The New Gravimetric Geoid Model of Qatar: QG2020

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Key words: Gravity field, Geoid, GNSS, Reference frames

SUMMARY

With the advent of GNSS, geoid undulations models are the new norm to obtain precise orthometric heights. Global geoid models, such as EGM2008 and EIGEN-6C4, are already able to provide few decimeters level accuracy but are still not able to properly model the short wavelengths of the Earth's potential. Consequently, when higher accuracy is necessary, the global models need to be refined for the area of interest.

The state of Qatar was using officially a geoid model (Qatar95) based on the OSU91A global model. Qatar95 was clearly outdated because the OSU91A global model has low accuracy and low spatial resolution and few terrestrial gravity data for this area were included for its computation. In addition, Qatar95 was constrained with levelling observations which, although improving the consistency with the official vertical datum, was causing significant deformations in some areas. More recent global geoid models such as EGM2008 still show differences of around ±30 cm with GNSS/levelling data. For EIGEN-6C4, GOCE-OGMOC and XGM2019e these differences are smaller but still around ±10 cm.

To compute the new official geoid (QG2020) for the State of Qatar, purely based on gravity, a field campaign has been performed in February 2020 during which 399 new gravity and GNSS measurements were made, covering the whole country with an average spacing of 5 km. Using the Remove-Compute-Restore technique (using EIGEN-6C4 to model the long wavelengths of the Earth's gravity field) and Least-Squares Collocation, these gravity values were converted into the new geoid. The new geoid has been linked to the national vertical datum of Qatar, at the main fundamental benchmark.

We describe here QG2020 focusing on the methodology and its validation with three different sets of GNSS/levelling data. The new geoid QG2020 is made available in various digital formats that can be used in most GNSS equipment and software packages. The formal (relative) error (predicted standard deviation) of the computed geoid is about 1 cm, reaching 2 cm near the coastline.

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1. INTRODUCTION

In Qatar orthometric heights (H) are used (Qatar Survey Manual, 2009). On the other hand, GNSS provides heights (h) above a reference ellipsoid. The relationship between these two heights is (Hofmann-Wellenhof and Moritz, 2006):

$$H = h - N \quad (1)$$

Where N is called the geoid undulation above the reference ellipsoid. In this research we describe the computation of a new geoid model, called QG2020, based on new terrestrial gravity data, which can be used to convert the GNSS derived ellipsoidal heights in official orthometric heights in Qatar. Such a new model is necessary because, despite the recent satellite missions of GRACE and GOCE, even the most recent global geoid models are still not accurate enough. The satellite data only measures the long wavelength of the Earth's gravity field, longer than 150 km in case of GOCE and 200 km for GRACE and need to be complemented with other measurements such as terrestrial gravity data to capture the shorter variations in gravity. One of the most successful geoid models that combines all these types of observations was EGM2008 (Pavlis et al., 2012). Since its publication, more GRACE and GOCE data have become available which has been used to improve EGM2008. One of those refined models is EIGEN-6C4 (Förste et al., 2012) that also has high spatial resolution (spherical harmonics up to degree 2190, which correspond to wavelengths of 18 km in Qatar). We also tested the experimental gravity field model XGM2019e (Zingerle et al, 2019) and GOCE-OGMOC (Gruber and Willberg, 2019), both of which have a maximum degree of 2190.
EGM2008 compared with Qatar95 shows differences of ±30cm. Differences between the recent global models are still of the order of ±10cm, indicating the need for a refined geoid model for Qatar. To realize such a model, new gravity data were needed which are discussed in the next section.

2. TERRESTRIAL GRAVITY CAMPAIGN

The gravity campaign in Qatar lasted from 5th until 29th of February 2020. During that period 399 points were observed. The measurements were made with three spring gravimeters simultaneously. To correct for the fact that gravity changes with height, at each point GNSS observations were made using RTK. This was possible due to the good coverage of the nine reference stations that form the QCORS network (only in few areas, like southeast, we needed to acquire data during more time to achieve the requested accuracy of few centimeters).

Qatar has no absolute gravity point which is needed to convert all these relative measurements into absolute ones. This is not a problem for the geoid computations, but it will be necessary if anyone plans to use these points in the future for other purposes (including comparisons and integration with other gravity surveys).
The refined Bouguer anomalies for each observed point (i.e., the observed minus normal gravity values on the geoid corrected for the height and the effect of the topography) are shown in Figure 1. One can observe some negative anomalies along the west coast of Qatar where most of the natural gas extraction takes place. In addition, Figure 1 shows a smooth gravity field with small variations of a few mGals which is beneficial for the computation of an accurate geoid. Note that an arbitrary constant has been added to ensure zero mean of these anomalies over Qatar.

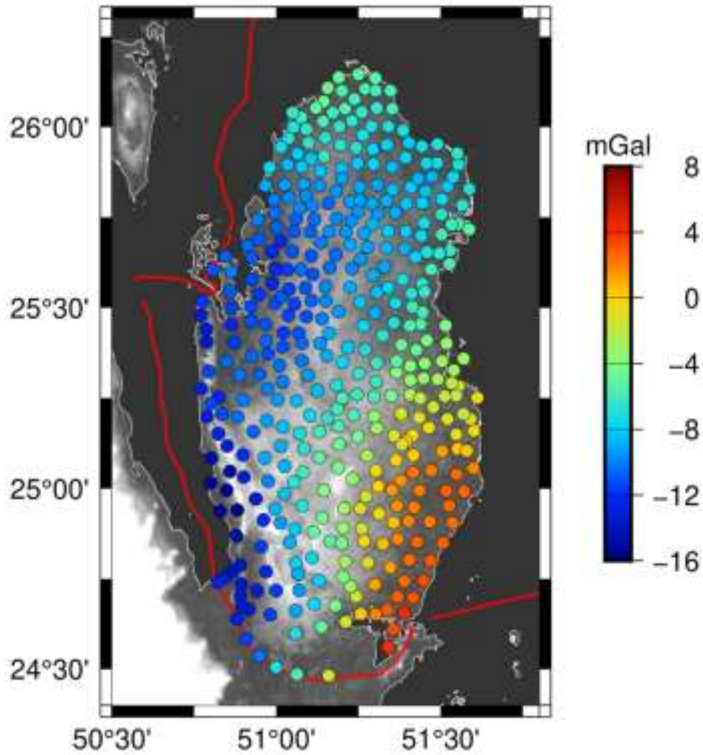

Figure 1 - Refined Bouguer Anomalies over the State of Qatar.

3. GEOID COMPUTATION

The geoid was computed using the standard Remove-Compute-Restore technique (Schwarz et al, 1990; Bos et al., 2015). The global geopotential model provides the medium to long-wavelength field of the geoid. To model the short wavelength, the topography was smoothed and subtracted from the high-resolution digital terrain model. The difference between these two surfaces was used to compute the Residual Terrain Corrections (Forsberg and Tscherning, 1981) although the effect was small (less than 0.2 mGal). Afterwards the observations were moved to the reference ellipsoid and the gravity values as given by the global geopotential were subtracted. The resulting residuals are shown in Figure 2. To these differences, an empirical spatial covariance function was fitted (Tscherning and Rapp, 1974), see Figure 3. Using this function and Least-Squares Collocation, the corrections for the EIGEN-6C4 model were computed (Arabelos and Tscherning, 1998). These are shown in Figure 4 (panel a) together with the predicted formal uncertainty (panel b).

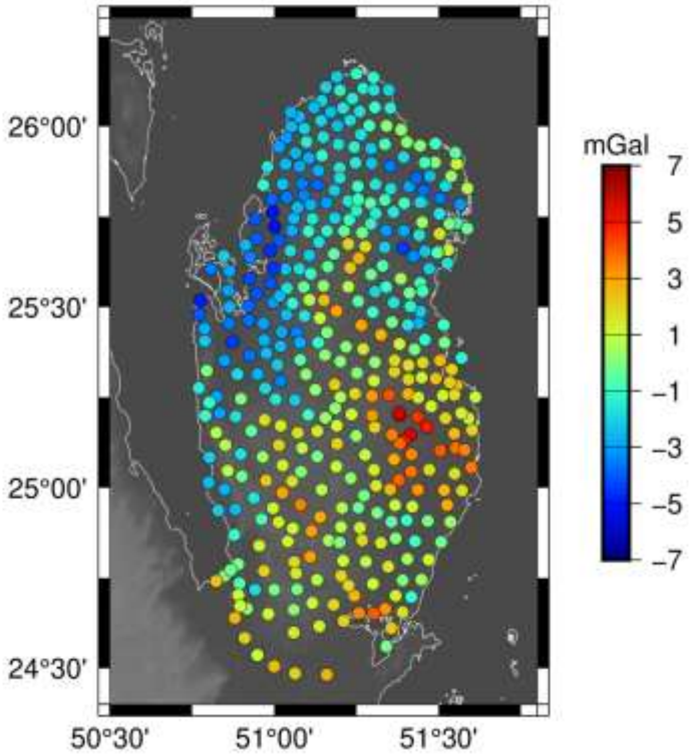

Figure 2 - Observed gravity values on the ellipsoid minus EIGEN-6C4.

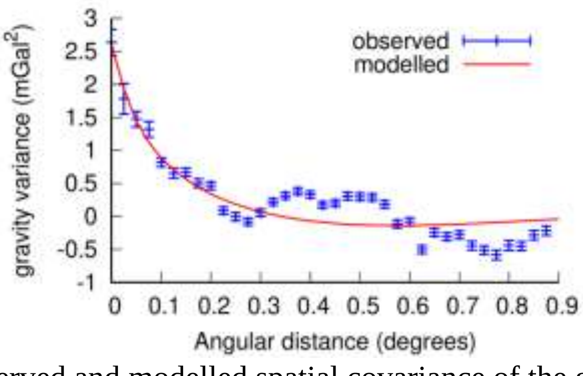

Figure 3 - Observed and modelled spatial covariance of the gravity residuals.

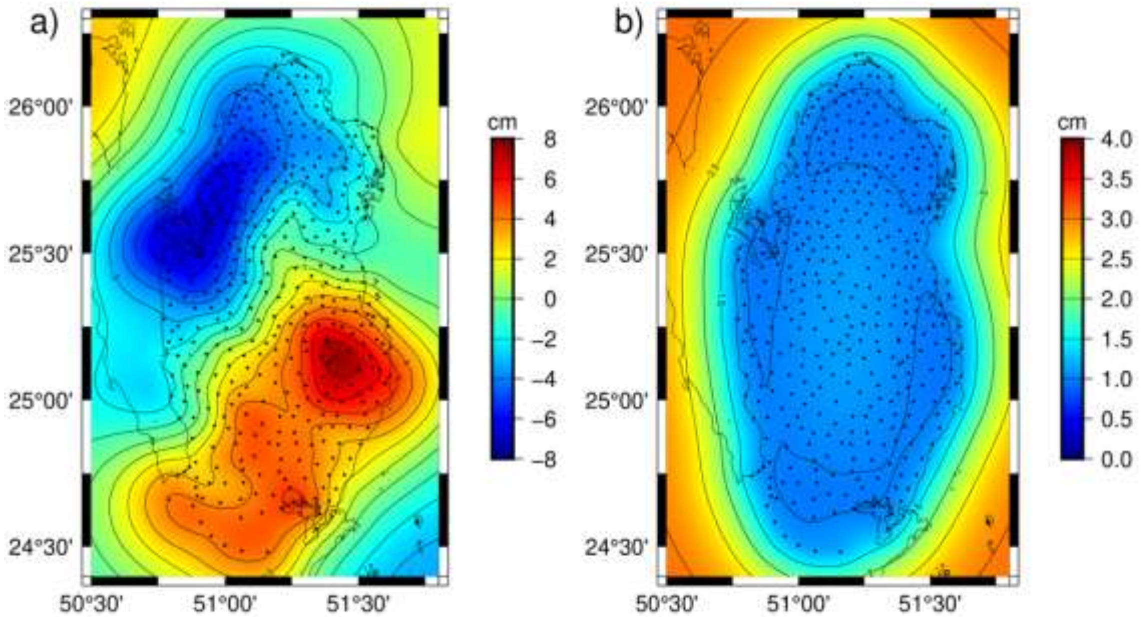

Figure 4 - Panel a) show the correction to the EIGEN-6C4 model computed using least-squares collocation. Panel b) show the corresponding uncertainty of these corrections. The black dots in both panels show the location of the 399 gravity observations.

Using the 10 m resolution digital terrain model of CGIS and the Residual Terrain Corrections method (Forsberg 1984), we verified that the effect of the topography on the geoid is only a few mm since Qatar is a flat country (the highest point is only about 100 m). In addition, Least-Squares Collocation provides us height anomalies ζ. These have been converted into proper geoid undulations, which has an effect of only 1 mm over the large dunes in the South-West but was much less for the rest of the country. Although small, both effects have been taken into account.

The Vertical Datum of Qatar is defined at the Fundamental Benchmark B (FBMB) at the old airport of Doha with an orthometric height value of 8.0036 m (Qatar Survey Manual, 2009). We made new GNSS observations at this point and observed an ellipsoidal height of -21.163 m (WGS84). We shifted the QG2020 vertically in order to obtain also 8.0036 m when the QG2020 is applied. The final geoid is shown in Figure 5.

The geoid computations described in this section have been done for the three models EIGEN-6C4, XGM2019e, and GOCE-OGMOC but we only show the results for EIGEN-6C4, since this was the selected global model based on the independent validation using existing leveling lines and GNSS data as described in the next section.

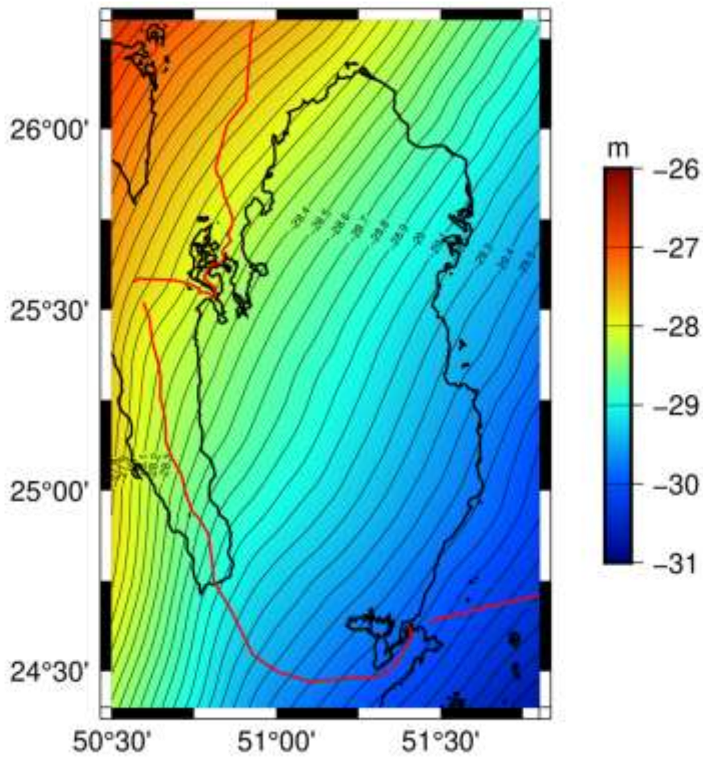

Figure 5 - The GQ2020 geoid.

4. VALIDATION OF THE QG2020

The current Qatar95 and the new geoid QG2020 have been compared at points for which both the ellipsoid (h) and orthometric heights (H) are known. Using a data set with 105 points with ellipsoidal heights observed with RTK produced a standard deviation of 4.6 cm while when we used the current Qatar95 model, this value was 7.1 cm, see Table 1. This corresponds to a ratio of improvement of 1.5. This estimation of the absolute error not only reflects the geoid uncertainty but also GNSS and levelling errors. For the geoid computations we used EIGEN-6C4 to model the long wavelengths since it provides the best fit with the observations. When we used XGM2019e or GOCE-OGMOC, the standard deviations of the fit were slightly larger: 4.9 and 5.1 cm respectively.

Two independent checks based on static GNSS observations also show significant improvements: a first one based on observations carried out during the gravimetric campaign using 13 points shows an improvement from 6.1 cm to 3.3 cm on the standard deviations of the residuals for the Qatar95 and QG2020 models, respectively, and are listed in Table 2, whereas the computations carried out by CGIS on 49 points shows a correspondent improvement from 7.9 cm to 4.6 cm.

Table 1 - Statistics of the Residuals using 105 GNSS ellipsoidal heights observed in 2020 with RTK (cm).

GEOID UNDULATION	STD	MIN	MAX
$\delta N_{QATAR95}$	7.1	-21.7	17.3
$\delta N_{QG2020\ (EIGEN\text{-}6C4)}$	4.6	-19.7	10.1
$\delta N_{QG2020\ (XGM2019)}$	4.9	-25.7	6.3
$\delta N_{QG2020\ (GOCE\text{-}OGMOC)}$	5.1	-25.8	6.0

Table 2 - Statistics of the Residuals using 13 GNSS ellipsoidal heights observed in 2017, computed with post processing (cm).

GEOID UNDULATION	STD	MIN	MAX
$\delta N_{QATAR95}$	6.1	-14.0	7.7
$\delta N_{QG2020\ (EIGEN\text{-}6C4)}$	3.3	-8.2	4.1
$\delta N_{QG2020\ (XGM2019E)}$	3.9	-14.2	1.5
$\delta N_{QG2020\ (GOCE\text{-}OGMOC)}$	4.0	-14.9	0.9

5. CONCLUSIONS

A campaign has been performed in February 2020 during which 399 new gravity and GNSS measurements were made, covering the whole State of Qatar. Using the Remove-Compute-Restore technique and Least-Squares Collocation, these gravity values were converted into a new geoid called QG2020. The new geoid has been linked to the national vertical datum of Qatar, at the main fundamental benchmark.
The new geoid QG2020 is made available in various digital formats that can be used in most GNSS equipment and software packages. The formal (relative) error (predicted standard deviation) of the computed geoid is about 1 cm, reaching 2 cm near the coastline.

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BIOGRAPHICAL NOTES

Machiel S. Bos obtained in 1996 his M.Sc. from the Delft University of Technology. In 2001, he received his Ph.D. from the University of Liverpool. Afterward, he held various post-doc positions in Sweden, the Netherlands, and Portugal. Currently, he is a researcher at the University of Beira Interior (UBI), Covilhã, Portugal. His scientific interests include ocean tide loading, GPS time series analysis, and geoid computations.

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Mudher N. Abdullah got the BSc in Surveying Engineering 1982 (University of Baghdad). In 1989, he received his MSc degree in photogrammetry and remote sensing, Mphil in surveying engineering from the University of Glasgow. He held many scientific positions in Iraq and worked as assistant professor in Baghdad university. He was the General manager of GIS&RS center for the MOWR (Ministry of water resources) in Iraq. He is working now as consultant engineer for CGIS in Qatar. His scientific interests include geoid computations, applied models for remote sensing and GIS mapping.

Hazem Barakat received his PhD in geomatics in 1997 from Purdue University in USA. He was the project director of the consulting firm, Gannett Fleming, that was contracted by CGIS to perform this New Geoid model in Qatar. He is also an Associate Professor at Faculty of Engineering in Cairo University.

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