Establishing the 'air truth' from 10 years of airborne gravimeter data

A commercial airborne gravity meter built by Canadian company Sander Geophysics has now been tested periodically for 10 years over a specially selected repeat line. Stefan Elieff and Stephen Ferguson* report on the findings.

A 40 km repeat line established by Sander Geophysics (SGL) east of Ottawa has over the years been flown more than 100 times with a variety of aircraft producing 5000 line km of test data. The average of all passes along the line represents a very accurate 'air truth' used to quantify the accuracy of the company's purpose built airborne gravimeter. The data set can also be used to demonstrate the importance of line spacing and final gridded spatial resolution when considering real-world survey results.

The Ottawa repeat line is located approximately half-way between Montreal and Ottawa (Figure 1). During the development of the company's AIRGrav system it was a convenient test area because of its proximity to the head office at Ottawa airport and the fact that the Geological Survey of Canada had surveyed the area with ground gravimeters. Results from 17 passes along a different line in the area were published shortly after the system began commercial surveying (Argyle et al., 2000). With over 100 passes flown to date along the current line it is possible to expand and update this analysis.

AIRGrav system

The AIRGrav system was designed and built specifically to operate under the unique conditions found in fixed wing aircraft and helicopters. It uses high precision accelerometers mounted on a three-axis inertially stabilized platform, combined with high resolution differential GPS (DGPS) to correct for aircraft motions. The gyro-stabilized inertial platform makes the gravimeter much less affected by horizontal accelerations than systems which use modified sea gravimeters. This design approach has resulted in a gravity instrument which can be flown in a survey aircraft during normal daytime conditions. AIRGrav was designed primarily for petroleum exploration, where it is an economical alternative to ground and shipborne surveys, but it also has application in regional geophysics, mineral exploration, and scientific research. The system has been flown exclusively by SGL acquiring 875,000 line km over the past nine years. Eight systems are currently operating and additional systems are being built.

Establishing the 'air truth'

At the time of writing, 117 passes along the repeat line were available. Normal quality control criteria were applied, leaving 100 of the original 117 passes. The eliminated passes are analogous to re-flights in an actual survey. This rate of rejection is higher than for a typical survey but is expected since the purpose of flying the Ottawa repeat line is trouble shooting or testing new equipment to detect problems before

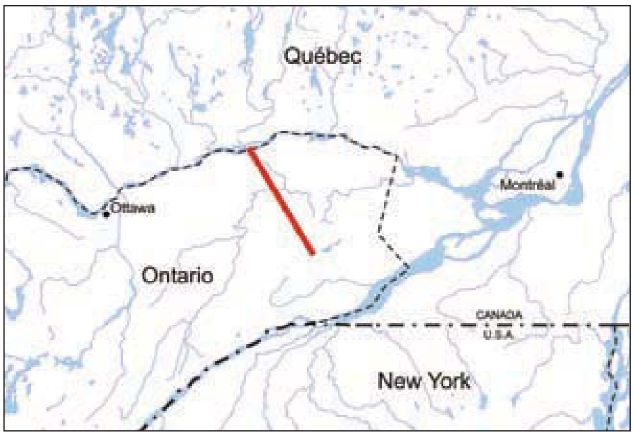

Figure 1 *Location of the Ottawa repeat line east of Ottawa.*

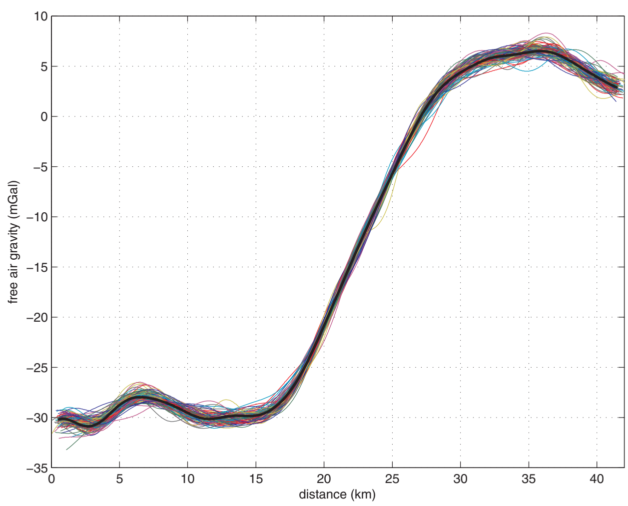

Figure 2 *100 passes along the repeat line (coloured lines) and the average of all passes (heavy black line). A 100 second full-wavelength filter (0% pass at 75 seconds, 100% pass at 150 seconds) was used for this figure.*

**Corresponding author E-mail: selieff@sgl.com.*

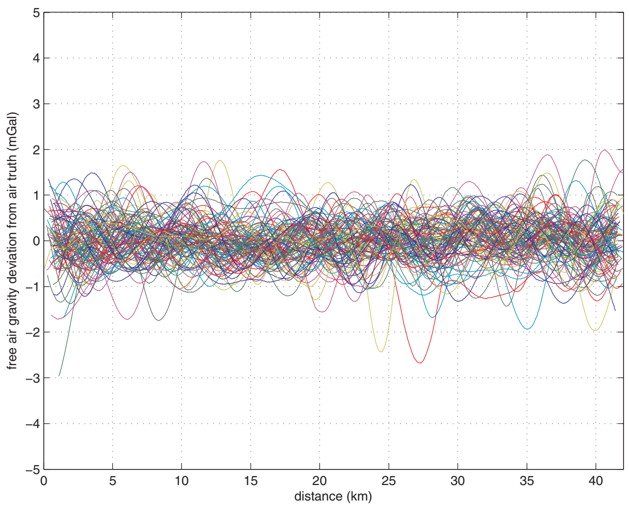

Figure 3 *Deviations from the average line for each of the 100 passes shown in Figure 2.*

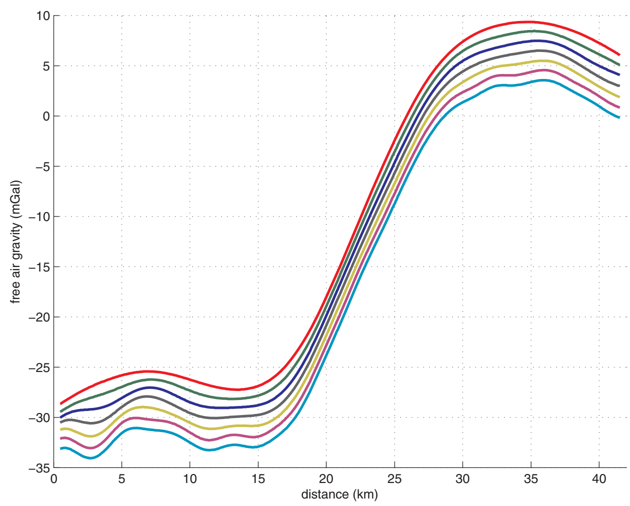

Figure 4 *The air truth filtered using a range of low pass filters from 70 s (light blue at bottom) to 170 s full-wavelength (red at top). Profiles are shifted vertically for clarity.*

mobilization to a survey, ensuring fewer re-flights in the field. The repeat passes and deviations of each pass from the average are shown in Figures 2 and 3.

Using the average of all passes as an air truth is preferable to using a ground truth derived from the Geological Survey of Canada data. The ground points have uneven coverage, need to be upward continued to translate them to flying height, and do not always fall underneath the repeat line, requiring interpolation. These factors, plus any error contained in the ground readings themselves, will introduce errors into an analysis.

There is a lower limit on the amount of filtering that can be used when computing the average line because noise increases exponentially at shorter wavelengths in airborne gravity data. Even 100 passes are not enough to average out this noise at short wavelengths. The accuracy of the average line was estimated by computing the standard deviation of the difference between the average line and every data point from the repeat passes. The accuracy of the average line should be this standard deviation divided by the square root of the number of passes. Results are shown in Table 1 for filters ranging from a 20 s (full-wavelength) low pass filter up to a 170 s low pass filter.

At longer wavelengths, the 100 passes flown have produced a very accurate average reference line. At the shortest wavelengths, 100 passes are insufficient to eliminate significant noise from the average. Since we wish to extend the analysis of system accuracy to these shorter wavelengths, we will use the 70 s filtered average as the air truth and pessimistically assume that any signal present at shorter wavelengths is noise. Any real signal being captured by the system at shorter wavelengths will be a relatively small fraction of the overall noise signal and will not have a discernible impact on the analysis done here. When analyzing system accuracy at longer wavelengths, the air truth has a matching filter applied since the goal is quantifying accuracy at that wavelength. The air truth is shown in Figure 4 with the various filters applied.

Aside from the small assumption made above concerning signals below 70 s, the actual geological signal present on the line is not important for the analysis that follows. A flat line devoid of any geological signal would provide just as much information about the accuracy of the system. Repeatability tests such as this only quantify noise at a given wavelength. The filter applied, along with the flying speed, determines resolution at that wavelength regardless of the noise. Geological signals along a repeat line can provide helpful visual clues about the effect noise (accuracy) and filtering (resolution) are having on the detectability of a particular anomaly, but will not quantitatively change anything.

No attempt has been made to compensate for variations in flying speed from one pass to another. The majority of passes were flown close to the average speed of 55 m/s. Individual passes flown slower or faster will have a little more or less resolution than the average line. This will create a small amount of additional error in the results that is unrelated to system accuracy.

Repeat line and intersection statistics

Intersection statistics form part of the system's quality control procedures. The accuracy of an individual line is estimated by calculating the standard deviation of all intersection differences

Full-wavelength filter mid-point (sec)	20	30	46	56	70	84	100	120	140	170
Estimated accuracy of average line (mGal)	1.40	0.47	0.23	0.12	0.08	0.06	0.05	0.04	0.04	0.04

Table 1 *Estimated accuracy of the average line for a series of low-pass filters.*

Survey	Ottawa repeat line	Timmins test survey	North Africa survey		North Africa survey		Northern Canada helicopter survey	
Line accuracy 100s full-wave-length filter	**0.46 mGal**	**0.41 mGal**	**0.58 mGal**		**0.58 mGal**		**0.54 mGal**	
Half-wavelength spatial resolution @ flight speed	2.8 km	2.8 km	2.8 km		2.8 km		1.8 km	
Line spacing	-	0.5 km	1.0 km		2.0 km		0.6 km	
Estimated grid accuracy	-	**0.15 mGal**	**0.16 mGal**	**0.10 mGal**	**0.21 mGal**	**0.13 mGal**	**0.30 mGal**	**0.22 mGal**
Half-wavelength spatial resolution of grid	-	1.4 km	3.0 km	4.5 km	3.0 km	4.5 km	1.5 km	2.0 km

Table 2 *Comparison of line data accuracy and resolution with final grid accuracy and resolution. These surveys are also included in Figure 5. Grid noise statistics were computed using the method in Sander et al. (2002).*

along that line and dividing by the √2 since intersection differences are a sum of the errors of two intersecting lines. Similarly, the overall accuracy of all the lines in a survey is the standard deviation of every intersection mismatch divided by √2.

Intersection statistics and repeat line statistics are the same thing: a measure of repeatability. Every point along a pass of a repeat line is an 'intersection' with other passes. The overall accuracy of all passes along the repeat line can be computed the same way, except we can compare directly to the air truth so there is no need to divide the result by √2. Results are shown in Figure 5. The only corrections made to the lines were constant shifts. No sloped or variable levelling corrections were applied.

The Ottawa repeat line data accuracy falls within the range found in surveys. The statistics have the advantage that they don't suffer from directional filtering differences that are sometimes created when control and traverse lines, oriented in different directions, are filtered. The Timmins surveys, flown in an area of strong short-wavelength geological signal, show this artifact clearly where the estimated accuracy reaches a minimum and then falsely appears to worsen at longer wavelengths. Figure 5 demonstrates that intersection statistics can be used in place of a repeat line for quality control in surveys since they are equivalent.

Power spectral density estimate

The differences between the air truth and individual passes were used for a power spectral density estimate of the AIRGrav system noise. As noted earlier, any signal present shorter than 70 s wavelength is assumed to be noise for this study. The power spectrum was computed for each pass using a multi-taper method (Thomson, 1982). Results are shown in Figure 6a and 6b. The characteristics of the low pass filters used are clearly shown, as is the steepening upward increase in noise at shorter wavelengths. A theoretical GPS noise limit postulated elsewhere (van Kann, 2004) is also shown. The average power spectrum at longer wavelengths estimated here actually lies somewhat below that theoretical limit. When only the best 50 passes are used, the noise falls even further below the limit.

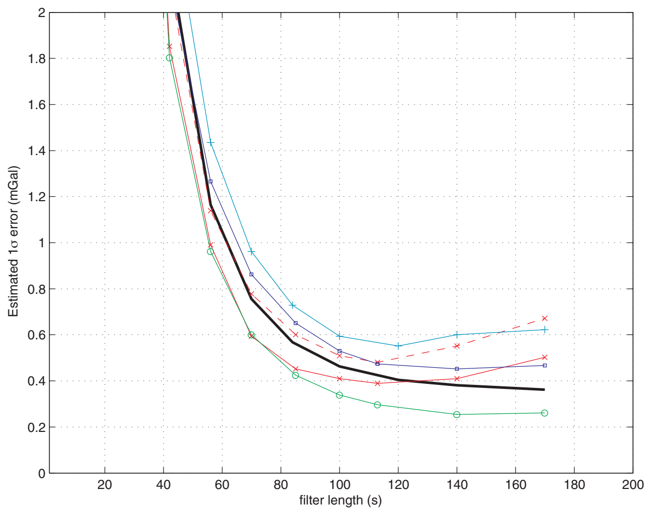

Figure 5 *Estimated accuracy of line data for the Ottawa repeat line and various surveys. Black = Ottawa repeat lines; solid red = Timmins test survey (see Elieff and Sander (2004) for a report on this survey); dashed red = Timmins full survey; light blue = north African survey; dark blue = northern Canada helicopter survey; light green = eastern Canada survey. The upward turn in the Timmins and African surveys is an artifact of control-traverse line direction and not an actual increase in error.*

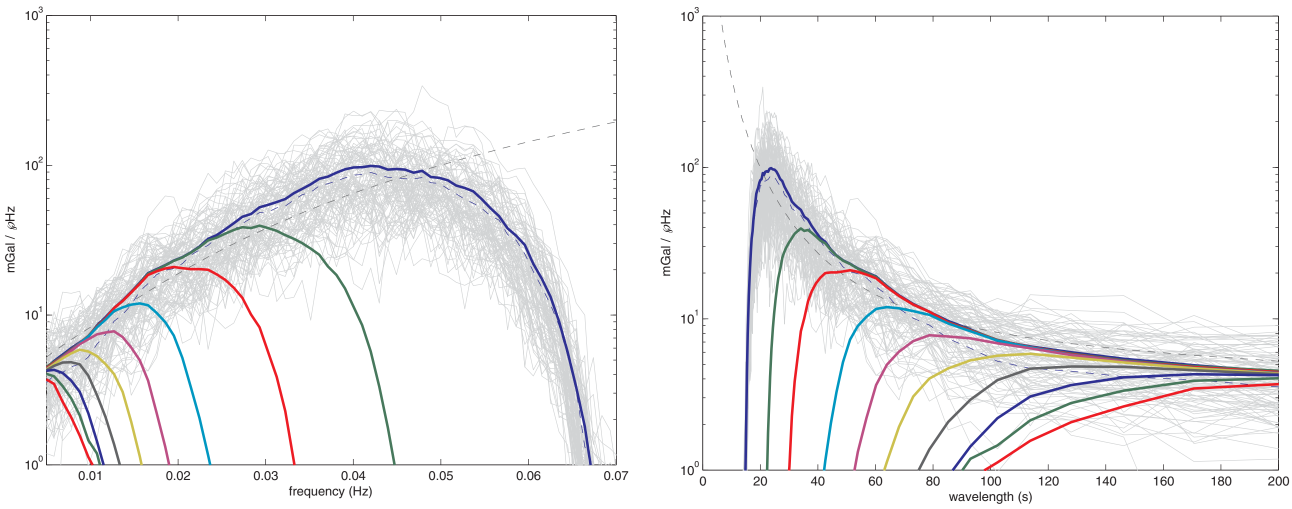

Figure 6a and 6b *Noise spectrum for AIRGrav lines as a function of frequency (a) and wavelength (b). Different coloured lines are for different low pass filters ranging from 20 s mid-point (dark blue, highest amplitude) to 170 s mid-point (red, lowest amplitude). Grey lines are individual passes with the 20 s filter applied. Dashed black line is a theoretical GPS noise limit from van Kann (2004). Dashed blue line is the 20 s filter average spectrum when only the best 50 passes are used.*

Theoretical limits are a useful tool, but have built in assumptions which may not entirely apply for a particular system.

Line data versus final grid data

The results obtained above apply to gravity line data. This is an incomplete picture. Virtually all AIRGrav surveys are flown with a line spacing that over-samples the survey area to further reduce noise in the final data grid (Sander et al., 2002, 2003). This is similar to the stacking of seismic data. To illustrate this, the analysis presented above was repeated using groups of 4, 9, and 16 lines averaged together. Figures 7 and 8 show the decrease in noise which follows the expected 1/√N improvement for a system governed by random non-systematic errors, where N is the number of lines being averaged.

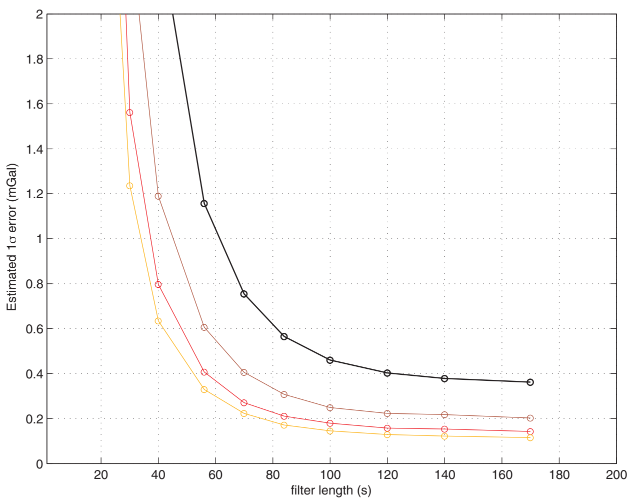

Figure 7 *Estimated accuracy of line data for the Ottawa repeat line for individual passes (top curve) and groups of 4, 9, and 16 passes averaged together (progressively lighter red curves from top to bottom).*

The final survey accuracy will depend on line spacing, flight speed, and the balance between resolution and accuracy desired by the client, but typical numbers are well below the simple line accuracy figures derived above from intersections or a repeat line. This is demonstrated using results from some surveys flown (Table 2).

Other factors inevitably come into play so there is naturally some variation between surveys flown with equivalent line spacing and spatial filtering parameters. For example, GPS conditions are generally worse in far northern latitudes. Intersection and grid accuracy estimates can be influenced by the geological signal present. In any case, the expected capabilities of the system are best represented by considering the accuracy and resolution of the final spatially filtered grids.

Alternate noise estimation methods

SGL recently participated in a series of test flights in Calgary and over the North Pole where the AIRGrav system and a Canadian Micro Gravity GT-1A gravimeter were installed together in a Twin Otter. An independent analysis of data from both systems was conducted by the researchers who were selecting an instrument for ice sheet research in Antarctica (Studinger et al., 2008). They compared noise estimates using an alternate method (Green and Lane, 2003) with the more common root mean square estimates used here and found that the Green and Lane method biased the results towards lower noise levels when there were fewer passes of a repeat line. Accuracy-resolution estimates that have been made using the Green and Lane method cannot be directly compared with root mean square values for the AIRGrav system because of this inherent bias. When presented with a comparison between gravity systems it is important to be aware of which methods were used to

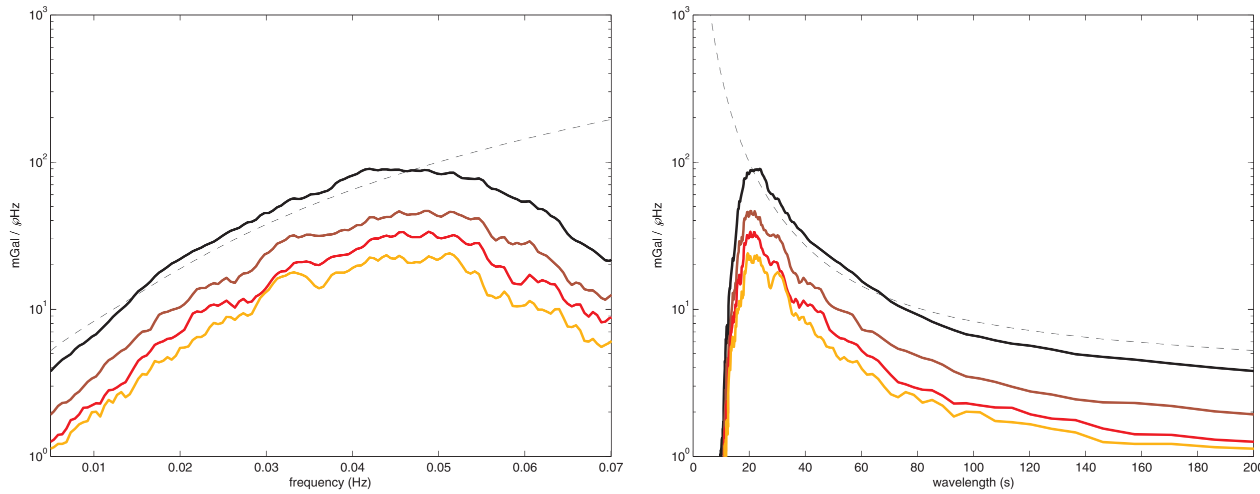

***Figure 8a and 8b** Noise spectrum for AIRGrav lines as a function of frequency (a) and wavelength (b). Curves are for individual lines (top curve) and groups of 4, 9, and 16 lines (progressively lighter red curves from top to bottom), achieving progressively lower noise level. Dashed black line is a theoretical GPS noise limit from van Kann (2004).*

derive the numbers. Similarly, two low-pass filters which have identical numbers for their names may have different underlying characteristics.

Conclusion

The Ottawa repeat line clearly demonstrates the accuracy and resolution of the AIRGrav system. The results from these repeat lines correspond well with quality control estimates made for several surveys. These results were achieved while flying in normal daytime turbulence conditions. The advantages of close line spacing in reducing random error allow the system to achieve results well beyond theoretical limits derived from GPS error estimates.

References

Argyle, M., Ferguson, S., Sander, L. and Sander, S. [2000] AIRGrav results: a comparison of airborne gravity data with GSC test site data. *The Leading Edge* **19**(10), 1134–1138.

Elieff, S. and Sander, S. [2004] AIRGrav airborne gravity survey in Timmins, Ontario, in Lane, R.J.L. (Ed) Airborne Gravity 2004 - Abstracts from the ASEG-PESA Airborne Gravity 2004 Workshop. *Geoscience Australia Record*, **18**, 1-5.

Green, A. and Lane, R. [2003] Estimating noise levels in AEM data. *16th Geophysical Conference and Exhibition, Australian SEG*, Extended Abstracts.

van Kann, F. [2004] Requirements and general principles of airborne gravity gradiometers for mineral exploration. In Lane, R.J.L. (Ed) Airborne Gravity 2004 - Abstracts from the ASEG-PESA Airborne Gravity 2004 Workshop. *Geoscience Australia Record*, **18**, 1-5.

Sander, S., Ferguson, S., Sander, L., Lavoie, V. and Charters, R.A. [2002] Measurement of noise on airborne gravity data using even and odd grids. *First Break*, **20**(8), 524-527.

Sander, S., Lavoie, V., Peirce, J. and Charters, R.A. [2003] Advantages of close line spacing in airborne gravimetric surveys. *The Leading Edge*, **22**(2), 136-137.

Studinger, M., Bell, R. and Frearson, N. [2008, forthcoming] Comparison of AIRGrav and GT-1A airborne gravimeters for research applications. *Geophysics*, **73**(6).

Thomson, D. J. [1982] Spectrum estimation and harmonic analysis. *Proceedings of the IEEE*, **70**, 1055–1096.