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Full Length Research Paper

Coastal geoid improvement using airborne gravimetric data in the United Arab Emirates

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Military survey department (MSD) of The United Arab Emirates (UAE) has undertaken the Airborne Gravity Survey Project for the marine area of the country. The main purpose for the implementation of the airborne gravity survey for the marine area is to improve the existing gravimetric geoid of the UAE. The airborne gravity data was estimated to have accuracy better than 2.0 mGal. The first gravimetric geoid for the country has been established after the completion of nation-wide gravity survey of 5 km grid spacing by the MSD in 2003. The 2003 geoid was hampered by the lack of gravity data along the near coast area (including marine) as well as the eastern part of the country. The geoid has subsequently been computed from all available data: airborne gravity, surface gravity (including older data), satellite altimetry gravity and EGM08 reference field, as well as detailed height data from the shuttle radar topography mission (SRTM). The geoid computations were all done with the GRAVSOFT suite of programs from DTU-Space and University of Copenhagen. The computations involve a rigorous downward continuation from airborne to surface level by least-squares collocation. The result is a gravimetric geoid model "uae2009_gravgeoid2", that is, a geoid model which refers to a global vertical datum. The change of geoid models computed with or without the new airborne gravity data showed differences of 30 cm or more, largest along the coast of the Northern Emirates and Fujairah. Using available global positioning system (GPS) leveling data from the 2003 report, a new geoid fitted to the UAE height system "uae2009_geoid" has been constructed and made available. The fitted geoid is dependent on the quality of the available GPS-leveling data, which have many apparent errors. Therefore the gravimetric geoid has been transformed by a single constant as well, to yield a shifted gravimetric geoid, "uae2009_gravgeoid", roughly consistent with the UAE vertical datum and more suitable for any future adaptions of the geoid to local GPS-levelling data. The accuracy of the gravimetric geoid is estimated to be 3 to 5 cm across most of the UAE. Lower geoid accuracy of about 5 cm is expected over mountainous region in the north-eastern part of the country.

Key words: Geoid, gravity, airborne gravimetry, global positioning system (GPS), satellite altimetry.

INTRODUCTION

The geographical coverage of the land gravity data in the UAE has been improved substantially by detail gravity survey at 5 km grid covering the country in 2003. The detail gravity survey campaign has been conducted by Military Survey Department (MSD) of the UAE in association with Fugro Ground Geophysics (FGG). The survey has been conducted over a period of two months covering land areas of all the Emirates. The main transportation used during the detail gravity survey was a

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helicopter. Positioning for detail gravity stations have been determined using differential GPS technique. A total of 6,086 points of new gravity values has been measured over land area of the country. Free-air gravity anomaly values have been deduced from the gravity measurement following appropriate reduction procedures. Combined with other data, the gravity values have been used to compute the first gravimetric geoid of the UAE at ±5 cm level accuracy (Adel, 2007).

The main purpose for the implementation of the airborne gravity survey for the marine area is to improve the existing coastal geoid of the UAE. The existing geoid was hampered by the lack of gravity data along the near coast area (including marine) as well as the eastern part of the country. The new geoid has to be computed from all available data: new airborne gravity, existing surface gravity (including older data), satellite altimetry gravity and EGM08 reference field, as well as detailed height data from the SRTM mission. The new geoid is expected to have accuracy better than ±3 cm. A precise knowledge of geoid is of particular interest for global positioning system (GPS)-leveling application and in support of future height modernization initiative in the country.

THEORETICAL BACKGROUND

The basic method of the UAE gravimetric geoid computation is spherical Fast Fourier Transform (FFT) with modified kernels. The merging of airborne and surface data has been done in an optimal fashion by least-squares collocation, along with formal error estimation.

The basic concept of the computations is the "remove-restore" technique, where the anomalous gravity potential T is split into three parts:

$$T = T_{EGM} + T_{RTM} + T_{res} \quad (1)$$

Where,

T_{EGM} is the anomalous gravity potential of a spherical harmonic model.

T_{RTM} is the anomalous gravity potential generated by the Residual Terrain Model, that is, the high-frequency part of the topography computed by prism integration from SRTM height data.

Tres is the residual anomalous gravity potential residual, that is, the potential corresponding to the un-modeled part of the residual gravity field computed by spherical FFT.

The outcome of the remove-restore technique is a gravimetric geoid referring to a global datum. To adapt the geoid to fit the local vertical datum and to minimize possible long-wavelength geoid errors, a fitting of the geoid to GPS control is needed as the final geoid determination step. The software package GRAVSOFT is the base of all computations. This software has been upgraded in the later years with a Python use interface.

By the RTM method used here, in principle the quasi-geoid 'ζ' is modeled:

$$\zeta = \frac{T(\phi, \lambda, H)}{\gamma(\phi, H)} \quad (2)$$

Where, γ is the normal gravity, φ and λ are the geographical latitude and longitude, and H is the orthometric height. The quasi-geoid (ζ) and the classical geoid (N) can be viewed as "the geoid at the topography level" and the "geoid at sea-level", respectively. The relation between the N and ζ is given by the approximate formula:

$$\zeta - N \approx -\frac{\Delta g_B}{\gamma} H \quad (3)$$

Where, Δg_B is the Bouguer anomaly and H the topographic height.

In this exercise the "classic" gravimetric geoid (*N*) has been computed, that is, the geoid corresponding to orthometric heights, measured from the geoid mean sea level inside the mass (ζ) corresponds to "Molodensky" normal heights. The "N-ζ " corrections are small in the UAE. By computing *N* rather than ζ, the UAE geoid ($N_{UAE2009}$) is thus directly applicable to give heights in a conventional orthometric height system by:

$$H = h_{GPS} - N_{UAE2009} \quad (4)$$

SPHERICAL HARMONIC REFERENCE MODEL EGM08

The Earth Gravity Model 2008 (EGM08) is a new spherical harmonic expansion, complete to degree and order 2190, released by the US National Geospatial-Intelligence Agency with cooperation of the International Association of Geodesy on evaluation of the data. For details see http://earthinfo.nga.mil.

We have used the EGM08 to full degree as reference field in the present computations, primarily because we assume the EGM08 will contain data sources from neighboring countries (especially Oman and Saudi Arabia). It is not known which data exactly included in EGM08, but it is known that in the Gulf region classified 15' mean gravity data was used, which was subsequently interpolated to 5' by an RTM interpolation scheme.

The EGM08 is presented by more than 4 mio spherical terms of (quasi-) geoid the representation is of the following form:

$$\zeta_{EGM96} = \frac{GM}{R\gamma} \sum_{n=2}^{N} \left(\frac{R}{r}\right)^{n} \sum_{m=0}^{n} \left(C_{nm} \cos m\lambda + S_{nm} \sin m\lambda\right) P_{nm}(\sin\phi) \quad (5)$$

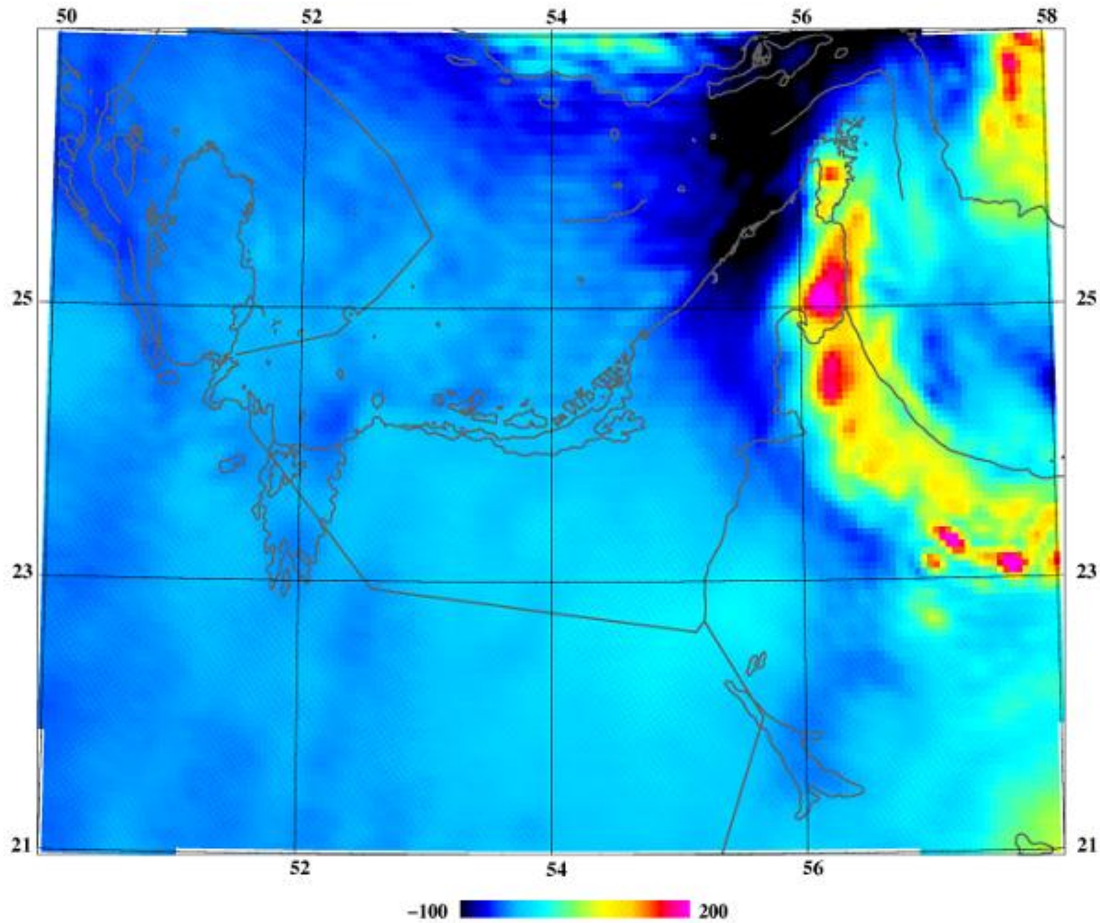

Figure 1. Gravity anomaly from EGM08 fields (Unit mGal).

Where, N in this case is 2190. This corresponds to a spatial resolution of 5', albeit over much of the world terrestrial gravity data is only used to a resolution of 15' due to data classification issues.

EGM08 is like its predecessor EGM96 determined from a combination of satellite tracking data, satellite altimetry (in the oceans) and mean gravity anomalies (on land). For EGM08 a much improved GRACE model, based on more than 5 years of satellite measurements, has been used, as well as improved satellite altimetry solutions in the open oceans (Sandwell and Smith, 2009) and DNSC08 in the coastal regions. EGM08 is a major step ahead in the modeling of earth's gravity field (and thus geoid), with reported geoid fits at the level of 5 to 10 cm RMS or better in many regions of the world.

Because of the ultrahigh degree of expansion (n=2190) the present computations have been done with geocol17 (GRAVSOFT), where expansions beyond degree 360 was not yet implemented in the simple harmexp setup used in the 2003 computations. Figure 1 shows the gravity signals from EGM08 computed on a 3' x 3' grid.

It has been found that there are major differences between EGM08 and EGM96 field being observed especially in the mountains area of the Fujairah Emirate. Some improvement in the computed geoid over this region is expected.

Overall the EGM08 and EGM96 geoid levels are nearly the same, with an offset of only 8 cm (Table 1). It should be pointed out, however, that the EGM08 geoids refer to a global geoid model, and cannot be directly used for converting GPS heights to local heights in the UAE.

DATA

The UAE2009 geoid computation utilize the 2003 Fugro helicopter gravity survey, done on a near-perfect 5 km grid spacing (Figure A1). This data set have been augmented with additional surface data sources shown in Figure A2 and with 2001 data from Dubai Emirate for a comprehensive bias-free land surface data set.

Marine gravity data exists from 3 sources as shown in Figure A3. These data are consistent within 1 mGal in internal biases (after adjusting the 1954 survey from Potsdam to IGSN). These data have therefore been treated as one marine source. A second marine source from Bureau Gravimtrique (BGI), used for the 2003 geoid, was suspected to have large errors, and are not used in the computations.

Satellite altimetry gravity has been derived from the global

Table 1. Difference between EGM08 and EGM96 in the UAE.

Quantity	Mean	Std. Dev.
EGM08-EGM96 geoid (m)	-0.08	0.41
EGM08-EGM96 gravity (mGal)	0.26	17.72

DNSC08 solution. The DNSC08 solution is developed by Ole Andersen at DTU-Space from ERS, GEOSAT and Topex global satellite altimetry, inverted to marine gravity anomalies by FFT using GRAVSOFT (DNSC = Danish National Space Center, former name of DTU-Space). Because of the lack of data on land, satellite altimetry cannot be used very close to the coast. Therefore the DNSC08 data have been thinned and only used when the distance to the coast was at least 15 km. The data coverage is shown in Figure A4. The data overlaps with the airborne and marine gravity surveys, and satellite altimetry is therefore given a relatively low weight of 5 mGal in the collocation solution.

Detailed SRTM 3" resolution DEM data for the UAE region was downloaded from NASA/USGS web sites, and reformatted from the binary ".hgt" files to GRAVSOFT format, and averaged to 9" resolution. The detailed SRTM data files showed regions with unknown data (flagged as 9999 in the GRAVSOFT system), clearly corresponding to the SRTM satellite mission orbits. The data voids were filled in with data from the 30" SRTM file, used as basic DEM in the 2003 geoid computation.

This combination was done in job "combine_dem" using GRAVSOFT modules *gcomb* and *select*, resulting in a basic DEM file uae_dem9s.gri. The basic DEM file was subsequently averaged to 1.2' (0.02 degree) grid cells, corresponding to the wanted resolution of the updated geoid model.

The terrain reduction used is RTM – residual terrain modeling. In this method a reference height surface is used as base for removing topography above or filling in topography below the reference surface. The reference height surface was constructed by Gaussian smoothing of the DEM with a full-width resolution of 6' (Figure 2), roughly corresponding to the use of EGM08.

REDUCTION OF GRAVITY DATA FOR EGM08 AND TERRAIN

The various data were reduced for EGM08 and terrain effects, and the results shown in Table 2. The RTM corrections were done by prism integration assuming a density of 2.67 g/cm^3 using the GRAVSOFT tc module. The terrain corrections mainly affects the land data, and only limited smoothing is taking place, because the medium wavelengths of the terrain are already included in EGM08. Figure A5 shows the combined data set of reduced land, marine and airborne data.

The airborne gravity data show a good agreement to the surface data. A few errors, mainly due to turbulence can be seen on a few tracks. With an RMS error estimate of 2 mGal for the airborne data (1-sigma) some outliers must be expected up to the 3-sigma level. These spurious effects have negligible significance on the geoid.

To estimate the consistency between the airborne data and the surface data on the longer wavelengths, Table 3 shows the result of a direct comparison of airborne to marine data (Mobil/GECO data only) and land data. The comparison was done by predicting from the surface data to the thinned (30 s sampling) airborne gravity location points, and only doing a comparison when data are within 3 km, that is, approximately half the filter resolution of the airborne data. Upward continuation effects are neglected for this specific comparison.

From Table 3 it can be seen that the recent marine data fit to 2 mGal RMS with the airborne gravity, in excellent accordance with the error estimate of the airborne data. A bias is seen between marine and airborne data. It cannot be judged if this bias comes from the marine gravity or the airborne gravity; the airborne gravity does not show a bias to the land data (although the comparison base is limited to a few coastal tracks and a mountain flight). It is quite likely that the marine data have biases, since marine data port references can often be erroneous. We have therefore not done any modifications to biases to any of the surveys for the present geoid computation. Since the longer wavelengths of the geoid will be controlled by GRACE the effect of data biases on the geoid should be minor.

It should be pointed out, though, that the absolute level of the airborne survey is based on the absolute gravity value at the absolute station in the basement of the MSD office in Abu Dhabi. This value was measured by Fugro using an A10 absolute gravimeter. It is assumed that this value is not corrected for atmosphere (+0.87 mGal).

DOWNWARD CONTINUATION AND DATA GRIDDING

The downward continuation of airborne gravity and the gridding of data have been performed using block-wise least-squares collocation, as implemented in the *gpcol1* module of GRAVSOFT. This module uses a planar logarithmic covariance function, fitted to the reduced data. In least squares-collocation the gravity anomaly signal "s" at a ground grid point is estimated from a vector "x" containing all available surface and airborne data by:

$$\hat{s} = C_{sx}[C_{xx} + D]^{-1} \tag{6}$$

Where, covariances C_{xx} and C_{sx} are taken from a full, self-consistent spatial covariance model, and D is the (diagonal) noise matrix.

Because the gravity field of the earth is known to follow Kaulas rule, it is important to select covariance models which have an implied PSD decay in accordance with this (Olesen et al., 2000). An example of such a self-consistent covariance model on a spherical earth is the Tsherning-Rapp model (for example, Moritz, 1980), and for a flat earth the simpler planar logarithmic covariance model (Forsberg, 1987). In the latter model, the gravity covariance between anomalies at two altitudes is given in the following form:

$$C(\Delta g^{h_1}, \Delta g^{h_2}) = -\sum_{i=1}^{4} \alpha_i \log\left(D_i + \sqrt{s^2 + (D_i + h_1 + h_2)^2} \right) \tag{7}$$

Where, α_i are weight factors combining terms relating to two depth value terms (D,T), with $D_i = D + iT$. The depth D is taking the role analogous to the Bjerhammar sphere depth of spherical collocation, and T is a long-wavelength "compensating depth" attenuation factor. For the UAE, with a very smooth gravity field, a reasonable fit to the covariances was obtained with D = 3km and T = 50 km. This corresponds to a correlation length of approximately 13 km.

The collocation runs are done in 1° × 1° blocks, with a 0.6° border. The data are subsequently patched together into a GRAVSOFT grid for further geoid processing. Two downward continued grids were computed by jobs *gpcol1.job* and *gpcol2.job*:

(1) A grid downrd1.gri with only surface data and DNSC08 altimetry
(2) A grid downrd2.gri with all data combined, including airborne gravity

In these collocation runs land gravity was giving a standard deviation of 1 mGal, marine and airborne gravity 2 mGal, and

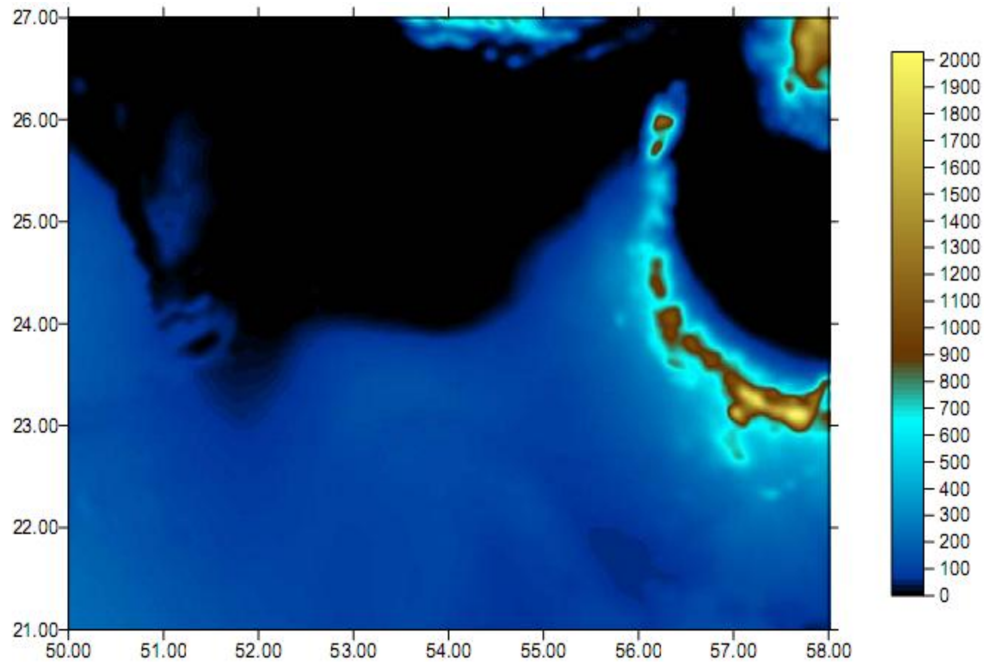

Figure 2. Reference DEM surface used for the geoid computations.

Table 2. Statistics of data, EGM08 and terrain-reductions (unit: mGal).

Data set	Original data		Reduced for EGM		RTM and EGM08 reduced	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Land gravity	-30.13	38.80	-0.38	6.12	0.41	5.53
Marine gravity	-33.15	4.50	-1.27	3.40	-1.27	3.40
Airborne gravity	-32.56	35.40	2.06	7.77	2.10	7.78
DNS08 altimetry	-35.87	23.49	-0.15	2.44	-0.15	2.44

Table 3. Comparison of reduced airborne and surface data within 3 km (Unit mGal).

Dataset (Airborne – Surface)	Comparison points num.	Mean offset	Std. Dev.
GECO and Mobil Marine	102	3.65	2.07
FUGRO Land Gravity	33	-0.77	4.99
DNSC Satellite Altimetry	121	2.22	5.51

satellite altimetry 5 mGal. Figure 3 shows the two reduced data grids, which as expected shows a high variability over the mountains, but a reasonably consistent and error-free behavior elsewhere.

It is clearly seen that the airborne survey has measured major anomalies offshore the northern emirates. In this region a major change to the coastal geoid is expected.

GEIOD COMPUTATION AND ANALYSIS

The geoid is subsequently computed by spherical Fourier method, using 100% zero padding and a Wong-Gore Stokes function modification band of 80 to 90 (Forsberg et al., 1999). This involved a series of FFT transforms with grid sizes of 600 × 800 points. From the reduced gravity data, the final quasi-geoid ζ is computed from:

$$N = \zeta_{FTT} + \zeta_{RTM} + \zeta_{EGM08} + (N-\zeta^{*}) \qquad (8)$$

Where, the first term ζ_{FTT} is computed by the Fourier transform of residual gravity, second term ζ_{RTM} is the terrain "restore" part (computed also by FFT from the

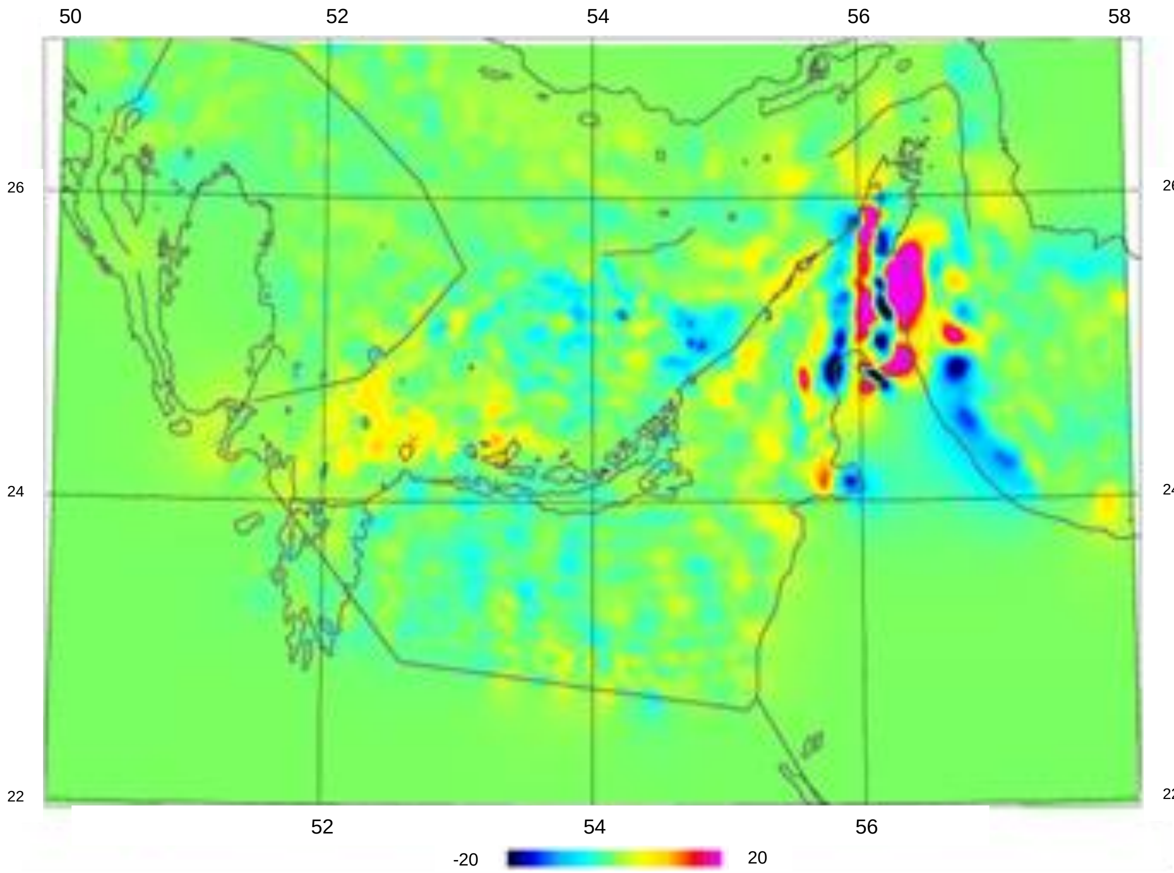

Figure 3. Collocation grids, top: #1 grid (no airborne); lower: #2 with airborne (in mGal).

Table 4. Statistics of the geoid restore steps (Unit in m).

Quantity	Geoid 1 (without airborne data)			Geoid 2 (with airborne data)		
	Mean	**Std. dev**	**Abs min/max**	**Mean**	**Std. dev**	**Abs min/max**
Geoid part from FFT	0.00	0.06	0.83	0.00	0.06	0.66
Geoid part from RTM	0.00	0.12	2.58	0.00	0.12	2.58
Correction from Quasi-geoid to geoid	-0.01	0.03	-0.86	-0.01	0.03	-0.86
Final Geoid	-31.80	2.85	-36.45	-31.80	2.84	-36.45

heights), and ζ_{EGM08} the EGM08 geoid effect at sea level. The last term in Equation (8) is the correction between quasi-geoid at sea-level and the classical geoid. Table 4 outlines the statistics of the geoid restore steps.

The difference between the geoids with and without airborne data gave a mean value of 0.00 and a standard deviation of 0.03 m, with a maximal difference of 53 cm (Figure 4). It is seen that the new airborne data significantly change the geoid both off Northern Emirates and Fujeirah, as well as the far westernmost Abu Dhabi coastal region.

The final geoids are gravimetric geoids in a global datum. Opposed to 2003, we have initially left the gravimetric geoids to the computed level. In the previous computation (2003) a constant shift of 79 cm was applied for roughly fitting the gravimetric geoid to the UAE height datum. The gravimetric geoids are compared to the GPS levelling derived geoid heights at 362 points (file msd_all_n.dat, 362 points) as shown in Table 5 and Figure A6).

The final computed gravimetric geoid (UAE2009_gravgeoid2.gri) is shown in Figure 5. In order to roughly fit the UAE height system, this gravimetric geoid has been shifted by 84 cm to give the shifted geoid (UAE2009_gravgeoid.gri). The difference between the shifted 2003 and 2009 geoids are shown in Figure 6.

The comparison of the gravimetric geoids show an improvement after using the airborne data, and also

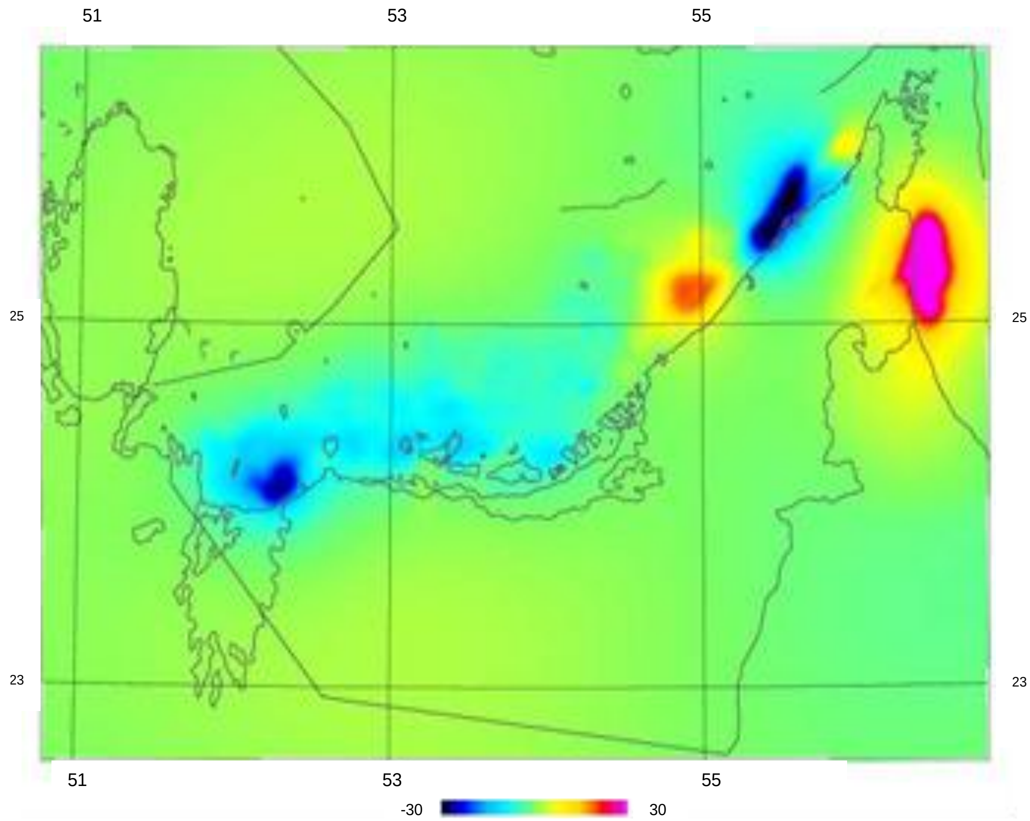

Figure 4. Difference between geoid with and without airborne data (unit in cm).

Table 5. Comparison of gravimetric geoids to GPS-levelling (unit in m).

Geoid model	Mean	Std.dev.	Min	Max
UAE2009 geoid1 (wihout airborne data)	0.85	0.15	0.48	1.14
UAE2009 geoid2 (with airborne data)	0.84	0.13	0.50	1.16
UAE2009 geoid2 (constant shifted)*	0.00	0.13	-0.34	0.32
UAE2003 geoid (constant shifted)*	0.03	0.17	-0.43	0.34
EGM96	0.87	0.39	-0.43	2.25
EGM08	0.87	0.16	0.45	1.26

*The 2009 geoid offset by 84 cm, and 2003 geoid by 79 cm, to roughly fit the UAE height datum.

significantly reflect better quality of the global reference field EGM08 compared to EGM96. It should be pointed out that the original GPS-levelling data set contained a number of outliers, rejected in 2003, and therefore the quality of the GPS levelling is not sufficient to judge the errors in the geoids, which are estimated to be well below 5 cm for most of the UAE.

Conclusion

The new airborne gravity data from the 2009 survey has been used together with earlier reformatted, quality controlled and checked land and marine gravity data, as well as updated satellite altimetry gravity, DEM data from SRTM for geoid computations. FFT and collocation has been used, with remove-restore of the new EGM08 geopotential model, complete to spherical harmonic 2190. Over most of the UAE the relative gravimetric geoid accuracy is estimated to be 2 to 3 cm from collocation error estimates. However, in mountainous northeastern region vary large tectonic gravity anomalies, and especially the lack of gravity data in Oman, makes the gravimetric errors potentially much larger, 10 to 20 cm or more. In spite of the (limited) new airborne data offshore this region, some problems in the geoid are still evident.

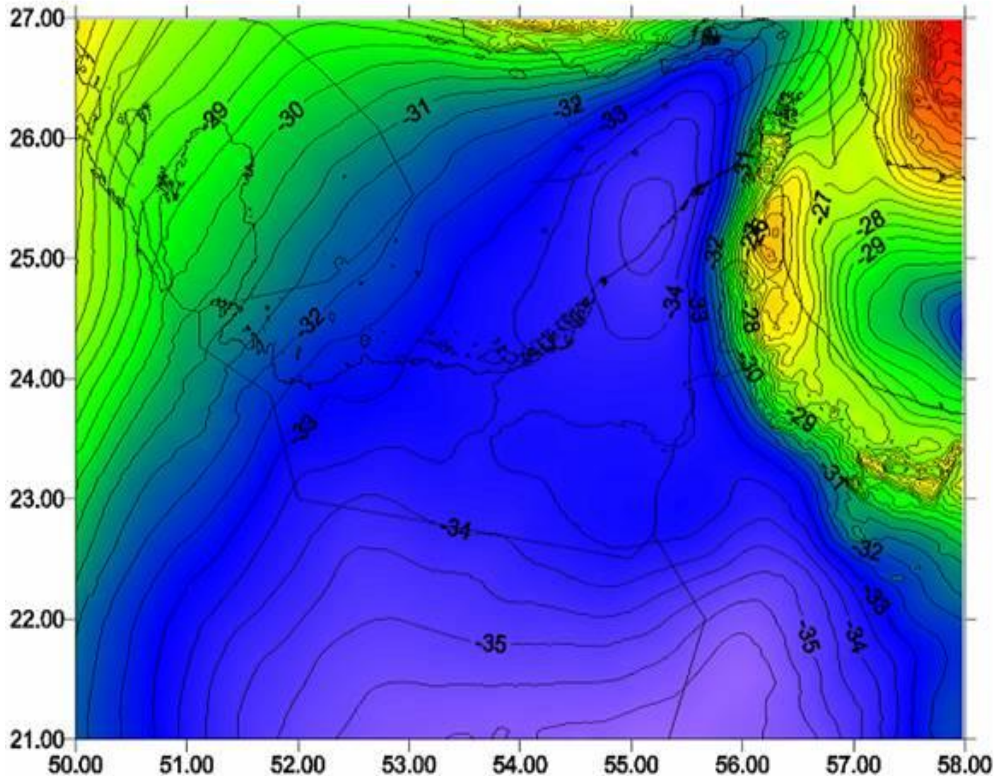

Figure 5. Computed gravimetric geoid "UAE2009_gravgeoid2" (Contour interval 50 cm).

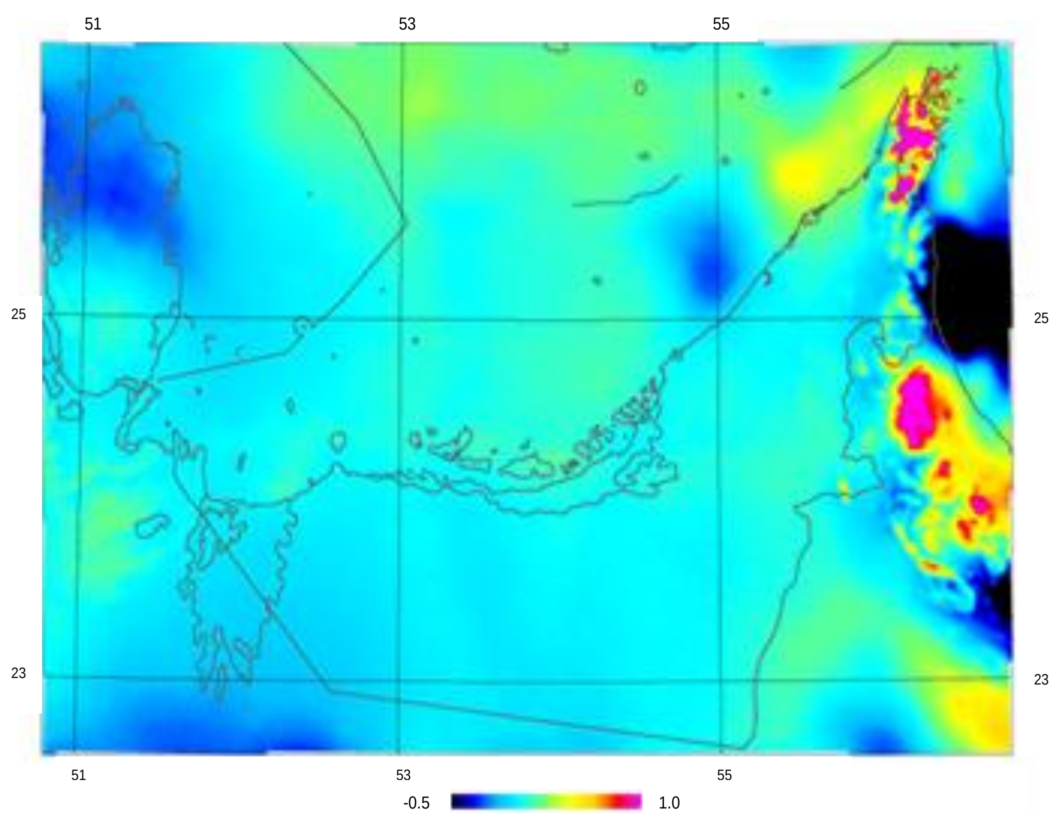

Figure 6. Difference between 2009 and 2003 shifted gravimetric geoids (Unit in m).

Unfortunately due to airspace restrictions, only limited airborne data offshore Fujairah are available where geoid variations are the largest.

Overall results indicate that the new gravimetric geoid inherently should have a high accuracy, since excellent gravity survey data is underlying the computations, with long wavelength control provided by the high accuracy GRACE information in EGM08. The GPS-fitted geoid still shows problems relating to errors in GPS leveling. It is recommended to review the datum definitions and quality of the leveling data in the country.

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APPENDIX

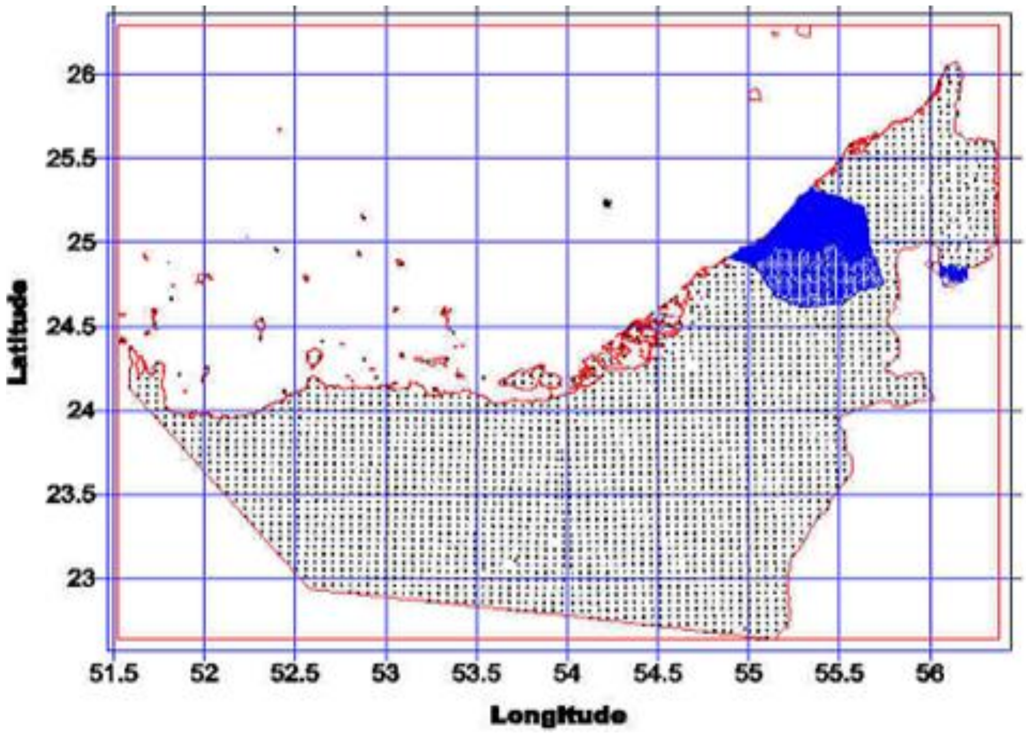

Figure A1. Fugro land gravimetry 2003 (This survey controlled by absolute gravity measurements at MSD in Abu Dhabi).

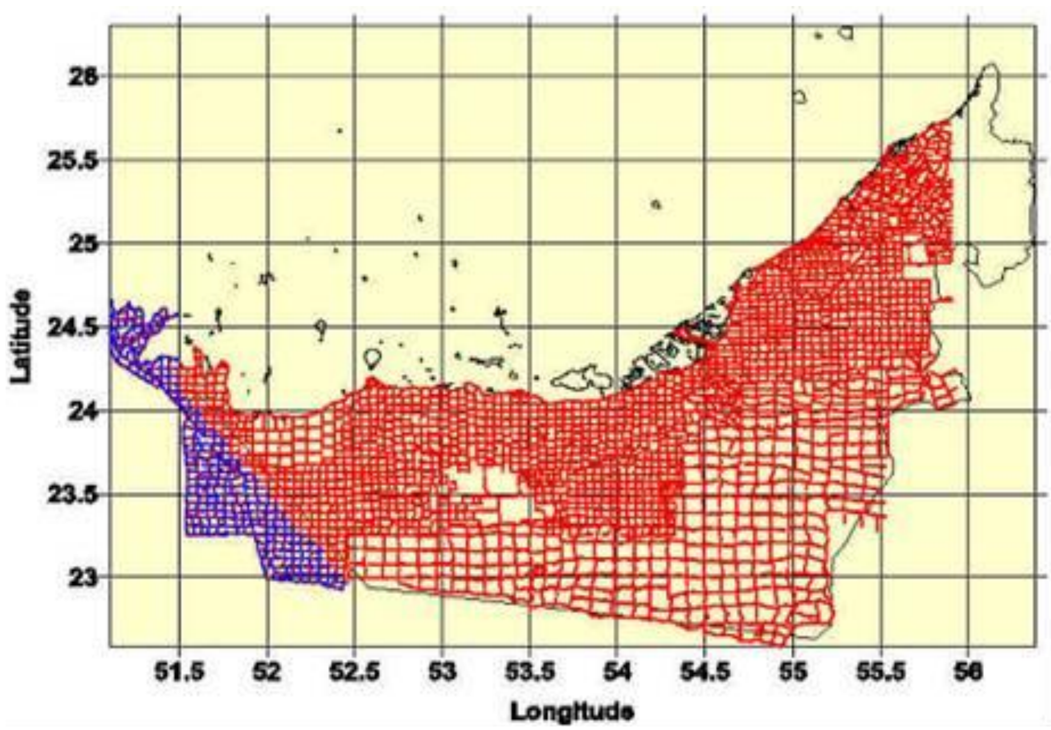

Figure A2. Location of old land data (Ray, 1947 to 1956). Only data in the Western region (Now under Saudi control and marked with blue) were used.

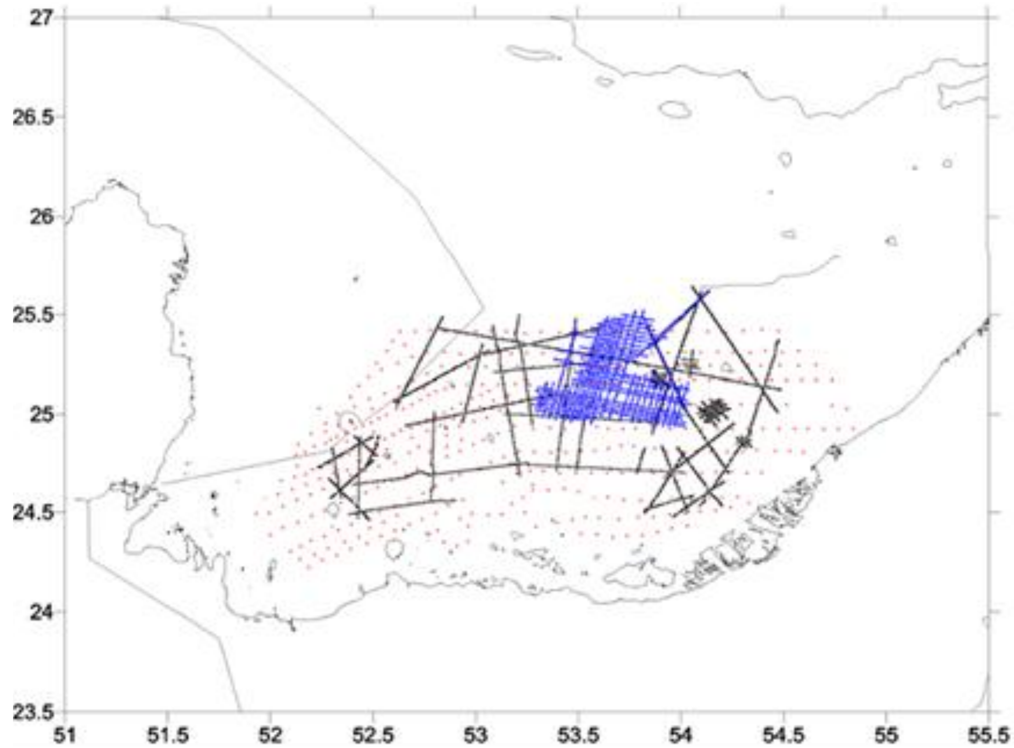

Figure A3. MSD marine gravimetry available for the geoid determination (Black: GECO, 1980; Blue: Mobil, 1981 to 1982; Red: 1954 ocean bottom survey).

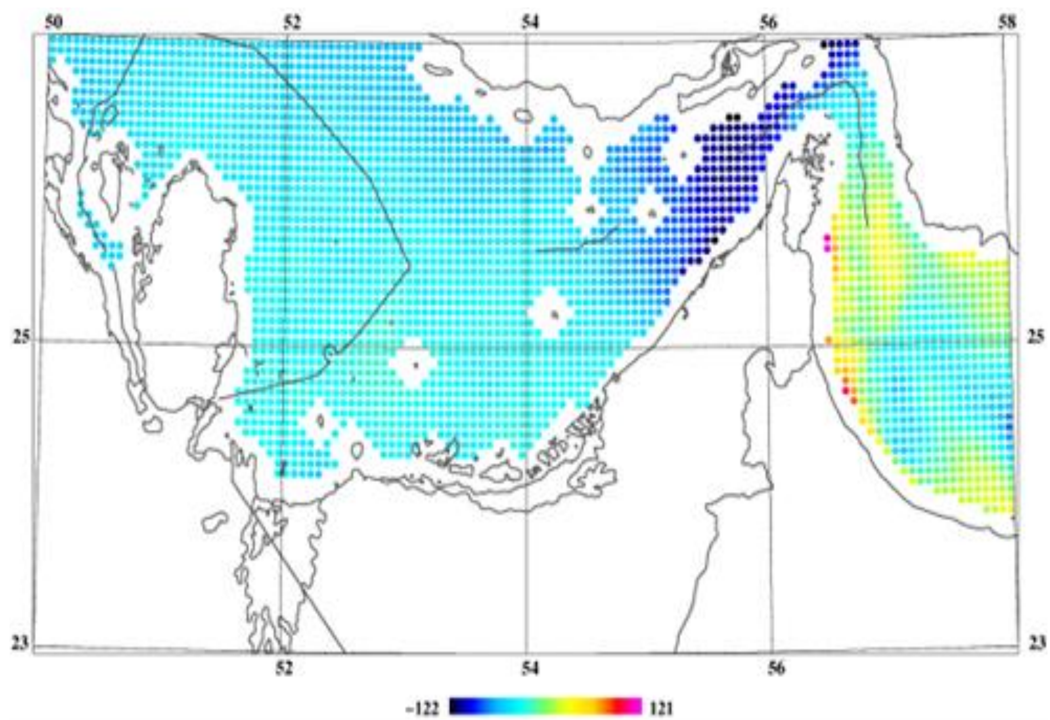

Figure A4. Selected satellite altimetry gravity anomalies (Colour scale in mGal).

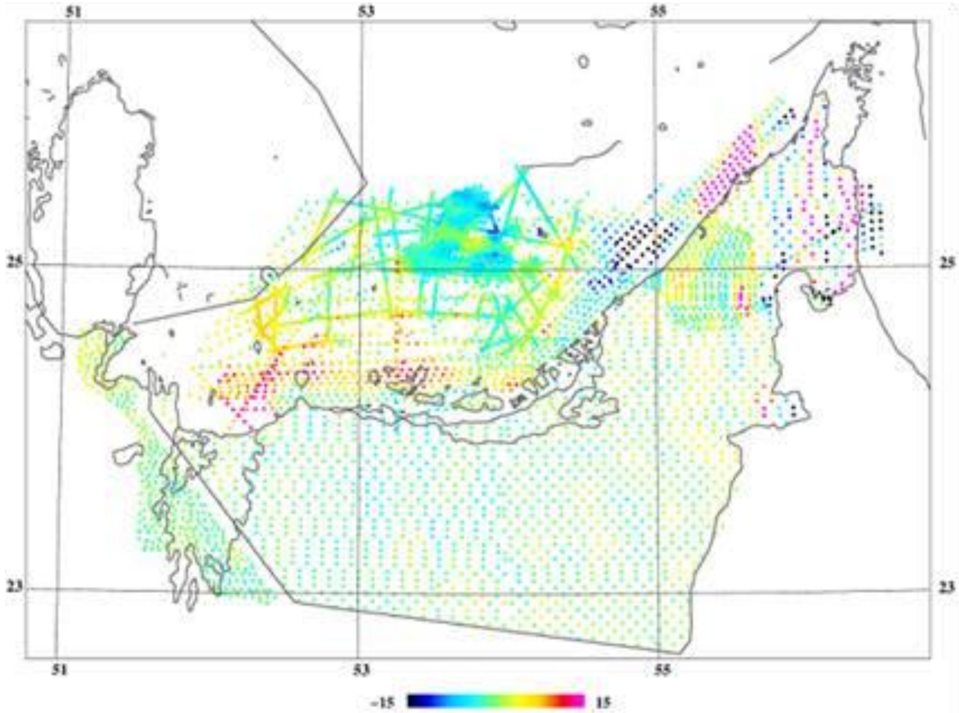

Figure A5. EGM08 and RTM reduced data in UAE. The residuals may be due to errors in data, or errors in EGM08, and are large in the mountains (Colour scale in mGal).

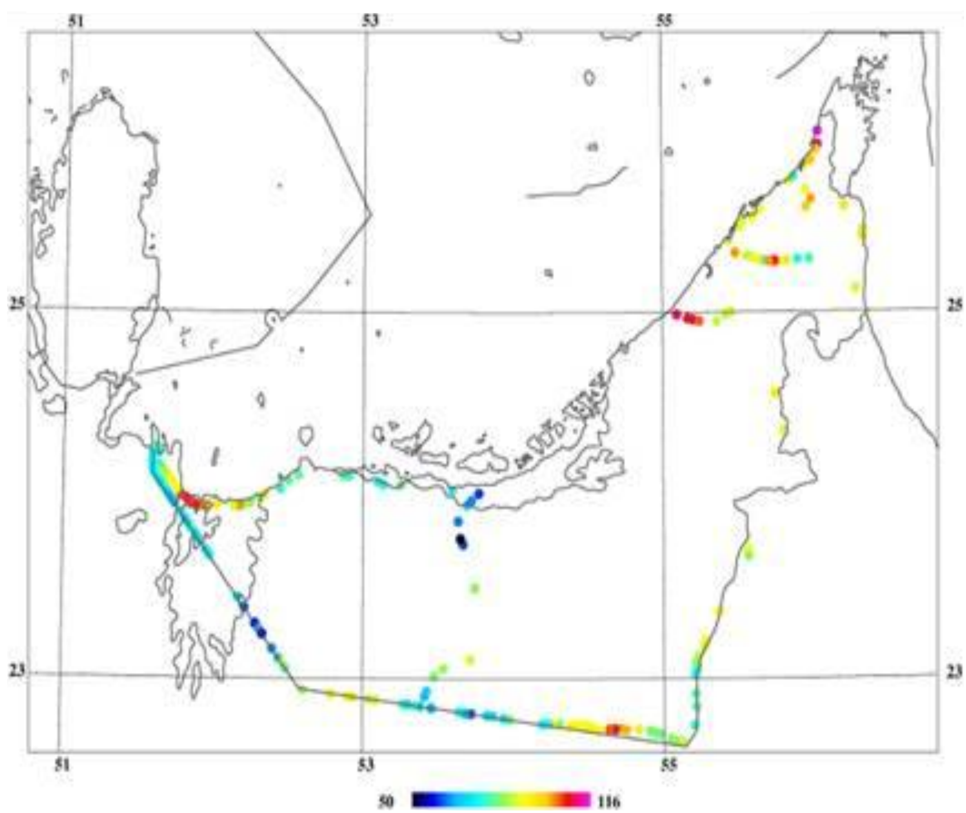

Figure A6. Difference between GPS-levelling geoid and the gravimetric geoid 2 at 362 points (Unit in cm).