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Processing of Airborne Gravity Data, Case Study in a Western Desert of Egypt.

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ملخص البحث :

تقدم هذه الورقة نظرية قياس الجاذبية الجوي القياسي والمعالجة والتقييمات الداخلية للبيانات التي تم الحصول عليها باستخدام مقياس الجاذبية الجوية. ويعتمد هذا النظام العالمي للأقمار الملاحية ووحدة قياس القصور الذاتي لقياس مجال الجاذبية الارضية. واجرت البيانات التي تم جمعها عن طريق هيئة المواد النووية مسحا للجاذبية المحمولة جوا لمناطق محددة في مصر لأغراض جيولوجية. تعتمد طريقة معالجة البيانات علي الطريقة الغير مباشرة التي يعتبر فيها مرشح كالمان الموسع هو الاساس ف تقدير العملية . يتم الحصول علي شذوذ الجاذبية عن طريق طرح التسارع الحركي والجاذبية الطبيعية , واضافة بعد تصحيحات اخري مثل ايوتفوس و الهواء الحر. وعلاوة على ذالك تم اجراء حساب الدقة الداخلية اعتمادا على مرحلتين رئيسيتين وهما تكرار خطوط الطيران و تحليل التقاطعات وكانت النتائج الضوضاء كالتالي 0.59 ملى جال و 0.82 ملى جال على التوالي.

الكلمات المفتاحية : الجاذبية المحمولة جوا, المعالجة, التقييم

ABSTRACT:

This paper presents the theory of scalar airborne gravimetry, processing and internal assessments of data acquired using INS gravimeter. This system depends on the integration between a Global Navigation Satellite System (GNSS) and an inertial measuring unit (IMU) for measuring the gravity field of the earth. The data collected through NMA (Nuclear Material Authority) conducted an airborne gravimetric survey over a specific area of the western desert in Egypt for geological purposing. The data processing is based on the indirect method in which Extend Kalman Filter (EKF) is the essential of the process's estimation. The gravity anomaly is obtained by subtracting the kinematic acceleration and normal gravity from the raw measurements. Due to some wrong assumptions in the normal gravity algorithm, other corrections such as Eötvös and free-air were added. Moreover, the internal accuracy calculation was performed depending on two major stages, the internal accuracies were based on the repeatability and crossover analysis indicated noise level 0.59 mGal and 0.82 mGal respectively.

Kay wards: Airborne Gravimetry, Processing, Evaluation

1.Introduction :

Measuring the Earth's gravitational field has an important role in various scientific fields, such as geophysics and geodesy, which use the measurements of the gravitational field to imagine what is the interior of the Earth through the inverse modeling and the studying of geological structures, which are important in mineral and oil exploration, studying the movement of water in seas and oceans, and in geoid modeling as well. recently, the techniques to measure the gravitational field have developed from the terrestrial measurements which recorded in static mode to the measurements in a dynamic environment such measurements are recorded from the shipborne or the satellites orbits, and with development of the navigation systems and inertial measurement unit technology, the airborne gravity has been become one of the operational tools in monitoring and measuring the gravity field. It offers the opportunity to survey areas that not easily accessible. There are two main significant issues in airborne gravity processing, the first one is how to separate the kinematic accelerations derived from the GPS data from the raw measurements, as when gravimeter mounted on a moving platform, it doesn't only measure the gravitational attraction but also the kinematic acceleration due to the platform movement and the second one is how to keep the sensor orientation during the flights. To overcome these problems, and extract the vertical component of gravity field from raw measurements, an airborne gravimetry system consists of two measurements; GNSS system &IMU systems. For Separation of the gravitational from kinematic acceleration and for determining the sensor orientation during the dynamics of aircraft. Significant issues in an airborne gravity have been discussed in different literatures, such issues were summarized in [1], [2] Some of them referred to the accuracy for aircraft parameters such the position, velocity, and acceleration. The proposed research work presents the mathematical background of the processing and evaluation stages of airborne gravity data related to the scalar airborne gravimetric system with implementation on real data acquired by the GT-1A inertial gravimetry system.

2. DATA

2.1. Airborne Gravity Data

In order to evaluate the accuracy of the airborne gravity measurements in Egypt, a sample in the western desert was acquisition based on the Russian GT-IA airborne gravimeter system provided by Moscow Gravimeter Technology Ltd, Russia [3] as shown in Figure 1. The survey comprises the acquisition and processing of airborne gravity. Survey covering an area of approximately 1200 km^2 with flight altitude 620 m and flight line spacing was in range of 4000 m x 10000 m.

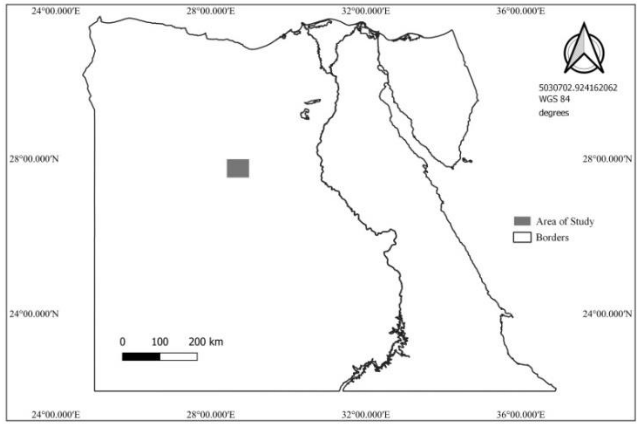


Figure 3: The served area map in Egypt.

3. Pre-processing of airborne gravity data

Airborne gravimeter measures the full vertical acceleration along which its axis is aligned, then the positioning measurements make it possible to accurately model and remove species forces related to aircraft motion to get a gravity signal e.g. such artifacts movements need to be corrected for the vertical accelerations experienced by the aircraft derived from GNSS (Global Navigation Satellite System) data. So, the differential correction of GNSS/INS fusion is needed to perform such correction.

4. Gravity Data Reduction

4.1The gravimeter drifts

Also called static test, since such measurements are recorded before the aircraft takes off, so that the aircraft gravity observation can be associated with the gravity reference point on the parking apron. The gravimeter drift is calculated using the reference measurements as:

$$g_d = g_{m0}\left(\frac{t_1 - t}{t_1 - t_o}\right) - g_{m1}\left(\frac{t_0 - t}{t_1 - t_0}\right) \qquad \text{Equation 1}$$

with t_0 and t_1 are times of start and end time ref ce measurement at airborne, t is the current. GPS time during the flight, g_{m0} and g_{m1} are the averaged raw gravimeter measurements during start and end reference.

4.2Eötvös Correction

This correction corresponds to the vertical components of Coriolis and centripetal acceleration Because of the rotational platform motion relative to the Earth. It was determined according to 1]:

$E_{Eötvös} =$

$2vw_{Eart} \cos\varphi \sin\alpha$ Equation2

Where, $E_{Eötvös}$ is the Eötvös correction, V is the aircraft velocity, VE and VN th Eas and the North components of the aircraft velocity, a is the semi-major axis of the reference ellipsoid, h is the altitude of the aircraft, w_{Earth} is the angular velocity of the Earth, φ an α are the latitude and the azimuth angles of the aircraft.

4.3 Free air correction

For the GRS80 ellipsoid, the s-order formula becomes [5]:

$$\boldsymbol{gh} = -(0.3087691 - 0.0004398\, sin^2\varphi)\, h + 7.2125 * 10^{-8} h^2 \qquad \text{Equation 3}$$

With h is the height of the aircraft in meters above the ellipsoid (gravity disturbance) or the geoid (gravity anomaly, as H =h + N, H: Orthometric height and N: geoid undulation).

5. Quality assessment of the airborne gravity

The airborne gravity data evaluation process is carried out in two stages, the internal evaluation and the external evaluation. This section presents methods for the internal evaluation of the quality of the airborne gravity measurements. Both the repeat lines and cross-over differences methods were represented here, the quality is evaluated in terms of the variance between gravity anomaly estimates at the same point in terms of horizontal coordinates. The variance between two flight lines, A and B, can expressed as[6]:

$$E_{A,B} = \widehat{\delta g}_A - \widehat{\delta g}_B \qquad \text{Equation 4}$$

5.1The repeat lines

The repeat line is a necessary method aimed for evaluating the accuracy resolution of the airborne measurement system and calibrating of the final filter used in post-processing the data sets based on the gravity difference between two repeatable flight lines. The result from airborne repeat measurements are going to be affected by both gravimeter and GPS noise due to the dynamic environment as well as navigational errors (small differences in trajectory).

Two methods are generally used to calculate the repeated line, the primary one is recommended by [7] for finding the collected errors in gravity data obtained along repeat lines, the second has used the RMS variances between repeat lines [8].
In the standard method, the root mean square error is used to calculate the internal and the overall consistency of each repeat line and all repeat lines data which calculated as follow:

$$\varepsilon_j = \pm\sqrt{\frac{\sum_{i=1}^{n}\delta_{ij}^{2}}{n}} \quad , (j = 1, 2, 3, \ldots.., m), (i = 1, 2, 3, \ldots.., n) \qquad \text{Equation 5}$$

$$\delta_{ij} = F_{i} \cdots \qquad \text{Equation 6}$$

$$F_{ij} = \frac{\sum_{j=} f_{ij}}{m} \qquad \text{Equation 7}$$

$$\varepsilon = \pm\sqrt{\frac{\sum_{j=1}^{m}(\sum_{i=1}^{n}\delta_{ij}^{2})}{m.n}} \qquad \text{Equation 8}$$

with δij is the difference between the observed value Fij at the i^{th} point along the j^{th} repeat line and the average value Fi of all repeated measurements at that point; m is the repeat lines number; n is the point's number on the overlapping segment of repeat lines. The root mean square difference less than 1 mGal is considered satisfactory.

5.2The Cross-Over Analysis

Airborne gravity surveys are often planned in periods of parallel line sections to cross large areas without spending extra time and fuel. In combination with ground velocity and altitude, the distance between these parallel line sections is planned to achieve the desired resolution. To evaluate the accuracy of the obtained gravity anomaly, A few cross-track lines are usually flown [6].

The cross-over study aims to evaluate the accuracy of filtered airborne gravity anomaly and obtain a realistic estimate for its conversance function. The result of the cross-over analysis allows us to separate between the white and colored noise and the usually accepted assumption of pure white noise. Accordingly, Geophysicists can use cross-over production when interpolating anomalous maps to identify the nature of the hotspots, whether they are signals or only the result of colored noise [9].

Cross-over Difference is the bias in gravity value caused by the intersection between survey and tie lines. It can be used to calibrate and evaluate the airborne gravity data. The derived statistics from the variances are used to evaluate the results. The statistical measures are calculated as follow:

With μ as the mean, σ is the standard deviation, RMS is the Root Mean Square, and RMSE is the Root Mean Square Error. The Root-Mean Square Error (RMSE) assumes that the error difference is distributed equally to estimate the uncertainty on each cross point. The statistics value RMSE is commonly used in the evaluation of airborne gravimetry [6]:

$$\mu = \frac{\ }{N}\sum_{i=1}\epsilon i \qquad \text{Equation 9}$$

$$\sigma = \sqrt{\frac{\ }{\ }\sum_{\eta-1}(\epsilon_i - \mu)^2} \qquad \text{Equation 10}$$

$$\epsilon_{max} = \max[\epsilon_i] \quad , \quad \epsilon_{min} = \min[\epsilon_i] \qquad \text{Equation 11}$$

The Root Mean Squares deviation:

$$RMS = \sqrt{-\sum_{n=1}\epsilon_i{}^2} \qquad \text{Equation 12}$$

$$RMSE = {}^{RMS}/_{\sqrt{2}} \qquad \text{Equation 13}$$

Cross-over adjustment In an airborne gravity survey, Crossover variations in gravity values from intersecting survey lines can be used to determine the accuracy of gravity values. Due to both GPS and the gravimeter, crossover adjustment of observed gravity values will reduce the effe t of bias and drift [2].

Let $\bar{g}_i{}^j$ be the observed gravity value at a point I along survey line q; $\bar{g}_i{}^j$ is corrupted by a bias and drift, plu

$$\bar{g}_i{}^j = g^j + a^j + b^j t^j + \epsilon^j \qquad \text{Equation 14}$$

With $\bar{g}_i{}^j$ is the gravity anomaly at point i along the flight line a^j and b^j are the bias a d drift, respectively, t^j is the time at point i relative to the beginning time of the line j, and ϵ^j is the random error. Each crossover point can be formulated as:

$$V_b^{kl} = a^k + b^k t_p^k - a^l - b^l t_p^l + X_p^{kl} \quad (k = 1, \dots n;\ l = 1, \dots m; p = 1, \dots N)$$

Equat 15

With X^{kl} is the variance of the gravity value at point p along with lines k and l, V_l^{kl} is the residual, and n, m, and N are the flight lines and crossover point's number, respectively. Equation 16 may be written in matrix form gives as follow:

$$V = AX + \qquad \text{quation 16}$$

With V, L represents the residuals V_l^{kl} and observations X^{kl}, A is the design matrix, and X represents the biases and drifts solved by the least-squares estimator.

6. Results

6.1Pre-processing Results

The survey flights are processed by using CMG (Canadian Micro Gravity) proprietary software package developed by the Department of Mechanics and Mathematics in Lomonosov Moscow State University. The data processing sequence comprise three stages as follow;

In the first stage, the GTNAV module is used for time data synchronization and DGPS calculation by data combination from the base, rover GPS and Inertial Measurement Unit (IMU). The calculation of the precise positions for the moving platform with Doppler frequency shift, and differential GPS carrier phase methods; the attitude and velocities are calculated from the IMU measurements.

In the second stage, the GTQC module was used as evaluation and reformatting of the gravimeter data and the DGPS solution such as; PDOP value, satellite's number, the position and velocity accuracies as shown in table 1. Figure 3 shows quality indicators of GPS/INS platform data.

In the third stage, the GTGrav module was used for processing of the gravity data, i.e. drift, vertical acceleration, georeferanceing, Eötvös, normal gravity field correction, and altitude corrections as shown in figure 4. During the correcting process, 100s full wavelength, the Extended Kalman Filter (EKF) was used to attenuate the high-frequency noise due to edge effects about 5 km at both ends of the flight lines. the modeling of the free-air anomaly was calculated iteratively and finally, primary free-air gravity anomalies were acquired with a spatial resolution (half wavelength) about 3.5km. From GTGRAV the data were imported into the Geosoft Oasis Montaj environment, where each stage of leveling was performed, final corrections and adjustments were applied to the data, and the final products were produced. It is proposed to use a minimum grid cell size of 1km, which is appropriated (1/4 of line spacing) for the survey line spacing (4 km) of this survey as this will efficiently store the data while preserving the full resolution of the data after applying low pass filters. Figure 5 shows the processed survey flights before and after the adjustment with spatial resolution 3.5 after applied 100s filter length.

Table 9: QC parameters specifications.

l	Normal specification	Value during flight
SVs	6 or more	10
PDOP	Less than2.5	1.7
RMS	Less than 1.0m	0.15
V RMS	Less than 0.05 m/s	0.02
Alpha1	Less than 0.0333 rad	0.000002
Alpha2	Less than 0.0011636 rad	0.0000015

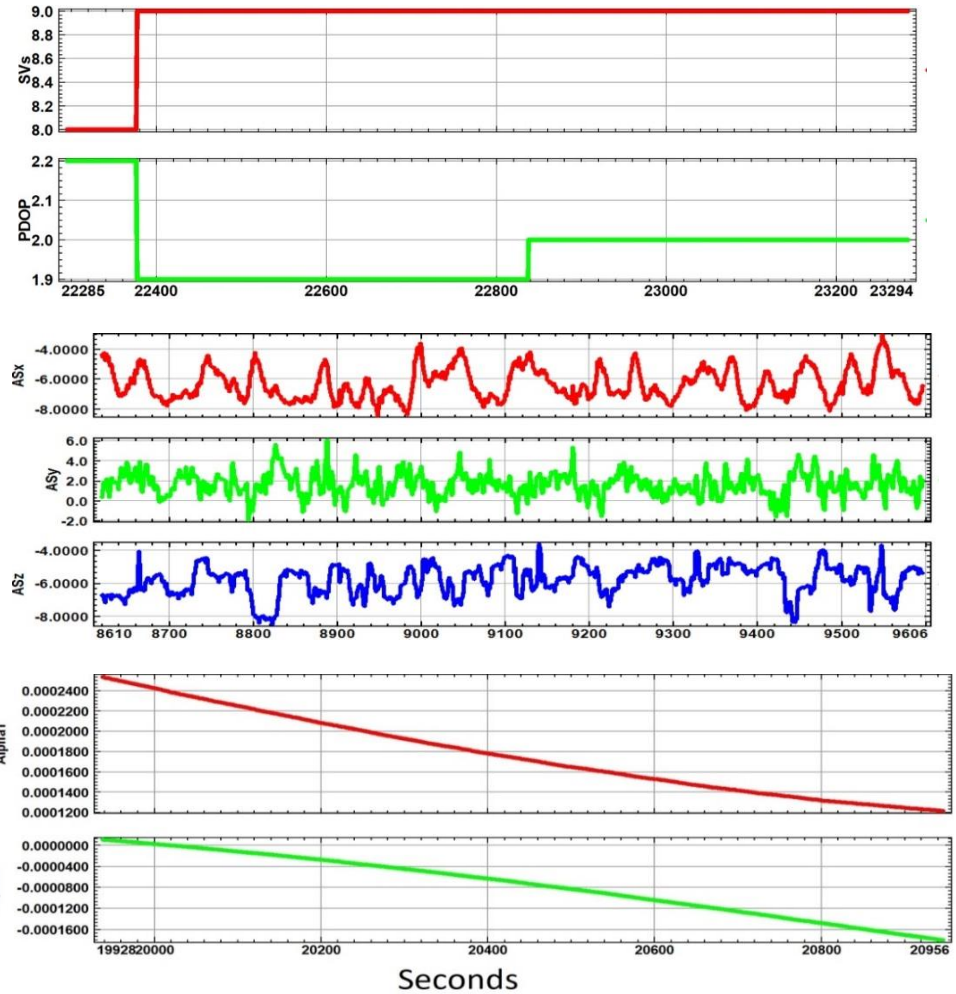


Figure 4: The quality control indicators from the integration outputs of GPS/INS platform measurements from the selected sample line.

6.2Gravity Data Reduction and Free air Anomaly Extraction Results

During the field survey, the data are usually evaluated to verify that all systems are efficient and are performing well. After each flight, the gravity data are examined for the stability in the time intervals between measurements and to identify any data losses. the initial free-air gravity anomaly is calculated using the GNSS/INS optimal solution for horizontal and vertical positioning. This initial anomaly should show gravity values that are smoothly varying within a reasonable range, with a high correspondence between neighboring profiles. Figure 4 show the flow chart of airborne data reduction.

In post processing, once the carrier phase positions are calculated using precise ephemerides, corrections derived from the latitude, longitude, and ellipsoidal height of the aircraft are applied to the gravity measurement to generate the free-air gravity anomaly. Acceleration of the aircraft along the vertical axis must first be calculated and subtracted from the gravimeter measurements. All corrections calculated is showed in Figure 5.

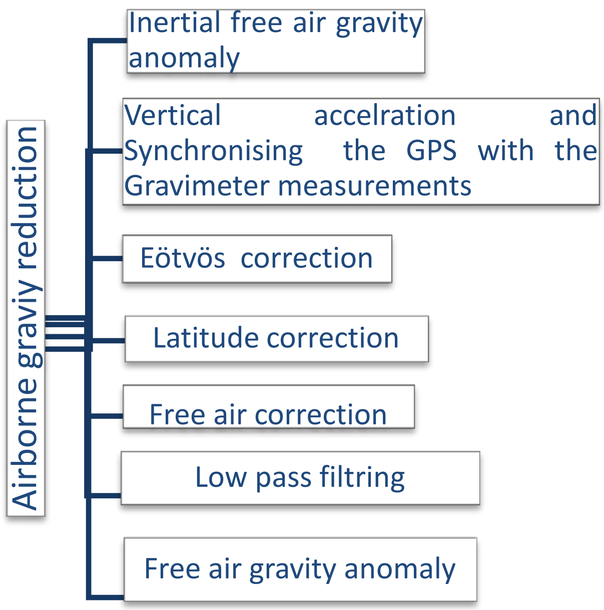
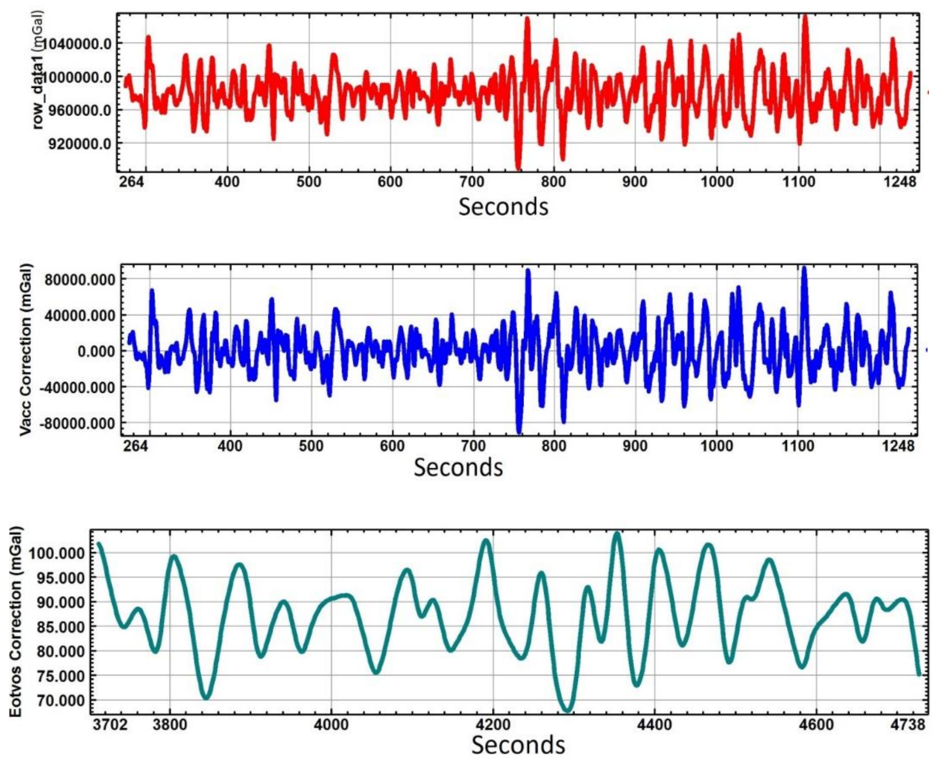


Figure 5: The flow chart of airborne data reduction.



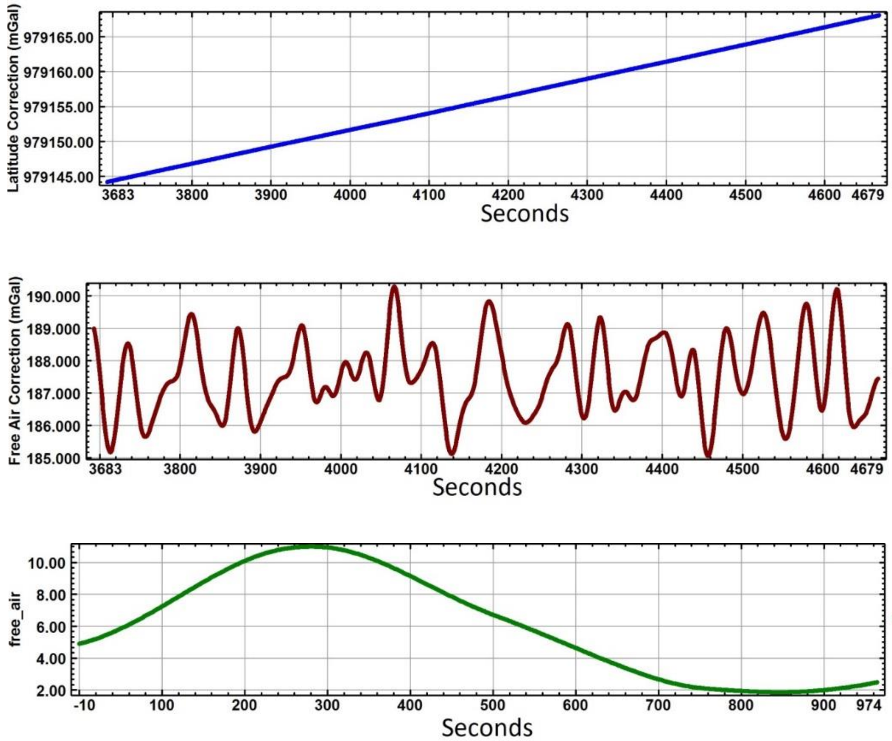


Figure 6: The raw measurements with data corrections required to obtain the free-air gravity anomaly filtered with a 100 s from the selected sample line.

6.3Repeat line results

10km repeat-line was flown 4times along the same track. The results from repeat flight measurements be affected by both gravimeter and GPS noise due to the dynamic environment as well as navigational errors (small differences in trajectory). The differences between the two passes of each flight were used to assess internal consistency of the airborne gravity measurements. It is considered a repeatability; SD < 1 mGal and mean difference < 0.2 mGal as satisfactory.

The gravity data was then reduced by the same method as gravity survey data using a range of Kalman filter lengths (60, 80, 100, 120, 140s) corresponding to resolutions of 1.7- 6km. The filter length 120s was used as optimal filter for an aircraft velocity 70m/s. Note that no leveling or spatial filtering has been applied to the data. Noise levels were estimated using Green and Lanes method [7]. Figure 6 shows the repeat lines after reduction.

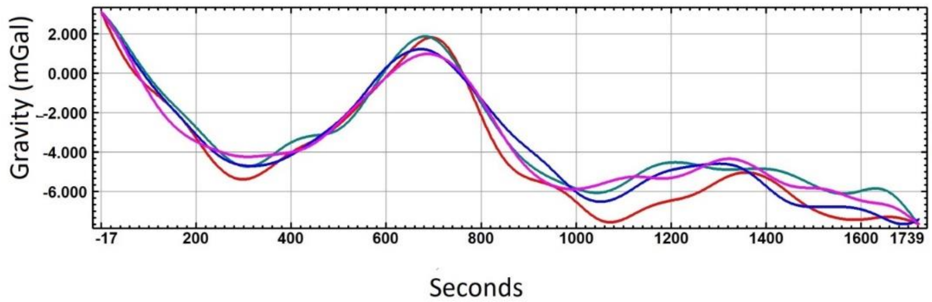


Figure 7: the repeat lines after reduction.

6.4Crossover analysis results

Crossover differences of gravity anomaly from intersection survey lines can be used to evaluate the quality of gravity values in an airborne gravity survey. In this test, the seven flights of grid flight formed the survey grid. There were seven survey lines along a south-north direction and four control lines along the east-west direction; after being filtered by a 120-s cutoff low-pass filter, the true gravity value can be obtained. There were 28 crossover points in this case. Figure 7 shows the distribution of crossover points and the magnitude of crossover differences. From Figure 7 we can see that the crossover differences are large at some crossover points, and it means that the observed gravity value more or less contained systematic errors.

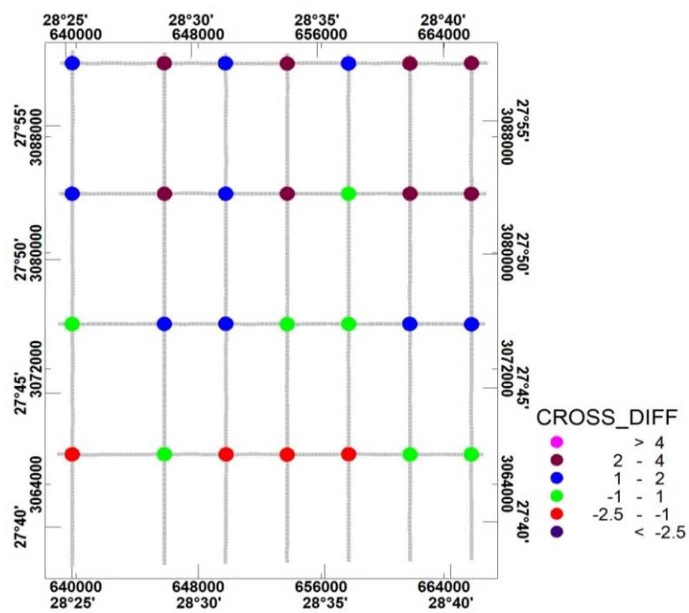


Figure 8: The distribution of crossover points and the magnitude of crossover differences before crossover adjustment.

Crossover adjustment(Leveling): Crossover adjustment of observed gravity value can reduce the effect of bias and drift due to both GPS and the gravimeter [10]. The influence of the leveling procedure on the signal should be unequal in directions parallel and perpendicular to the survey lines, the most significant adjustments should be made perpendicular to traverse lines. Leveling procedure contains two steps [11]:

After compensating the systematic errors for grid gravity anomaly based on aforementioned strategy, Figure 8 shows the distribution of crossover points and the magnitude of crossover differences after crossover adjustment.

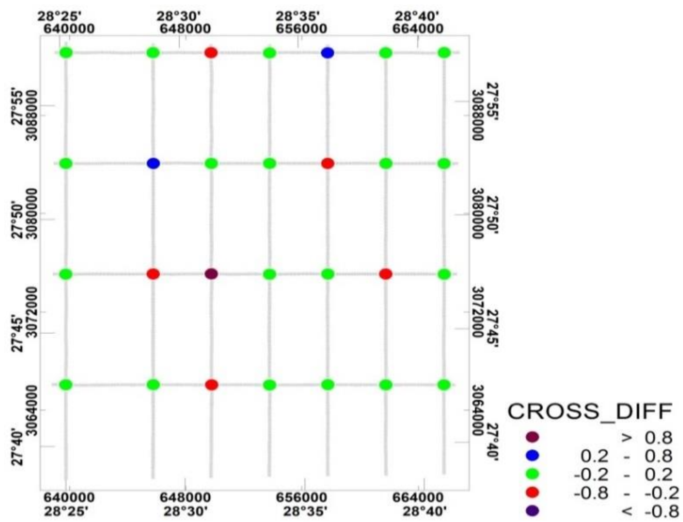


Figure 9:The distribution of crossover points and the magnitude of crossover differences after crossover adjustment.

Comparison of Figure 8 with Figure 7 shows that crossover differences become much smaller. This means that the crossover adjustment has successfully recovered the systematic errors and reduced the crossover differences.

7. Conclusion

This study is focused on the demonstration of the mathematical background of processing and evaluation of airborne gravity data acquired using GT-1A gravimeter based on the indirect method in which Extend Kalman Filter (EKF) is the essential of the estimation process. The survey was conducted in the western desert, integration of DGPS/INS and routine gravity data processing from one line in the survey area are used to show to what extent the data quality, it shows that all parameters within tolerance. The gravity disturbances were obtained using EKF with 100s filter length with spatial resolution 3.5km at aircraft speed 70m/s. The internal accuracies are based on dynamic test and the crossover residuals, the standard deviation of repeatability and crossover differences of gravity disturbance estimates before and after crossover adjustment are approximately 1.1mgal, 2.6mgal, and 1.2mGal respectively.

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