A Comparison of Inertial Platform, Damped 2-axis Platform and Strapdown Airborne Gravimetry

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Abstract. The results of the comparison of three different airborne gravimeter systems will be presented. The systems used were a 3-axis inertially stabilized platform (AIRGrav from Sander Geophysics), an air-sea gravimeter (a LaCoste and Romberg linear gravimeter from the Geodetic Survey Division of Natural Resources Canada), and a gravimeter based on an off-the-shelf strapdown inertial navigation system (SINS, jointly operated by Intermap Technologies Corporation and the University of Calgary).

The testing was conducted in the spring of 2000, over a relatively flat area which presents considerable variation in the gravity field. The testing area is well covered with ground gravity values. The upward continuation to flying height of a grid of these values was used as a reference. Gravity estimates along the flight lines were calculated for each system using a common GPS solution for data reduction.

The performance of the systems is evaluated by means of comparisons of these estimates with the upward continued reference field. The behaviour of the systems is characterized as a function of time and frequency. Because the aircraft speed was very nearly constant during the campaign, this information is used to characterize their behaviour as a function of spatial resolution on the ground. This is in turn used to draw some conclusions regarding their performance for different applications including geoid determination and resource exploration.

For a common L1-only DGPS solution, the AIRGrav system shows an average agreement with the reference at the level of 0.2 to 1.0 mGal for half-wavelengths down to 2.0 km, with deviations in bias of 0.24 to 0.48 mGal for the survey lines flown in a given day and inline average drift of 0.001 to 0.003 mGal/km. The L&R system was unfortunately plagued with technical problems, and was operational for only one flight. During this flight, the L&R system shows an average agreement with the reference at the level of 4.4 to 28.1 mGal for half-wavelengths down to 2.0 km, with deviations in bias of 3.35 mGal and inline average drift of 0.070 mGal/km. After a crossover adjustment and the use of a geopotential model to tie the relative gravity measurements to the absolute gravity field, the SINS gravimeter shows an average agreement with the reference of 0.8 to 4.8 mGal for half-wavelengths down to 2.0 km, with deviations in bias of 0.74 to 1.51 mGal for survey lines flown in a given day and inline average drift of 0.019 to 0.079 mGal/km.

1 Introduction

Over the last few years, the performance of scalar airborne gravimeters has increased considerably, to the point that leading edge systems can provide images of the gravity field at the level of 1-2 mGal for spatial resolutions as high as 2 km. This level of performance has been made possible by recent advances, mainly in the areas of sensor modelling and processing methodologies. The goal of this research is to evaluate three of the currently available scalar airborne gravimetry systems. This is accomplished by mounting them together on the same aircraft during a measurement campaign and by carefully controlling the processing methodologies that are used, i.e. three estimates of the gravity field are generated such that all parameters other than the gravimeter are common to each.

The data used in this paper was collected as part of the *Airborne Gravity for Exploration and Mapping (AGEM)* project of the GEOIDE Network Centre of Excellence (NCE). The campaign consisted of lines flown over the Alexandria test area (near Ottawa, Canada). The three systems evaluated in the test are:

- The three-axis stabilized platform system called AIRGrav that has been designed and is operated by Sander Geophysics Limited (SGL),
- an SL-1 LaCoste and Romberg (L&R) linear gravimeter that is owned and operated by the Geodetic Survey Division (GSD) of Natural Resources Canada, and
- a gravimeter based on an off-the-shelf strapdown inertial navigation system (SINS gravimeter), the Honeywell LRF-III that is owned by Intermap Technologies Corporation (Intermap) and operated jointly by Intermap and the University of Calgary (U of C).

Details about the principles upon which these gravimeters are based can be found in Schwarz and Li (1996) and Czompo and Ferguson (1995).

The results reported in the paper are divided into three parts. Following a description of the test in Section 2 and a discussion of the methodology in Section 3, Section 4 characterizes the performance of the systems for medium and high-resolution gravimetry. Section 5 concentrates on their performance for low-resolution gravimetry. The third is a discussion of these results and is given in Section 6.

Throughout the paper, the terms *spatial resolution* and *half-wavelength* are used synonymously, and the terms *high-resolution, medium and low* refer to the parts of the gravity spectrum corresponding to spatial resolutions below 5 km, between 5 km and 100 km and above 100 km, respectively. The distinction made between the information presented in Sections 4 and 5 has been chosen as a matter of convenience for several reasons including the following:

- the longest lines flown in the Alexandria campaign were approximately 100 km, which (according to the Nyquist sampling theory) implies that the maximum half-wavelength of the features that can be resolved from the measurements is 100 km,
- it is usually medium and high-resolution information about the gravity field that is of interest in geophysical applications such as resource exploration,
- the eventual availability of global geopotential models from future satellite gravity missions dedicated to measurement of the Earth's gravity field (e.g. Champ, GRACE and GOCE) will likely eliminate the requirement for low resolution airborne gravimetry measurements except at the Earth's poles, and
- the SINS gravimeter being used in this paper is only designed for use in relative gravimetry (which corresponds roughly to the ranges of medium and high-resolution gravimetry defined above).

2 Test Description

The Alexandria gravity test area covers an area of about 70x120 km and is conveniently located with respect to the Ottawa airport and the main office of SGL. There are only minor variations in the height of the terrain, but considerable variations in the gravity field, meaning that it is ideally suited for evaluating the performance of airborne gravimeters without the disturbing effects of the topography. Figure 1 shows a map of the test area with the flight lines and the reference station locations.

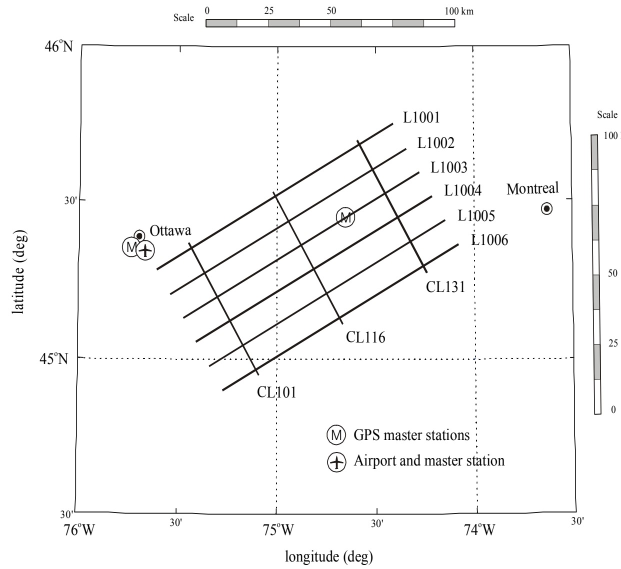

Figure 1 Flight lines and GPS master stations

A gravity disturbance reference at an ellipsoidal height of 600m was produced from a network of point-wise gravity measurements provided by the Geodetic Survey Division (GSD) of Natural Resources Canada. The distribution of the ground measurement data in the area is quite irregular, with an average spacing about 3 km. The ground measurements were reduced using the free air correction only, to a uniform grid of gravity values at the ellipsoid. Then the gridded values were upward continued, using a Fourier Transform technique (Blakely,1995), to obtain the gravity disturbance reference at the flying height. The derived gravity reference was used to assess the quality of the airborne gravity estimates. Figure 2 shows the reference gravity field.

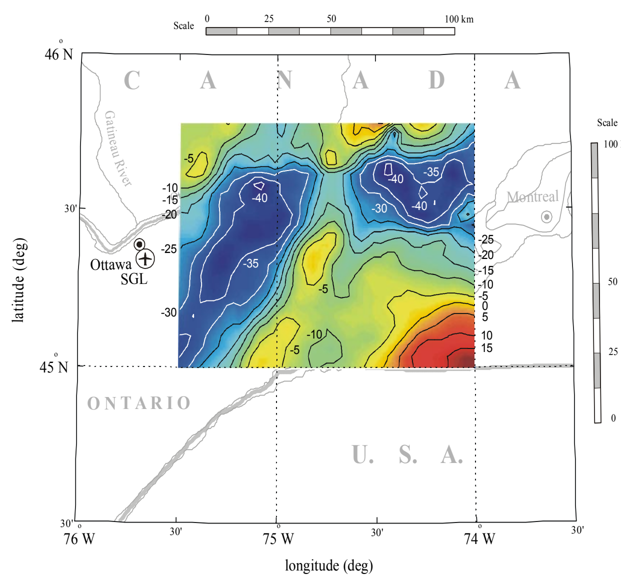

Figure 2 Reference Gravity Field

Figure 3 Cessna 208B Grand Caravan

A Cessna 208B Grand Caravan airplane (as shown in Figure 3) owned and operated by Sander Geophysics Ltd. was used throughout the campaign.

This aircraft carried all three gravity instruments, their data acquisition systems, and a variety of GPS receivers. The comparison of the three gravity systems will be based on three flights of the campaign. The April 19 and April 20 flights took place in the afternoon, during periods of moderate turbulence. The third flight, May 04, took place in the morning to minimize the effect of turbulence on the gravimeters and the disturbing effects of the atmosphere on DGPS. The vertical acceleration for the three flights was 0.46, 0.61, and 0.15 m/sec^2 (RMS) respectively. In all three flights, the average flying height was 575 m and the average velocity was 45 m/s.

3 Methodology

The model for airborne gravimetry is given by the following well-known expression for the scalar estimate of the gravitational vector:

$$g_u = \dot{v}_u - f_u + e\,, \qquad (1)$$

where f_u is the upward component of the specific force from the inertial sensor, $\dot{v}_u$ is the upward component of the vehicle acceleration that is derived from DGPS, and the symbol e represents the Eötvös correction that is due to frame rotation and is a function of the position and velocity of the aircraft and the rotation rate of the Earth. Since it is more convenient to model small quantities, equation (1) is rewritten to represent the difference δg_u between the magnitude of the actual gravity vector g_u and the normal gravity vector γ_u, based on an ellipsoid of revolution having the same mass and rotation rate as the Earth. The model for the anomalous part of the gravity field is therefore given by:

$$\delta g_u = \dot{v}_u - f_u + e - \gamma_u\,. \qquad (2)$$

In this research, the upward component of the specific force f_u is obtained from each gravimeter and used to derive estimates of the gravity disturbance δg_u. In order to control the experiment, the values of $\dot{v}_u$, e and γ_u are derived using the same differential GPS (DGPS) solution in each case. The DGPS solutions used were obtained using SGL's processing software GPSoft.

The spatial resolution of estimates of the gravity field derived using equation (2) is generally limited on the upper end by the amount of smoothing that has to be done to suppress the noise present in the measurements. Spatial resolution is proportional to the product of the aircraft speed and the time period over which the measurements are smoothed, as given by the following equation:

$$x = sT/2\,, \qquad (3)$$

where s is the aircraft speed, x is the equivalent half Fourier wavelength of the measured gravity signal (projected onto the ground) and T is the time period over which the smoothing is done. Therefore, for a fixed flying speed s, the smoothing period T must be reduced in order to shorten x (i.e. in order to increase the spatial resolution of an airborne gravity system). In order to achieve a specified level of accuracy, a system displaying less noise than another will require less smoothing and will therefore have a higher spatial resolution. Conversely, such a system will perform better for a given smoothing period. If the smoothing is being applied using a low pass filter with a cutoff frequency f, then the substitution of the relationship $T = 1/f$ into equation (3) relates the spatial resolution to that cutoff frequency:

$$x = s/(2f)\,. \qquad (4)$$

These concepts form the basis of many of the analyses that are carried out in this research. In Section 4, the quality of the solutions is characterized for their medium and high-resolution components. Practically, this is done by comparing the values of δg_u estimated by each system to the gravity disturbance coming from the upward continued reference δg_{ref} within the bandwidth corresponding to half-wavelengths shorter than 100 km. Because the flying speed s is close to constant in airborne gravimetry, these residuals can be used in two ways to characterize the performance of the systems for relative gravimetry. The first is by bandlimiting them using lowpass filters (with varying cutoff frequencies f). This is the standard procedure used in the field of airborne gravimetry to remove unwanted noise and to quantify the performance of a given system over a given flight line for specific spatial resolutions. It is carried out in Section 4 for each of the systems on each day of the three days of the survey considered herein. Table 2 shows the spatial resolutions corresponding to the filters that are used, as calculated according to equation (4) using the average flying speed of 45 m/s.

Table 1 Spatial resolutions corresponding to various smoothing periods

Smoothing period (s)	360	300	180	120	90	60
Spatial resolution (km)	8.1	6.8	4.1	2.7	2.0	1.4

The second way in which the above-mentioned residuals are used in Section 4 provides a more general characterization of the behaviour of each system. Frequency domain spectra of the residuals can be used to derive the error spectra as a function of spatial resolution according to equation (4). By using these to derive cumulative RMS error spectra and averaging over many flight lines, this approach provides a general description of the performance of each of the systems as a function of spatial resolution. This is done for each system on each day of the survey by using FFT techniques to derive error power density spectra from the residuals, integrating the these spectra as a function of frequency and scaling them appropriately.

In Section 5, the quality of the solutions is characterized for the low-resolution components. This is done by again comparing the values of δg_u estimated by each system to the gravity disturbance coming from the upward continued reference δg_{ref} (this time with no bandlimitation) and by deriving the average bias and the slope of these residuals for each system and each day of the survey.

4 Performance of the systems for relative gravimetry

This section describes the performance of the systems for relative gravimetry. Tables 2 through 4 show the standard deviation of the agreement between the solutions estimated by each system and the gravity disturbance coming from the upward continued reference within the bandwidth corresponding to half-wavelengths between 100 km and the wavelengths shown in Table 1. The values in these tables were generated by:

- bandlimiting the residuals using FIR filters with smoothing periods of 360, 300, 180, 120, 90 and 60 s, effectively bandlimiting them to the smallest half-wavelengths given in 2,
- estimating and removing a straight line of best fit from the residuals for each of the flight lines (effectively bandlimiting the data to longest half-wavelengths shorter than the length of the flight lines (approximately 100 km), and
- computing the standard deviations of the resulting bandlimited residuals.

It is clear from the Tables 2 through 4 that the data provided by the AIRGrav system demonstrates a lower noise level that of the SINS gravimeter. Unfortunately, the results from the LaCoste and Romberg are available only for the flight of May 4 due to hardware problems during the flights with moderate turbulence. Even the results from this day are quite noisy, again due to problems with the meter. Better results with this type of system have been achieved in other comparisons, see for instance Glennie et al. (2000). It can be seen that with the AIRGrav system, resolution of the gravity field with a resolution of 1.4 km can be achieved with an accuracy on the order of 1 to 2 mGal on flights with moderate turbulence or less, and with the SINS system to an accuracy of 1.6 mGal under smooth flying conditions.

Table 2 Average agreement of the systems (1-σ) with the reference for April 19

	Smoothing periods (s)					
Gravimeter	360	300	180	120	90	60
AIRGrav	0.33	0.35	0.47	0.62	0.76	1.13
SINS	1.08	1.14	1.41	1.59	1.76	2.71
L&R	N/A	N/A	N/A	N/A	N/A	N/A

Table 3 Average agreement of the systems (1-σ) with the reference for April 20

	Smoothing periods (s)					
Gravimeter	360	300	180	120	90	60
AIRGrav	0.23	0.30	0.62	0.77	1.09	2.03
SINS	1.13	1.26	1.89	2.08	2.71	4.80
L&R	N/A	N/A	N/A	N/A	N/A	N/A

Table 4 Average agreement of the systems (1-σ) with the reference for May 4

	Smoothing periods (s)					
Gravimeter	360	300	180	120	90	60
AIRGrav	0.29	0.33	0.54	0.63	0.70	1.02
SINS	0.83	0.95	1.23	1.27	1.32	1.61
L&R	4.43	5.34	8.23	9.72	12.59	28.16

Figure 4 presents Fourier spectra of the residual gravity error and give a more complete representation of the behaviour of the gravimeters as a function of frequency. According to equation (4), the plots in Figure 4 offer a general description of the RMS performance of each gravimeter as a function of spatial resolution for each survey, e.g. the RMS agreement of each system with the upward continued reference can be estimated for different filtering periods (and therefore different spatial resolutions). For example, using Figure 4a, it can be seen that if the solutions from April 19 were bandlimited to 0.02 Hz (meaning that they are limited to a maximum spatial resolution of approximately 1.13 km), the RMS performance levels of the AIRGrav and SINS would be approximately 1.5, and 3.2 mGal, respectively. Figure 4 also presents evidence that the advantage gained by using the AIRGrav system over the SINS gravimeter is most marked at very low frequencies (due to the bias instability of the SINS), and at frequencies above about .015 hz when there is moderate turbulence. In the region between these two frequencies, the systems show a constant difference in error for the April 19 and 20 flights, the result of the power spectral densities of the two having a constant ratio. During calm flight conditions, as on May 4, the additional error between .004 hz and .025 hz for the two systems actually gets smaller with increasing frequency, due to the systems having a similar power spectrum density in this range. The characteristics of the errors from each system will be discussed in more detail in Section 6.

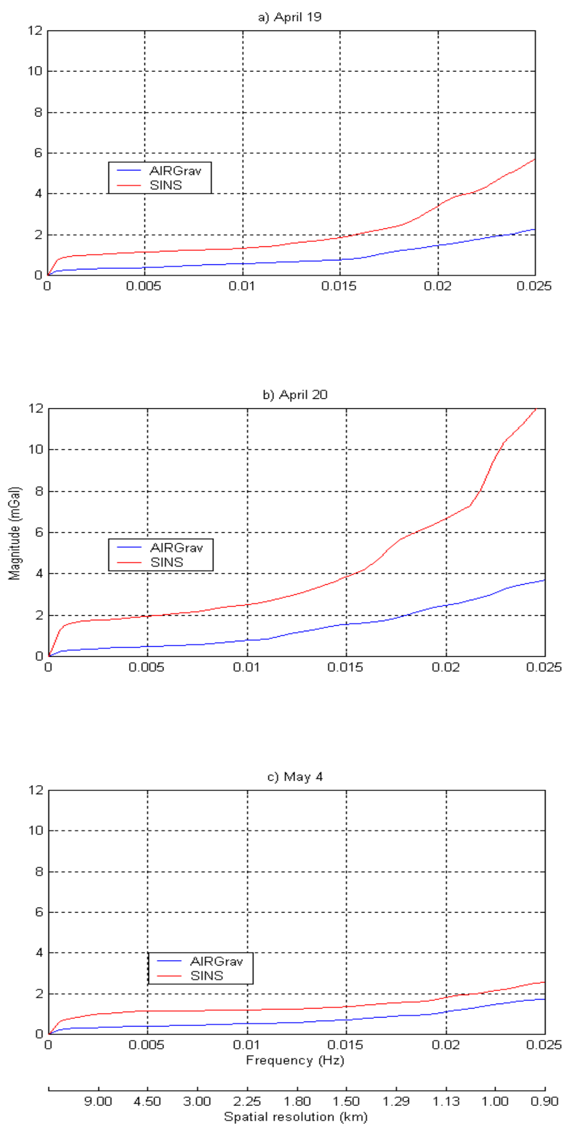

Figure 4 Cumulative Gravity Error for AIRGrav and SINS

5 Low frequency performance of the systems

Although the Nyquist sampling theorem limits the largest spatial resolution that can be resolved in the Alexandria campaign to approximately 100 km (the length of the longest lines flown is actually 105 km), it remains of significant interest to evaluate the performance of the systems for low-resolution surveying. An evaluation of an airborne gravimeter should quantify the accuracy with which each system can provide information that can be related to the absolute gravity field. Tables 5 through 7 show the low frequency performance of the data coming from the three systems using the *drift* and *bias* of the measured data with respect to the upward continued reference. These were computed as the mean values and slopes of the lines of best fit that were derived for each flight line in the last section. Also shown are the standard deviations of the biases that are an indication of the consistency of the bias over a whole survey. For example, a system with a small deviation in the observed biases can be related to the absolute gravity field using a single gravity control point.

Table 5 Low frequency performance of the systems for April 19

Gravimeter	Average drift (mGal/km)	Average bias (mGal)	σ of the biases (mGal)
AIRGrav	0.003	-0.61	0.32
SINS	0.013	60.87	3.63
L&R	N/A	N/A	N/A

Table 6 Low frequency performance of the systems for April 20

Gravimeter	Average drift (mGal/km)	Average bias (mGal)	σ of the biases (mGal)
AIRGrav	0.001	-0.04	0.48
SINS	0.065	71.80	2.56
L&R	N/A	N/A	N/A

Table 7 Low frequency performance of the systems for May 4

Gravimeter	Average drift (mGal/km)	Average bias (mGal)	σ of the biases (mGal)
AIRGrav	0.0005	-0.39	0.24
SINS	0.048	90.03	11.27
L&R	0.070	-0.94	3.35

The AIRGrav system clearly excels in terms of low frequency performance. It provides data with average biases between 0.04 and 0.61 mGal and average drifts over a 100 km flight line that are no more than 0.3 mGal. The variation of the biases between flight lines is between only 0.24 and 0.48 (1-σ), which made it possible to relate the gravity measurements to the absolute field using only a single gravity control point located in this case on the tarmac at the outset of the survey.

For the L&R, the average offset for May 4 is 0.94 mGal and the average drift over a 100 km flight line is 6.9 mGal. This is much larger than is normally expected for a system of this type and thus can not be used as a basis for comparison.

The SINS gravimeter has average drifts between 1.2 and 6.5 mGal over a 100 km flight line. The variation of the biases between flight lines is around 3 mGal on April 19 and 20 and around 11 mGal on May 4. The deviations in the biases are smaller on April 19 and 20 because the Honeywell LRF-III had been on for over an hour prior to the survey on both occasions, allowing a time dependent bias to settle out (see Section 6 for more details). This was not the case on May 4. This level of performance is clearly not good enough to allow for the relative information to be related to the absolute gravity field in the same way as the AIRGrav and LaCoste and Romberg systems, ie by using a single gravity control point at the outset of the survey. For relative gravimetry, however, a crossover adjustment can be used to make the measured data consistent within a given area. By flying a number of flight lines in the direction perpendicular to the main lines, a sufficient number of such points can be obtained to allow for the estimation of a residual offset and slope for each flight line. This process should result in good levels of agreement between the solutions at the points where the flight lines intersect. In turn, this will mean that the relative gravity information is fit to an arbitrary plane in space that can either be related to the absolute gravity field or presented as relative information by removing a plane of best fit. Although the relative information is usually sufficient for many geophysical applications (such as resource exploration). Relating it to the absolute gravity field might be crucial for geodetic applications such as geoid determination. The relationship with the absolute gravity field can be established by either a) using known values of the field for at least three locations in the test area, or b) through the use of a global geopotential model that is evaluated to some degree and order chosen to complement the bandwidth of the relative information. In principle, the accuracy of the resulting field is given by the accuracy of the relative information (see Section 3) and the accuracy of the information used to relate it to the absolute field.

The values of average drift and offset are shown in Table for the SINS gravimeter following such a crossover adjustment (using the data from April 20 and May 4 which were collected along flight lines perpendicular to those of April 19). The EGM 96 model (Lemoine et al. (1996)) was used to arrive at the field represented in Table . It was evaluated to degree and order 190 (degree 190 roughly corresponds to the largest half-wavelength given by the length of the flight lines in the test area).

This approach significantly reduces the average drifts and biases of the data coming from the SINS gravimeter while requiring only external gravity information from an expansion of the global geopotential model to degree and order 190. Although the values in Table 8 are not as small as the corresponding values for AIRGrav, they are sufficiently small enough for many geodetic applications. Although a bias of about 4.5 mGal still exists between these estimates and the reference field, the variation of the biases between flight lines is now only 0.74 to 1.51 mGal (1-σ). This makes it possible to relate the gravity measurements coming from the SINS gravimeter to the absolute field using only a single gravity control point within the test area. This and other observations made in this section will be discussed in more detail in Section 6.

Table 8 Low frequency performance of the SINS gravimeter after adjustment

Survey	Average drift (mGal/km)	Average offset (mGal)	σ of the biases (mGal)
April 19	0.019	-4.30	0.90
April 20	0.079	-4.62	0.74
May 4	0.048	-4.49	1.51

6 Discussion

This section discusses the observations made in the last two sections in light of the present and future requirements for airborne gravity data. Using data that was upward continued from terrestrial gravity measurements as a truth field, the residuals for each system were derived for each flight line on April 19 and 20 and May 4. By linearizing the measurement model of equation (2) and making the safe assumption that current DGPS technology provides position and velocity errors with standard deviations below 0.5 m and 0.05 m/s (1-σ) in flight, the significant errors influencing these residuals are (Schwarz and Li (1996)):

$$d\delta g_u = d\dot{v}_u - df_u + \left(f_n \varepsilon_e - f_e \varepsilon_n\right) + a dT \,, \quad (5)$$

where the first term represents the errors in the determination of aircraft acceleration by DGPS, the second term represents the inertial sensor errors in the upward direction, the term in brackets represents errors caused by misalignment of the inertial measurements in the east and north directions (i.e. the angular error in the realization of a level platform), and the last term represents errors in the process that arise as a result of imperfect synchronization of the DGPS and inertial time series. Since the same DGPS solutions and reference gravity fields are used in every case presented in this paper, better performance of a given gravimeter is due to better performance in terms of either one or more of the inertial sensor errors, the assumed alignment and the synchronization errors. Further, the inertial sensor errors are made up of random measurement noise, biases and to some extent scale factors. The combined effect of these errors has been studied in two different bandwidths; for half-wavelengths longer than 100 km in Section 4 and for half-wavelengths between 100 km and some minimum values (1.4 to 8.1 km) in Section 3.

The performance of the AIRGrav system is clearly better than the others for the bandwidth corresponding to medium-resolution gravimetry (i.e. half-wavelengths between 5 and 100 km). This is shown in Tables 2 through 4 by the agreement of the solutions with the reference field for the smoothing period of 180 sec. where the error for the AIRGrav system is approximately one third of that of the SINS gravimeter. This observation is supported by the portions of the cumulative RMS error spectra in Figure 4. For frequencies below 0.005 Hz where the error curve is lower for the AIRGrav system than the SINS gravimeter. Possible explanations for this include:

- a more stable estimate of sensor orientation by the AIRGrav system (due to the reduced dynamic range required of its gyroscopes as a result of the three axis platform),
- the tight temperature control on the accelerometers using in the AIRGrav system.

In contrast to the second of these points, the accelerometers used by the Honeywell LRF-III SINS gravimeter are subject to an uncompensated temperature-dependent biase that can creep into this portion of the spectrum, see Bruton (2000) for details.

The performance of the AIRGrav system is better than the others for the bandwidth corresponding to high-resolution gravimetry (i.e. half-wavelengths shorter than 5 km). However, the difference between its error and that of the SINS decreases for the data collected on May 4, as seen in Table 4 and in Figure 4. A study of the error power spectrum density of the two systems shows that in the range .005 Hz to .013 Hz (4.5 km to 1.7 km resolution), the systems have a similar noise level. Because the May 4 survey took place under considerably more benign turbulence, it is likely that the differences in performance between the AIRGrav and the SINS in this bandwidth in more turbulent conditions are due mainly to errors induced by the dynamics of the aircraft. Because the effects of misalignment and time synchronization errors increase as the dynamics increase, they are therefore the most likely culprits.

In Section 4, the performance of the systems was evaluated for the bandwidth corresponding to low-resolution gravimetry (i.e. for half-wavelengths longer than 100 km). It is seen there that the deviations in the biases of the data provided by the AIRGrav system are at the level of 0.24 to 0.48 mGal (1-σ) for the survey lines flown on a given day and that the in-line drifts are at the level of 0.001 to 0.003 mGal/km. After a crossover adjustment and the use of a geopotential model to tie the relative gravity measurements to the absolute field, the data provided by the SINS gravimeter exhibits deviations in bias of 0.9 to 1.5 mGal (1-σ) for the survey lines flown on a given day and in-line drifts of 0.02 to 0.08 mGal/km. These numbers suggest the accuracy with which the systems can be used to provide a measure of the absolute gravity field when at least one gravity control point is available in the test area. Clearly, the AIRGrav system performed best in this bandwidth in this campaign.

It should be pointed out that the performance of the SINS gravimeter in the bandwidth corresponding to half-wavelengths longer than the length of the flight lines is dictated by the accuracy of the geopotential model that is used for orienting the relative gravity measurements with respect to the absolute field. As shown by the lighter line in Figure 5, the absolute accuracy of the EGM96 model currently decreases with increasing frequency, reaching the level of 6 mGal for the harmonic degree corresponding to half-wavelengths of 100 km (a degree amplitude value can be likened to a 1-σ value). This information was computed as the square root of the error degree variances given in Lemoine et al. (1998). Given this, the observed biases in Table 8 (4.3 and 4.5 mGal) are to be expected. Several alternatives exist for improving this situation. The first has already been mentioned and depends on using gravity control in the area of the test. This is probably the approach that would currently yield the best accuracy, if the data is available. The second is to increase the area in which the airborne gravity survey is carried out, thereby decreasing the dependence of the solution on the geopotential model. For example, if the flight lines were 200 km long, then an expansion of the geopotential model to degree and order 100 would only be needed. According to the lighter line in Figure 5, this would reduce the errors coming from the dependence on the global model by nearly a factor of three. The third alternative is to make use of the information coming from the geopotential models that will be made available following global satellite missions that are dedicated to gravity field determination (e.g. Champ, Grace and GOCE). The darker line in Figure 5 shows the behaviour that is expected of the anomalies computed from a global model based on data collected during the GOCE mission. It is based on the equations for error degree variances given in ESA (1999). Clearly, the use of such a global model would be significantly more reliable across the whole spectrum. For example, for the data presented herein, the expected accuracy of the expansion to degree and order 190 is better than 1 mGal.

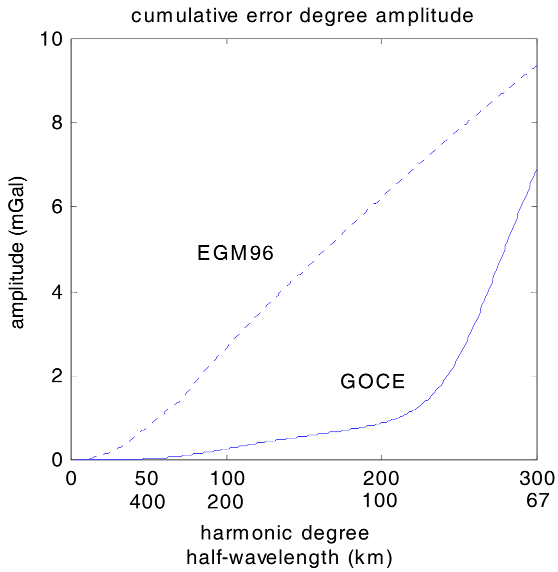

Figure 5 Error degree amplitude values for current and future global models

7 Summary and recommendations

A flight test campaign to compare the ability of three different gravimeters to resolve short and medium wavelength gravity variations was carried out. Two of the systems functioned well and their results were presented; both the AIRGrav and the SINS demonstrated the ability to resolve these wavelengths. The AIRGrav system performed consistently better than the SINS system for all of the flights considered. Although it is considerably larger than the SINS, the AIRGrav has been designed to fit in any small aircraft or helicopter normally used for geophysical survey. It also has the advantage of regular calibration of its sensors, tight synchronization of the data with GPS time, the ability to be used under most flight conditions, and of not being restricted to straight and level flight.

AIRGrav can be further improved by better modelling of the platform errors. In order to realize the full potential of the system, the estimation of the aircraft vertical acceleration using GPS, perhaps in combination with other sensors, needs to be improved. This is seen as the biggest challenge to better airborne gravimetry.

The SINS system has the advantage of being smaller and lighter than either the L&R or AIRGrav systems. It is easily mounted in any small aircraft or helicopter. It has the lowest cost to purchase of the three, but operating costs are probably comparable. The changes of bias in the measured gravity are mitigated by the use of crossover adjustment and the use of a geopotential model, and by allowing the system to warm up prior to a flight.

The SINS system would benefit by better control of the temperature of the unit, and by modelling the sensor errors as a function of temperature. Better misalignment modelling and time synchronization would reduce the deleterious effects of increasing aircraft dynamics. Until the new geopotential models from the dedicated satellite missions are available, measured points in the area of interest can be incorporated into the solution in order to tie the relative information to the absolute field. If three or more points are used, the information about the orientation of the relative gravity data can be strengthened as well as allowing a better determination of the biases.

The Lacoste and Romberg system used in this test did not function as well as it has in previous tests. Some of the reasons are given in Halpenny (2001). Results from L&R systems in use by other agencies have shown results at the 1.5 to 2 mGal level with a filtering time of 180 seconds, ie corresponding to a resolution of 4.1 km in this series of flights. It is unfortunate that a direct comparison can not be made.

Since the GPS solution contributes a large part of the noise in high-resolution gravity estimation, careful selection of the observables and the processing methodology used in the solution is essential. The results given in this paper are based on using L1 float ambiguity solutions for data reduction, since the ionospheric activity was low and the baseline relatively short. This will not apply to all surveys however, and results will vary depending on the conditions (see Bruton et al (2001) and Ferguson and Hammada (2000)).

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