Airborne Gravity 2004

Abstracts from the ASEG-PESA Airborne Gravity 2004 Workshop

Edited by Richard Lane
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Preface

The "Airborne Gravity 2004 Workshop" was held in Sydney on August 15, in conjunction with ASEG-PESA Sydney 2004 (the ASEG's 17th Geophysical Conference and Exhibition). The aims of the workshop were to provide participants with a review of the current state of the art in airborne gravity instrumentation, to present case histories of the use of these methods in minerals and petroleum applications, and to distribute sample data sets. "Airborne gravity" is used in this context to include both airborne gravimeter and airborne gravity gradiometer methods.

The program was split into 2 sessions. The morning session provided a review of the systems, with presentations covering a number of systems currently in operation as well as some that are still under development. The focus shifted in the afternoon session to case histories, with examples from surveys spanning the globe; from Antarctica to the tropics of Papua New Guinea, from Africa through Australia to Canada.

To capture the essence of the day and to promote the ongoing development of airborne geophysical methods, speakers were invited to submit papers for inclusion in a workshop volume. The papers were reviewed prior to publication in this Geoscience Australia Record. Participants received a copy at the workshop, and additional copies of the Record are available on an ongoing basis from Geoscience Australia (www.ga.gov.au).

Units

Physical quantities should be expressed in SI units. The Bureau International des Poids et Mesures (BIPM) is the custodian of this system. To quote from their website (www.bipm.fr): "Its mandate is to provide the basis for a single, coherent system of measurements throughout the world, traceable to the International System of Units (SI)."

The SI unit for acceleration is “metre per second squared” (m/s²). The signals encountered in gravity surveys for exploration are small, and the prefix “micro” is commonly used (micrometre per second squared, µm/s²). The gal (or Gal), equal to 1 cm/s², is a derived unit for acceleration in the CGS system of units. A prefix of “milli” is commonly used (milligal, mGal). In rare cases in the literature, a "gravity unit" (gu) may be encountered. In this publication, the µm/s² has been the preferred unit for gravity measurements, but mGal has been accepted.

1 µm/s² = 10⁻⁶ m/s²
1 mGal = 10 µm/s²
1 gu = 1 µm/s²

The gravity gradient is a gradient of acceleration and so the appropriate units are acceleration units divided by distance units. Thus, “per second squared” (s⁻²) is appropriate in the SI system. Typical gravity gradients measured in exploration are extremely small, and the prefix “nano” is appropriate in most circumstances (per
nanosecond squared, ns$^{-2}$). The eotvos unit (Eo), although not recognised in either the SI or CGS systems, is used almost universally in geophysics as the unit for gravity gradient measurements. It is equal to 1 ns$^{-2}$. In this publication, the ns$^{-2}$ and Eo have both been accepted as units for gravity gradient measurements.

\[
1 \text{ ns}^{-2} = 10^{-9} \text{ s}^{-2} \\
1 \text{ Eo} = 1 \text{ ns}^{-2}
\]

**Acknowledgments**

The Airborne Gravity 2004 Workshop Organising Committee would like to acknowledge the support of the ASEG-PESA 2004 Conference Organizing Committee and the Conference Secretariat. Support from Geoscience Australia, BHP Billiton and the NSW Department of Primary Industries - Mineral Resources helped to make the workshop a success. The diligence of Mario Bacchin, Katharine Hagan, Angie Jaensch, Jim Mason, Peter Milligan, Ian Hone and Roger Clifton enabled this Record to be produced in time for the Workshop, despite a tight deadline. Finally, a vote of thanks goes to the speakers who committed their time and energy to deliver presentations on the day and to compose this permanent record of the event.
The FALCON® airborne gravity gradiometer survey systems

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Introduction

It is almost five years since BHP Billiton performed the first airborne gravity gradiometer (AGG) survey over a mining province: the FALCON® AGG system survey of the Bathurst Camp, New Brunswick (Dransfield et al., 2001).

Since that survey, three FALCON® AGG systems have been introduced into operational use; “Einstein” in October 1999, “Newton” in April 2000 and “Galileo” in June 2002. These systems acquire airborne gravity data with the sensitivity and spatial resolution necessary for minerals exploration (Christensen et al., 2001; Mahanta et al., 2001; Liu et al., 2001), and by doing so have raised the interest of the geophysics community in airborne gravity.

The systems are operated by Sander Geophysics (Newton and Einstein) and by Fugro Airborne Surveys, Perth (Galileo).

The FALCON® AGG systems are based on gravity gradient instrument (GGI) and inertial platforms developed by Bell Aerospace (now Lockheed Martin). However the design used in the FALCON® systems is unique. This design was determined on the basis of extensive feasibility studies to optimise performance for the airborne application.

In 2003, Bell Geospace began operations with another airborne gravity gradiometer system, the FTG (full tensor gradiometer) system. The FTG system has the original Bell Aerospace design used in US Navy submarines, and which was used in early feasibility studies. Its introduction to airborne operation has broadened the options for acquisition of airborne gravity gradient data and raised questions of the comparative performance of FALCON® and FTG systems.

In almost five years of operations with the FALCON® systems, we have continued to make incremental improvements in system performance, reliability and productivity. The basic and operational parameters of the FALCON® systems will be discussed below, including discussion of factors which limit their performance.

Instrumentation

The FALCON® AGG technology has been described previously (Lee, 2001). The key technology is a GGI sensor mounted in an inertial platform. The GGI uses a set of four low-noise inertial-grade accelerometers (called an accelerometer complement) mounted orthogonally on a rotating block. The summed output of these accelerometers provides the gravity gradient signal. The precision of matching the sensitivity of these accelerometers is critical to achieving satisfactory rejection of the common mode accelerations, and is maintained by active compensation feedback circuits. The inertial platform reduces angular rotations to which the GGI is inherently sensitive in addition to maintaining the orientation of the GGI.

Significant differences of the FALCON® design from the original GGI design used in US Navy and USAF programs are an increase in the spacing of the accelerometers by a factor of approximately two, the inclusion of a second independent accelerometer complement on the GGI rotor, and the almost vertical alignment of the rotor axis. In these respects it is closer in design to the Lockheed Martin 4-D system (DiFrancesco and Talwani, 2002).

The AGG monitors the dynamic environment of the GGI (principally accelerations and rotations) and uses this information in post-processing compensation to remove any noise contributions, which can be modelled from this information. These models include residual sensitivity, and non-linearity of sensitivity, to acceleration and rotation, and corrections for the gravity self-gradient of the AGG and the aircraft (Lee, 2001).

Each FALCON® system includes a laser scanner (Riegl LMS-Q140i-80) for measurement of the terrain below the aircraft. Range measurements from this scanner are used to construct a digital elevation model (DEM) of the terrain and from this the topographic contribution to the gravity gradient is calculated for
correction of the measured gradients (Stone and Simsky, 2001). GPS is an integral part of the FALCON® survey systems for generation of the DEM, positioning of the gravity gradient (and other measurements) and for time synchronisation between the various data streams.

Other instrumentation supporting and complementing the gravity gradiometer includes a stinger mounted caesium-vapour magnetometer, and optional scintillation spectrometer. There is also a capability for vector magnetometry (Christensen and Dransfield, 2002; Dransfield et al., 2003).

Survey Operations

Survey operation with the FALCON® AGG systems is only slightly more involved than other airborne geophysics surveys such as magnetometry. The principal differences are the need to keep the systems continuously powered to maintain the necessary high degree of thermal control of the GGI, and the need to re-acquire the state of the navigation algorithm for the inertial platform on a daily basis prior to flight. The temperature of the FALCON® system in the aircraft cabin is maintained whilst on the ground, requiring a ground support heating or cooling system.

Survey parameters

In general the parameters for FALCON® surveys are dictated by operational safety, rather than any requirement of the survey instrumentation. Cessna Grand Caravan aircraft were selected, in preference (at the time) to de Havilland Twin Otter aircraft after a risk analysis indicated that the apparent safety advantage of a twin-engine aircraft is not valid for low level survey flight. It was essential that the aircraft have an engine with superlative reliability.

Other measures taken to improve safety of the air crew include the use of full-face cover helmets for protection in case of direct bird strike, continuous tracking of the aircraft location from the base of survey operations (“flight-following”) and carriage of appropriate survival equipment.

A principal safety issue is always the selection of the nominal clearance for the flight. Clearance as low as 80 m has been possible in terrain with low relief and vegetation (i.e., Canadian arctic) while a clearance of 120 m is usually possible. A drape surface is pre-planned by our survey contractor for each survey, based on the climb and descent rates the aircraft can achieve, but inevitably leading to a greater clearance in some parts of the survey.

We set a minimum line length of 10 km, and a minimum 4 km survey width. While these could be reduced, any survey for which this was necessary would be unrealistically small. There is no restriction on line spacing, however most surveys have a line spacing of between 100 m and 400 m depending on target size. Although the directly measured horizontal curvature components of the gravity gradient, $G_{NE}$ and $G_{UV}$, where the subscripts refer to a north, east, and down right-handed coordinate system and $G_{UV}$ is equal to $(G_{NN}-G_{EE})/2$, are unaffected by line spacing, the transformation to vertical gravity ($g_D$) and its vertical gradient ($g_{DD}$) does impose requirements on sampling. In practice, we find that we can recover good quality $g_D$ and $g_{DD}$ data from surveys at line spacings of up to 1 km but that the quality deteriorates for greater line spacings. Control lines perpendicular to the survey line direction, are usually flown at 2 – 5 km spacing. There is a short lead-in required before the start of each line, but this is provided by the end-of-line turn manoeuvre without loss of survey efficiency.

In the normal survey configuration (i.e., no radiometrics), the aircraft flight endurance can be up to 6 hours. This does reduce at higher temperatures and altitudes, and can also be reduced by runway length and surface. Time available for surveying is reduced by ferry time, end of line manœuvres, and a short calibration procedure carried out on some flights prior to the first survey line. We have achieved over 1000 line-km in a single flight, but the average is usually around 500 line-km. Average production rate is approximately 3000 line-km per week, with 7500 line-km having been achieved under optimal conditions when two flights per day were possible.

The gravity gradient noise is, to an extent, dependent on the turbulence experienced, as there is some residual un-modelled sensitivity to the acceleration environment. For this reason we set a threshold limit on the turbulence experienced during the survey. This is monitored continuously during the survey flight and the flight is curtailed if the threshold is reached. Take-off time is varied in many locations to take advantage of the variation in turbulence through the day. Often this means take-off at sunrise, but in some areas it is late in the day that gives the smoothest flying conditions.

Pre-flight procedures are largely automated and include the required navigation update, plus calibration and noise measurements for verification of gravity gradiometer performance. Flight procedures for operation of
the AGG are likewise automated to ensure reliable system operation, and the system output is monitored for anomalies throughout the survey. Automation has improved system reliability very considerably, by eliminating scope for incorrect instrument setting interfering with system performance, and ensuring that pre-checks of important parameters are made. In-flight automation extends to first pass processing of the gravity gradient and laser scanner data to produce a reduced data set suitable for further processing to the final gravity gradient products.

Data processing

Survey data is assessed in the field after each flight against quality criteria. These criteria include the estimated noise level of the gravity gradient and magnetometer data, positional accuracy of the GPS data, navigation performance of the inertial platform, and completeness of laser scanner terrain data. Both raw and post-compensation gravity gradient noise is assessed. Failure on any criterion will require a re-flight of affected lines.

Data are also processed in the field to the stage of compensated line gradient data. A standard set of compensations is applied for the residual sensitivities of the GGI. These data are exported to a database and transferred electronically to the Falcon Operations centre in Melbourne for final processing. In some cases, final processing may be done in the field. Final processing involves more sophisticated compensation, terrain correction and transformation to \( g_D \) (vertical gravity) and \( G_{DD} \) (vertical gravity gradient) data.

Boggs and Dransfield (2003) report on the long wavelengths in transformed \( g_D \) data. The transformation to \( g_D \) and \( G_{DD} \) is performed by integration techniques (both in the spatial and wave-number domains) and by equivalent source techniques. Each method differs in boundary conditions and in approach to provide numerical stability. We improve our confidence in results by comparing them across all methods. We find the largest differences occur at the longest wavelengths.

As indicated by Boggs and Dransfield (2003), a gravity gradiometer has a limited ability to recover the gravity field at wavelengths larger than the smallest dimension of the survey area. They go on to demonstrate a typical error in \( g_D \) of 0.1 mGal/√km for wavelengths less than this dimension and describe a method for merging Falcon® system data with surface gravity data to provide a product with complete long wavelength information.

A reporting schedule and delivered data formats are agreed with the customer for each survey. Typically, final reports are delivered within 3 months of completion of the survey.

Commercial Availability

The FALCON® AGG system is restricted in its use by the US State Department. It may only be used in countries approved in the applicable export license approvals. The list of approved countries does change, as countries are added through an amendment process, and countries can be removed by the US State Department at any time. To date FALCON® AGG surveys have been carried out in Australia, Botswana, Canada, Chile, Mexico, Papua New Guinea, Peru, South Africa, USA, and Zambia. Currently, the Newton system is in North America, and services North and South America, Einstein is in southern Africa, and Galileo is being mobilised from Australia to join Einstein in southern Africa.

Further restrictions apply under the export license. There are strict limits on access to unprocessed data and to detailed information concerning the instrumentation and its performance.

BHP Billiton makes the FALCON® technology available to the mineral exploration community through its partnership program. In general this is through alliances, joint ventures and participation opportunities, rather than a fee-for-service basis. BHP Billiton will fly on a fee-for-service basis for mineral commodities that it regards as not being of strategic interest and for oil and gas. This policy maximises system utilisation, helping to defray fixed costs.

Performance

The performance of the FALCON® systems is assessed in a variety of ways.

Measurements of the total signal level (called "quiescent noise") whilst the aircraft is stationary before survey flying serve as an indicator that the system is functioning normally. These measurements are automatically performed before every flight. At high altitude, there is an insignificant amount of gravity data in the short wavelength part of the total signal. At the start of each survey, a high altitude line is flown and the short
wavelength signal band (called “raw noise”) is recorded and used to check that the compensation feedback systems of the AGG are properly adjusted.

Post-flight, we apply compensations and then examine each survey line separately to check for residual noise. As the survey lines usually contain significant signal (from topography and self gradients, if not from geology), it is necessary to account for this signal in making a valid noise estimate. We are fortunate to have essentially two instruments in one, so that the signal component can be separated, and un-correlated noise estimated, by differencing the two horizontal curvature gradient signals. Comparison of this noise estimate with high altitude raw noise shows that more than 80% of the noise is un-correlated so that this difference provides a good estimate of noise.

Difference noise is our prime measure of AGG data quality.

The difference noise is calculated as the standard deviation of half the difference and presented as an RMS error over a DC to 0.18 Hz bandwidth. At survey speed, 0.18 Hz corresponds to about 300 m. The noise level varies with turbulence, which we calculate as the RMS vertical acceleration in the frequency band 0.3 to 10 Hz. Typical difference noise in the horizontal curvature gradients is between 4 and 7 Eö as turbulence increases to 1 m/s². Occasionally we obtain noise down below 3.5 Eö. Lines with a difference noise above 7 Eö are re-flown. Expressed as a noise density, the typical difference noise is 13 Eö/√Hz.

A further assessment can be made after generation of the final product gD and GDD data.

Separate processing of the two complements of data to yield a difference noise estimate in gD and GDD is only done on occasional surveys. A typical recent survey had a difference noise in gD of 0.3 mGal and in GDD of 6 Eö (the horizontal curvature difference noise on this survey was 4.4 Eö). The bandwidth is difficult to estimate due to the complexities of the processing but was about 0.18 Hz for this survey. This puts the noise density for GDD at 17 Eö/√Hz. The gD difference noise is not white so that a noise density is misleading.

We have done several studies using the difference between ground gravimeter survey data and Falcon data. Typically, we find GDD error predicted from these comparisons to be in the range 20 to 28 Eö/√Hz (corresponding to 8 to 12 Eö RMS in a 0.18 Hz bandwidth). The gD predicted error from these studies is found to increase from about 0.15 mGal at 500 m wavelength to 0.5 mGal at 10 km wavelength. Boggs and Dransfield (2003) demonstrate a typical error in gD of 0.1 mGal/√km for wavelengths less than the smallest survey dimension. These results are higher than the difference noise estimates but often there are clear shortcomings in the quality of the ground gravity data used in the comparison so that these results represent an upper limit on FALCON® noise.

We are not in a position to make a direct comparison of the performance of the FALCON® systems with that of the Bell Geospace FTG systems, as we do not have access to data from the latter system. The paper by Hinks et al. at this workshop is expected to provide a direct comparison (Hinks et al., 2004). While there are known differences in the gradiometer designs, which we believe provide the FALCON® systems with a significant performance advantage, this cannot be quantified without knowing the performance of the FTG systems. We also believe that the performance as measured by the accuracy of the product gradient maps is dependent on the performance of the algorithms used for transformation of the measured gradients. BHP Billiton has invested a significant effort in development of the algorithms we use, and make use of redundancy in this process to improve our understanding of the reliability of the results.

We regard our ability to make an accurate topographic correction, based on reliable and accurate terrain data that is collected concurrent with the gradiometer data, to be one factor, which improves our ability to deliver accurate results.

The FTG systems do measure additional components of the gravity gradient tensor, and this has been claimed as an advantage. Undoubtedly there is additional information available from the three additional components of the tensor that the FTG systems measure. For a single (stationary) measurement this information resolves some of the ambiguities in source location, remembering that as a potential field measurement, some ambiguity will always remain. However these ambiguities are also resolved by measurements at different locations, so that any practical survey flown to cover a contiguous survey area, will also serve to achieve the same outcome. Our success in providing reliable gD and GDD maps from the FALCON® system surveys is confirmation of this. On client request, we also deliver full tensor data calculated in the same way as the GDD data i.e., by transformation from the measured horizontal curvature data.
Beyond resolution of ambiguities, the additional gradient component measurements can be expected to contribute an improvement in noise performance, in the same way that the second accelerometer complement of the FALCON® instrument makes a contribution.

References

Hinks, D., McIntosh, S., and Lane, R., 2004, A comparison of the Falcon® and Air-FTG™ airborne gravity gradiometer systems at the Kokong Test Block, Botswana: This volume.