SAVRS/SAVRF Predefinition

Satellite altimetry and GOCE contribution to the pre-definition of the Kingdom of Saudi Arabia (KSA) Vertical Network

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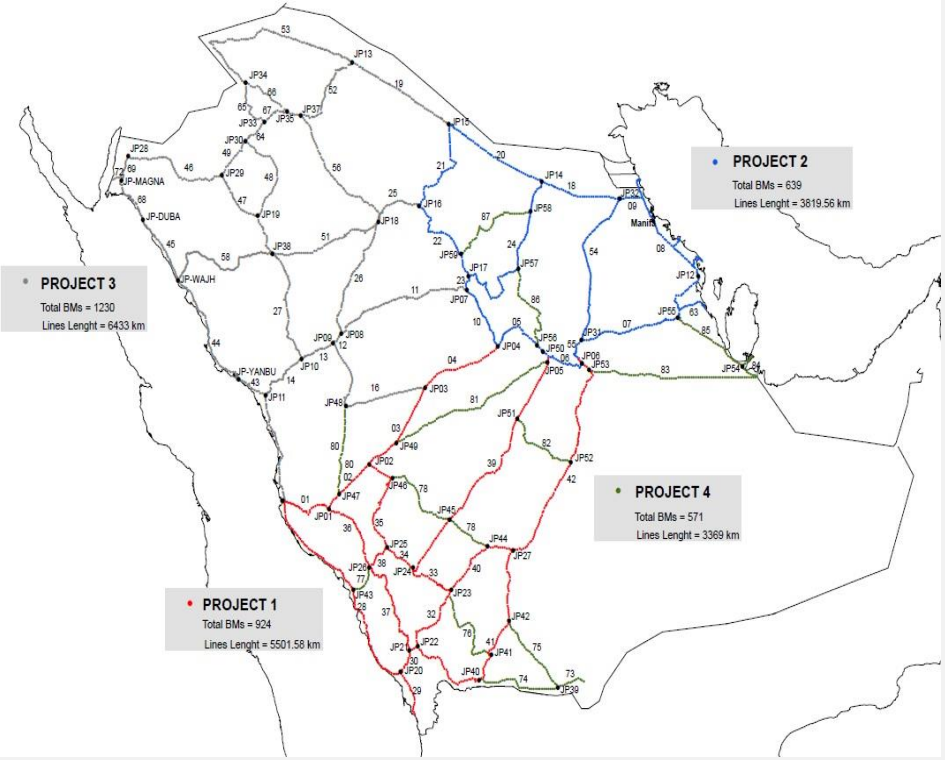
OUTLINE

- Problem statement
- Methodology/Theory
- Data availability
- Processing
- Results
- Conclusions

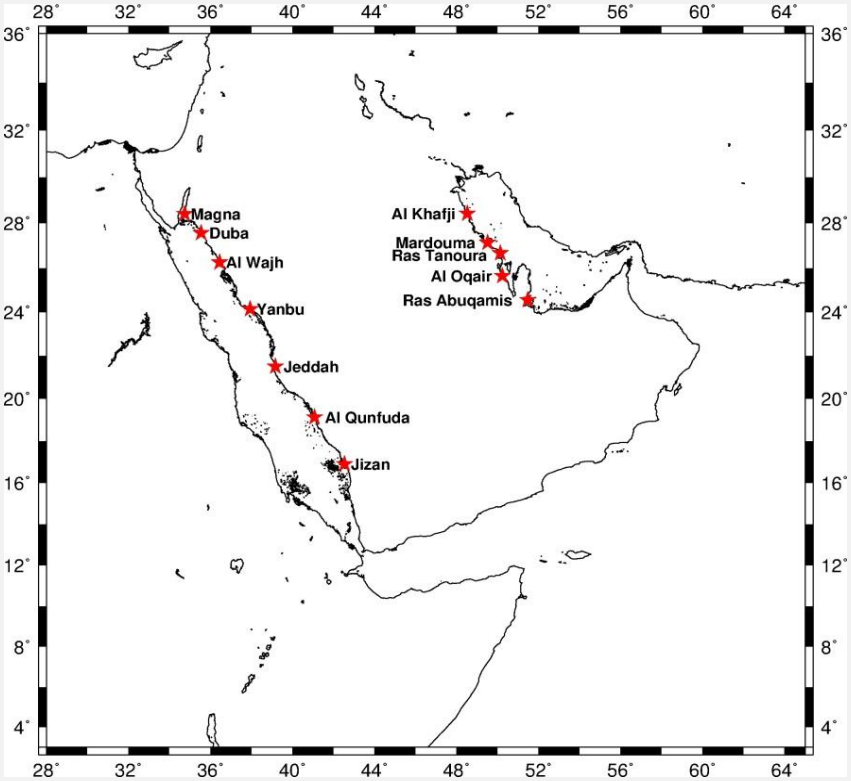
Necessity of the project and goals

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



The KSA VD as outlined by the performed levelling traverses carried out by GCS after Salawu A (2016)

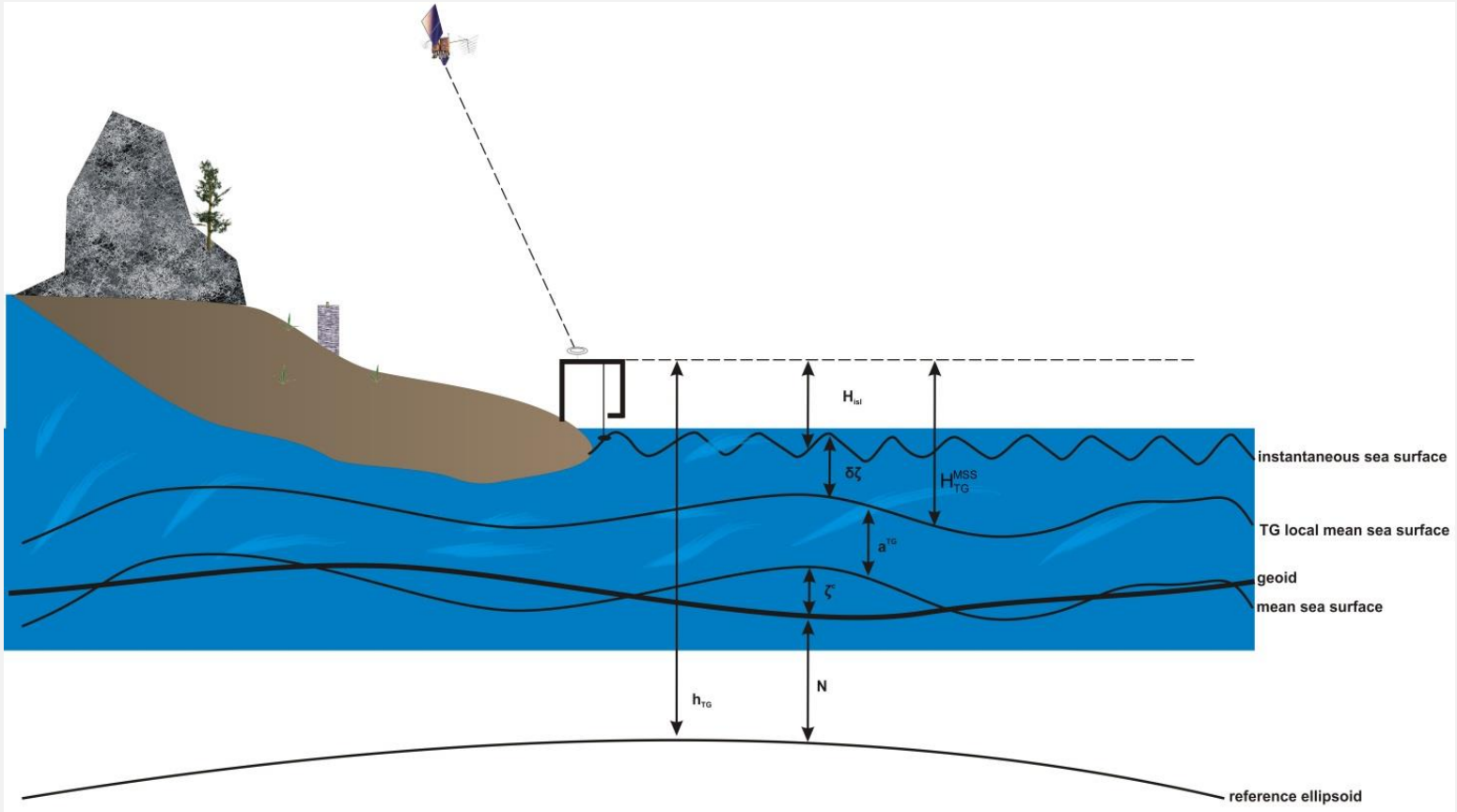
12 TG stations in both western and eastern parts of the KSA coast



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

Necessity of the project and goals

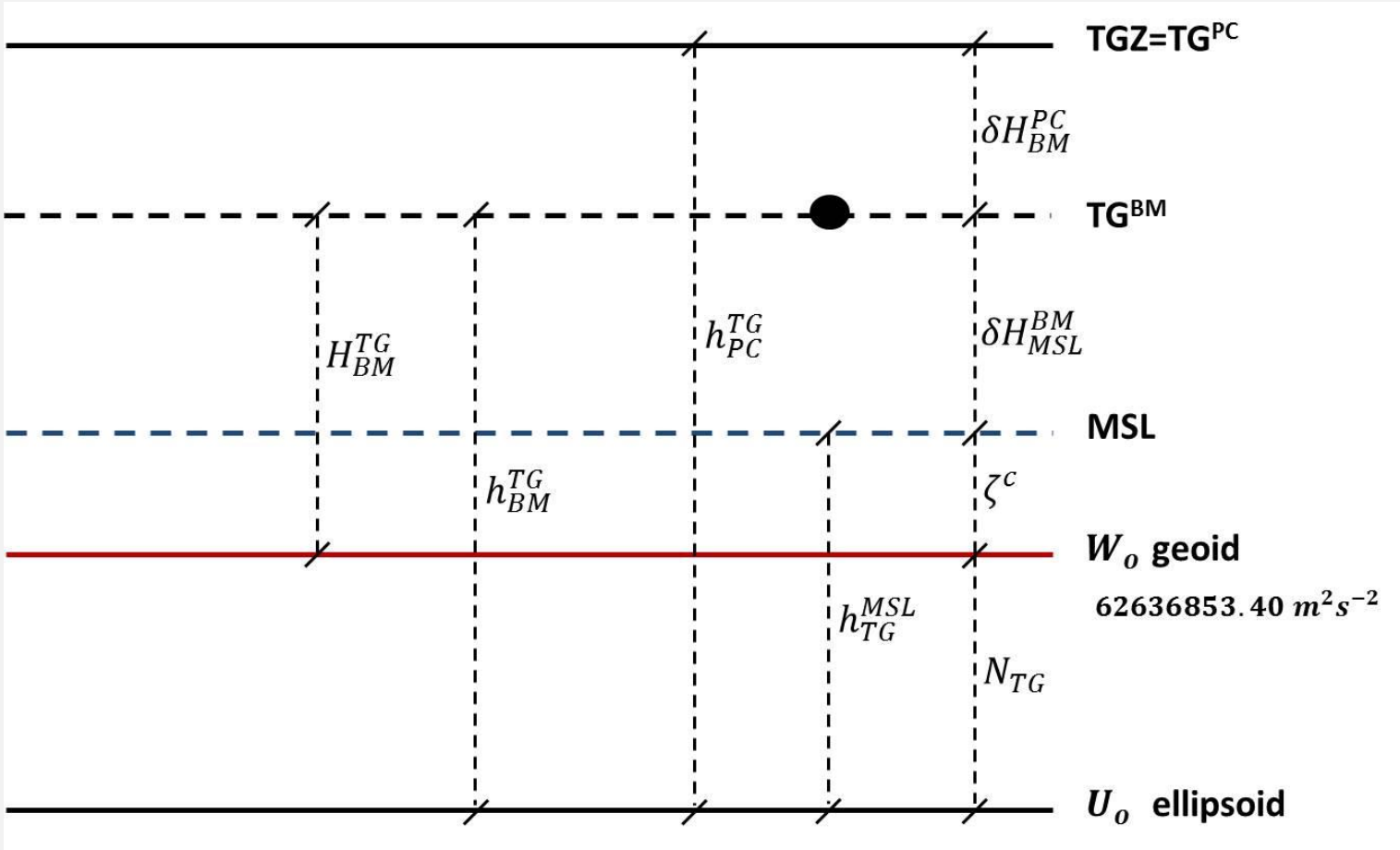
To define the VRS and realize the VRF, link with ellipsoidal heights at the TG locations is needed



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

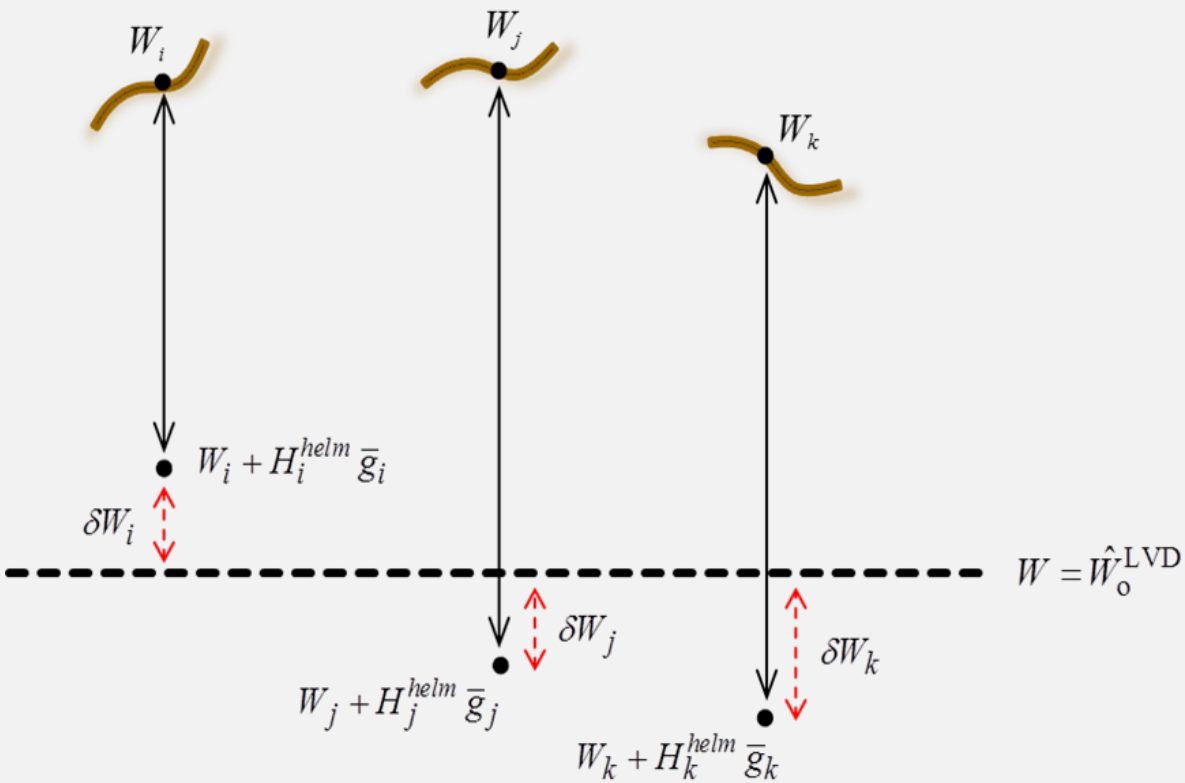
Necessity of the project and goals

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



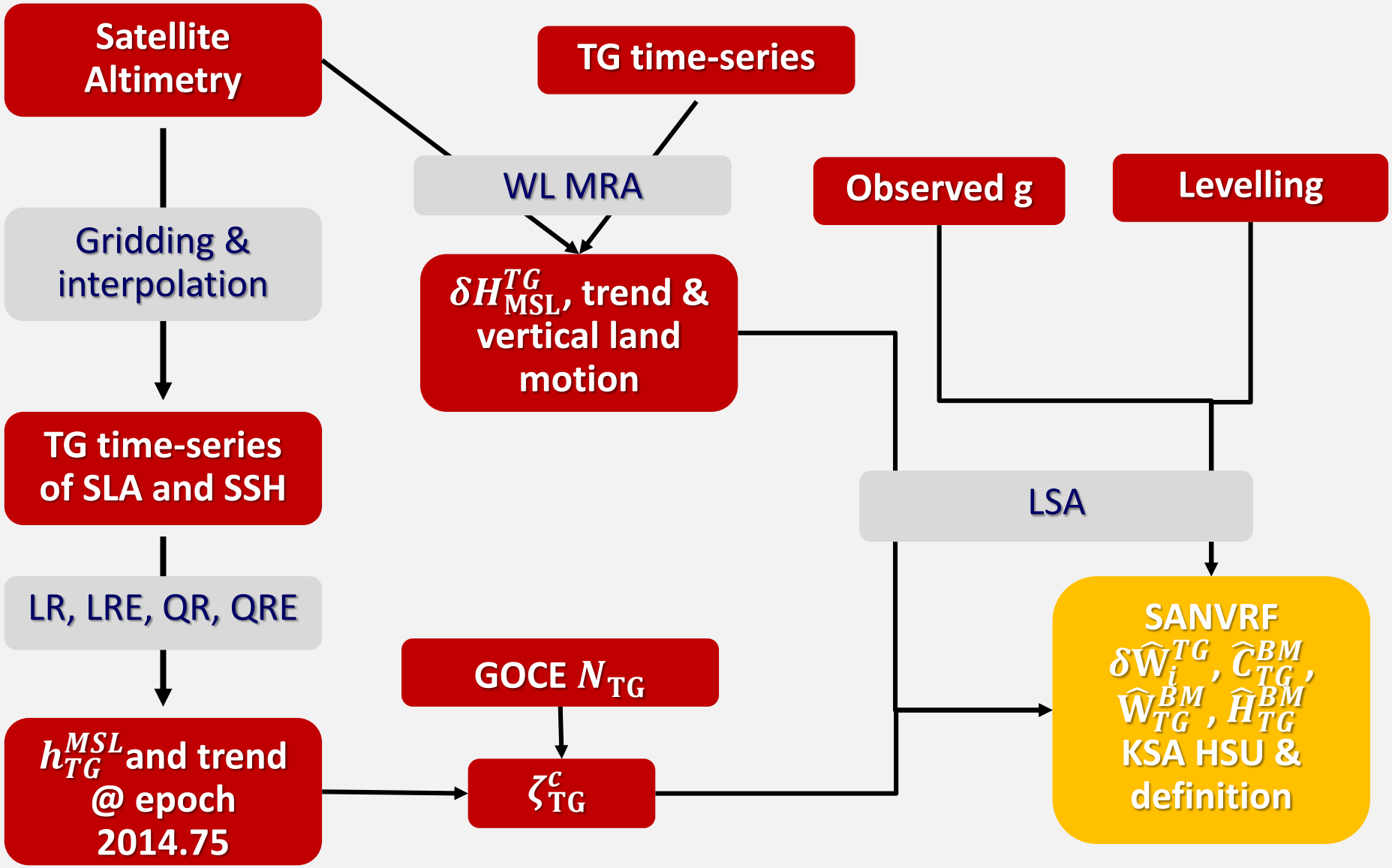
Necessity of the project and goals

Then HSU can be carried out employing all leveling, geoid, gravity, and TG data

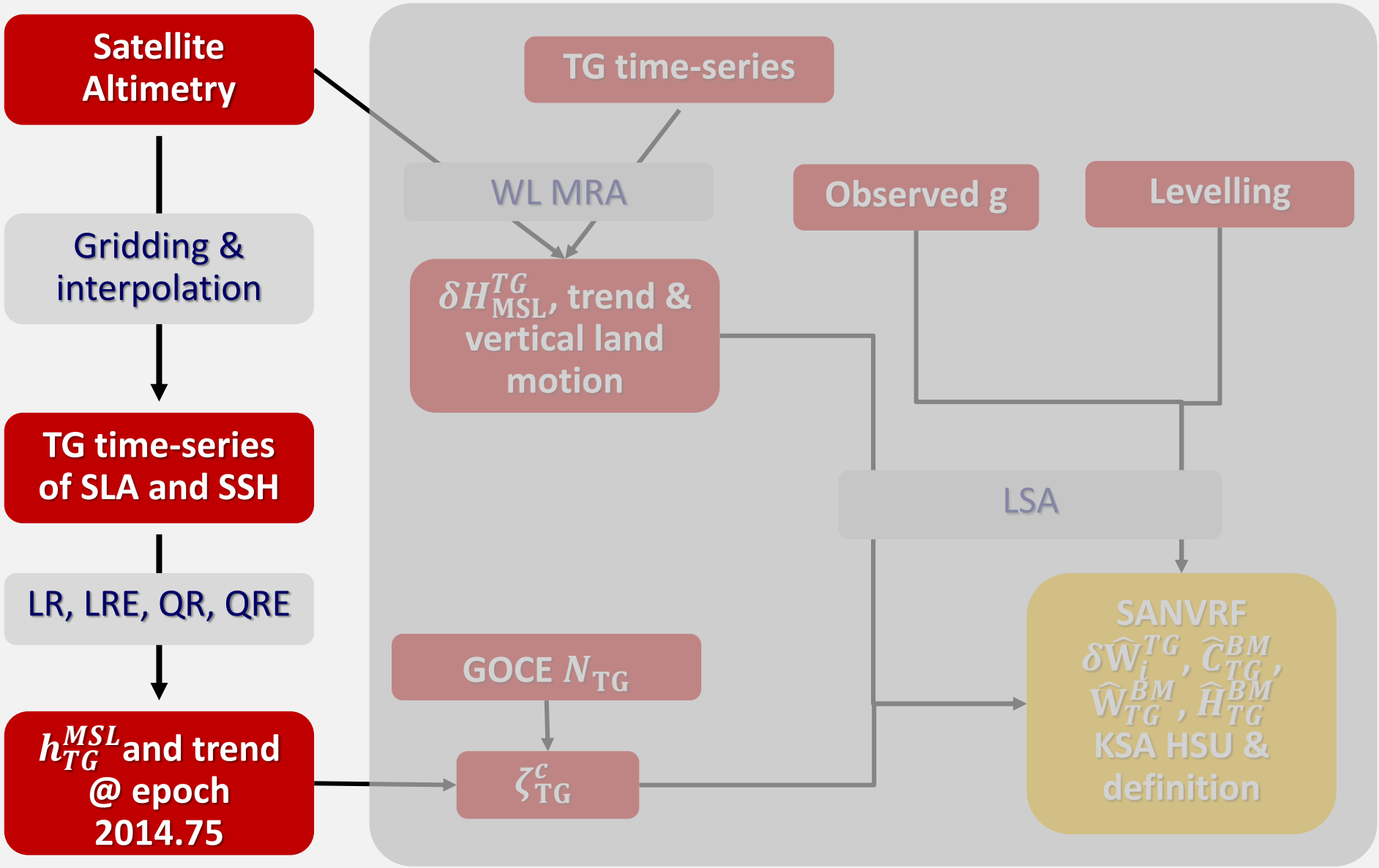


Zero-height geopotential value determination from a network of stations (after Grigoriadis et al. 2014)

Methodology



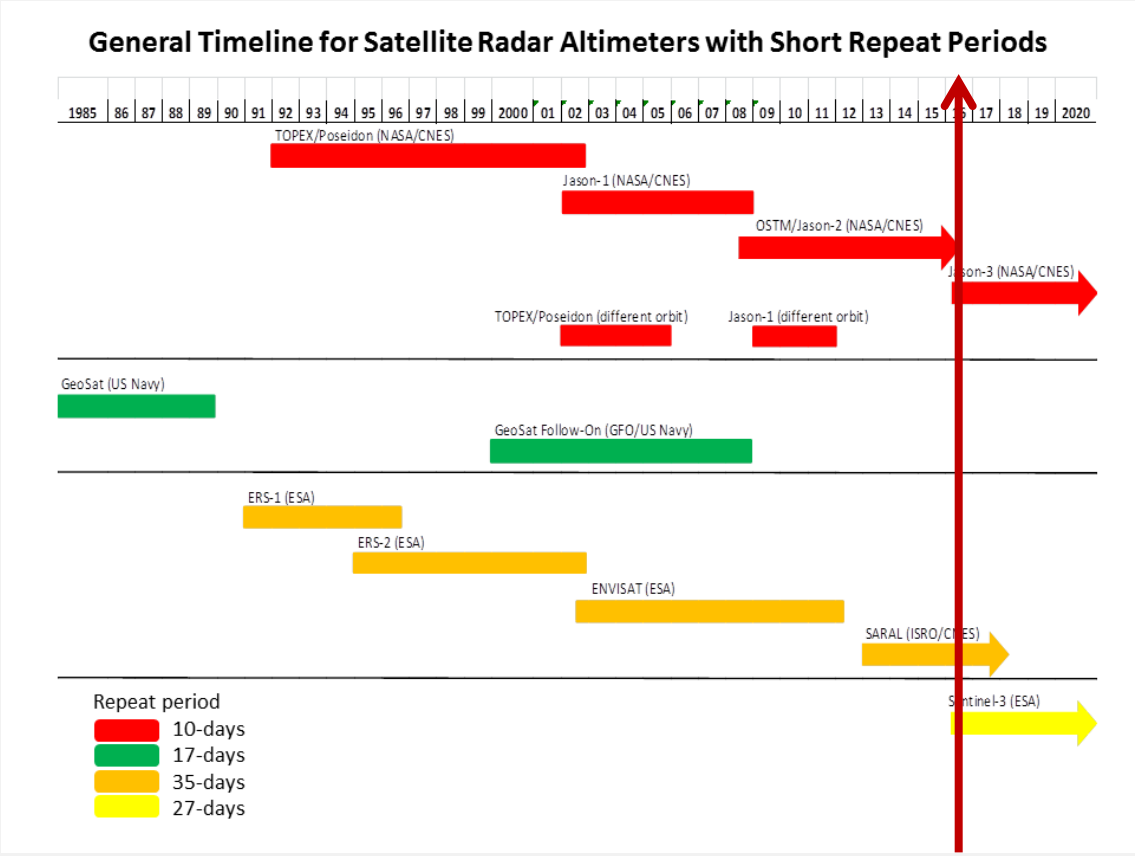
h_{TG}^{MSL} and trend



h_{TG}^{MSL} and trend

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

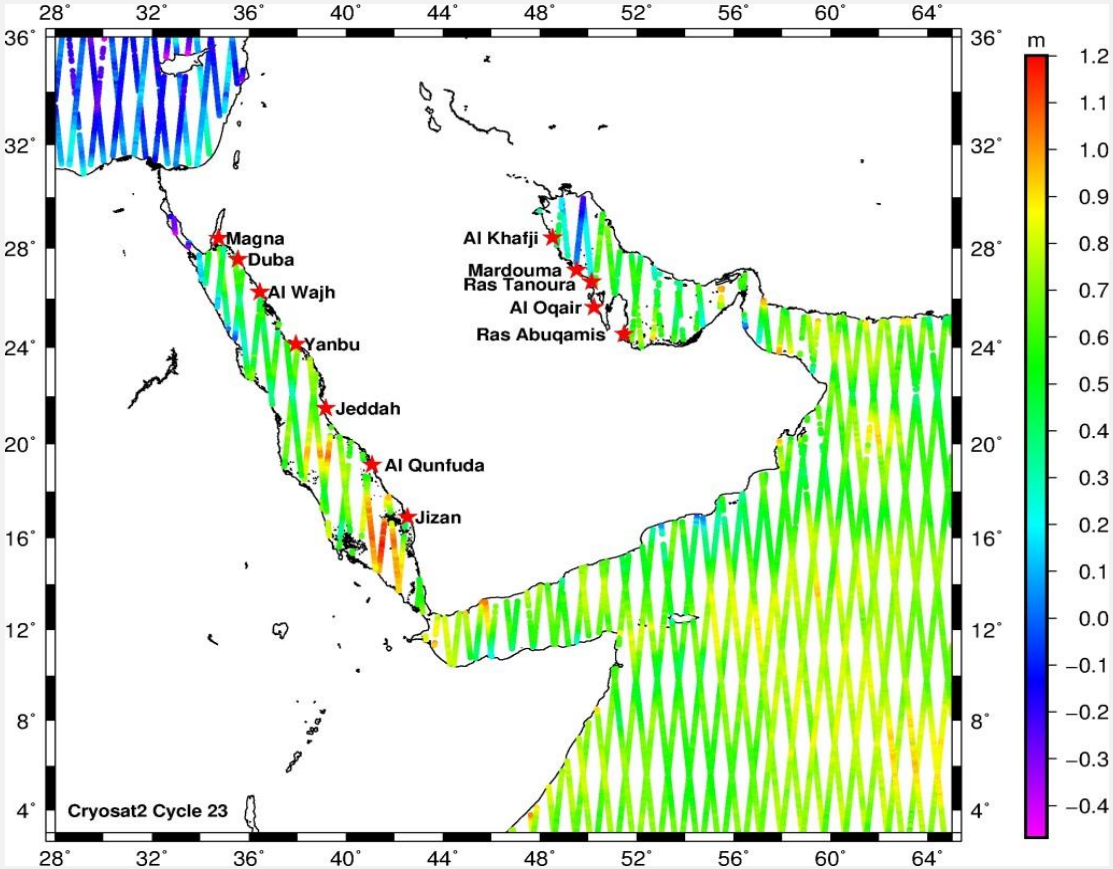
Satellite altimetry data availability



h_{TG}^{MSL} and trend

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

Satellite altimetry data availability around KSA



h_{TG}^{MSL} and trend

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

h_{TG}^{MSL} and trend

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

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 (see Saudi Aramco TGs) in order to include new information in the TG station list

h_{TG}^{MSL} and trend

- **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**

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

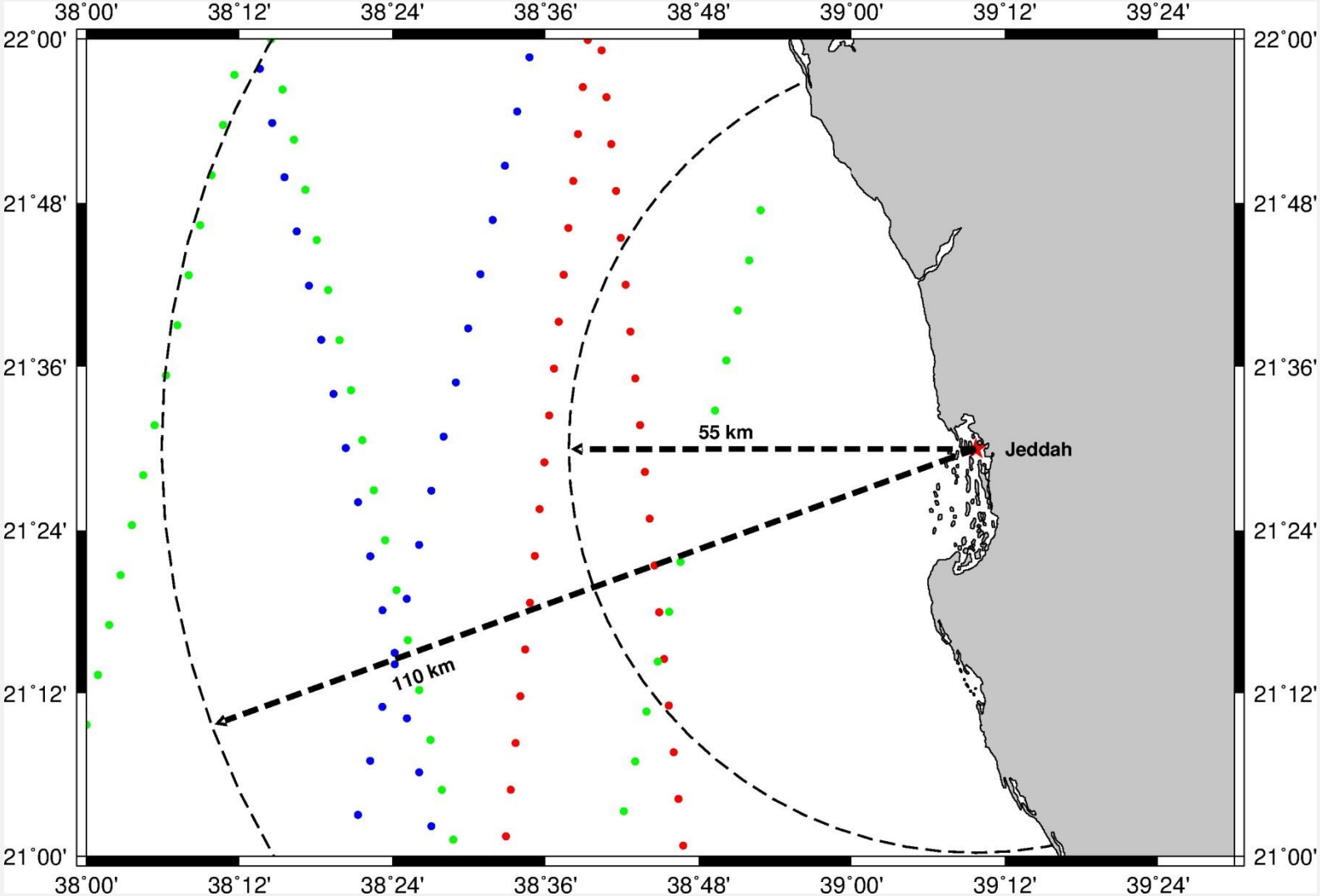
- **Latest IAG adopted zero-level geopotential (2015)**

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

- **Mean Earth's radius has been taken equal to**

$$R = 6371008.7714\ m$$

TG specific cases



JEDD 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

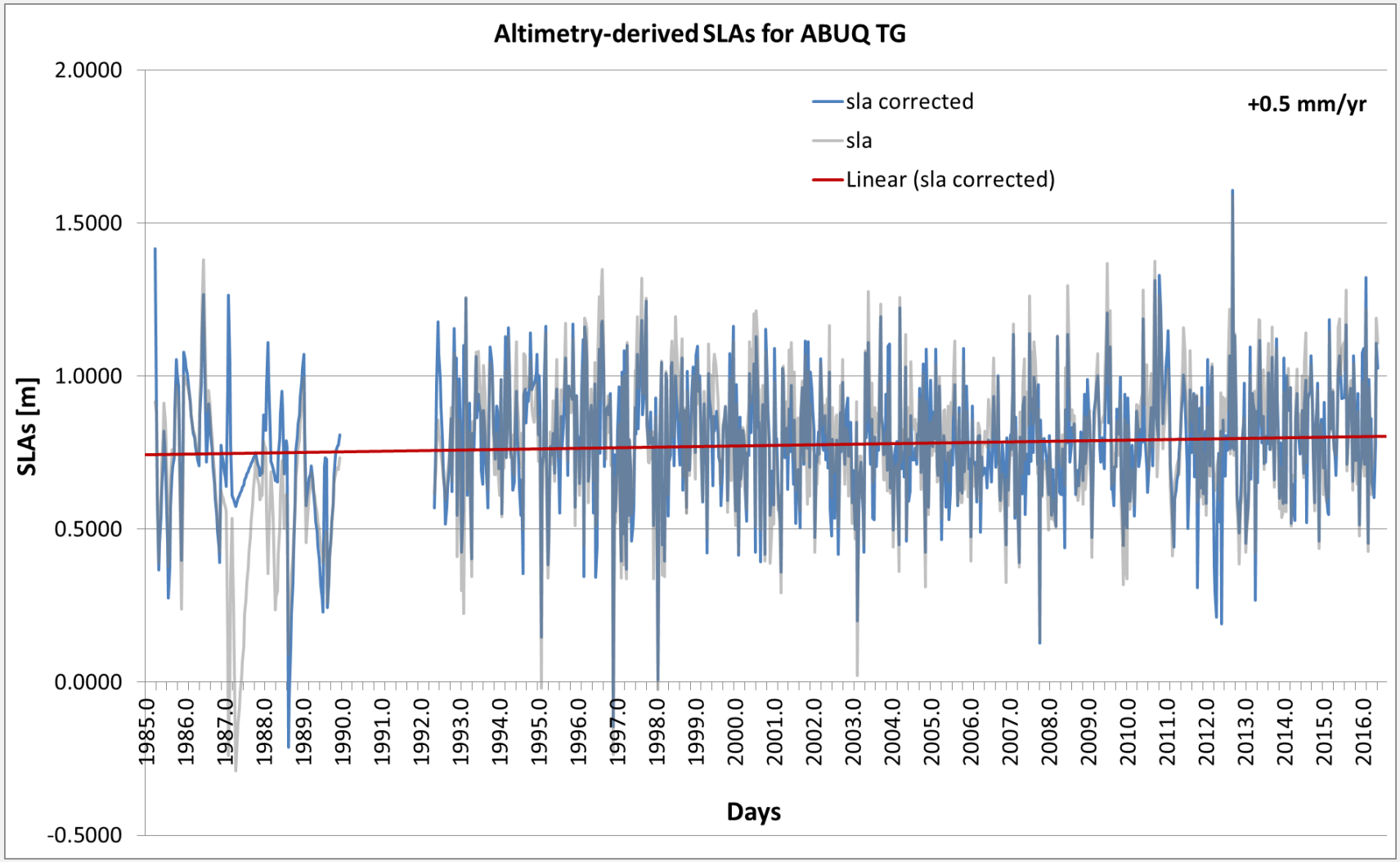
For all TGs sea level rise trends have been estimated for

- 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

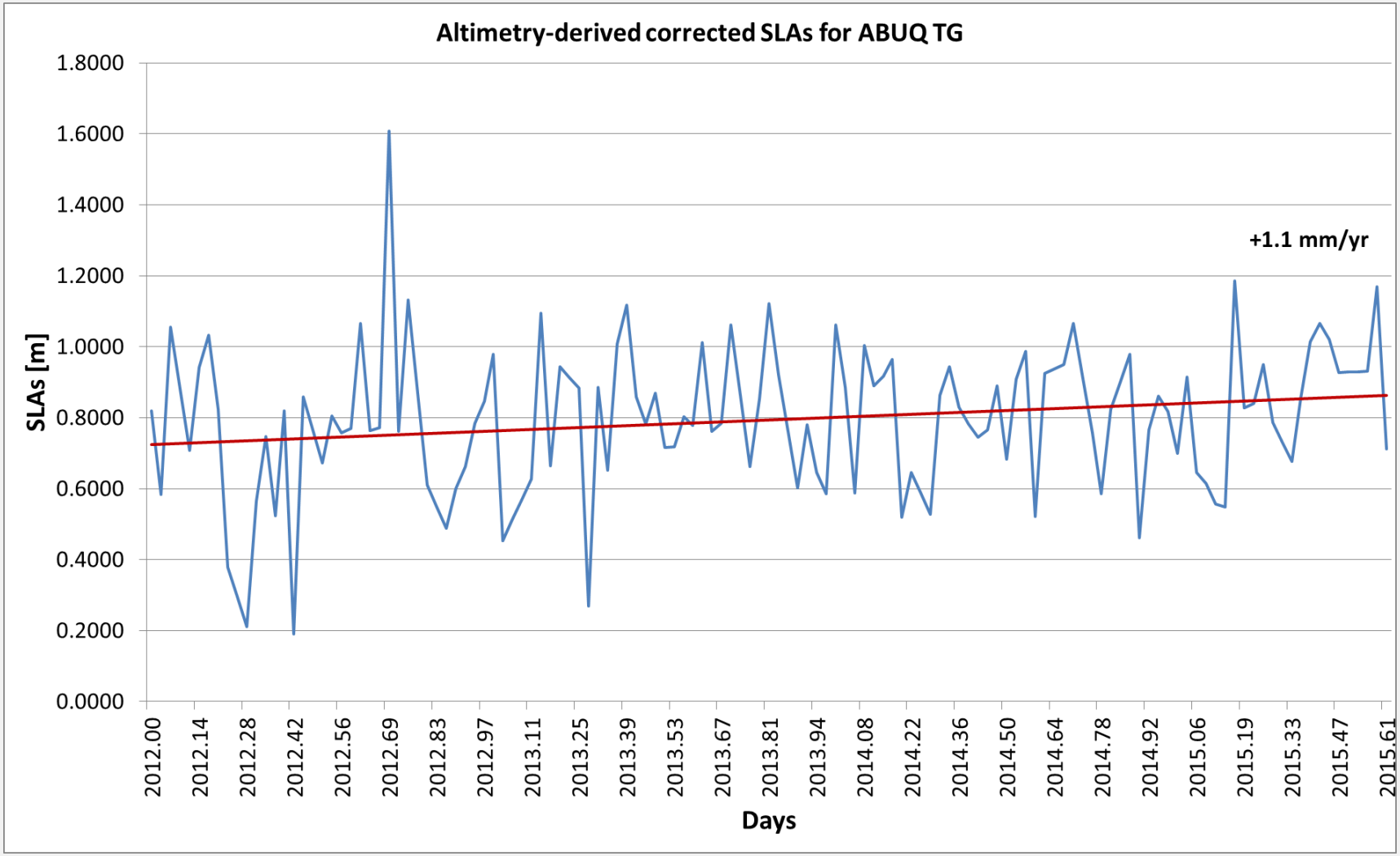
Also, MSL ellipsoidal heights at the 2014.75 epoch have been determined in support of coherency analysis with TG records

TG time-series construction/analysis



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

TG time-series construction/analysis



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

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

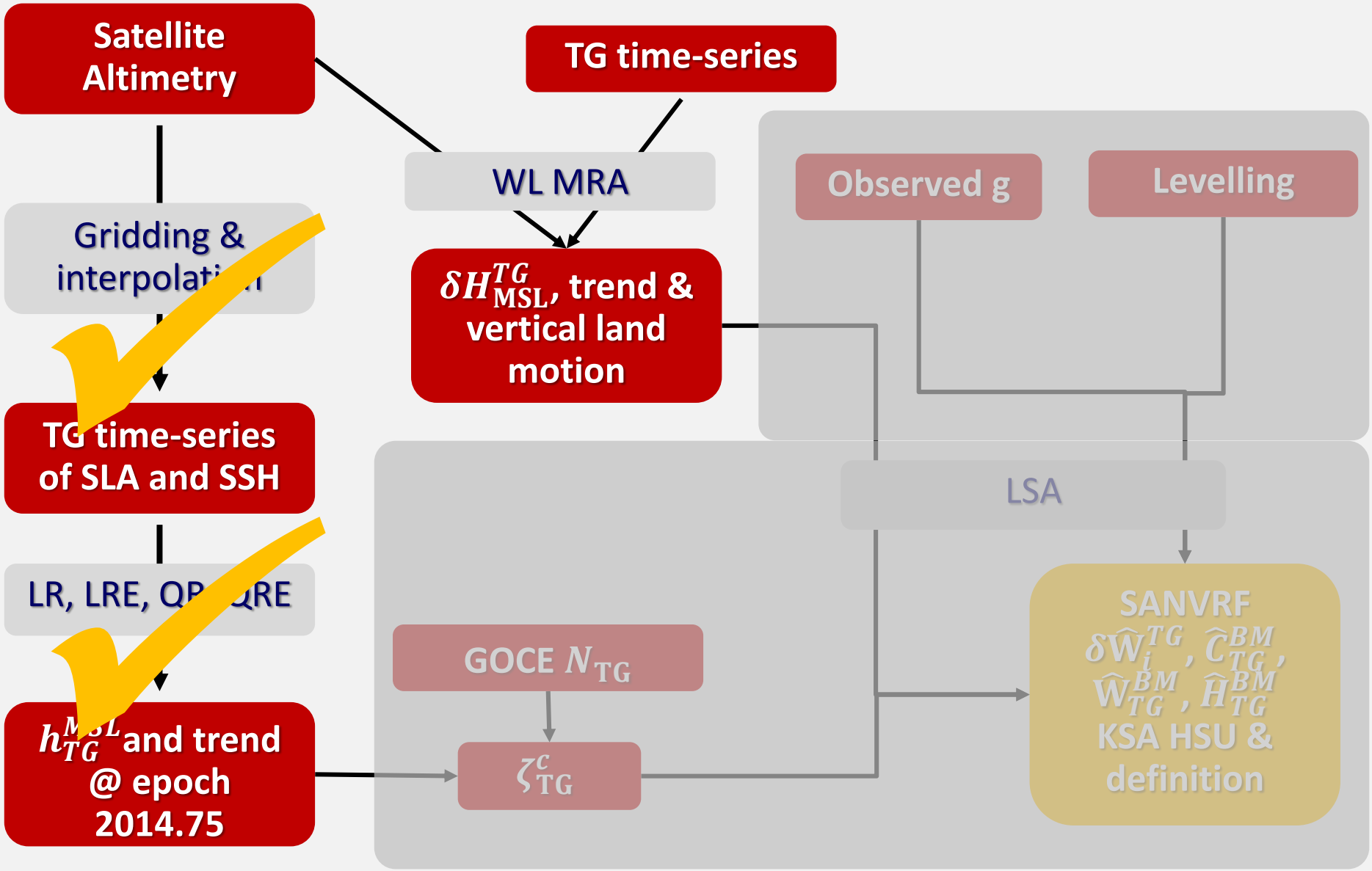
$\overline{SLA}^{model}$	#recs	#rec id	Date t_o	Date t_i	h_o [m]	Trend [mm/yr]	h_{ti} [m]
LT	130	100	2012.000	2014.7500	-28.74564	+1.07	-28.63864
LR	130	100	2012.000	2014.7500	-28.74457	+1.07	-28.63757
LRE	130	100	2012.000	2014.7500	-28.74755	+1.10	-28.63476
QR	130	100	2012.000	2014.7500	-28.74306	+1.04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

TG h_{BM}^{TG} and H_{BM}^{TG}

TG ellipsoidal and otrhometric heights for KSA HSU @ epoch 2014.75

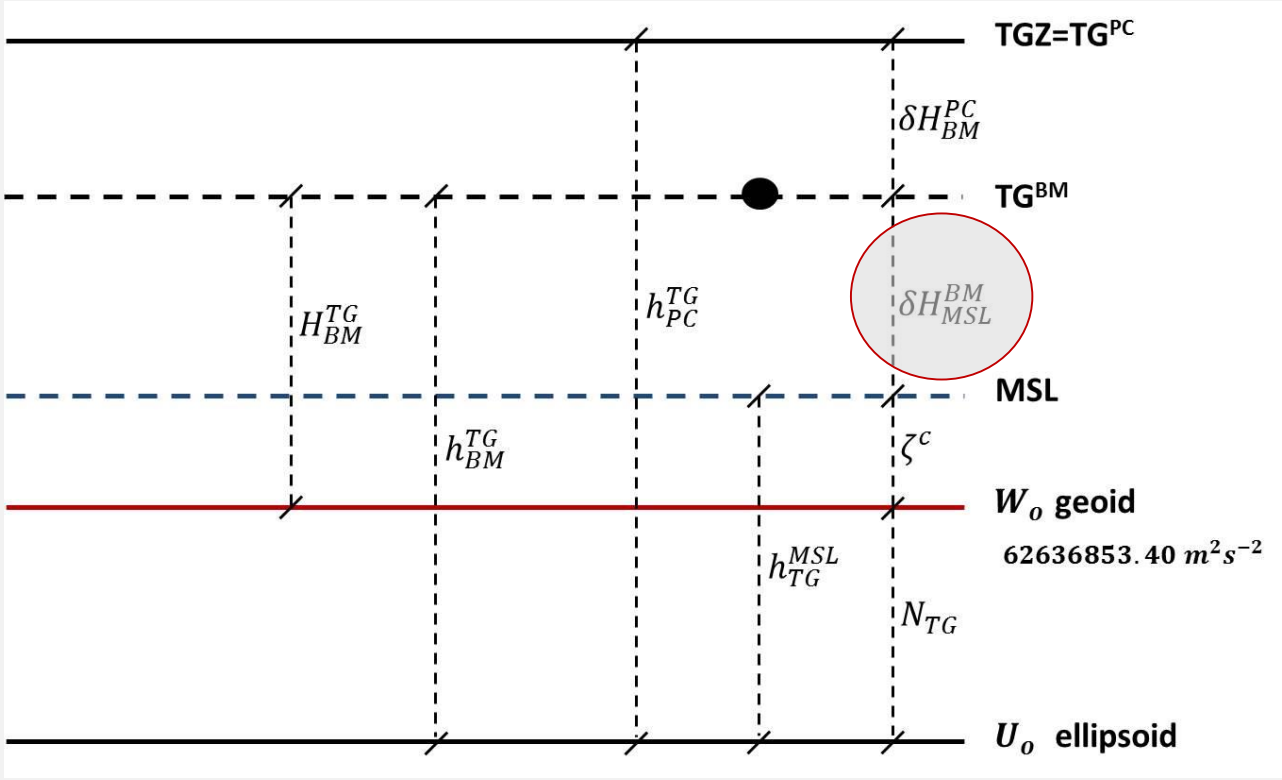
TG	$h_{BM\ LRE}^{TG\ 2014.75}$	$h_{MSL\ LRE}^{TG\ 2014.75}$	$\delta H_{MSL}^{BM\ WL\ MRA}$
ABUQ	-28.6348	-29.4608	0.8895
OQAR	-25.8125	-26.1572	0.4352
TANO	-23.8028	-24.8783	1.0307
MARD	-21.0752	-21.7277	1.3324
KHAF	-15.1328	-16.4093	1.1602
JIZA	-3.6376	-3.9956	0.4113
QUNF	1.5567	0.7272	0.8998
JEDD	6.0963	5.5203	0.665
YANB	9.7910	9.0920	1.0594
WAJH	13.0814	12.2504	
DUBA	16.1917	14.3247	0.6984
MAGN	15.7250	15.0100	0.7868

h_{TG}^{MSL} and trend



$\delta H_{MSL}^{BM\ WL\ MRA}$ from WL MRA

Analyze up to date TG and altimetry observations for all new 12 TG stations along the Red Sea and the Gulf coast conducted during last 3.5 years using Wavelet Multi-Resolution Analysis (WL MRA) and **determine** the MSL at a specified reference epoch and its trend for all 12 TG stations

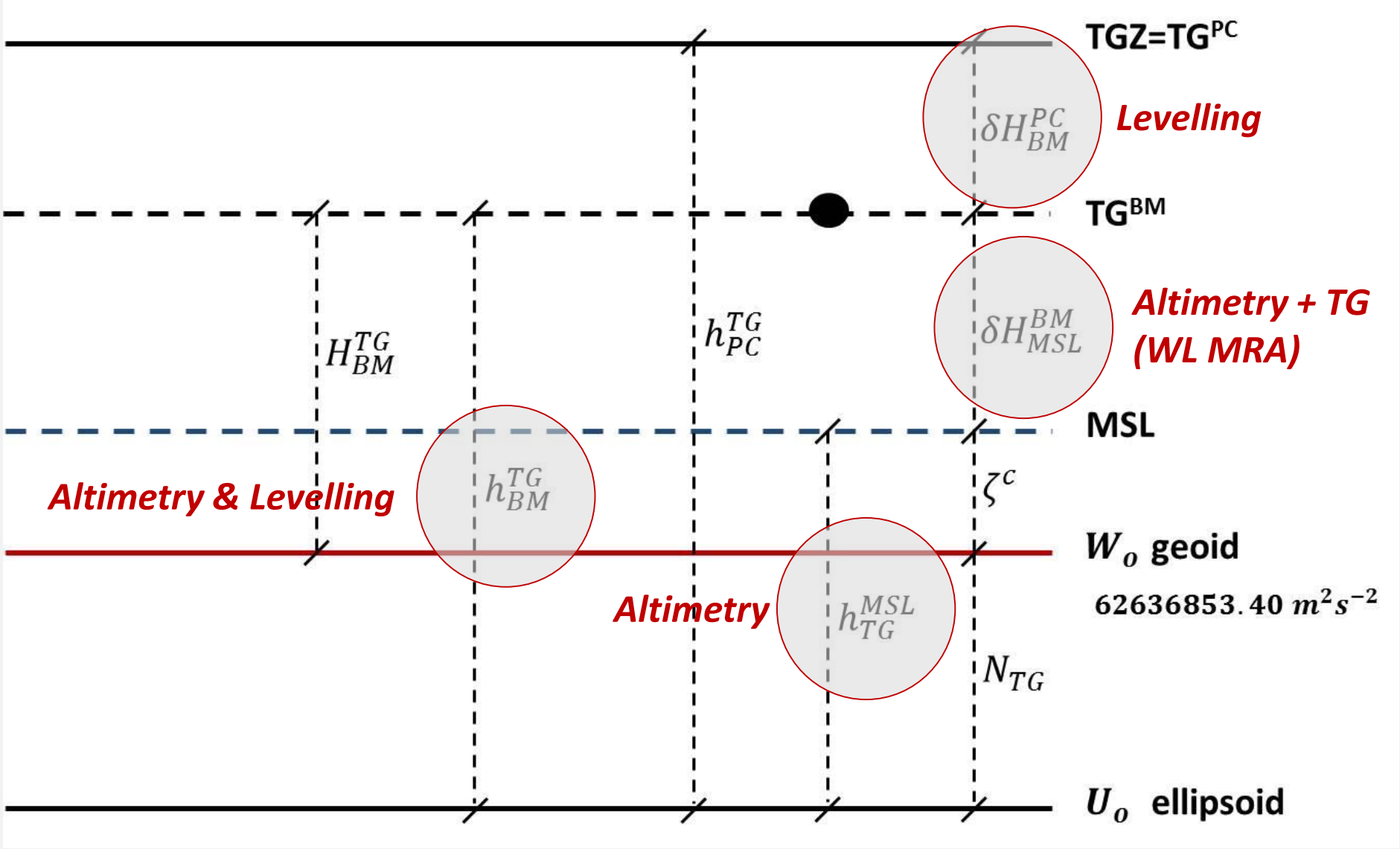


$\delta H_{MSL}^{BM\ WL\ MRA}$ from WL MRA

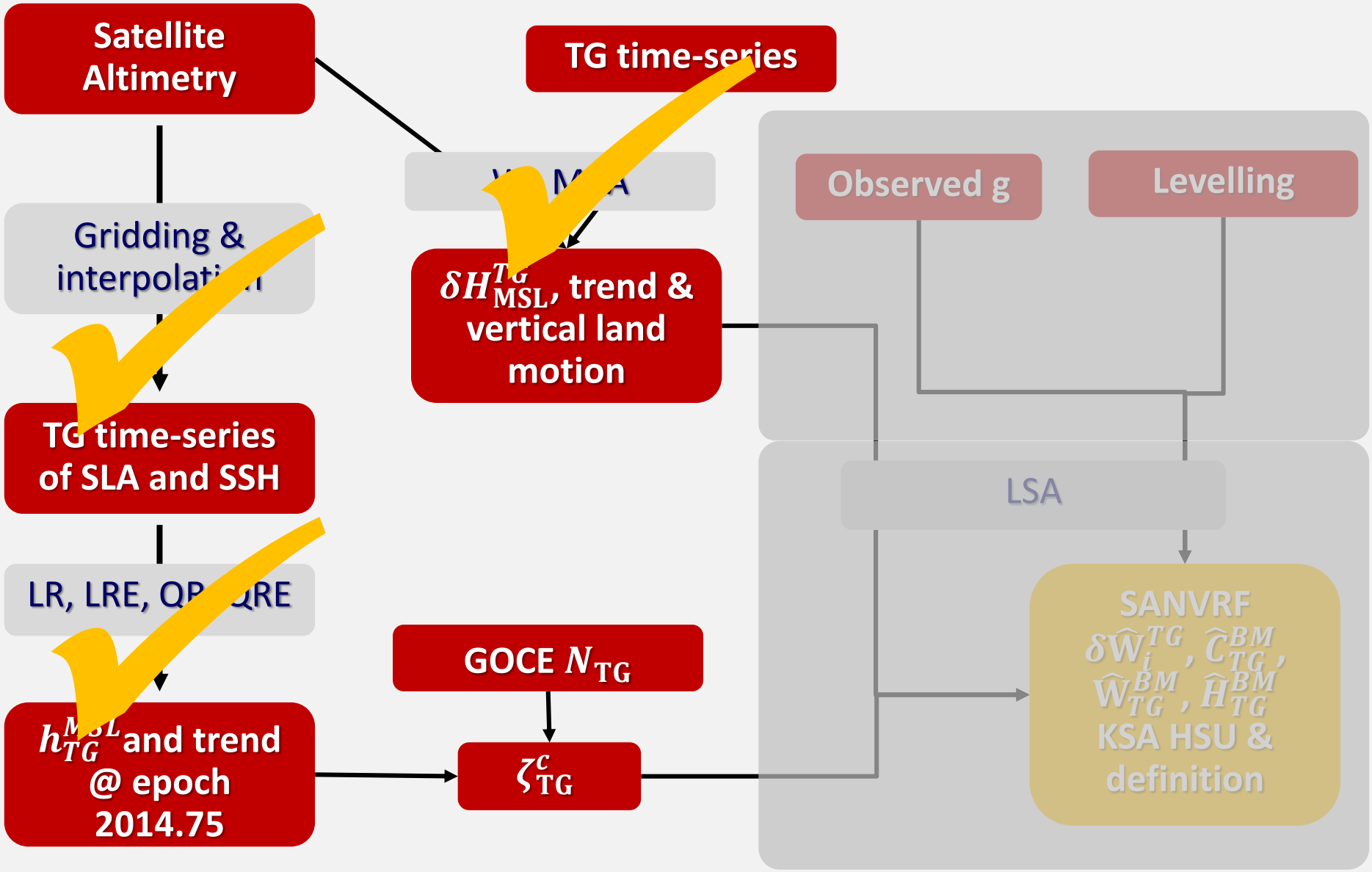
Objective 1: to develop a methodology for deriving MSL and its trend by removing the effect of all periodic components originating from tides, seasonal and other weather effects together with local vertical motions of TG station

Objective 2: to develop a methodology for analysis of the residuals of TG time series after removing all periodic components by application of WMRA and independent of any assumptions regarding the geoid - linked only to sea level records, repeated precise leveling between 3 Tide gauge benchmarks (TGBMs), the Zero Tide gauge benchmark (ZTGBM) and the two vertical land motion BMs (VLMBMs)

What we know so far….



SANVRF pre-definition



N^{TG} from GOCE

Models	n_{max}	Data	References
EGM2008	2190	S(GRACE), G, A	Pavlis et al., 2012
EIGEN-6c4	2190	S(GOCE, GRACE, LAGEOS), G, A	Förste et al, 2016
GOCO05s	280	S(GOCE, GRACE, CHAMP, SLR)	Pail et al., 2016
GOCO05c	720	S(GOCE, GRACE, CHAMP, SLR)	Mayer-Gürr, et al. 2015
DIR-R5	300	S(GOCE, GRACE, LAGEOS)	Bruinsma et al, 2010
TIM-R5	280	S(GOCE)	Brockmann et al., 2014

(Data: S = Satellite Tracking Data, G = Gravity Data,
A = Altimetry Data)
GRACE (Gravity Recovery And Climate Experiment)
CHAMP (CHAllenging Mini-satellite Payload)
GOCE (Gravity field and steady state Ocean Circulation Explorer)
LAGEOS (Laser GEOdynamics Satellite)
SLR (Satellite Laser Ranking)

N^{TG} from GOCE

Geoid height	Data
$N^{EGM2008}$	Geoid height by using EGM2008 only, complete to d/o 2190
$N^{EIGEN6c4}$	Geoid height by using EIGEN6c4 only, complete to d/o 2190
$N^{GOCO05c}$	Geoid height by using GOCO05c only, complete to d/o 720
$N^{GOCO05c}_{720+}$	Geoid height by using GOCO05c to d/o 720 and EGM2008 from d/o 721 to 2190
N^{DIR-R5}	Geoid height by using DIR-R5 only, complete to d/o 300
N^{DIR-R5}_{300+}	Geoid height by using DIR-R5 to d/o 300 and EGM2008 from d/o 301 to 2190
N^{DIR-R5}_{280+}	Geoid height by using DIR-R5 to d/o 280 and EGM2008 from d/o 281 to 2190
N^{DIR-R5}_{220+}	Geoid height by using DIR-R5 to d/o 220 and EGM2008 from d/o 221 to 2190
N^{TIM-R5}	Geoid height by using TIM-R5 only, complete to d/o 280
N^{TIM-R5}_{280+}	Geoid height by using TIM-R5 to d/o 280 and EGM2008 from d/o 281 to 2190
N^{TIM-R5}_{220+}	Geoid height by using TIM-R5 to d/o 220 and EGM2008 from d/o 221 to 2190
$N^{GOCO05s}$	Geoid height by using GOCO05s only, complete to d/o 280
$N^{GOCO05s}_{280+}$	Geoid height by using GOCO05s to d/o 280 and EGM2008 from d/o 281 to 2190
$N^{GOCO05s}_{220+}$	Geoid height by using GOCO05s to d/o 220 and EGM2008 from d/o 221 to 2190

Which one to choose?

Use the DTU2015 DOT as reference for the KSA vertical network adjustment

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

SANVRF minimally constrained adj.

Separate adjustments for each geoid model and combinations was performed (grey below indicate residuals better than when using DTU2015)

SANVRF minimally constrained adj.

Based on DTU2015

TG name	$H_{BM}^{o\,TG}$	$\hat{v}$	$\hat{H}_{BM}^{TG}$	$\hat{\sigma}_{H_{BM}^{TG}}$
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	$H_{BM}^{o\,TG}$	$\hat{v}$	$\hat{H}_{BM}^{TG}$	$\hat{\sigma}_{H_{BM}^{TG}}$
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
APOSTERIORI VAR. FACTOR : 1.053
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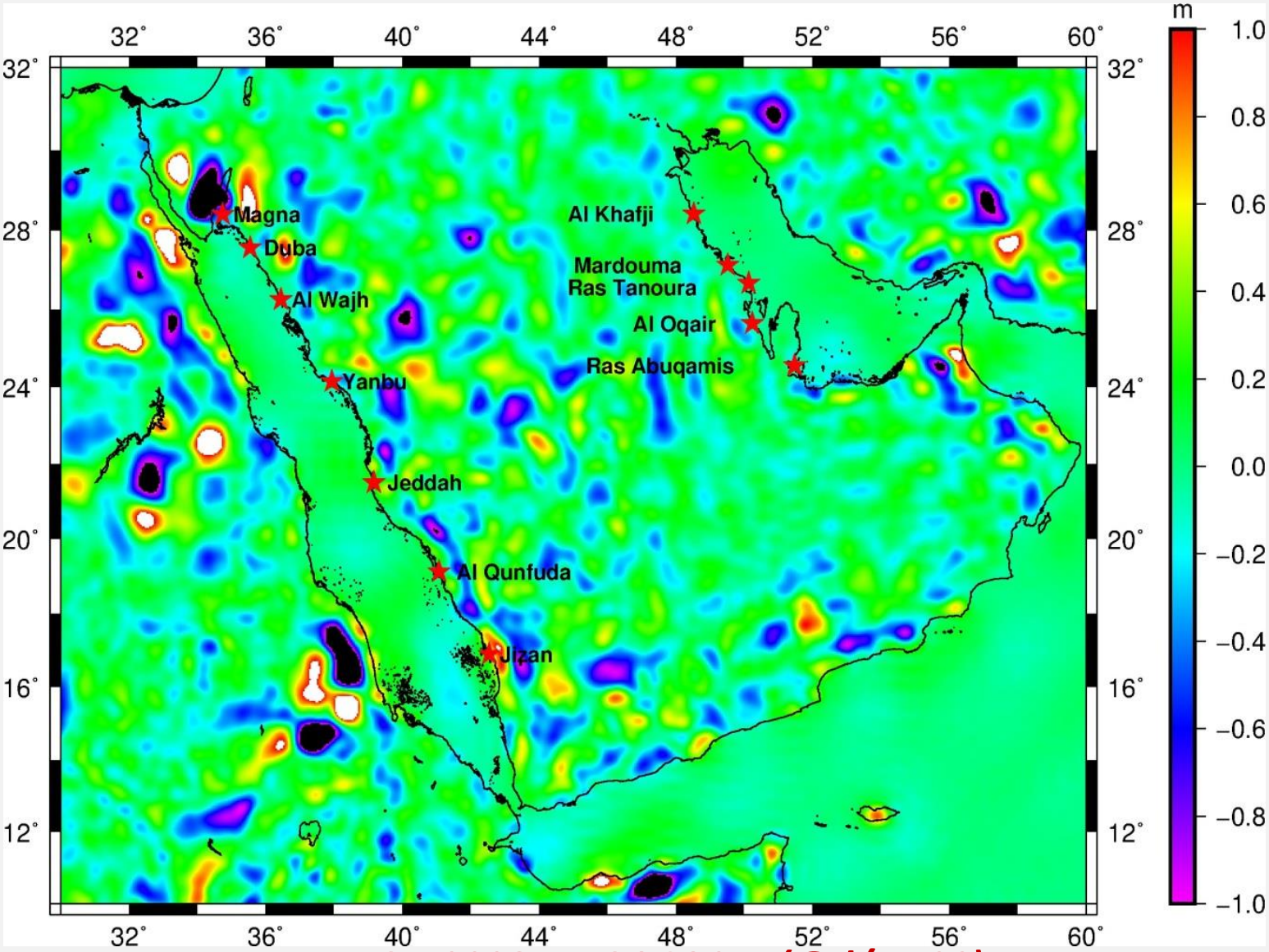
Geoid model differences



EGM2008 vs. GOCO05c (@d/o 720)

N^{TG} from GOCE

Which one to choose?

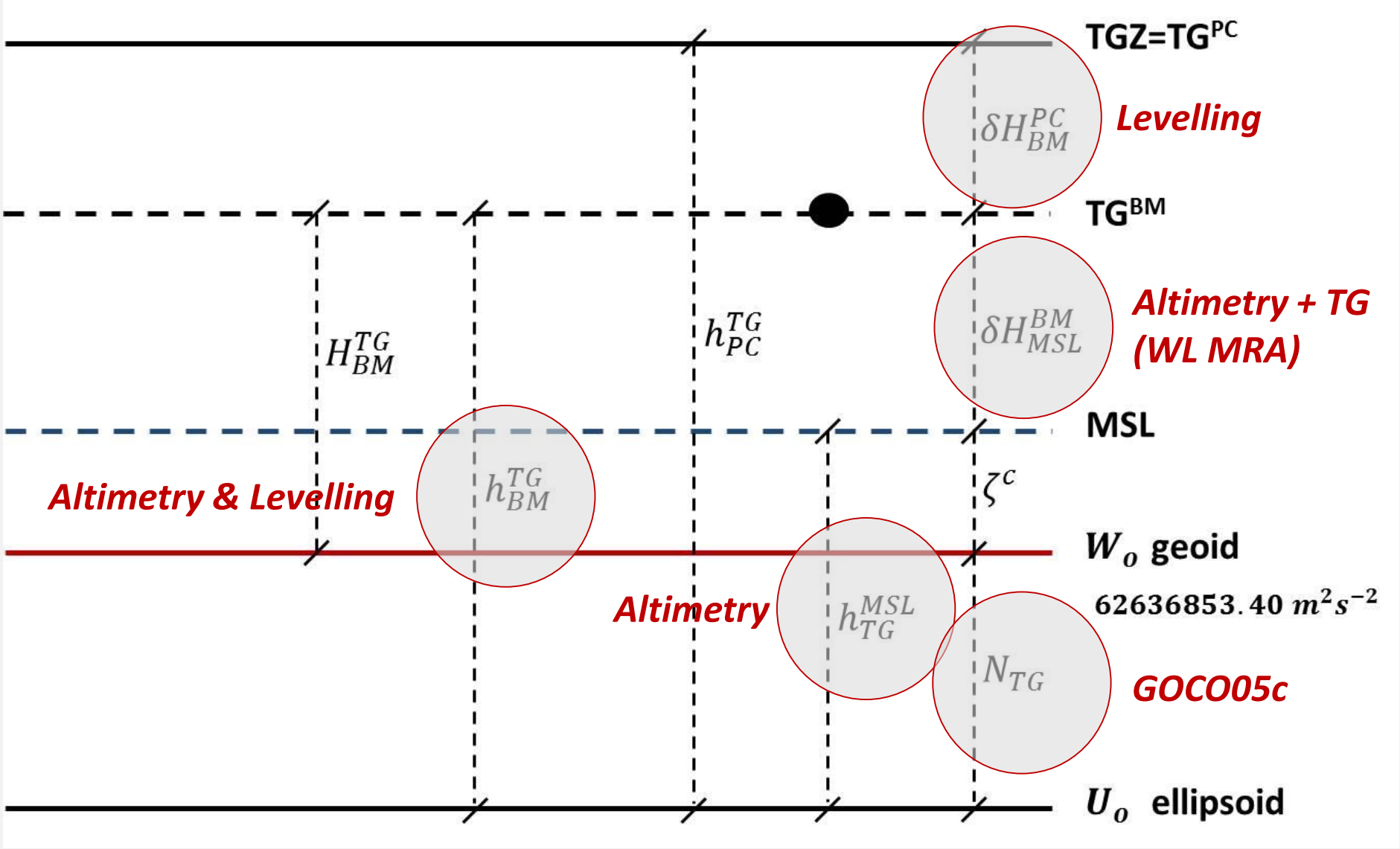
EIGEN6c4 smooths out the GOCE contribution

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 topographical 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

What we know so far….



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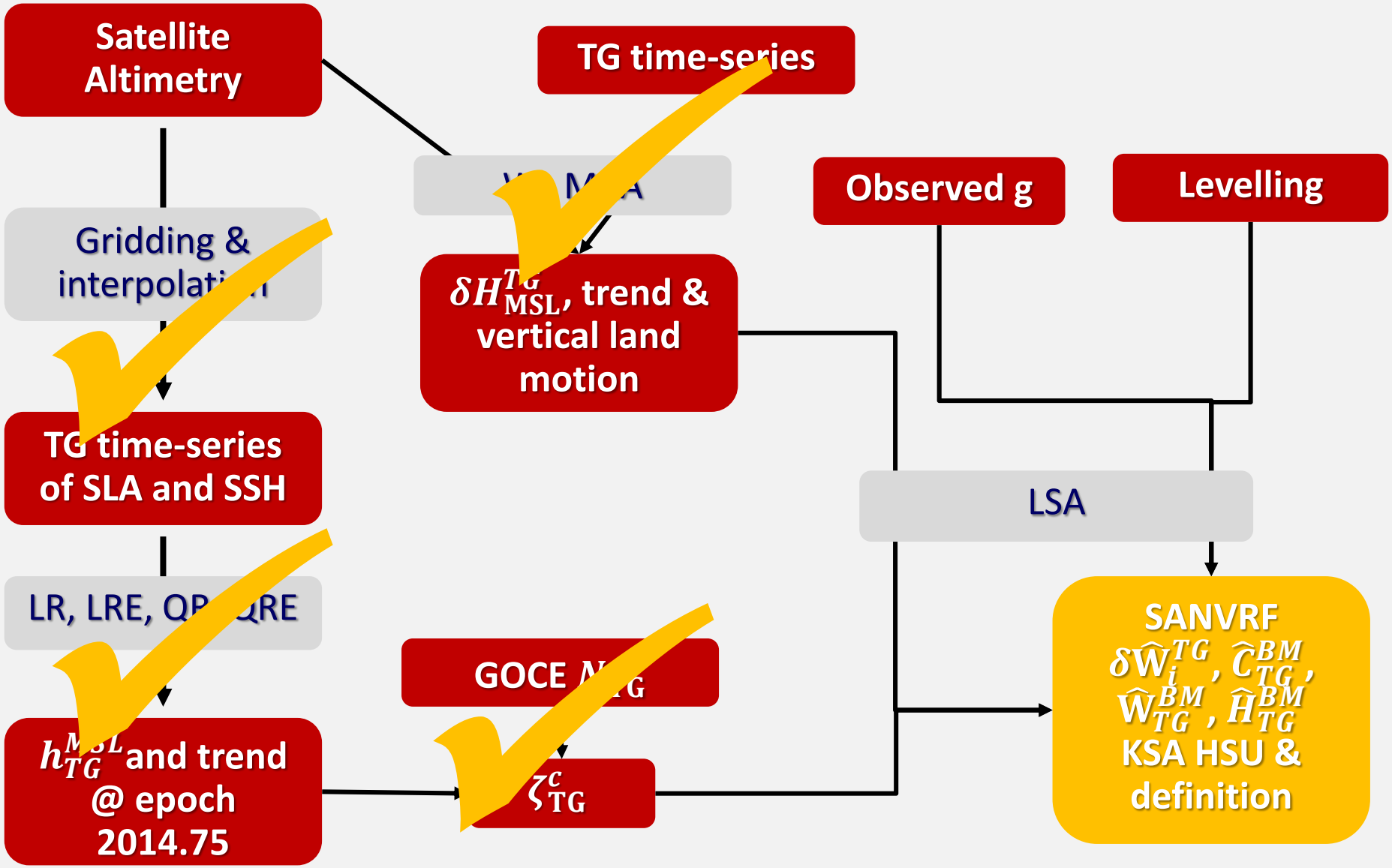
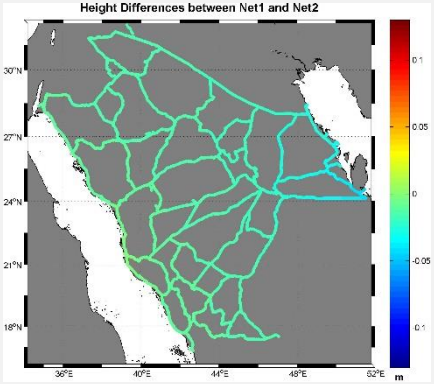


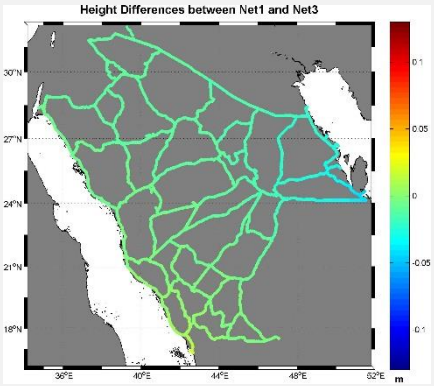
SANVRF minimally constrained adj.

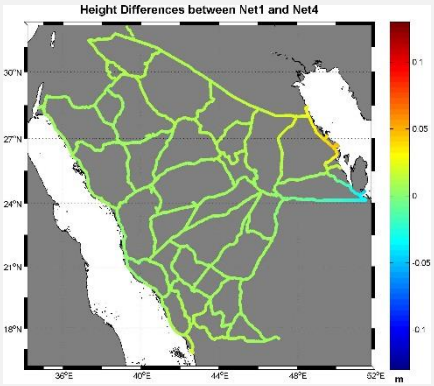
Based on the derived quantities in the previous schema, GOCO05c derived DOT (+Altimetry+WL MRA) has been used to adjust the KSA vertical network

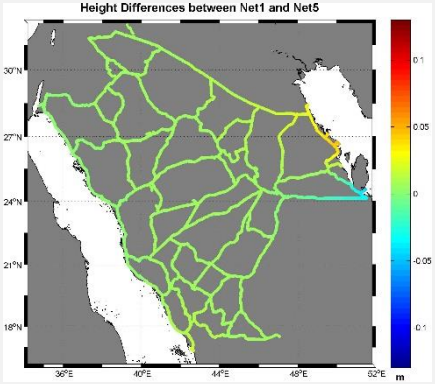
Perform various scenarios by keeping different stations fixed

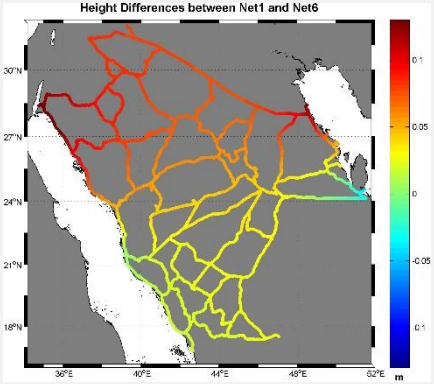
SANVRF constrained adj.

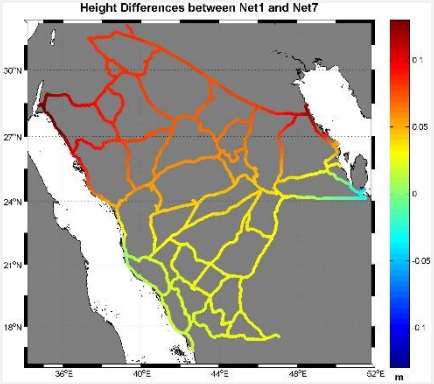


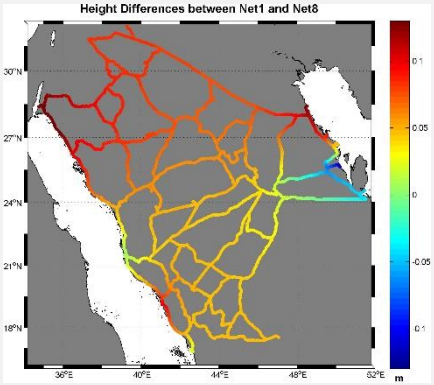


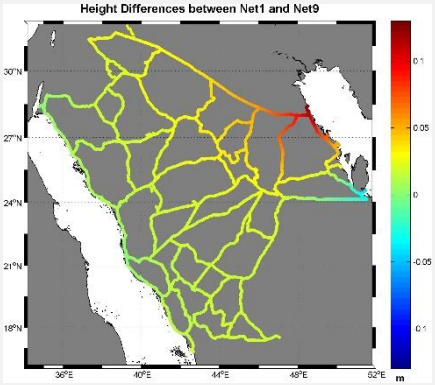


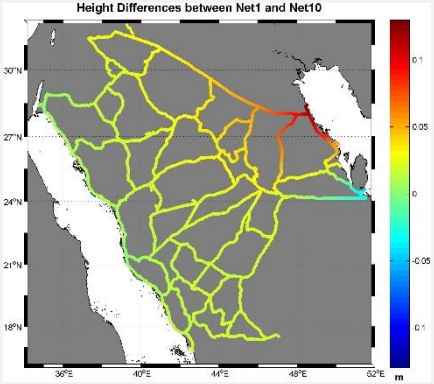


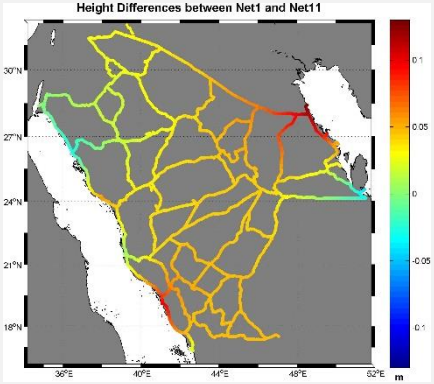












Orthometric height differences based on various adjustment scenarios @ the leveling BMs

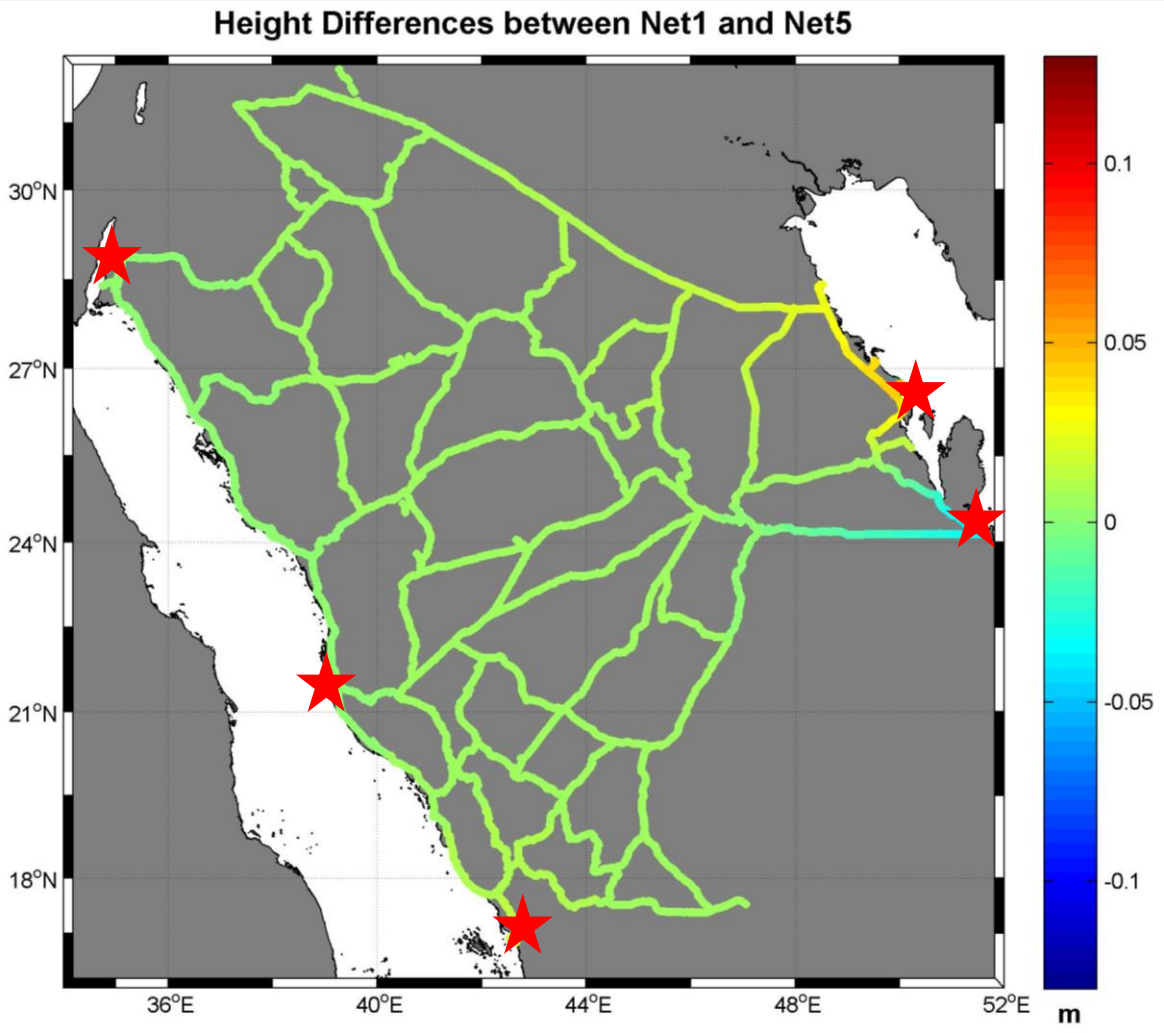
SANVRF constrained adj.

Orthometric height differences for the KSA BMs relative to net1. Unit: [m]

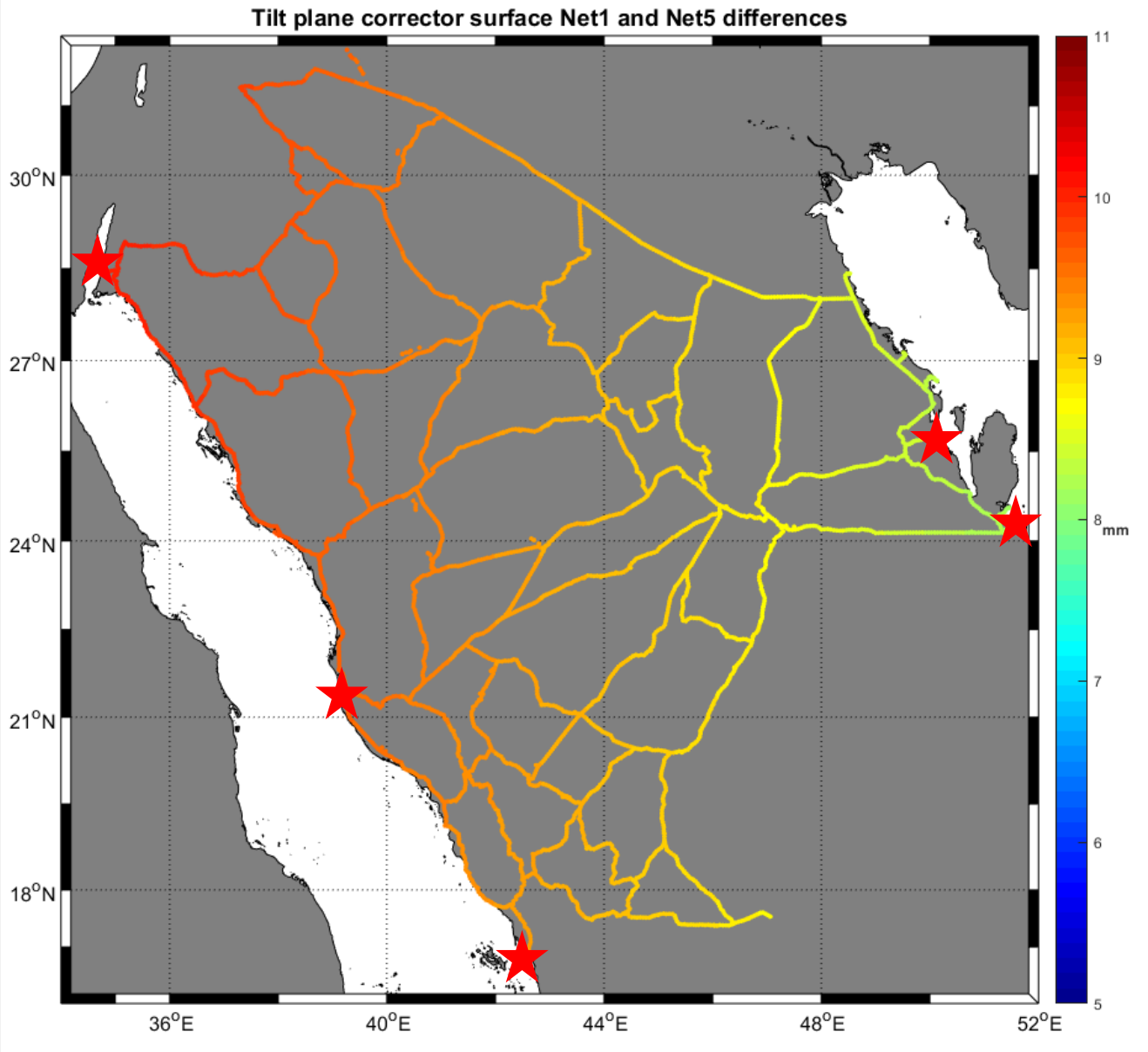
	max	min	mean	rms	std
net1-net2	-0.0001	-0.0461	-0.0153	0.0167	0.0068
net1-net3	0.0174	-0.0461	-0.0094	0.0128	0.0086
net1-net4	0.0495	-0.0459	0.0074	0.0109	0.0080
net1-net5	0.0495	-0.0459	0.0062	0.0102	0.0081
net1-net6	0.1380	-0.0458	0.0508	0.0592	0.0305
net1-net7	0.1380	-0.0458	0.0515	0.0599	0.0306
net1-net8	0.1381	-0.1138	0.0556	0.0649	0.0334
net1-net9	0.1277	-0.0458	0.0228	0.0289	0.0177
net1-net10	0.1278	-0.0458	0.0236	0.0300	0.0185
net1-net11	0.1279	-0.0458	0.0380	0.0440	0.0221
net1-net8 adj	0.0710	-0.1738	0.0000	0.0305	0.0305
net1-net8 NS $a_i^T \hat{x}$	0.0826	0.0267	0.0556	0.0572	0.0136
net1-net11 adj	0.0765	-0.1046	0.0000	0.0206	0.0206
net1-net11 EW $a_i^T \hat{x}$	0.0209	0.0591	0.0379	0.0388	0.0081

CONCLUSIONS

- Keeping Jeddah, Ras Abuqamis, Jizan, Ras Tanoura, and Magna fixed (minimal distortions over the entire network)



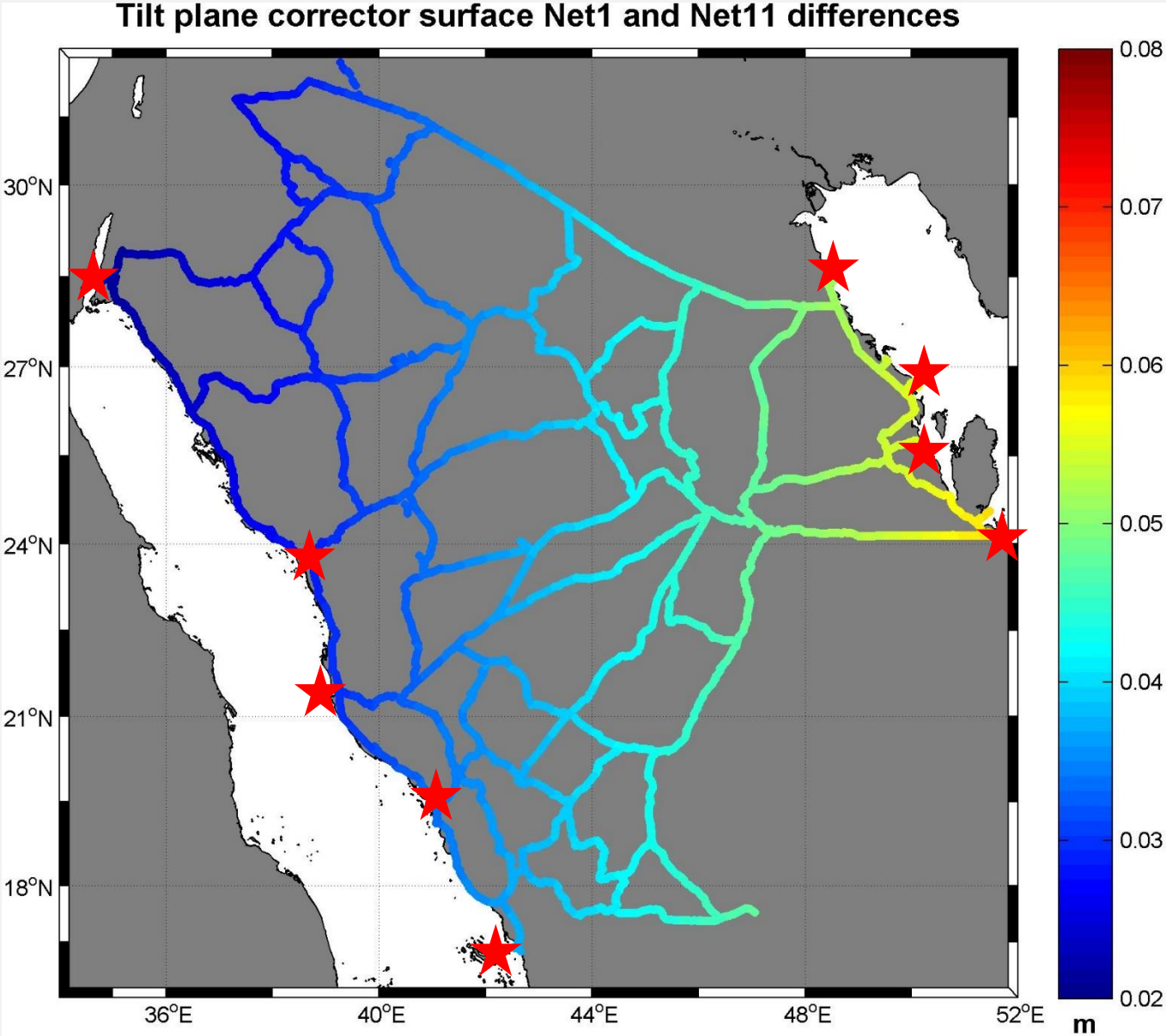
CONCLUSIONS



Keeping 5 TG's fixed

good geometry mm-level EW-tilt

CONCLUSIONS



Keeping 9 TG's fixed

good geometry & EW-tilt

SANVRF constrained adj.

Final adjusted orthometric heights for the KSA TGs

BM ID	$\widehat{H}_{TG}^{BM}$ $[m]$	$\widehat{\sigma}_{H_{BM}^{TG}}[m]$	$\widehat{C}_{TG}^{BM}$ $[m^2/s^2]$	$\widehat{W}_{TG}^{BM}$ $[m^2/s^2]$
DUB-S	1.47704	0.02197	14.46237	62636838.93763
JED-S	1.35645	0.00103	13.27610	62636840.12390
JZA-S	1.14809	0.02049	11.23367	62636842.16633
KFJ-S	1.85610	0.02225	18.17448	62636835.22552
MAG-S	1.42784	0.02330	13.98094	62636839.41906
MAR-S	2.03920	0.02299	19.96517	62636833.43483
OQR-S	1.05567	0.02319	10.33449	62636843.06551
QUN-S	1.61963	0.01514	15.84970	62636837.55030
RAQ-S	1.58629	0.02456	15.52815	62636837.87185
RAT-S	1.71052	0.02335	16.74641	62636836.65359
YAN-S	1.73843	0.01686	17.01762	62636836.38238
WAJ-S	1.28946	0.01974	12.62442	62636840.77558

Jeddah only is kept fixed

SANVRF constrained adj. ($\widehat{C}_{TG}^{BM}$)

Final adjusted orthometric heights for the KSA TGs

BM ID	$\widehat{C}_{TG}^{BM}$ $[m^2/s^2]$	$\widehat{\sigma}_{C_{BM}^{TG}}[m]$	$\widehat{H}_{TG}^{BM}$ $[m]$	$\widehat{W}_{TG}^{BM}$ $[m^2/s^2]$
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

Jeddah only is kept fixed

SANVRF – JEDDAH14

- Status: **Adopted**
- Organization: **General Directorate of Geodesy, GCS**
- Tidal system: **Free Tide**
- Epoch: **2014.75**
- Primary Bench Mark: **Jeddah TGBM-S**
- Latitude: **21.49833 [degrees]**
- Longitude: **39.16422 [degrees]**
- LSA type: **Fixed geo-potential number above MSL of Jeddah TGBM-S**

SANVRF – JEDDAH14

- 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]

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

- A major workload, which has though been automatized, so as to produce in ~2.5h a complete SLA TG series for any given (new) station in the KSA & Arab peninsula region

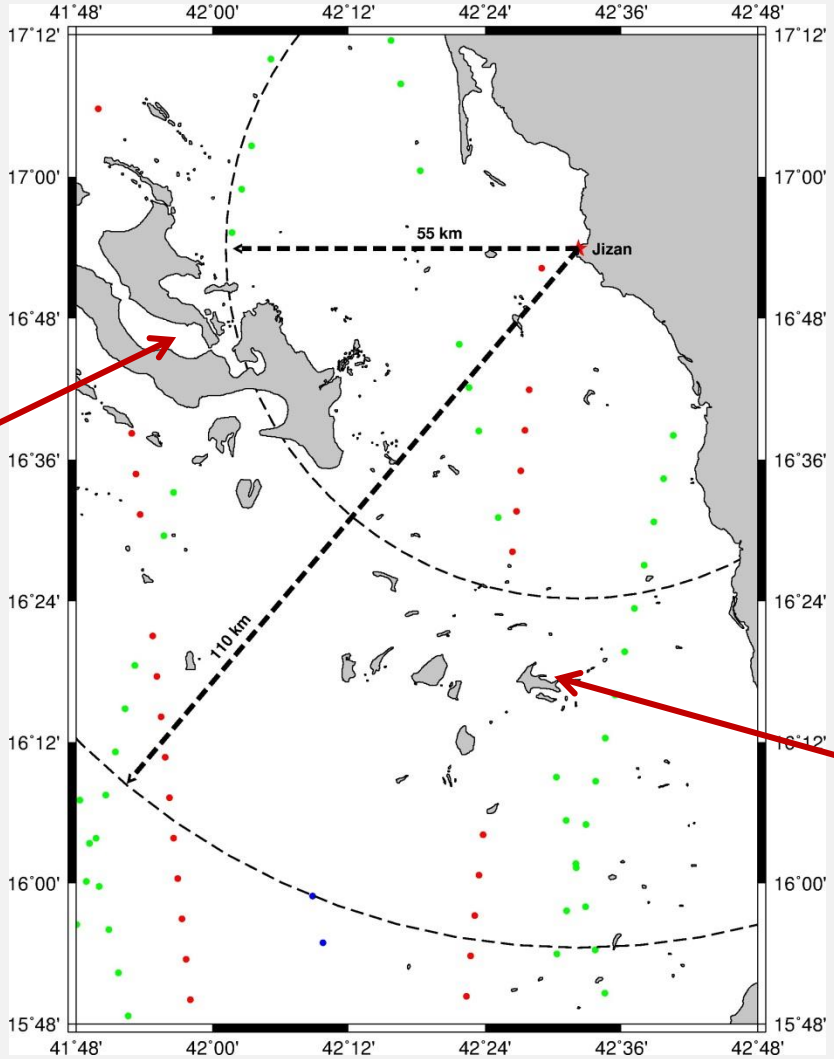
- The derived TG BM ellipsoidal heights from altimetry can be used as mockup of the real ellipsoidal heights until the latter are obtained in 2018/2019.

CONCLUSIONS

- The estimated TG ellipsoidal heights are independent from any geoid and MDOT related model and refer to the latest IAG W_o. They can refer to any other plausible reference geopotential surface, by a simple shift
- The so-derived, based on a locally-adapted gridding and interpolation approach, SLA, MSL MSS and orthometric heights are preferable to those derived from a global model.
- The latter does not manage to sense high-frequency variations in the SLA with is present in the per 10-day SLA record generated in this work.
- GOCO05c to its full d/o and without any spectral enhancement is the GGM to be used over the KSA since it brings new information from GOCE, not present in EGM2008, and keeps the signal power to its maximum d/o
- The adopted JEDDAH14 VRF creates minimal distortions over the entire set of leveling BMs

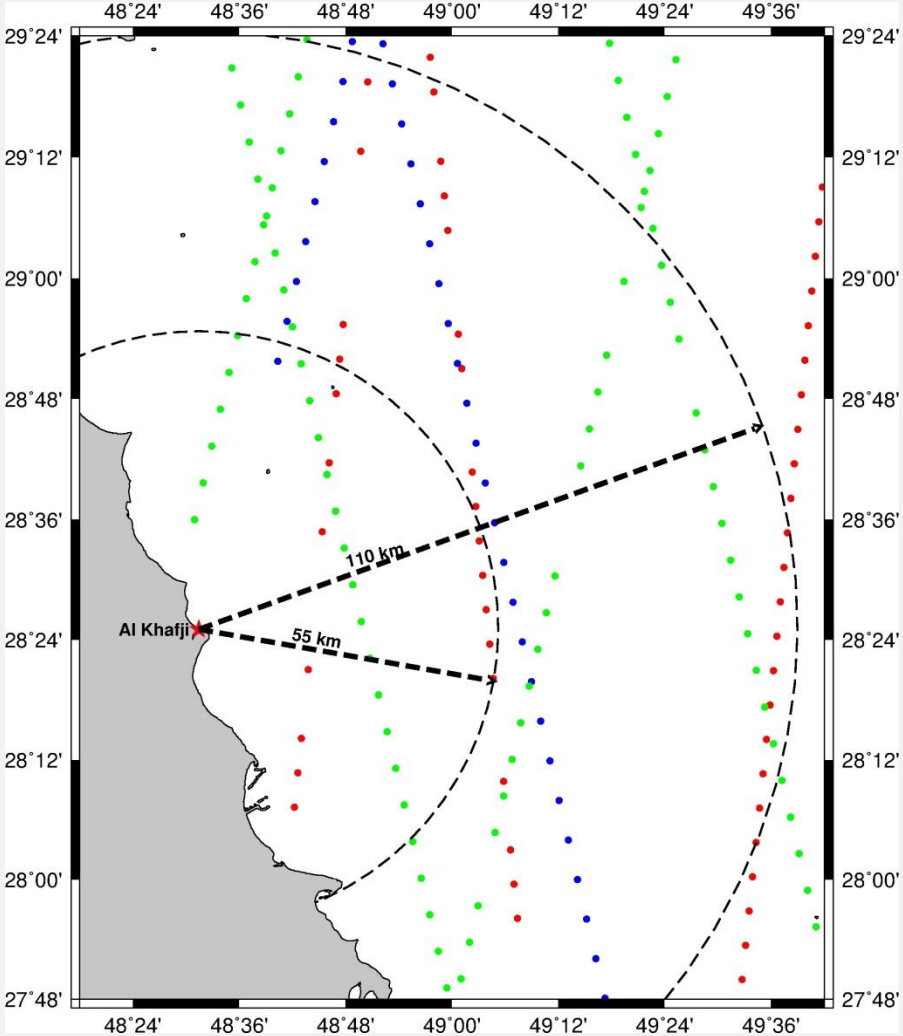
Back-up slides

TG specific cases



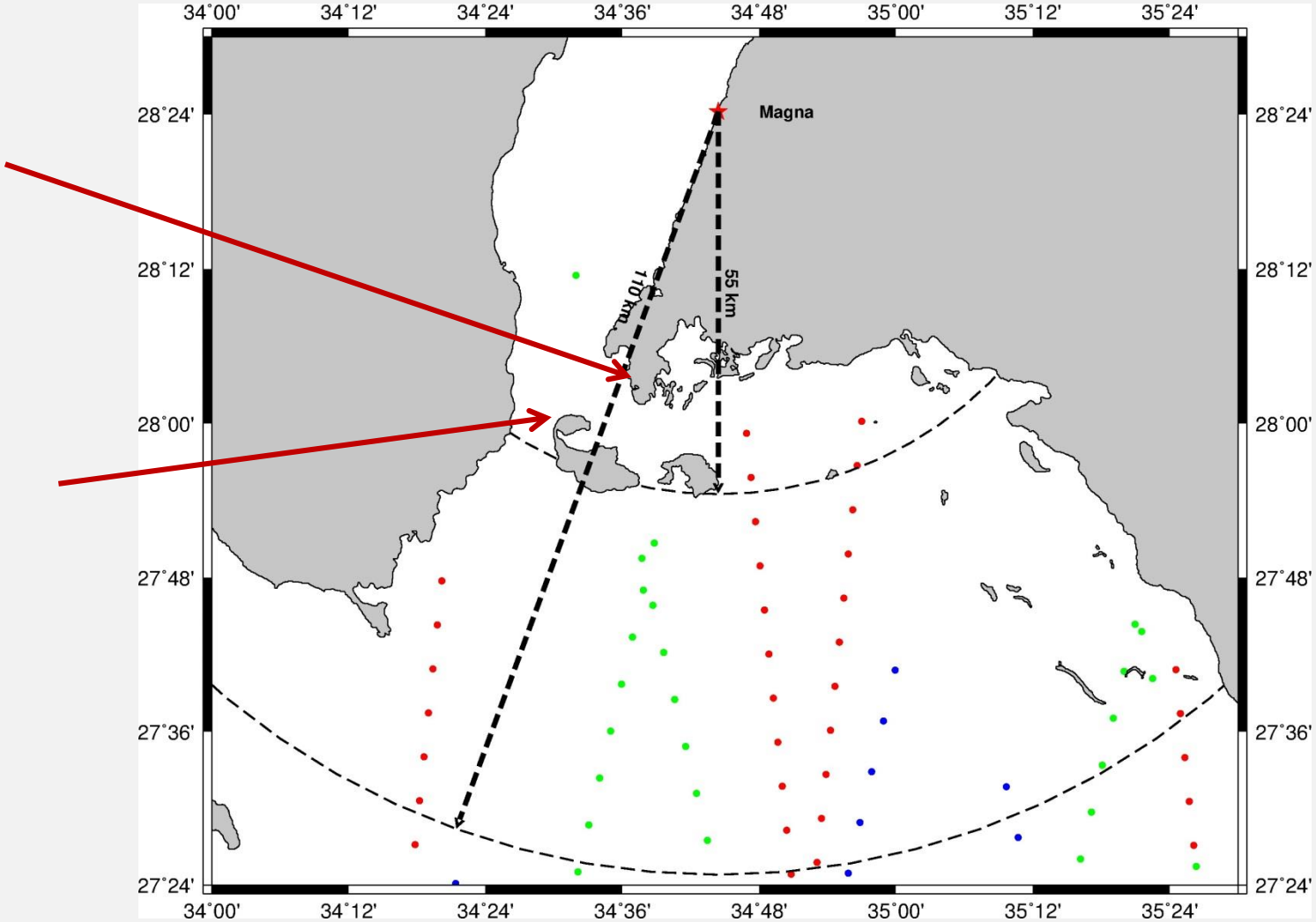
JIZA satellite altimetry data availability from Cryosat-2 Cycle 23 (red), ENVISAT Cycle 110 (blue) and SARAL/AltiKa Cycle 1 (green) mission

TG specific cases



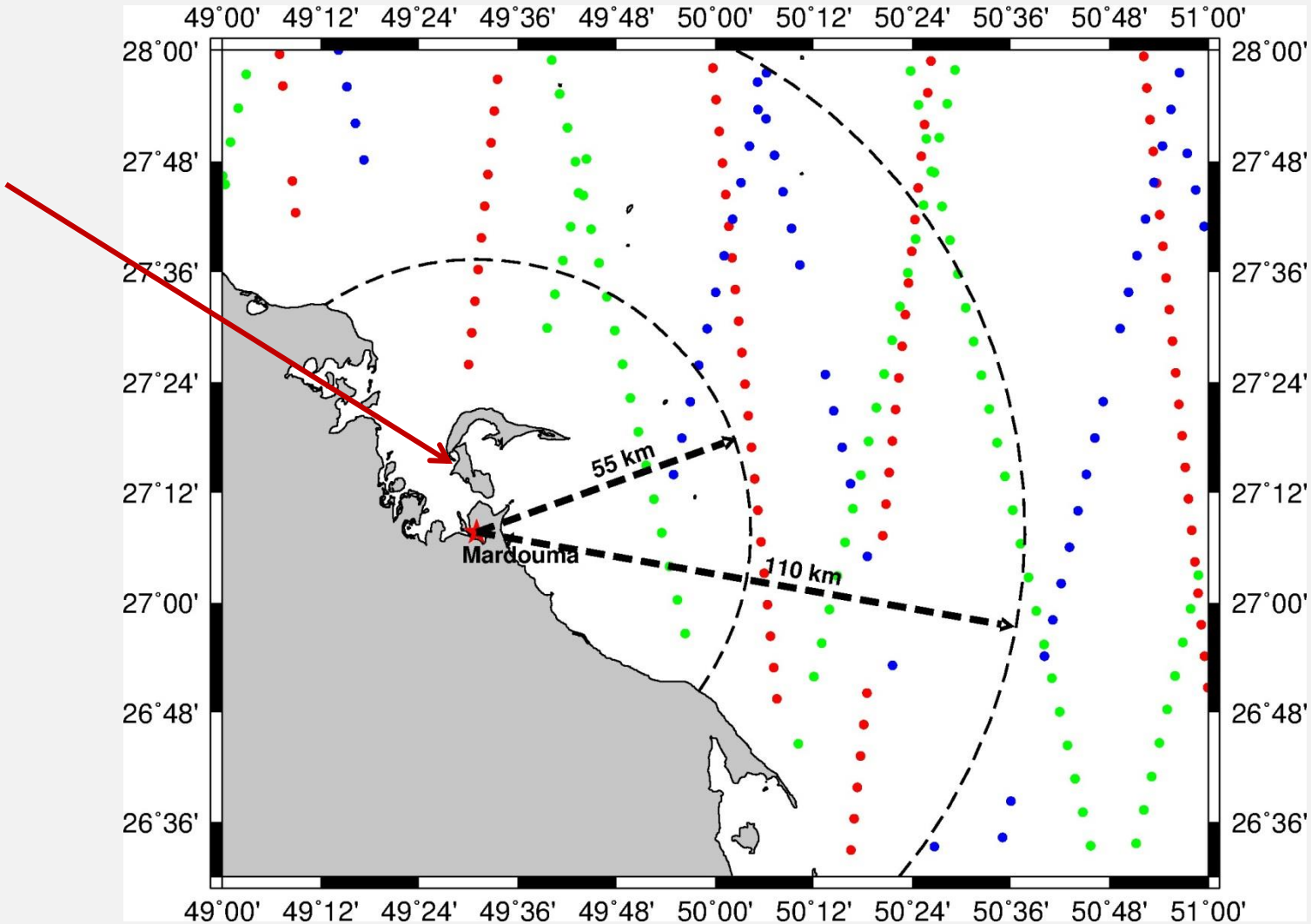
KHAF satellite altimetry data availability from Cryosat-2 Cycle 23 (red), ENVISAT Cycle 110 (blue) and SARAL/AltiKa Cycle 1 (green) mission

TG specific cases



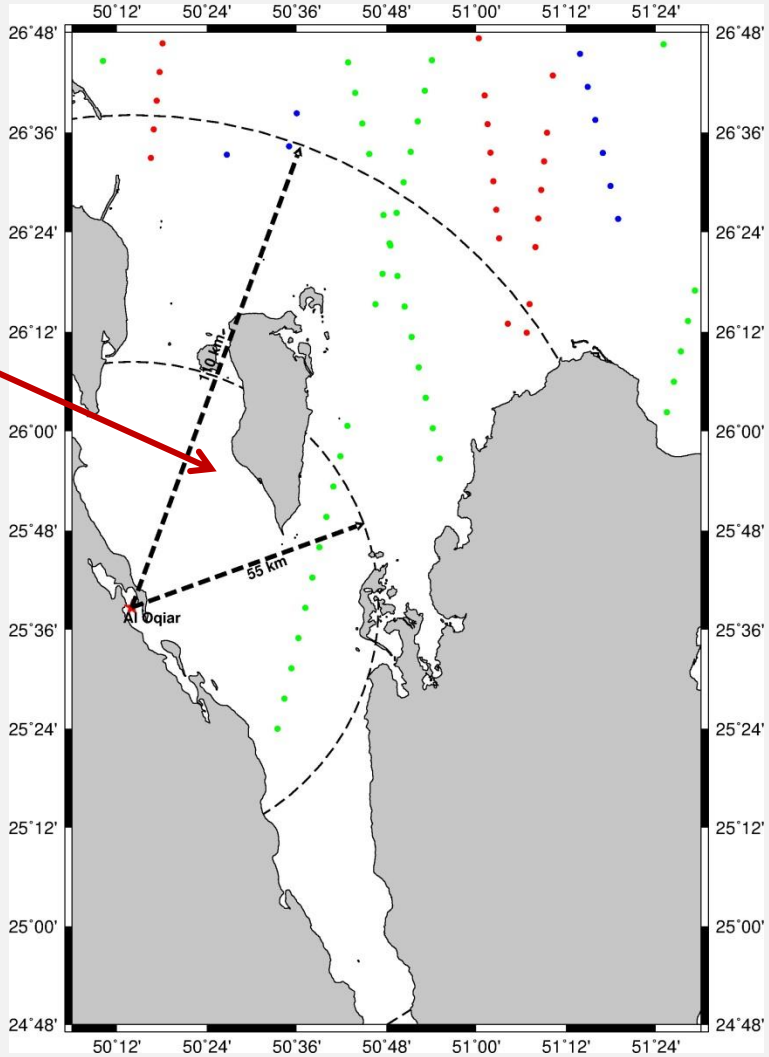
MAGN satellite altimetry data availability from Cryosat-2 Cycle 23 (red), ENVISAT Cycle 110 (blue) and SARAL/AltiKa Cycle 1 (green) mission

TG specific cases



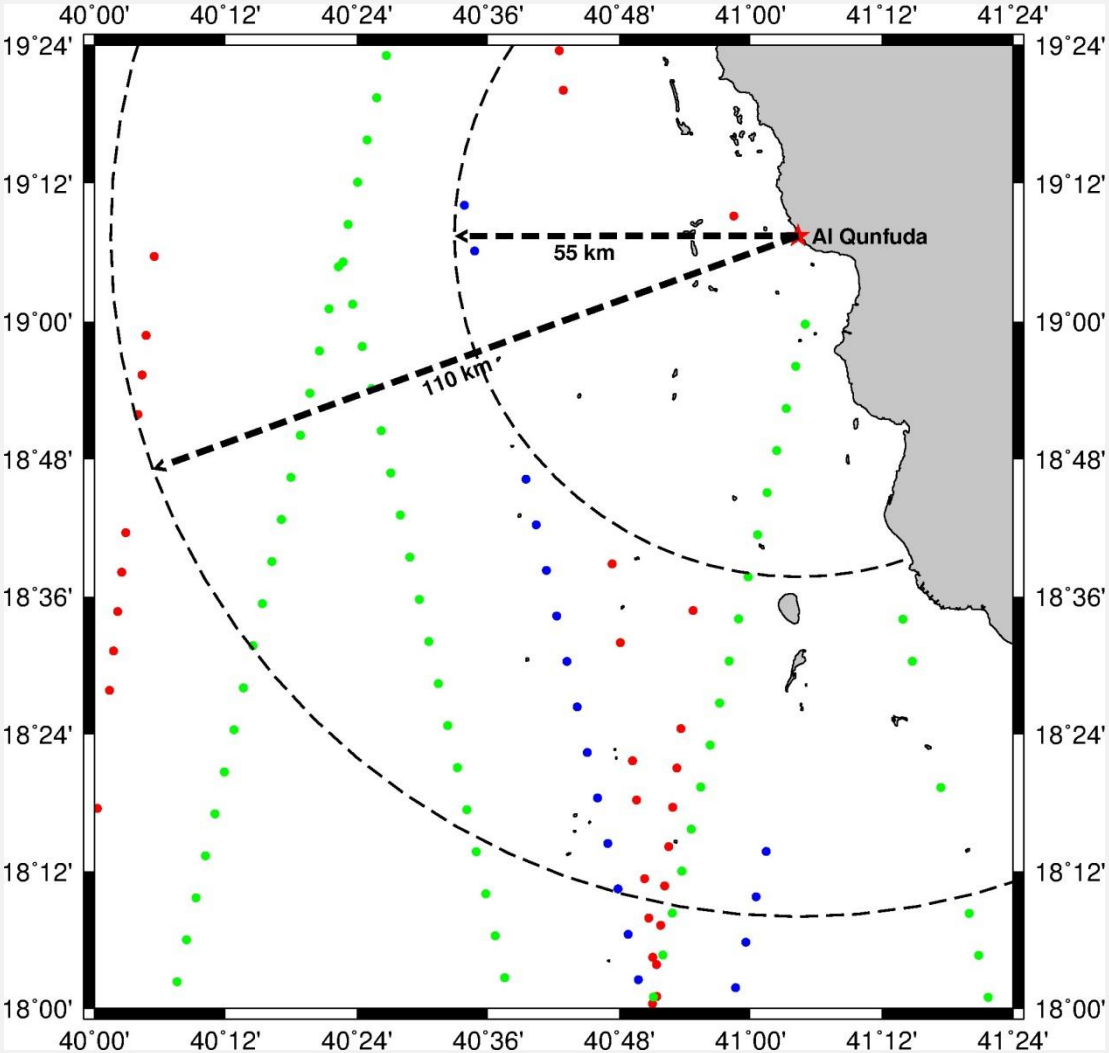
MARD satellite altimetry data availability from Cryosat-2 Cycle 23 (red), ENVISAT Cycle 110 (blue) and SARAL/AltiKa Cycle 1 (green) mission

TG specific cases



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

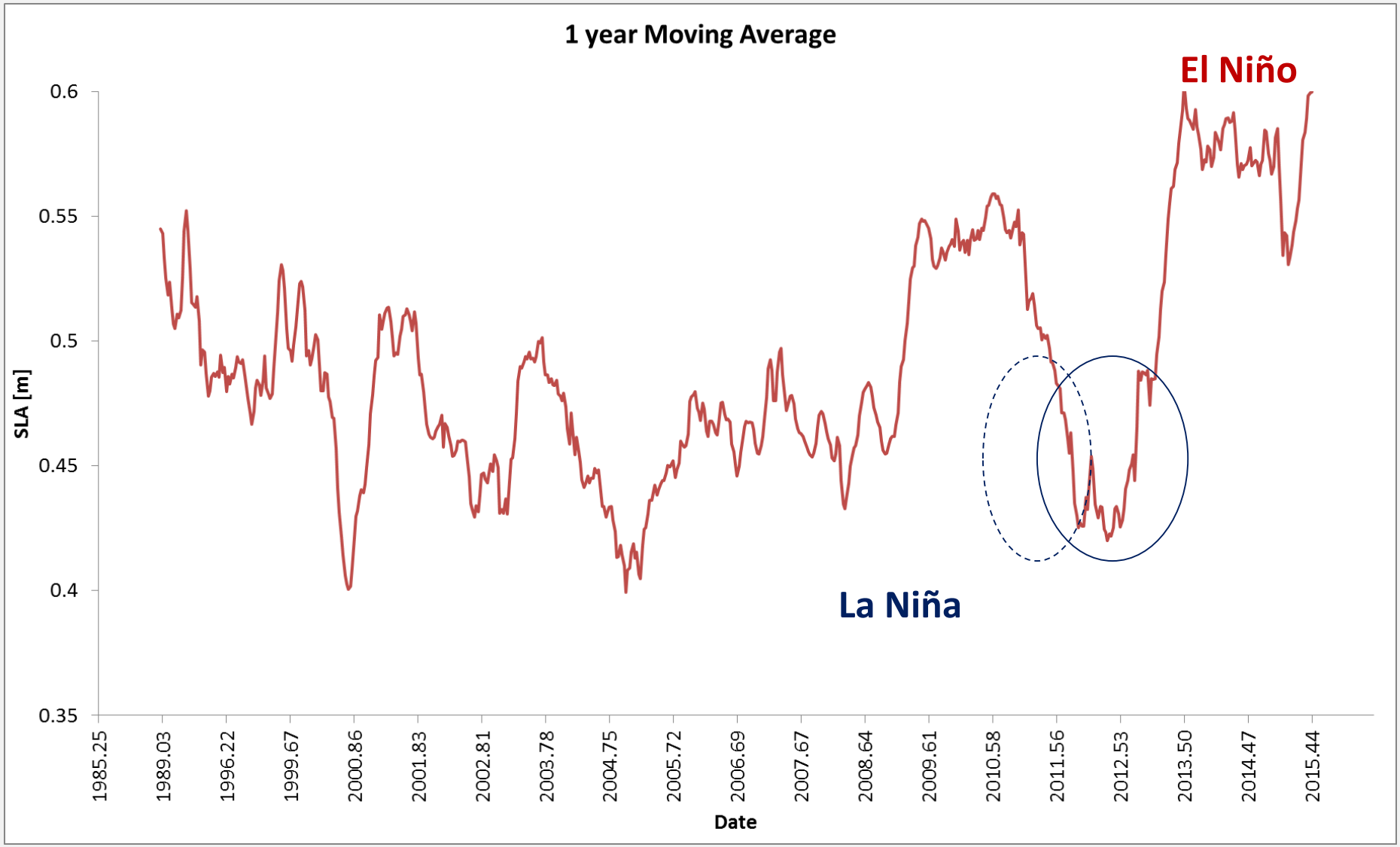
TG specific cases



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

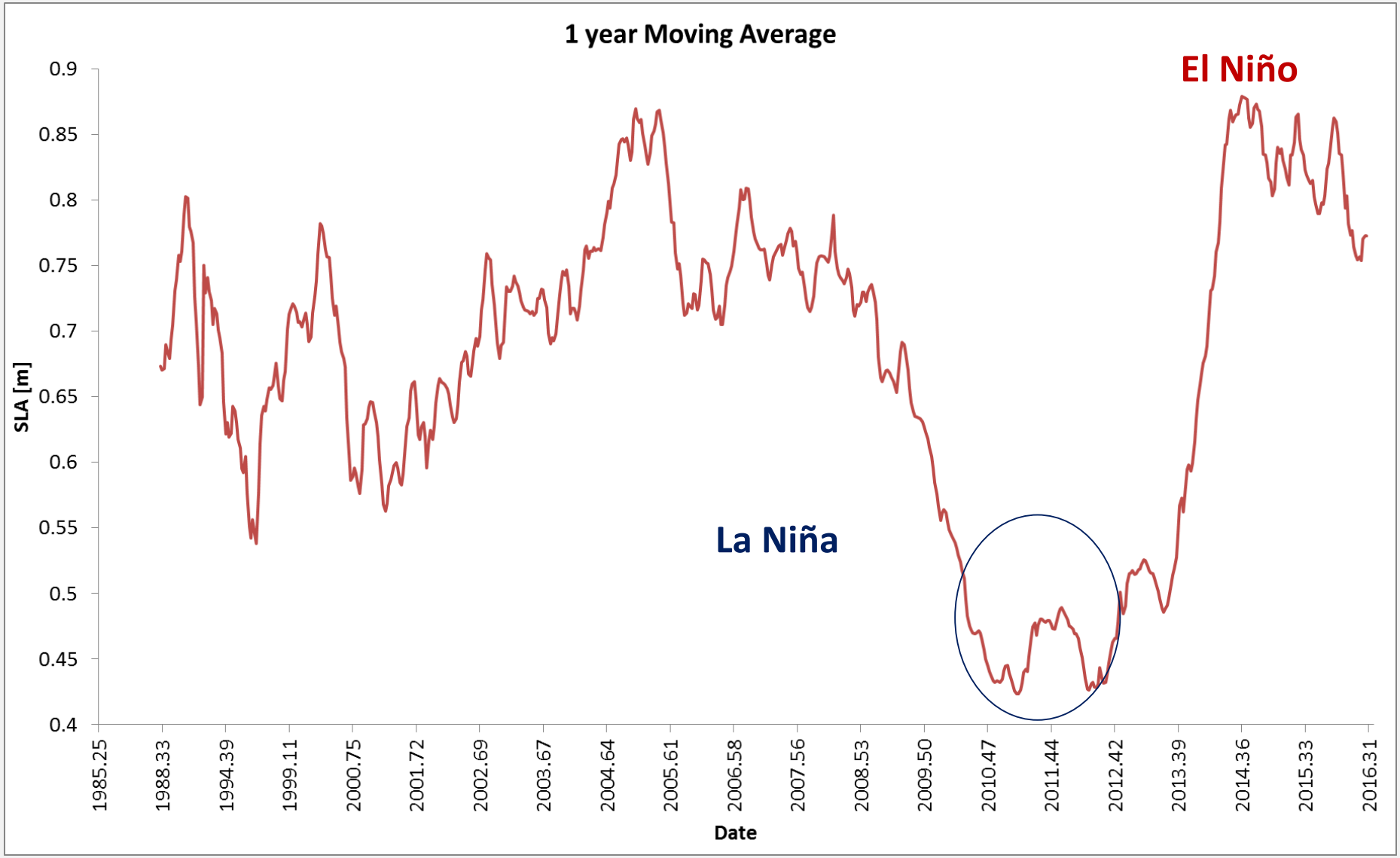
Some interesting cases

TG Red Sea vs. Arab Sea



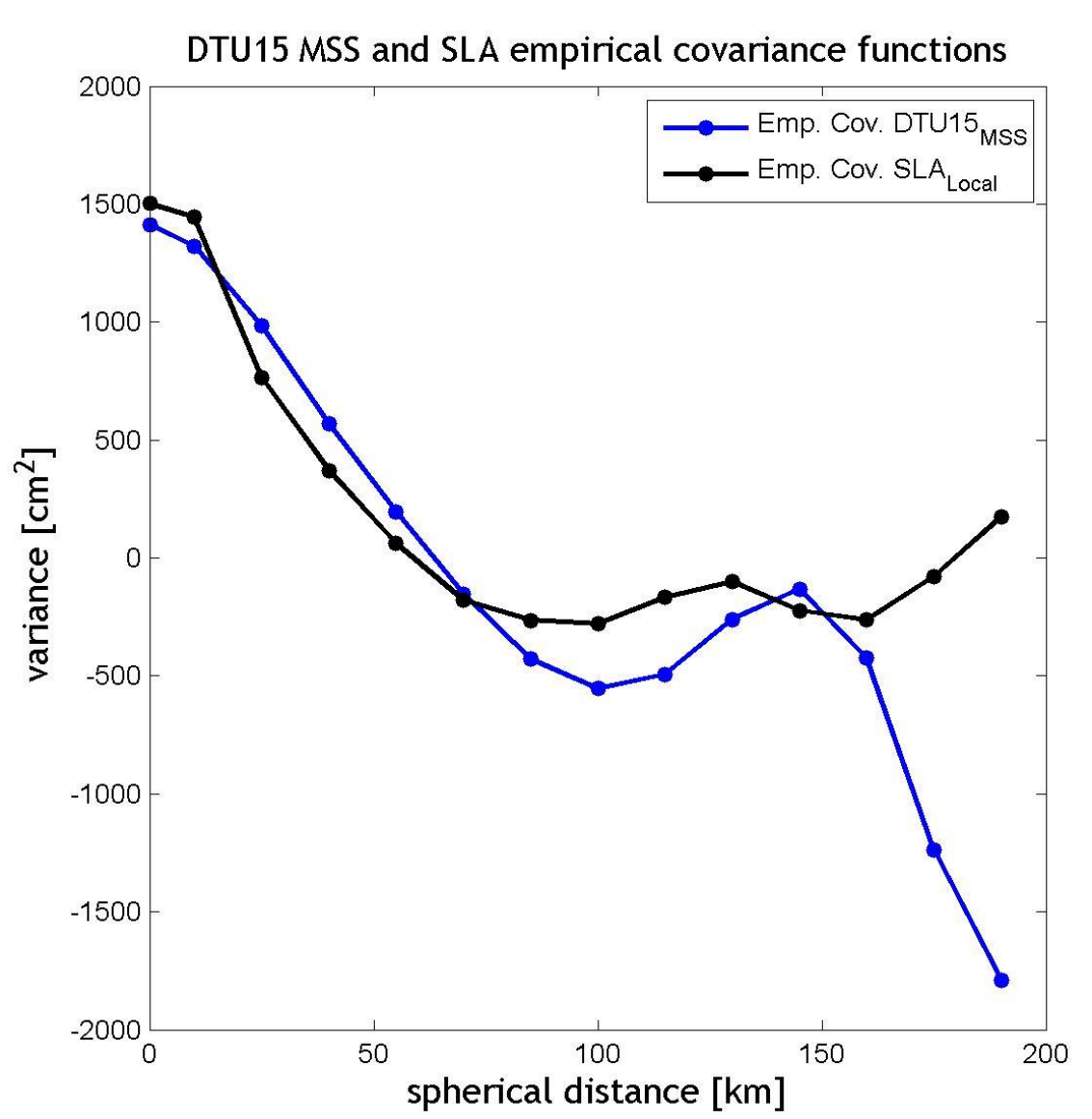
QUNF annual variations for the period 1985-2016 as derived by satellite altimetry

TG time-series construction/analysis



ABUQ annual variations for the period 1985-2016 as derived by satellite altimetry

SLA gridding and interpolation



DTU15 and SLA empirical covariance functions around ABUQ used for LSC prediction

SLA empirical covariance is used to determine whether the MSS field has the same statistical characteristics