AIRBORNE GRAVIMETRY: A STATUS REPORT

Prepared for the Surveyor General
Land Information NewZealand

by

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January 2001

1. Introduction

The idea of using an airborne platform for gravity surveys originated in the 1960s when such data began to be used, in conjunction with airborne magnetic measurements, to assist in geophysical exploration activities. Although, at that time, the gravity sensor had a theoretical resolution of 0.05 mGal, the disturbing accelerations to the aircraft were very difficult to determine due to the inaccuracy of the navigation systems of the day. With the development of GPS technology, however, the situation changed rapidly. Torge (1989), for example, noted that helicopter borne systems, under ideal operational conditions, had achieved precisions of ±5 mGals and that depending upon flight altitudes, aircraft borne systems had *"yielded field resolutions of 20 ..50 km and accuracies of ± 50 .. 100 μms^{-2} "*.

By 1995 accuracies had improved well beyond the 10 - 15 mGal level thus offering the possibility of significant improvements in geoid determination over what would otherwise have been gravity sparse regions (Hein, 1995). Indeed, by 1999, it was reported that: *"Airborne gravimetry is a proven operation to determine the Earth's gravity field for geophysical applications over remote areas* --" (Jekeli et al, 1999). Clearly, in the last 10 years, there has been a maturing in the technique such that it is now able to make a significant contribution to geophysical and geodetic studies.

This paper gives a status report on collecting gravity data by airborne methods, looking particularly at issues such as techniques, data densities, accuracies, and costs. The overall goal is one of assessing the applicability of this technique to the New Zealand situation.

2. The Rationale For Airborne Gravimetry

An earth model, which is described by a spherical harmonic expansion that is complete to degree and order 360, delivers a resolution of the earth's gravity field to a half wavelength of approximately 55 km. Recent satellite altimeter missions (e.g., SEASAT, GEOSAT, ERS-1 and TOPEX/POSEIDON), have delivered oceanic data that offer the possibility of gravity field resolutions to even shorter wavelengths. Unfortunately, satellite altimeter data, while being useful for determining these shorter wavelength features of the earth's gravity field, still do not give the detailed structure that is necessary for high accuracy local geoid determination. Furthermore, they cease to operate effectively in near coastal regions. Thus, unless there is an abundance of shipborne gravity surveys in coastal regions, an elongated and narrow country such as New Zealand will have difficulty with any local geoid determination that relies heavily upon a dense and accurate network of gravity data. These problems are then exacerbated by the mountainous nature of New Zealand's terrain in which conventional gravimetric surveys in such areas have largely been limited to sites located on or beside a few major roads.

By using spectral analysis techniques, Schwarz and Li (1995), have concluded that theoretically the determination of the geoid to 1cm (rms) will require the gravity field to be resolved to a minimum wavelength of 14 km in flat terrain and 5 km in mountainous terrain. For a 10 cm geoid these numbers increase to 70 km and 40 km, respectively.

Unfortunately, achieving the needed improvements in our knowledge of the gravity field by static surface gravity measurements, particularly of ocean and mountainous areas, is a time-consuming and expensive task. Airborne gravimetry, on the other hand, offers an efficient means of determining the short wavelength features of the earth's gravity field (1 - 100 km or longer), that are unable to be easily resolved by other techniques. It is for this reason that airborne gravimetry deserves particular consideration in the New Zealand.

3. Methods For Airborne Gravimetry Measurement

Airborne gravimetric techniques face a number of difficulties that are not typically found in land (or even sea) based operations. Torge (1989), lists these as follows:

- high platform velocities necessitate short averaging times and high navigation accuracies.
- the wide spectrum of disturbing accelerations that require assessment, dampening and filtering.
- elevation changes (uncertainties) directly influence the value of gravity.
- The power of the gravity field (especially the short wavelength part), attenuates steadily with altitude thus causing the signal to noise ratio to decrease at a higher altitude. In general, the higher the altitude of the aircraft the decrease in the short wavelength resolution capability of the gravimetric system.

Three principle methods are used for the collection of airborne gravimetric data, each of which is discussed below.

3.1 Scalar Gravimetry.

There are various implementations of this technique, two of which will be described here. A good summary of the various scalar gravimetric techniques may be found in Schwarz and Wei (1994).

In principle, scalar gravimetry requires both a device that determines the sum of the gravimetric and kinematic accelerations occuring to the airborne platform, plus a vertical positioning system (e.g., radar or laser altimeter, or a GPS receiver), that determines the kinematic accelerations alone. The gravity vector is determined by differencing between the two. In practice, the most critical part of the problem is this separation of the gravitational acceleration from the non-gravitational accelerations that are occurring to the aircraft. These non-gravitational accelerations can be larger than the gravity signal itself by factors of 100 to 1000. This separation is only possible using high precision DGPS data together with appropriate low-pass filtering techniques such as is described by Hehl (1994).

To date the scalar technique has been the most popular for airborne gravimetry, having a basic error model of the type described by Hein (1995). More detailed error models are given by Wei and Schwarz (1994).

The historical, and most common implementation of this particular technique, comprises a modified sea-air gravimeter with a damped two-axis platform, mounted in either a helicopter or an aircraft (e.g., LaCoste & Romberg, Bell, or Dodenseewerk KSS-31), that is oriented in a vertical direction. It is an implementation of scalar gravimetry that has seen significant advances in accuracy in the last ten years. Klingele and Halliday (1995), for example, report on a project in which the entire country of Switzerland was flown by a Twin-Otter aircraft equipped with a modified LaCoste and Rhomberg marine gravimeter and a GPS/Loran receiver. The flying altitude was 5 200m and flight lines were parallel to each other and separated by about 11 km. Four tie lines were also flown. RMS accuracies of the results were derived by a comparison with ground data that had been upward continued, and were found to be in the order of 6 mGal. A similar project undertaken in the Antarctic (an 11 500 km survey consisting of 22 parallel flight lines, spaced at 12 km), enabled the recovery of the free air anomaly field to an accuracy of "a few milligals for wavelengths of the order of 12 km" (Jones and Johnson, 1995). An autopilot was not used in this latter survey and thus some accuracy degradation probably occurred. Wei and Schwarz (1998) report that, in general, airborne gravity surveys of this nature are now able to be completed to an accuracy of 3-5 mGal and a spatial resolution of 10 km or better. This is confirmed by Timmin et al (1999), who report even better results over a number of recent airborne gravity data collection campaigns in near-coastal oceanic regions. This implementation of scalar gravimetry is now routinely operational, is available on a commercial basis, and claims internal data consistencies approaching 1 mGal with resolved half wavelengths of 3 km (c.f., Grumert, 1995; Harrison et al, 1995).

Other, more recent implementations of the scalar technique, use an inertial navigation system (INS) both as a stabilizing mount for a separate gravimetric sensor and as the gravimetric sensor itself. Initial test results indicated that accuracies of 1 mGal with a spatial resolution of 2 - 3 km can be achieved over a profile length of 50 km in areas with medium gravity field variability (c.f., Salychev et al 1994; Salychev, 1995). These results were achieved at a 500 m flight altitude with a flight speed as low as 50 m/s and a maximum change in gravity over the test area of 30 mGal.

Wei and Schwarz (1998), report on data collected over the Rocky Mountains in 1995 in which a strapdown INS (a LASEREF III), two GPS receivers with a zero baseline on the aircraft, and multiple GPS master stations on the ground were used. An east - west profile of 250 km in length was selected across the mountains and four flights made over the same ground track. The flying altitude was about 5 500m, i.e., between 2 500 and 5 000 m above the ground with an average flying speed of 430 km/h, thus implying a spatial resolution (half wavelength of cutoff frequency), of 5.0 - 7.0 km when using filter lengths of between 90 and 120 s. Their accuracy evaluation, based upon repeated flights and a comparison with upward continued terrestrial gravity using a detailed terrain model, showed a standard deviation between the airborne gravity data and the ground truth data of about 3 mGal for both filter lengths. Their results are the first to be reported using the INS/GPS methodology and suggest that a relative geoid of 2-3 cm over a distance of 200 km could be achieved by this method.

Wei and Schwarz (1998) report that the major advantages in using strapdown INS technology for airborne gravimetry are its size, cost, power supply, and operational flexibility. Such systems can be purchased as "off the shelf" units and do not require costly system modifications.

3.2 Vector Gravimetry.

In this particular measurement technique, three accelerometers of an inertial navigation system (INS), replace the gravimeter. The technique itself, which has been extensively studied (c.f., Jekeli, 1995; Schwarz et al., 1992), has important theoretical advantages over scalar gravimetry. Principally, the along track relative geoid can be determined directly by the along track integration of the horizontal gravity components rather than from surveys of the vertical component over large areas as is required by the Stokes solution to the geopotential boundary value problem. Using a minimum quantity of data, it also enables the computation of gravity gradients that in turn reveal sharper contrasts in crustal structure (Pawlowski, 1998).

The principal difficulty with the method lies with the errors in the gyroscopes that provide orientation of the system in inertial space. As Jekeli and Kwon (1999) point out, a large north or east orientation error couples the large vertical acceleration into the east (or north) gravity component. A leveling error of 1″, for example, produces a 5 mGal gravity error.

Using vector methods, Jekeli and Kwon (1999) processed the data set collected over the Canadian Rockies that was described in Sec. 3.1. They compared their results with equivalent information derived from NIMA (National Image and Mapping Agency) 2′ x 2′ gridded terrestrial gravity data. This ground truth data, which was upward continued to an altitude of 5000m, was reasonably assumed to have standard deviations which were less than 5 mGals. Significant systematic differences between the ground truth data and the airborne gravity data were found in all components of the gravity vector. These systematic errors, at least in the north and east components of the gravity vector, appeared to be correlated with aircraft motion and flight direction. The vertical errors (biases), were considered to be a function of the inseparability of unknown accelerometer, gravity and orientation biases in the Kalman filter. By using the fact that ground tracks had been repeated, and by assuming that the gravity vector components were known at the end points of each flight line, these biases were able to be eliminated after a series of filtering operations.

Best results obtained between the two data sets, after filtering and bias removal from the INS/GPS data, yielded differences with standard deviations of approximately 8 mGals for the horizontal components of the gravity vector and 3mGal for the vertical component. While the data smoothing techniques applied implied a resolution of about 3.5 km, the resolution of the truth data (as implied by its upward continuation), was considered to be little better than 10 km. Indeed, following detailed analysis, it was concluded that the ground truth data often lacked the accuracy and consistency of the airborne data (Jekeli, personal communication). This study has the following important implications:

- It is the first time that the total gravity vector has been determined from airborne INS and GPS data to a reasonable accuracy and resolution without the use of any external orientation information or prior statistical hypotheses about the gravity field.
- It used a medium accuracy INS together with geodetic quality GPS receivers.
- It demonstrated that the accuracy of the horizontal component of the gravity vector depended critically on the dynamic stability of the aircraft during flight, indicating that optimally, the flight lines should be long, straight and level.

3.3 Gravity Gradiometry.

The Gravity Gradiometer Survey System (GGSS) has its origins in the 1960s when the U.S. Air Force abandoned airborne gravimetry due to the inadequacy of the navigational techniques of the time for determining the kinematic accelerations of the airborne vehicle. The alternative adopted, the gravity gradiometer, rather than measuring accelerations directly, measured differences in acceleration. A number of prototype systems were developed in the 1970s culminating, in 1983, in the award of a contract for the production of the GGSS (c.f., Jekeli, 1993). Due to lack of ongoing funding for the project, only one airborne field test was undertaken with the system. These indicated that the GGSS could recover 5′ x 5′ mean gravity anomalies to an accuracy of a few mGals on a grid of orthogonal tracks spaced 5 km apart and at an altitude of 700m above the terrain (Jekeli, 1993). The system has never been moved beyond the prototype mode and is not operational.

3.4 Conclusion.

If one is confined strictly to commercially available operational airborne gravimetric systems, then scalar gravimetry offers the only solution. Vector gravimetry, however, while apparently lacking a commercial supplier, clearly has potential as a means of determining the total gravity vector. It does enable the determination of very accurate geoidal profiles. Gravity gradiometry, on the other hand has not moved beyond a prototype system and would require some millions of dollars for such a programme to be satisfactorily advanced to even a moderately operational mode Jekeli, 1993).

4. Costs and Operational Constraints.

As was noted earlier, one of the most critical aspects of the problem is the determination of the non-gravitational accelerations that occur to the carrying aircraft. The occurrence of such accelerations, their determination, and the subsequent resolution of the gravity signal, is a function of the following factors.

- The navigation system used to position the aircraft. Experimental work undertaken by Wei and Schwarz (1995) over two different flights using two different aircraft, indicated an accuracy in GPS derived accelerations of 0.5 - 1.0 mGals when using a filtering period of 120 seconds, 1.0 mGal for a filtering period of 90 seconds and 1.5 - 2.0 mGals for a filtering period of 60 seconds. When flight speed is taken into account these values refer to spatial resolutions (half wavelength of cut-off frequency), of 6 km, 4.5 km and 3 km respectively.

- The speed of the aircraft. The faster the flight, the less the effects of turbulence and thus the fewer the high frequency accelerations. Conversely, however, the faster the speed of the aircraft, the more terrain that is covered and the less the resolution of the gravity data. Commercial operators quote achievable accuracies of ±1 mgal when flying at a ground speed of 80 knots (Grummert, private communication).

- The altitude of flight. As mentioned earlier, and under the assumption that system errors are the same at all altitudes, the signal to noise ratio will improve with a lower flight altitude thus improving the ability of the system to resolve the short wavelength components of the gravity field. Schwarz and Li (1995), give the following table that contrasts gravity field resolution with flying height (h) above the terrain.

Recoverable Gravity Field Wavelengths in Airborne Gravimetry

Terrain	h = 0.5 km	h = 2 500 m	h = 5 000m
Flat Areas	> 5 km	> 10 km	> 14 km
Mountainous Areas	> 4 km	> 6 km	> 11 km

- The use of an autopilot so as to provide both a smoother flight path and the maintenance of a reference altitude. Harrison et al (1995) see this as an important factor in obtaining high quality data, although there is a suspicion that some of the Calgary data may actually have been contaminated by the use of the autopilot.

- The prevailing weather conditions. Low turbulence conditions are essential if high frequency aircraft accelerations are to be avoided. In the two experimental flights reported by Wei and Schwarz (1995) (see above), one was undertaken under very stable conditions and the other under “bumpy” conditions. The results from the second were “considerably worse” than those of the first. Commercial operators suggest strongly that flights be undertaken at night when turbulence from ground heating is low (Grummert, private communication).

- The design of the aircraft. It is much preferred to use an aircraft, such as a Twin Otter, that has high stability at low speeds. Such an aircraft should be equipped with both terrain avoidance and weather radar systems.

- The design of the survey. Primary flight lines should be as long as possible and run parallel to the axis of the terrain. As a quality assurance measure, tie lines should be flown at a spacing of three or four times that used for the primary lines.

Harrison et al (1995) comment that their system is now sufficiently well developed so as to be able to be loaded onto a 6-8 passenger aircraft of opportunity.

The costs of using a commercial operator to collect airborne gravity data are not clear. One U.S. commercial operator quotes an indicative price of $US (100 + taxes)/line km of data collected. This includes the use of their aircraft, staff and equipment. While this commercial operator much prefered to use his own purpose equipped Twin Otter, he did concede that mobilization costs in operating in New Zealand would be considerable and that the use of a local aircraft of opportunity could be considered.

Some of the issues that would need to be resolved before costs could be fully assessed are:

(i) The availability of experienced contractors and their location. An Australian contractor, for example, would potentially be less expensive than a U.S. contractor.
(ii) The willingness of such contractors to use aircraft of opportunity.
(iii) The extent of any surveys that need to be undertaken.
(iv) The density of the data to be collected.
(v) The degree to which LINZ might provide direct support (e.g., personnel) to assist in such an operation.

5. Conclusions

Airborne gravimetry is now a commercial operation with a proven track record. The technique used is that of scalar gravimetry, employing a modified land-sea gravimeter that is oriented in the vertical direction. A second implementation of scalar gravimetry, using an off-the-shelf, strapdown INS can equally be used for vector gravimetry. This technique, while not yet in a commercial mode, offers a great deal of promise when factors such as size, cost, power supply and operational flexibility are all considered. It is a technique that might well be able to be developed in New Zealand in collaboration with overseas partners through an appropriate bid to the Public Good Science Fund.

Existing commercial implementations of scalar gravimetry appear to be delivering data accuracies better than 3 mGals with resolved half wavelengths less than 3 km. These data, however, need to be collected with care, under low turbulence conditions, and using an appropriate aircraft. The literature does not indicate a distinction in data collection accuracies between mountainous areas and plains, but it does indicate clearly that more gravity information is required over mountainous areas for any given geoid resolution. If, for example, a 10 cm geoid is required then the minimum gravity field wavelength to be resolved is approximately 70 km in flat areas and 40 km in mountainous areas. For a 1 cm geoid these numbers reduce to 14 km and 5 km respectively. These numbers, however, are based upon a generalised (global) gravity covariance function, and can be expected to vary in specific regions. Furthermore, the geoid is resolved only after the integration of local gravity data that itself needs be considerably more dense than a single wavelength. This suggests that flight profiles separated by (say) 15 - 20 km over the more rugged parts of New Zealand, when combined with existing data sources, should enable the resolution of a 10 cm geoid. Schwarz and Li (1995), indicate that the required data can be collected at a flight speed of 300 km/h and at an aircraft altitude of 5 000m above the terrain.

The other key factors in data accuracy relate to the choice of aircraft, equipment, and the operational conditions experienced.

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