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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-axis stable platform gravimeter system such as the LaCoste and Romberg (LCR) S-model marine gravimeter or a strapdown inertial navigation system (INS), showing comparable accuracies. In June 1998 three flight tests were undertaken which tested an LCR gravimeter and a strapdown INS gravity system side by side. To the authors' 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. The results and analysis of these flight tests are presented. The measurement method and error models for both the stable platform and strapdown INS gravity systems are presented and contrasted. An intercomparison of gravity estimates from both systems is given, along with a comparison of the individual estimates with existing shipborne gravity profiles. 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 is near the combined noise level 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.

Key words: Airborne gravimetry – Strapdown gravity system – Analysis of flight tests – DGPS/INS integration

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1 Introduction

The use of a LaCoste and Romberg (LCR) S-model marine gravimeter for airborne gravity surveys has been well documented in the past 7 years (see e.g. Brozena 1992; Forsberg and Kenyon 1994; Brozena et al. 1997; 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 LCR gravimeters have made them the established method for airborne gravity disturbance determination. In the past 4 years successful airborne gravity flights have also been accomplished using a strapdown inertial navigation system (INS) together with differential GPS (DGPS), see Wei and Schwarz 1998; Glennie and Schwarz, in press. 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-axis 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 min (Valliant 1992). In general, the 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 following equation (Olesen et al. 1997):

$$f_u = S + Kv_b \tag{1}$$

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 centre 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

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

$$\delta g = f_u - \dot{v}_u + \left(\frac{v_e}{R_n + h} + 2\omega_e \cos\varphi\right) v_e + \frac{v_n^2}{R_m + h} - \gamma \tag{2}$$

where f_u is the upward component of specific force (from INS); v_e, v_n and v_u are the east, north and up components of the vehicle velocity [from the global positioning system (GPS)]; R_m and R_n are the meridian and prime vertical radii of curvature; ϕ and h are geodetic latitude and height; ω_e is the Earth's rotation rate; and γ 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 Eq. (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

$$d\delta g = f_e \varepsilon_N - f_n \varepsilon_E - \mathbf{A}\mathbf{df}^b - d\dot{v}_u + \left(\dot{\mathbf{A}}\mathbf{f}^b + \mathbf{A}\dot{\mathbf{f}}^b\right) dT \tag{3}$$

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

$$\mathbf{A} = [-\cos\theta \sin\phi \quad \sin\theta \quad \cos\theta\cos\phi] \tag{4a}$$

$$\dot{\mathbf{A}} = [\dot{\theta}\sin\theta\sin\phi - \dot{\phi}\cos\theta\cos\phi \quad \dot{\theta}\cos\theta \quad -\dot{\theta}\sin\theta\cos\phi - \dot{\phi}\cos\theta\sin\phi] \tag{4b}$$

ϕ and θ 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 $\mathbf{df}^b$ are the specific force vector and the error in the specific force vector respectively; $d\dot{v}_u$ is the error in vertical global positioning system (GPS) acceleration; f_e, and f_n are the east and north specific force measurements; and ε_N and ε_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 called RISG (rotation invariant scalar gravimetry) has also been tested for the strapdown INS system (see e.g. Wei and Schwarz 1998). This approach uses only the output of the orthogonal accelerometer triad for gravity disturbance determination. However, previous investigations have shown that the SISG approach consistently performs better than RISG. Therefore, in the following only the SISG results for the strapdown INS system are presented. For a detailed discussion of the RISG approach the reader is referred to Glennie (1999).

2.2 Airborne gravity using the LCR model S gravimeter

In principle, Eq. (2) for the SISG determination of gravity disturbances applies to the LCR gravimeter as well. However, differences arise in the gravity disturbance estimation due to differences in the nature of attitude control and measurement of vertical specific force. As a result, two additional correction factors are applied on the right-hand side of Eq. (1) for the LCR measurements. These factors are: c_{cc}, cross-coupling and beam position corrections, and c_{tilt}, correction due to platform misalignment. The cross-coupling errors arise due to the method of vertical specific force measurement used. Essentially, the horizontal accelerations experienced by the platform cross-couple into the vertical specific force output whenever the vertical accelerometer beam is not in the null position. The formula for the cross-coupling correction is given in Valliant (1992) as

$$c_{cc} = a_1 v_b^2 + a_2(f_y p_b) + a_3(f_x v_b) + a_4(f_y v_b) + a_5(f_x^2 v_b) \tag{5}$$

where, a_1, $a_2, \ldots a_5$ are statistically or empirically determined coefficients, v_b is the beam velocity; p_b is the beam position; and f_x and f_y are the cross-track and along-track accelerometer measurements. The general method used to determine the coefficients is described in Valliant (1992). Once estimated, the cross-coupling coefficients are considered to be instrument constants. Typical values for the cross-coupling correction, after low-pass filtering (normally to $T_c = 200$ s), are 1–5 mGal, although it can be as high as 25 mGal in higher dynamics.

The tilt correction to the LCR gravity estimates is necessary due to the method of platform stabilization. As a result of the damped horizontal feedback applied in the LCR meter, the platform may become significantly off-level, especially right after turns (i.e. periods of higher horizontal accelerations). This misalignment can be estimated by comparing the horizontal accelerometer output to DGPS-determined horizontal accelerations using the formula (Olesen et al. 1997)

$$c_{tilt} = \frac{f_x^2 + f_y^2 - \alpha_e^2 - \alpha_n^2}{2g} \tag{6}$$

where α_e and α_n are kinematic aircraft acceleration in the east and north directions, and g is the magnitude of gravity. Care must be taken when applying the tilt factor due to the non-linearity of this correction.

In order to compare the error sources for the LCR gravimeter and strapdown inertial gravimetry, a first-order error linearization of Eqs. (2), (5) and (6) is performed, giving

$$\begin{aligned} d\delta g = {} & df_u - d\dot{v}_u + \frac{f_x}{g} df_x + \frac{f_y}{g} df_y - \frac{\alpha_e}{g} d\alpha_e - \frac{\alpha_n}{g} d\alpha_n \\ & + (a_3 v_b + 2a_5 f_x v_b) df_x + (a_2 p_b + a_4 v_b) df_y \\ & + (2a_1 v_b + a_3 f_x + a_4 f_y + a_5 f_x^2) dv_b \\ & + (a_2 f_y) dp_b - v_b^2 da_1 + f_y p_b da_2 + f_x v_b da_3 \\ & + f_y v_b da_4 + f_x^2 v_b da_5 \end{aligned} \tag{7}$$

where da_1, da_2, ... da_5 are errors in the coefficients, dv_b is the beam velocity error, and dp_b is the beam position error. All other terms have been previously defined. Equations (3) and (7) show that DGPS vertical acceleration errors have an identical effect on the SISG and LCR gravity estimates. The remaining errors on the first line of Eq. (7) are similar to those for the RISG approach to airborne gravity. In general, the RISG error behaviour has been shown to be quite similar to that of the SISG method (Glennie 1999), and therefore it can most likely be concluded that the first line of Eq. (7) will give similar error characteristics to the first four terms in Eq. (2). However, it is important to note that the horizontal accelerometers of the platform system are of lower quality than the vertical one, and therefore horizontal accelerometer errors are a significant source of gravity disturbance error for the LCR system. In examining the other errors in Eq. (7), it is difficult to relate them to either the RISG or SISG approach to strapdown airborne gravity. Of the remaining terms in Eq. (7), the most significant appear to be due to errors in beam velocity and errors in determining the cross-coupling coefficients. It should also be noted that a time synchronization error has not been included in Eq. (7). In principle, the term due to time synchronization error should be identical between the SISG approach and the LCR 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, the two systems were flown side by side for the first time.

3 Test description

The Danish National Survey and Cadastre (KMS), and the University of Calgary undertook an airborne gravity test on 6, 8 and 9 June 1998 in the Disko Bay area off the west coast of Greenland. The test occurred at the beginning of a larger airborne gravity survey campaign off the north coast of Greenland (Forsberg et al. in press). 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, an 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; Glennie and Schwarz in press). 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; 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 Fig. 1.

For the first flight (6 June), master GPS stations were located at Kangerlussuaq and Ilulissat (see Fig. 1). Data for the Q-Flex unit were not collected on the first day. For 8 and 9 June, 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 m, with an average flight velocity of approximately 70 m/s. In order to provide an independent reference, four flight lines were flown over the top of existing shipborne gravity data profiles, one on 6 June, one on 8 June, and two on 9 June. The accuracy of the ship data is estimated to be approximately 1 mGal or better.

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 are 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.

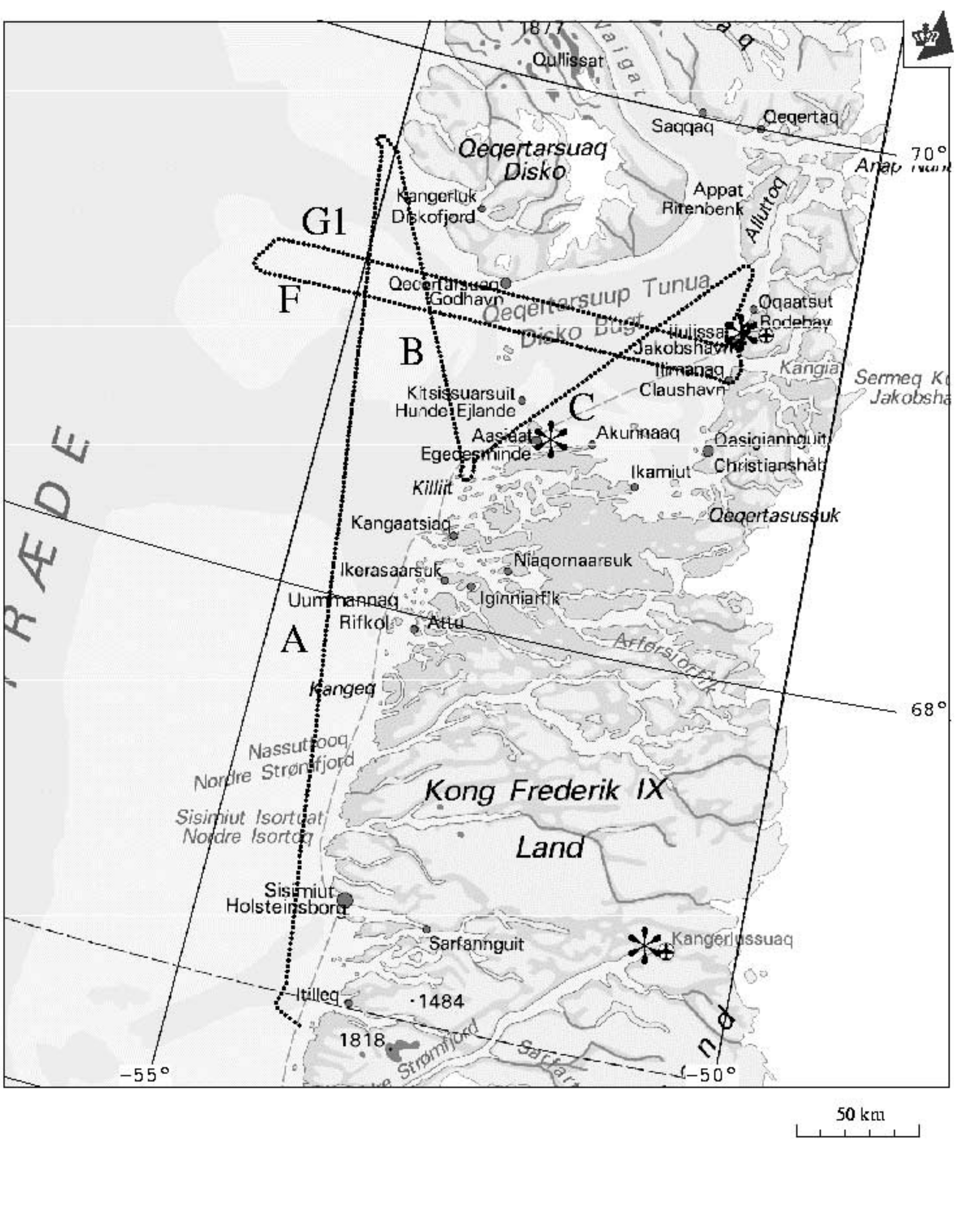

Fig. 1. Flight lines and master station locations (∗), June 1998 (Source: KMS)

These lines will be denoted by A, B, C (6 June) and F and G1 (8 June) (see Fig. 1). Flight lines A and G1 were partly flown over the 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 second-order Butterworth low-pass filter with a cut-off frequency of 0.005 Hz, or a full-wavelength period of 200 s. For this flight test this corresponds to a spatial resolution of 7 km (half-wavelength). The LRF III gravity estimates were also low-pass filtered to the same cut-off frequency. It should be noted that an 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 University of Calgary acceleration estimate is computed using a low-pass finite impulse response (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 s. 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 root mean square (RMS) of the differences was computed, and therefore these values are divided by $\sqrt{2}$ to obtain 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 (i.e. trend) 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).

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 to be 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 along existing shipborne gravity profiles. This allowed an independent check of the individual system estimates. Due to the low flight elevation an upward continuation of the ship measurements was not performed. The results of the comparison between the system estimates and the shipborne gravity are displayed in Table 3. Plots showing the individual system estimates and the reference are displayed in Figs. 2, 3 and 4 for flight lines A, F and G1 respectively. Note that a linear bias has been removed from the LRF III estimates.

For 6 June (lines A, B, C) the agreement between the LRF III and LCR estimates is quite good, with an average RMS difference of 2.3 mGal. This agreement appears to be close to the combined expected noise levels of the two measuring systems. Earlier crossover point results for the LCR system from the AGMASCO project yielded RMS differences of 2.3 mGal (Olesen et al. 1997), and the LRF III system showed a noise level of 1.6 mGal for crossover point results (Glennie and Schwarz in press). In addition, for flight line A, the LCR and LRF III estimates also agree quite well with the ship

Table 1. Comparison of LCR and LRF III gravity estimates, in mGal (T_c = 200 s)

Flight line	LCR vs LRF	
	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

Table 2. Crossover adjustment results for the LCR data

	RMS
Before adjustment	2.6
After bias adjustment	1.5

Table 3. Comparison of LCR and LRF III with reference, in mGal (T_c = 200 s)

Flight line	LCR	LRF III
A	1.7	2.0
G1	2.3	3.8

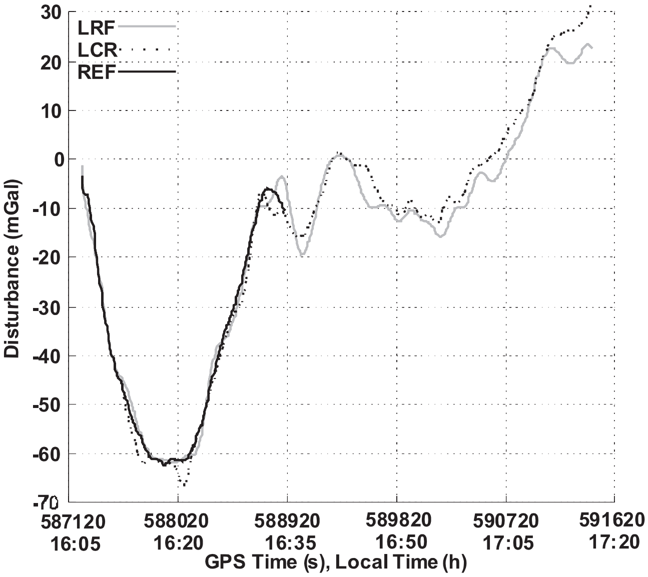

Fig. 2. Reference, LCR and LRF III estimates, line A, 6 June 1998 (T_c = 200 s)

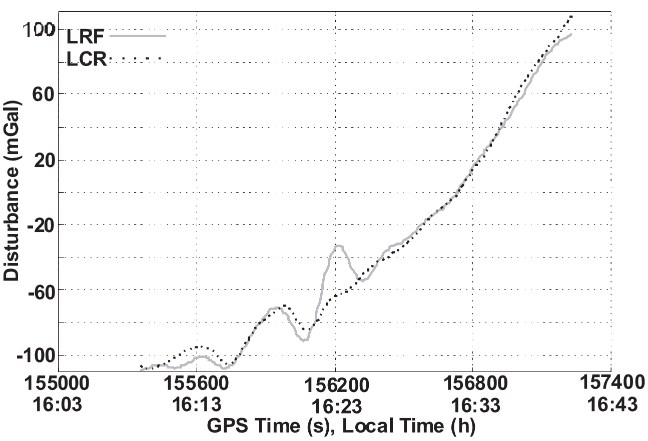

Fig. 3. LCR and LRF III system estimates, line F, 8 June 1998 (T_c = 200 s)

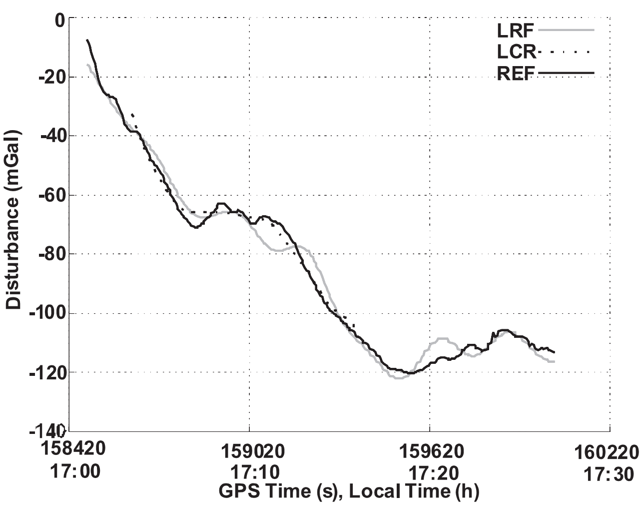

Fig. 4. Reference, LCR and LRF III estimates, line G1, 8 June 1998 (T_c = 200 s)

gravity reference. This excellent agreement is displayed in Fig. 2. Note that the LCR data is not available for the first five minutes of flight line A due to the earlier mentioned hardware problems.

The agreements between the system estimates for the second day (8 June, lines F and G1) are worse than those found for the first day. Figure 3 displays a graph of the LRF III and LCR gravity disturbance estimates for flight line F. The graph shows that the two estimates agree quite well in general, except for a three-minute period in the LRF III estimate at approximately 156 200 s. In fact, if this deviation is removed the RMS agreement between the two estimates is below 3.0 mGal, which is consistent with the 6 June results.

The estimates for flight line G1 are given in Fig. 4. Note that the LCR estimate is only available for approximately half of the flight line displayed, as some data at both ends had to be discarded due to hardware problems. The agreement between the LCR and the reference is quite good. However, the LRF III estimate shows two small jumps at approximately 159 150 and 159 650. Again, if these small jumps are ignored the LRF III and LCR estimates show the same level of agreement as 6 June.

A thorough investigation has yielded an explanation for the three jumps that show up in the estimates obtained using the LRF-III in flight lines F and G1. They are due to intermittent failures of the clock that was used to collect the raw data coming from that system. This is confirmed by examining Fig. 5, which shows the time intervals between measurements acquired using that faulty clock for line F on 8 June. Because the data rate of the LRF-III is 50.0 Hz, the time intervals shown in Fig. 5 should always be 0.02 s. This is clearly not the case. The most important irregularity shown in Fig. 5 is that which occurs at 156 200 and demonstrates a timing error of nearly 0.06 s. Recall from Fig. 3 that this corresponds exactly to the time period during which the solution provided by the LRF-III differs from that of the LCR. Similar jumps also occur at the two periods in line G1 where the results of these systems differ.

Efforts to interpolate the raw measurements during these periods were unsuccessful because the clock problem resulted in incorrectly time tagged data as well as missing data. However, it is reassuring to know that the differences between the LRF-III and the LCR can be easily identified in the current data sets and can be completely avoided in future missions.

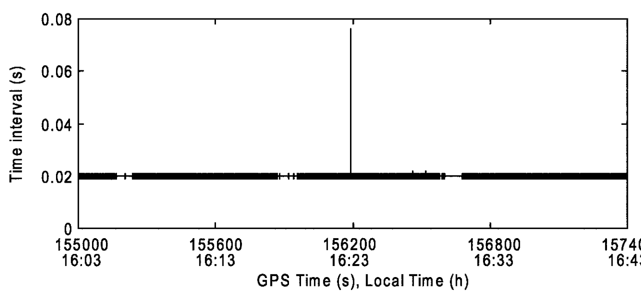

Fig. 5. An example of the data acquisition problem affecting the LRF-III data in line F, 8 June 1998

All results for the June 1998 test in Greenland were obtained using a low-pass filter with an averaging time of 200 s, corresponding to a half-wavelength spatial resolution of 6 km. This filtering period was used because the LCR data is normally filtered to this level. However, the strapdown INS estimates presented in other investigations (e.g. Wei and Schwarz 1998; Glennie 1999) showed very good results with 60-, 90- and 120-s filter lengths. Initially, these filtering periods were also used for the Greenland strapdown INS data. However, the results were significantly worse than those given in previous investigations. A detailed analysis has shown that the GPS data collected in Greenland were of significantly poorer quality than those obtained in other tests. For example, the typical size of the double-difference phase residuals was five to ten times larger and showed significant short- and long-term oscillations. The most likely source for this increase in the residual errors is high ionospheric activity during the test, as indicated by a geomagnetic observatory in Greenland.

5 Conclusions

Based on the analysis of profiles A, B and C (6 June) it can be concluded that the accuracy of relative gravity determination from the LRF III unit and the LCR gravimeter appears to be at the same level after the removal of a linear bias. An RMS agreement of approximately 2–3 mGal is obtained for all three lines. The three jumps in the LRF III results on 8 June (profiles F and G1) need further examination. To put them into perspective, they account for a total of about 9 out of 265 min of gravity profiles. This is considerably less than the total of 22 min of data that had to be discarded for the LCR system due to hardware problems. If the three jumps in the LRF III estimates are removed, then the agreement between the two systems for 8 June is at the same level as that for 6 June. It can therefore be concluded that the strapdown INS/DGPS approach to airborne gravity gives the same level of gravity-field information as the more established LCR gravimeter at all but the longest wavelengths. Combining the two measuring systems could give enhanced performance by stabilizing the long-term estimates of the strapdown INS with the gravimeter measurements until an INS unit with improved bias performance is realized.

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