Review of modern airborne gravity focusing on results from GT-1A surveys

Adam Wooldridge[*] reviews improvements in airborne gravity systems over the last 10 years and, on the evidence of 200,000 line km, demonstrates the overall capability of the GT-1A system under standard survey conditions.

By far the largest market for airborne gravity is the petroleum sector where regional gravity surveys play an important role in identifying and mapping sedimentary basins. Combined with airborne magnetics, gravity is typically used as a first stage in frontier environments where results provide important details of the basin structure and sediment thickness, often key to assessing petroleum potential. From a budget perspective, airborne gravity and magnetic survey is a relatively cost effective and rapid means of covering large exploration licences. In addition airborne gravity datasets can be used to optimize seismic planning as well as assisting with interpolation between regional seismic lines more than recovering costs in subsequent savings.

Sedimentary basins produce large long wavelength gravity lows due to the density contrasts between the lower density sedimentary package and crystalline basement. These anomalies are invariably over 10 mGals in amplitude and well over 10 km in wavelength, easily within the accuracy resolution capabilities of airborne gravity systems. Basin structure, on the other hand, produces small subtle gravity anomalies on the limit of – or beyond the limits of accuracy resolution of modern airborne gravity systems. As a result there is a strong motivation to improve both the accuracy and resolution of systems.

Unlike airborne gradiometer systems which, in principle, measure the gradient of the Earth's gravitational field independent of aircraft accelerations, airborne gravity systems measure a combination of aircraft accelerations and the Earth's gravitational field. As a result most of the design and processing is aimed at maintaining the gravity sensing unit in a vertical orientation and accurately measuring the aircraft's corresponding vertical movement using differential GPS velocities. Currently commercial gravimeters utilize gyro-stabilized platforms to maintain the vertical orientation with any residual platform misalignment errors recorded either using dynamically tuned gyros or via a control loop which is used to measure horizontal accelerations. In simple terms, subtracting the GPS derived vertical accelerations of the aircraft from the total vertical gravity measured by the instrument will provide residual gravity (in practice additional corrections are required such as corrections for platform misalignment, horizontal accelerations, accelerations, Eötvös effect, drift, and minor temperature variations).

As the dynamic range of aircraft acceleration is several orders of magnitude greater than the geologic anomalies of interest, all airborne gravity systems rely on relatively long down-line filtering to improve the accuracy of the calculated residual gravity. The down-line filters are often complex in nature, for example the GT-1A processing uses non-stationary predictive Kalman filters to generate residual gravity. The reliance on long wavelength down-line filters to reduce the gravity data introduces a fundamental limitation to the resolution achievable with airborne gravity systems and is the key to understanding the accuracy resolution attributes of the data.

This paper reviews the currently available instruments for commercial survey as well as the methodologies used to estimate the accuracy and resolution of an airborne gravity survey and the means to improve both parameters. As part of the accuracy resolution review, cross-over and test line results are presented based on more than 200,000 line km of recently completed airborne gravity survey using the GT-1A, providing one of the first comprehensive reviews of the systems capabilities. Finally the extent to which the accuracy resolution of a system can be improved using slower aircraft speed and tighter line spacing is assessed.

Airborne gravity systems

At the time of writing there are four commercial airborne gravity systems available for survey:

1. The LaCoste and Romberg modified marine Air II meter is a highly damped spring gravity sensor mounted on a two axis stabilized platform which was developed in the early 1990s and released for commercial survey in 1995 (Williams and Macqueen, 2001). The instrument has been flown consistently on a number of different projects and by the late 1990s was by and large the established instrument for commercial airborne gravity. Although results presented by Williams and Macqueen (2001) indicate that the instrument is capable of achieving sub mGal accuracies for a 100s full wavelength down-line filter, much of

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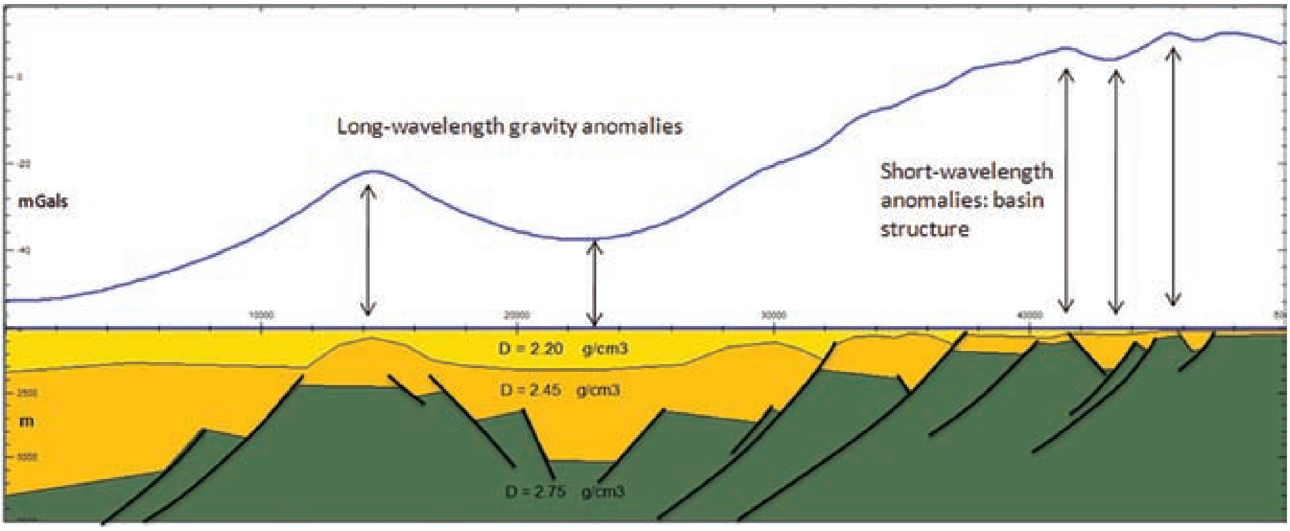

***Figure 1** Modelled gravity anomaly over a typical basin illustrating the relative amplitude and wavelength of the gravity response due to the broad basin and detailed basin structure. As anomalies attributed to basin structure are subtle, this calls for improvement in the overall accuracy resolution of airborne gravity systems.*

the published literature indicates that typical accuracies under survey conditions are greater than 2 mGals, e.g., Bastos et al. (2000); Glennie et al. (1999); Bruton et al. (2001); Wooldridge (2004a). The Air II instrument has largely become redundant with the introduction of more accurate Airgrav and GT-1A instruments and has recently been replaced by the Scintrex TAG system (Air III).

2. The AIRGrav system consists of a three-axis gyro stabilized inertial platform with three orthogonal accelerometers. A Schuler-tuned inertial platform is used to maintain the vertical orientation of the gravimeter independent of the aircrafts acceleration (Sander et al., 2004). One of the major advances in this type of system was the improvement in the INS platform and use of an accurate three axis accelerometer rather than a spring-type sensor removing the reliance on a control loop to measure horizontal accelerations. As a result the instrument is capable of operating in typical flying conditions experienced in aeromagnetic surveys (Sander et al., 2004) and has been demonstrated to consistently deliver results of better than 0.6 mGals for a 100 s full wavelength down-line filter (Elieff and Ferguson, 2008).
3. The GT-1A system was developed by Gravimetric Technologies in the Russian Federation. The system again relies on a Schuler-tuned three-axis inertial platform (Gabell et al., 2004; Berzhitzky et al. 2002) with vertically constrained gravity sensing element allowing for operation in more turbulent conditions compared with the Air II system (Wooldridge, 2004a). Unlike the AIRGrav system, the quality of GT-1A results are impacted by increased turbulence (Studinger et al., 2008) preventing the possibility of tight drape flying with the instrument and often necessitating a requirement for night flying when conditions are less turbulent. Presented results demonstrate that under ideal conditions the system is capable of accuracies better than 0.5 mGals for 100 s down-line filter lengths (Wooldridge (2004b)). Based on results presented in this article, the system is capable of consistently delivering results of better than 1 mGal for a 100 s full wavelength down-line filter with an overall average of better than 0.7 mGals.
4. The TAGs system has recently been introduced by Scintrex. The system is a modification of the original L&R-Air II gravimeter with two-axis gyro-stabilized platform and zero-length spring concept. Improvements have been made to the spring tension tracking loop and stabilized platform control loop. Following flight test data from 2006 to 2009, Scintrex has claimed that the system is capable of

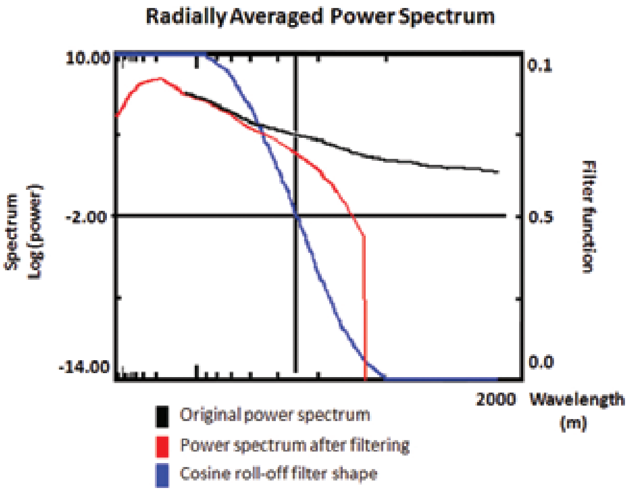

***Figure 2** Approximation of the 80 s down-line Kalman filter used to reduce GT-1A data at an aircraft speed of 60 m/s. The filter shape is illustrated in blue with an example of a power spectrum and resultant filtered spectrum illustrated in black and red respectively.*

achieving sub-mGal accuracies for a 100 s full wavelength down-line filter.

Estimating accuracy resolution

Down-line filters of between 50 and 200 s are typically used to reduce residual gravity. By shortening the filter length, the system resolution is improved at the expense of accuracy which degrades exponentially. The effective resolution of the system is generally equated to the half wavelength of the down-line filter multiplied by the aircrafts speed (as a result half wavelength filter lengths are often quoted rather than the full wavelength filter). In practice the relationship is more complex due to the structure of the filter used to smooth the data. An approximation of an 80 s Kalman filter used to reduce GT data at an aircraft speed of 60 m/s is illustrated in Figure 2. The filter is similar in characteristics to a full wavelength cosine roll-off filter with 100% pass at 10 km, 50% pass at 4.8 km, and 0% pass at 3 km.

Several methods for calculating uncorrelated noise in airborne gravity datasets are used. Typically contractual

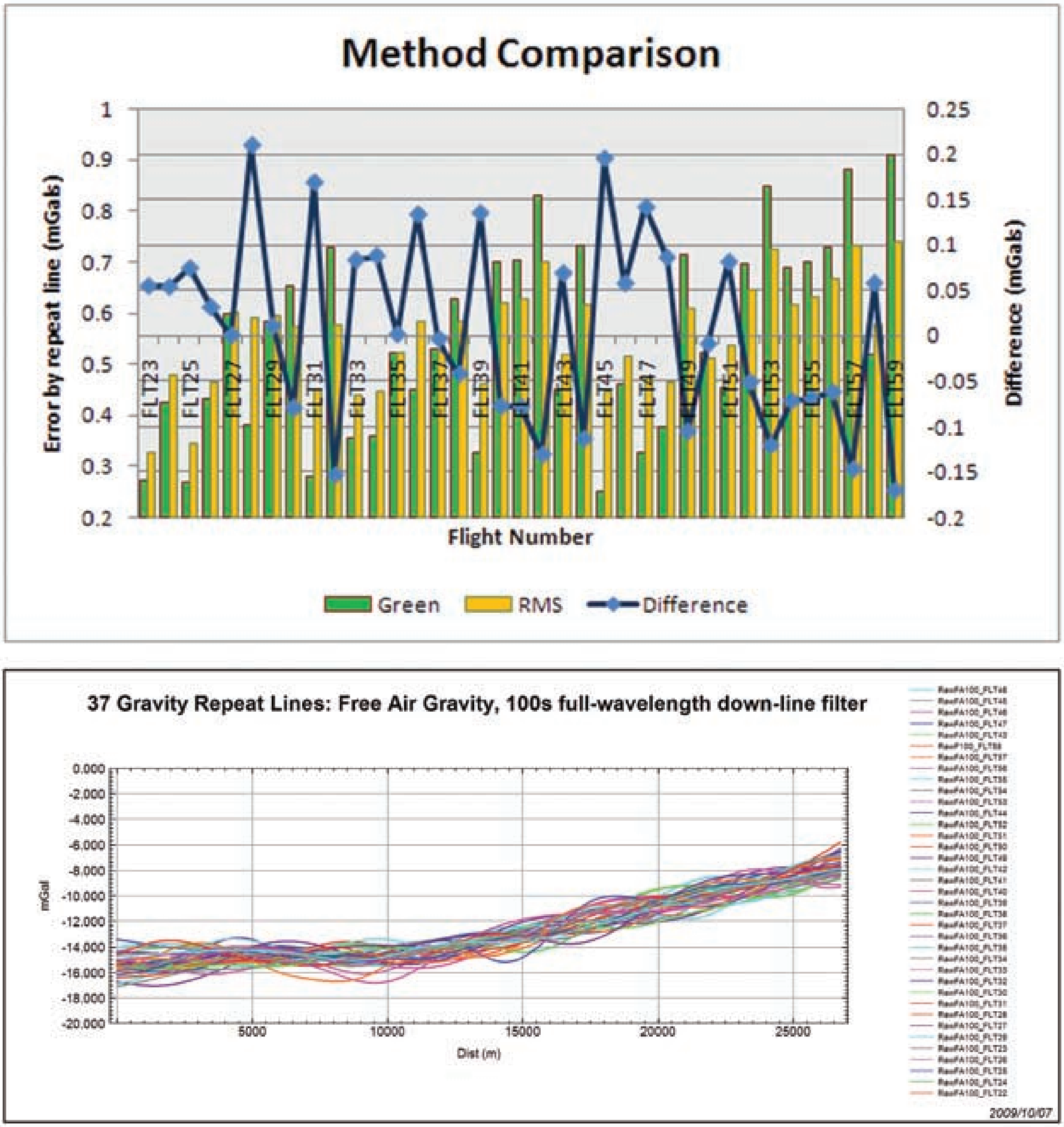

Figure 3 Repeat line results from 37 lines collected on a recent GT-1A survey. The graph illustrates the difference between Green and Lane's method and RMS differences for progressive numbers of repeat lines.

tolerances rely on cross-over differences between traverse and tie lines after first order levelling has been applied. A simple grid based method subtracting gridded odd and even traverse lines is effective when the line spacing is tight enough to provide sufficient oversampling in the dataset (Sander et al., 2002).

Method	Result (mGals)
Green and Lane	0.593
RMS	0.602
Average deviation from mean	0.512

***Table 1** Comparison of methods used to determine uncorrelated noise.*

Statistically, repeat line data provides a more robust estimate of uncorrelated noise. Two methods are typically used to calculate repeat line noise: a statistical method suggested by Green and Lane (2003) for calculating additive errors in repeat line data; and a more standard method using the RMS differences between repeat lines. As the choice of method for noise calculations produces slightly different results it is worth briefly describing the differences and demonstrating the outcome on a dataset of 38 repeat lines collected on a recent GT-1A survey.

Green's method is based on a linear model for additive errors (X) that are described as a function of the line (l) and sample (i). The data are used to calculate the arithmetic mean for each location using all the lines and the arithmetic mean

Survey line kms	Cross-over error	Repeat line error	# Repeat lines	Survey type
10 629	0.63	0.41	18	Drape
10 500	0.85	0.54	14	Drape
2 300	0.55	0.59	7	GPS Height
5 560	0.56	0.60	11	Drape
11 700	0.96	0.82	30	Drape
5 790	0.61	0.67	15	GPS Height
16 160	0.69	0.62	12	Drape
4 545	0.53	0.79	4	GPS Height
2 950	0.70	0.68	6	GPS Height
5 740	0.62	0.58	9	GPS Height
8 817	0.46	0.71	13	GPS Height
5 430	0.86	0.60	11	Drape
15 370	0.69	0.68	15	GPS Height
3 600	0.51	0.65	6	GPS Height
49 411	0.69	0.69	84	GPS Height
20 000	0.75	0.72	36	GPS Height
3 800	0.73	0.75	7	GPS Height
33,000	0.53	0.70	62	GPS Height
215,302	0.67	0.70	361	

***Table 2** Accuracy results from 100 s free air data for recently completed surveys. Cross-over errors have undergone first order levelling; repeat line analysis undertaken using Green and Lane's method.*

Aircraft	Normal Cruise speed	Stall speed	Typical survey speed
Pilatus PC6	125 Kts	52 Kts	90 – 110 Kts
Eurocopter AS350 B3 helicopter	127 Kts	N/A	60 – 110 Kts
Cessna C208	155 Kts	61 Kts	120 - 150 Kts
Piper Navajo	164 Kts	70 Kts	130– 160 Kts
Cessna C406	181 Kts	75 Kts	150– 180 Kts

***Table 3** Typical airspeeds for a number of standard survey aircraft.*

of the entire data set. The residual can then be described as a function of the error X_l, where ^{o} denotes the mean

$$D_{l,i} = X_{l,i} - X_{o,i} - X_{l,o} + X_{o,o}$$

The residual is then used to calculate the standard deviation of the noise on a line by line and dataset basis.

Studinger et al. (2008) raised concerns on using Green and Lane's method (commonly used for analyzing GT-1A data) as their analysis demonstrated an intrinsic bias for lower noise readings especially for a small number of repeat lines. Studinger et al (2008) favour the use of a simpler RMS difference between repeat line points distributed by √2. To compare differences between the methods we have applied both to a series of 37 repeat lines flown daily on a large airborne gravity project. Each method has been recalculated as lines are added to demonstrate the progressive differences between the methods with increasing number of repeat lines. As expected the RMS method records slightly higher noise estimates for a smaller number of lines with differences between the methods decreasing as repeat lines are added. The major reason for the differences is the independence of Green and Lane's method to DC shifts in the data. As survey data is flown with tie-lines and cross-over tolerances allow for first-order levelling, we believe the method provides a closer estimate of the overall survey data quality. To conclude, the exercise results are presented in Table 1 for all 37 lines using Green's method, RMS differences distributed by √2, and a deviation from the mean of all lines.

To date most of the gravity data presented for the GT-1A has been based on relatively small case studies. New Resolution Geophysics has flown in excess of 200,000 line km of survey using the GT-1A mounted on a dedicated Pilatus PC6 aircraft. Cross-over and repeat line results for these surveys are presented in Table 2 demonstrating the overall accuracy achievable for the system under standard survey conditions in a variety of often difficult exploration environments.

Improving accuracy resolution

As the resolution of the gravity system is directly proportional to survey speed, choice of the aircraft platform can make a significant difference in results. This has encouraged the use of helicopters or, in our case, slow flying aircraft such as the Pilatus PC6 for survey platforms which result in improvements of more than 30% compared with more typical survey aircraft. Table 3 compares survey aircraft speeds from a number of typical survey aircraft.

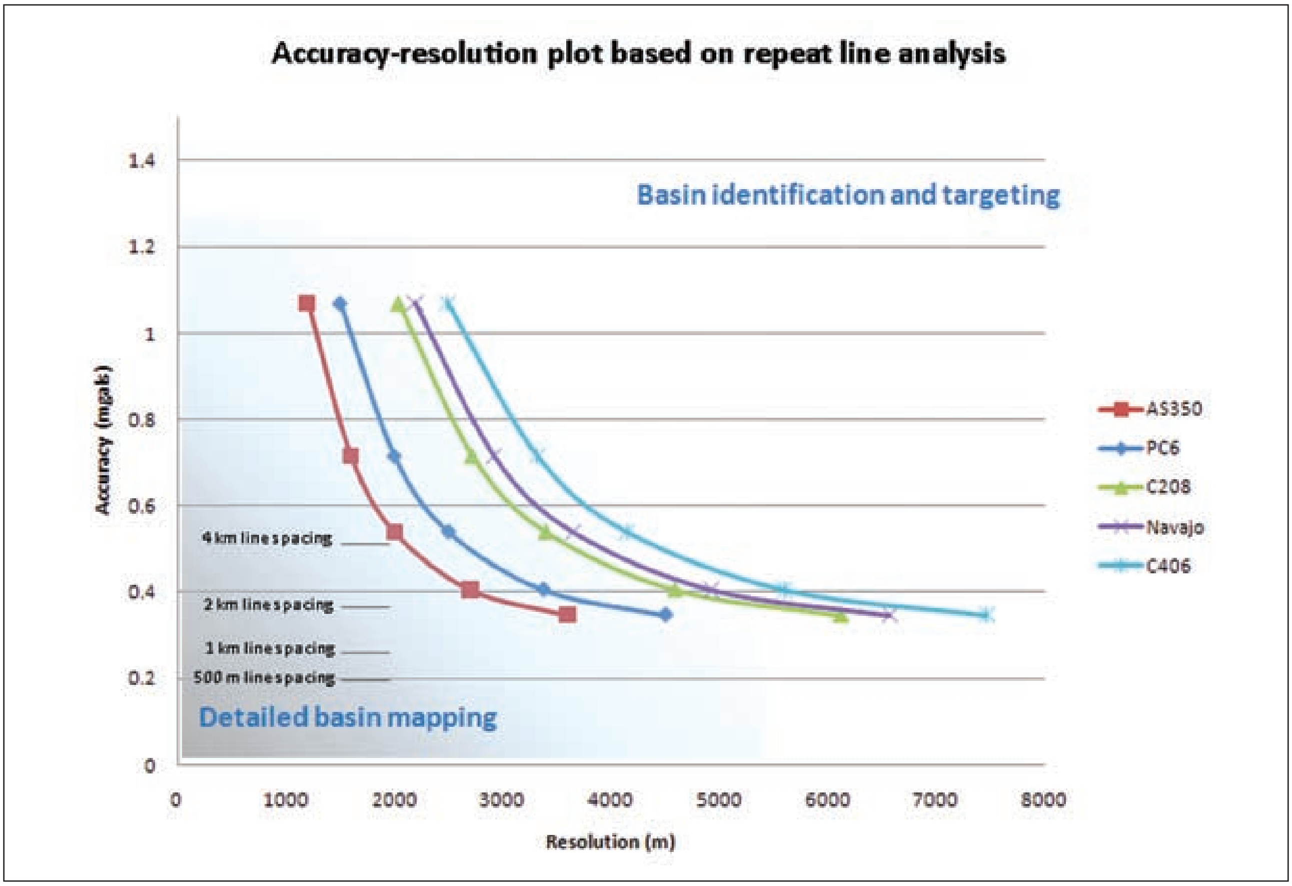

Figure 4 Accuracy vs resolution plots based on an average repeat line results for a GT-1A system extrapolated to provide comparisons for different aircraft speeds. The effect of oversampling the dataset using tighter line spacing is illustrated.

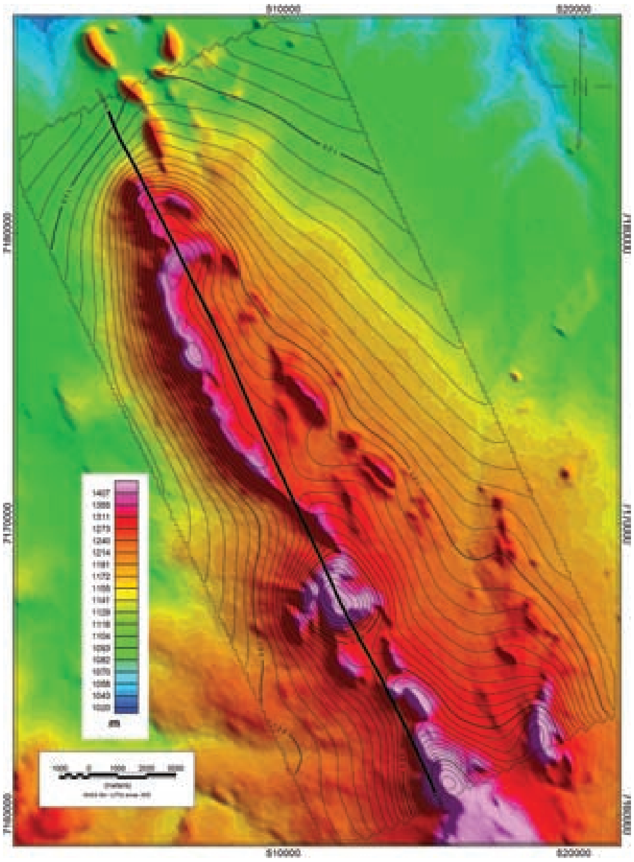

Figure 5a Digital terrain model with contours of the full 3D terrain model overlain.

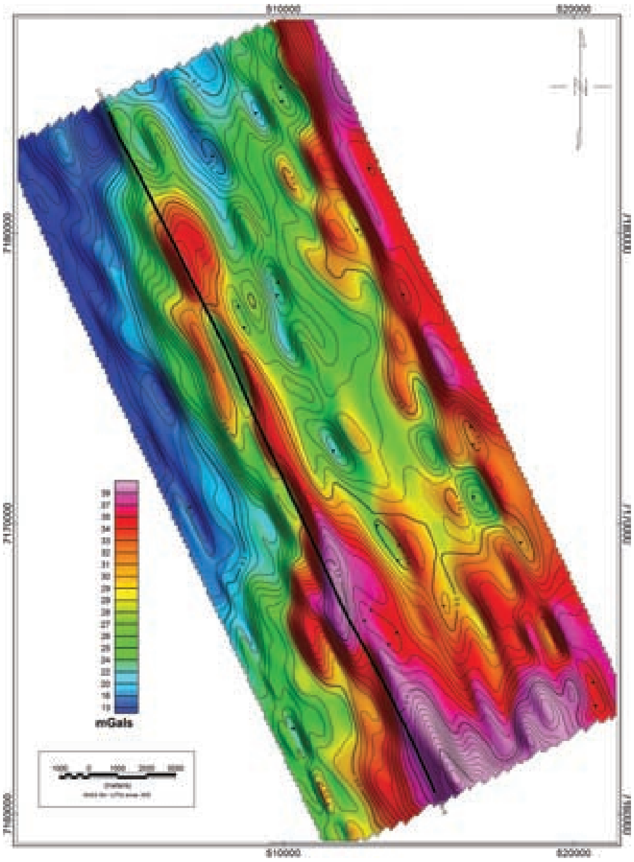

Figure 5b Free air gravity collected at a 500m line spacing reduced using a 60 s downline Kalman filter.

Due to the relatively long down-line filters applied to airborne gravity data, it is often the case that the cross-line resolution is better. This provides a useful means of removing uncorrelated noise, ultimately improving the survey accuracy. Gridding line data using a standard technique, such as minimum curvature described by Brigs (1974) and Swain (1976), will extend geological features across survey lines where they correlate and restrict the extent of uncorrelated noise between lines. The net result is to limit the cross-line wavelength of noise which can then be removed using a 2D FFT filter with similar characteristics to the down-line filter. As a result the overall accuracy of an airborne gravity survey can be improved by flying at line spacings less than the full wavelength of the down-line filters applied.

Figure 4 below illustrates the effect of different aircraft platforms and survey line spacing on the overall accuracy resolution of the gravity survey. Both these parameters have important implications when detailed basin mapping is required.

Pushing the accuracy resolution envelope

In order to explore the limits of accuracy resolution obtainable with a GT1A system, a high resolution gravity survey was flown over a series of well defined metaquartzite ridges which provide a useful control model. The survey was flown at a line spacing of 500 m using a Pilatus PC6 in both strike, parallel, and cross-strike directions. The results of the strike parallel survey are shown to provide better resolution for detailed airborne gravity surveys where down-line filtering often exceeds the cross-line sampling.

As a control, the ridges have been modelled in full 3D using a density of 2.7 g/cm^3 in line with published density results carried out by the SA Council for Geoscience (Mare and Tabane, 2004). Contour results of the 3D model have been overlain on the shuttle radar digital terrain in figure 5a.

Results are presented for free air gravity reduced using a 60 s down-line Kalman filter corresponding to a resolution of 1.5 km (half wavelength of the filter x 100 kt aircraft speed). This is a relatively noisy dataset when gridded at 100 m cell size (Figure 5b). By applying a cosine roll-off spectral filter with midpoint at 3000 m we create a dataset with similar resolution in all directions. Due to the extra cross-line information we are able to remove much of the uncorrelated noise in the data (Figure 5c). Note that the large regional gravity high on the eastern side of the survey is attributable to dense ultramafics of the Bushveld Igneous Complex.

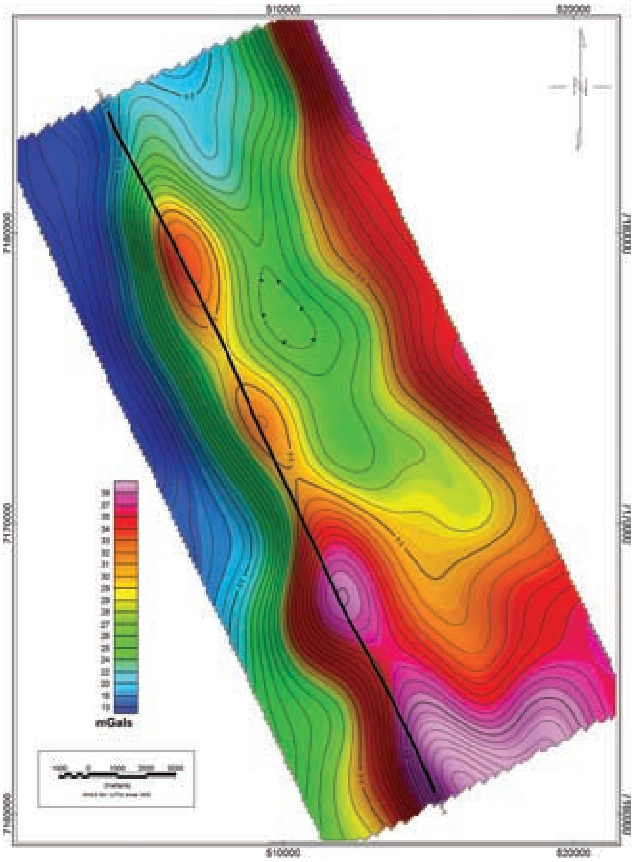

Figure 5c *60 s free air gravity processed using a grid based FFT filter with similar characteristics to the downline filter.*

A profile plot of one of the survey lines is illustrated in Figure 5c. The plot illustrates the original 60 s Kalman filter, free air data, spectral filtered 60 s free air data, and modelled free air data with identical spectral filter applied. A trend has been removed from all datasets. The profile plot demonstrates the effectiveness of using additional survey lines to remove uncorrelated noise in the dataset through spectral filtering.

Although a special case, the test study demonstrates the feasibility of generating high resolution and accuracy gravity datasets (~ 0.2 mGals @ 1.5 km) using slow survey speed and detailed line spacing.

Conclusions

Although airborne gravity systems have become routine technology in petroleum exploration for basin mapping, there is still room for significant improvement in accuracy resolution if detailed basin structure is to be mapped.

In this paper the relative accuracies of different airborne gravity systems have been compared. Survey cross-over and repeat line data from more than 200,000 line km of airborne gravity using the GT-1A system demonstrate the average accuracy resolution capability of the system (< 0.7 mGals using a 100 s down-line filter). In order to improve data quality, two simple approaches are suggested: fly slower (choice of aircraft platform) and fly at tighter line spacing (oversampling). Results from a special case study demonstrate the relative improvement obtained from an oversampled dataset, albeit at the expense of tighter line spacing.

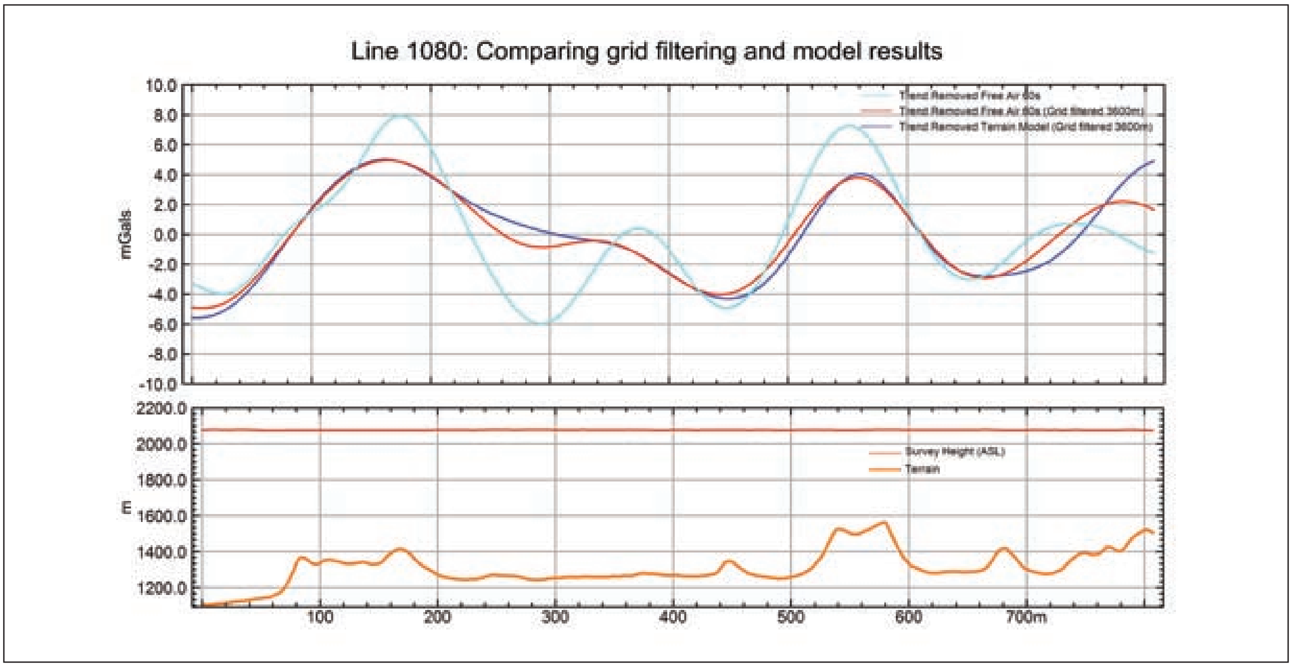

Figure 5d *Profile plots of a line of data comparing the 60 s Free Air data, FFT grid filtered 60 s data and grid filtered full 3D model. Given that most of the Free Air gravity response is attributable to the ridges, both modelled data and grid processed Free Air data demonstrate an excellent correlation. Profiles demonstrate the effectiveness of the grid filtering in removing uncorrelated noise in the 60 s Free Air data.*

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