Satellite Altimetry Data Analysis for Mean Sea Level Determination and Vertical Datum Definition of Kingdom of Saudi Arabia (KSA)

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Introduction & Objectives

Nowadays, the analysis of satellite altimetry data in coastal areas is considered as an essential part of vertical datum definition of a country or region. The combination of Tide Gauge (TG) data, GPS/GNSS/Leveling data, land gravity and precise leveling data, Global Geopotential Models (GGMs) and regional geoid models can lead to a precise determination of the local shift δW_o of the gravity potential of the Mean Sea Level (MSL) at every TG station

In order to derive the MSL on specific TG locations and at a common time epoch, all available satellite altimetry data in the Red Sea and the Arabian Gulf are utilized. For this purpose the MSL at a reference epoch together with its trend need to be estimated in coastal areas

On a later stage, the estimated MSL will be combined with most recent GGMs and regional KSA geoid together with available gravity values in order to define a new KSA vertical datum, necessary for a new Saudi Arabia National Vertical Reference System

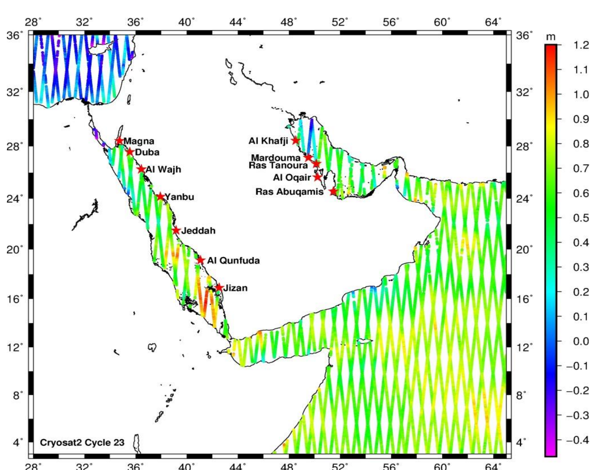
The results have been analyzed and conclusions regarding the contribution of satellite altimetry data application are drawn together with the estimations of MSL at TG stations, necessary for the definition of the KSA vertical datum and its connection to an International Height References System (IHRS)

Satellite altimetry data availability and methodology

Satellite altimetry provides an extensive (1986-today) record of homogeneous in accuracy and resolution observations of the sea level

All available data until epoch 2016.6 have been employed, comprising of sea level anomalies (SLAs) from the ERM missions of GEOSAT, ERS1/2, Topex/Poseidon, Envisat, Jason1/2, GFO, Cryosat and SARAL/AltiKa

A time-series of ERM 10-day observation sets from all satellites was created between 1985-2016 consisting of a total number of ~11M SLAs → 960 10-day files with complete records



Satellite altimetry data availability around KSA (Cryosat, Jason2 and SARAL/AltiKa)

This resulted in 8,000-33,000 observations in every 10-day record

For each 10-day record a TG specific analysis has been performed (for all 12 TGs) in order to investigate gridding and interpolation algorithms

These are to be used in order to determine the SLA value for each TG for each 10-day period

A total number of 12x960 = 11,520 gridding operations and 11,520 interpolations is needed

For gridding and interpolation splines, least squares collocation and bilinear weighted schemes have been tested and validated for the accuracy they provide

- DTU2015 (MSS) and EGM2008 (geoid heights) have been used as reference models in order to test gridding and interpolation accuracy. 2 models x 12 TG x 3 methods = 72 accuracy investigation schemes
- Then carry out the gridding and interpolation for each TG station for each 10-day observation period
- Need to optimize the procedure computationally in order to carry it out within a reasonable amount of time. A combination of bash scripts, GMT, GravSoft, Fortran and C++ coding → ~2.5 hours per station to construct the entire time-series
- Robustness, so that the entire set can be predicted for any new TG station within a reasonable time in order to include new information in the TG station list

Conventions in computation

- TF (tide-free) system
- GRS80 ellipsoid with

$$GM_o = 398600.5000109\ m^3 s^{-2}$$
$$U_o = 62636860.850\ m^2 s^{-2}.$$

- Latest IERS Earth's geocentric gravitational constant

$$GM = 398600.4418\ 109\ m^3 s^{-2}$$

Latest IAG adopted zero-level geopotential (2015)

$$W_o = 62636853.40\ m^2 s^{-2},$$

- Mean Earth's radius has been taken equal to

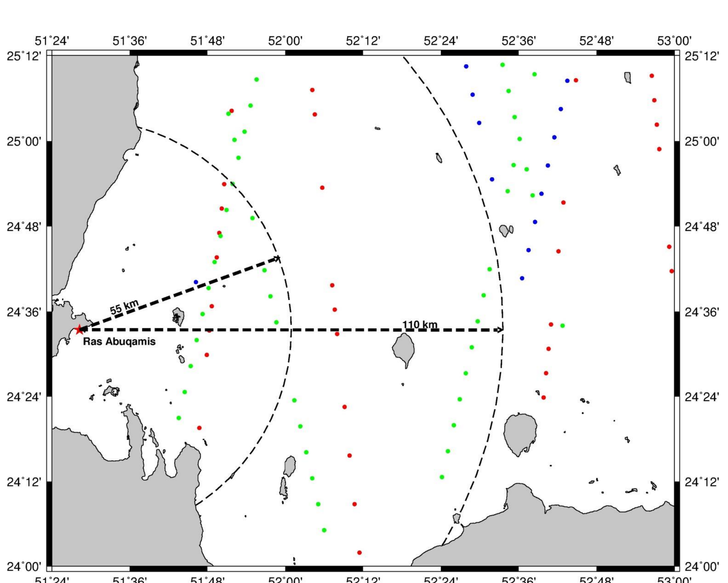
$$R = 6371008.7714\ m$$

All satellite altimetry SLAs are corrected for geophysical effects (atmosphere, sea state, tides, etc.) used the same models

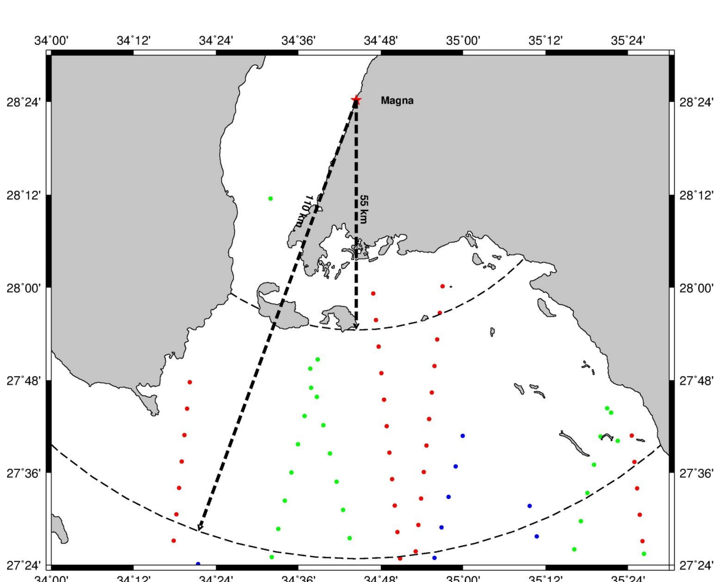
All satellite altimetry SLAs are corrected for instrumental errors as well

For each station, both SLAs and corrected SLAs for the IB effect have been determined

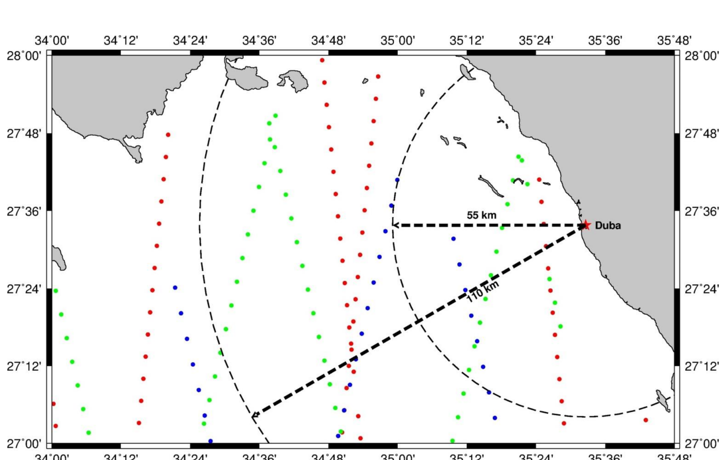
$$\begin{aligned} h_{TG}^{MSL\ TF} &= h_{TG}^{MSL\ MT} - 1.3(0.099 - 0.296\sin^2\varphi) \\ &= \overline{SLA}^{corr} + N_{TG}^{EGM2008\ MT} - 1.3(0.099 - 0.296\sin^2\varphi) \\ &= \overline{SLA}^{corr} + N_{TG}^{EGM2008\ TF} \\ &= \overline{SLA}^{corr} + \left(N_{TG}^{TF}\Big|_{n=2}^{2190} + N_{o\,TG}^{TF}\right) \end{aligned}$$



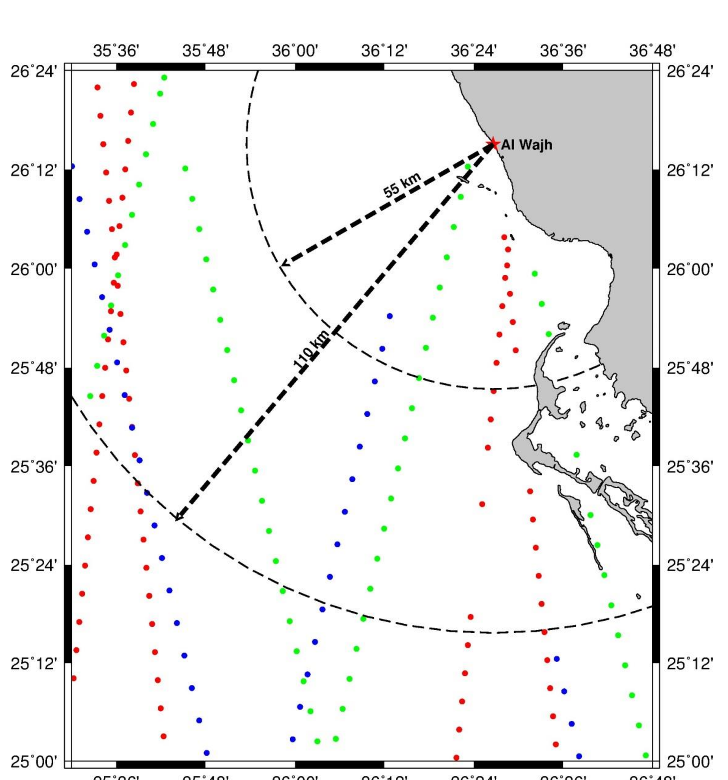
ABUQ satellite altimetry data availability from Cryosat-2 Cycle 23 (red), ENVISAT Cycle 110 (blue) and SARAL/AltiKa Cycle 1 (green) mission



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



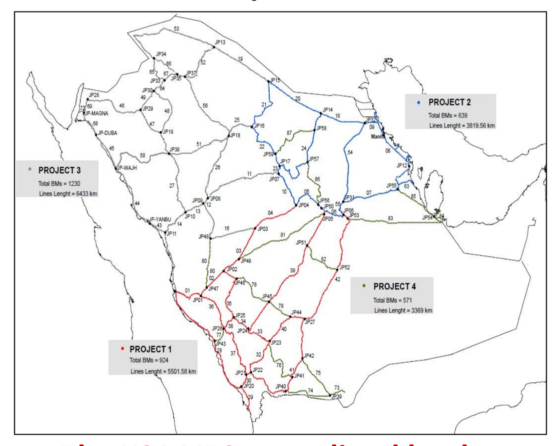
DUBA satellite altimetry data availability from Cryosat-2 Cycle 23 (red), ENVISAT Cycle 110 (blue) and SARAL/AltiKa Cycle 1 (green) mission

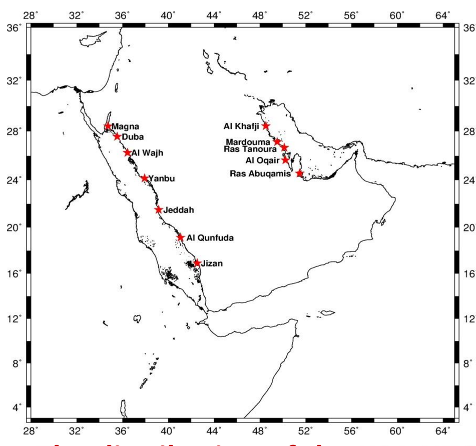


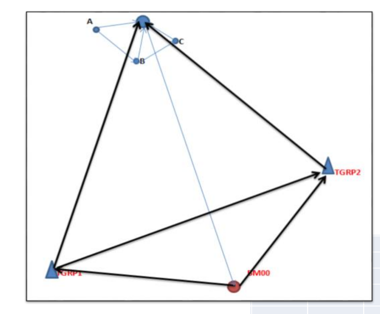
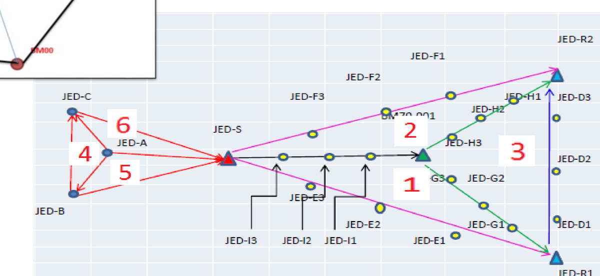
WAJH satellite altimetry data availability from Cryosat-2 Cycle 23 (red), ENVISAT Cycle 110 (blue) and SARAL/AltiKa Cycle 1 (green) mission

KSA VRS data availability and set up

In the KSA an extensive effort has been carried out for the re-establishment of the leveling network (~21k km of leveling interconnecting 3,552 BMs), gravity data collection and TG station installation (12 stations in the Red Sea and Arab Sea).


The KSA VRS as outlined by the performed leveling traverses

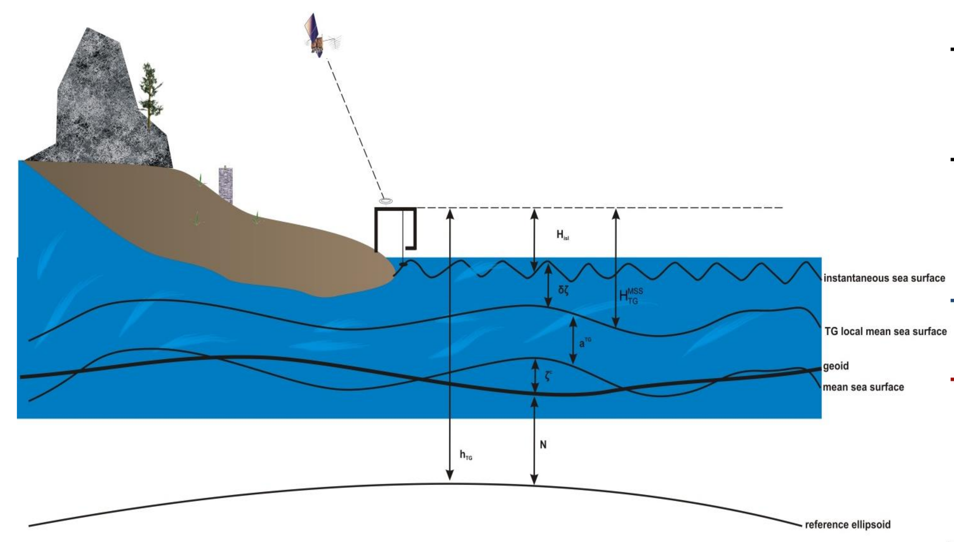

The distribution of the KSA NTGN TGs in the Red and Arab Seas



A general shape of TG deformation network (left) and TG loops (right)

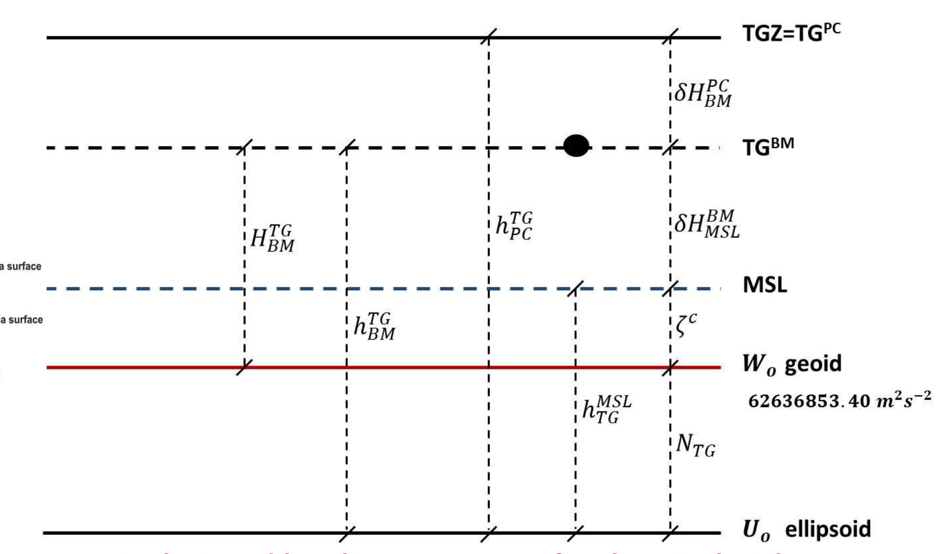
The TGs and the leveling BMs are linked with 1st order leveling, while ellipsoidal heights at the TG BMs are yet to be measured (project to be completed within 2017-2018)

Therefor, to define the KSA VRS, link with ellipsoidal heights at the TG locations is needed

HSU in KSA with TG, Leveling and GNSS-like data from altimetry



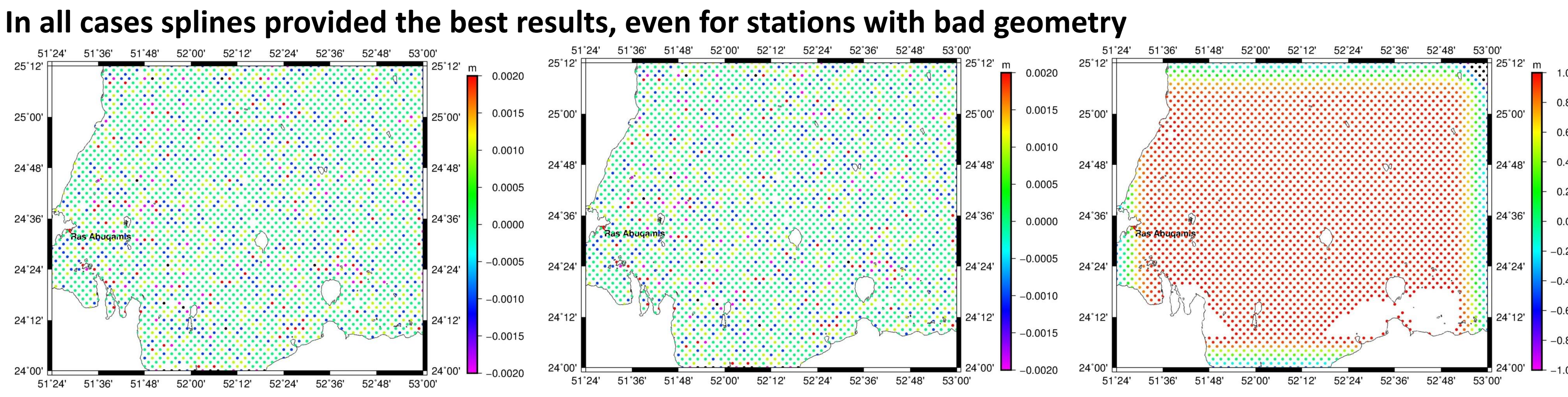
HSU over a TG, CORS, satellite altimetry and GOCE/gravimetric geoid setup



Typical TG and leveling BM set-up for the KSA height system unification

TG time-series construction from satellite altimetry

In all cases splines provided the best results, even for stations with bad geometry



MSS differences between the predicted and original field around ABUQ with splines (left), weighted bilinear (center) and LSC (right)

For all TGs sea level rise trends have been estimated for

- 1986-2016.6
- 1992-2016.6
- 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 determined in support of coherency analysis with TG records

Statistics of altimetry derived SLAs and MSL ellipsoidal heights at the ABUQ TG. Unit [m]

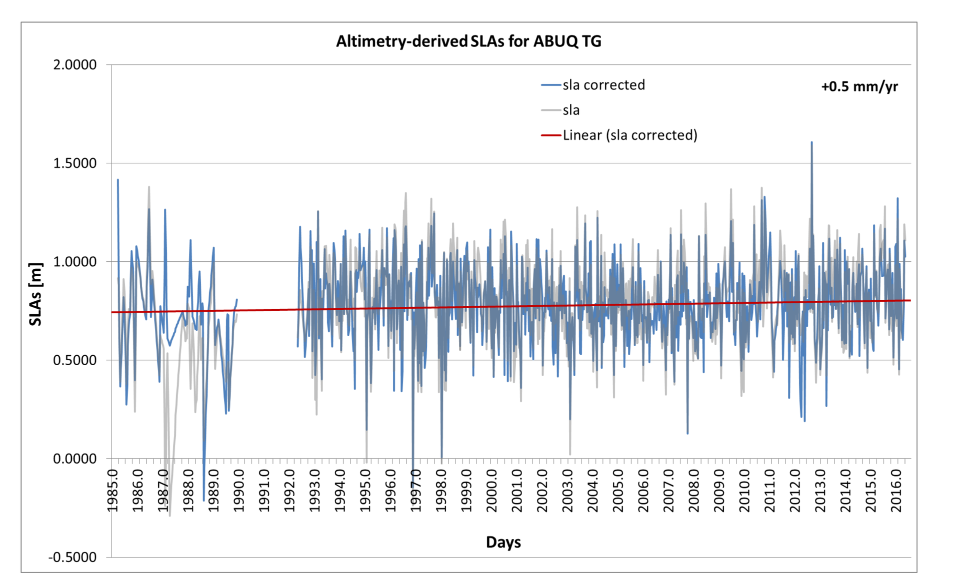
	max	min	mean	rms	std
$\overline{SLA}$	1.5920	-0.2890	0.7705	0.8061	0.2370
$\overline{SLA}^{corr}$	1.6090	-0.2120	0.7751	0.8012	0.2030
$h_{TG}^{MSL\ MT}$	-28.6261	-30.4471	-29.4600	29.4607	0.2030
$h_{TG}^{MSL\ TF}$	-28.6896	-30.5106	-29.5235	29.5242	0.2030
h_{PC}^{TG}	-26.7049	-28.5259	-27.5388	27.5395	0.2030
h_{BM}^{TG}	-27.8599	-29.6809	-28.6938	28.6945	0.2030
$h_{BM}^{TG\ 2012-2015.6}$	-27.8599	-29.2789	-28.6750	28.6757	0.2086
H_{BM}^{TG}	2.4387	0.6177	1.6048	1.6176	0.2030
IB local	0.2640	-0.1710	0.0336	0.0879	0.0812
IB G&L	0.2520	-0.1840	0.0154	0.0889	0.0876
IB global	0.0810	-0.0540	-0.0232	0.0251	0.0095
Std [cm]	19.2000	0.0000	3.2445	4.8626	3.6218

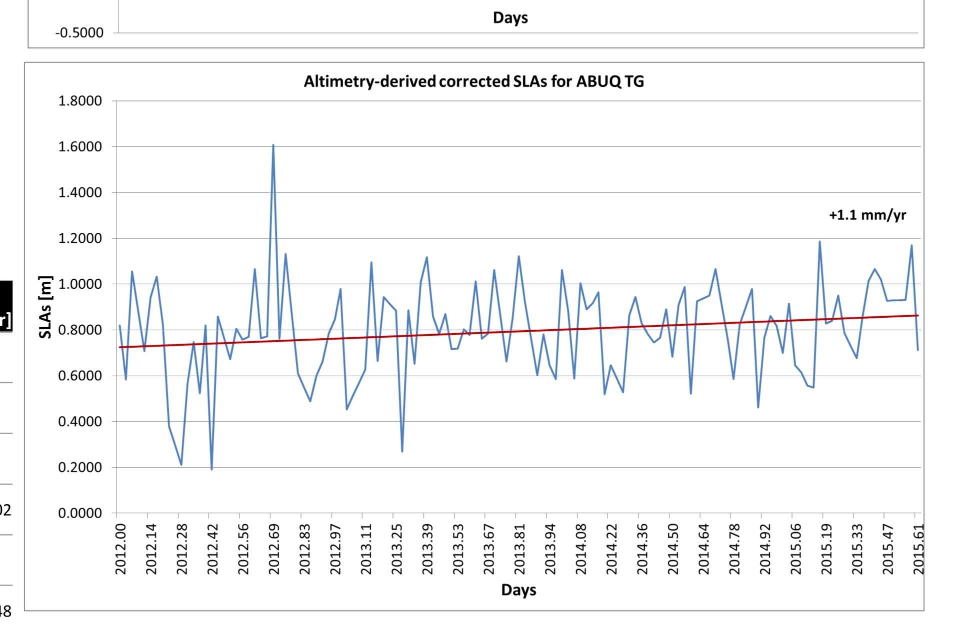
$\overline{SLA}^{corr}$ trend equations for ABUQ

$\overline{SLA}^{model}$	c	b	a	epoch	Epoch t_o	Trend [mm/yr]	Error [mm/yr]
LT		+0.00051	+0.74304	1985.25-2016.60	1985.25	+0.51	
LT		+0.00107	+0.72326	2012.00-2015.60	2012	+1.07	
LR		+0.00050	+0.74907	1985.25-2016.40	1985.25	+0.50	
LRE		+0.00110	+0.74608	1985.25-2016.40	1985.25	+0.55	±0.02
LR		+0.00107	+0.72436	2012.00-2015.60	2012	+1.07	
LRE		+0.00110	+0.72134	2012.00-2015.60	2012	+1.10	±0.48
QR	$+5.54342\cdot10^{-7}$	+0.00010	+0.72587	2012.00-2015.60	2012	+1.00	
QRE	$-7.61125\cdot10^{-7}$	+0.00120	+0.71915	2012.00-2015.60	2012	+1.20	±0.14

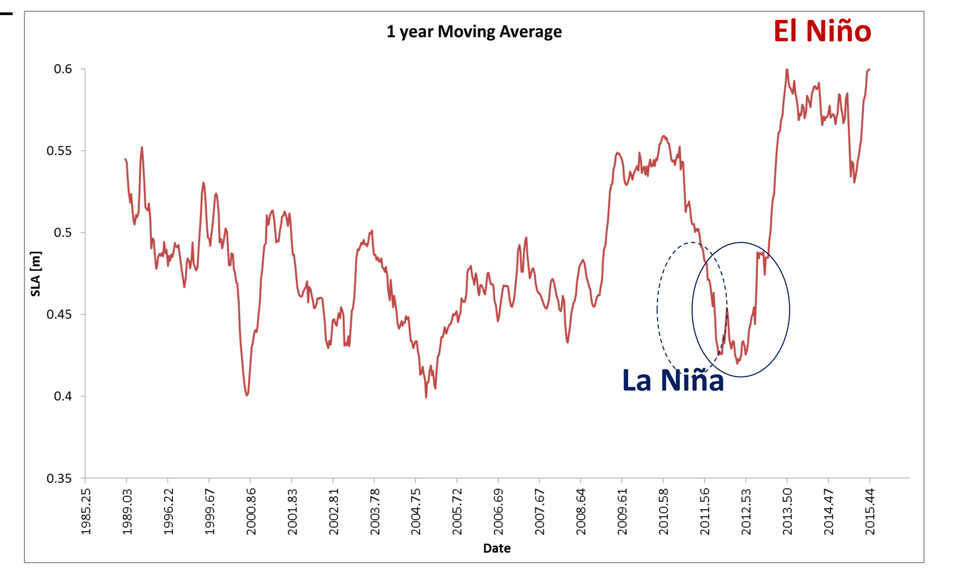
Trend equations for ABUQ h_{BM}^{TG} for the period 2012-2015.6 and h_{BM}^{TG} prediction

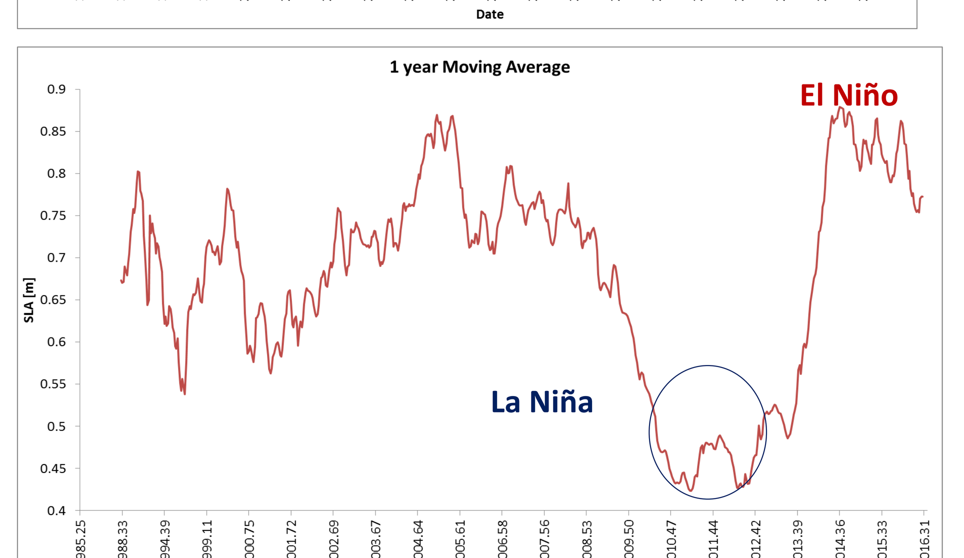
$\overline{SLA}^{model}$	#recs	#rec id	Date t_o	Date t_i	h_o [m]	Trend [mm/yr]	h_{ti} [m]
LT	130	100	2012.000	2014.7500	-28.74564	+1.07	-28.63864
LR	130	100	2012.000	2014.7500	-28.74457	+1.07	-28.63757
LRE	130	100	2012.000	2014.7500	-28.74755	+1.10	-28.63476
QR	130	100	2012.000	2014.7500	-28.74306	+1.04	-28.63765
QRE	130	100	2012.000	2014.7500	-28.74975	+1.20	-28.63689





$QUNF$ (top) vs. ABUQ (bottom) annual variations for the period 1985-2016 as derived by satellite altimetry (Red vs. Arab Sea)





Conclusions

The approach is localized, based on the special characteristics of each TG station (land intrusion, existence of islands, etc.) as well as the statistical properties of the dynamic sea level

This approach has never been followed for the analysis of sea level related records and provides an independent source of sea level and ellipsoidal heights for the TGs

The estimated TG ellipsoidal heights are independent from any geoid and MDOT related model

Definition of the KSA LVD $\widehat{W}_o^{LVD}$ and its connection to a global zero-level geopotential will be achieved given the final adjusted orthometric heights at the TGs

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