Airborne Gravity 2004

Abstracts from the ASEG-PESA
Airborne Gravity 2004 Workshop

Edited by Richard Lane
Airborne Gravity 2004

Abstracts from the ASEG-PESA Airborne Gravity 2004 Workshop

Edited by Richard Lane
## Contents

**“Airborne Gravity 2004 Workshop” Record**
R.J.L. Lane, M.H. Dransfield, D. Robson, R.J. Smith and G. Walker………………………………………v

Requirements and general principles of airborne gravity gradiometers for mineral exploration
F. van Kann…………………………………………………………………………………………………………………………...1

The Air-FTG™ airborne gravity gradiometer system
C.A. Murphy……………………………………………………………………………………………………………………….7

The FALCON® airborne gravity gradiometer systems
M.H. Dransfield and J.B. Lee………………………………………………………………………………………………….15

A superconducting gravity gradiometer tool for exploration
J.M. Lumley, J.P. White, G. Barnes, D. Huang and H.J. Paik…………………………………………………………21

A high resolution airborne gravimeter and airborne gravity gradiometer
B. Tryggvason, B. Main and B. French………………………………………………………………………………………41

The AIRGrav airborne gravity system
S. Sander, M. Argyle, S. Elieff, S. Ferguson, V. Lavoie and L. Sander………………………………………………49

The GT-1A mobile gravimeter
A. Gabell, H. Tuckett and D. Olson…………………………………………………………………………………………55

A synopsis of airborne gravity data presentation, modelling, interpretation and inversion software
G. Walker…………………………………………………………………………………………………………………………………63

Acquisition and preliminary impressions of airborne gravity gradient and aeromagnetic data in the Eastern Papuan Basin, Papua New Guinea
A. Nelson………………………………………………………………………………………………………………………………65

Evaluation of a full tensor gravity gradiometer for kimberlite exploration
D. Hatch………………………………………………………………………………………………………………………………73

Integrating ground and airborne data into regional gravity compilations
R.J.L. Lane……………………………………………………………………………………………………………………………81

Airborne gravity data acquisition and processing: A case study in the Prince Charles Mountains, East Antarctica
M. McLean, D. Damaske, V. Damm and G. Reitmayr……………………………………………………………………99

AIRGrav airborne gravity survey in Timmins, Ontario
S. Elieff and S. Sander……………………………………………………………………………………………………………111

Examples of FALCON™ data from diamond exploration projects in Northern Australian
D. Isles and I. Moody………………………………………………………………………………………………………………121

A comparison of the Falcon® and Air-FTG™ airborne gravity gradiometer systems at the Kokong Test Block, Botswana
D. Hinks, S. McIntosh and R.J.L. Lane………………………………………………………………………………………125

### Analysis of errors in gravity derived from the Falcon® Airborne Gravity Gradiometer
D.B. Boggs and M.H. Dransfield………………………………………………………………………………………………135
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.
Analysis of errors in gravity derived from the Falcon® airborne gravity gradiometer

David B. Boggs
BHP Billiton
David.B.Boggs@BHPBilliton.com

Mark H. Dransfield
BHP Billiton
Mark.H.Dransfield@BHPBilliton.com

Abstract

Falcon® airborne gravity gradient data can be converted to vertical gravity via direct integration techniques (Gunn, 1975) or equivalent source methods (Dampney, 1969), and hence compared with conventional gravimetry data. Either conversion process amplifies long wavelength features from the gravity gradient data and therefore reconstructs regional scale features poorly.

Recent Falcon surveys over a number of areas with pre-existing ground gravity have allowed proper assessment of the extent of this problem. Comparison of Falcon and ground data from three different areas indicated that derived vertical gravity is very good at wavelengths less than the minimum survey dimension, spectral analysis showing errors are typically 0.1 mGal / \(\sqrt{\text{km}}\) for wavelengths below this limit.

A similar analysis by Bruton et al., (2001), of profile gravity data from three airborne gravimetry systems, showed error of different spectral character to that achievable via Falcon, with steadily decreasing contribution to the total error from longer wavelengths. The independent analysis of the airborne gravity systems indicated that the limiting wavelength, beyond which airborne gravimetry profiles becomes more accurate than a detailed Falcon gradiometry survey data, is approximately 10-20 km.

Here we show that this shortcoming of Falcon gravity data can be rectified with the use of regional-scale gravity databases, sparse marine track data, or satellite-derived gravity, to conform the Falcon gravity to the regional data beyond a certain wavelength. Given typical survey dimensions of 10-100 km, and provided that the reliable range of wavelengths in the Falcon and regional data overlap sufficiently, it is possible to derive gravity data having errors of approximately 0.1 mGal / \(\sqrt{\text{km}}\) and sampling all features with wavelengths greater than 300 m.

Introduction

The Falcon airborne gravity gradiometer (AGG) measures the two horizontal differential curvature gradients (Lee, 2001), quantities also measured by the original Eötvös torsion balances (Heiland, 1968; Telford, 1990). Within a north, east, down coordinate system and using subscripts for derivatives, these quantities are second derivatives of the gravitation potential referred to as \(G_{NE}\) and \(G_{UV} = ((G_{NN} - G_{EE})/2)\). Differential curvature gradients measure the degree of distortion of the gravitational equipotential surface from a spherical shape. Traditional gravimeters, on the other hand, measure the vertical acceleration due to gravity \(G_D\), arguably a less abstract quantity.

Gravimeters and gravity gradiometers both measure derivatives of the gravitational potential. Well known algorithms allow conversion between these various derivatives to produce theoretically equivalent quantities. Such conversions, based on integration of the gravity gradients and equivalent source techniques, are applied routinely to Falcon gravity gradient data to derive the more familiar vertical gravity. A limitation of these processes is that accurate recovery of long wavelength information in the Falcon \(G_D\) product is not possible, particularly at wavelengths greater than the survey dimensions.

Although this limitation was expected, until recently it was of no concern, direct detection of mineral deposits being the sole aim of Falcon surveys. In these situations, important information is contained almost exclusively in relatively short wavelengths. Extension of the use of the system to contract services in oil and gas exploration, where target signals are at relatively longer wavelengths, has led to requirements both to quantify noise and improve representation of regional gravity features in the Falcon gravity, \(G_D\).
Previous estimations of error in the Falcon $G_D$ have used various forward projections and approximations based on the known noise character of the gravitational gradient measurements. Recent surveys flown over areas covered by pre-existing surface gravity have permitted more rigorous analysis of the error characteristics of the Falcon gravity by comparing results with a known reference field.

A key result stemming from the analysis comprised improvements to the processing software allowing use of regional ground, marine track or satellite gravity in conjunction with the Falcon gravity gradients, to ensure that the final Falcon gravity product can represent accurately the gravitational field at all scales.

**Analysis of Falcon® gravity using reference data**

Analysing accuracy of derived Falcon gravity requires availability of a known reference gravity field, located on the same flight surface and with equivalent compensations applied. An obvious complication with surface gravity is that it is generally measured 100 metres lower than the equivalent Falcon products. Other differences are that surface gravity data usually have free-air and Bouguer slab corrections applied. By contrast, Falcon gravity gradient data does not require a free-air correction, and a full terrain correction is normally applied because of the higher sensitivity of gravity gradients to irregular terrain.

Despite these differences, Bouguer corrected surface gravity data are nearly equivalent to terrain corrected Falcon data. Additionally, free-air corrected surface gravity data are nearly equivalent to Falcon data with no terrain correction, especially when topographic undulations are mild. Upward continuation of surface gravity can compensate for differences in measurement surfaces; however, little difference to the end results occurs except in wavelengths less than 1 km. Such relatively small features are often inadequately sampled by the surface gravity in any case, and this can lead to more serious errors in the reference data due to aliasing.

Numerous Falcon surveys have been conducted in regions previously covered by conventional surface gravity surveys. Density of the existing data is generally variable from site to site, and in some cases the data have been of sufficient quality to allow derivation of a detailed reference gravity field. Three such sites, covering a broad range of wavelengths, have been selected for the purposes of this analysis.

To analyse the Falcon $G_D$ performance in comparison to the available reference data, we used a procedure similar to that described by Bruton et al., (2001). Reference fields were prepared by gridding available surface data and applying upward continuation to adjust for the mean altitude difference. The Falcon gravity data were then subtracted from the reference field to derive “error” grids. Any residual first-order (linear) trend was removed from the grids and amplitude spectra of the residuals were then computed, characterising the error in the respective Falcon gravity data.

Amplitude spectral analyses were performed by standard Fourier methods (as described in appendix A) as well as low-pass filtering at preset wavelengths followed by computation of the variances of the residual grids. Bruton et al., (2001) also used this latter method to analyse performance of some airborne gravimeter systems. It can be used to derive power spectral density estimates by noting the reduction in variance relative to the increase in filter wavelength at each step. This alternate PSD computation method is an application of Parseval's theorem (Champeney, 1973, p.58) and was confirmed to produce results identical to the standard methods. Results from the analysis of Bruton et al., (2001) have also been converted in this manner to allow comparison of the Falcon AGG system with a high-quality airborne gravimetry system.

In each test area, the analysis was performed on two separate Falcon gravity products. The first product involved use of only the Falcon gravity gradients by themselves to derive vertical gravity, hereafter referred to as the “raw” or “un-conformed” Falcon gravity. The second preparation also used third party regional gravity data for the purpose of conforming the Falcon product to a regional surface. Conforming data involved summation of the appropriately filtered data: a high-pass filter to remove erroneous long-wavelength features from the Falcon data and a low-pass filter to remove overlapping spectral regions from the regional data. The resulting product is hereafter called the “conformed” Falcon gravity.

In practice, surface gravity sampled at a regional scale with a Nyquist wavelength of approximately 10 to 20 km is often available, allowing conformed Falcon gravity to be produced for many Falcon surveys. The most visible effects of conforming the Falcon gravity are often at wavelengths much greater than the survey dimensions, appearing as almost linear trends at the scale of the Falcon survey.

As well as spectral analysis of errors in both the raw and conformed Falcon gravity, we provide images of the conformed Falcon and reference gravity at each test area for direct visual comparison.
Test surveys

Location 1 – Mount Woods, South Australia
The first area comprised a Falcon survey of 15 km x 45 km with 200 meter line spacing, also covered by variable density ground gravity (mostly 800 m north-south lines x 400 m stations), making it suitable for analysis of Falcon performance in the 1km - 10km wavelength band. Approximately one-half of the survey is restricted from publication due to confidentiality agreements, so we use just the unrestricted (12 km x 24 km) portion in this analysis. Ground gravity data was accrued sporadically over a ten-year period and several levelling problems are apparent in the resulting data set. The levelling problems are less evident in the reference field prepared from the data (Figure 1) due to the 100 m upward continuation operation.

To derive the conformed Falcon gravity product, a simulated regional survey was contrived from the available ground gravity by decimating stations to a grid spacing of approximately 4 km, with regional conformance of the Falcon gravity at all wavelengths beyond 12 km. By not compensating for the levelling problems in the ground gravity, we simulated errors likely to occur in a regional gravity data set. The resultant conformed gravity is shown in Figure 2, actual station positions selected for the simulated regional survey being shown as black dots in Figure 1. The unconformed gravity derived for this area (not shown) was similar to the conformed gravity product if just the North-South linear trend were removed.

Qualitatively, the conformed Falcon gravity appears very similar to the reference data, the RMS difference between the two being just 0.8 mGal. A visual inspection of the error grid also showed some features trending North-South, obviously indicative of the residual levelling errors in the reference data.

Figure 1. Reference gravity for location 1. Positions of the simulated regional data are shown as dots.
Figure 2. The conformed Falcon gravity product for location 1.

Location 2 – Wilgunya, Queensland
The second test area was a significantly larger survey, comprising an irregular shaped block of around 120 km x 70 km with 200 m spaced lines, located in central Queensland, Australia. Available reference data sources comprised sparse ground gravity from Geoscience Australia’s (GA) Australian National Gravity Database, as well as a more detailed survey having 4 km station coverage over 90% of the area. The lack of high-resolution ground gravity in this area meant that no assessment of Falcon’s performance below wavelengths of around 8 km was justified, although the large survey footprint allowed assessment of performance in the 8 km – 80 km wavelength region.

The reference grid was derived by merging all the available ground gravity, followed by minimum curvature gridding and upward continuation by 100 m. A simulated regional gravity data set, for use in conforming the Falcon gravity, was again created by decimating the available ground gravity to approximately 10 km station spacing. The reference gravity as well as positions of the simulated regional gravity survey are plotted in Figure 3. It is worth pointing out that the GA database has such regional data for most of the Australian continent, similar databases being available for other continental regions.

Conformed and unconformed Falcon gravity products were created, the crossover to regional being defined as wavelengths beyond 30 km. Both products appeared very similar, although closer inspection revealed that peak-to-peak amplitude of the regional gravity anomaly in the unconformed result was approximately 10% less than in the reference grid. Similarity of the conformed data (Figure 4) to the reference grid was significantly better, the RMS difference between the two being only 1.8 mGal. Visual inspection of this error
grid revealed that most of the contribution to this difference occurred near the positions of the sharp high and low gravity anomalies and therefore could, at least in part, be due to aliasing of these features within the sparsely sampled reference data.

Figure 3. Reference gravity for location 2. Positions of the simulated regional survey are shown as dots.

Figure 4. The conformed Falcon gravity product for location 2.

Location 3 – Bass Strait, Victoria

The third data set comes from an offshore Falcon survey of 30 km x 40 km, having 300 m line spacing and being located in water 70 m deep within Bass Strait, between the mainland and Tasmania. A detailed marine gravity survey (360 m lines, 98.4% of data smoothed to an effective cut wavelength of 562 m) was used as the reference gravity for this test. Spectral analysis of the error grid for wavelengths between 1 km and 30 km therefore was expected to indicate error in the Falcon gravity data for this area.

Additional regional data sources available consisted of sparse GSA marine track data and satellite derived gravity. These independent regional data sources let us properly assess the accuracy of the conformed Falcon gravity product. The satellite gravity data were selected for the regional data source in this case, its global coverage making it the obvious choice for offshore regions.

Unfortunately, the satellite-derived gravity used is limited to wavelengths beyond 10 – 25 km, with relatively large errors at the shortest wavelengths (Anderson and Knudsen, 2000). Therefore we decided to limit introduction of regional data in the conformed Falcon product to wavelengths beyond 60 km, the estimated accuracy of satellite data at these wavelengths being around 1 mGal according to relations provided by Fairhead and Green (2001). Considering the dimensions of the Falcon survey (30 km), we expected some contribution to the overall error due to insufficient overlap of reliably sampled wavelengths from the two sources.

Despite these expected shortcomings, the conformed gravity product (Figure 6) compared favourably with the reference gravity grid (Figure 5). RMS difference between the two grids was 1.6 mGal, significantly less than for the unconformed Falcon data, which had RMS difference of 3.1 mGal.
Spectral analysis results

For each test location, we computed power spectra of the differences between the reference gravity field and both the conformed Falcon gravity and the raw Falcon gravity. The resultant 2-D power spectral densities were integrated and translated into a single dimension, to indicate contribution to variance of the error grids as a function of wavelength only (see Appendix A). Results for all test surveys and both the conformed and unconformed Falcon gravity are shown in Figure 7 and Figure 8. Note that the error spectra suggest little improvement between unconformed and conformed Bass Strait data, and this is not surprising given the 60 km wavelength used for transition to the satellite data. Despite the apparent lack of improvement indicated by Figure 7 and Figure 8, introduction of features beyond 60 km wavelengths did reduce the RMS error from 3.1 to 1.6 mGal via restoration of the almost linear regional trend apparent in the data of Figure 6.

A significant feature of the unconformed Falcon error spectra are that error levels appear roughly constant at 0.1 mGal/√km until wavelengths approach the minimum bounding dimension of the survey. Conforming the Falcon gravity to a regional was able to reduce error beyond these wavelengths, and limited the total RMS error to 1-2 mGal in all cases. Assuming these observations are representative of Falcon gravity capabilities, we can make some statements about reliability.

Firstly, at wavelengths approaching and beyond the minimum bounding dimension of the survey, raw Falcon gravity becomes less reliable. Below this wavelength, RMS error should be approximately 0.1√λ mGal or less, where λ represents a high-pass cut-off wavelength (in km). Secondly, provided regional data exist that adequately sample wavelengths beyond λ, a conformed Falcon gravity product typically can be derived with RMS error of 1-2 mGal or less. Note that the reference fields used in previous analyses were not perfect and probably have contributed to the RMS errors estimated from the previous results, particularly at Test Location 2.

Finally, for comparison with the Falcon gravity capability, Figure 7 and Figure 8 show an amplitude spectral density of the noise in profile data from the best of the airborne gravimeters analysed by Bruton et al., (2001). Although the data analysis methods of each technique were not strictly the same (1-D spectral analysis of profile data was performed by Bruton et al., whereas we have performed a spectral analysis of 2-D Falcon data), the curve provides the first quantitative measure of the relative performance of airborne gravimetry and airborne gradiometry. It indicates that a Falcon AGG survey generally can outperform current airborne gravimeters when measuring features with wavelengths of less than 10 - 20km.
Amplitude spectra of errors in conformed (Figure 7) and unconformed (Figure 8) Falcon data. Errors were determined by differencing Falcon gravity from the reference data at each test location. Spectra have been clipped to wavelengths corresponding to content of the reference data at each site. Error spectral density for an airborne gravimeter is also plotted for reference.

Conclusions

The detailed spectral analysis of data from the three Falcon surveys presented has pointed to an attainable noise of approximately 0.1 mGal/√km. This figure implies that the RMS error in Falcon survey data is roughly 0.3 mGal for wavelengths below 10 km, which is satisfactory for mineral exploration purposes. Accuracy at wavelengths longer than the survey’s bounding dimensions appears to diminish, this being attributable to the integration step required to convert gravitational gradients to vertical gravity measurements.

The method of conforming the Falcon data to a regional gravity data source can correct this shortcoming, achieving RMS differences to the reference data of 0.8, 1.8 and 1.5 mGal for data from each of the test locations. A proportion of these residual differences are attributable to signal improperly sampled within the reference data. Some proportion of differences may also be attributed to differences in method of terrain correction, approximations in upward continuations and also errors in the reference data measurements.

Comparison with a similar analysis of some airborne gravimeters (Bruton et al., 2001) showed that accuracy of a Falcon survey can exceed airborne gravimetry for wavelengths shorter than 10 – 20 km, provided the Falcon survey is big enough. Given that peak contributions to the total energy from a monopole gravity source occur at wavelengths of approximately 2 to 8 times depth to target (Appendix A), this would imply Falcon is more suited to detecting such sources if they are located within approximately 2 – 4 km of the ground surface. This result accords with previous analysis by Dransfield (1994) and Li (2001).

Finally, the analysis has demonstrated that hybridisation of regional gravity and gradiometry data can produce a result superior to either method in isolation. Thus, results acceptable for mineral, oil and gas exploration purposes can be derived in most situations from a Falcon survey combined with a pre-existing regional gravity data source, such as satellite or sparse continental gravity databases.

References

Appendix A – notes on the use of power spectral density

Champeney (1973) defines the power spectrum density (PSD) of a function, \( f(r) \), in N dimensions as:

\[
P_f(k) = \lim_{V \to \infty} \frac{1}{V} \left| \int_\mathbb{S} f(r) \cdot e^{-2\pi i k \cdot r} \right|^2
\]

For spatial functions, the power spectrum indicates contributions to the variance (i.e., ‘power’) in \( f(r) \) as a function of wave-number. The quantity \( (2\pi)^N P_f(k) \, dk \) represents the contribution to the variance from the signal with wave-numbers in the hypercube having corners \( k \) and \( k + dk \).

Translation of wave-numbers to wavelength \( \lambda = 2\pi/|k| \) is straightforward and is often used to present power spectra in terms of the latter. However, re-scaling of the data to units of “power/unit of wavelength” (from original “power/units of wave-number”) is usually neglected and the authors believe that the PSD loses some of its original meaning under this partial translation, as the integrated area under the PSD curve no longer represents contribution to the variance of the original function. Rescaling appropriately requires the original units be multiplied by a factor of \((|k|^2/2\pi)^N\) and, if the original power spectrum was in more than one dimension, gathering power from all equivalent wavelengths via an integration process. It is worth pointing out here that this integration step is not equivalent to the more commonly used radial averaging scheme.

Under such a translation, the relative importance of wavelengths that contribute to a simple gravity anomaly can also easily be seen (Figure 9). Selection of an instrument best suited to detect such an anomaly (be it airborne gravimeter or airborne gravity gradiometer) follows if the noise power spectra of both systems are also known.

**Figure 9.** Analytical result for the energy spectrum of gravity from a monopole source at a depth of 100m, presented as a function of wavelength. The energy spectrum is derived via the same method as power spectral density, with the exception that it is not normalised for total area (the 1/V factor).