Height modernization in the Emirate of Sharjah: determination of a gravimetric geoid, precise orthometric heights and the Mean Sea Level variation around the Strait of Hormuz

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Key words: Geoid, orthometric heights, hydrography, sea surface topography, geodetic GNSS, levelling, gravimetry, Strait of Ormuz

SUMMARY

Bayanat and Fugro recently carried out the modernization works of the geodetic and hydrographic infrastructure of the Emirate of Sharjah in the United Arab Emirates, which led to a redefinition of all the datums in force.

This project was exceptional in that it integrated, with regard to terrain, geodetic GNSS measurements, geodetic levelling, tide gauge observations, absolute and relative gravimetry, then in office, computations of geodetic GNSS and levelling networks, hydrographic reference levels, and finally a gravimetric geoid model and its hybrid declination.

So, the project gave us the opportunity to determine different forms of heights, from Mean Sea Levels (MSL) or Lowest Astronomical Tides (LAT) to ultimate rigorous orthometric heights, through ellipsoidal heights, geopotential numbers, heights resulting from standalone geodetic levelling, and geoidal undulations.

As this work was carried out from start to finish according to the rules of art and using the latest computation methodologies available - notably taking into account the lateral variations in density of the topographic masses for geoid computation, or applying topography, density and geoid effect corrections for computing orthometric heights, the project also made it possible to answer the question of the variation of Mean Sea Level (MSL) on both sides of the Strait of Hormuz, or more exactly along the Arabo-Persian Gulf and the Gulf of Oman as well as between these two gulfs, variation still uncertain due to the unreliability of satellite altimetry in coastal areas.

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1. GNSS, GGM, GEOID AND SEA SURFACE TOPOGRAPHY

With the advent and then the generalization of GNSS as a geodetic and topographic survey technique, the ellipsoidal heights obtained from GNSS measurements must always be transformed into orthometric (or normal) heights using geoid undulations (or quasi-geoid height anomalies), but which are only accurately known in a number of developed countries. Outside these countries, topographic surveyors rely on Global Gravity Field Models (GGM), which are inaccurate at small and medium wavelengths in many regions. For demanding applications in terms of height accuracy (linear infrastructures, hydraulic networks, studies of flood-prone areas, coastal erosion, etc.), a GGM is not sufficient and hybrid gravimetric geoid models, derived from local gravimetric geoids and GNSS-levelling benchmarks (or more exactly, levelling benchmarks known in orthometric heights - in the sense of Tenzer et al. 2005 - and accurate ellipsoidal heights), are required.
Near the coast, the Topography of the Sea Surface (TSS) is computed using the geoid and tide gauge observations. Offshore (high seas), its equivalent is the Mean Dynamic Ocean Topography (MDT), computed using the mean sea surface (MSS, measured mainly from satellite altimetry) which integrates both geoid variations and metocean variations.

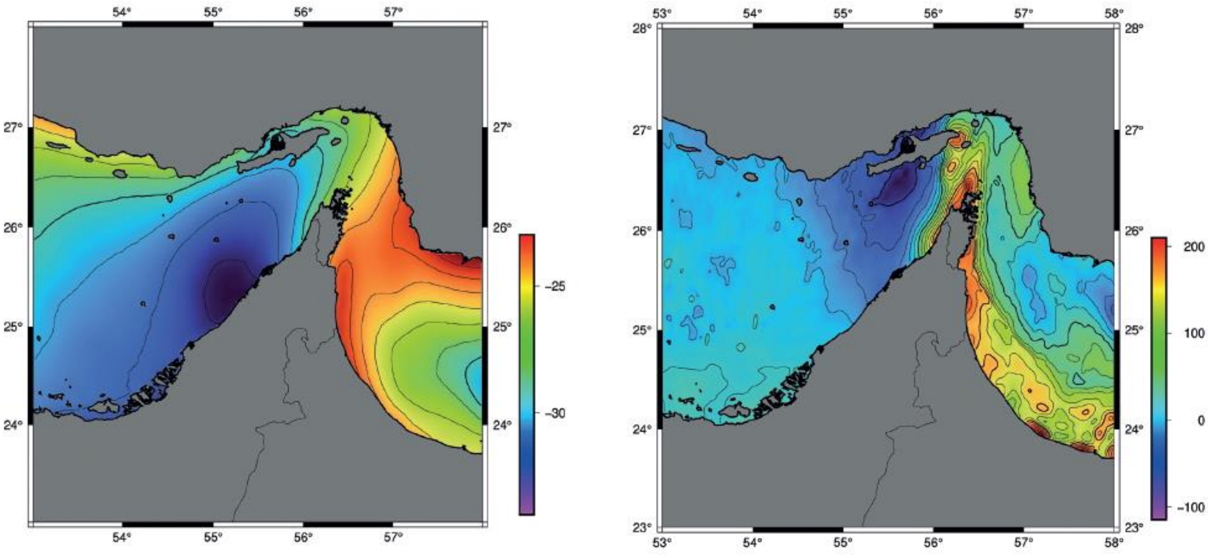

Figure 1 : DTU18 MSS (Andersen et al. 2018) in the study area, values in m (left). Gravity field derived from satellite altimetry in the study area, values in mGal (right). Boundaries are only indicative and not official.

While the MDT/TSS is considered unreliable near the coast due to sea surface disturbances and backscattering from land (Abileah et al. 2013), which both reduce the accuracy of satellite altimetry, it is always very interesting to compare a recent global MDT with a TSS resulting from in-situ measurements of the MSL using tide gauges and a local geoid determined from in situ measurements by means of levelling, terrestrial gravimetry and aerial gravimetry carried out at sea in a coastal strip of appropriate width.
Here, such a comparison made all the more sense since recent MSS all show strong variations of the sea surface above the ellipsoid (Figure 1 left), a significant variability of the Free-air gravity anomalies derived from satellite altimetry (Figure 1 right), large errors related to these anomalies reaching 12 mGal at 15 km from the coast and more than 20 mGal near the shore, and that the metocean variations (mainly due to currents and winds) still remain uncertain in the absence of oceanographic in-situ measurements.

2. PLANIMETRIC COORDINATES AND ELLIPSOIDAL HEIGHTS

As part of this project, Bayanat and Fugro have re-established the geodetic, levelling, gravimetric and hydrographic references and determined their realization throughout the territory of the Emirate of Sharjah, characterized by the presence of two coasts and a mountain range in between.
The geodetic infrastructure includes 31 geodetic reference points, including 23 First-order control markers in addition to 8 active GNSS Continuous Operating Reference Stations (CORS). Their precise coordinates, including positions and ellipsoidal heights, were established using geodetic GNSS equipment and methodology. This precise survey has been extended to the 67 First-order levelling benchmarks.
17 days of GNSS observations of the CORS were used. Geodetic tying-in to the ITRF2014 was ensured by integrating 30 CORS of the IGS regional network in the GNSS network. Data processing was performed using GAMIT-GLOBK v10.7 (MIT) software and controlled using BERNESE v5.2 (AIUB) software, which allowed estimating uncertainties of 2 mm in East and North coordinates and 5 mm in ellipsoidal height.

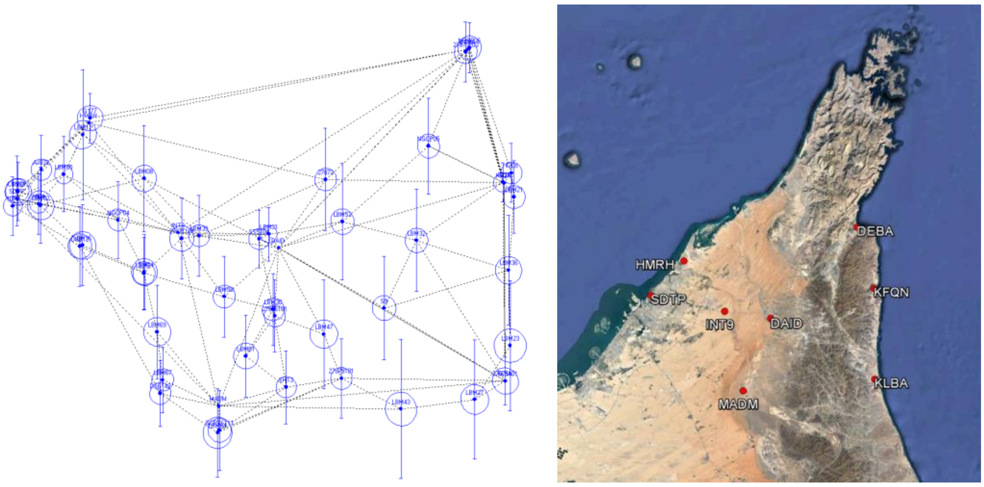

Figure 2 : 1st order network and levelling subnetwork (left) and CORS network (right).

The First-order network (Figure 2) was observed according to best practices (state-of-the-art). The final least squares adjustment, carried out with Geolab v2017 (Bitwise) was constrained to the 8 CORS coordinates, providing uncertainties of 5 mm in East and North coordinates and 13 mm in ellipsoidal height.
The transformation from ITRF2014 at mean Epoch of measurement into ITRF2000 at reference Epoch 2000.0 (realization in force in the UAE) was carried out using transformation parameters published by the IERS as well as ITRF2014 (Altamimi et al. 2017) and GEODVEL (Argus et al. 2010) tectonic plate motion models (MORVEL56 (Argus et al. 2011) model was also tested but ultimately was not retained).

3. ABSOLUTE AND RELATIVE GRAVIMETRIC GRID

To model the gravimetric geoid, a grid of gravity points was measured according to a regular mesh with spacing of 2 km in the Emirate of Sharjah and 5 km in the surrounding emirates so as to complement the existing gravimetric database (public or confidential data) resulting from terrestrial gravimetry, coastal airborne gravimetry and marine gravimetry campaigns. The 67 benchmarks were also observed. Gravity measurements were carried out according to the best practices (state-of-the-art) of micro-gravimetry (Figure 3).
3 absolute gravity stations (24-hour sessions) were established to allow tying in the network to IGSN71, scaling, and limiting error propagation. Post-processing was performed by the University of Montpellier with Micro-g Lacoste g9 software. Data was corrected for polar motion, Earth tides, ocean loading and atmospheric pressure. Computation provided gravity values accurate to 4 µGal.

Figure 3 : Absolute and relative gravity survey. Left: FG5 absolute gravimeter. In the center: CG6 measurements of the vertical gradient of gravity. Right: GNSS and CG5 relative gravity combined.

The relative gravity measurements were reduced by taking into account the gravimeter calibration constants, Earth tides, ocean and atmospheric loading, gravimeter drift (least squares inversion), normal gravity on the reference ellipsoid and Free-air correction calculated to second order, in accordance with the rules of art in geodesy.
Final least squares adjustment of the network was constrained to the 3 absolute gravity points, providing uncertainties of the gravity mesh points of 32 µGal in average, and therefore very satisfactory. The verification of the harmonic behaviour of the different datasets was performed using Least Squares Downward Continuation (LSDWC), hence checking the absence of outliers. This algorithm incorporates the laws of gravitational harmonicity (Poisson

integration), making it possible to generate a grid of gravity anomalies from scattered data in the sense of physical geodesy equations (Foroughi et al 2016).

4. HYDROGRAPHIC REFERENCE LEVELS

Observing the Mean Sea Level (MSL) makes it possible to follow the evolution of its dynamics, including its thermodynamics, over time. MSL variability largely reflects the effect of ocean-atmosphere exchanges, as well as global ocean circulation. By accurately determining the Mean Dynamic (ocean) Topography (MDT), defined as the difference between MSL and geoid, it is possible to compute the horizontal gradient of the MSL, which means the ocean circulation at the surface, notably the geostrophic currents.

Radar tide gauges, recording sea level variations, have been installed in four seaports in the Emirate of Sharjah, located along the Arabo-Persian Gulf (Khalid Port and Al Hamriyyah) and the Gulf of Oman (Khor Fakkan and Kalba port), therefore on both sides of the Strait of Hormuz (see Figure 4). The water level time series, covering a period of two years, were smoothed using a low-pass filter in order to remove high-frequency variations. The filtered data was then studied using a harmonic analysis method, which consists of representing the tide signal as the sum of a finite series of *n* harmonic functions.
For each port (tidal observatory), this harmonic analysis of the time series, carried out by least squares adjustment, made it possible to obtain the characteristics of the 37 main constituents that normally have the greatest effect on tides, hence making up the tidal spectrum and allowing predicting the tide signal with centimetre-scale accuracy, according to the American National Oceanic and Atmospheric Observation Agency (NOAA Special Publication NOS CO-OPS 3, 2007). Mean sea level can be defined as the constant component Z_0 of the tidal height function after least squares adjustment.

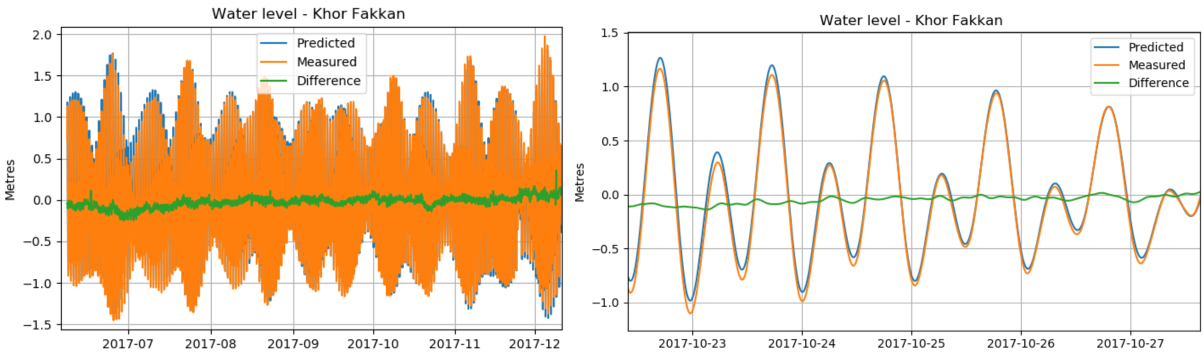

Figure 4 : Comparison between measured and predicted tide referenced to MSL in Khor Fakkan over the period 06/2017 to 01/2018 (left). Enlargement of the comparison between 23 and 27/10/2017 (right).

For the four ports, the amplitude and phase of each of the 37 harmonic constituents were computed from two years of sea level observations, and nodal corrections were applied to account for the irregularities induced by the movements of the lunar orbit. The choice of the least squares adjustment method (as opposed to frequency analysis) was motivated by the relatively short duration of the observations, which reduced the impact of meteorological effects

on the results. The Root Mean Square Error of the least squares adjustment ranged from 3.7 to 6.5 cm depending on the tide gauges.
Tidal predictions were generated using all of the harmonic components (amplitude and phase) resulting from the analysis. The predicted tide which corresponds to a theoretical signal was then compared to the tide actually measured (Figure 4), and their difference made it possible to measure the residual signal of metocean origin (mainly the effects of wind, current and atmospheric pressure).
To check the robustness of the 8 main harmonic constants (M2, S2, N2, K2, O1, K1, P1, Q1), the tidal waves were recomputed from sliding window sub time-series of 3 and 6 months extracted from the complete dataset. The statistical analysis of the variation of these components allowed controlling in first approximation these waves which represent 90% of the tidal signal. Indeed, the highlighted cyclic anomalies were found to affect only a fraction of the samples.
Finally, for the four tide gauges, the statistical study of the differences between the predicted tides and the sea level observations showed that the time of the various Lowest Astronomical Tide over the measurement period coincided very well (within 2 minutes for Khor Fakkan and up to 48 minutes for Khalid, so less than an hour for the 4 ports), which validated the harmonic analysis carried out. The analysis of the variation of these components made it possible to estimate the accuracy of computed Mean Sea Level and Lowest Astronomical Tide to between 2 and 4 cm depending on the tide gauges.
The MSL at Al Hamriyyah Port has been defined as the reference level (0 m orthometric height) of the Emirate's vertical datum.

5. GEODETIC LEVELLING

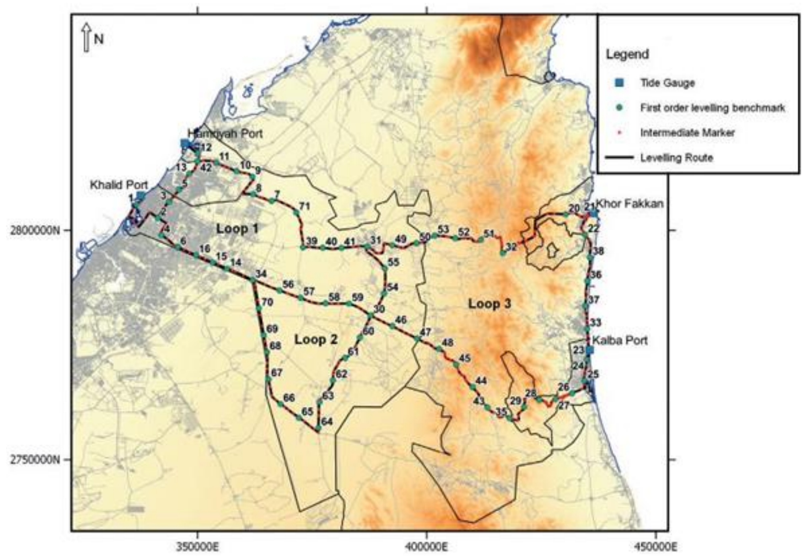

Figure 5 : New levelling network of the Emirate of Sharjah. Boundaries are only indicative and not official.

A First-order levelling network of 400 km in length consisting of 67 levelling marks evenly distributed along 3 main loops was observed in both forward and backward directions (i.e.

800 km travelled in total) and forms the realization of the Emirate of Sharjah vertical datum (Figure 5).
Measurements were carried out according to first order requirements (NOAA Manual, 1981, FGCS Specifications, 2004), including calibration of digital levels, check of Invar rods over the entire temperature variation range and use of pairs of temporary benchmarks at ~2 km spacing). In addition, gravity observations were made at each levelling benchmark.
Corrections were computed according to NOAA Technical Memorandum NOS NGS34.
All three loops closures were found in the range $(1-3)\ mm\ \sqrt{L(\text{km})}$ (i.e. 10, 24 and 42 mm for loop lengths of 102, 145 and 187 km, respectively) while the differences between the forward and backward routes were 4.3, 4.9 and 8.9 mm.

6. RIGOROUS ORTHOMETRIC HEIGHTS

As the equipotential surfaces of the gravity field are not parallel to each other, the differences in level measured by geodetic levelling depend on the followed path. These differences in height must therefore be corrected to take into account the variations in gravity along the levelling paths and make it possible to determine rigorous orthometric heights (in the sense of Tenzer et al. 2005). Helmert's orthometric heights could have been considered as possible heights, but they're insufficient when it comes to evaluating a geoid accurate to 2 or 3 cm.
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:

$$\bar{g} = \frac{1}{H^O}\int_0^{H^O} g.dH^O$$

Determining $\bar{g}$ requires measuring the gravity all along the plumbline but it is hardly feasible due to the physical presence of the topography. To overcome this difficulty, it is possible to compute rigorous orthometric heights through Helmert orthometric heights. Therefore, the dermination of the rigorous orthometric heights of the levelling benchmarks realizing the vertical datum of the Emirate of Sharjah was carried out in two stages, using GeoHeight software (Fugro France) and RigOrtH (University of New Brunswick - UNB).

1– Least squares adjustment of the levelling-gravimetry network in geopotential numbers and computation of the Helmert orthometric heights:
The height differences determined by geodetic levelling were combined with the gravity measurements carried out on each benchmark to compute the differences of geopotential numbers.
The differences in geopotential numbers were adjusted by least squares, then the adjusted geopotential numbers were converted to Helmert orthometric heights using the approximation of mean gravity along the vertical from the well-known Poincaré-Prey reduction using a constant density ρ of 2670 kg/m^3, given by:

$$H^{Helmert} = \frac{C}{\bar{g}^H} \text{ with } \bar{g}^H = g - \left(\frac{1}{2}\frac{d\gamma}{dh} + 2\pi G\rho\right)H$$

The differences between the so-obtained Helmert orthometric heights and geometric heights derived from geodetic levelling alone vary from a few millimetres to several centimetres depending on the areas (a few tenths of a mm to a few mm per levelling section), reaching **7.1 cm** at their maximum ; **these corrections are therefore very significant**.

2– Determination of rigorous orthometric corrections:
Helmert's orthometric heights are biased due to the approximation performed when determining $\bar{g}$, average of the real gravity along the plumbline arc connecting the geoid to the measurement point. However, according to Santos et al. (2006), $\bar{g}$ can be accurately determined if broken into unit components, as follows:

$$\bar{g}\,(\Omega) \approx \bar{\gamma}(\Omega) + \overline{\delta g}^{NT}(\Omega) + \bar{g}_B{}^{T}(\Omega) + \bar{g}_R{}^{T}(\Omega) + \bar{g}^{\delta\rho}(\Omega)$$

where Ω represents the position (latitude and longitude) of a computation point; $\bar{\gamma}(\Omega)$ is the integral-mean value of the normal gravity along the plumbline between the geoid and the point; $\overline{\delta g}^{NT}(\Omega)$ 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.
Using the above expression of $\bar{g}^{H}$, $\bar{g}$ can be further decomposed as follows (Santos et al., 2006):

$$\bar{g}\,(\Omega) \approx \bar{g}^{H}(\Omega) + C_{\gamma}(\Omega) + C_{\delta g^{NT}}(\Omega) + C_{\delta g_B^T}(\Omega) + C_{\delta g_R^T}(\Omega) + C_{\delta g^{\partial\rho}}(\Omega)$$

where C_{γ} and $C_{\delta g_B^T}$ (Normal gravity and Bouguer shelf corrections) are simply calculated, so that the computation of rigorous orthometric heights consists mainly in evaluating the corrective terms $C_{\delta g_R^T}$, $C_{\delta g^{\partial\rho}}$ and $C_{\delta g^{NT}}$, respectively corresponding to the effect of the residual terrain (surrounding variations of topography), the effect of the lateral variations in density of the topographic masses, and the effect of the gravity disturbance generated by the geoid at longer wavelength. These corrections are computed using GTOPO30 Digital Elevation Models (30 second resolution) and UNB TopoDens global model of lateral variation of density derived from the lithological map (30 seconds resolution).

In the study area, the sum of these corrections (terrain, density and geoid) ranges between 0.0 and **1.5 cm**, which are therefore added to the Helmert corrections previously described, **which is far from being negligible given the accuracy required** to assess then to fit the gravimetric geoid to obtain a hybrid gravimetric geoid, notably in the Al Hajar mountain range, or to accurately connect the four tide gauges together to determine the Mean Sea Level differences along the Emirate coasts and a fortiori between the Arabo-Persian Gulf and the Gulf of Oman.
It shall be noted that Helmert orthometric corrections, terrain, density and geoid corrections increase with height and that they were here computed for points whose altitude remains relatively low (up to 470 m, with neighbouring peaks reaching up to 1,100 m). These corrections would be even more significant for benchmarks located on high plateaus or mountain ranges.

7. GRAVIMETRIC GEOID

The local 1-minute gravimetric geoid model was computed using SHGeo 2019 software, based on the Stokes-Helmert method (enhanced version jointly developed by University of New

Brunswick and Fugro), dedicated to the computation of geoid models. A complete description of SHGeo method can be found in Ellmann, A. and P. Vaníček (2007) or Janák et al. (2017).

Two approaches can be used for the computation:

The "Two–space" approach (or "Helmert space") converts Free-air gravity anomalies into so-called Helmert anomalies by condensing the effect of the topographic masses into a layer of infinitesimal thickness on the geoid, reducing this effect by several orders of magnitude. It is only in such a space that the Stokes integration is valid from a mathematical and physical point of view; indeed, the geoid cannot be calculated harmonically if any topography persists.

The "Three–space" approach (or "No-Topography" space, Yang, 2005) converts Free-air gravity anomalies into so-called No-Topography anomalies (removal of Helmert topographic effects). In this case, the effects of the topographic masses are removed, yielding a smoother gravity field (longer wavelength), and reducing the errors during the iterations of the Least Squares Downward Continuation (LSDWC) of the anomalies down to the level of the geoid. The short wavelengths are reintroduced by the addition of the condensed topographic effects after application of LSDWC.
Due to the presence of a mountain range, this latter approach was preferred for the computation of the gravimetric geoid model of the Emirate of Sharjah, the first approach being only applied for purpose of quality control. Indeed, using No-Topography 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 main calculation steps can be summarized with the following sequence:
1– Computing No-Topography (NT) gravity anomalies at observation points by subtracting "real" topographical effects (Direct Topographical Effect and Secondary Indirect Topographical Effect) from Free-air anomalies;
2– Interpolating a regular grid of NT anomalies at 1-minute resolution 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;
3– Downward continuing the NT anomalies onto the geoid by inversion of the Poisson integral (LSDWC). This downward continuation was done with an integration radius of one arc-degree;
4– Converting the NT anomalies on the geoid into Helmert anomalies (restitution of the effects of the topographical masses: condensed Direct Topographic Effects and Secondary Indirect Topographic Effects were added to the NT anomalies on the geoid);
5– Removing the reference field Helmert anomalies (long wavelength reference gravity field model) from the Helmert anomalies on the geoid, yielding residual Helmert anomalies (or Stokes anomalies);
6– Transforming the residual anomalies into residual undulations (residual Helmert cogeoid) using Stokes integration;
7–Adding a reference field Helmert cogeoid (restitution of the long wavelength undulations) to

the residual Helmert cogeoid to obtain the Helmert cogeoid;
8– Converting cogeoid into geoid by transformation of the condensed masses into real masses; this conversion is performed by 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 6.
The heart of the computation is based on Stokes integration which transforms gravity anomalies into geoidal undulations by applying the formula:

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

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

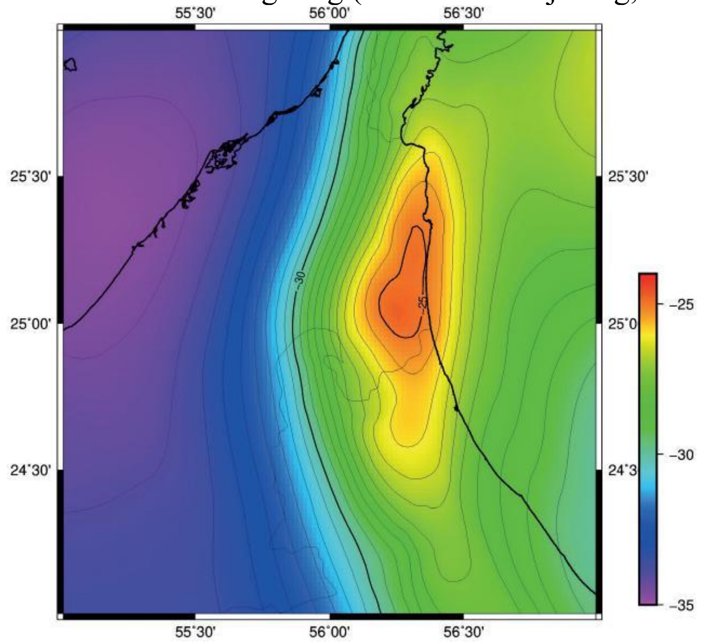

Figure 6 : Gravimetric geoid of the Emirate of Sharjah, undulations in m.

Multiple tests were performed to find the optimal combination of stokes integration radius and maximum degree/order of the satellite gravity field model. An integration radius of 0.57° combined with a reference gravity field computed at degree/order 320 proved to be the optimal parameters for the study area, i.e. yielding the lowest residuals when evaluating the computed gravimetric geoid model using GNSS–levelling benchmarks. This means that these parameters made it possible to reduce as much as possible the differences between the undulations modelled by the geoid and their counterparts obtained from ellipsoidal heights and rigorous orthometric heights on the 67 GNSS–levelling benchmarks.
The resulting geoid model accuracy was evaluated using the 67 benchmarks accurately known in rigorous orthometric heights and ellipsoidal heights.

The accuracy of the local gravity model was estimated at 3.9 cm (Table 1). Compared to GECO (Gilardoni et al. 2015) -the best global geopotential model in the study area-, the gravimetric model is more than twice as precise and allows a remarkable reduction in the difference between the largest and the smallest residual (which therefore decreases from 61.4 cm to 15.9 cm).

Geoid model	Mean residual [m]	Standard Dev. [m]	Minimum residual [m]	Maximum residual [m]
Best global model (GECO)	+0.081	0.111	-0.164	+0.450
Raw local gravimetric model	+0.981	0.039	-0.095	+0.064
Hybrid local gravimetric model	0.000	0.010	-0.026	+0.019

Table 1 : Evaluation of a global geoid model, the local gravimetric model and the hybrid model (local gravimetric model adapted on the 67 benchmarks); the minimum and maximum residuals are calculated after subtracting the mean deviation, corresponding to the offset applied to translate the model to zero of the vertical datum (MSL at Al Hamriyyah).

8. HYBRID GRAVIMETRIC GEOID

To make the geoid match the realization of the vertical datum throughout the Emirate, the computed gravimetric geoid was shifted to make it consistent with the MSL at Al Hamriyyah (N0). It was then fitted by least-squares collocation (using an ordinary kriging) to the 67 available benchmarks, hence obtaining a hybrid gravimetric geoid.
It shall be noted that this geodetic fitting was all the more made necessary due to the lack of sufficiently dense and accurate gravity points available beyond the borders (in Oman). Indeed, the appropriate density of gravity points in the area of interest has allowed the short-wavelength influence of the gravity field to be well modelled. However, to be accurately modelled without using such benchmarks, the influence at medium wavelength caused by distant topographic/geological features (notably the Al Hajar mountain range) would have required the availability of a similar gravity grid beyond the borders.

To check the hybrid gravimetric, geoid model, three blind tests were performed. Each blind test consisted of generating a hybrid gravimetric geoid model using only one third of the 67 levelling marks available (similar to reference points).
The so-generated three models were evaluated on the one hand by comparing them with the geoidal undulations computed on the remaining two-thirds of points (considered as control points), and on the other hand by comparing them with the hybrid gravimetric geoid model computed using the entire set of GNSS-levelling points.
The three blind tests provided standard deviations of the control point residuals ranging from 2.1 cm to 3.3 cm. These values are considered to be pessimistic factors of the achievable accuracy (the evaluation is carried out on the unused points).
These good standard deviations as well as the absence of outlying points out made it possible to validate in advance the hybrid model generated with all the available points.

The comparison between the three hybrid gravimetric geoid models generated from the three subsets of GNSS-levelling points and the model generated with the entire set of points (Figure 7) showed that using only part of the GNSS-levelling points introduces biases
locally (up to +/- 5 cm) but that the global evaluation validates the final hybrid gravimetric model (standard deviations over the entire geoid model of respectively 1.3 cm for the first subset, 1.3 cm for the second subset, and 1.7 cm for the third subset).

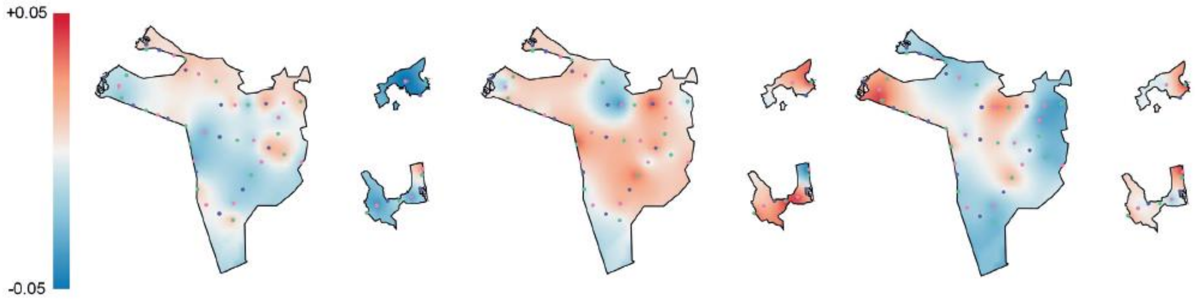

Figure 7 : Blind tests: deviations in metres between the hybrid geoid computed using all benchmarks and the 1st sub-sample (left), 2nd sub-sample (center) and 3rd sub-sample (right). Boundaries are indicative and not official.

Finally, the fit over the entire set of GNSS-levelling benchmarks provided a standard deviation of the residuals of 1.0 cm (see Table 1). Given the density and the distribution of the GNSS-levelling points, the accuracy of the hybrid gravimetric geoid model of the Emirate of Sharjah developed here was conservatively estimated to 2.5 cm.

9. STUDY OF THE TOPOGRAPHY OF THE SEA SURFACE AROUND THE STRAIT OF HORMUZ

As the survey methodologies implemented during both the field data acquisition phases and the data processing phases of this project have complied with the most stringent survey procedures, the high accuracy achieved for all types of heights also allowed evaluating the variations in the Topography of the Sea Surface along and between the Arabo-Persian Gulf and the Gulf of Oman on both sides of the Ormuz Strait. Figure 8 presents both the Mean Sea Levels (MSL) observed at the various tide gauges located on the Arabo-Persian Gulf (Khalid Port and Al Hamriyyah) and on the Gulf of Oman (Khor Fakkan and Kalba port), and their counterparts modelled from satellite observations (CNES-CLS18 MDT).

Once the levelling network fitted to the MSL measured at Al-Hamriyyah (Arabian Gulf), comparisons gave average sea level differences of −13.0 cm at Khalid port (Arabo-Persian Gulf)), −6.3 cm at Khor-Fakkan and −0.1 cm at Kalba (both in the Gulf of Oman). According to the literature (Farzaneh and Parvazi, 2018), the Mean Sea Surface (MSS) varies considerably in the Arabo-Persian Gulf and Gulf of Oman (variations exceeding 15 m, mainly due to variations of the geoid), but the four tide gauges in operation are located in areas where the Topography of the Sea Surface (TSS) should have a similar height.
Along the Arabo-Persian Gulf coast, the Mean Dynamic Topography (MDT) models are consistent with the TSS derived from our results, decreasing very slightly to the west, as shown

by the MSL variation reached between Al-Hamriyyah and Khalid, (-13 cm), whose uncertainty due to some possible local effects –albeit limited– was estimated below 2 cm.
The MSL gradient along the coast of the Gulf of Oman raises more questions: the TSS decreases slightly but clearly northwards (–0.062 m from Kalba to Khor-Fakkan, with an estimated uncertainty less than 3 cm), but this trend cannot be verified by any model due to the variability in both amplitude and direction of the TSS slope near the coast in the Gulf of Oman.
Likewise, between the Arabo-Persian Gulf and the Gulf of Oman, whereas the two TSS appear to be of the same order of magnitude in the area of interest (almost the same MSL in Al-Hamriyyah and Kalba), no model seems capable to confirm to which extent this is effectively the case. Indeed, compared to our TSS determined from tidal measurements and rigorous orthometric heights, the latest freely accessible MDT model (CNES-CLS18 MDT (Rio et al. 2018)), based on the GGM GOCO05s, therefore consistent at low degree and order of spherical harmonics with our geoid) was found to be biased by (small) systematic errors of the TSS slope of 2 to 7 mm/km in each of the two seas and almost no difference in level of the TSS between them (Figure 8).

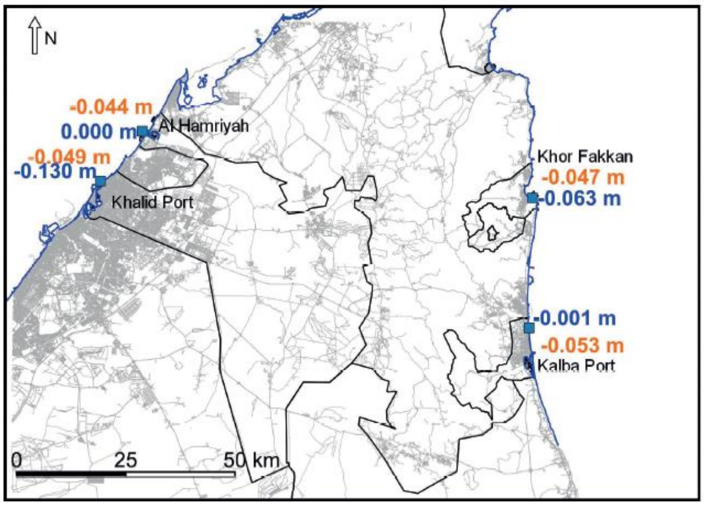

Figure 8 : Differences on the 4 ports between the TSS resulting from the determination of the MSL and the geoid (measurements of 2019, in blue) and the MDT CNES-CLS18 interpolated and readjusted for minimize the differences on the 4 tide gauges (2018 model, in orange). Boundaries are only indicative and not official.

The inaccuracy of the TSS slope nearshore had been anticipated at geoid computation stage using the satellite gravity error model. All data within 15 km of the coast had been masked, which represented an acceptable compromise to retain as much data as possible while only using those data whose order of accuracy would be similar to that of marine gravimetry (3.5 to 5 mGal). Although this choice allowed keeping data with uncertainties mostly between 0.5 and 5 mGal, higher uncertainties were noticed off Khor-Fakkan (12 mGal) and Kalba (7 mGal), and much more close to the coast (but this data had then been masked).
So, although all studies recognise that deriving accurate MSL from satellite altimetry in coastal areas is hardly achievable due to, among other things, corrupted waveforms, backscattering from land, and errors in most corrections (Vignudelli et al., 2019), this geoid study suggests that the resulting inaccuracy depends on the area of interest and can be anticipated using the

error model provided with the satellite-derived gravity data. Nevertheless, so far, in-situ observations using tide gauges remain the only accurate mean for measuring the MSL variations in coastal areas.
Although slightly underestimating the TSS slopes in these coastal areas, the CNES-CLS18 MDT turned out quite accurate in the study area, certainly due to the fact that its associated MSS is based on measurements of Jason-1/2 and Cryosat-2 missions (the contribution of these missions was notably highlighted by Sandwell et al., 2019), as well as the integration into the model of in-situ measurements of SVP drifters (Surface Velocity Program) in the Gulf of Oman. Once fitted to the MSL of the hydrographic reference port (here Al-Hamriyyah), the model can be used to estimate MSL in first approximation up to a few tens of kilometres from the reference port. Even better, the model can be calibrated using two tide gauges in each sea and the TSS extrapolated much further if its slope is uniform enough.

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