Assimilation of satellite altimetry, gravity, leveling and GOCE data for the definition of the Saudi Arabia National Reference Frame (SANVRF)

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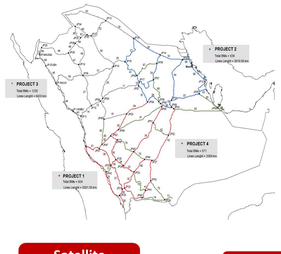
Introduction and Problem Statement

The definition, realization and availability of a common, nationwide and modernized Vertical Reference System (VRS) and Vertical Reference Frame (VRF) is of utmost importance, since it sets the base of all geodetic, surveying and engineering applications. A rigorous VRS/VRF realization supports regional scale projects and possible ties to an International Height Reference System (IHRS). The Kingdom of Saudi Arabia (KSA) has taken unique initiatives for the establishment and re-measurement of its entire geodetic infrastructure. Within that frame, a) high-accuracy spirit leveling measurements have been carried out to form the new National Vertical Network (NVN), b) absolute and relative gravity surveys have been conducted to form the new National Gravity Network (NGN), and c) 11 Tide Gauge (TG) stations have been established to form the National TG Network (NTGN). On the other hand, the current KSA VRS is outdated, exhibits significant tilts and biases, while local VRFs are in place as well. To provide KSA with a modern VRS/VRF the aforementioned data have been used for the definition and realization of a new height system. Given that the only missing information for such an assimilated processing were the ellipsoidal heights at the TG benchmarks (BMs), a 30-year satellite altimetry time-series has been constructed using all available past and current missions.

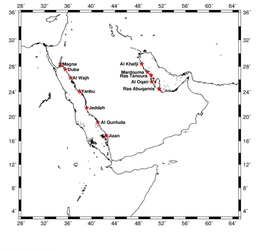
The current work focuses on the presentation of all processing steps for the construction of the altimetry-derived sea level record for each TG station, the estimation of the TG Mean Sea Level and its trends, and the derivation of TG ellipsoidal heights. Then, the use of GOCE-based Global Geopotential Models is presented, while the estimation of geopotential numbers for all TGs is outlined. Finally, unconstrained and constrained Least Squares (LS) adjustments of the entire TG and Levelling network are carried out, estimating the output errors and the distortions introduced to the final network.

Data availability, project necessity and methodology

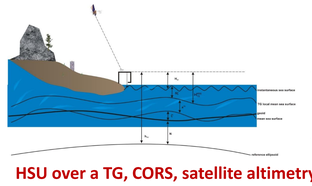
~21k km of leveling observations interconnecting 3,494 BMs throughout the Kingdom

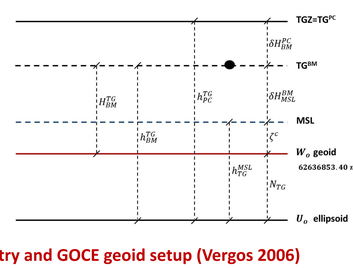


12 TG stations in both western and eastern parts of the KSA coast

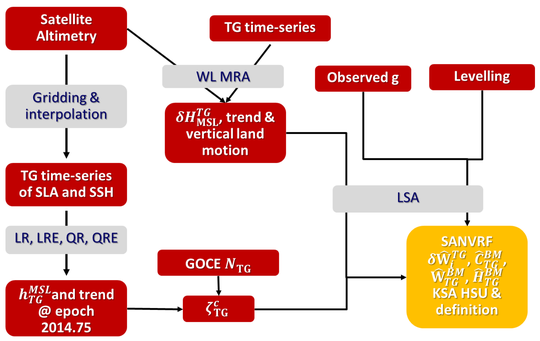


To define the VRS and realize the VRF, link with ellipsoidal heights at the TG locations is needed





HSU over a TG, CORS, satellite altimetry and GOCE geoid setup (Vergos 2006)



Methodology for SANVRF determination using altimetry, GOCE and terrestrial data

Conventions

- TF (tide-free) system
- GRS80 ellipsoid with
  $GM_o = 398600.5000109\ m^3s^{-2}$
  $U_o = 62636860.850\ m^2s^{-2}$.
- Latest IERS Earth's geocentric gravitational constant
  $GM = 398600.4418\ 109\ m^3s^{-2}$
- Latest IAG adopted zero-level geopotential (2015)
  $W_o = 62636853.40\ m^2s^{-2}$,
- Mean Earth's radius has been taken equal to
  $R = 6371008.7714\ m$

A time-series of ERM 10-day observation sets from all satellites was created between 1985-2016.6 consisting of a total number of ~11M SLAs → 960 10-day files with complete records

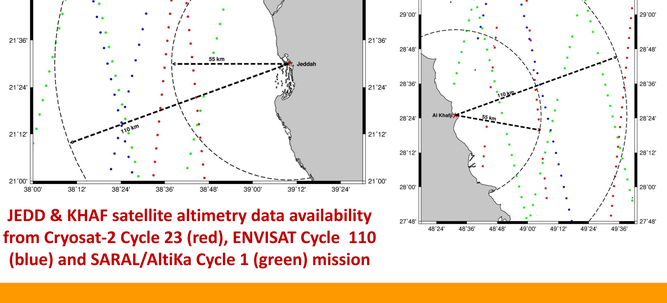
For gridding splines, least squares collocation and bilinear weighted schemes have been tested

For interpolation splines, least squares collocation and bilinear weighted schemes have been tested

Use DTU2015 and EGM2008 as reference models in order to test gridding and interpolation accuracy

The ones providing the best results in terms of prediction accuracy will be used for the final prediction

Combination of bash scripts, GMT, GravSoft, Fortran and C++ coding → ~2.5 hours per station to construct the entire time-series

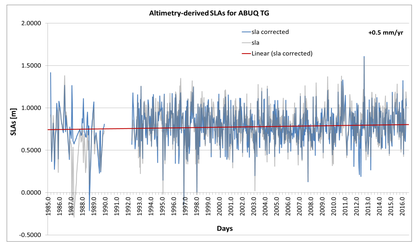


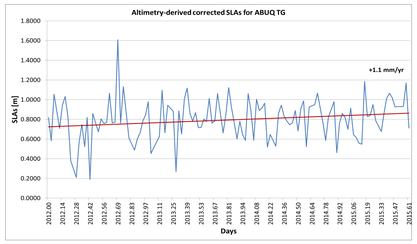
JEDD & KHAF satellite altimetry data availability from Cryosat-2 Cycle 23 (red), ENVISAT Cycle 110 (blue) and SARAL/AltiKa Cycle 1 (green) mission

TG time-series construction/analysis from altimetry

For all TGs sea level rise trends have been estimated for, 1986-2016.6, 1992-2016.6 and 2012-2015.6 (to be inline with the TG records)

Simple linear trend (LT), linear regression (LR), linear regression with errors (LRE), quadratic regression (QR), quadratic regression with errors (QRE) have been devised. Also, MSL ellipsoidal heights at the 2014.75 epoch have been determined in support of coherency analysis with TG records.





ABUQ $\overline{SLA}$ and $\overline{SLA}^{corr}$ variations for the period 1985-2016 & 2012-2015.6 as derived by satellite altimetry

TG ellipsoidal and otrhometric heights for KSA HSU @ epoch 2014.75

TG	$h^{TG\ 2014.75}_{BM\ LRE}$	$h^{TG\ 2014.75}_{MSL\ LRE}$	$\delta H^{BM\ WL\ MRA}_{MSL}$
ABUQ	-28.6348	-29.4608	0.8895
OQAR	-25.8125	-26.1572	0.4352
TANO	-23.8028	-24.8783	1.0307
MARD	-21.0752	-21.7277	1.3324
KHAF	-15.1328	-16.4093	1.1602
JIZA	-3.6376	-3.9956	0.4113
QUNF	1.5567	0.7272	0.8998
JEDD	6.0963	5.5203	0.665
YANB	9.7910	9.0920	1.0594
WAJH	13.0814	12.2504	
DUBA	16.1917	14.3247	0.6984

Geoid selection for testing the estimated $h^{TG\ 2014.75}_{MSL\ LRE}$

Use the DTU2015 DOT as reference for the KSA vertical network adjustment. Employ the latest Release 5 GOCE models with and without spectral enhancement.

Employ the levelled differences of the 3,790 BMs consisting of BMs of the levelling network itself, the TG BMs as well as the deformation network around them.

In total 8,252 levelled differences have been available to be used in the network adjustment. Separate adjustments for each geoid model and combinations was performed.

SANVRF Minimally constrained adjustment and height residuals

Based on DTU2015

TG name	$H^{o\,TG}_{BM}$	$\hat{v}$	$\hat{H}^{TG}_{BM}$	$\hat{\sigma}_{H^{TG}_{BM}}$
Duba	1.4349	0.18239	1.61729	0.02197
Jeddah	1.4967	0.00000	1.49670	0.00103
Jizan	1.3529	-0.06456	1.28834	0.02049
Al Khafji	1.9427	0.05365	1.99635	0.02225
Magna	1.4195	0.14859	1.56809	0.02330
Mardouma	2.1119	0.06755	2.17945	0.02299
Al Oqiar	1.2038	-0.00788	1.19592	0.02319
Al Qunfuda	1.7493	0.01058	1.75988	0.01514
Ras Abuqamis	1.6651	0.06144	1.72654	0.02456
Ras Tanoura	1.8063	0.04447	1.85077	0.02335
Al Wajh	1.3622	0.06747	1.42971	0.01974
Yanbu	1.4349	0.07568	1.87868	0.01686

APRIORI VARIANCE FACTOR : 1.000
APOSTERIORI VAR. FACTOR : 1.053
NUMBER OF OBSERVATIONS : 8345
DEGREES OF FREEDOM : 4556
CONFIDENCE LEVEL : 0.95

Based on GOCO05c

TG name	$H^{o\,TG}_{BM}$	$\hat{v}$	$\hat{H}^{TG}_{BM}$	$\hat{\sigma}_{H^{TG}_{BM}}$
Duba	1.3387	0.13833	1.47704	0.02197
Jeddah	1.3564	0.00000	1.35645	0.00103
Jizan	0.6573	0.49077	1.14809	0.02049
Al Khafji	1.7278	0.12834	1.85610	0.02225
Magna	1.2551	0.17273	1.42784	0.02330
Mardouma	1.9484	0.09081	2.03920	0.02299
Al Oqiar	1.1706	-0.11495	1.05567	0.02319
Al Qunfuda	1.5191	0.10051	1.61963	0.01514
Ras Abuqamis	1.6324	-0.04615	1.58629	0.02456
Ras Tanoura	1.6608	0.04972	1.71052	0.02335
Al Wajh	1.3188	-0.02935	1.28946	0.01974
Yanbu	1.6800	0.05839	1.73843	0.01686

APRIORI VARIANCE FACTOR : 1.000
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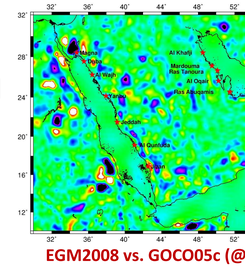
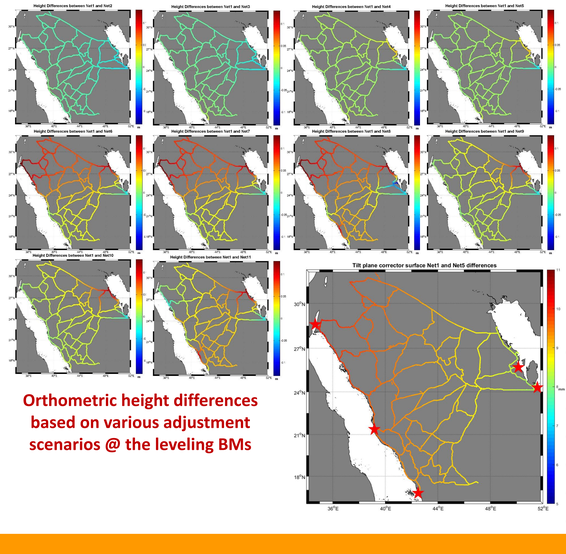


EGM2008 vs. GOCO05c (@d/o 720)

EIGEN6c4 smooths out the GOCE contribution.

GOCO05c preserves GOCE contribution and maintains a stronger signal content up to d/o 720.

No spectral enhancement, since EGM2008 above d/o 721 contains lateral noisy effects over the high mountains not supported by the underlying topographic masses.
The differences between EGM2008 and EIGEN6c4 are almost identical either at d/o 720 and 2190, showing that little information is contributed above d/o 721.



Orthometric height differences based on various adjustment scenarios @ the leveling BMs

BM ID	$\hat{C}^{BM}_{TG}$ [m^2/s^2]	$\hat{\sigma}_{C^{TG}_{BM}}$[m]	$\hat{H}^{BM}_{TG}$ [m]	$\hat{W}^{BM}_{TG}$ [m^2/s^2]
DUB-S	14.54330	0.02147	1.48531	62636838.85670
JED-S	13.35410	0.00005	1.36442	62636840.04590
JZA-S	11.31290	0.02002	1.15619	62636842.08710
KFJ-S	18.25770	0.02174	1.86460	62636835.14230
MAG-S	14.06230	0.02277	1.43615	62636839.33770
MAR-S	20.04800	0.02247	2.04766	62636833.35200
OQR-S	10.40410	0.02266	1.06278	62636842.99590
QUN-S	15.93030	0.01478	1.62787	62636837.46970
RAQ-S	15.61670	0.02401	1.59534	62636837.78330
RAT-S	16.82900	0.02282	1.71896	62636836.57100
YAN-S	17.09820	0.01646	1.74666	62636836.30180
WAJ-S	12.70500	0.01929	1.29769	62636840.69500

Final adjusted orthometric heights for the KSA TGs

- LSA type: Fixed geo-potential number above MSL of Jeddah TGBM-S
- Geopotential number of TGBM-S w.r.t. WMSL, CTGBM-S: 6.5086 [m^2/s^2]
- Fixed height above Mean Sea Level of Jeddah TGBM-S: 0.6650 [m]
- Ellipsoidal height of MSL at TGBM-S: 5.5203 [m]
- MSL rate at TGBM-S: 0.10±0.02 [mm/y]
- Height of TGBM-S above MSL in old Jeddah 1969 vertical datum: 0.6832 [m]
- Transformation shift from old Jeddah'69 to Jeddah'2014: -0.0182 [m]
- Status: Proposed
- Organization: General Directorate of Geodesy, GCS
- Tidal system: Free Tide
- Epoch: 2014.75
- Primary Bench Mark: Jeddah TGBM-S
- ϕ=21.49833°
- λ=39.16422°

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