String Magnetic Gradiometer System: Recent airborne trials

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Summary

A novel sensor design for measuring magnetic gradient fields has been developed by Gravitec Instruments Ltd, New Zealand. The sensor features a single string element that reacts only to the gradient field, ignoring the much stronger total-field of the Earth. Laboratory tests of the system show the room temperature noise floor is down to 0.1 nT/m over the measurement bandwidth of DC–1 Hz. For the current sensor design and room temperature operation, thermal noise is the dominant noise source. The signal to noise ratio can be enhanced further either by cooling the sensor down (~ $(T/300)^{1/2}$ fold noise decrease, where T is the operation temperature), or by increasing its length ($(L_0/L)^{3/2}$ fold noise decrease, where $L_0 = 250$ mm is the current length of the string). The sensor is being tested in the field on-board a geophysical survey aircraft to determine the noise floor outside the lab and to measure the gradient from the geological target at Gingin, Perth Australia.

Introduction

This paper summarizes a development programme for an airborne magnetic gradiometer which has been undertaken by Gravitec Instruments and certain key technical partners over the course of the past two years. The core technology is very similar in concept to that underlying Gravitec's gravity gradiometer programme and although currently the two are run as independent programmes, it remains a longer term goal to combine them into a single measuring system for gravity and magnetic gradients.

The work set out in this paper is ongoing. The main programme is focused on further flight trials but in addition there are two parallel programmes underway. One is to refine the Digital Signal Processor (DSP) in order to operate a multi-channel string sensor system using one digital signal processing unit and one host processor. The other is to build a second generation suspension system incorporating certain features designed to facilitate sustained airborne deployment.

Two-Channel System

Each channel represents a direct magnetic gradiometer capable of measuring either B_{XZ} or B_{YZ} components of the magnetic gradient tensor. Its operational concept has been described by Veryaskin (2001). The advantages to magnetic surveying of the measuring magnetic gradient tensor are discussed by Schmidt and Clark (2000). Each channel consists of a single-axis sensor head (Figure 1), a preamplifier, a DSP unit and a laptop for operator control and data logging. Each DSP unit and laptop can be separated from the measuring part of the MG channel via a long cable (up to 7 meters).

The core of the signal processing unit, a floating point DSP, runs independently of the laptop and deals with signal filtering and decimation, second stage demodulation, and feedback to the sensor to control the input signals and increase the dynamic range. The laptop uploads the DSP code, controls the initial automatic calibration for the sensor and allows the operator to set feedback parameters. It also provides a graphical display of the real-time operation of the sensor and hard drive storage for data logging.

The signal into the sensor is a combination of a high frequency RF carrier signal and a low frequency audio signal. The RF signal is tuned to the resonance of the pickup coils while the audio frequency is tuned to the mechanical resonance of the string. Both provide first stage gain for the output while suppressing sources of interference. The RF carrier signal is cancelled at the pickup coils, producing a double sideband, suppressed carrier signal at the output. This signal is synchronously detected and digitized with 16 bit over sampling converters with subsequent filtering and decimation increasing the effective resolution to 20 bits.

A feedback system maintains the local gradient measured by the sensor at constant level, compensating any changes due to external gradient sources. This increases the dynamic range of the sensor, maintains the linearity of the string and ensures the string signal is sufficiently strong for signal processing. The feedback can be used to provide an independent calibration signal that is used to visually check the noise level performance of the sensor whilst in the field. The typical calibration signal for the sensors is 1.6 nT/m peak with a nominal operating noise floor of 0.16 nT/m. The DSP outputs an arbitrary digital signal that can be scaled to nT/m. This gradient signal is output at 10 samples per second with a filtered bandwidth of 1 Hz.

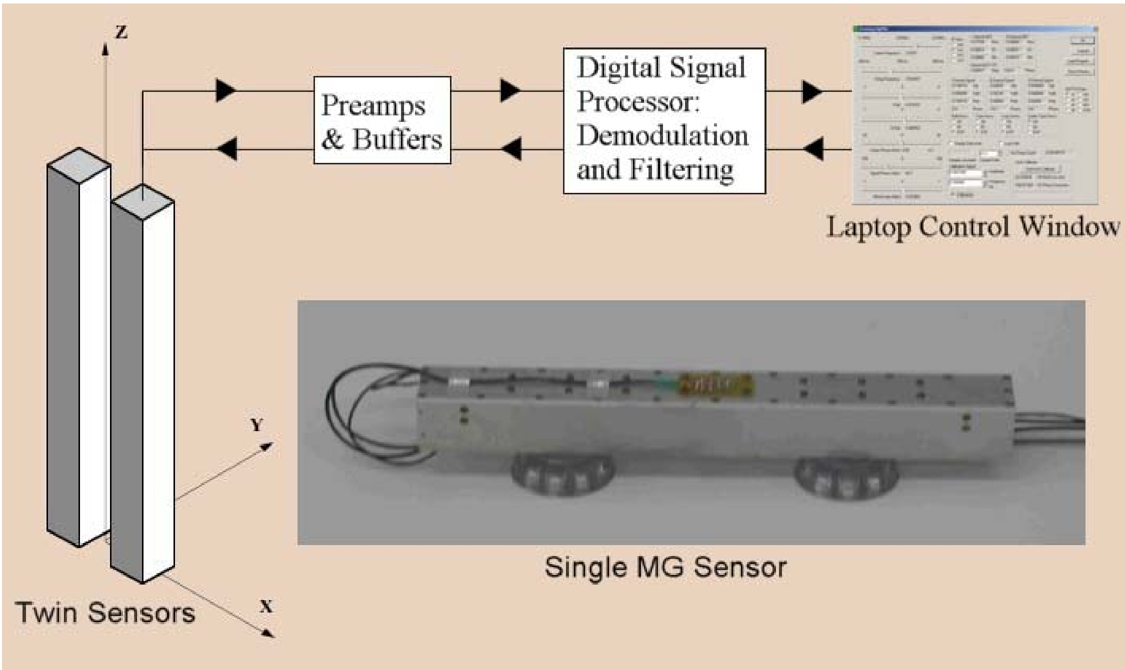

Figure 1: Single channel MG system showing the connection between the sensors, DSP, and laptop. At this stage the twin system incorporates 2 sensors, 2 DSPs and 2 laptops.

Stinger Deployment and Noise Isolation

The sensor is susceptible to vibration and acoustic noise in the vicinity of the string's second violin mode at which the string is excited in the presence of a quasi-static magnetic gradient. The acoustic and vibration noise in the aircraft stringer has required the construction of a suspension system to isolate the sensors within the range of 600–800 Hz (700 Hz is the typical signal carrier frequency). Acoustic isolation is achieved by surrounding the sensor in a <1% vacuum. This also assists the vibration isolation. Vibration isolation is achieved by a 4-stage spring suspension system that reduces the vibration by more than 80 dB over the range of frequencies (650–850 Hz) the string will operate.

It utilises techniques developed for gravitational wave research. Spring elements are designed to contribute both torsional and linear spring elasticity in 3 dimensions. Catherine wheel springs (Blair, 1994; Tanawaki *et al.*, 1998), linear membrane springs (Vol Moody *et al.*, 2002) and torsion elements are used. To obtain robust performance and linearity in the presence of high vibration, the normal modes frequencies are chosen to be ~50–100 Hz, thus creating a suspension system which is relatively stiff, and with steep roll off above 200 Hz. It has been found in laboratory tests that the suspension is capable of isolating the system for 0.025–0.05 g shaking. The vibration isolation performance agrees moderately well with a one-dimensional model, which predicts 200 dB isolation at 900 Hz (Figure 2). The measured transfer function at high frequency (above 200 Hz) is limited by the instrument noise floor.

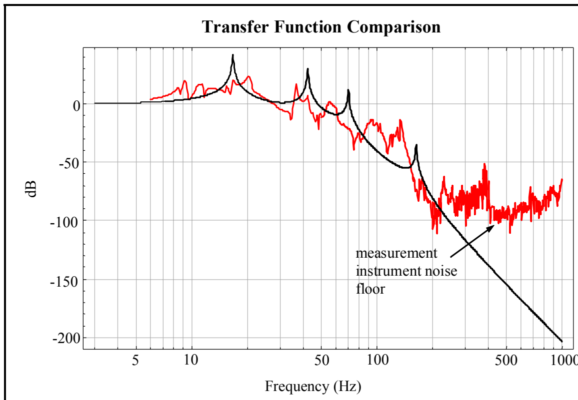

Figure 2: Calculated (black line) and measure (red line) isolation characteristics of the 4-stage isolation system.

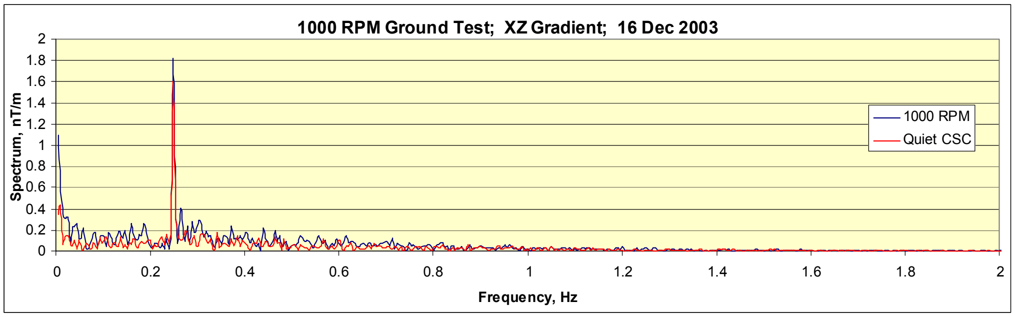

Figure 3: Spectrum for the MG sensor while aircraft engines are running at 1000 RPM. The spectrum is calibrated in nT/m and shows a noise floor of 0.2 nT/m with engines running. The 1.6 nT/m peak calibration signal is clearly visible at 0.25 Hz.

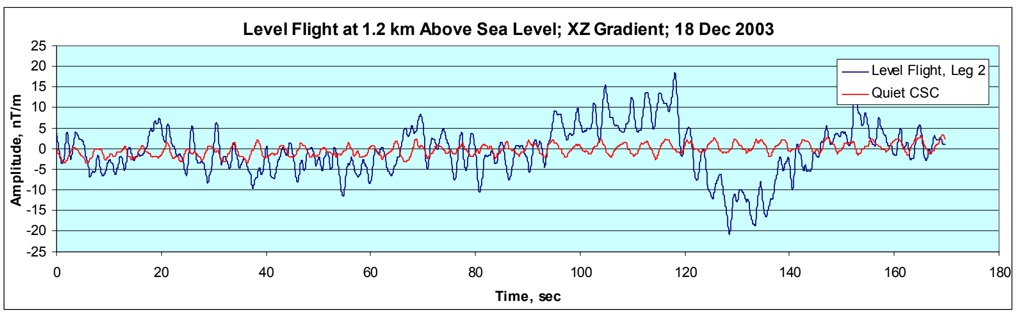

Figure 4: Uncompensated time domain recording for high altitude level flight. Various features on this plot (*i.e.* the gentle increase from 100 s–120 s, the fall from 120 s–130 s, and the rise from 130 s–140 s) correlate with maneuvres of the aircraft in flight, indicating that heading error variation is the cause of these excursions. The GPS altitude is 1200 m and the heading is 167°.

Results from First Stage Airborne Trials

Recently airborne trials were conducted in Perth, Western Australia on board a surveying aircraft. The tests were conducted using a Cessna 404 twin-engine aircraft fitted with a stinger mounted on the back of the aircraft. The testing regime included ground tests with engines off, ground tests with engines running at 1000 RPM, and straight and level flight-tests at 4000 feet. The high altitude tests were conducted over ocean in order to be as far from sources of magnetic gradient as possible, apart from the unavoidable gradients from the aircraft and the sensor housing. The ground tests were performed out at the compass bay at Jandakot airport, Perth. Continuous recordings of 210 seconds were taken to allow for sufficient samples (2048 samples at 10 samples/sec) to calculate the spectrum for the sensor.

Figure 3 shows the spectrum for the sensor recording during one of these ground tests. The blue line shows the noise floor for the sensor recorded while the engines were running at 1000 RPM. The peak seen at 0.25 Hz is an independent calibration signal that provides a gradient signal of 1.6 nT/m peak at the location of the sensor element. The red line shows a spectrum recorded during quiet conditions, providing a reference noise floor for the sensor. The spectral noise floor lies at 0.2 nT/m, even with engines running. This compares to the lowest noise floor thus far achieved for room temperature operation of this sensor of ~0.1 nT/m.

Figure 4 shows an uncompensated time domain recording taken at 4000 feet. The blue line shows the signal recorded from the sensor during the flight. The red line shows a typical time domain plot recorded during quiet conditions. The calibration signal is easily distinguishable as the modulation in the red line. The larger features (especially the features occurring between 100 seconds and 140 seconds) correlate to maneuvers of the aircraft during the level flight. The sensor housing rather than the aircraft causes the majority of the heading error. After heading error compensation the residual signal is estimated to have an envelope between 2–5 nT/m based on the results in Figure 4. However this noise envelope is dominated by the heading error which is caused by magnetic impurities close to the Sensor. These are currently being addressed and it is expected that in the next series of flight trials the resolution will be much closer to the target level of 0.1 nT/m.

Conclusions

Initial field-testing of the sensor in a survey aircraft has shown that it is sufficiently isolated to perform with a noise floor of 0.1 nT/m (low enough to detect a range of basement magnetic anomalies). Flight tests show noticeably more noise, however most of this correlates to aircraft maneuvers during flight. Heading error is the most likely cause for this noise. Once this issue is addressed it is expected that the noise floor of the sensor during flight will be comparable with the noise floor achieved in the lab and on the ground with engines running.

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