficient for high quality geophysical surveying. Moreover, the technical overlap between the two sensors creates the possibility that both instruments could be combined into a single mobile system, enabling the simultaneous logging of gravity and magnetic gradient data. This paper sets out the theoretical and practical implementation of such a system, which would allow the development of a new direction in mobile gravity and magnetic gradiometry.

The basic principle and theoretical framework

The basic principle of operation for both the gravity (GG) and the magnetic (MG) gradiometer takes advantage of some specific dynamic properties of a metallic current carrying string (wire) fixed at both ends. By “string” no practical limitation as to material or to its cross-section is implied: an elongated object having one long dimension and two much shorter ones, which is capable of carrying an electric current, of being transversely deflected by magnetic and gravitational forces and of providing a restoring force, is a force gradiometer. The string must have a highly uniform mass per unit length distributed along its long dimension. If this condition is satisfied with sufficient accuracy then the string’s dynamics can be described by the following force balance equation

$$\eta \frac{\partial^2}{\partial t^2} x(z,t) + h \frac{\partial}{\partial t} x(z,t) - \alpha \frac{\partial^2}{\partial z^2} x(z,t) + \beta \frac{\partial^4}{\partial z^4} x(z,t) =$$

$$= \eta \left[\tilde{g}_x(0,t) + \tilde{T}_{xz}(0,t) z \right] - I_s(t) \left[B_y(0,t) + B_{yz}(0,t) z \right] + \text{thermal noise} \qquad (1)$$

with boundary conditions corresponding to the clamped ends of the string, i.e. $x(0,t) = x(l,t) = 0$. Here l is the length of the string and $x(z,t)$ is the displacement of the string in one of the orthogonal directions transverse to z direction which is chosen to point along the string’s length.

In Eq.1 η denotes the string's mass per unit length, h is the friction coefficient per unit length, α and β are positive constants which determine the restoring force per unit length of the string. The first term in the right side of Eq.1 represents the effective "gravi-inertial" force per unit length, and the following shortcuts are used:

$$\tilde{g}_x(0,t)=g_x(0,t)-a_x(t)$$
$$\tilde{T}_{xz}(0,t)=T_{xz}(0,t)-\Omega_x(t)\Omega_z(t)-\frac{\partial}{\partial t}\Omega_y(t) \qquad (2)$$

In Eq.2 ax and g_x are kinematic and gravity accelerations, T_{xz} is the gravity gradient of g_x along z direction and Ω_X, Ω_Y, Ω_Z are pitch, roll and yaw rates.

The second term in the right side of Eq.1 represents the Ampere force per unit length acting upon the string in an external nonuniform magnetic field **B**(z,t) provided that there is a current $I_s(t)$ in the string.

The periodic boundary conditions (with the spatial period equal to l) imposed upon the string mean that the general solution of Eq.1 can be represented as an infinite sum over the string's discrete number of eigenfunctions which meet the boundary conditions

$$x(z,t)=\sum_{n=1}^{\infty} c_x(n,t)\,\mathrm{Sin}\left(\frac{\pi n}{l}z\right) \qquad (3)$$

where $c_x(n,t)$ is an amplitude of the string's displacement in x-direction for a particular eigenmode n (n = 1,2,3...). By substituting Eq.3 into Eq.1 and by multiplying both sides by Sin(πn'z/l), and then by integrating both sides over z from 0 to l, one can obtain the master-equation for $c_x(n,t)$

$$\frac{d^2}{dt^2}c_x(n,t)+\frac{2}{\tau}\frac{d}{dt}c_x(n,t)+\omega_n^2 c_x(n,t)=$$
$$=\frac{2}{\pi n}\left[1-(-1)^n\right]\left[\tilde{g}_x(0,t)-\frac{1}{\eta}I_s(t)B_y(0,t)\right]-(-1)^n\frac{2l}{\pi n}\left[\tilde{T}_{xz}(0,t)-\frac{1}{\eta}I_s(t)B_{yz}(0,t)\right]+$$
$$+\text{ thermal noise} \qquad (4)$$

Eq.4 describes a usual forced harmonic oscillator with the relaxation time τ and a particular resonant frequency ω_n. The eigenfrequencies are not necessarily separated by one octave gap in the spectrum domain and depend upon the kind of string is used.

It can readily be seen that for n = 2,4,6... vector characteristics of all forces (except the thermal noise related force) acting on the string disappear from the right side of Eq.4. This means that tensor characteristics of a gravitational or a magnetic field can be determined by measuring the displacements of a string which correspond to even eigenmodes only. It is also straightforward to see that there is a flexibility here in providing a gravity gradient related output or an output related to magnetic gradient, i.e. a string can act as a GG sensor only, or as a MG sensor only.

For instance, if a string is pumped with a high-frequency current then the corresponding magnetic force is modulated at so high a rate that it does not fit into the string's effective bandwidth which is normally limited to a few kHz even for very stiff strings. However, the current can act as a carrier signal of a heterodyne-type high-frequency modulation for any low-frequency displacements of the string provided that an effective resonant mechanical-displacement-to-voltage transducer is used in combination with the string (see "Hardware design features" following).

Hardware design features

In the present sensor hardware design the transducer is a resonant inductive bridge tuned to the carrier frequency and inductively coupled to the string. Its inductive part consists of a set of pick-up coils connected in a gradiometric configuration, allowing only those signals to pass which result from the string's displacements due to gradients. Those signals which are coupled to accelerations are attenuated by the bridge.

It is worth noting that the high-frequency modulation described above could not in itself provide a measurement of static gravity gradients. A static deflection of the string from its unperturbed position (i.e. straight line) leads to a static signal again after rectifying the carrier signal. It can easily be lost in the quasi-static drifts caused by mechanical creep, temperature variations and offset voltage instabilities unless an additional low-frequency modulation of the gravity gradient coupled signal is provided.

This additional modulation is a very specific feature of the sensor hardware. It is the direct equivalent of the rotational modulation forming an integral part of traditional absolute gravity gradiometers which are based on doubled differential accelerometers operating at room temperature. In brief, the string is fed back in an "on-off" manner and in this way it is possible to switch periodically the signal mode (n=2) of the string from a state of high stiffness to one of a low stiffness whilst all other eigenmodes, including the main parasitic mode (n=1) coupled to accelerations, are always kept in the state of high stiffness and remain unmodulated. The situation is similar to some extent to a variable gain operational amplifier which is switched periodically from a state of zero gain to one with a finite value. Then a DC voltage applied to its input is converted into an alternating pulse signal proportional to the DC one.

By applying this kind of modulation it is possible to avoid the problems of static measurements and those associated with rotational modulation and at the same time, obtain a variable gravity gradient signal. This signal appears to be periodic with the same period as the modulation process and, therefore, can be locked-in to a reference feedback activation signal. Unlike the example with a variable gain op-amp, there are some specific aspects of the pulse feedback modulation which lay beyond the scope of this paper.

A GG sensor based on these principles has now been constructed and has undergone multiple laboratory testing. The primary sensor (a string), the resonant bridge and the first stage amplification electronics were mounted inside a cylindrical housing (6 cm in diameter and approx. 30 cm in length), shielded against high-frequency electromagnetic background and cooled down to 77 K (liquid nitrogen temperature) in an off-the-shelf 30 litres cryogenic vessel. The envelope of its instrumental narrowband noise was estimated to be about +/- 2.4 Eotvos per 10 sec average. Testing was conducted in a strapdown manner meaning that neither isolation from the ground nor special signal conditioning and filtering were undertaken.

An MG sensor has also been built and has undergone laboratory testing. In its present design a string is simply pumped by an additional AC sinusoidal current, the frequency of which is tuned to the second (n=2) eigenmode of the string. As depicted in Eq.4, the string is excited at that eigenmode in the presence of a static magnetic gradient giving a low-frequency (normally at the rate of a few hundred Hz) modulation of the high-frequency carrier signal. After amplifying and rectifying the carrier signal, a low-frequency sinusoidal signal appears with an amplitude proportional to the magnetic gradient. It can be detected by the use of a quadrature receiver, i.e. by separating one of the quadrature components.

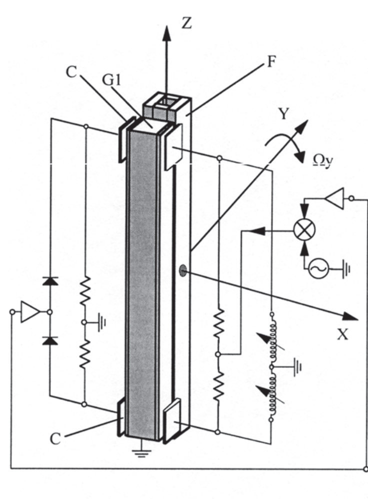
The laboratory tests indicate that the sensor's instrumental noise envelope of less than +/- 0.03 gamma/m per 10 sec average is easily achieved. The sensor has proven to be highly immune to vector components of an external magnetic field and in principle is also immune to any kind of mechanical movements. It does not contain magnetic materials and can also provide a linear output in the dynamic range of tens of thousands of gammas per metre. In addition, there is the potential for considerable improvements in the current performance.

The combined system

The concept of a combined gravity & magnetic gradiometer system is the result of further development and the improvements made on the GG and MG sensors. Each sensor contains a single string which is limited in its mechanical degrees of freedom in such a manner that linear displacements of the string are possible in one direction only (the sensitive axis). This reduces energy transfer from, and the string's excitement by, the spare degrees of freedom which do not participate in the process of measurement.

The system comprises four sensors in metallic housings (G1,G2,M1,M2; see Fig.1): two for measuring T_{XZ} and T_{YZ} gravity gradients, and two for measuring their magnetic counterparts. The housings are mounted vertically around a square metallic frame (F) whose cross-sectional size (3 cm x 3 cm) is the same as that of each housing. Each sensor's housing represents a beam balance (28 cm long) which can rotate about its centre of mass on a hollow round bearing (not visible) around the other horizontal axis perpendicular to the sensitivity axis of the particular sensor. This makes it possible to avoid kinematic coupling between linear accelerations of the frame (F) and the rotational degree of freedom of the sensors' housings.

In turn, the rotational degree of freedom is used for a fine active stabilisation of the sensors' housings against pitch and roll. This is done by the use of 16 capacitive electrodes (C, four for each sensor housing) situated on two round lids (L) joined to the frame. Half of them are placed at the bottom lid and the other half at the top lid in such a manner that each sensor housing forms four capacitances. In addition, each of the capacitances creates a torque which is exerted on a particular sensor housing. The net torque plus those created by the rotating frame compensate each other. Therefore, the string housings are always kept in their vertical positions. A self-explanatory scheme is shown in Fig. 1.



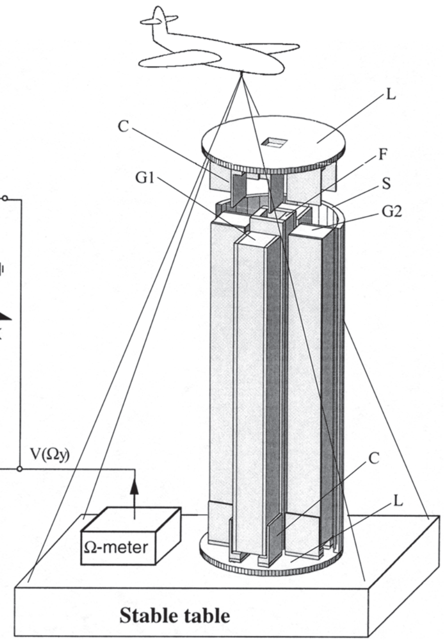


Figure 1. The novel G&M gradiometer system comprises four parallel channels: two for the measurement of T_{xz}, T_{yz} gravity gradients and two for the measurement of B_{xz}, B_{yz} magnetic gradients. The size & weight of the total assembly is sufficiently small to allow the system to operate on an off-the-shelf stable table for its preliminary stibilisation. Then by measuring residual pitch, roll and yaw rates (Ω_x, Ω_y, Ω_z) it becomes possible to actively fine-tune the stabilisation mechanism imbedded into the sensor housings (G1,G2,M1,M2) and, in fact, to cancel the major contribution to the error budget of the $d\Omega_i/dt$ inertial additive to the measured gravity gradients (see Eq.2). Finally, minimum variance gravity & magnetic gradient estimates can be obtained by the use of a Kalman filter.

The top and bottom lids (L) are joined by a round metallic shell (S) and all together form a closed cylindrical chamber which is cooled down to liquid nitrogen temperature in order to reduce thermal noise and increase the mechanical stability of the sensors. All parts of the system, including the strings, are matched with their thermal expansion coefficients and can easily tolerate multiple thermal shocks without deterioration. Portable off-the-shelf cryogenic facilities are readily available for keeping the system at low temperature and would not increase the system's size and weight to the level which may prevent use of a commercial stable table for mobile deployment.

Conclusions

Combining the GG and MG sensors into a single mobile system is the logical next step in the continuing development of this innovative technology and is the direct result of the progress made on the hardware design since the development programme began three years ago. In particular the reduced size and weight have made it possible not only to combine them into a portable system with unified data logging hardware, but also to implement a refined stabilisation scheme making it possible to consider mobile deployment from a single stabilised platform.

The unique features of this technology provide a very high level of protection against environmental noise, both for the GG part within the system and for its MG counterpart. In addition the size and weight of the system and the flexibility of its intrinsic design make it highly adaptable and cost effective for a range of commercial uses. The question for the exploration community is how to best exploit the prospect of a system with the capability of simultaneously gathering gravity and magnetic gradient data from a mobile platform.