

A Comparison of Stable Platform and Strapdown Airborne Gravity

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Abstract. To date, operational airborne gravity results have been obtained using either a damped two-axes stable platform gravimeter systems such as the LaCoste and Romberg (LCR) S-model marine gravimeter or a strapdown inertial navigation system (INS), showing comparable accuracies. In June of 1998 three flight tests were undertaken which tested a LCR gravimeter and a strapdown INS gravity system side-by-side. To our knowledge this was the first time such a comparison flight was undertaken. The flights occurred in Disko Bay, off the west coast of Greenland. Several of the flight lines were partly flown along existing shipborne gravity profiles to allow for an independent source of comparison of the results.

This paper presents the results and analysis of these flight tests. The measurement method and error models for both the stable platform and strapdown INS gravity systems are presented and contrasted. The results of the flight tests show that the gravity estimates from the two systems agree at the 2-3 mGal level, after the removal of a linear bias. This near the combined noise levels of the two systems. It appears that a combination of both systems would provide an ideal airborne gravity survey system; combining the excellent bias stability of the LCR gravimeter with the higher dynamic range and increased spatial resolution of the strapdown INS.

Keywords. Airborne gravimetry, gravimeter, strapdown inertial navigation system (SINS)

(1994), Brozena et al. (1997) and Bastos et al. (1998). Over the years these systems have been improved and are now showing an airborne gravity estimation accuracy at the 2-3 mGal level. The excellent results reported with the LCR gravimeters have made them the established method for airborne gravity disturbance determination. In the past four years successful airborne gravity flights have also been accomplished using a strapdown INS/DGPS system, see Wei and Schwarz (1998) and Glennie and Schwarz (1999). The strapdown system has shown the same level of gravity estimation accuracy as the LCR systems, but using significantly shorter averaging times. However, it is difficult to directly compare the results obtained by the two systems because the test conditions are seldom comparable. It is therefore desirable to fly the two systems side-by-side to provide a direct method of comparison.

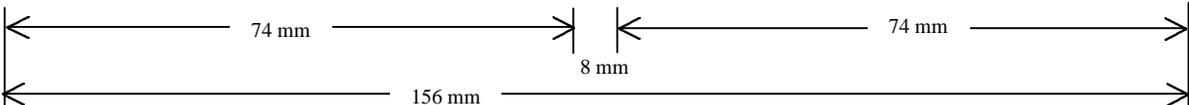
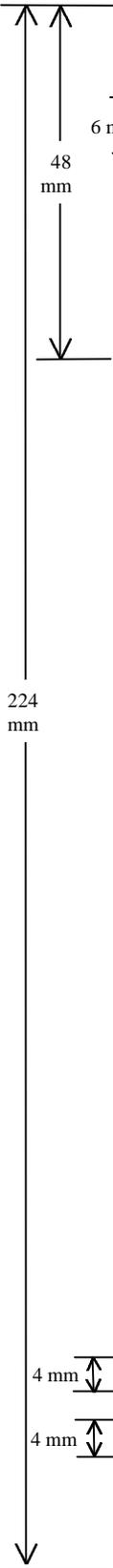
The prototype strapdown INS/DGPS system developed at The University of Calgary consists of a Honeywell Laseref III (LRF III) inertial system. This is a navigation grade strapdown system with stand-alone performance of 1.0 nm/h. The LRF III contains QA-2000 accelerometers and GG1342 dithered ring laser gyroscopes.

The modified LCR air/sea gravimeter is a highly damped spring gravity sensor mounted on a two-axes stabilized platform. The major difference between the use of this platform system and a strapdown INS system is the maintenance of a direction in space (i.e. orientation). For the strapdown system the relationship between the body frame and the local-level frame is computed by numerically integrating the output of the gyroscopes. For a platform system, alignment with the local-level frame is realized mechanically by using the output of horizontal accelerometers and gyroscopes in a feedback loop. The feedback loop normally has a user selectable damping period of 4 to 18 minutes, Valliant (1992). In general, the

1 Introduction

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The use of a LaCoste and Romberg S-model marine gravimeter for airborne gravity surveys has been well documented in the past seven years, see for example Brozena (1992), Forsberg and Kenyon



longer the damping period, the greater the reduction in error due to horizontal accelerations.

In addition to having entirely different methods of orientation control, the strapdown INS system and the LCR gravimeter also use significantly different methods of vertical specific force measurement. The QA 2000 accelerometers in the LRF III measure acceleration using quartz flexure suspension technology. Essentially, acceleration is measured by the displacement of a proof mass that is pendulously supported with only one degree of freedom. The acceleration sensed is proportional to the restoring force required to keep the proof mass in the null position. More details on the principle behind the QA accelerometer can be found in Foote and Grindeland (1992).

The vertical acceleration sensed by the LCR gravimeter is based upon the zero-length spring principle. The beam of the system is overdamped, and acceleration is determined by a combination of spring tension S , and beam velocity v_b , using the equation (Olesen et al. (1997)):

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$$\longrightarrow f_u = S + K v_b \quad (1)$$

where K is a scale factor which is determined by laboratory calibration or in-flight through a regression technique. The beam is kept roughly at the center of its dynamic range (null position) by adjustment of the spring tension. The spring tension can be automatically adjusted or manually set by the user. More details on the zero-length spring gravimeter can be found in Valliant (1992) or LaCoste (1988).

Our objective in this paper is to compare these two different methods of airborne gravity disturbance determination. In the next section the mathematical formulations and error models for each approach are given and contrasted. Following that a comparison of the two systems flown side-by-side in an actual flight test is given.

2 Mathematical Models for Airborne Gravity

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2.1 Airborne Gravity by Strapdown INS/DGPS

In the local-level frame the model of airborne gravimetry can be expressed by Newton's equation of motion in the gravitational field of the earth.

When considering scalar gravimetry, only the vertical component of this equation is required. The equation can be rearranged for gravity disturbance determination, and is of the form:

$$d\mathbf{g} = f_u - \dot{v}_u + \left(\frac{v_e}{R_n + h} + 2\mathbf{w}_e \cos \mathbf{f} \right) v_e + \frac{v_n^2}{R_m + h} - \mathbf{g} \quad (2)$$

where f_u is the upward component of specific force (from INS), v_e , v_n , v_u are the east, north and up components of the vehicle velocity (from GPS), R_m , R_n are the meridian and prime vertical radii of curvature, φ , h are geodetic latitude and height, \mathbf{w}_e is the earth rotation rate, and \mathbf{g} is normal gravity. A detailed derivation of this formula can be found in Schwarz and Wei (1997). The sum of the third and fourth terms in equation (2) is often called the Eötvös correction. This approach has become known as SISG (Strapdown Inertial Scalar Gravimetry).

A first-order error model for the SISG approach to airborne gravity can also be obtained. The error model of SISG has been derived in, for example, Schwarz and Wei (1994) and Schwarz and Li (1996), and is given as:

$$d\mathbf{dg} = f_e \mathbf{e}_N - f_n \mathbf{e}_E - \mathbf{A} d\mathbf{f}^b - d\dot{v}_u + (\dot{\mathbf{A}} \mathbf{f}^b + \mathbf{A} \dot{\mathbf{f}}^b) dT \quad (3)$$

where \mathbf{A} and $\dot{\mathbf{A}}$ are row matrices of the form

$$\mathbf{A} = [-\cos q \sin f \quad \sin q \quad \cos q \cos f] \quad (4a)$$

$$\dot{\mathbf{A}} = \begin{bmatrix} \dot{q} \sin q \sin f - \dot{f} \cos q \cos f \\ \dot{q} \cos q \\ -\dot{q} \sin q \cos f - \dot{f} \cos q \sin f \end{bmatrix}^T \quad (4b)$$

and f , q are the roll and pitch angles of the transformation from the body frame to the local-level frame, dT is a synchronization error between the INS and GPS data streams, \mathbf{f}^b and $d\mathbf{f}^b$ are the specific force vector and the error in the specific force vector respectively, $d\dot{v}_u$ is the error in vertical GPS acceleration, f_e , and f_n are the east and north specific force measurements and \mathbf{e}_N and \mathbf{e}_E represent misalignment in the north and east directions. The dot above a quantity denotes time differentiation.

It should be noted that another method of gravity disturbance determination call RISG (Rotation Invariant Scalar Gravimetry) has also been tested for

the strapdown INS system, see Wei and Schwarz gravimeter. However, the actual synchronization error (i.e. value of dT) would be system dependent.

The strapdown INS system and the LCR gravimeter system have significant differences in orientation maintenance and acceleration measurement techniques. These differences are made evident by trying to relate the error models of the two approaches. Therefore, a flight test with the two systems operating side-by-side allows a unique opportunity to compare the two methods for consistency, and additionally to try to detect and eliminate design specific errors in each system. In the June 1998 test, for the first time, the two systems have been flown side-by-side.

3 Test Description

The Danish National Survey and Cadastre (KMS), and The University of Calgary undertook an airborne gravity test on June 6, 8, and 9 of 1998 in the Disko Bay area off the west coast of Greenland. The test was at the beginning of a larger airborne gravity survey campaign off the north coast of Greenland (Forsberg et al. (1999)). The major purpose of this flight test was a comparison of existing airborne gravity measurement systems, as well as a testing period for the LCR gravimeter in preparation for the north Greenland survey.

For the June 1998 test three airborne gravity systems were flown: a strapdown INS/DGPS system, a LaCoste and Romberg (LCR) modified 'S' type air/sea gravimeter, and an orthogonal triad of QA 3000 Q-Flex accelerometers. The strapdown INS system is the Honeywell Laseref III owned by Intermap Technologies Ltd. of Calgary, Canada. This strapdown system has been flight tested for airborne gravity determination twice by The University of Calgary, see Wei and Schwarz (1998) and Glennie and Schwarz (1999). The LCR gravimeter is owned by the University of Bergen, Norway and previously has been successfully flown in campaigns for the AGMASCO (Airborne Geoid Mapping System for Coastal Oceanography) project, see Hehl et al. (1997) and Bastos et al. (1998). The Q-Flex triad was developed by Dr. G. Boedecker at the Bavarian Academy of Sciences, Munich in cooperation with the AGMASCO project. The results from the Q-Flex triad will be reported elsewhere.

The three independent systems were mounted in a Twin Otter airplane. Two dual frequency GPS antennas were mounted on the fuselage of the aircraft. The front antenna was attached to a Trimble 4000 SSI receiver, while the rear antenna signal was split between another Trimble 4000 SSI and an Ashtech Z-XII receiver. The Ashtech receiver was required to provide time synchronization for the strapdown INS. Three days of testing were undertaken. The flight patterns for the three days are shown in Figure 1. For the first flight (June 6th) master GPS stations were located at Kangerlussuaq and Ilulissat (see Figure 1). Data for the Q-Flex unit was not collected on the first day. For June 8th and 9th, master GPS stations were located at Kangerlussuaq, Ilulissat and Aasiaat. The master stations at Kangerlussuaq and Aasiaat were equipped with Trimble 4000 SSI receivers while the Ilulissat site was occupied with an Ashtech Z-Surveyor receiver. All flights were performed during the afternoon (local time) over the ocean. Average flight heights were approximately 300 metres, with an average flight velocity of approximately 70 m/s.

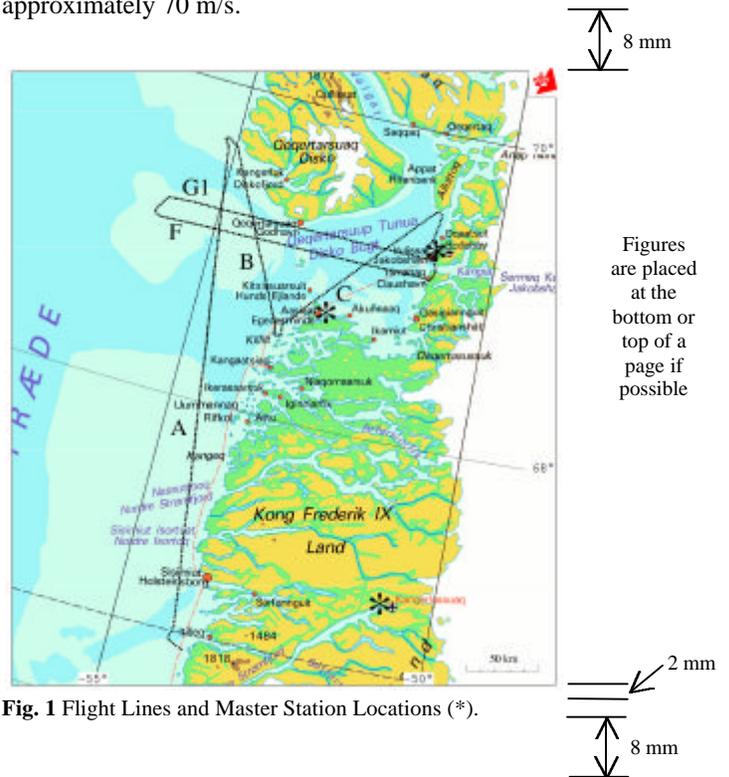


Fig. 1 Flight Lines and Master Station Locations (*).

To provide an independent reference, four flight lines were flown over top of existing shipborne gravity data profiles, one on June 6, one on June 8, and two on June 9.

4 Test Results

Hardware problems plagued this initial test. The LCR gravimeter was affected by data loss and communications malfunctions that gave rise to occasional outages of data. It was later isolated as being due to power supply problems. Additionally, on the third day of testing a brief power problem in the airplane caused a malfunction of the strapdown INS data-logging computer. As a result, there is no strapdown inertial data available for the third day and therefore only the first two days of testing will be reported on. A total of five flight lines were flown for the first two days of testing. These lines will be denoted by A, B, C (June 6th) and F and G1 (June 8th), see Figure 1. Flight lines A and G1 were partly flown over top of existing shipborne gravity profiles, and therefore an independent reference is available for these lines.

In order to provide a common basis of comparison for the two system estimates similar filtering operations must be applied to each. The data processing scheme for the LCR gravimeter employs a 2nd order Butterworth low-pass filter with a cut-off frequency of 0.005 Hz, or a full-wavelength period of 200 seconds. For this flight test this corresponds to a spatial resolution of 6 km (half-wavelength). The LRF III gravity estimates were also low-pass filtered to the same cut-off frequency. It should be noted that the identical filter was not used, only the same cut-off frequency. Therefore, distortion due to transfer function differences between the two filters may cause discrepancies in the results. However, it is expected that this effect will be negligible compared to the overall system errors.

The same DGPS position estimates were used to determine aircraft kinematic acceleration for both systems. Obviously, the position estimates must be differentiated twice to determine acceleration. KMS uses a first-order Taylor Series central difference approximation to differentiate the data. The U of C acceleration estimate is computed using a low-pass FIR differentiating filter. Bruton et al. (1999) describe and compare these two methods of differentiation. The conclusion in this reference is that the above two methods are nearly equivalent for the frequency band of interest in airborne gravity.

Therefore, differences in the estimates between the LCR and the LRF III systems should represent the combined noise levels of the two systems' specific force estimates plus any differences due to lever arm

effects (due to different measurement origins). In order to compensate for the lever-arm effect the offset between the LCR and LRF III was used along with the strapdown INS angular velocities to compute a lever arm velocity. This velocity was then differentiated to compute a relative lever-arm acceleration that was subsequently low-pass filtered to 200 seconds. The filtered lever-arm acceleration corrections were then applied to the LRF III data.

The results of the comparison between the LCR and the LRF III estimates for all five flight lines are displayed in Table 1. The RMS of the differences was computed, and therefore, these values are divided by $\sqrt{2}$ to get an idea of the standard deviation (σ) for each measuring unit, assuming the systems have the same accuracy. It should also be noted that a linear bias has been removed between the two system estimates. The linear biases have a slope of approximately 0.01 mGal/s. This linear bias is due mostly to the behaviour of the accelerometer biases for the LRF III strapdown INS system, see Glennie (1999).

Table 1. Comparison of LCR and LRF III Gravity Estimates, in mGal ($T_c = 200$ sec)

Flight line	RMS	σ
A	2.4	1.7
B	3.0	2.1
C	1.4	1.1
F	7.7	4.4
G1	4.0	2.9

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The LCR gravimeter showed a very stable bias behaviour. Table 2 shows the RMS crossover errors for the LCR before and after applying a constant bias for each flight track for all three days of testing, based on a total of 15 crossovers. The small value of the crossover errors indicates LCR accuracies below 2 mGal, and illustrates the long-term stability of the spring gravimeter system. However, it should be noted that the low RMS after the bias adjustment is likely too optimistic due to the small number of crossovers. For all three days, a comparison of the LCR estimates to available ground truth yielded an overall RMS difference of 3.1 mGal for the unadjusted data set.

Two of the flight lines common to both systems during the Greenland test (A and G1) were partly

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