

Airborne Gravity Gradiometry in the Search for Mineral Deposits

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ABSTRACT

Operational gravity gradiometers were developed by Bell Aerospace (now Lockheed Martin) for a variety of applications during the 1980s. A development project between BHP (now BHP Billiton) and Lockheed Martin led to the development of a new gravity gradiometer based on what was then Lockheed's most advanced technology. This is the simply named Airborne Gravity Gradiometer (AGG). In October 1999 at the Bathurst Camp, New Brunswick, Sander Geophysics flew the world's first airborne gravity gradiometer survey for BHP Billiton. In the eight years since that first survey, the number of operating gravity gradiometer systems has grown. Some of the applications have been for oil and gas and some of these in marine rather than airborne surveys but most of the airborne surveys have been in mineral exploration. Airborne gravity gradiometers have been of considerable value in both direct detection and in geological mapping for a large variety of mineral commodities and deposit styles. Diamonds have been the biggest single target with numerous kimberlites directly detected at Ekati, including the previously unknown diamondiferous Impala pipe. The diamondiferous Abner pipe in Australia and the Daniel diamond-bearing palaeochannel, draining the Finsch mine are also airborne gravity gradiometer discoveries. Airborne gravity gradiometry has proved useful in the search for coal, base metals in iron-oxide-copper-gold deposits, porphyries, Broken-Hill type deposits and volcanogenic massive sulphides, iron in massive haematite, nickel sulphides and gold. There have also been useful applications in the search for oil and gas. The Santo Domingo Sur copper deposit in Chile is the most advanced project that is a gravity gradiometer discovery.

INTRODUCTION

In Exploration 97, Reeves et al. (1997) "anticipated that one or more gradiometer systems will be acquiring production data by 1999". They were correct.

Operational gravity gradiometers had been developed by the Bell Aerospace Niagara Falls, NY facility in several research projects for the U.S. government during the 1980s (DiFrancesco, 2001). Bell Aerospace has since become a part of Lockheed Martin and I will use "Lockheed Martin" to refer to the facility and the organisation from now on. This research included an airborne test of a Full Tensor Gradiometer (FTG) called the Gravity Gradiometer Survey System (GGSS) in 1986 (Jekeli, 1988). While the GGSS did measure real gravity gradients, the noise levels were high and the test was performed using a system mounted in a Winnebago which was driven into a Hercules C-130 – certainly not a practical application.

In 1996, BHP (now BHP Billiton) entered into an agreement with Lockheed Martin to develop a new gravity gradiometer (van Leeuwen, 2000). This was based on a technology, newer than the GGSS FTG, developed by Lockheed Martin for an arms verification application (DiFrancesco, 2001). The new design was called the Airborne Gravity Gradiometer (AGG). AGG

technology forms the core of the BHP Billiton Falcon technology. [Falcon is a registered trademark of BHP Billiton.]

In October 1999, the first airborne gravity gradiometry survey was flown over the Bathurst Camp in New Brunswick by Sander Geophysics for BHP Billiton (Dransfield et al., 2001a). Bell Geospace, who had been operating FTG systems for marine gravity gradiometer surveys, adapted one of their systems for airborne use and, in early 2003, the Bell Geospace Air-FTG flew its first commercial survey (Murphy et al., 2007). [Air-FTG is a registered trademark of Bell Geospace.]

By the end of 2006, the number of operational gravity gradiometers had grown to nine: Bell Geospace operate three Air-FTG systems and ARKeX operate two (the first being built in 2004), under the name FTGeX. These five systems all use FTG technology. BHP Billiton have three AGGs and one Digital AGG. A brief technical overview of these systems is given below.

HISTORY

The history of the use of gravity gradiometry in resource exploration begins with the invention of the Eötvös torsion balance by Baron Loránd von Eötvös (1896). Eötvös' invention was motivated by his interest in the fundamental properties of

the gravity field but its application in resource exploration was soon realised and, by 1929, there were 170 torsion balances being used in North America (Heiland, 1929) and they have also been used in Austria, China, Croatia, Egypt, Germany, Great Britain, Hungary, Italy, Persia, Rumania and Russia (Dransfield, 1994). The primary application was in mapping salt domes for oil exploration.

Additional details concerning this first period of gravity gradiometry in resource exploration may be found in Eckhardt (1949).

The torsion balance was supplanted in exploration by the faster gravimeter during the 1930s but continued to be of interest in fundamental physics, in particular for investigations of the equivalence principle (see, for example, the discussion in Dicke, 1964).

From a selection of prototype gravity gradiometers developed in the 1970s (Forward, 1981; Trageser, 1970 and Metzger, 1977) the US Navy selected the Bell Aerospace Gravity Sensors System (GSS) for gravity compensation of its inertial navigation systems. In 1983, the Air Force Geophysics Laboratory (AFGL) of the USA, selected this same gravity gradiometer for the Defence Mapping Agency (DMA) proposed regional gravity mapping program (Jekeli, 1988).

The AFGL program culminated in the airborne testing of a GGSS system, mounted in a Winnebago driven into a Hercules C-130 aircraft and flown in a test survey in the Oklahoma Texas Panhandle. The GGSS performance was limited by GPS, gyroscope and temperature control problems. More seriously, there were problems with GGI performance, assumed to be due to the challenging acceleration environment of the aircraft (Pfohl et al., 1988). The AFGL program did not result in the use of airborne gravity gradiometry by the DMA.

In the early 1990s, Lockheed Martin developed a gravity gradiometer with lower noise and improved frequency response for arms control verification (DiFrancesco, 2001).

In 1998, Bell Geospace took delivery of an FTG built by Lockheed Martin for ship-borne gravity mapping for oil and gas exploration (Bell Geospace web site). Bell Geospace named this the 3D-FTG (full tensor gradiometer) system. Bell Geospace accepted a second system in 1999.

In parallel, BHP Billiton, undertook an exclusive agreement with Lockheed Martin for a gravity gradiometer specifically designed for airborne use (the AGG) based on the arms control verification model. This system was successfully built and delivered to BHP Billiton in late 1999 (van Leeuwen, 2000). Trademarked as Falcon, the BHP Billiton AGG system performed the world's first airborne gravity gradient survey in October of that year (Dransfield et al., 2001a). BHP Billiton took delivery of two further AGGs in 2000 and 2002.

Subsequently, Bell Geospace modified their two FTG systems for airborne use (Air-FTG).

In March 2005, ARKeX, a company formed out of Oxford Instruments and ARK Geophysics to develop and operate the Oxford Instruments superconducting gravity gradiometer technology, commenced airborne operations with an FTG system built by Lockheed Martin and called FTGeX by ARKeX. A second FTGeX should be delivered to ARKeX in 2007.

The most recent initiatives in airborne gravity gradiometry have been the deployment of an Air-FTG system in an airship by Bell Geospace and de Beers (Hatch et al., 2006b) and the

development of a digital AGG by Lockheed Martin (Boggs et al., 2005) and its deployment in a light helicopter by BHP Billiton (Boggs et al., 2007).

THE GRAVITY FIELD

General relativity describes gravity in terms of the curvature of space-time. The curvature of space-time near the earth is well described by its space-like part: the rank two tensor known in exploration geophysics as the gravity gradient tensor, \mathbf{G} . This tensor is the spatial gradient of the more familiar gravitational acceleration vector, \mathbf{g} , whose vertical component is measured by a gravimeter and is commonly called "gravity" in the geophysical literature.

The gravity gradient tensor has nine components corresponding to the three spatial directions of the gradient and the three components of the gravity acceleration vector. However, only five of these components are independent, the tensor being symmetric by construction and, since gravity is a potential field, traceless (ie., the diagonal components of the tensor sum to zero).

In moving-base gravity gradiometry, the sensor is kept at fixed orientation with respect to geographic coordinates that are well approximated by the Cartesian, geographically referenced directions North, East and Down. Consequently, I can refer to components of either \mathbf{g} or \mathbf{G} with the subscripts N, E and D. For example, g_D is the vertical gravitational acceleration usually measured by a gravimeter and G_{ND} is its gradient in the north direction. Alternatively, of course, since the gravity gradient tensor is symmetric, G_{ND} is also the gradient of g_N in the down direction.

For the case of measurements of gravity or its gradient either on or above the surface of the earth, the measurements are idealised to be on a horizontal surface and most of the gravity signal power is in the vertical direction which then assumes a particular significance. It is natural, and common practice, to use the following five independent components of the gravity gradient:

G_{DD} , the vertical gravity gradient;
 G_{ND} and G_{ED} , the horizontal gravity gradients and
 G_{NE} and $G_{UV} = (G_{NN} - G_{EE})/2$, the curvature gravity gradients.

The fifth of these independent components, G_{UV} , is also the gradient in the U direction of the gravitational acceleration in the V direction where the U (north-east) and V (north-west) axes are an orthogonal pair of horizontal directions rotated by 45° from the N and E directions.

Another approach to selecting five independent components is via invariants of the tensor, using either the eigenvalues and eigenvectors (Dransfield, 1994) or the generalised determinants (Pedersen and Rasmussen, 1990). Neither of these approaches appear to have been used extensively in applications.

An important consequence of gravity being a potential field is that it is possible to re-construct any components of \mathbf{g} and \mathbf{G} from measurements of one or more other components. This is routinely exploited in exploration geophysics. For example, the

vertical gravity gradient can be re-constructed from measurements of gravity and gravity can be re-constructed from measurements of the curvature gravity gradients. The quality of any such re-construction depends on the error, the Nyquist wavenumber and the area covered in the original measurements. These reconstruction techniques are well known from aeromagnetic survey applications and are based on original work in the Fourier domain by Bhattachayya (1965) and using equivalent sources by Dampney (1969).

Confusion can arise. Comparisons are occasionally made between the usefulness of the gravity field and the gravity gradient field for particular applications. These comparisons are valid – the gravity gradient emphasises shorter wavelength information than the gravity field – but are conceptually unrelated to comparisons between gravimeters and gravity gradiometers since measurements made by either instrument may be readily transformed into either field. Any comparison between a gravimeter and a gradiometer that is based on the relative usefulness of the gravity or gravity gradient field is naïve. An appropriate method of comparison between instruments is to examine the errors in the same domain. For example, the much lower error and higher Nyquist wavenumbers possible in airborne gravity gradiometry but not in airborne gravimetry mean that re-constructions of gD from gravity gradient measurements are more accurate than direct measurements of gD at the shorter wavelengths of interest in mineral exploration (Boggs and Dransfield, 2004).

GRAVITY GRADIOMETER FUNDAMENTALS

There are a number of significant advantages to performing exploration surveys from the air: primarily these are speed of coverage, ease of access and uniformity of coverage – often, particularly for larger areas, the first two advantages also result in lower costs. Airborne gravimeter surveys are limited by the equivalence principle, producing gravity data that has neither sufficient accuracy nor sufficient spatial resolution for mineral exploration and there is no real prospect that airborne gravimeters can ever overcome these limitations (van Kann, 2004).

The equivalence principle says that measurements on board the aircraft cannot distinguish accelerations due to gravity from those due to the motion of the aircraft. The gravity gradiometer can make this distinction. Consequently, the gravity gradiometer can deliver the accuracy and spatial resolution required for mineral exploration.

In its simplest conception, a gravity gradiometer is a spatially separated pair of accelerometers with a common sensing axis and mounted on a common base. The gravity gradient is the difference in the measured accelerations divided by the separation. Since they are mounted on a common base, the accelerations due to the dynamic behaviour of the aircraft will be rejected provided that the accelerometers are well matched. For a gravity gradiometer with a 10 cm accelerometer separation to achieve a useful noise limit of $10 \text{ Eö}/\sqrt{\text{Hz}}$ in a typical low-level survey acceleration environment of $1 \text{ ms}^{-2}/\sqrt{\text{Hz}}$ requires a matching of one part per billion (Lee, 2001).

Rotational motion of the aircraft will produce pseudo-gradients (Dransfield, 1994). The rotational acceleration tensor is anti-symmetric so that the symmetry of the gravity gradient tensor can be exploited by a second pair of accelerometers aligned so that each pair has its common sensing axis parallel to the baseline of the other pair. The sum of the signal from the pairs will add the gravity gradients but cancel the rotational accelerations. This depends on accurate matching of the response of each accelerometer pair, typically to 10 parts per billion (van Kann, 1992).

Pseudo-gradients due to products of rotational velocities must be eliminated by the navigation system, requiring three-axis rotational control at the 10 micro-radian level. In addition, excellent temperature and pressure control are required.

These very demanding requirements mean that the construction of useful airborne gravity gradiometers is a significant technical challenge.

The instrument error in gravity gradiometer data may be characterised as the sum of an intrinsic noise, independent of aircraft dynamics, and a dynamic noise that increases with aircraft dynamics. This dynamic noise will increase with the level of turbulence experienced on a gravity gradiometer survey. In order that measured data have an error less than the maximum allowed for the survey, the aircraft should avoid surveying in high turbulence conditions and any survey lines flown in high turbulence with consequent high noise should be re-flown. This limitation has a direct impact on system productivity and hence on cost. The total noise affects data quality.

CURRENT GRAVITY GRADIOMETERS

All operational airborne gravity gradiometers are based on technology (Hofmeyer and Affleck, 1994) developed by Lockheed Martin at their facility in Niagara Falls, New York.

Lee (2001) describes the underlying technology:

“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.”

There are two implementations of the GGI design (DiFrancesco, 2001) used in airborne gravity gradiometers.

The FTG implementation has three GGIs mounted with mutually orthogonal rotation axes, each at the same angle to the vertical. Each of the GGIs has one complement of accelerometers mounted on a circle with a diameter of approximately 15 cm.

The AGG implementation has only one GGI, mounted with its rotation axis near vertical. The GGI has two complements of accelerometers mounted on a circle with a diameter of approximately 30 cm.

For an individual GGI, the intrinsic noise power is inversely proportional to the number of complements and to the square of the circle diameter. Thus the intrinsic noise power in the GGI used in the AGG is eight times lower than that in the GGI used in the FTG. However, the FTG has three GGIs so that overall, the intrinsic noise power in the AGG is two and two-thirds smaller than in the FTG (DiFrancesco, 2001).

The angle of the GGI rotation axis to the vertical is also important. Typical light aircraft acceleration spectra show that the vertical acceleration has twice the power of the horizontal accelerations. The orientation of the GGIs in the FTG causes them to be exposed to a higher level of aircraft acceleration than the GGI in the AGG. This leads to a higher level of dynamic noise in the FTG implementation relative to the AGG implementation with a consequent impact on productivity and cost. Figure 1 shows how improvements in rejection of aircraft dynamics lead to higher productivity.

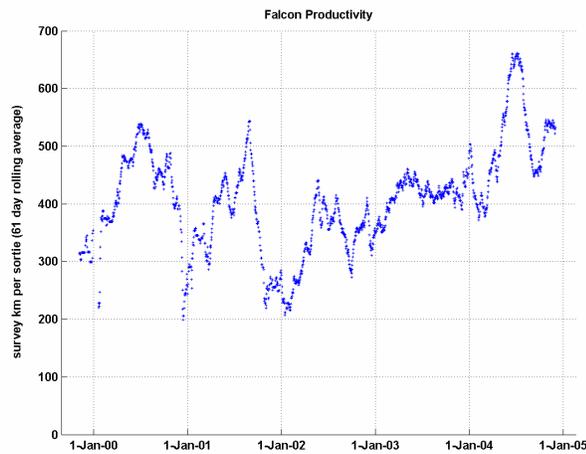


Figure 1: Falcon productivity history expressed as the average number of survey kms flown per sortie. There is a seasonal variation as cooler weather in southern winters coincides with lower turbulence. After 2000, turbulence restrictions were implemented, immediately reducing noise (Figure 2) and good flying conditions in 2001 delayed the impact on productivity. Reductions in sensitivity to aircraft motion through technical improvements led to significant productivity improvements over 2002-2004. After Dransfield and Walker (2005).

The AGG implementation is used in the BHP Billiton Falcon systems and the FTG implementation in the Bell Geospace Air-FTG and in the ARKeX FTGeX systems. Noise figures have been published for Falcon (Boggs et al., 2007) and Air-FTG (Murphy et al., 2007), both for survey data flown in a Cessna Grand Caravan. The Falcon noise was 2.5 Eö RMS filtered to a 300 m wavelength at 55 ms⁻¹ ground speed. The Air-FTG noise was 3.5 Eö RMS filtered to a 800 m wavelength at 60 ms⁻¹. Murphy et al. (2007) use the phrase “400 m spatial wavelengths” but make it clear that this is equivalent to 400 m sample spacing which is of course an 800 m Nyquist wavelength). The most direct comparison of these results is via

noise densities: Falcon noise density was 6 Eö/√Hz and Air-FTG noise density was 13 Eö/√Hz.

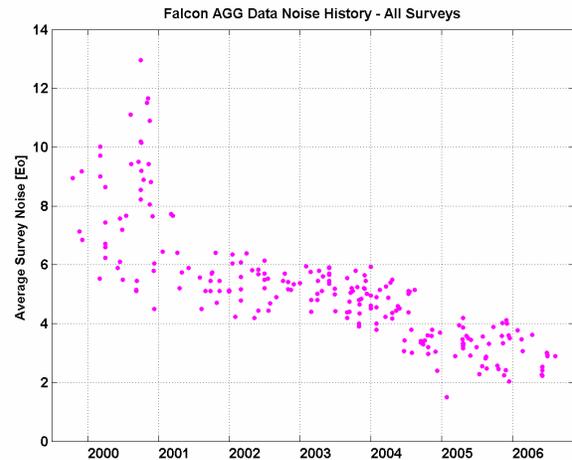


Figure 2: Falcon noise history. Each point on the figure is the average RMS noise for a completed Falcon survey plotted at the completion date of that survey. Improvements in operating procedures, instrument control and data processing have all contributed to the lowering of noise with time. The single point below 2 Eö RMS in early 2005 was for a test survey of the digital AGG. All data are from surveys flown in a Cessna Grand Caravan. Data to January 2005 is after Dransfield and Walker (2005).

These results both represent very significant improvements since these systems commenced operation. Murphy et al. (2007) claim that the Air-FTG noise, filtered to 800 m wavelength, has reduced from 15+ Eö RMS to 5.4 Eö RMS to 3.5 Eö RMS over 3 years.

The Falcon system has had a similar history (Figure 2). In 2005, the average noise, filtered to 300 m wavelength, was also 3.5 Eö RMS. The higher bandwidth of the Falcon technology provides a spatial resolution nearly 3 times better than the Air-FTG technology.

PLATFORMS

The choice of aircraft is important. I have shown that aircraft dynamical behaviour has a direct impact on both noise and productivity because of the limited rejection of aircraft dynamics. There are other factors affected by choice of aircraft. Given a fixed filter bandwidth (the usual situation with moving-base gravity gradiometers), spatial resolution is inversely proportional to aircraft speed so that a slower aircraft delivers better resolution. The gravity gradient varies inversely with distance so that lower flying height delivers higher signal. There are also operational and safety considerations which set a minimum aircraft speed.

Airborne gravity gradiometers are flying surveys from fixed-wing aircraft (in Cessna Grand Caravans), airship (Zeppelin LZ N07) and helicopter (in a Eurocopter AS350-B3). These platforms are each appropriate to different conditions.

Fixed-wing

Most airborne gravity gradiometry surveys for Falcon, Air-FTG and FTGeX systems have been flown in single turbine engine Cessna Grand Caravans. Typically, the Caravan has a survey ground speed of 55-65 ms^{-1} (~120 knots) and a ground clearance of 80-100 m in gentle terrain. It is the cheapest to operate of all three alternatives, provides the fastest coverage of survey area and is able to carry any of the currently available gravity gradiometers.

Airship

One of the Air-FTG systems has surveyed in Botswana for de Beers in the Zeppelin airship as described by Hatch et al. (2006a). The airship has been flown at 16 ms^{-1} (32 knots) and a ground clearance of 80 m. The high elevations and generally high daytime temperatures of Botswana limit the lift capability of the airship and consequently, survey operations can only take place at night. All gravity gradiometers could be carried by the airship. The major advantage of the airship over other platforms is its very low acceleration levels that result from its high inertia. This leads to low dynamic gradient noise.

Helicopter

One of the Falcon systems has been installed in a Eurocopter AS350-B3 helicopter (Boggs et al., 2007). The helicopter flies at 30 ms^{-1} (60 knots) at typical ground clearances of 25-60 m. Like the airship, it is fully laden when carrying a gravity gradiometer which limits application over high elevation terrain at high temperatures. Successful surveys have been flown in the Canadian arctic (some results are described below), including surveys with a frequency domain EM system. The AS350-B3 helicopter is only capable of carrying the light-weight digital AGG – all other gravity gradiometers are too massive. The distinguishing advantage of the heli-borne system is the greater resolution and sensitivity that come from flying lower and slower. This makes it particularly applicable for detailed mapping of small, near surface features.

Cross-Platform Comparison

It is useful to be able to compare the performance of gravity gradiometers across platforms travelling at different speeds. Murphy et al. (2007) propose a noise power density in the wavenumber domain, calculated by squaring the noise density and multiplying by the survey speed.

Figure 3 uses published information from Murphy et al. (2007), Hatch et al. (2006b), Boggs et al. (2007) and the data presented in this paper to compare the Air-FTG systems in a Caravan and airship and the Falcon systems in a Caravan and helicopter. This comparison ignores the helicopter advantage of flying lower and all operational, safety and cost variables.

The Air-FTG system has generally the highest sensitivity to aircraft motion, resulting in the highest error and variability in that error when mounted in a fixed-wing aircraft. However, this is fully compensated for by the use of the airship platform which is both very stable and very slow. The Falcon system has much lower sensitivity to aircraft motion and hence clearly outperforms the Air-FTG when in the same fixed-wing aircraft. Heli-borne Falcon has about the same noise power density as the airship-borne Air-FTG. Heli-Falcon has a further advantage, not shown in this figure, of being able to fly lower than the other systems so that it has much greater sensitivity to near-surface geology than the others.

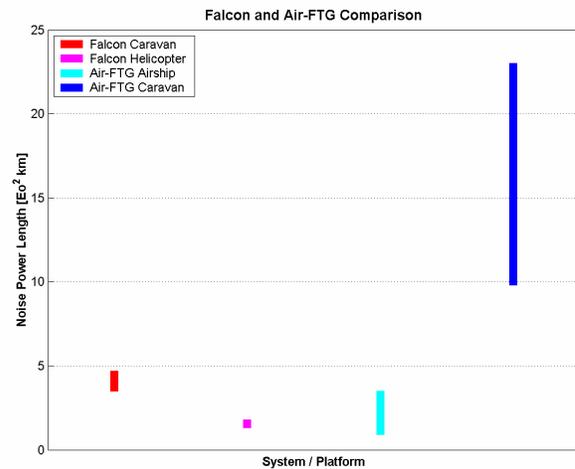


Figure 3: The error levels across four airborne gravity gradiometer installations are compared. This comparison is given in noise power density. The bandwidth is divided by the aircraft velocity so that it can be expressed in wavelength, a form which is more directly related to the signals of interest. Lowest noise power density corresponds to better sensitivity and resolution.

COMPARISON WITH GRAVIMETRY

Since one can use measurements from a gravimeter to calculate the gradients or those from a gradiometer to calculate the field, any comparison between the two types of instruments depends on the situation in which they are used. The prime advantage of the gradiometer is its greater accuracy when used in a moving vehicle. The prime advantages of the gravimeter are its low capital cost and smaller size and weight.

Comparisons need to consider accuracy across the entire wavenumber spectrum.

Airborne Gravity

As already described, airborne gravimetry is limited by the equivalence principle. In practical terms, reduction of gravity error relies on increased filtering and a loss of short wavelength information. Decreased filtering to preserve short wavelengths results in higher error. Typically, the error is 10 mGal RMS at

1 km wavelength down to 1 mGal RMS at 3.5 km (van Kann, 2004). As shown in Figure 4, the Falcon airborne gravity gradiometer, flying in a Cessna Grand Caravan, has an error of 0.1 mGal RMS at 1 km wavelength – an improvement of 100 times over airborne gravimetry. This ratio decreases with increasing wavelength until unity at about 20 km with an error of 0.45 mGal RMS.

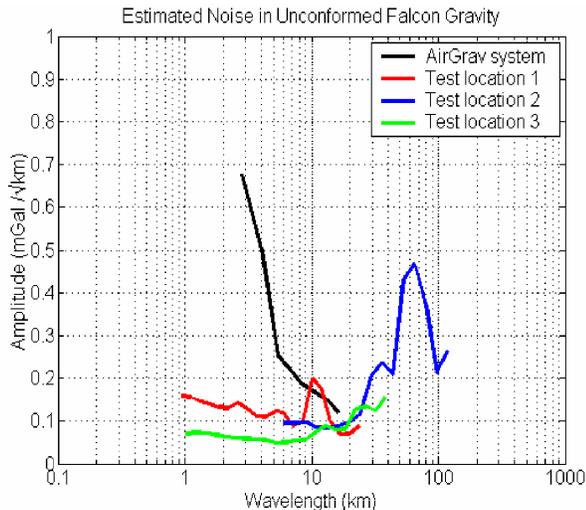


Figure 4: A comparison of error spectra in gravity measurements from an airborne gravimeter and an airborne gravity gradiometer after Boggs and Dransfield (2004). The black line shows errors from the Sander AirGrav system after Bruton et al. (2001). The coloured lines are from the Falcon system and are calculated as the difference between ground (red and blue lines) and marine (green line) gravity data and Falcon gravity data over the same area. The gravity gradiometer has lower noise at wavelengths below about 20 km.

Ground Gravity

Ground gravity surveys can, with reasonable care, routinely achieve ties with RMS errors of 0.1 mGal; very careful measurements will improve on this figure. We have already seen that a Falcon system in a Caravan can match this accuracy at 1 km wavelength but that this error increases to 0.45 mGal RMS at 20 km wavelength. Figure 3 provides guidance on how this will vary with the other gradiometers. Murphy (2004) shows a comparison between an Air-FTG survey and a ground gravity survey.

It is important to remember that the airborne gravity gradiometer data are filtered at shorter wavelengths. Typical wavelengths are 300 m for a Cessna Grand Caravan Falcon survey, 800 m for a Cessna Grand Caravan Air-FTG survey, 100 m for a Eurocopter AS350-B3 Falcon survey and 300 m for a Zepplin Air-FTG survey. At shorter wavelengths, the airborne gravity gradiometer data will not reproduce the ground gravity.

A comparison between Falcon gravity gradiometry and marine gravity is included in Rose et al. (2006).

TERRAIN CORRECTIONS

Often, the largest signal in a gravity gradient survey is due to the terrain, so it is important to consider terrain noise as well as system noise. Small errors in either the terrain elevation data or the navigation data can lead to significant gravity gradient errors at the low ground clearance typical of airborne geophysical surveys. From a simple 2D model, Dransfield (1994) estimates a required accuracy in terrain model and in navigation of better than 1 m for a gravity gradient error of 1.8 Eö at 80 m flying height. This is consistent with the experience at BHP Billiton. Modern differential GPS systems routinely provide navigation data with an accuracy of better than 1 m. The aircraft flying Falcon AGG surveys are equipped with Riegl laser scanners used, in conjunction with the GPS data and aircraft orientation data, to construct digital elevation models (DEMs) with the required accuracy. This methodology is described more fully in Stone and Simsky (2001) and Lee et al. (2004).

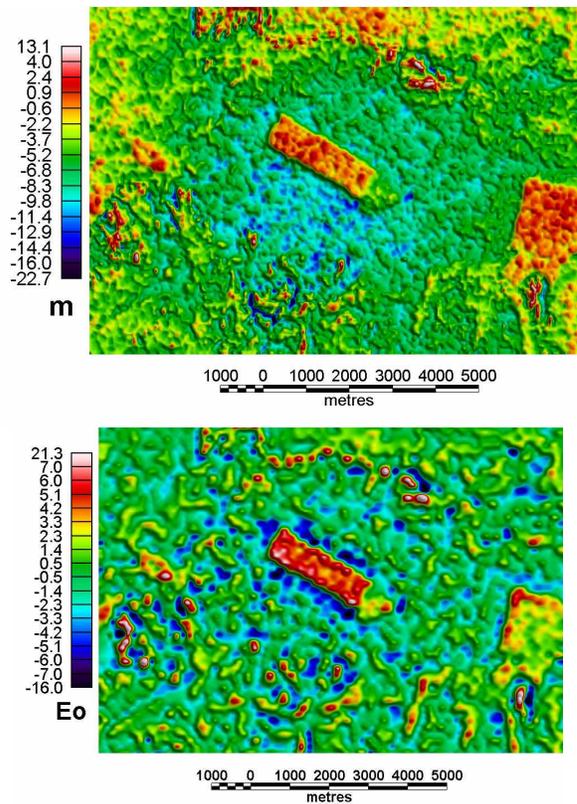


Figure 5: The difference between a DEM generated from the laser scanner and the SRTM DEM over the same area (top) Below that is the vertical gravity gradient error that results from using the SRTM DEM instead of the laser scanner DEM for an AGG survey flown at a ground clearance of 80 m. The central circular region is a forest with a rectangular portion of cleared ground at its centre. The remaining area is covered with low vegetation except for another cleared area on the right of the images. Small, high amplitude, features (particularly around the margin of the circular forested area) result from the poorer resolution of the SRTM data. As the figure shows, these could produce terrain correction errors of up to 21 Eö, some of which could be easily interpreted as exploration targets. After Dransfield and Walker (2005).

Figure 5 provides a demonstration of the importance of high quality DEMs. For this purpose, Dransfield and Walker (2005) compared the DEM from a Falcon system with the DEM from the shuttle radar topography mission (SRTM) over the same area in Zambia. The SRTM data have errors in vertical height of up to 23 m. The errors are primarily due to forest through which the shuttle radar could not penetrate and narrow ridge or hill tops not resolved by the limited spatial resolution of the SRTM data. In contrast, the narrow beam of the laser scanner means that it receives returns from the forest floor in all but the most dense vegetation and its rapid sampling rate provides extremely good resolution. The figure also shows the error in the final vertical gravity gradient data that would have resulted from using the SRTM data for terrain corrections in this survey. These errors are up to 21 Eö and are easily sufficient to produce false anomalies and make interpretation difficult.

EXPLOITING THE TENSOR

The advent of airborne gravity gradiometry has made it possible to exploit a number of mathematical techniques and relations that are not available in gravimetry. Here I give a very brief overview of some of these with references to recent work.

Drawing a parallel with aeromagnetic surveying where magnetic gradiometry is used to optimise data quality in data gridded from widely spaced survey lines, the gradients may be exploited in sampling techniques to produce better images and maps of the gravity field (While et al., TBP).

The Euler equation relates the field to its gradients and can be exploited to estimate the position of a causative source based on measured potential field data and an assumed source geometry. Zhang et al. (2000) demonstrate, using marine gravity gradiometry rather than airborne but the principle clearly carries over, that the use of the full tensor provides a better outcome in Euler deconvolution than using just the gradients of the vertical gravity field.

It is also possible to directly map invariants of the tensor as suggested by Pedersen and Rasmussen (1990) or the eigenvalues (Dransfield, 1994). These approaches can be useful in discriminating particular geometries of sources within the earth. Mikhailov et al. (TBP) exploit the invariants in Euler deconvolution of the full tensor.

In situations where both the magnetic and gravity gradient fields have been simultaneously measured over an area, it ought to be possible to exploit Poisson's relation to map lithology as suggested by Price and Dransfield (1994).

All of these approaches seek to extract additional information from the data to aid in interpretation. A more direct approach is to invert the measured data to a density model of the earth. Zhdanov et al. (2004) demonstrate, using focused inversion, that gravity gradients improve 3D inversions of gravity data by inverting data over the Cannington deposit in Queensland, Australia. They achieve an excellent match with the known geology.

APPLICATIONS IN MINERAL EXPLORATION

By October 2005, the Falcon systems had flown 1 million line-km of surveys, almost entirely for mineral exploration. Many more km will have been flown since then and many more by the Air-FTG and FTGeX systems in operation. It is clear that airborne gravity gradiometry has become a major part of mineral exploration efforts.

Airborne gravity gradiometry has been used in exploration for a wide variety of commodities and deposit styles both as a means of direct detection and as a means of improving geological mapping.

In this section, I give a brief description of some of these applications as an overview. Three particular examples are described in more detail. These are the Ekati Falcon surveys for diamonds, the Candelaria Falcon survey for copper and the West Musgrave Falcon survey for nickel.

Coal

The use of airborne gravity gradiometry in coal seam mapping in the Latrobe Valley, south-east Australia was described by Mahanta (2003). The coal seam, mapped as a vertical gravity gradient low in Figure 6, terminates where exposed along its southern edge and where the vertical gravity gradient reaches its lowest values. The seam then dips shallowly to the north-west under gravel cover, resulting in a gradual reduction in the amplitude of the gravity signal. Typical thicknesses of this seam are around 30-50 m at dips a little below 10°. The detectability of coal seams will generally be favoured by greater seam thickness and dip. Mahanta (2003) shows that the Falcon AGG can detect seams of greater than 10 m thickness at dips greater than 10°.

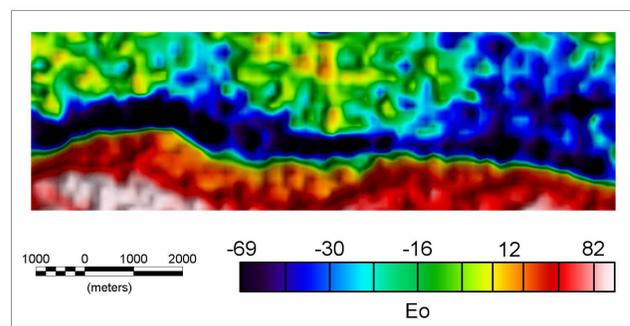


Figure 6: Mapping a coal seam in the Latrobe Valley with airborne gravity gradiometry. The data are from a survey flown in 2002 at 200 m line spacing and a ground clearance of 130 m. The low density of the coal produces a gravity low, truncated sharply at the Nosedale Monocline to the bottom of the image and dipping shallowly under gravel cover to the top-left. [Cleared for open publication 07-S-1806.]

COPPER (IOCG)

An obvious direct detection target for airborne gravity gradiometry is the iron oxide copper gold (IOCG) style of copper mineralisation typified by the Olympic Dam deposit. Falcon AGG surveys have successfully detected the Ernest Henry (Dransfield et al., 2001b) and Prominent Hill (Diorio et al., 2003) deposits. Other reported gravity gradient surveys for IOCG deposits are the King George Falcon survey (Mahanta et al., 2001) and the Air-FTG survey in the Wernecke Mountains of north central Yukon.

Most significant of all is the Candelaria survey flown in Chile which led to the Santo Domingo Sur discovery (Dransfield and Walker, 2005).

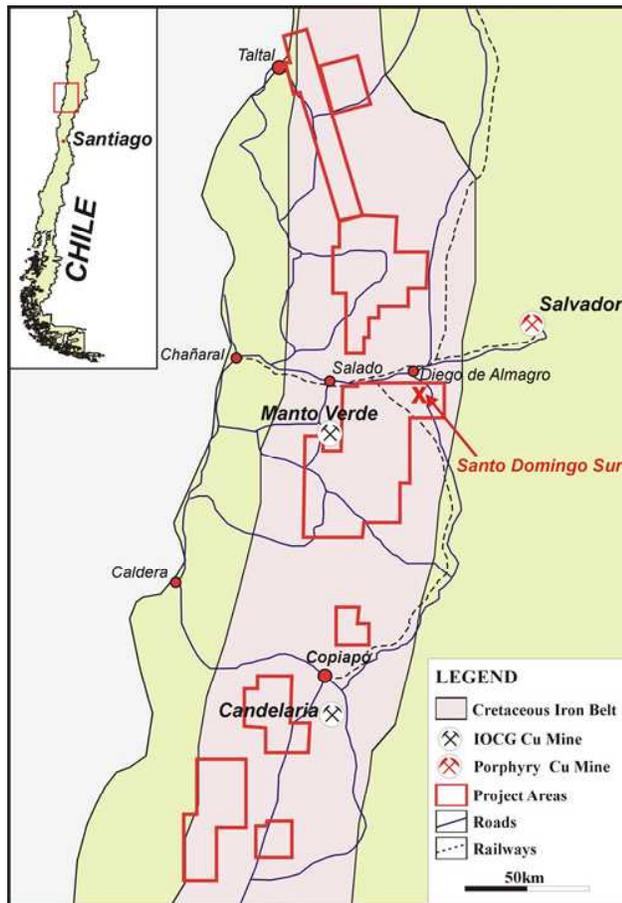


Figure 7: Map of the Far West Candelaria copper project areas in northern Chile showing the existing copper-(gold) mines such as Manto Verde and Candelaria. The Santo Domingo Sur deposit location is indicated by a red cross.

The Candelaria Project started in 2002 when Far West Mining and BHP Billiton formed a Strategic Alliance to explore for IOCG deposits in northern Chile’s Candelaria copper belt. The Cretaceous belt stretches over a length of almost 1200 km from just north of Santiago in the south to the city of Antofagasta in the north along the coastal cordillera of Chile.

The Candelaria Copper Belt is a highly prospective IOCG province and hosts numerous copper deposits including Candelaria (460 Mt @ 0.95% Cu) and Manto Verde (350 Mt @ 0.75% Cu).

In late 2002, the alliance partners flew a 10,700 line km Falcon airborne gravity gradiometer survey covering 5,145 sq km in 8 blocks along a 300 km strike length of the Candelaria copper belt (see Figure 7). Interpretation of the gravity and magnetic data identified more than 70 target areas, each containing one or more distinct gravity anomalies. Between February 2003 and May 2005, 18 target areas were tested by reverse circulation drilling and encouraging IOCG mineralisation was discovered in three target areas (3d, 4a and 4c).

The first announcement from Far West, in July 2003, was for the 4c target area where the first hole into Falcon target 4c3 intersected IOCG mineralisation averaging 2.5% copper and 0.33 g/t gold over a 60 m interval. However, the southern part of the 4a area (now called Santo Domingo Sur) has proved to be more significant (Figure 8).

Far West completed its 100% earn-in on the Candelaria project from BHP Billiton in May of 2005. BHP Billiton’s interest is now reduced to a 2% net smelter return royalty.

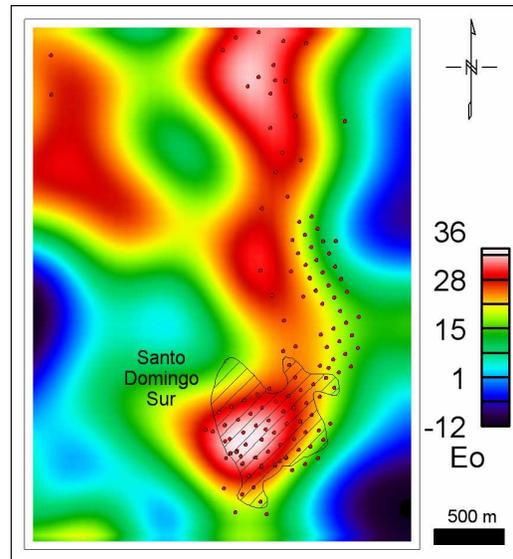


Figure 8: The figure shows the close correspondence between the mineralisation mapped by drilling and the gravity signature. [Cleared for open publication 07-S-1806.]

In the period from April 2005 to March 2006, Far West Mining conducted four phases of exploration drilling at its emerging Santo Domingo Sur deposit which is part of its Candelaria Project in Chile. As of May 3, 2006 the deposit has an NI 43-101 compliant indicated resource of 139.4 Mt of 0.59% copper at a 0.3% cut-off and contains in excess of 1.64 billion pounds of copper. The geology and mineralogy of the deposit show characteristics similar to the giant Candelaria deposit that is located approximately 120km to the south.

The Santo Domingo Sur discovery is a direct result of applying the advanced Falcon airborne gravity gradiometer system.

Diamonds (kimberlites and palaeochannels)

All the known major diamond deposits are primary sources – kimberlites and lamproites – but are extremely rare and their occurrence is largely independent of surface geology. An important consequence of their rarity and the shortage of vectors to prospective ground is the need to use exploration methods that allow the explorer to rapidly cover very large areas. Combined with the fact that the intrusives usually have significantly different physical properties to the host rock, this makes airborne geophysics particularly attractive.

Aeromagnetic and airborne electromagnetic prospecting have been particularly popular and the availability of detailed airborne gravity data from gravity gradiometry since 1999 has seen very strong demand for its application in diamond exploration. BHP Billiton's Falcon systems had flown 1 million line kilometres by October 2005 and more than half of these were in diamond exploration. Bell Geospace's Air-FTG systems have also flown a significant proportion of their surveys for diamonds and one of the Air-FTG systems has a major commitment for diamond exploration in Botswana.

Of the secondary sources, palaeochannel deposits ought to have a density contrast with host rocks and so should also be detectable by airborne gravity gradiometry.

Here are a few examples of new diamond discoveries found by airborne gravity gradiometry.

A Falcon survey flown to the west of Kimberley in South Africa in 2001 delineated a palaeochannel interpreted to be draining the Finsch Diamond Mine. A Joint Venture was formed with Tawana Resources, which commenced drill-testing the gravels in the channel. Results to date indicate that significant quantities of diamond bearing gravels have travelled downstream from the heavily eroded Finsch kimberlite. The survey also identified several new kimberlites (Tawana Resources NL, Annual Report, 2006).

Micro-diamonds were recovered from the W09 crater facies kimberlite discovered in drilling a Falcon target generated from a 2001 survey just south of the Ekati mine. The pipe has a surface expression of 100 m by 200 m (Dransfield and Walker, 2005).

Isles and Moody (2004) reports the discovery of two new kimberlite pipes (Persephone and Niobe) just south of the Aries pipe in north-west Australia.

In January 2005, Gravity Diamonds announced the discovery of the diamondiferous Abner kimberlite following drilling of an airborne gravity gradient anomaly (Dransfield and Walker, 2005).

These examples are all from the Falcon technology mounted in a fixed-wing aircraft. The use of an Air-FTG system on board an airship and a Falcon system on board a helicopter is expected to lead to an increase in the success rate.

This is supported by a direct comparison between gravity gradiometer data collected from a fixed-wing platform and from a helicopter platform which can be made using the results of surveys conducted over the BHP Billiton Ekati tenement in North West Canada. The following comparison is based on Liu et al. (2001) and on a presentation by R.A.M. Maddever (personal communication, 2006) to the Australian Earth Sciences Convention in Melbourne, Australia.

The second airborne gravity gradiometer built, a Falcon system called Newton, was delivered to BHP Billiton by Lockheed Martin in April 2000 and was immediately deployed to Ekati. Following two successful test surveys over the Point Lake and Pigeon kimberlite pipes at Ekati, BHP Billiton decided to survey the entire Ekati tenement.

The Ekati survey was flown at 100 m line spacing and with a nominal terrain clearance of 80 m. A total of 39,000 line-km were flown in the three months from late April to the end of July. The final, fully terrain-corrected, vertical gravity gradient data are shown in Figure 9.

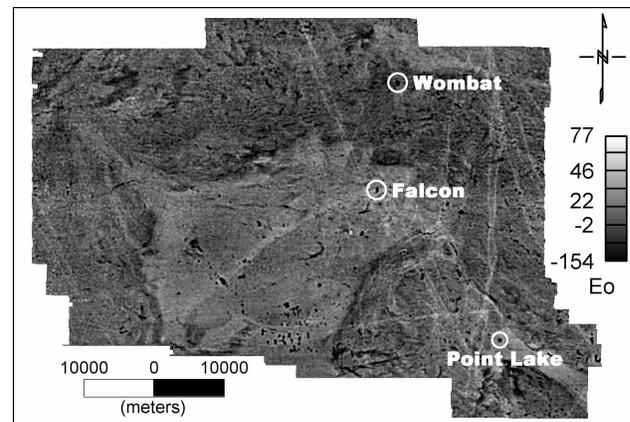


Figure 9: An image of the vertical gravity gradient from the Falcon Ekati survey after Liu et al. (2001). Key features visible in this image are isolated dark gravity lows some of which are due to kimberlite pipes, long sinuous light features due to intrusive dykes and broad variations in shade due to the host geology. [Cleared for open publication 07-S-1806.]

The figure is notable for illustrating three outcomes of the survey. Broad regional features corresponding to the host geology are clearly mapped – these have been verified by geological mapping. Long, approximately linear features correspond to intrusive dykes – the Falcon system's ability to discriminate such dykes at a separation of 300 m is an unequivocal demonstration of its 300 m resolution. Finally, a number of small near-circular gravity lows are visible.

Some of the latter are due to small hills, believed to consist of a mixture of glacial sediments and ice, whose low density has resulted in over-correction of terrain effect. Use of a smaller density in the terrain correction separates these anomalies from those of economic interest.

Of the 136 kimberlite pipes known in the tenement at the time of the survey, 55% were identified as anomalies in the gravity gradiometer data. The survey led directly to the discovery of three new kimberlites in an already very well-explored tenement (Dransfield and Walker, 2005) including the diamondiferous Impala pipe.

The error in the vertical gravity gradient data from the Ekati survey was estimated at 7.6 Eö RMS in a 0.18 Hz bandwidth (300 m wavelength at the nominal aircraft speed of 105 knots). Improvements in BHP Billiton's processing techniques led to these data being re-processed in 2004 with a reduction in vertical gravity gradient error to an estimated 5.7 Eö RMS in a 0.18 Hz bandwidth. At this error level, we found that

approximately 65% of known kimberlite pipes were now detectable.

In May 2006, following successful tests at Bulgary Ridge, New York (Boggs et al., 2007), the helicopter-borne digital AGG system, called Feynman, commenced production surveying at Ekati over areas flown in the Newton Falcon surveys. Survey specifications were for a 50 m line spacing flown at a nominal 50 m ground clearance and 30 ms⁻¹ ground speed. Filtering is to a 0.3 Hz bandwidth. Images of the resulting vertical gravity gradient data over the Central Ekati block are shown in a comparison with the original Ekati survey data after re-processing in 2004 (Figure 11).

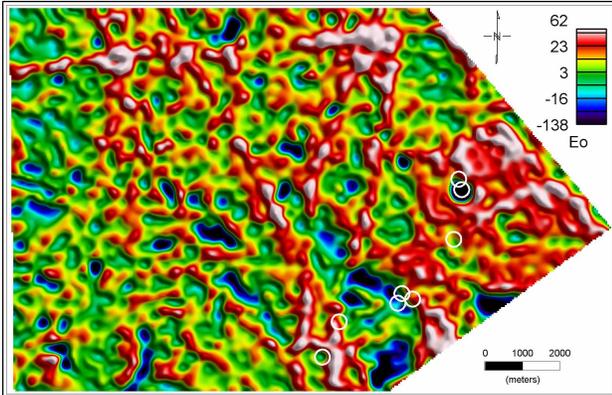


Figure 10: A portion of the data from the Falcon Ekati survey showing known kimberlites (white circles). These data were acquired by a fixed-wing aircraft in 2000 and re-processed in 2004. This area was re-flown as a heli-borne Falcon survey in 2006 (see below). [Cleared for open publication 07-S-1806.]

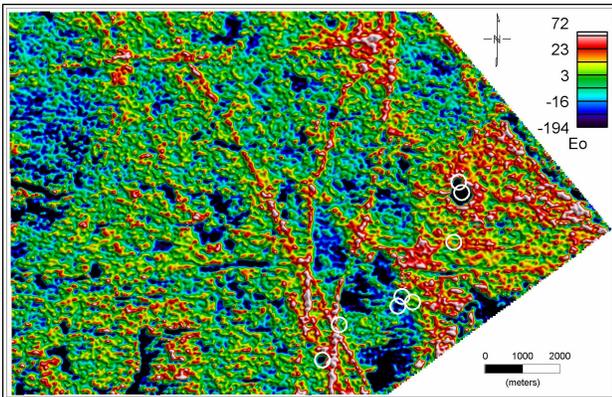


Figure 11: The Falcon Central Ekati survey vertical gravity gradient. Known kimberlites are indicated by white circles. The spatial resolution is dramatically improved in comparison to the fixed-wing survey (Figure 10) due to the slower flight speed and lower flight height. [Cleared for open publication 07-S-1806.]

The improvement in spatial resolution is immediately apparent providing clear vindication of the advantages of flying lower and slower. In particular, note the known kimberlite pipe closest to the bottom of the figure (circled in white). It is not visible in the fixed-wing data but is a clear target in the helicopter data. Figure 12 shows in profile the impact of flying lower and slower over this pipe.

Feynman gravity gradient data has successfully detected over 90% of the known pipes in the Ekati tenement areas that it has flown.

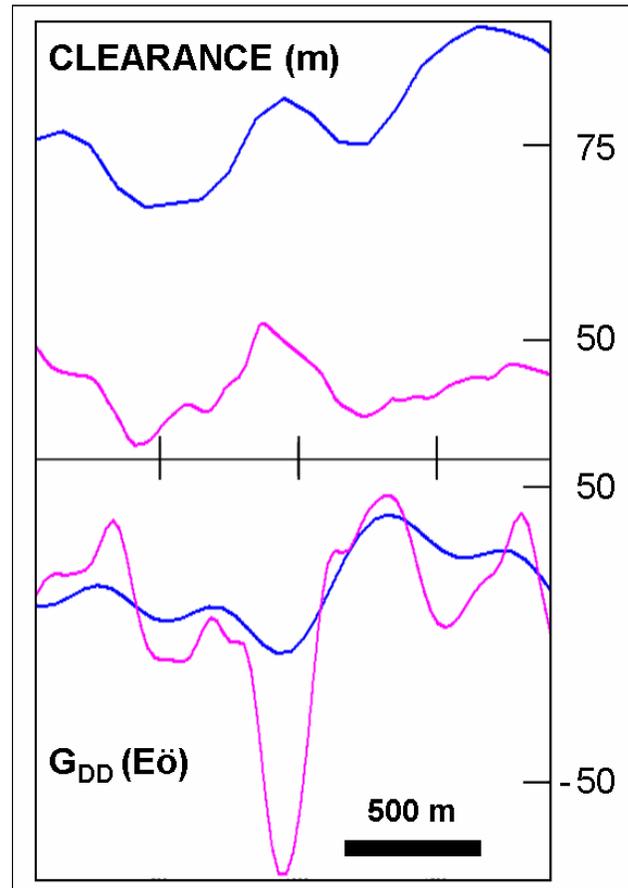


Figure 12: The effect of flying lower and slower. The data are from a horizontal profile taken across the lowest circled kimberlite in Figure 10 and Figure 11. The fixed-wing Falcon vertical gravity gradient (blue, bottom), flown at 80m (blue, top) and low-pass filtered at 300 m barely detects the small known kimberlite at location 950 m. The heli-borne vertical gravity gradient (magenta, bottom), flown at 45 m (magenta, top) and low-pass filtered at 100 m detects the pipe unequivocally. [Cleared for open publication 07-S-1806.]

Copper-zinc (VMS)

Volcanogenic massive sulphide deposits are well known as deposits that typically have a good gravity response due to their high density (see, for example, Walker and Mannard, 1974; Grant and West, 1965 and Fritz and Sheehan, 1984) and ground gravity has been extensively used in their detection.

The very first airborne gravity gradient survey was flown over part of the Bathurst Camp, including the Heath Steele and Stratmat deposits (Dransfield et al., 2001a). The Stratmat deposit consists of narrow lenses associated with gabbroic intrusives and it is likely that most of the gravity signal here is due to the intrusives rather than the deposit. At Heath Steele, the volume of

mineralisation is more substantial so that the gravity signal is likely to be more directly associated with the deposit.

The correspondence between gravity highs and zones of mineralisation in the survey area can be clearly seen in Figure 13.

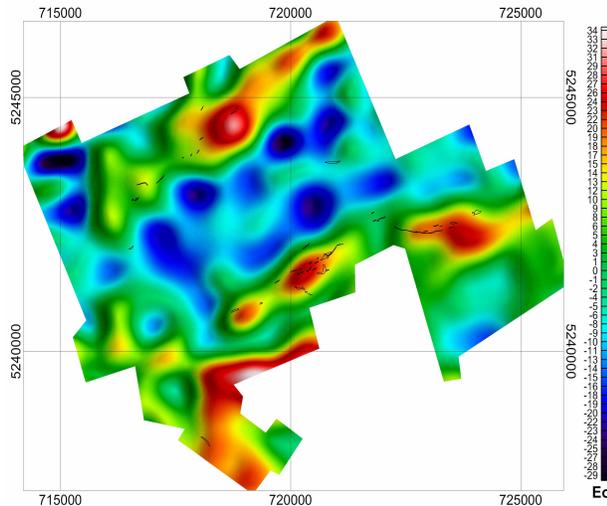


Figure 13: The vertical gravity gradient image from the Falcon Bathurst survey flown in 1999. The Heath Steele deposit is associated with the gravity high at 720 000 E, 5 242 000 N; the Stratmat deposit with the gravity high at 718 000 E, 5 245 000 N. [Cleared for open publication 07-S-1806.]

Other minerals

Airborne gravity gradiometry has also been shown to be useful for a range of other minerals and deposit types.

Perhaps the most obvious of these is iron ore exploration, particularly for massive haematite deposits whose high densities make them good gravity targets. Dransfield et al. (2001b) reported results of the Republic Falcon survey in north-west Michigan, USA, where the gravity gradients clearly mapped the banded iron formations. Lee et al. (2001) similarly report a demonstration Falcon survey over the Middleback Ranges in South Australia. The Air-FTG gravity gradiometer has flown in the Quadrilatero Ferrifero, Brazil mapping the structures associated with iron mineralisation (Mataragio et al., 2006).

Christensen et al. (2001) show that airborne gravity gradiometry would have detected the Cannington silver-lead-zinc deposit and Lane (2006), in a detailed evaluation of a Falcon survey over the Broken Hill lead-zinc mine, shows that the original deposit would have been detected by the survey. The same survey led to significant zinc intersections at the Goldfinger target (Anderson et al., 2006).

A model study of gold deposits in the greenstone belts of Western Australia's Yilgarn Craton suggests that airborne gravity gradiometry would be useful in detecting the low density weathered zones associated with these deposits (Bayat, 2007).

Glass Earth have flown an Air-FTG survey as part of an airborne geophysical mapping program in the search for gold in New Zealand (described on their web site at http://www.glassearthlimited.com/gel_news.html).

BHP Billiton have used their Falcon system in regional mapping as part of a porphyry copper exploration program in Mongolia (BHP Billiton Annual Review, 2006).

Dyke (personal communication, 2007) demonstrated, in a presentation to the ASEG, Western Australia branch, the use of airborne gravity gradiometry to map the gabbronorite intrusions that host the massive NiS mineralisation of the Neebo-Babel deposits in the West Musgraves, Western Australia. The magnetisation of these intrusives is weak and variable and ground access difficult so that airborne gravity gradiometry is particularly useful.

APPLICATIONS IN OIL AND GAS EXPLORATION

The subject of this review is airborne gravity gradiometry for mineral exploration but there is some value in a short digression into the applications in oil and gas exploration.

There are a number of important and useful such applications for gravity in oil and gas exploration. Airborne gravity gradiometry can contribute to any of these, providing significantly lower noise and higher resolution data than airborne gravimetry and faster coverage with reduced access issues than surface gravimetry.

In general, the major areas of application are those that provide extra information when seismic data is limited or in mapping large areas in order to target an expensive seismic survey effectively.

Gravity gradiometry has already proven itself in these fields.

Rose et al. (2006) report the successful mapping of an Eocene channel in a Falcon survey over a portion of the Gippsland Basin, Australia's major domestic oil source.

O'Brien et al. (2005) report the successful use of FTG data in a 3D inversion constrained by seismic information to calculate the base of the K2 salt body in the Gulf of Mexico down to depths of 20 000 feet.

Nelson et al. (2004) report the successful application of airborne gravity gradiometry in structural mapping in the Papua New Guinea fold belt, a region where "jungle cover, rugged topography, and paucity of roads" make exploration on the surface difficult and expensive.

An additional example, not reported previously, is from the Cliffs oil field in the Perth basin, Western Australia. The oil accumulation is controlled by a horst block which is clearly mapped in the gravity as shown in Figure 14.

In the Bonaparte Gulf off the north-west Australian coast, Nexus flew a Falcon survey to map salt diapirs (Dransfield and Walker, 2005). As shown in Figure 15, a known salt diapir was successfully detected and a number of targets with a similar response were identified.

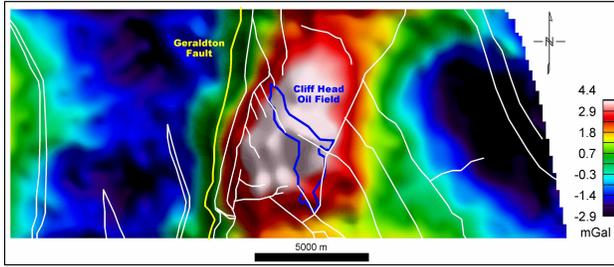


Figure 14: An image of the gravity mapped by the North Perth Falcon survey with structural geology (white lines) and the outline of the Cliffs oil field (blue lines) drawn over the top. The oil field is controlled by an uplifted horst block which produces a clear gravity high. [Cleared for open publication 07-S-1806.]

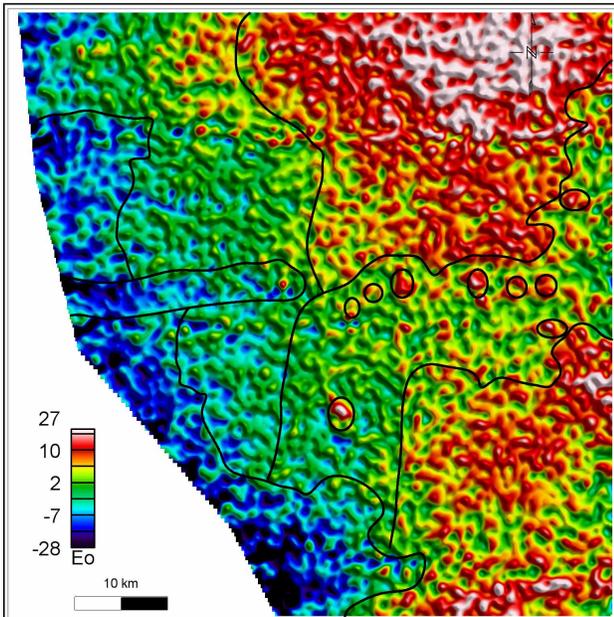


Figure 15: The vertical gravity gradient over the NT/P66 Falcon survey in the Bonaparte Gulf, Australia. The survey was flown to map salt diapir targets and the gravity high at 480,000 E, just below the centre of the image is a known salt diapir from seismic data. [Cleared for open publication 07-S-1806.]

FUTURE SYSTEMS

Research and development teams are working on gravity gradiometer technologies quite different in concept to the rotating gravity gradiometer technology currently in use. Before a brief overview of these technologies, I find it useful to note what improvements might be useful. What should developers be aiming for?

One important consideration is the impact of terrain correction noise. Dransfield (1994) uses a simplistic model to demonstrate the crucial importance of navigation and surface elevation error in terrain corrections for low-level airborne gravity gradiometry and that the resulting gravity gradient error is inversely proportional to the fourth power of the survey height

above small terrain features. Stone and Simsky (2001) demonstrate an overall 20 cm accuracy and claim that this level of accuracy is easily sufficient to keep terrain correction error small compared to gravity gradiometer error for Falcon gravity gradiometry. Since 2001, Falcon gravity gradiometer noise levels have halved and survey altitudes have reduced from 80 m in a fixed-wing aircraft to 60 m in a helicopter. These two changes are equivalent to requiring that terrain correction noise now be 6.3 times smaller than was required in 2001. It is possible that terrain correction error is already more important than instrument noise in some surveys.

The relative importance of terrain correction noise suggests that major reductions in airborne gravity gradiometer noise might no longer be the most important driver for future systems.

The biggest recent advances in airborne gravity gradiometry were announced in 2006. These were the use of gravity gradiometers in an airship (Hatch et al., 2006b) and a helicopter (Boggs et al., 2007). These two implementations resulted in a very significant improvement in effectiveness as I have already described. They were driven by a recognition of the limitations of the current AGG and FTG technologies.

These limitations are size, weight, and cost and, for the FTG, sensitivity to turbulence. An additional limitation is the export license regime, arising from the fact that the rotating gradiometer technology was initially deployed for military applications, and which prevents the use of the technology in many countries and limits access to the data and to the instruments. I believe that these useability limitations are now more important than sensitivity limitations.

There are a number of new gravity gradiometer technologies under development (Difrancesco, 2007). The important ones are those that have or are constructing an instrument working in the laboratory with reasonable prospect of successful operation in a moving platform. These are the superconducting orthogonal quadrupole rotator (OQR), the superconducting magnetically suspended mass (MSM) and the atom beam interferometer (ABI).

The technologies are well described in a number of publications: the OQR, being developed by Rio Tinto and the University of Western Australia, in van Kann (1992), the MSM (ARKeX) in Lumley et al. (2001) and the ABI in Snadden et al. (1998) (Stanford University) and Rowlands et al. (1996) (Swinburne University of Technology). Matthews (2002) includes a comparison of some of the fundamental design concepts.

The primary aim of the developing superconductivity technologies is lower noise. I expect this to include lower sensitivity to turbulence. I also expect that these will meet the aim of avoiding the restrictive usage regime that currently applies to the rotating gradiometer technology. Unfortunately, none of the superconducting technologies aims to deliver a gravity gradiometer lighter, smaller or of lower cost than the current state-of-the-art. Indeed, the need to keep a superconducting gravity gradiometer at temperatures below 10 K with a large dewar of liquid helium and the expense of superconducting technology makes it unlikely that these can ever meet the aims that I regard as most valuable.

Atom beam interferometer gravity gradiometers are based on a technology that is less mature than superconductivity but,

without the need for a large volume of coolant, do hold out a better prospect for smaller and lighter systems in the future.

My expectation is that the rotating gravity gradiometer technology will be the predominant technology for airborne gravity surveys in mineral exploration for the next ten years.

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