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Airborne Gravimetry Survey for the Marine Area of the United Arab Emirates

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The Military Survey Department (MSD) of the United Arab Emirates (UAE) undertook an airborne gravity survey project for the marine area of the country in 2009, especially to strengthen the marine and coastal geoid in the near-shore regions. For the airborne gravity survey, 5 km spacing coast-parallel flight lines were planned and surveyed. These lines were supplemented by cross-lines in order to assess the quality of the airborne gravity surveys. The flight lines were extended 10 km, spacing lines further offshore. A Beech King Air 350 aircraft was used for the surveys, collecting data at a typical flight speed of 170 knots and a typical flight elevation of 900–1500 m, depending on weather conditions and topography. Gravity was measured with a ZLS-modified LaCoste and Romberg gravimeter (S-99), augmented with a Honeywell strap-down inertial navigation system unit. The estimated accuracy for the airborne gravity data is better than 2.0 mGal r.m.s., as judged from the airborne track crossovers. The new airborne gravimetry data changed the UAE coastal geoid by up to 30 cm in some regions, highlighting the importance of airborne gravity coastal surveys.

Keywords Airborne gravimetry, gravity anomaly, marine geoid

1. Introduction

Since the early 1990s, airborne gravity measurements have developed into a reliable production system to accurately measure the gravity field of the earth from aircraft. The development of airborne gravimetry has mainly been driven in the commercial domain by the need for accurate and high-resolution gravity anomaly mapping for oil, gas, and mineral exploration. Accuracies below 1 mgal are now reported for state-of-the-art systems (Williams and MacQueen 2001; Elieff and Ferguson 2008). In the government and
academic domain, long-range global positioning system (GPS)-based aerogravity for regional geophysics was pioneered by both U.S. and Russian researchers (Brozena 1992), and later implemented in smaller aircraft by several groups (Bell et al. 1992; Klingele et al. 1995). The dedicated applications for coastal geoid determination were developed in the late 1990s as part of both U.S. Arctic Ocean projects (Forsberg and Brozena 1996) as well as in the European Union project AGMASCO (Airborne Geoid Mapping System for Coastal Oceanography) (see Forsberg et al. 1996). The system setup and experience developed in the AGMASCO project have since been used extensively for small aircraft and long-range surveys in many different regions of the world (e.g., Olesen et al. 2000; Forsberg et al. 2007; Olesen and Forsberg 2007), and is also the base of the presented survey of the United Arab Emirates (UAE) coastal region in this paper.

The airborne gravity technology is important to the UAE because for most marine areas in the UAE, gravity data are sparse or not available at all (Alshamsi 2006). Consequently, the determination of a precise geoid model at centimeter level accuracy for the UAE region, in particular along the developed coastal area, has been hampered or made impossible by the lack of gravity data over the marine area. Precise knowledge of the geoid is of particular interest for GPS-leveling applications, coastal engineering, and in support of the future height modernization initiative of the country.

The UAE marine airborne project, which covered the marine area of the country, was implemented in two weeks during February 2009 using a Beech King Air 350 aircraft of the UAE Air Force. The compact aerogravity system developed by the National Space Institute of the Technical University of Denmark (DTU-Space), in cooperation with the University of Bergen, Norway, was used and installed in the King Air aircraft. The primary instrument used for measuring the gravity was a spring-type LaCoste and Romberg (LC&R) gravimeter (serial number S-99, modified by ZLS Corporation). This paper describes the implementation of airborne gravity survey operation, data processing, and analysis of the results, illustrating the relative ease with which such a project can be undertaken.
2. Airborne Gravimetry Concept

The basic principle of airborne gravimetry is depicted in Figure 1. The total acceleration $g^*$ at a point in the airplane is measured by a modified marine gravimeter and/or a high performance inertial-grade accelerometer triad. The total acceleration is composed of the Earth’s gravity field $g$ and accelerations $a$ related to the motion of the airplane relative to the Earth’s surface. Given the position of the airplane to any instant, it is possible to compute the acceleration $a$ and recover the gravity field $g$ at all positions.

The position of the airplane is obtained by kinematic carrier-phase differential GPS, where the combined observations from GPS receivers in the airplane and from a reference station in the area of interest make it possible to estimate the instantaneous position of the airplane with the required precision. The GPS positions determined by differentiation then give the acceleration $a$. The measurement of the vertical component of $g^*$ is done by the LCR gravimeter sensor, mounted on a damped two-axis gyro-stabilized platform. Off-leveling corrections for the tilt errors of this stabilized platform can be done by combining the horizontal components of $a$ with the horizontal components of $g^*$, as measured by horizontal accelerometers on the platform (for details see Olesen 2003).

The LCR&R gravimeter is a relative measurement instrument, and the airborne measurements are tied to ground gravity values through still base readings at the airport. This gives the gravity measurement at aircraft altitude as:

$$g = f_Z - \ddot{h} + \delta g_{Eotvos} + \delta g_{tilt} - f_{Z_0} + g_0$$  \hspace{1cm} (1)

where $f_{Z_0}$ is the corresponding base reading, $g_0$ is the airport gravity value, $f_Z$ is the airborne gravimeter reading, $\dot{h}$ is the vertical GPS acceleration, $\delta g_{Eotvos}$ is the Eötvös correction, and $\delta g_{tilt}$ is the off-level correction.

Eq. (1) can be used to recover the gravity, but because of the noise in the measurement of both gravity and GPS accelerations, it is necessary to apply a low-pass filter to Eq. (1). Because gravity $g$ varies strongly with height, gravity anomalies are in practice the fundamental output from airborne gravity. Either gravity disturbance (i.e., using GPS ellipsoidal heights) or classical (free-air) gravity anomalies (i.e., aircraft GPS heights are reduced for an a priori geoid, such as EGM08) can be used. For comparisons and merging of airborne data with existing data sets, gravity free-air anomalies are chosen to be the final product. The full reduction scheme for the airborne readings is given by the following fundamental equation:

$$\Delta g = f_Z - \ddot{h} + \delta g_{Eotvos} + \delta g_{tilt} - f_{Z_0} + g_0 - \left( \gamma_0 + \frac{\partial \gamma}{\partial h} (h - N_{EGM08}) \right)$$

$$+ \frac{\partial^2 \gamma}{\partial h^2} (h - N_{EGM08})^2$$  \hspace{1cm} (2)

Here $\Delta g$ is the derived free air gravity anomaly, $\gamma_0$ is the normal gravity, $h$ is the GPS ellipsoidal height, and $N_{EGM08}$ is the Earth Gravity Model 2008 geoid undulation. Note that second-order height effects must be taken into account in computing a sufficiently accurate free-air anomaly, except for surveys at low elevations (for details see Heiskanen and Moritz 1967).

Since the geoid depends on the gravity field, in principle the geoid model should be updated with the new gravity data. However, since the EGM08 geoid fits most parts of the world better than 20–30 cm (Pavlis et al. 2008), the error in the geoid gives an affect
below 0.1 mGal, much smaller than the accuracy of the airborne free-air anomalies, and can therefore be neglected.

3. UAE Airborne Gravity Data Acquisition

The survey equipment used are LC&R air-sea gravimeter S-99, a Honeywell H764G INS (inertial navigation system), and numerous geodetic GPS receivers. The LC&R systems record system data at 1 Hz. Combined with GPS and INS dynamics data, the DTU-Space processing scheme allows gravity anomalies to be recovered at resolutions of around 5 km, corresponding to low-pass filter half-widths of 60–90 sec, depending on air speed. The instrument outputs are recorded on a central data logger and either tagged or correlated with UTC from the GPS receivers. The primary role of the integrated INS/GPS navigation system (Honeywell H764G) is used for aircraft attitude determination (for GPS antenna offset correction), as well as an auxiliary gravity sensor, which will provide detailed aircraft dynamics data useful in improving gravity survey accuracy in turbulence.

The flights of the survey grid lines are guided by an onboard computer system using the onboard GPS receivers (several GPS units were used, including both Trimble 4000 SSI and Javad receivers), all collecting data at 1 Hz in internal memory. At least two ground receivers are placed at the airport location and one remote site in the operations area to collect ground reference data. Typical accuracy of the airborne GPS positioning results are around 10–30 cm, with vertical, filtered disturbing accelerations and Eötvos corrections determined better than 1 mGal.

Since airborne gravity quality is critically dependent on pilot experience, especially how a precise track is maintained without too many deviations in heading and speed, a home-made special display for the pilots was used during the flights. Figure 2 shows such a display, copied from the end of the first flight. Red is the flight track, and lines in the

![Figure 2. Example of the pilot’s real-time display for the western offshore lines (February 15, 2009). (Figure available in color online.)](image-url)
Table 1
UAE 2009 airborne gravity flights (UAE Forces King Air 350)

<table>
<thead>
<tr>
<th>Date/JD</th>
<th>Flight</th>
<th>Take off UTC</th>
<th>Landing UTC</th>
<th>Airborne time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb. 15/046</td>
<td>Offshore W</td>
<td>0454</td>
<td>0735</td>
<td>2:41</td>
</tr>
<tr>
<td>Feb. 16/047</td>
<td>Coastal W</td>
<td>0639</td>
<td>1005</td>
<td>3:26</td>
</tr>
<tr>
<td></td>
<td>Offshore NE</td>
<td>1242</td>
<td>1607</td>
<td>3:25</td>
</tr>
<tr>
<td>Feb. 17/048</td>
<td>Coastal NE</td>
<td>0955</td>
<td>1223</td>
<td>2:28</td>
</tr>
<tr>
<td>Feb. 19/050</td>
<td>Offshore W</td>
<td>0951</td>
<td>1338</td>
<td>3:47</td>
</tr>
<tr>
<td>Feb. 20/051</td>
<td>Coastal W</td>
<td>1249</td>
<td>1610</td>
<td>3:21</td>
</tr>
<tr>
<td>Feb. 21/052</td>
<td>Cross lines W</td>
<td>1320</td>
<td>1652</td>
<td>3:32</td>
</tr>
<tr>
<td>Feb. 22/053</td>
<td>Offshore NE</td>
<td>1321</td>
<td>1652</td>
<td>3:33</td>
</tr>
<tr>
<td>Feb. 23/054</td>
<td>Coastal NE</td>
<td>1428</td>
<td>1742</td>
<td>3:14</td>
</tr>
<tr>
<td>Feb. 25/056</td>
<td>Dubai + Fujairah</td>
<td>1240</td>
<td>1623</td>
<td>3:43</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>33:10</td>
</tr>
</tbody>
</table>

ocean are airspace boundaries and assumed territorial limits. The display is used to keep the autopilot (in heading mode) within a nominal 50 m of the planned flight track.

Airborne gravity data were acquired at a nominal flight speed of 170 knots, with aircraft altitude above 1500 m only in the far eastern line covering the mountainous Fujairah emirate. The quality of individual flight data were checked by field computations of GPS baselines, combined with results from the LCR gravimeter. Visual inspection/plotting quickly identify problematic data and make the necessary background information for decisions to re-fly a line. Only very limited re-flights were needed and only to cover minor gaps due to excessive offline navigation or excessive turbulence. Table 1 summarizes the progress of the airborne gravity data acquisition. Overall, 33 hours were flown for the survey. The coverage of the

Figure 3. Ground track pattern for all aerogravity survey flights. Background colors show SRTM topography. (Figure available in color online.)
acquired airborne gravity data is shown in Figure 3. Many flight lines were quite short to avoid crossing into the air space of neighboring countries.

4. Airborne Gravity Data Processing

The standard DTU-Space procedure for the airborne gravity processing is graphically illustrated in Figure 4 (from Olesen 2002). Table 2 describes each symbol used for the parameters and derived data as in Figure 4.

Airborne gravity results are tied to the gravity value at the aircraft parking spot at Al Dhafra Air Base by base readings performed either before or after each flight. The aircraft parking spot was subsequently tied to the UAE fundamental absolute gravity station at the MSD facility in Delma Street, Abu Dhabi, with the use of a LC&R land gravimeter. A value of 978867.547 mGal was assigned to the aircraft parking spot based on the value of 978889.262 mGal for the absolute station at MSD basement.

A GPS reference station was operated in Al Dhafra Airport during all flights. This station was used in the differential postflight trajectory determination for all flights. Coordinates for this reference station in the ITRF2005 frame were derived from the AUSPOS GPS service provided by Geoscience Australia. The aircraft trajectories were determined with the GrafNav software package from WAYPOINT. All data were filtered with a three-time cascaded 125-second Butterworth filter giving an effective filter length of 175 seconds, corresponding to a resolution of 7 km at air speed 80 m/s. Some turbulent airborne gravity data have also been processed with a slightly longer filter of 150 seconds.
Table 2
Parameter names for the airborne gravity data processing, cf. Figure 4

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>S, B, CC, f_X, f_Y</td>
<td>Spring tension, beam position, cross coupling, cross and long horizontal accelerometer output</td>
</tr>
<tr>
<td>( \varphi, \lambda, h )</td>
<td>Latitude, longitude and ellipsoidal height</td>
</tr>
<tr>
<td>( \alpha, \chi, \eta )</td>
<td>Aircraft attitude angles: yaw, pitch and roll</td>
</tr>
<tr>
<td>( H^* )</td>
<td>Altimeter reading</td>
</tr>
<tr>
<td>( h_{L,CR} )</td>
<td>Height of gravimeter above ellipsoid</td>
</tr>
<tr>
<td>( H_{L,CR} )</td>
<td>Height of gravimeter above sea surface</td>
</tr>
<tr>
<td>( f_Z )</td>
<td>Computed vertical gravimeter output</td>
</tr>
<tr>
<td>( \delta g_{\text{Eotvos}} )</td>
<td>Platform off-level effect</td>
</tr>
<tr>
<td>( q_X, q_Y )</td>
<td>Kinematic horizontal accelerations derived from GPS positions</td>
</tr>
<tr>
<td>( \delta g_{\text{alt}} )</td>
<td>Eötvös correction</td>
</tr>
<tr>
<td>( v_E, v_N )</td>
<td>Eastern and northern velocity from GPS positions</td>
</tr>
<tr>
<td>( H, \dot{H} )</td>
<td>Vertical accelerations from GPS and altimeter</td>
</tr>
<tr>
<td>( N_{\text{EGM08}} )</td>
<td>Geoid model</td>
</tr>
<tr>
<td>( \Delta g )</td>
<td>Unfiltered airborne gravity anomaly</td>
</tr>
<tr>
<td>( f_{Z0}, g_0 )</td>
<td>Airport base reading and corresponding gravity value</td>
</tr>
<tr>
<td>( \Delta g_{\text{surf}} )</td>
<td>Gravity anomaly from surface data</td>
</tr>
</tbody>
</table>

Butterworth. The impulse response and spectral behavior of both filters are shown in Figure 5.

5. Data Validation and Results
The final data set comprises 97 line crossings (see Table 3). An analysis of the misfit in the crossing points shows a 2.7 mGal crossover difference (r.m.s.). It should be emphasized that no sort of bias adjustment has been applied to the data in order to reduce the misfit in the line crossings. This crossover error indicates a 1.9 mGal noise on the data, assuming the...
Table 3

Crossover analysis results (units: mGal)

<table>
<thead>
<tr>
<th>Filter</th>
<th>No of crossings</th>
<th>Max difference</th>
<th>RMS difference</th>
<th>Indicated noise level</th>
</tr>
</thead>
<tbody>
<tr>
<td>125 sec</td>
<td>97</td>
<td>10.3</td>
<td>2.91</td>
<td>2.06</td>
</tr>
<tr>
<td>150 sec</td>
<td>97</td>
<td>9.6</td>
<td>2.68</td>
<td>1.90</td>
</tr>
</tbody>
</table>

noise to be uncorrelated from track to track. These are the numbers using the 150-second filter. For the shorter 125-second filter, the \( RMS \) misfit and indicated noise level are 2.9 and 2.1 mGal, respectively. The results from the crossover analysis are depicted in Figure 6. It should be noted that no downward continuation has been done on these results; therefore, a small fraction of the errors is coming from the varying flight elevations.

Figures 7 and 8 show the resulting free air anomaly picture in the western and eastern part of the survey area. The western part is characterized by a rather benign and smooth gravity field; the eastern part is characterized by mountains and the geologically unique Oman Ophiolite Complex, which exhibits very strong variations in the gravity field. The gravity field structures seem to line up nicely, with very little tendency to trackiness in the picture, indicating a healthy and self-consistent airborne data set.

The comparison to the geopotential Model EGM08 shows significant differences between the airborne data and this model (Figure 9). These differences are due to errors in EGM08 coming from the inclusion of satellite altimetry derived gravity results in the model. Gravity based on satellite altimetry is by nature weak near the coast, and this is also

Figure 6. Cross-over errors (150-second filter) and processed data lines (data near the end of the lines are not useful). (Figure available in color online.)
the main reason for employing the airborne gravity technique in near-coastal regions. As this example shows, the airborne data alter the gravity picture significantly near the coast compared to a situation with EGM08 only.

The relatively large differences between the EGM08 offshore, and the new aerogravity survey data, will have a large impact on the UAE coastal geoid as well. Figure 10 shows the difference between two geoid models computed by remove-restore methods using all available proprietary gravity data in the UAE (no gaps exist in land cover), including some older offshore gravity data in some regions and DNSC08 satellite altimetry-derived gravity.
Figure 8. Free-air anomalies from the airborne survey (western Fujairah region). (Figure available in color online.)

The geoid computations have been done using state of the art remove-restore methods, based on EGM08 and SRTM terrain models, using least-squares collocation downward continuation and spherical FFT techniques for geoid computation, similar to the method outlined in Forsberg et al. (2003). It is seen how the impact of the new airborne data is in excess of 30 cm in some coastal regions.

Figure 9. Comparison of airborne data to the EGM08 geopotential model. Significant differences are seen in the eastern part of the survey area, showing that EGM08 has substantial errors here. (Figure available in color online.)
6. Conclusions

An airborne gravity survey for the UAE offshore region has been successfully carried out during the period February 15–25, 2009, using a UAE Forces Beech King Air 350 aircraft, and an LC&R gravimeter as the primary gravity instrument. Gravity lines of 5–10 km spacing were flown, dependent on the distance to the coast. Flight lines were relatively short due to the complicated coastline geometry and UAE borders as well as the need to avoid crossing into neighboring countries. Cross-over analysis indicates that the derived gravity anomalies are better than 2 mGal r.m.s. accuracy. The comparison to EGM08 shows major EGM08 errors over the coastal waters in the far west, offshore the northern emirates (including Dubai) and especially offshore Fujairah on the Indian Ocean coast. The geoid impact of the new airborne survey is more than 30 cm, and the data will thus certainly improve the existing gravimetric geoid of the UAE and complement most engineering applications requirements.

References


