An Enhanced Geodetic Network and Geoid Model for Municipalities of Abu Dhabi Emirate

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Key words: Geoid, Gravity, GNSS, ITRF2014, Rigorous orthometric heights, Stokes-Helmert

SUMMARY

Nowadays, the combination of both an up-to-date geodetic network, with accurate positions and ellipsoidal heights, and a high accuracy gravimetric or hybrid gravimetric geoid model, is clearly the optimal combination to ensure accurate georeferencing of all survey works in both position and height, which is the prerequisite for efficient management of integrated land/water. The availability of a dense CORS network allows obviously improving the integrity and accuracy of the related survey works while also providing a very convenient, cost-effective surveying and positioning solution. The availability of accurate complementary First order geodetic markers allow both strengthening the robustness of the survey works and providing redundant solutions for contingency in case of a CORS failure. Finally, a hybrid gravimetric geoid model provides an accurate, convenient, height reference surface enabling all survey practitioners to obtain orthometric heights above MSL in the national vertical datum directly from GNSS observations.

From mid−2017 to mid−2019, Abu Dhabi Municipality (ADM) and Fugro have executed a two-fold geodetic project intended to upgrade the existing geodetic infrastructure of Abu Dhabi Emirate.

Abu Dhabi GPS Reference Stations network, consisting of 32 CORS, was recomputed in both ITRF2014 at Epoch 2019.0 and historical ITRF2000 at Epoch 2000.0, which allowed confirming significant station displacements for a small number of CORS over the 12 last years. 53 geodetic control points, consisting of pillars (40 new, 13 existing), were observed to complement the AD GRS network.

Gravity grids at 1−km and 2.5−km spacing, totalling more than 12,000 points were surveyed over the entire Emirate, and 4 new absolute gravity stations were established across the Emirate, hence constraining the relative gravity network and avoiding error propagation. These grids were used to compute a high accuracy gravimetric geoid model using the Stokes-Helmert method. A Stokes’ integration radius of 1.5° and a degree/order of the reference field of 270 were found as the optimal parameters to compute the gravimetric geoid model at 1’ resolution. It was then fitted by least squares collocation onto the GPS−Levelling network for consistency purpose with the national Ras Ghumays vertical datum realization. The accuracy of the final hybrid gravimetric geoid model was estimated to better than 2 cm.
1. INTRODUCTION

Abu Dhabi Emirate’s Continuously Operating Reference Stations (CORS) geodetic network (named Abu Dhabi GPS Reference Stations Network or AD GRS) was first established in 2008. By that time, station coordinates were referenced into ITRF2000 at Epoch 2000.0 for consistency purpose with the Emirate’s official geodetic reference system, datum and realization. The Emirate’s vertical datum realization unification has been carried out over more than one decade. Main levelling operations were completed in 2016, hence achieving a homogeneous levelling network, consistent with Ras Ghumays tide gauge reference benchmark over the whole territory.

In 2017, Abu Dhabi Municipality (ADM) jointly embarked with Fugro on a two-fold, two-year geodetic project: on one hand, densify the CORS network with First order geodetic pillars evenly distributed across the territory, check the CORS stability over time and recompute their coordinates wherever required, and, on the other hand, establish 4 new absolute gravity stations, carry out relative gravity survey at 1–km and 2.5–km grid spacing over the territory, and compute a high accuracy gravimetric geoid model for the entire Emirate, i.e. covering Abu Dhabi, Al Ain and Al Dhafr / Western regions.

The CORS recomputation was motivated by unquestionable clues of ground deformation. Indeed, for years ADM has realized that a number of stations were likely to have slightly moved in height and/or position. A number of station displacements had then been ascertained by a study jointly conducted by Abu Dhabi Municipality and Norplan in 2015. On the vertical side, evidences of levelling misclosures had been put to evidence by Abu Dhabi and Al Ain Municipalities, which had led to question the stability of some levelling sub sections. In 2013, UAE University and Sarmap had carried out an InSAR study, which disclosed some areas of subsidence and uplift in Al Ain region. In 2019, Fugro performed a Multi-Temporal InSAR ground deformation study of the Al Ain area. Over 60 Sentinel 1A Radar images were used spanning 3 years from 2016 to mid-2019. The study put to evidence large bowls of subsidence (see Figure 1), which were correlated with figures of groundwater pumping for agricultural purpose in a large part of the Al Ain region. These areas were also found to affect a number of levelling lines along which benchmarks heights had shown questionable.

Along with the CORS stability study results, this last Permanent Scatterers InSAR study has demonstrated that the ground deformation process was still going on, hence confirming the need for a recomputation of the CORS and a modernization of the vertical datum realization.
2. GEODETIC NETWORK

2.1. CORS geodetic network

2.1.1. Technical approach

The AD GRS network geodetic tying-in was performed using MIT’s Gamit – Globk (v10.7) software suite with GNSS data collected on 31 active local CORS (AD GRS) spanning 31 days (between the 1st and the 31st of December, 2018). The computation was carried out in two steps. First, the network was tied to the ITRF by including the observations recorded on 30 permanent stations of the IGS regional network, which provided a local solution consistent with the IGS regional realization; this step did not only yield local CORS absolute referencing but also allowed strengthening the local network consistency with additional constraints in every direction. Then, the regional solution was combined to a global solution incorporating baseline estimates from hundreds of stations of the IGS network, hence correcting the regional solution for those biases inherent to the particular geometry of the regional network, not perfectly balanced.

2.1.2. GPS data processing

In the first step, we used GPS double-differenced phase observations from each day of the tying-in session to estimate station coordinates, the zenith delay of the atmosphere at each station, and orbital and Earth Orientation Parameters (derived from polar motion and UT1−UTC provided by the IERS) by applying loose constraints to all parameters. We provided orbital control and tied the 31 local CORS to the ITRF by including in the survey dataset the observations recorded on 30 regional CORS from the IGS network. These IGS reference stations were selected according to data availability, stability, distance and orientation (see Figure 2).

In the second step, we used the loosely constrained estimates of station coordinates, orbits, the Earth Orientation Parameters and their covariance matrices from each day, aggregated by days,
as quasi-observations in a Kalman filter (Globk) to estimate a consistent set of coordinates. These regional quasi-observations were combined with quasi-observations from a global analysis of over hundreds of stations performed by the Geodesy and Geodynamics group of the department of Earth, Atmospheric and Planetary Science at MIT. We applied strong constraints on the IGS core network stations and released constraints on the GPS satellites and the Earth Orientation Parameters.

Finally, we computed the local CORS coordinates by applying a three-dimensional spatial similarity with 6 parameters (3 translations, 3 rotations) minimizing the deviations between the positions of the IGS stations included in our solution and their positions given by the ITRF processing centre. The final AD GRS network fitting solution was computed in 4 iterations from the 14 most consistent IGS stations. The post-fit RMS of the final adjustment was less than 2.5 mm, which demonstrates the consistency of the retained referencing network.

![Figure 2: local CORS and regional IGS tying-in network (background map from Google)](image)

This methodology allowed computing AD GRS CORS positions with relative accuracy better than 2 mm in latitude and longitude and 5 mm in ellipsoidal height at 95% confidence level (2σ). Network absolute tridimensional accuracy was found better than 1 cm in ITRF2014 (more exactly IGS14) at Epoch 2019.0 (final epoch of measurement).

### 2.2. First order geodetic network

#### 2.2.1. GNSS data acquisition

53 First order Geodetic Control Points (GCP, monumented with pillars) were observed so as to complement the CORS network. With the 32 CORS, the enhanced Abu Dhabi Emirate geodetic reference network altogether consists of 85 points. 6 GNSS geodetic receivers were simultaneously recording data on GCP. GNSS observations were carried out according to the rule book (3 to 4 leg loops, at least one common baseline between adjacent loops, loops made up of independent baselines, every point being occupied at least twice, observations ranging from 3 to 6 hours depending on distance, with a number of core triangles exceeding 24 hours, and field surveyors filling e–forms on smartphones for ease of metadata quality control).

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2.2.2. GNSS data processing

GNSS baselines were processed primarily using AIUB’s Bernese software for the medium to long baselines, and Spectra’s SPSO (mirroring Trimble’s TBC) for the short ones. Indeed, academic software have often demonstrated underperforming for short baselines (notably with sessions not exceeding 4 hours). Bernese and SPSO were found to match the local CORS coordinates computed with Gamit–Globk. 3D difference comparison yielded standard deviation of 3 mm (from −7 mm to +8 mm). These differences (about thrice the usual differences when comparing Gamit and Bernese) stemmed from their respective observation durations (31 days of observation for the local CORS versus 3 days at best for the GCP).

The complete AD GRS network was adjusted by least squares using Bitwise’s Geolab software. First, an inner constraints least squares adjustment (LSA) was performed to assess the network consistency and weight the baseline variance/covariance matrices. Then, the LSA was reiterated with all local CORS constrained to their Globk coordinates. Uncertainties were ascertained using χ2 testing. The final First order GCPs coordinates were found accurate to 3.7 mm in E, 3.4 mm in N and 19.0 mm in Ellipsoidal Height (95% confidence level, 2-σ).

2.3. Coordinates transformation

To be consistent with the Emirate’s ITRS official geodetic realization, the coordinates computed in ITRF2014 at Epoch 2019.0 were transformed into ITRF2000 at Epoch 2000. Coordinates were first translated to ITRF2014 at Epoch 2000.0 using a plate motion model. Then, they were transformed into ITRF2000 applying IERS’s 14-parameter transformation, implemented at Epoch 2000.0.

Three proven plate motions models – ITRF2014 (Altamimi et al., 2016), GEODVEL (Argus et al., 2010) and MORVEL56 (Argus et al., 2011) – were tested. To select the best model and decide whether to apply a translation to the new coordinates or not, the transformed coordinates were compared with their historical counterparts using all 29 available common stations.

Figure 3 : Residuals between ITRF2010 Epoch 2000.0 (computed from 2019’s campaign) and ITRF2010 Epoch 2000.0 (computed from 2007’s campaign)
Whereas the third model (geophysical origin) exhibited larger differences, the two first models (kinematic origin) provided velocity differences smaller than 0.9 mm/year Eastward and 1.2 mm/year Northward, which translated to 17 mm in East and 23 mm in North over 19 years. ITRF2014 plate motion model turned out the most suitable one, exhibiting mean differences of 0 mm, 6 mm and 5 mm in X, Y and Z, respectively. Figure 3 shows the distribution of the residuals.

For every tested plate motion model, four local CORS were found to have large residuals in ellipsoidal height, and two CORS in horizontal position. These differences might be explained by multiple factors such as subsidence (e.g. due to groundwater pumping, hydrocarbon extraction, building settlement...), change of GNSS antenna setup or model, or by the inaccuracy of the original coordinates. Since there was no obvious trend in the residuals (magnitude or orientation) that could be caused by the inaccuracy of the plate motion model, but that there were significant residuals on spots, it was possible to conclude that the new local ITRF2000 at Epoch 2000.0 realization (derived from 2019’s campaign) was more consistent than its original counterpart.

So, the new Abu Dhabi Emirate First order geodetic network was estimated accurate to better than 2 cm in horizontal position and 3 cm in ellipsoidal height (95% confidence level, 2-σ) in ITRF2000 at Epoch 2000.0.

3. GRAVITY SURVEY
3.1. Gravity and GNSS data acquisition

The objective was to establish a land gravity grid at spacing of 1 km in developed and developing areas and 2.5 km in the rest of the Emirate territory, including absolute gravity stations as appropriate, as shown in Figure 4.

Land relative gravity were measured using 5 Scintrex CG5 and CG6 gravimeters. Each gravimeter was properly calibrated on a 1500 m elevation gradient calibration baseline. To enable gravimeter drift correction, gravity measurements were conducted according to simple loop, modified ladder loop or line sequence patterns. Daily gravity loops were combined into gravity polygons so that the relative gravity network be made up of closed polygons.

All daily loops were completed within 10 hours so that the gravimeter fused quartz spring drift could be corrected accurately enough.
The gravimeters were transported by 4WD car or all-terrain vehicles. Instruments were placed inside dedicated transportation bags with special interface to absorb most vibrations. The bags were belted and maintained so as to keep the instrument in near-vertical position. Depending on the access path condition, the survey crews allowed for a stabilisation period before logging data. Shelter boxes were used to minimize vibration due to the wind. Pictures of terrain and gravity measures are provided in Figure 5.

Figure 5: Typical terrain and relative gravity combined with GPS measurement (second left: wooden shelter against wind and sun; second right: wooden board for sandy terrain)

GNSS observations were simultaneously carried out using Leica GS16 geodetic receivers. Gravity grid positions and ellipsoidal heights were obtained using both AD GRS RTK (VRS mode) and post processing (static or PPK) for crosscheck and contingency purposes. Therefore, irrespective of the AD GPS CORS, local GNSS reference stations were temporary set up in operations areas in order to enable GNSS post-processing for all grid points.

Absolute gravity data were measured using a Micro–g LaCoste FG5 ballistic gravimeter at 4 stations evenly distributed throughout the territory, each of them consisting of an inner point located inside a building and connected by relative gravity and geodetic levelling to an outer point located outside. All recording sessions were 24-hour long. This absolute gravity core network had three objectives, (i) provide gravity results in the correct gravity datum (IGSN-71), (ii) avoid propagating gravity errors when cumulating relative gravity loops from one point to another up to a distant area (long distances), and (iii) ensure the relative gravity network correct scaling. Absolute gravity was transferred to ground point by relative gravimetry implemented using a 3-height tripod, as shown in Figure 6.
3.2. Gravity and GNSS data processing

Absolute gravity data were processed using Micro–g LaCoste g9 software. Gravity data was corrected for Polar motion, Earth tide (from ETGTAB program), Ocean Tide Loading (FES2004), and Atmospheric pressure. Relative gravity data were corrected for Earth tides, Ocean Tide Loading, air pressure, instrument calibration value, and instrumental drift, using Royal Observatory of Belgium’s T-Soft, Fugro/University of Montpellier’s GravProcess NG, and IGN’s MCGravi (least square inversion). GNSS data were processed using Spectra’s SPSO (baselines connecting grid points to local reference stations and nearby CORS) and compared versus AD GRS VRS solution wherever available.

The complete land gravity network (12,324 grid points) was adjusted by least squares using Bitwise’s Geolab software. First, an inner constraints LSA was performed to assess the network relative accuracy and weight the gravity baseline uncertainties. With Madinat Zayed station’s absolute gravity held fixed (centre of the Emirate), closures on Sila (west), Abu Dhabi (north northeast) and Al Ain (east) were 19, 37 and 3 µGal, respectively. Then, the LSA was reiterated constraining the network onto all 4 absolute gravity stations. Final gravity uncertainties were ascertained using $\chi^2$ testing.

As a result, all grid points positions and ellipsoidal heights were found accurate to 5 cm
(standard deviation). On absolute stations, vertical gradients ranged from -2.976 to -3.186 µGal/cm, with standard deviations from 0.012 to 0.032 µGal/cm. Absolute gravity stations were found accurate to 4.3 µGal. Grid points adjusted gravity values were found accurate to 24 µGal in average (ranging from 4 to 63 µGal), which was deemed very accurate considering the network extent (see position of all grid points and their gravity value in Figure 7).

### 4. COMPUTATION OF A GRAVIMETRIC GEOID MODEL

#### 4.1. Compilation of existing data

Gravity datasets from previous surveys, carried out over and around UAE (neighbouring countries, the Gulf and the Oman Sea,) over the last decades, were collected wherever available from various sources (BGI, NOAA, ADNOC, Universities...). A number of identified datasets could not be obtained due to confidentiality considerations. The most recent edition of the marine gravity anomalies from satellite altimetry by Sandwell et al. (2014) was chosen to provide additional coverage in marine areas.

The geoid computation process required using a Global Gravity field Model (GGM). A satellite only model such was necessary to model the long wavelength of the gravity field. A combined model was required to fill all surrounding areas where gravity data are too sparse. We evaluated the different GGMs and found that the optimal combined/satellite-only reference fields over the area of interest was GECO/GOCO05s. For computing topographical effects, the SRTM1 global DTM was used. The 1 arc-second DEM was used within a 3° radius of each observation point to include most of the high topography surrounding the area of interest. Indeed, mountain range summits can reach 2000 m and more in the area of influence (Al Hajar range in UAE and Oman, Zagros mountains in Iran).

#### 4.2. Gravity data evaluation

Least Squares Downward Continuation (LSDWNC) was used on both the existing gravity datasets (once corrected for datum inconsistencies) and the adjusted gravity points to identify outlying data points. This technique is used in geoid computation (e.g. Foroughi, 2018) to combine scattered gravity observations, transformed into a harmonic space, and to solve for a consistent grid of gravity anomalies on the geoid. In our application, we additionally use LSDWNC as a data analysis tool by analysing residuals of the solution at each observation point.

A traditional Poisson downward continuation works by solving the system of equations:

\[ \mathbf{s} = \mathbf{B} \mathbf{g} \]

where \( \mathbf{s} \) and \( \mathbf{g} \) are vectors of gravity anomalies at the topographical surface and geoid respectively, and \( \mathbf{B} \) is a matrix defined by the linear relationship between the two based on Poisson’s integral. In LSDWNC, the values in \( \mathbf{s} \) are scattered, such that the system can be solved by least squares with redundant observations allowing calculation of residuals and estimation of result accuracy. The system of equations is solved in an iterative way with convergence based on expected accuracy of the results.

LSDWNC residuals for the newly acquired dataset suggested a small number of large outliers, with residuals exceeding 1 mGal (116 altogether, 1% of the dataset, which were removed), as...
shown on Figure 8. The larger residuals found in the eastern region were not deemed worrisome, as larger variations of the gravity field are expected in this mountainous region. An accuracy estimation of 0.05 mGal (based on LSDWNC convergence) characterize the free-air anomaly dataset, which perfectly matched the gravity network LSA results, complying with precise geoid modelling requirements. Results of LSDWNC implemented on the existing gravity datasets showed that its precision ranged from 0.2 to 1 mGal.

4.3. Stokes-Helmert method implementation

All computations were performed using UNB/Fugro’s SHGeo 2019 (enhanced version jointly developed by UNB and Fugro) dedicated to computation of geoid models. A complete description of the SHGeo method can be found in Ellmann, A., and Vaníček, P. (2007) or Janák et al. (2017). SHGeo can compute geoid models with two approaches: The Two–space (or No Topography space) method or the Three–space (or Helmert space) method. For the Abu Dhabi Emirate, a three-space method was used for the computation (Yang, 2005), in which LSDWNC is performed on No-Topography (NT) anomalies (Vaníček et al., 2004) rather than Helmert anomalies. This has two main advantages:

– Using NT anomalies gives a smoother gravity field so fewer details are lost in the iterative downward continuation procedure; and
– Short wavelengths of smooth input data can be recovered when adding the condensed effect after downward continuation.

The computation sequence can be summarized as follows:

– Computing NT gravity anomalies at observation points by subtracting the “real” topographical effects (Direct Topographical Effect and Secondary Indirect Topographical Effect) from the free-air anomalies;
– Creating a regular 1’ x 1’ grid of NT anomalies using inverse distance weighted interpolator, taking into account the accuracy of the scattered free-air anomalies. To limit interpolation errors, no gridding was performed where scattered gravity anomalies were too sparse;
– Downward continuing the NT anomalies onto the geoid. This downward continuation was
done with an integration radius of 1 arc-degree;
– Converting the NT anomalies on the geoid into Helmert anomalies (restitution of topographical masses: Condensed Direct Topographic Effects and Secondary Indirect Topographic Effects were added to the NT anomalies on the geoid);
– Removing the reference field Helmert anomalies from the Helmert anomalies on the geoid, yielding residual Helmert anomalies (or Stokes anomalies);
– Converting these latter to the residual Helmert cogeoid using Stokes integration;
– Adding a reference field Helmert cogeoid to the residual Helmert cogeoid to obtain the Helmert cogeoid;
– Adding the primary indirect topographical effects at each cogeoid points to switch back into the real space, hence obtaining the gravimetric geoid presented in Figure 9.

![Figure 9: Gravimetric geoid. Values in m. Contour interval is 20 cm.](image)

The computation centers on Stokes’s integration, which transforms gravity anomalies into geoidal heights, using the formula:

\[ N(\Omega) = k \iint_{\Omega'} \Delta g(\Omega') S(\Omega, \Omega') d\Omega', \]

where \( \Omega \) represents the position (latitude and longitude) of a computation point; \( \Omega' \) the position of an integration point; \( k \) a constant; \( S(\Omega, \Omega') \) the Stokes’s kernel (Stokes, 1849); \( \Delta g(\Omega') \) is the gravity anomaly on the geoid at point \( \Omega' \); and \( N(\Omega) \) the geoid-ellipsoid separation at point \( \Omega \).

This formula only works in a space where the gravity field is harmonic, hence the conversion to the Helmert space. In practice, the integration region is divided into a near zone with higher weighting and a far zone with lower weighting (Vaníček and Sjöberg, 1991).

Several tests were performed with Stokes’ integration radius ranging from 0.5° to 2°. Likewise, tests were performed with reference field degree/order ranging from 100 to 360. Considering the distribution and the quality of the different gravity data sets, we’ve finally retained a Stokes’ integration radius of 1.5° and a degree/order of the reference field of 270, which happened to be the optimal parameters, i.e. yielding the lowest residuals when evaluating the computed gravimetric geoid model using GPS–levelling benchmarks.
5. GEOID MODEL EVALUATION AND DEVELOPMENT OF A HYBRID GRAVIMETRIC GEOID MODEL

5.1. Gravimetric geoid model evaluation

5.1.1. GPS–levelling benchmark dataset

726 validated GPS–levelling benchmarks with known ellipsoidal height \((h_e)\) and so–called “orthometric elevation” \((H_{RG})\), although based on levelling only, were made available for evaluating and fitting the gravimetric geoid model onto Ras Ghumays vertical datum realization (levelling network). This first order levelling network was found adequately covering the Emirate except in the eastern part (Al–Ain region) where a significant number of LBM were destroyed due to road development work or proved unreliable due to ground motion.

5.1.2. Importance of rigorous orthometric heights

The known elevations \((H_{RG})\) in the GPS–levelling dataset came from geodetic levelling only and did not consider local gravity variations (gravity data unavailable). Actually, rigorously evaluating the gravimetric geoid model should have required using rigorous orthometric heights, obtained by first determining Helmert orthometric heights, then correcting for remaining topographical effects (terrain, density) and remaining variations in the gravity disturbance (Santos et al., 2006). As such rigorous orthometric heights were not available, it was decided to at least evaluate the magnitude of the required corrections.

The orthometric heights \((H^O)\) are defined as in Heiskanen and Moritz, 1967:

\[
H^O = \frac{C}{\bar{g}}
\]

Where \(C\) is the geopotential number and \(\bar{g}\) the integral-mean value of gravity along the plumbline between the geoid and the point, given as:

\[
\bar{g} = \frac{1}{H^O} \int_0^{H^O} gdH^O
\]

Determining \(\bar{g}\) requires measuring the gravity all along the plumbline but it is hardly feasible due to the physical presence of the topography. \(\bar{g}\) is commonly determined using the Poincaré–Prey reduction, which leads to Helmert orthometric heights:

\[
\bar{g} = g_p - \left(\frac{1}{2} \frac{dy}{dh} + 2\pi G \rho\right) H^O
\]

However, \(\bar{g}\) can be more accurately determined when broken into components of various origins, as described in Santos et al. 2006:

\[
\bar{g}(\Omega) \approx \bar{y}(\Omega) + \bar{g}^{NT}(\Omega) + \bar{g}_B^T(\Omega) + \bar{g}_R^T(\Omega) + \bar{g}^{\delta \rho}(\Omega)
\]

where \(\Omega\) represents the position (latitude and longitude) of a computation point; \(\bar{y}(\Omega)\) is the integral-mean value of the normal gravity along the plumbline between the geoid and the point; \(\bar{g}^{NT}(\Omega)\) is the geoid-generated gravity disturbance (the sum of the two latter terms represent the geoid-generated gravity); \(\bar{g}_B^T(\Omega)\) and \(\bar{g}_R^T(\Omega)\) are the integral-mean gravity values of the Bouguer shell and the terrain roughness residual to the Bouguer shell, respectively; \(\bar{g}^{\delta \rho}(\Omega)\) is the integral-mean gravity value of the lateral variations in mass–density from the assumed...
average within the topography.

The influence of the orthometric correction (as defined in Heiskanen and Moritz, 1967) was computed on a subset of 30 LBM's located in the eastern region, forming a continuous levelling line with an elevation gradient of 294 m. The gravity values at all these LBM's were measured during the gravimetric survey. Along this line, the orthometric corrections ranged from -1.9 mm to +2.5 mm par sub section. After application of the corrections, the computed Helmert orthometric heights differed from 0 mm to +13 mm from their known values.

The obtained Helmert orthometric height were then corrected to rigorous orthometric height (as defined in Santos et al., 2006) by computing the geoid, topography, and density effects with UNB's RigOrtH software. These 3 corrections altogether ranged from 0 mm to +6 mm. The addition of the latter to the Helmert orthometric height led to a total correction to be added to the known height ranging from 0.0 cm to 2.0 cm, so quite significant. Also, it was noted that this correction was to be applied on LBM at rather low elevation (maximum height 323.137 m). For any LBM that would be located on nearby Jebel Hafeet (1046 m elevation), the Helmert orthometric corrections would reach around +15 cm while the geoid, topography, and density effects would be +5.6 cm, leading to a total orthometric correction of 20 cm.

5.1.3. Accuracy of the computed gravimetric geoid model

For each validated GPS–levelling benchmark, the observed geoid height \( N_{GPS} = h_e - H_{RG} \) was compared to its gravimetric counterpart \( N_{Geoid} = N_{Geoid} - N_{GPS} \). After removal of the average difference of –88.2 cm coming from the vertical offset between the raw gravimetric geoid model and the Ras Ghumays MSL, this difference ranged from –15.4 cm (with blue dots on following Figure 10) to +17.3 m (with red dots) with a standard deviation of 4.8 cm. However, this range merged different backgrounds together. Therefore, to further evaluate the gravimetric geoid precision, notably its added value compared to GECO, the GPS–levelled dataset was divided into 3 subsets, respectively covering the Western, Abu Dhabi, and Al Ain regions.

![Figure 10: Spatial distribution of \( \Delta N_{Gravi} \). Plotted values in blue are samples of \( \Delta N_{Gravi} \).](image-url)
As a result, the following Table 1 shows that the computed gravimetric geoid model clearly improved the GGM in the Western region (in this area, the standard deviation was divided by more than a factor 2, down to 3.3 cm, and the difference between the minimum and maximum difference dropped from 31.1 cm to 13.3 cm) and in Abu Dhabi region (standard deviation went down to 2.7 cm and the difference between the minimum and maximum difference dropped from 27.3 cm to 15.7 cm).

<table>
<thead>
<tr>
<th>Region</th>
<th>$\Delta N_{Grav}$ Standard deviation [m]</th>
<th>Minimum $\Delta N_{Grav}$ [m]</th>
<th>Maximum $\Delta N_{Grav}$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Western Region (375 LBM)</td>
<td>GECO 0.067 Gravimetric geoid 0.033 GECO -0.134 -0.078 +0.177 +0.100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abu Dhabi (214 LBM)</td>
<td>GECO 0.044 Gravimetric geoid 0.027 GECO -0.090 -0.077 +0.183 +0.080</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al Ain (137 LBM)</td>
<td>GECO 0.072 Gravimetric geoid 0.087 GECO -0.125 -0.156 +0.213 +0.170</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Regional evaluation of Abu Dhabi gravimetric geoid using GPS–Levelling points

In Al Ain yet, the computed gravimetric geoid model appeared to slightly degrade the global model (higher standard deviation). Due to the vicinity of the Al Hajar mountain range as well as the scarcity of surrounding data in the North–East and East of the Emirate, some specific trend appeared to be not perfectly captured by the computed gravimetric geoid model. However, when zooming on the results, it appeared that, while a long wavelength trend had not been captured indeed, the apparent decrease in accuracy concealed significant local improvement at short wavelength: on these areas, whereas the differences to GECO ($\Delta N_{GECO}$) exhibited a standard deviation of 5.3 cm, with the gravimetric geoid this value was reduced to **3.3 cm**, so a very significant improvement.

This result showed that the gravimetric geoid, based on dense gravity data, was accurate at local scale, which denotes its capability to perfectly capture the fine variations of the gravity field, but, due to the scarcity of gravity data in the North-east and East of Al Ain region, failed to capture the long wavelength trends induced by the topographic and geologic structures located beyond the Emirate boundary (notably Al Hajar mountain range).

Consequently, whereas the gravimetric geoid could be considered as self sufficient in the Western and Abu Dhabi regions (standard deviations of **3.3 cm** and **2.7 cm**), in the easternmost parts of Al Ain region, fitting the gravimetric geoid model onto GPS–levelling benchmarks was considered essential.

5.2. Development of a hybrid gravimetric geoid: Least Square Collocation fitting

To achieve a geoid model consistent with the realization of the Ras Ghumays vertical datum, a Least Squares Collocation (LSC, applied with a Gaussian covariance function) was performed on a cleaned GPS–Levelling dataset. 21 points were identified as less consistent, so the input dataset for the LSC was reduced to 705 points to minimize the distortion that could be introduced by inconsistent points. Figure 11 shows the contour lines of the obtained LSC correction surface. After applying both the global shift and the correction surface to the

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gravimetric model, residuals on GPS–levelling benchmarks were recomputed. The standard deviation of the 726 residuals was 1.6 cm, ranging from –7.9 cm to +7.9 cm.

![Figure 11](image)

**Figure 11**: Contour lines of the LSC adaptation surface (values in meter). Corrections range from –13.3 cm to +13.6 cm.

### 5.3. Blind tests: Independent evaluation with degraded hybrid geoid models

The final hybrid gravimetric geoid model evaluation was performed using the blind tests method. By splitting the GPS–Levelling dataset into three subsets (each one made up of 235 points) evenly distributed throughout the territory, three independent hybrid gravimetric geoid models were created. For each one, an evaluation was performed on the GPS–Levelling benchmarks of the other two subsets that had not been used in the LSC process. The maximum standard deviation was 2.1 cm, which proved the good consistency of the three subsets. This value represented the estimation of the accuracy of the final hybrid gravimetric geoid model (i.e. gravimetric geoid model fitted onto the 705 GPS–Levelling benchmarks).

Figure 12 presents the differences between the LSC performed with entire GPS–Levelling dataset and each LSC performed with each of the three subsets. As expected, a few local biases were visible (up to +/-5 cm) but the global evaluation validated the final hybrid gravimetric geoid model (standard deviations of 0.6 cm for (a), 0.8 cm for (b) and 0.8 cm for (c), average is 0.7 cm).

![Figure 12](image)

**Figure 12**: Comparison between LSC surface created with all GPS–Levelling benchmarks and with subset 1 (a), subset 2 (b) and subset 3 (c). The GPS-Levelling benchmarks of the subset 1 are pink, of the subset 2 yellow and the of the subset 3 green.
REFERENCES


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