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بلدية مدينة أبوظبي
ABU DHABI CITY MUNICIPALITY

SMART SURVEYORS FOR LAND AND WATER MANAGEMENT

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

(FIG peer-reviewed paper)

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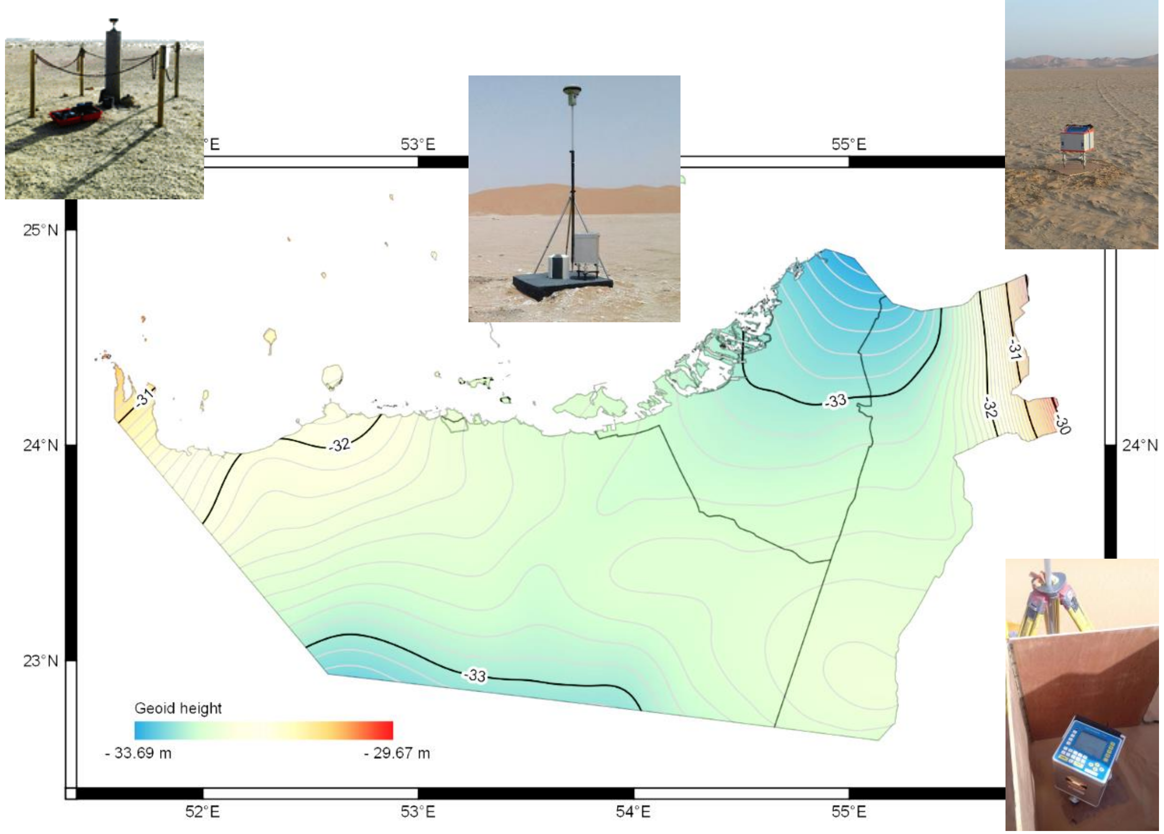

Figure 1: hybrid gravimetric geoid. Values in m. Contour interval is 20 cm

Why this project ? (1)

- CORS separation or status
  - CORS large separation outside developing areas
  - CORS status (maintenance/repair, telecom network limitations…)
  - ➢ Need for densification with passive geodetic controls
- CORS affected by ground deformation
  - Ground water or oil & gas pumping (put to evidence with our multi-temporal InSAR study in 2019
  - ➢ Need for updating CORS coordinates
- CORS providing accurate horizontal positioning but inconvenient ellipsoidal heights (or approximate orthometric heights if relying on a Global Gravity Model (e.g. EGM2008)
  - Use of CORS (NTRIP/VRS/NRTK…) can be leveraged if delivering orthometric heights
  - ➢ Need for a convenient height reference surface to be used along with CORS

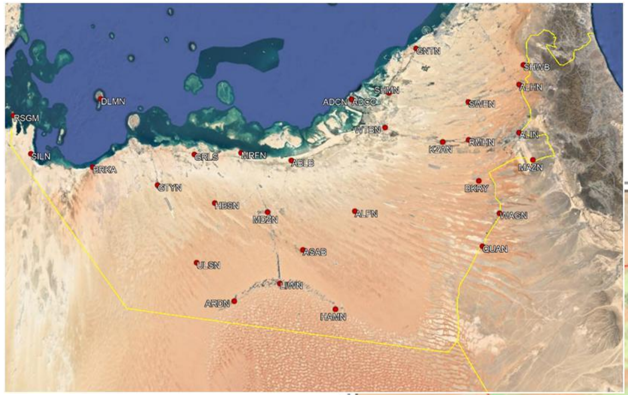

Figure 2 : local CORS (background map from Google)

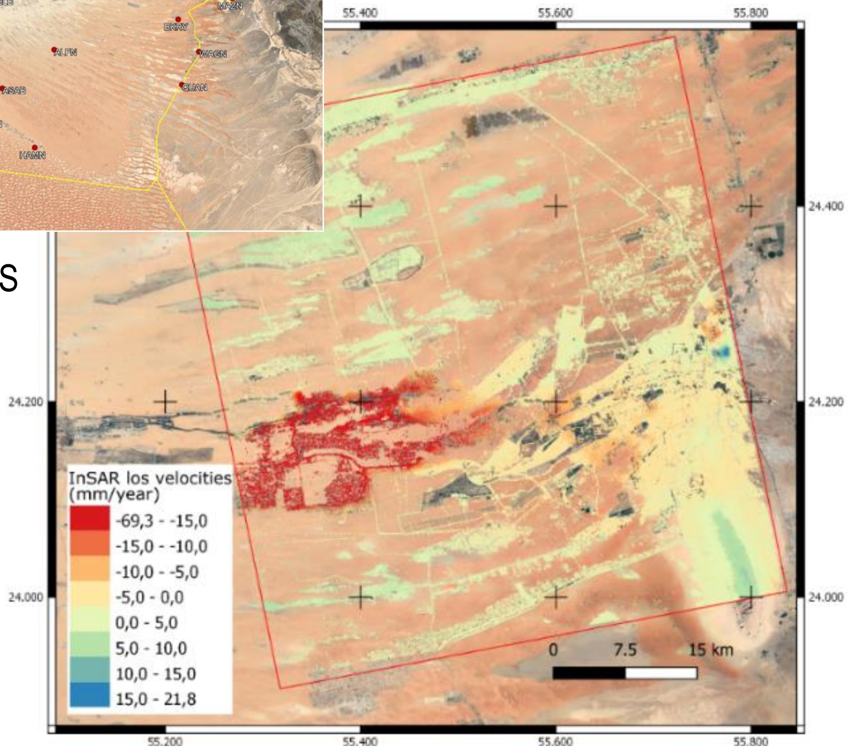

Figure 3 : 2019's PS-InSAR resulting ground velocities in Al Ain's agricultural areas

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Why this project ? (2)

- Generalized usage of GNSS techniques for more and more applications
  - Conversion of GNSS-derived ellipsoidal heights to orthometric heights inaccurate in the absence of reliable geoidal undulations
  - ➢ Need for a local geoid model accurate over the whole AOI
- Limitations of levelling networks
  - Benchmark destruction due to infrastructure development or road reconstruction
  - Benchmarks heights becoming unreliable in those areas subject to subsidence or uplift (groundwater/agriculture, underground mining, O&G reservoirs, urban/coastal…)
  - ➢ Need for a convenient, reliable, accurate, height reference surface

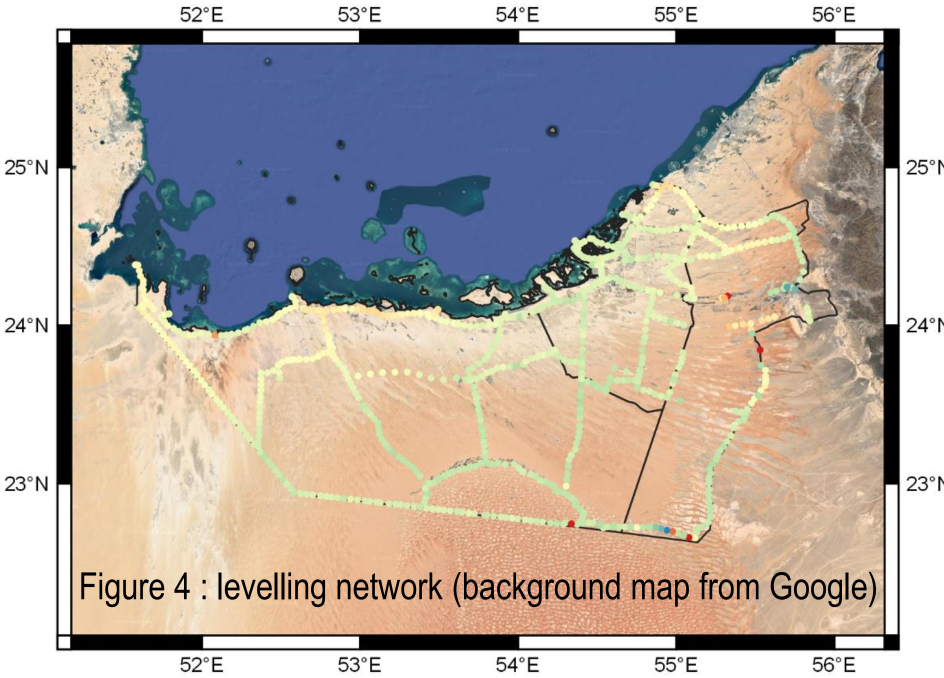
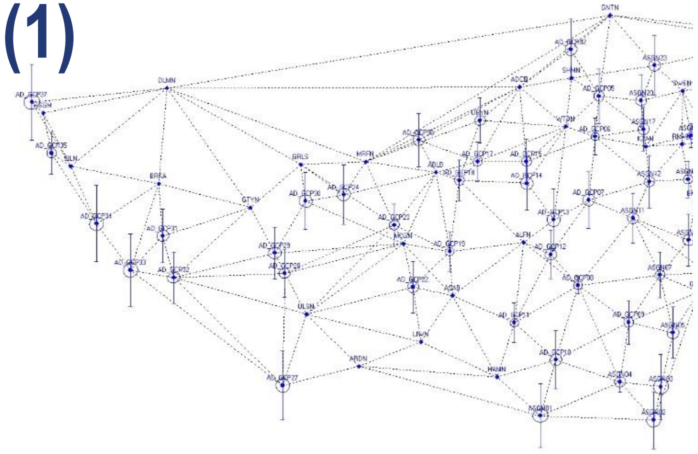


Figure 4 : levelling network (background map from Google)

➢ The combination of an up-to-date geodetic network (made up with both CORS and passive geodetic controls) with accurate positions and ellipsoidal heights, and a high accuracy gravimetric or hybrid gravimetric geoid model, is the optimal combination to ensure accurate georeferencing of all survey works in both position and height

An enhanced geodetic network (1)

- Geodetic network made of 31 local CORS (AD GRS) and 53 first order Geodetic Control Points



- Tying to ITRF2014 at Epoch 2019.0
  - Tying computation with Gamit-Globk (MIT)
  - 31-day observations recorded on 31 local CORS and 30 IGS CORS located in every direction
  - This regional solution was combined to a global solution incorporating baseline estimates from 300+ stations of the IGS global network (tying-in network corrected for geometric biases)
  - ➢ Post-fit RMS of final ITRF alignment better than 2.5 mm
- GCP first order network computation
  - Computation with Bernese (AIUB), constrained least squares adjustment with Geolab (Bitwise)
  - ➢ GCPs coordinates accurate to 3.7 mm in E, 3.4 mm in N and 19.0 mm in Ellipsoidal Height (2-σ, 95% confidence level)

Figures 5 and 6 : GCP 1et order network and IGS tying-in network (background map from Google)

An enhanced geodetic network (2)

- Geodetic fitting to UAE's official geodetic realization (ITRF2000 at Epoch 2000.0)
  - Use of IERS formulae and parameters for change of ITRF
  - Use of tectonic plate velocity model for change of realization Epoch
  - Local assessment of 3 available models ITRF2014 (Altamimi et al., 2016), GEODVEL (Argus et al., 2010) and MORVEL56 (Argus et al., 2011)
  - ➢ MORVEL56 (geophysical) showed larger differences, the two others models (kinematic) were more consistent with original coordinates (mean difference)
  - ➢ With all tested plate motion models, four CORS were found to have large residuals in ellipsoidal height, and two CORS in horizontal position
  - ➢ These differences might be explained by several factors : subsidence (due to groundwater pumping (NE), hydrocarbon extraction (C), building settlement (NW)), change of GNSS antenna setup/model (N), or by the inaccuracy of the original coordinates (small residuals in every direction)

Table1: Comparison between known coordinates and coordinates transformed from ITRF2014 at epoch 2019.0 to ITRF2000 at epoch 2000. Delta X, Delta Y and Delta Z refer to geocentric coordinates.

		Delta X [m]	Delta Y [m]	Delta Z [m]
ADM – ITRF2014	Min	-0.030	-0.028	-0.015
	Max	0.054	0.088	0.047
	Mean	0.000	0.006	0.005
	St Dev	0.013	0.018	0.010
ADM – MORVEL56	Min	-0.075	-0.042	0.071
	Max	0.008	0.074	0.134
	Mean	-0.046	-0.008	0.091
	St Dev	0.013	0.018	0.010
ADM – GEODVEL	Min	-0.034	-0.021	-0.022
	Max	0.045	0.093	0.051
	Mean	-0.005	0.012	0.000
	St Dev	0.013	0.018	0.013

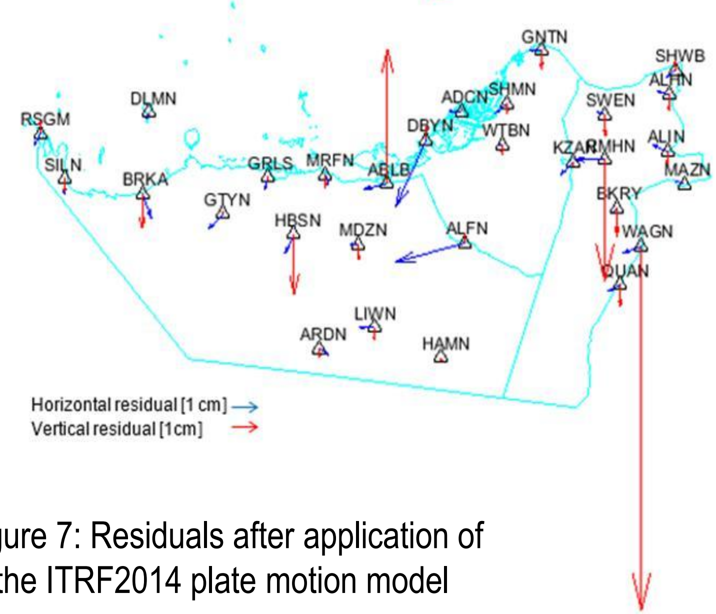
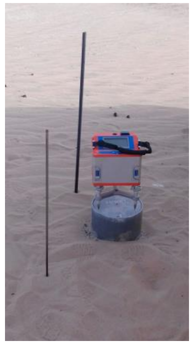


Figure 7: Residuals after application of the ITRF2014 plate motion model

A new gravimetric geoid model (1)

- Absolute and relative gravity data acquisition
  - Land gravity grid at 1-km spacing in developed/developing areas, and 2.5 km in the rest of the Emirate territory
  - GNSS observations were carried out simultaneously on common support. Positions were determined in RTK and checked with PPK computation (each with two references).
  - Establishment of 4 absolute gravity stations, including determination of vertical gravity gradients, for constraining the relative gravity network
- Gravity data processing
  - Absolute gravity computation by Univ. of Montpellier with g9 (Micro-g-Lacoste)
  - Relative gravity reductions (Free-air 2nd order) with T-soft and in-house software
  - Constrained Least Square Adjustment of the land gravity network
  - ➢ 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)



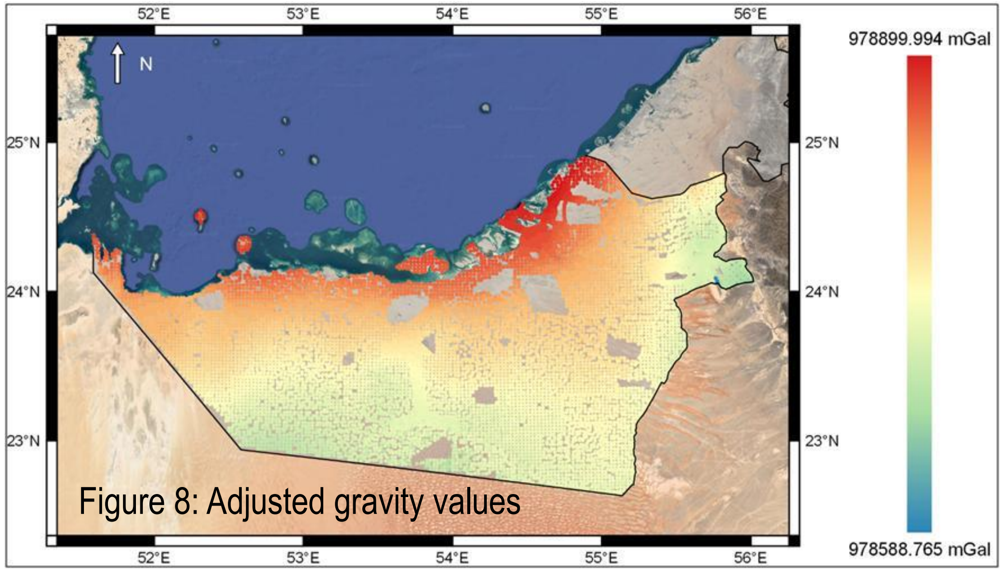


Figure 8: Adjusted gravity values

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A new gravimetric geoid model (2)

- Compilation of existing data
  - Existing terrestrial and marine gravity data were collected wherever available from various sources
  - The most recent edition of marine gravity anomalies from satellite altimetry by Sandwell et al. (2014) was chosen to provide additional coverage in marine areas (with a 15-km coastal strip mask).
  - The optimal combined/satellite-only reference fields over the area of interest happened to be GECO/GOCO05s
- 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
- Stokes-Helmert method implementation
  - Computation with SHGeo v2019 (Univ. of New Brunswick and Fugro) accounting for gravity lateral variations (derived from lithologic data)

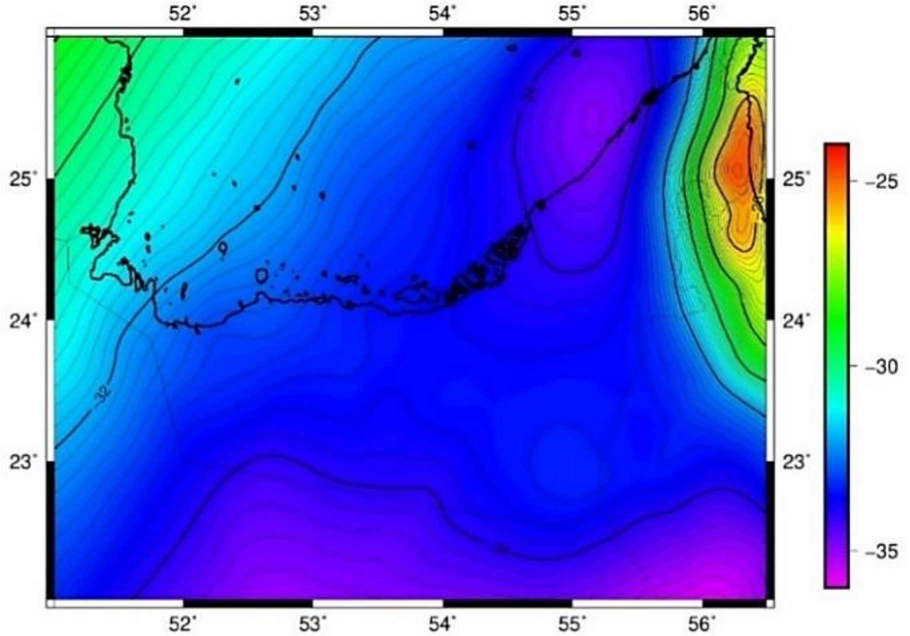


Figure 9: Gravimetric geoid. Values in m. Contour interval is 20 cm

Evaluation of the gravimetric geoid model (1)

- Independent evaluation is only possible with a network of GNSS-levelling benchmarks known in both ellipsoidal heights and orthometric heights
  - Evaluation is only possible along the levelling lines : the better the coverage, the more significant the evaluation
  - ➢ 726 validated GNSS-levelling benchmarks with known ellipsoidal height and elevation above MSL at Ras Ghumays (vertical datum in force in Abu Dhabi Emirate) were made available for evaluating the geoid model, so pretty well covering the territory

  - The accuracy of this evaluation is limited by the respective accuracies of the ellipsoidal heights and the orthometric heights of these LBM
  - ➢ LBM ellipsoidal heights accuracy was estimated using multiple determination comparison
  - ➢ But LBM orthometric heights accuracy estimation was not as straightforward : whereas levelling accuracy can be estimated from levelling loop closures, the so-called ‘orthometric heights’ heights had never been corrected for gravity (gravity data previously unavailable), as in many countries.

Evaluation of the gravimetric geoid model (2)

- A gravimetric geoid model is consistent with rigorous orthometric heights, but no other type of heights
  - Estimation of orthometric corrections was performed using the gravity measurements carried out for the project
  - ➢ Helmert orthometric corrections (as defined in Heiskanen and Moritz, 1967) were estimated to reach over 1.3 cm in low lying areas (-1.9 to +2.5 mm per sub section) but would exceed +15 cm in the mountainous area (Jebel Hafeet)
  - ➢ Rigorous orthometric heights (as defined in Santos et al., 2006) were estimated by computing the topography, density, and geoid effects. These 3 corrections altogether reach up to +0.6 cm in low lying areas, and would reach +5.6 cm in the mountainous area
  - ➢ Along the highest elevation levelling lines, sum of Helmert orthometric and rigorous orthometric corrections reached up to +20 mm, to be applied to the levelling-based elevations

- Estimation of GNSS-levelling undulations accuracy
  - ➢ So, in the highest levelling sections (NE), the presumed accuracy of the LBM' so-called 'orthometric heights' was to be lowered by a systematic error of up to 20 mm, then the resulting orthometric heights lowered accuracy was to be quadratically combined with its ellipsoidal height counterpart

Evaluation of the gravimetric geoid model (3)

- Global standard deviation of $\Delta N_{Gravi} = N_{Geoid} - N_{GNSS\text{-}lev.}$ was 4.8 cm
- Large improvement compared to GECO except in the eastern part of the country (Al Ain Municipality)
    - Due to the scarcity of gravity data in the areas located in the NE and E beyond the Emirate boundary, the gravimetric geoid failed to capture the long wavelength trends induced by the related topographic/geologic structures (notably Al Hajar mountain range)
    - However, when zooming on the results, it appeared that, this apparent decrease in accuracy at long wavelength concealed significant local improvement at shorter wavelength
    - StDev locally improve from 5.3 (GECO) to 3.3 cm (local geoid), and the higher residuals consistency shows that accuracy was actually largely improved at short wavelength

Table 2: comparison GECO - local geoid

	ΔN_{Gravi} Standard deviation [m]		Minimum ΔN_{Gravi} [m]		Maximum ΔN_{Gravi} [m]	
	GECO	Gravimetric geoid	GECO	Gravimetric geoid	GECO	Gravimetric geoid
Western Region (375 LBM)	0.067	0.033	–0.134	–0.078	+0.177	+0.100
Abu Dhabi(214 LBM)	0.044	0.027	–0.090	–0.077	+0.183	+0.080
Al Ain (137 LBM)	0.072	0.087	–0.125	–0.156	+0.213	+0.170

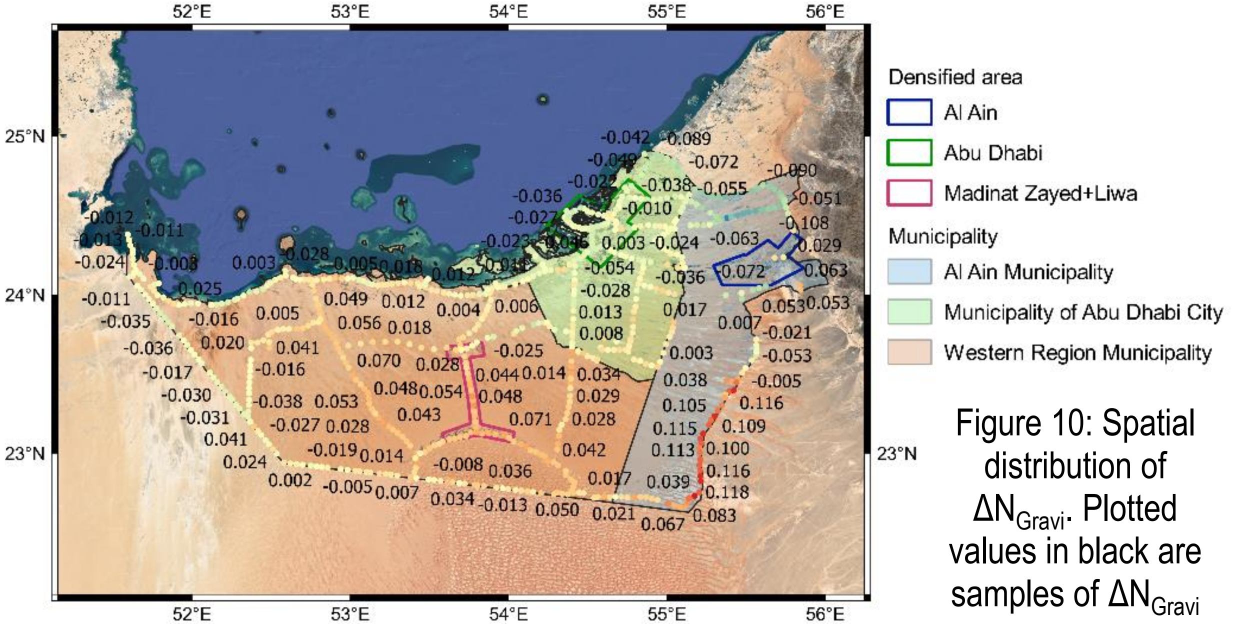
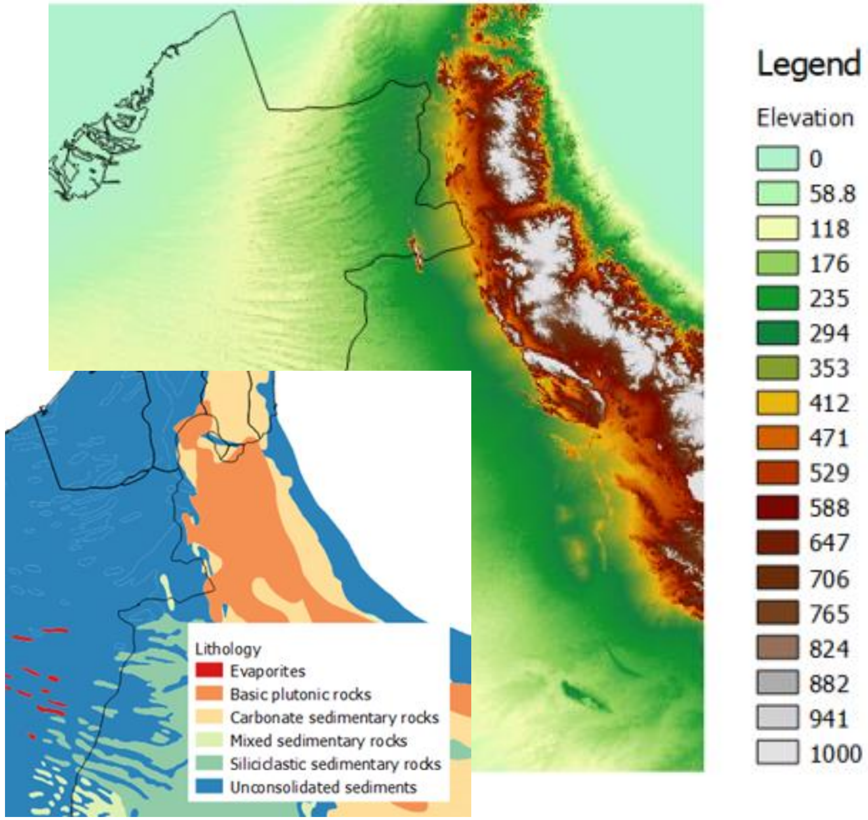


Figure 10: Spatial distribution of ΔN_{Gravi}. Plotted values in black are samples of ΔN_{Gravi}

Development of a hybrid gravimetric geoid (1)

- Gravimetric model shortcomings
  - Fail to capture the gravity field medium wavelengths induced by the topographical / geological structures located beyond the AOI boundaries (where gravity data is often sparse and possibly inaccurate (gravity datum shift, unreliable heights…)
  - Seldom match the levelling benchmarks realizing the local vertical datum (inaccuracies, heights not really orthometric…)
- To overcome them, the gravimetric geoid model was fitted by least square collocation to the GNSS-levelling benchmarks
  - ➢ Standard deviation of the residuals on the 726 GPS levelling benchmarks was 1.6 cm (ranging from -7.9 cm to +7.9 cm)
- Blind tests: Independent evaluation with degraded hybrid gravimetric geoids
  - ➢ 3 least square collocation surfaces made with one third of the available GNSS-levelling benchmark dataset and evaluated with the remaining points
  - ➢ The maximum standard deviation was 2.1 cm, which proved the good consistency of the three subsets

Figure 11: Topographical and lithological maps showing geoid-relevant structures beyond the Emirate boundary (NE area)



Development of a hybrid gravimetric geoid (2)

- The gravimetric geoid model is fitted to GPS-levelling benchmarks: least square collocation
  - Standard deviation of the residuals on the 726 GPS levelling benchmarks was 1.6 cm (ranging from -7.9 cm to +7.9 cm)
- Blind tests: Independent evaluation with degraded hybrid geoid models
  - 3 least square collocation surface made with one third of the available GPS-levelling benchmark dataset and evaluated with the remaining points
  - The maximum standard deviation was 2.1 cm, which proved the good consistency of the three subsets

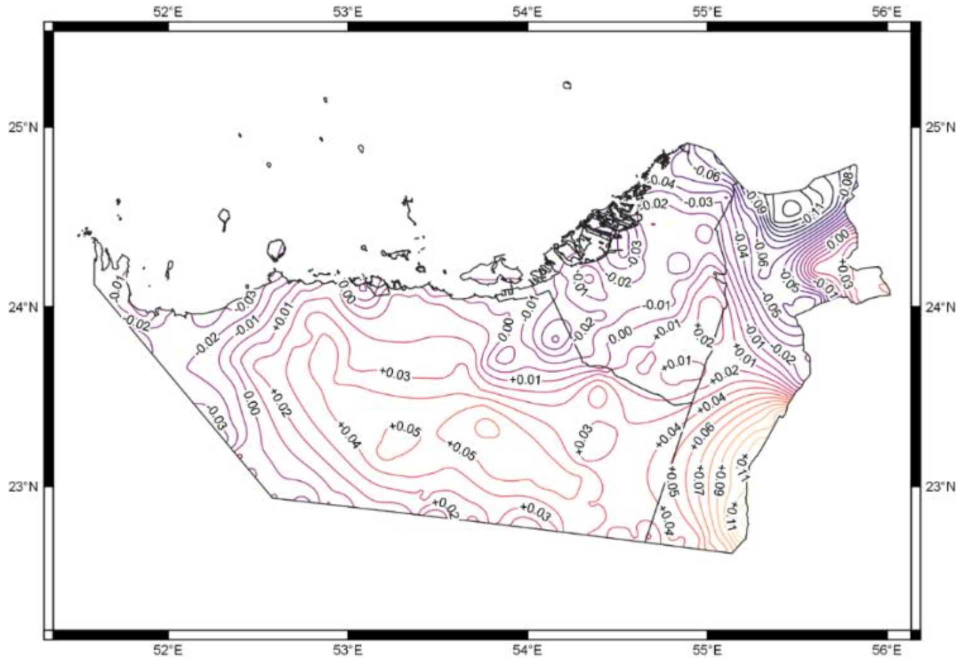


Figure 13: Contour lines of the LSC adaptation surface (values in meter). Corrections range from –13.3 cm to +13.6 cm

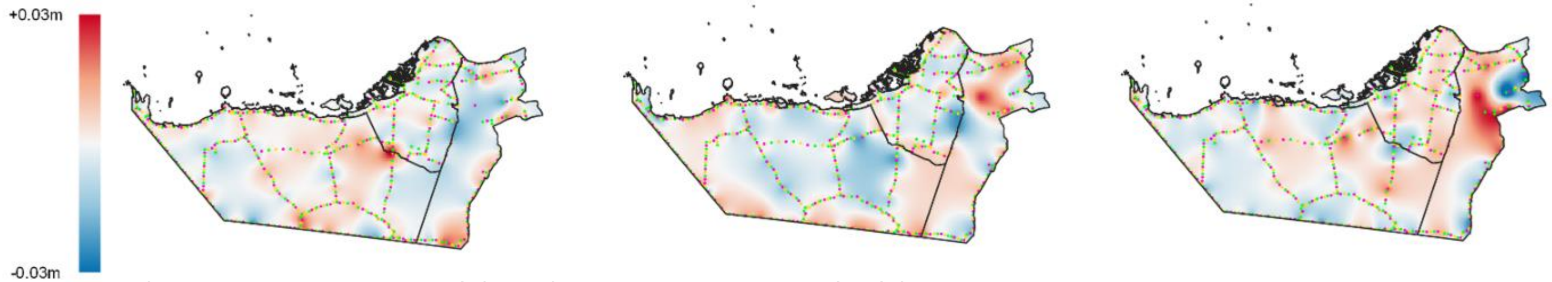


Figure 12: Comparison between LSC surface created with all GNSS–Levelling benchmarks and with subset 1, 2, and 3

Perspectives

- Topography of the Sea Surface is reputedly inaccurate nearshore
  - Satellite altimetry derived gravity is unreliable nearshore due to the corrupted waveforms in shallow waters (Vignudelli et al., 2019)
  - ➢ Global Gravity Models are hardly accurate in these areas
  - TSS height above geoid varies according to metocean conditions (currents, winds…)
- Improvement of TSS determination can lead to better knowledge of nearshore hydrodynamics, which in turn improves knowledge of coastal erosion
  - Prerequisite is determination of local geoid models in coastal areas
  - ➢ Implementation of land and airborne gravimetry to compute accurate geoid models
  - Heights of TSS above geoid can me measured with in-situ measurements
  - ➢ Use of tide gauge networks and Argo floats / Surface Velocity Profiles drifters

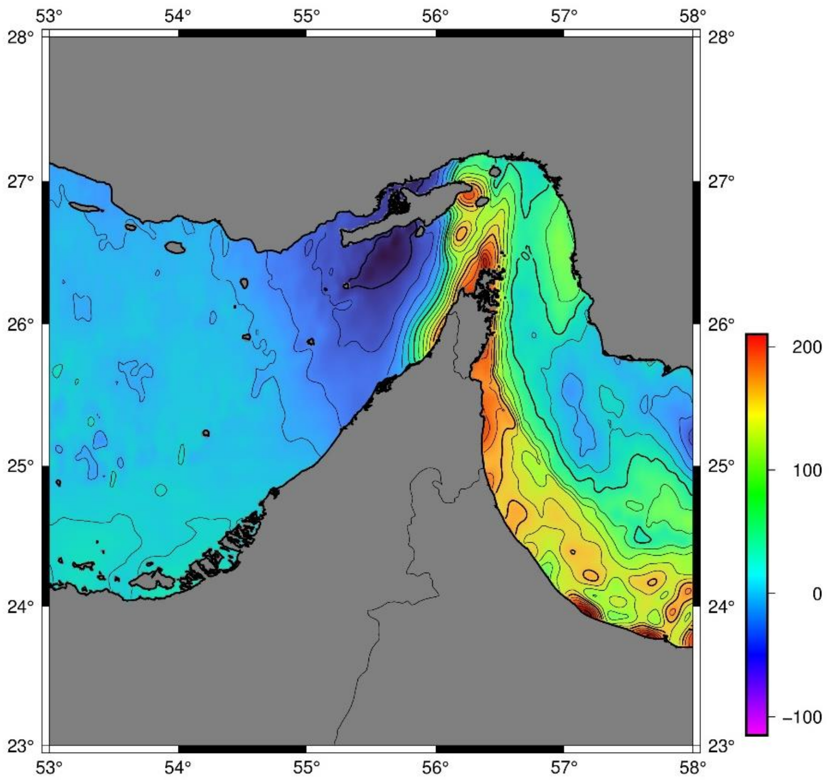


Figure 14: gravity field derived from satellite altimetry in the area of interest, values in mGal

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