Development of a versatile, commercially proven, and cost-effective airborne gravity system

STEPHEN WILLIAMS and JEFFREY D. MACQUEEN, Fugro-LCT, Houston, Texas, U.S.

The Fugro airborne gravity system was developed and continues to evolve in accordance with the following design criteria:

- reliability and aircraft independence
- measurement of geodetic-quality GPS velocities, rather than using less accurate velocities computed from GPS position
- use of exhaustive gravity sensor and platform modeling along with rigorous processing corrections to minimize filtering
- evaluation of system resolution and accuracy based on data acquired in "real-world" exploration conditions

Aircraft independence required that the gravity system not depend on flight characteristics of any specific aircraft and that the aircraft not require any extensive aircraft airframe or system modifications. The system has been installed on six aircraft that have been used to fly successful gravity airborne gravity surveys: Cessna 208, Cessna 404, Cessna 421, Rockwell AeroCommander 500 Shrike, Piper Aztec, and Airship Industries R-300 airship (i.e., a blimp).

This aircraft versatility and ease of gravity system installation (typically requiring less than one day) simplify mob/demob operations and reduce survey costs.

Measuring geodetic-quality GPS velocities required state-of-the-art dual-frequency GPS receivers and development of customized postmission GPS-processing software. The system tracks aircraft kinematics with extreme accuracy, thus reducing demands for extreme flight stability.

The guiding philosophy for the system could be summarized as "model, measure, and correct—don't overfilter." The goal is to minimize filtering by applying an extensive suite of corrections derived from GPS velocities, sensor, and platform modeling measurements prior to filtering.

Finally, we established that system resolution and accuracy were satisfactory by performing three independent analysis methods on data acquired in real-world exploration conditions.

System development and operations. The Fugro airborne gravity system is the result of a joint effort by three companies, including a leading U.S. defense contractor specializing in advanced GPS applications. The development team, which included geophysicists and geodesists, was headed by J. Christopher Harrison who directed, along with the late Lucien LaCoste, the world's first nonmilitary airborne gravity tests in 1959. Additionally, Harrison and LaCoste pioneered research in the understanding of cross-coupling effects in dynamic gravimetry measurements. Many important aspects of Harrison's extensive dynamic gravity knowledge have been incorporated in this airborne gravity system.

Flight-testing included three separate campaigns flown over an industry-sponsored gravity test range in Texas. In addition, Fugro was contracted to fly a gravity test range in Pennsylvania. Tens of thousands of line-kilometers of data, flown in typical real-world exploration survey con-

Editor's Note: Several new systems have been recently developed for acquiring airborne gravity data and airborne gravity gradiometry data. Therefore, the Meter Reader is currently running a series of articles that feature all commercial systems now available to the exploration industry. This is the third article in this series.

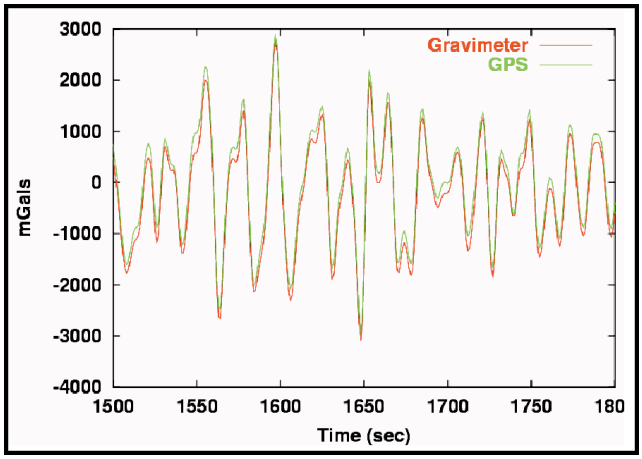

Figure 1. Comparison of GPS-derived vertical acceleration and vertical acceleration measured by gravity meter (6-s Gaussian filter applied).

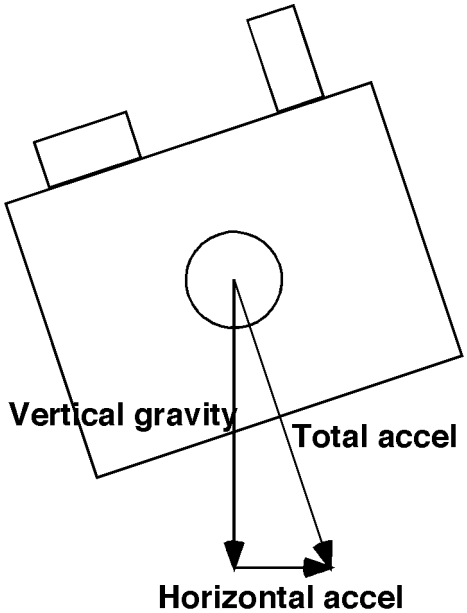

Figure 2. Effect of horizontal acceleration on leveling of gravity meter platform.

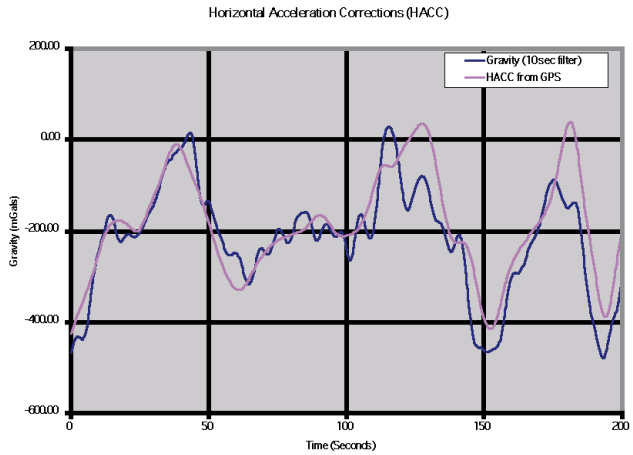

Figure 3. Horizontal acceleration correction.

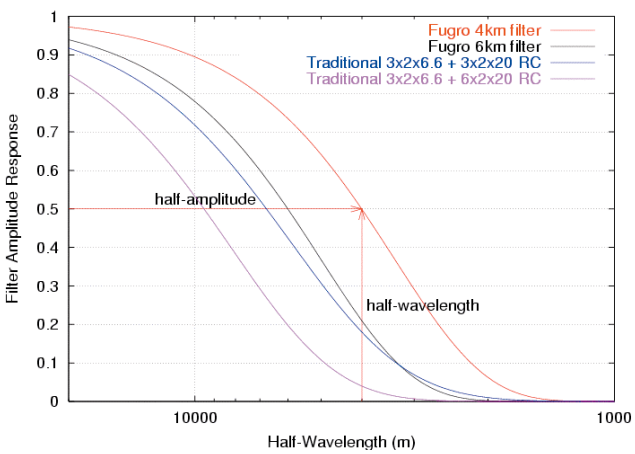

Figure 4. Gaussian and RC filter comparison (assuming aircraft speed of 100 knots). Half-amplitude and half-wavelength points are noted for 4-km filter.

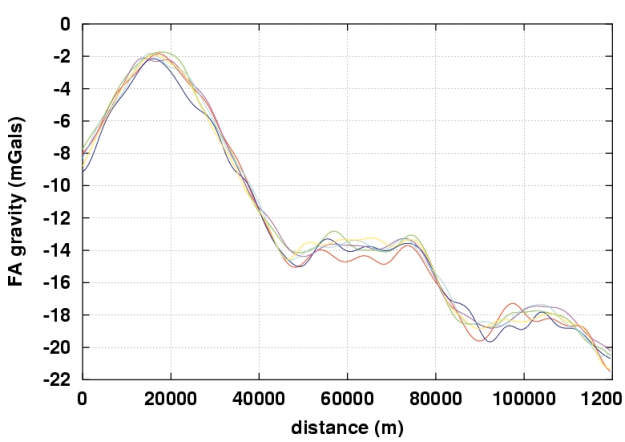

Figure 5. Data from six flights of a single line.

ditions (rather than waiting for ideal weather for flying) were collected, processed, and analyzed over four years prior to the first commercial airborne gravity survey in 1995.

The system uses a Lacoste & Romberg dynamic gravity meter upgraded to the ZLS UltraSys system. The ZLS model is a digital upgrade of L&R's widely tested and proven gravity meter sensor. These meters use the latest generation air dampers to minimize crosscoupling effects.

A unique three-stage vibration isolation platform was developed as a result of extensive vibration testing at the Boyd More Research Laboratory. The testing revealed a wide range of significant vibration effects on the gravity meter sensor, at both long and short periods, which have been eliminated by careful attention to platform mounting.

The gravity meter clock is synchronized to GPS time at the beginning of each flight and kept in synchronization (equivalent of 1 ms drift in 32 years) by an extremely stable rubidium oscillator. The large amplitudes and short periods of aircraft vertical accelerations make tight synchronization of gravity and GPS data a necessity.

GPS data are collected using geodetic-quality dual-frequency receivers. The system logs full carrier phase (required for maximum accuracy), dual-frequency (required for ionospheric effect removal) raw GPS data for up to nine satellites.

Data processing. In keeping with the philosophy of measuring acceleration effects and system noise and then correcting rather than overfiltering, the system uses independently measured aircraft accelerations derived from high-precision GPS navigation.

The use of extremely accurate GPS navigation allows removal of the major first-order noise sources in airborne gravity, namely aircraft vertical accelerations and the Eötvös effect (Figure 1).

With these effects removed, system developers were able to concentrate on modeling and removing subtler effects, such as horizontal acceleration, and extended- and long-period crosscoupling. The effect of horizontal acceleration on the gravity meter system can be most easily visualized by imagining that the stabilized platform control acts like a damped pendulum with its swing centered around the direction of maximum acceleration. In the absence of horizontal acceleration, this direction is vertical; however, as shown in Figure 2, in the presence of horizontal acceleration near the platform's resonant pendulum period, the total acceleration vector is no longer vertical and the platform control loops generate a tilt. The platform tilt affects the meter reading in two ways: The measurement is too small by a factor of $g(1 - \cos\theta)$, and it contains a resolved component of the horizontal acceleration $x \sin\theta$. To calculate horizontal acceleration corrections, Fugro developed a proprietary algorithm which uses the differential equation of the platform servo loop to calculate predictions of platform tilt as a function of vehicle acceleration history. Knowledge of the platform tilt enables accurate computation of both components of the off-level error (Figure 3).

These more subtle effects have traditionally been dealt with by applying a series of RC (resistor-capacitor) filters which can greatly attenuate or even eliminate signals at wavelengths of geologic interest. RC filters have long been used in dynamic gravity because of their simplicity in both analog and digital forms. In the modern dynamic gravity world of high-rate sampling and digital signal postprocessing, the disadvantages of relatively slow rolloff and substantial phase distortion have made RC filters obsolete. Figure 4 shows the advantage gained from the "model, measure, and correct—don't overfilter" approach in terms of less anomaly attenuation at short wavelengths.

The traditional filter descriptions 3×2×6.6 means 3 passes of two-way RC filtering and a 6.6-s time constant; 3×2×6.6 + 3×2×20 is a cascade of 3×2×6.6 followed by 3×2×20. RC time-constant filter responses are converted to half-wavelength assuming an aircraft speed of 100 knots.

The ability to use shorter time-based filtering minimizes

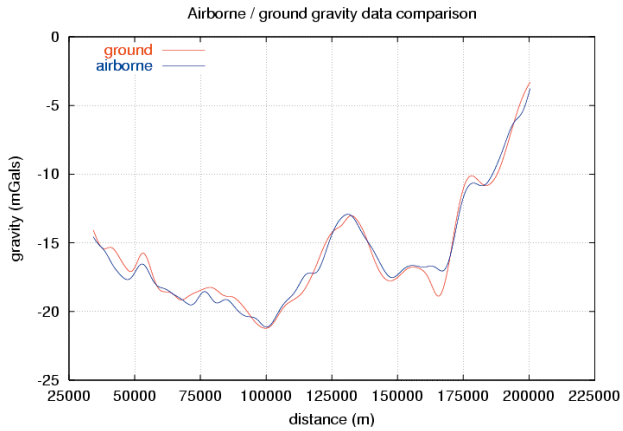

Figure 6. Comparison of air and ground gravity.

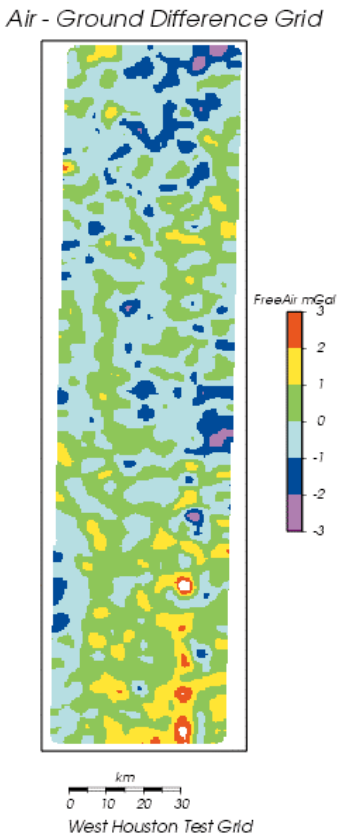

Figure 7. Air-ground difference grid.

reliance on extremely slow aircraft speeds to produce a desired spatial resolution. A spatial resolution of 4 km (half-wavelength, half-amplitude) can be achieved at an 80-knot survey speed using a 97-s filter or at a 120-knot survey speed using a 65-s filter. We have found that a survey speed of 100 knots will be more cost-effective and will give a greater margin of aircraft safety. In addition, proper modeling and correction of long-period crosscoupling effects allows for a survey layout requiring fewer tie-lines. The long-wavelength accuracy of the system is reinforced by the use of global geoid models to correct GPS-provided ellipsoidal elevations (relative to the WGS84 ellipsoid) to geoidal elevations (relative to sea level), thereby removing a potential long-wavelength error source (several mGal over tens of kilometers) in the free-air correction. This is particularly important when airborne gravity data are to be merged with ground or marine gravity data, which are processed using geoidal elevations.

Resolution and accuracy. The system has been tested over a ground gravity test range in a petroleum exploration area. Resolution and accuracy have been evaluated using three independent analysis methods—two evaluating internal consistency by flying repeat lines and assessing crossover errors and one evaluating external consistency by comparing airborne data with ground truth.

The half-amplitude, half-wavelength point of the processing filters is used as the resolution measure. This means that a gravity anomaly (approximated as a half-cycle of a sine wave) of the quoted resolution width, for example 6

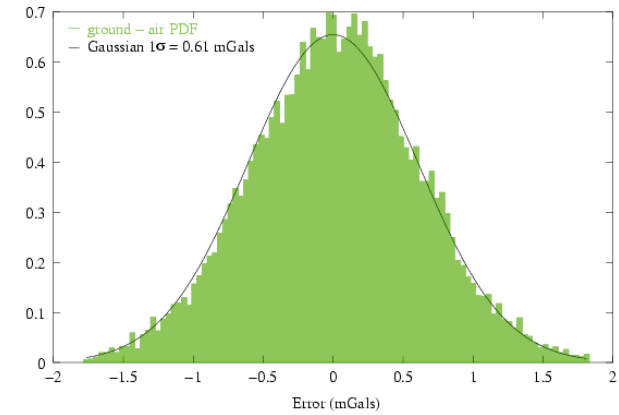

Figure 8. Histogram of ground-air difference.

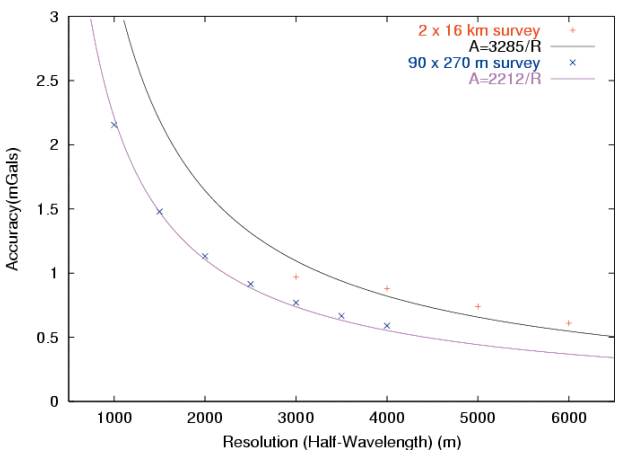

Figure 9. Resolution-accuracy tradeoff.

km, would be attenuated to half its original amplitude after final processing. The test survey was flown at an elevation of 610 m with a spacing of 2 km for flight lines and 16 km for tie-lines. In order to mimic real-world exploration conditions, data were acquired in turbulence ranging from very calm to conditions when it was very unpleasant to be on the aircraft.

The ground gravity data set consists of approximately 11 500 nearly uniformly distributed stations in a 165 × 50 km area (1.4 stations/km^2). Ground data were upward continued to the flight height for comparison purposes, but no further filtering was applied.

As part of the evaluation testing, a single flight line was flown multiple times to test the system repeatability. Figure 5 shows results of six repeats of this line. These data have been filtered to 6 km (half-wavelength, half-amplitude) resolution, not averaged. The standard deviation of these repeats around the mean profile is 0.66 mGal.

An additional measure of internal accuracy was provided by crossover errors produced from a map survey using tie and traverse lines. The rms crossover error (101 crossovers) before adjustment with 6-km filtering corresponds to a single-measurement accuracy of 0.69 mGal. This emphasizes the lack of long-wavelength drift errors in the system, which allows survey design with much wider tie-line spacing—improving survey economics.

Figure 6 is an example profile comparison of ground and airborne gravity data. With 6-km filtering, the standard deviation of the airborne data around the (unfiltered) ground data is 0.69 mGal. The ground and airborne data sets have been gridded at a 500-m interval for comparison (Figure 7).

This shows that the system has ± 1 mGal difference between ground and airborne data in more than 95% of the grid. A histogram of the map error between ground and airborne (Figure 8) shows an excellent fit with a Gaussian distribution, standard deviation 0.61 mGal.

In short, all internal and external evaluation methods give essentially the same answer—data accuracy of 0.6 mGal with a spatial resolution of 6 km.

A recent airborne survey, conducted over a rugged area in South America, provided an opportunity to evaluate the potential data quality improvement from flying closely spaced lines. At the client's specification, the survey was flown with a spacing of 90 m for flight lines and 270 m for tie-lines. The resulting profile data was gridded using a range of target resolutions, with accuracies calculated using the crossover errors of the input lightly filtered (250-m half-wavelength) profile data and the gridding weights. The resolution/accuracy trade-off for these data are plotted in Figure 9, together with the trade-off curve for widely spaced lines (2 × 16 km).

Conclusions. The Fugro airborne gravity system is aircraft-independent, uses reliable L&R gravity sensors, and has minimal tie-line requirements and corrections that minimize the need for extreme flight stability.

Tests indicate the system provides high-quality, minimally filtered data that have been verified by three independently measured methods. The test data were acquired in real exploration survey conditions.

Internal and external evaluations have quantified these improvements over salt domes and thick sediments in the petroleum environment. Internal evaluation consistent of six nonaveraged repeated lines and 101 network crossovers, along with external evaluation consistent of ground gravity comparison, results in an accuracy of approximately 0.6 mGal with 6-km half-wavelength, half-amplitude resolution.

Suggested reading. "Tests of an airborne gravity-meter" by LaCoste and Harrison (GEOPHYSICS, 1960). "Some theoretical considerations in the measurement of gravity at sea" by LaCoste and Harrison (*Geophysical Journal of the Royal Astronomical Society*, 1961).

Acknowledgments: The ground gravity data set was donated by Conoco for use in airborne gravity data evaluation. Due to contractual obligations, we cannot show the actual ground gravity data.

Corresponding author: jmacqueen@lct.com