FALCON gravity gradiometer technology

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Keywords: Airborne gravity gradiometry

ABSTRACT

BHP Billiton's FALCON airborne gravity gradiometer is a derivative of the Gravity Gradient Instrument (GGI) developed by Bell Aerospace (now Lockheed Martin) between 1975 and 1990. The basis of the GGI design is an accelerometer complement consisting of four accelerometers equi-spaced on a circle with their sensitive axes tangential to the circle. This configuration rejects both common mode acceleration and rotations about the axis perpendicular to the plane of the complement. The complement remains intrinsically sensitive to rotation rates about axes in the plane of the complement and is sensitive to the acceleration environment to the extent that there is imbalance in the accelerometer sensitivities. Rotation of the complement about the perpendicular axis moves the gradient signal to twice the rotation frequency, away from the effects of low frequency accelerometer bias changes. The GGI is mounted in a high-performance inertial stabilised platform to reduce rotation of the instrument so that its sensitivity to this motion does not represent a significant noise source.

The GGI accelerometers are designed for very low noise, requiring hard evacuation, high pendulosity, low spring constant and attention to the constrainment loop. Accelerometer pairs are aligned with precision and their sensitivities and frequency responses are matched. The scale factor (sensitivity) and alignment of the sensitive axis of each accelerometer are adjusted by compensation feedback loops to minimise accelerometer imbalance by monitoring the response of the system to specific stimuli.

The requirements of survey operations were taken into account during development of the system and the result is an instrument which requires limited preparation, is largely automated during surveys, places few restrictions on flight planning and has been operated in harsh ambient conditions. Data processing is streamlined and data quality can be checked immediately after a flight.

INTRODUCTION

BHP Billiton's FALCON airborne gravity gradiometer (AGG) (Lee, 2000, 2001; van Leerwen, 2000) is the result of a feasibility study and development program carried out by BHP and Lockheed Martin between 1991 and 2000. In this period the Gravity Gradient Instrument (GGI) technology developed by Bell Aerospace in the 1970s and 80s (Jekeli, 1988) was tested under dynamic conditions simulating survey conditions, to evaluate its performance against the requirements for detection of the gravity anomalies associated with mineral deposits. On the basis of this assessment, two systems with modified design were built, tested and installed in a Cessna Grand Caravan aircraft. A further program of test, modification, and development ensued before they were deployed in routine survey operations in 1999 and 2000. These instruments have proved suitable for use in mineral exploration with sufficient sensitivity and resolution for detection of the small localised gravity anomalies associated with mineral deposits and for regional mapping (Dransfield et al., 2001; Mahanta et al., 2001; Christensen et al., 2001). The most effective demonstration of this capability is perhaps the detection of the gravity anomalies associated with Kimberlite pipes of ~100 m diameter, and in resolving dykes separated by 300 m (Liu et al., 2001). The FALCON AGG is the first technology to provide gravity survey capability suitable for mineral exploration from a fixed wing aircraft.

The GGI technology was first tested in flight in 1986 (Jekeli, 1988; Jekeli, 1993) by Bell Aerospace and the US Air Force. With line spacing of 5 km, and 700 m terrain clearance, this trial did not attempt to demonstrate a capability for mineral exploration. The trial was compromised by problems with GPS positioning, temperature control and gyroscope drift and achieved noise levels of 30 to 40 E/Hz (E = Eötvös, 10^-9 s^-2). The noise power was approximately an order of magnitude higher than is needed for effective performance in mineral exploration, in the more turbulent conditions of surveying at low terrain clearance. We considered reliable detection of the gravity anomaly associated with the Cannington (Qld.) deposit was a suitable performance criterion for the AGG. On this basis, we determined that 14 E/Hz was the noise level above which we did not consider a gravity gradiometer viable for mineral exploration, and that 7 E/Hz was desirable. This noise performance must be achieved in the high dynamic environment of survey flying at low clearance (~100 m).

In low altitude survey conditions the acceleration environment is of the order of 1 ms^-2/Hz. For a gravity gradiometer with dimension 100 mm to achieve 10 E/Hz in these conditions requires rejection of the acceleration environment to one part in ~10^9. Likewise, accelerometer noise must be of the order of 10^-5 ms^-2/Hz. Rotations also represent acceleration gradients and must be reduced to less than ~30 μrad/s. These are the challenging requirements of gravity gradiometry, which have now been met with the GGI in the FALCON AGG system. This achievement required attention to all aspects of the instrument design. The accelerometers are designed for extremely low noise and include means for trimming their sensitivity. They are combined in the GGI to provide rejection of acceleration and some rotation. The GGI is mounted in an inertial stabilised platform to further remove rotation inputs. The environment of the GGI is controlled to minimise variation in the accelerometer characteristics and compensations reduce the effect of the remaining variation.

GGI ACCELEROMETERS

The Bell Aerospace model VII G accelerometer was developed as a modification of their model VII accelerometer specifically for application in the GGI (Metzger, 1977). The modifications (described below) were made to reduce the accelerometer noise and to allow adjustment of the accelerometer sensitivity, in order to match the sensitivities of a pair of accelerometers for rejection of the common mode signal.
Metzger (1977) identifies thermal Brownian noise as the performance limiting noise for the GGI accelerometers, although it is not usually a consideration in accelerometer design. Other factors affecting the accelerometer noise are identified as electromagnetic and electromechanical damping. For the model VII G accelerometer, Bell Aerospace used: hard evacuation; a non-conducting and high pendulosity proof mass; low spring constant; and high gain constraint loop, all modifications designed to reduce accelerometer noise.

The GGI accelerometers are of the force re-balance type. In these accelerometers (Lawrence, 1993) the position of a proof mass pendulum is sensed by a capacitance bridge circuit, and a force is applied to maintain this at a position to null the bridge. The force is applied by a current in a torque coil wound on the proof mass acting in a magnetic field generated by permanent magnets. The sensitivity of the accelerometer is therefore proportional to the magnetic field. In the model VII G accelerometer a trim coil on the permanent magnets provides a means to adjust the sensitivity of the accelerometer by adjusting the magnetic field on which the torque coil current acts (Metzger, 1982). This adjustment is used in the compensation loops (see below) to dynamically improve the common mode rejection of the GGI.

The noise power spectrum of a typical accelerometer at low frequency (f) shows a 1/f characteristic in the frequency range of interest for gravity gradient measurement (Metzger, 1977). This makes it advantageous to make measurements at higher frequencies, and this is achieved in the GGI by rotation of the accelerometer complement. This results in gradient signals modulated at twice the rotation rate of the complement.

GRAVITY GRADIENT INSTRUMENT

In the GGI, four accelerometers are mounted to a rotor so that they are equi-spaced on a circle, with their sensitive axes tangential to the circle with the same sense (Metzger, 1982). The rotor rotates at constant speed, typically 0.25 Hz, about an axis perpendicular to the plane of the accelerometers. This rotation results in the gravity gradient signal being modulated at 0.5 Hz, while the common mode signal due to static gravity is at 0.25 Hz, providing a further ability for common mode rejection. A variation of the GGI with eight accelerometers has also been developed (Hofmeyer and Affleck, 1994) which allows the bandwidth of the instrument not to be limited by the rotation rate. The four GGI accelerometers form a complement and their outputs are combined (summed) so that orthogonal accelerometers have opposite sense, and opposed accelerometers have the same sense (Figure 1).

Ideally the output of this accelerometer complement is

\[ 4\rho \left[ \sin(2\Omega t)G_x + \cos(2\Omega t) \left( \frac{G_x - G_y}{2} \right) \right] \]  

(1)

where \( \rho \) is the radius of the complement, \( \Omega \) is the rotation rate (rad/s, \( t \) is time; and

\[ G_i = \frac{\partial G}{\partial j} \]  

(2)

is the derivative of the i component of the gravity vector with respect to dimension j.

The sensitivity of the GGI to acceleration in the plane of the accelerometers is removed to first order by the matching of the accelerometer sensitivities. Sensitivity to acceleration perpendicular to the plane is removed to first order by the orientation of the accelerometer sensitive axes in the plane of the complement.

INERTIAL PLATFORM

The GGI complement is also sensitive to rotation. Rotation about axes in the plane of the accelerometers results in differential accelerations (an acceleration gradient) at the GGI accelerometers which is indistinguishable from gravity gradients. This contributes to the GGI output a signal:

\[ 4\rho \left[ \sin(2\Omega t)\omega_x, \cos(2\Omega t) \left( \frac{\omega_x - \omega_y}{2} \right) \right] \]  

(3)

where \( \omega_x, \omega_y \) are the rotation rates about the in-plane axes. To eliminate rotation as a significant component of the GGI output requires mounting the GGI in a high performance stabilised platform. This sensitivity to rotation is non-linear, which implies that rotation rates at all frequencies can contribute to the frequency band of the gravity signal through mixing. The stabilising platform must keep the magnitude of rotation rates about these axes below 30 \( \mu \)rad/s to ensure the rotation gradients are less than 1 E.

The sensitivity of the GGI complement to rotation rates about the axis perpendicular to the plane of the accelerometers is removed to first order by the orientation of the accelerometer sensitive axes tangential to the circle. Mounting the accelerometers with radial orientation would change this insensitivity in line with the change in the gravity gradient components to which the instrument was sensitive.

COMPENSATIONS

Successful measurement of the gravity gradient demands that the first order rejections mentioned above provide common mode rejection to approximately one part in 10^8. To maintain this level of rejection in the presence of changes in the accelerometer sensitivity and geometry, the GGI includes dynamic compensation loops. Changes in accelerometer sensitivity may be caused by environmental conditions or mechanical ageing (for example).

The primary compensations relate to matching the vector sensitivities of the accelerometers. The model VII G accelerometers include a provision for modifying their sensitivity by trimming the magnetic field in which the torque coil operates (Metzger, 1982). The GGI complement allows in-plane
misalignment of an accelerometer to be compensated by adjusting the sensitivity mismatch in the orthogonal pair of accelerometers.

Sensitivity mismatch in the GGI accelerometers coupled with rotation of the GGI and any tilt of the GGI plane away from horizontal, leads to the GGI output including a component at the rotation rate. This is separated from the gradient signal at twice the rotation rate and its magnitude and phase indicate the degree and location of the mismatch. Metzger (1982) describes how this signal is used in active compensation of the GGI to ensure rejection of in-plane accelerations in the GGI and of rotational accelerations about the perpendicular axis. In brief, the primary compensations demodulate the GGI output at the frequency and phase appropriate for each particular sensitivity. The magnitude of this demodulated signal is a measure of the mis-match in accelerometer sensitivity of a pair of accelerometers. The signal is low pass filtered and used to modulate the sensitivity of one of the GGI accelerometers in a negative feedback arrangement so as to remove or minimise the mis-match. Any noise associated with the signal modulating the sensitivity of a GGI accelerometer provides an additional source of acceleration sensitivity, which is not amenable to modelling. For this reason it is essential to apply sufficient filtering on these compensations, to ensure they do not add significantly to the instrument noise even in turbulent flight conditions. O’Keefe et al. (1999a) detail some methods for reducing this effect by distributing the feedback signal to two or more of the accelerometers.

Additional compensation for sensitivity to perpendicular acceleration, rotational accelerations about the perpendicular axis and for non-linearity of the accelerometer sensitivities are also included in the GGI (Metzger, 1977).

In the matching of accelerometer sensitivity, the frequency dependence of that sensitivity must also be considered. This is most critical in the signal band of the gravity gradient signal (centred at twice the rotation rate of the GGI), as any mismatch in this band will provide a mechanism for the acceleration sensitivity variation, coupled with static gravity, to feed noise directly into the signal band. It is also important outside this band because non-linear interactions allow these frequencies to feed back into the signal band. O’Keefe et al. (1999b) detail some methods for improving the match of frequency response of the GGI accelerometers through compensations in the accelerometer constraint loops.

POST-PROCESSING COMPENSATION

The compensations mentioned above are essential for the successful operation of the AGG, but are not sufficient to reduce its sensitivity to acceleration and rotation to the level required for mineral exploration. Additional compensation is provided in the processing of data from the instrument.

Post-processing compensation relies on monitoring the inertial (acceleration and rotation) environment of the GGI and constructing a model of the response of the GGI to this environment. Parameters of the model are adjusted by regression to match the sensitivity of the GGI during data acquisition. The modelled GGI output in response to the inertial sensitivities is subtracted from the observed output. Application of this technique to the output of the GGI, when it is adequately compensated by its internal mechanisms, results in the performance levels reported elsewhere (Dransfield et al., 2001; Mahanta et al., 2001; Liu et al., 2001; Christensen et al., 2001).

In addition to the compensation for residual inertial sensitivities, post-processing is also applied to remove true gradient signals resulting from the mass distribution of the aircraft and AGG. These gradients are fixed to the aircraft and vary (as seen by the inertially stabilised GGI) with the heading and attitude changes of the aircraft during the survey. They are removed by application of a model of the aircraft and platform self gradient as a function of the measured aircraft orientation.

SURVEY OPERATIONS

During development of the FALCON system, considerable effort has been put into ensuring survey operations would be reliable and efficient. These included: ensuring the system was optimised for the conditions of survey flight; automating system operations where possible; inclusion of other sensors in the system to eliminate additional survey flights; streamlining data processing in the field and automation of many aspects of gradiometer operation.

Logistics of operation demand that the time to prepare the system prior to a survey flight is minimised. Normally this is of the order of twenty minutes and the running up of the AGG is automated freeing the operator to attend to other tasks in parallel.

In flight the system is operated by the co-pilot through a simplified interface and with normal AGG operations automated. No significant run-in (less than 5 km) is required on survey lines. The system is capable of operation to at least 4 000 m altitude and has operated in ambient temperatures from -30 to +40 C.

First stage data processing and reduction is now performed in flight with immediate quality control (QC) review of the gradient data available post-flight. Summary data sets are also generated and reviewed as a QC measure and are suitable for remote diagnosis of system performance issues. The essential data for generation of the standard gravity and gradient maps are generated at the required sample rate in-flight and can be processed on site or transmitted to a remote site for map generation. The much larger complete data set is archived.

The survey aircraft includes a stinger magnetometer, GPS positioning, a laser scanner (Stone, 2001) and optionally radiometric crystals, eliminating the need for extra surveys for this necessary or complementary data. The acquisition of laser scanner data is essential for generation of a digital terrain model which is used for removal of the topographic contribution to the gravity gradient data.

CONCLUSIONS

The ability of the FALCON airborne gravity gradiometer to measure gravity gradients with the sensitivity and resolution required for mineral exploration applications is dependent on achieving high performance across all aspects of the system. The foundations lie in the design of the Bell Aerospace Gravity Gradient Instrument and the model VII G accelerometers. Progress from the performance shown by that instrument in its first airborne trials in 1986 to the current performance of the FALCON system has involved re-visiting many aspects of the design which affect performance: modification of the design of the GGI; improving accelerometer performance; optimising the operation of in-built compensations; and revision of the post-processing compensations. An extensive flight test program over a period of 18 months was critical to development and optimisation of these changes for performance in survey operations.

ACKNOWLEDGEMENTS

The AGG development was the work of Lockheed Martin engineers, in particular Clive Affleck, Giles Hofmeyer, Ernie
The BHP FALCON Team led by Edwin van Leeuwen and including Tim Monks (dec.), Bob Turner, Paul Osborn, Graeme O’Keefe, Ken McCracken, Gary Hooper, Peter Stone, Maurice Craig, Marion Rose, Michael Asten, Graham Creer, Graham Goodwin, Greg Adams, Mark Dransfield, Ken Witherly, Peter Diorio and Nick Fitton was closely involved in all aspects of the AGG development and provided the guidance required for the system to be operationally effective.

The Sander Geophysics engineers, operations and flight crew were instrumental in effectively interfacing the system in the survey aircraft and in the logistics of the extensive flight test program.

FALCON is a trade mark of BHP Billiton.

REFERENCES


