Experiences with AIRGrav: Results from a New Airborne Gravimeter

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Abstract. The results of the evaluation of a new airborne gravimeter developed by Sander Geophysics Limited (SGL) will be presented. This gravimeter is based on a platform type inertial navigation system, and is optimised for the airborne environment. A general description of the instrument is given.
The testing was conducted over a relatively flat area which is well covered with ground gravity values. The upward continuation to flying height of a grid of these values was used as a reference for the data reduction. The gravity anomaly was extracted through application of a series of low-pass filters on the inertial data, after removal of the kinematic accelerations and Coriolis effects using the processed GPS data. The results show an agreement with the ground truth well within 1.0 mGal for a 2km half wavelength spatial resolution.
The effects of varying flight conditions are assessed as to their impact on the quality of the data. Flight turbulences appear to have very little effect on determination of the gravity anomaly for half wavelengths as short as 2 km.

Keywords. Airborne gravimetry, gravimeter, Schuler tuned platform inertial system.

1 Introduction

The SGL Airborne Inertially Referenced Gravimeter system (AIRGrav) is the first Schuler tuned platform inertial system specifically designed for airborne gravimetry applications. The objective pursued by Sander Geophysics is to provide the industry with a gravimeter system capable of delivering a gravity anomaly profile with an accuracy of better than 1 mGal with the best half wavelength spatial resolution possible. This is a reasonable objective, in the sense that the study conducted by Wei, Ferguson, and Schwarz in 1991 has shown that the accuracy of GPS derived acceleration of a moving platform can be below the 1mGal level for averaging times of one minute. The system should be sufficiently resilient to maintain consistent performance over a fairly large range of flight conditions. This paper reports the results of some of the first tests of this new airborne gravimeter.

2 Gravimeter Overview

The gravimeter is based on a platform type inertial navigation system. The system has two main components: a cabinet containing the inertial platform hardware and some of the electronics, and a small rack containing power supplies, the remaining electronics, and the data recording computer. The inertial sensors, consisting of three navigation-grade accelerometers and two two-degree-of-freedom gyroscopes, are mounted on a block in a temperature-controlled environment. This sensor block is fully isolated from aircraft angular motion by three gimbals controlled by servo motors reacting to gyroscope outputs.
The gimbal arrangement has been designed to allow the accelerometers to be “tumbled”, that is, each accelerometer can be placed so that it is aligned with the gravity vector and aligned 180 degrees from it. This allows calibration at frequent intervals. Gyroscope drift calibration is also possible.
The data recording is done using PC compatible hardware and software. All inertial data are recorded at a rate of 128 hz, and GPS data from a dual frequency receiver at a rate of 10hz.

3 Some Relevant Features

The objective is to determine the scalar gravity. As a consequence the gravimeter inertial platform has to be maintained aligned to the local level horizontal plane with great accuracy. This in turn will ensure that the gravity is sensed by the vertical accelerometer. The leveling of the gravimeter inertial platform to the local level is performed during the alignment mode, just prior to the survey. The alignment procedure has two objectives. The first objective is the determination of the azimuth angle or the orientation of the platform system of axes with respect to the north. The second objective is the leveling of the platform to the local level horizontal plane. For this purpose, the alignment procedure undergoes several stages.

Two coarse alignments are first performed, then a first fine alignment, then a slew of the platform around the outer gimbal axis by a certain angle, and finally another coarse and fine alignment in the new orientation. The alignment procedure is completed by the application of the residual horizontal axis gyroscope drifts. A successful alignment procedure should reduce the horizontal accelerometer readings to close to zero. Figures 1 and 2 show the outputs of the horizontal accelerometers at the end of an alignment procedure and lowpass filtering to 0.1 hz.

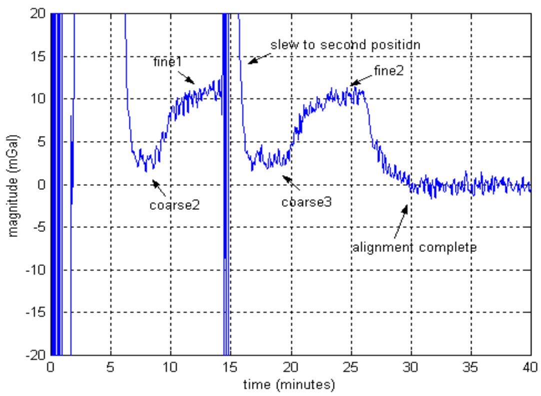

Fig 1 X accelerometer output

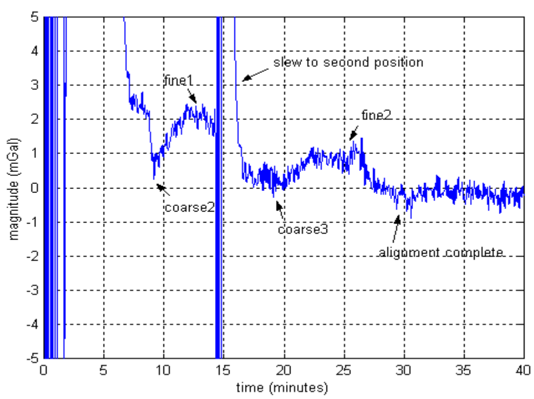

Fig 2 Y accelerometer output

Another aspect of importance in the airborne scalar gravimetry problem is the stability of the vertical accelerometer measurement throughout a survey. By monitoring the vertical accelerometer output at the start and the end of a survey, with the aircraft parked at the same location, the system has consistently shown less than 1 mGal drift over several hours of flight survey.

4 Test Description

The first flight tests of the SGL AIRGrav system started in the summer of 1999 in Ottawa, Canada. Initially the gravimeter was installed in a Cessna 404 Titan, a twin engine aircraft. Several flight tests were conducted with the C404. Subsequently, the system was installed in a Cessna 208B Grand Caravan, a single engine aircraft capable of lower flight speeds. A picture of this aircraft in flight is provided in figure 3.

Fig 3 Cessna 208B Grand Caravan

The installation of the gravimeter and recording equipment is straightforward and can be done in any small aircraft or helicopter. A GPS receiver and a receiver for real time corrections were used to generate accurate real-time pilot guidance signals. Two aircraft-mounted GPS antenna locations were used; the first on the aircraft fuselage immediately above the gravimeter location, the second on top of the aircraft tail. Both antennas were connected to NovAtel MiLLennium receivers.

In order to compute a double difference GPS solution, three remote GPS reference stations, all using Novatel MilLLenium receivers, were established. The first one was on the roof of the SGL building near the Ottawa airport, the second one was located in the airport field, four km from the company building, and the third one was located within the test area, about 80 km distant from the other two GPS reference stations.

All flight tests were flown over the Alexandria gravity test area near Ottawa. Figure 4 shows a map of the Alexandria gravity test area as well as the flight lines and the reference station locations.

Several upward continued grids of gravity anomalies at different flying heights were produced from a network of point-wise gravity anomalies provided by the Geodetic Survey Division (GSD) of Natural Resources Canada. The distribution of the ground measurement data in the Alexandria test range is quite irregular. The spacing of data points varies from 1 km to 10 km, with the average spacing probably about 3 km.

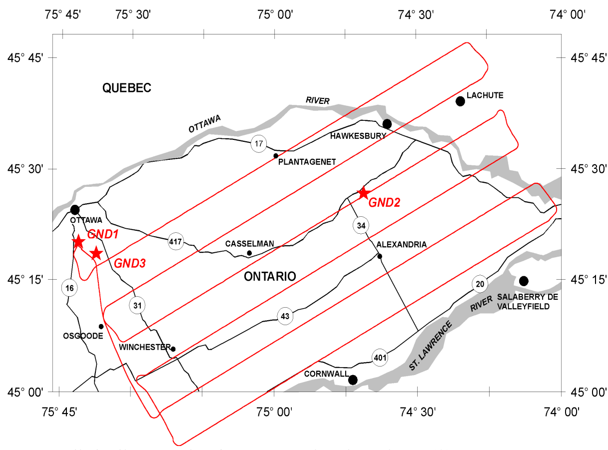

Fig 4 Flight lines and reference station locations (*)

The ground measurements were reduced using the free air correction only, to a uniform grid of gravity values at mean sea level. Then the gridded values were upward continued, using Fourier Transform techniques, to obtain the gravity reference at the flying height. No terrain corrections were applied since they are very small due to the flatness of the test area. The derived gravity reference, with an estimated accuracy of 0.5 mgal, was used to assess the quality of AIRGrav gravity anomaly estimates.

This paper will focus on the latest series of tests conducted by Sander Geophysics during the months of April and May, 2000. This series of test flights was performed to gather data in order to compare the results obtained using three different gravimeter systems flown simultaneously, and under the auspices of the GEOIDE network [http://www.geoide.ulaval.ca]. Only the results from AIRGrav will be presented here. A total of six survey flights were carried out during this campaign. Five flights took place during the day, and one during the early morning hours. The average flying height was 575 metres, with the exception of the fifth flight where the flying height was 1150 metres. The average flight velocity was 45 m/s.

5 Test Results

A total of six different flight lines were flown during this campaign as shown in figure 4. In order to assess the quality of our estimates, a gravity anomaly reference for each flight line and corresponding flying height was computed using the reference grid described earlier. The gravity anomaly was extracted using a lowpass filtering process. For this purpose, a battery of lowpass filters for different cut-off frequencies was designed to extract the gravity anomaly profile at different wavelengths [Hammada and Schwarz, 1997].

The GPS solution was computed by using a single GPS base station for the entire flight. The GPS base station inside the test range, labeled GND2 in figure 4, was used for the determination of the double difference GPS solution. Three different aspects of AIRGRav gravity anomaly determination are investigated. The first is the effect of using L1 only versus ionosphere-free GPS solutions on the gravity anomaly resolution. The second is the affect of aircraft dynamics on the gravity anomaly resolution. The third aspect is the accuracy of gravity anomaly resolution for different wavelengths.

5.1 L1 Only Versus Iono-Free Sensitivity

Intuitively, one would expect that an ionospheric-effect-free GPS solution would produce an improvement in the accuracy of gravity anomaly determination. In order to quantify the sensitivity of this accuracy with respect to both GPS solutions, a gravity anomaly estimate was computed for both GPS solutions. Then the two corresponding gravity anomaly errors were formed by subtracting the gravity anomaly reference. Furthermore, in order to minimize the effect of aircraft dynamics, the least turbulent flight (the sixth one) was considered. Figures 5, 6, and 7 show the rms error of the gravity anomaly with respect to frequency for lines 1001, 1002, and 1003 respectively. The gravity anomaly rms error was obtained by integrating the gravity error power spectral density with respect to frequency.

The iono-free GPS solution systematically introduces more noise in the high frequency range. However in the low frequency range, the iono-free GPS solution does not introduce an improvement compared to the L1 only GPS solution.

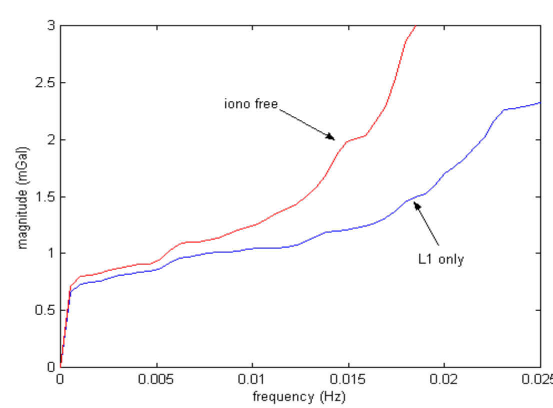

Fig 5 Gravity rms error versus frequency of line 1001

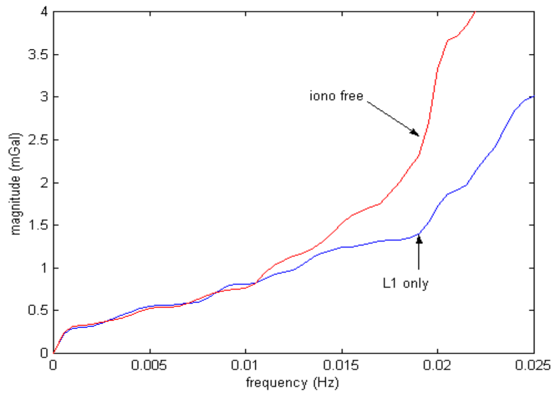

Fig 6 Gravity rms error versus frequency of line 1002

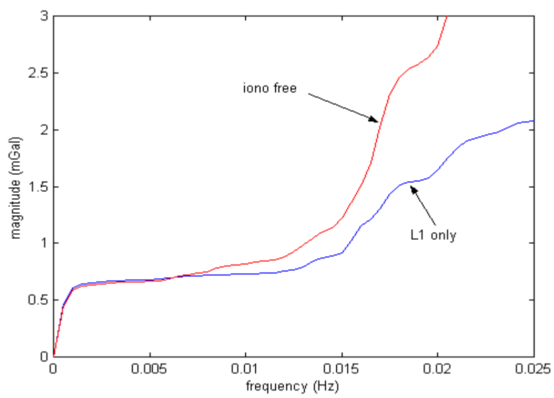

Fig 7 Gravity rms error versus frequency of line 1003

For instance, if we consider lines 1002 and 1003, both GPS solutions are equivalent for low cut-off frequencies, implying that the ionospheric activity is negligeable at these frequencies.

5.2 Aircraft Dynamics Sensitivity

Flying conditions can and do vary substantially from one survey flight to another and even during a particular survey flight. As a result, it is essential for the airborne gravimeter system to be insensitive to a fairly large spectrum of flight conditions. In this section, the flight conditions of several survey flights are quantified by the rms of aircraft vertical accelerations, taken in successive 5 minute intervals. Among the five survey flights considered, the fourth flight was the most turbulent and the sixth flight was the least turbulent as shown in figure 8. Figures 9 and 10 show the mean gravity anomaly rms error as a function of the rms aircraft vertical acceleration, for several low pass filters whose effective averaging times are shown.
Over all, the L1 only GPS solution is significantly less noisy than the iono-free solution using the 60

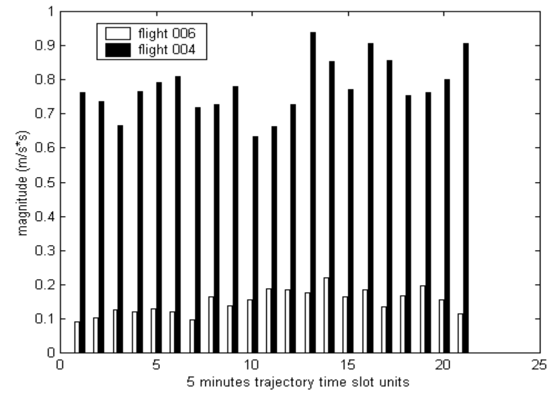

Fig 8 RMS vertical acceleration during flights 004 and 006

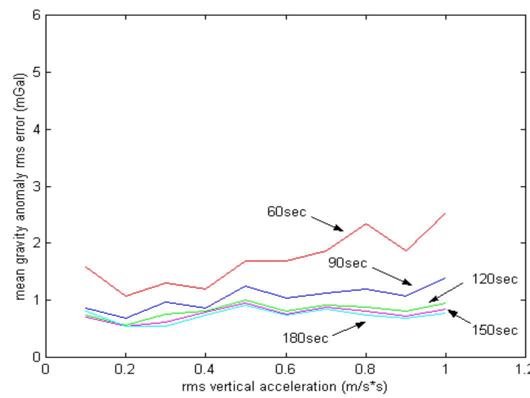

Fig 9 Accuracy of gravity anomaly resolution versus aircraft dynamics (L1 only)

and 90 second filters, which confirms our earlier conclusion. It is also interesting to note that the noise rises more rapidly with vertical acceleration for the iono free solution.

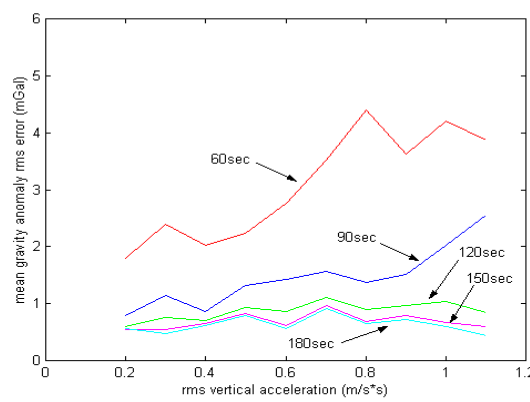

Fig 10 Accuracy of gravity anomaly resolution versus aircraft dynamics (iono-free)

This indicates that the additional error must be due to the iono-free GPS noise increasing with turbulence. One possible explanation is that the aircraft multipath noise increases with higher levels of turbulence; another is that the L2 tracking of the GPS receiver itself gets noisier.

Based on the series of flights under discussion, where there was a fairly large range of aircraft dynamics, the AIRGrav system shows very little sensitivity to aircraft dynamics for filter averaging times as short as 90 seconds, representing a 2 km half wavelength spatial resolution.

5.3 Accuracy of Anomaly Determination Versus Wavelength

All the flights (2 to 6) will be considered. The gravity anomaly estimate results for lines 1002 and 1003 are presented because these lines were flown in almost all flights. Tables 1 and 2 summarize the results for lines 1002 and 1003 respectively.

Over all, flight 4 was the most turbulent. Flights 3 and 5 were fairly turbulent. Flight 2 was moderately turbulent, while flight 6 was the least turbulent. Over a fairly large range of aircraft dynamics, the AIRGrav system demonstrates a gravity anomaly estimation accuracy with respect to the reference of 1 mGal with 90 second filtering. The standard deviation in the tables provides a measure of the variability of the rms error for a given line and cut-off frequency, under a range of flight conditions. Clearly, this measure shows a consistency well within the 1 mGal range for filter averaging time as short as 60 sec. Figures 11, 12, 13, and 14 display the gravity anomaly estimates versus the gravity reference of line 1003 for four different filter averaging times.

Table 1 Summary of results for line 1002

Filter average time (sec)	Half wave length (km)	Flight	Gravity rms error (mGal)	σ (mGal)	Mean (mGal)
60	1.3	2	1.56	0.85	1.94
		4	3.15		
		5	1.84		
		6	1.19		
90	2.0	2	1.00	0.36	1.18
		4	1.65		
		5	1.23		
		6	0.83		
120	2.5	2	0.80	0.21	0.91
		4	1.20		
		5	0.90		
		6	0.72		
180	4.0	2	0.59	0.21	0.75
		4	1.05		
		5	0.76		
		6	0.61		

Table 2 Summary of results for line 1003

Filter average time (sec)	Half wave length (km)	Flight	Gravity rms error (mGal)	σ (mGal)	Mean (mGal)
60	1.3	2	1.15	0.72	1.81
		3	2.73		
		4	1.62		
		5	2.37		
		6	1.16		
90	2.0	2	0.79	0.30	1.01
		3	1.40		
		4	1.02		
		5	1.12		
		6	0.67		
120	2.5	2	0.72	0.12	0.74
		3	0.71		
		4	0.74		
		5	0.93		
		6	0.61		
180	4.0	2	0.59	0.14	0.68
		3	0.62		
		4	0.64		
		5	0.92		
		6	0.61		

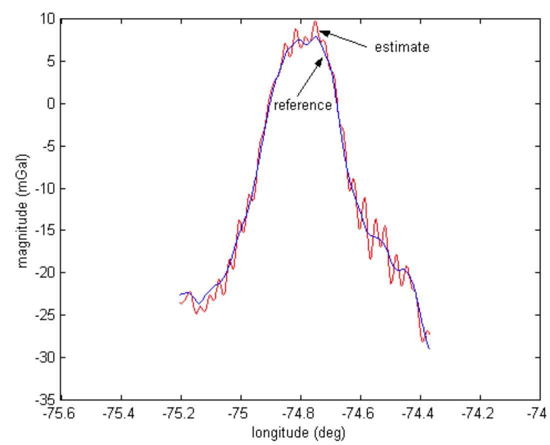

Fig. 11 60 sec. filter gravity anomaly estimate versus reference

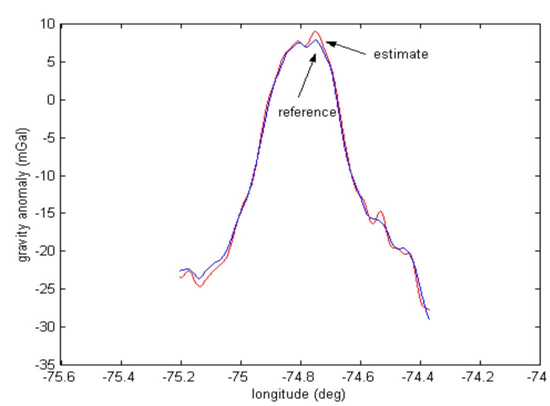

Fig. 12 90 sec. filter gravity anomaly estimate versus reference

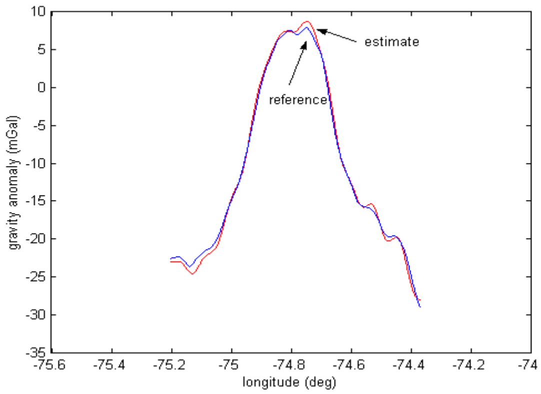

Fig. 13 120 sec. Filter gravity anomaly estimate versus reference

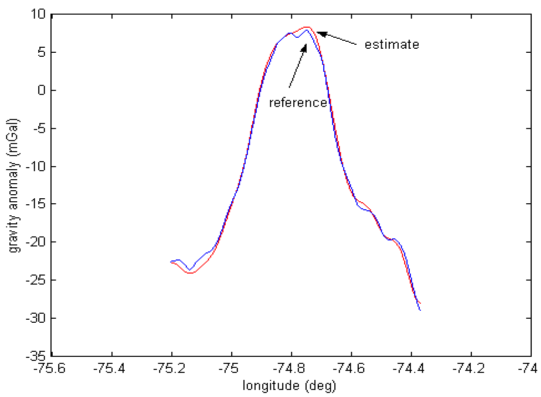

Fig. 14 180 sec. filter gravity anomaly estimate versus reference

6 Conclusions

The ionosphere-free GPS solution does not systematically produce a better gravity anomaly estimate in the low frequency range than the L1 only solution. On the other hand, the L1 only GPS solution systematically outperforms the ionosphere-free solution in the high frequency range.
The SGL AIRGrav system has shown that it is largely insensitive to aircraft dynamics. Over a range of aircraft vertical accelerations corresponding to flights in calm to fairly turbulent conditions, the system has delivered a gravity anomaly estimate well within the 1 mGal range for a half wavelength as low as 2.0 km. This system tolerance to turbulence levels typical of daytime flights, makes it a very appropriate tool for daytime airborne gravimetry surveys, in a standard geophysical survey aircraft.

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References

Hammada, Y ., and Schwarz, K.P. (1997) : ”Airborne Gravimetry: Model-based versus frequency domain filtering approaches.” International Symposium on Kinematic System in Geodesy, Geomatics and Navigation, Banff, Canada, 1997.

Wei, M ., Ferguson , S., and Schwarz , K.P. (1991): ”Accuracy of a GPS-derived acceleration from moving platform test.” International Association of Geodesy Symposium 110, Springer-Verlag, New York, USA.