Establishing an IHRS reference station

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OUTLINE

- IHRS/IHRF Why AUT1?
- Methodology/Theory
- Data availability
- Processing
- Results
- Conclusions

IHRF as a realization of IHRS

Realization of the IHRS: International Height Reference Frame (IHRF)

Primary needs:

1) Establishment of a vertical reference network as the main component of the IHRF.
2) Determination of potential values W_P (and their changes $\dot{W}_P$) at the reference network stations as accurate as possible.

Splinter Meeting IAG JWG0.1.2 GGHS2016 Thessaloniki, Greece (© Sánchez, 2016)

IHRF/IHRS Why AUT1?

IHRF as a realization of IHRS

Why AUT1?

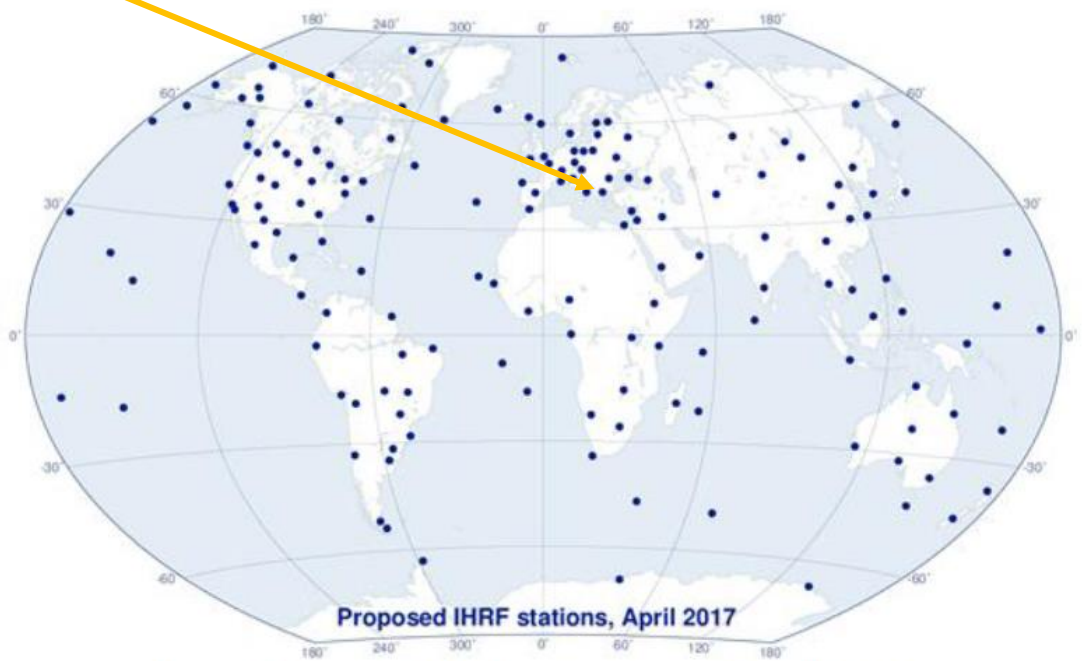


Fig. 1. Proposed IHRF stations as of April 2017.

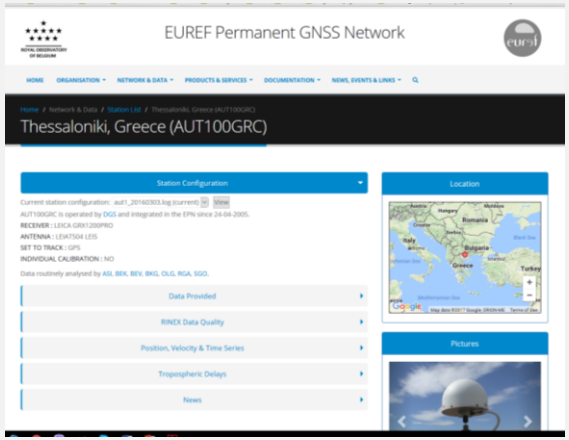
SWG0.1.2 Report of the IAG Vol. 40 – Travaux de l'AIG 2015-2017 (© Sánchez, 2017)

IHRF/IHRS Why AUT1?

IHRF as a realization of IHRS

Why AUT1?

- EUREF Station (Class A Station)



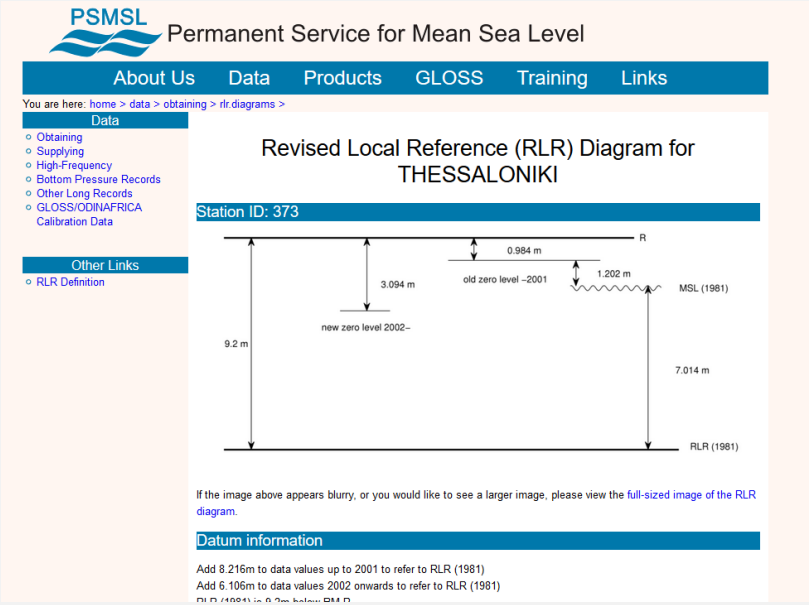
The AUT1 EUREF Class A station (© EUREF)

IHRF/IHRS Why AUT1?

IHRF as a realization of IHRS

Why AUT1?

- EUREF Station (Class A Station)
- HNHS TG station in proximity (9.2 km)



Thessaloniki SONEL TG station (© PSMSL)

IHRF/IHRS Why AUT1?

IHRF as a realization of IHRS

Why AUT1?

- EUREF Station (Class A Station)
- HNHS TG station in proximity (9.2 km)
- GravLab A10(#027) station in proximity (8 km)

GravLab A10 (#027) (© GravLab)

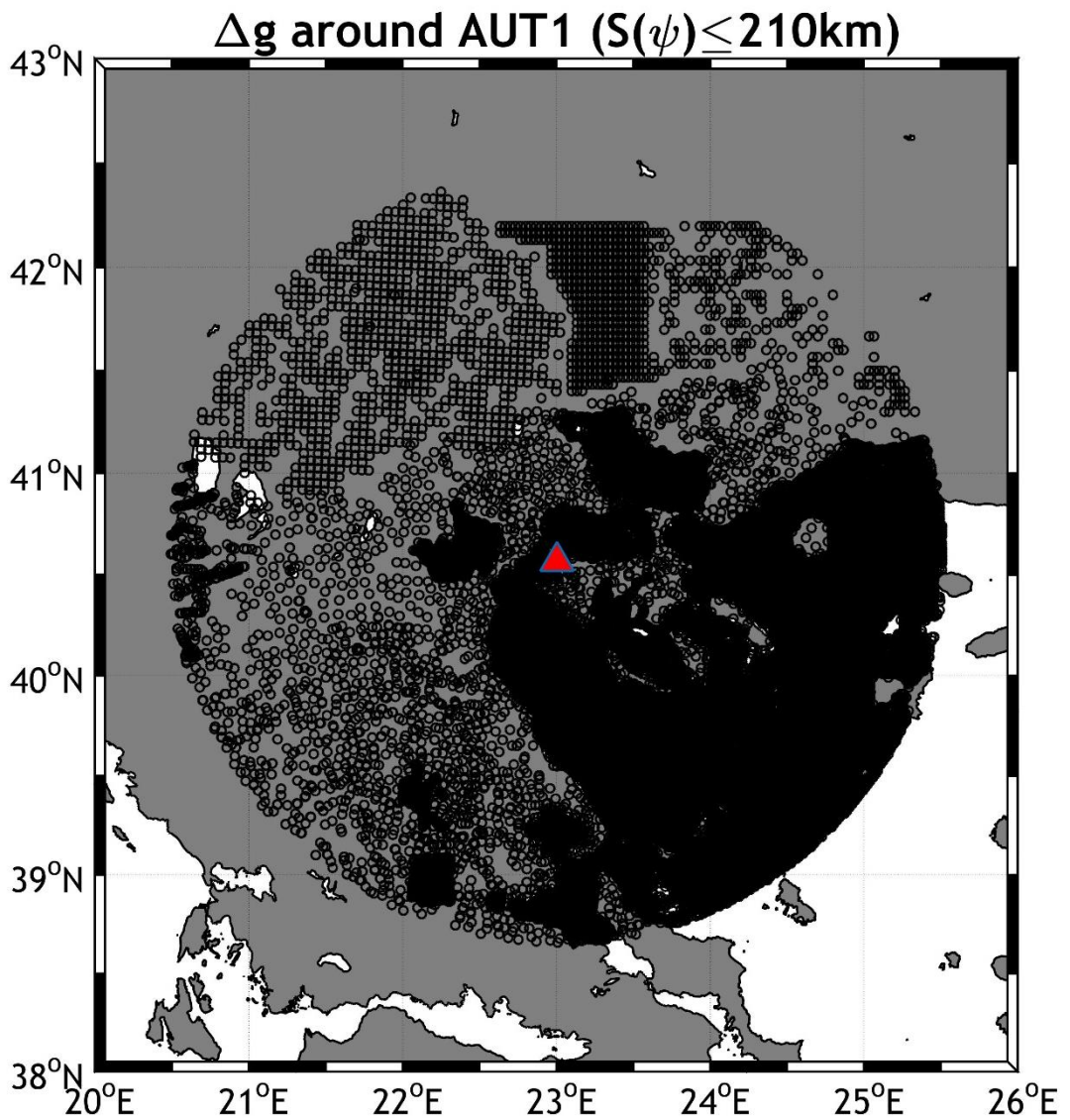
IHRF/IHRS Why AUT1?

IHRF as a realization of IHRS

Why AUT1?

- EUREF Station (Class A Station)
- HNHS TG station in proximity (9.2 km)
- GravLab A10(#027) station in proximity (8 km)
- Abundance of local gravity data (25208 pts. with S<210km)

IHRF/IHRS Why AUT1?



Distribution of available local gravity anomalies around AUT1

IHRF/IHRS Why AUT1?

IHRF as a realization of IHRS

Why AUT1?

- EUREF Station (Class A Station)
- HNHS TG station in proximity (9.2 km)
- GravLab A10(#027) station in proximity (8 km)
- Abundance of local gravity data (25208 pts. with S<210km)
- Levelling connection with the Hellenic VRF through dedicated 1st order spirit leveling

Methodology

Estimate the potential @ AUT1 employing ellipsoidal, orthometric and geoid heights (synthesis of GOCE GGM + local data through RCR)

$$\widehat{W}_{AUT1} = W_o^{CVD} - \Delta C_{AUT1}^{CVD/LVD}$$

$$(h_{AUT1} - H_{AUT1} - N_{AUT1})\bar{g}_i = \Delta C_{AUT1}^{CVD/LVD}$$

$$\bar{g}_{AUT1} = g_{AUT1} + 0.0424 H_{AUT1}$$

From EUREF (088/2005)

1st order leveling

Dedicated relative gravity campaign

Methodology

Determine N_{AUT1} using an RCR concept as:

$$\boxed{N_{AUT1} = N_0 + N_{GOCE}\Big|_{2}^{n_1} + N_{RTM}\Big|_{n_{1+1}}^{216,000} + N_{res}\Big|_{216,000}^{\infty}}$$

Methodology

Determine N_{AUT1} using an RCR concept as:

$$N_{AUT1} = N_0 + N_{GOCE}\big|_2^{n_1} + N_{RTM}\big|_{n_{1+1}}^{216,000} + N_{res}\big|_{216,000}^{\infty}$$

$$N_0 = \frac{GM - GM_o}{R\gamma} - \frac{W_o - U_o}{\gamma}$$

$N_{GOCE}\big|_2^{n_1}$ GOCO05s to d/o 220

$N_{RTM}\big|_{n_{1+1}}^{216,000}$ SRTM3″ DTM for the wider Hellenic area

$N_{res}\big|_{216,000}^{\infty}$ From Δg_{res} employing numerical integration, LSC, FFT, Stokes modifications (WG), radial spherical basis functions

Methodology – *Conventions*

- **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**

$$R = 6371008.7714\ m$$

Data availability

$$h_{AUT1} = 150.0785 \pm 0.0020\ m$$

1. POSITIONS/VELOCITIES PUBLISHED BY EUREF

EUREF has classified AUT100GRC (Thessaloniki, Greece) as a **class A station** which means that it can used as fiducial station for EUREF densifications.

LATEST RELEASE

EPN_A_ETRF2000_C1934.SSC - EPN_A_IGb08_C1934.SSC (March 25, 2017)

ETRF2000	epoch t_0	Position (m)			Velocity (m/y)		
		X	Y	Z	V_X	V_Y	V_Z
086/2005 - 035/2017	001/2005	4466283.764 ± 0.000	1896166.630 ± 0.000	4126096.571 ± 0.000	0.0027 ± 0.0000	0.0024 ± 0.0000	-0.0071 ± 0.0000

IGb08	epoch t_0	Position (m)			Velocity (m/y)		
		X	Y	Z	V_X	V_Y	V_Z
086/2005 - 035/2017	001/2005	4466283.430 ± 0.000	1896166.878 ± 0.000	4126096.789 ± 0.000	-0.0149 ± 0.0000	0.0209 ± 0.0000	0.0043 ± 0.0000

Click HERE to see a plot of how the station positions between successive cumulative solutions agree with each other.

+ **PREVIOUS RELEASES**

2. POSITIONS/VELOCITIES PUBLISHED BY THE IGS

IGS has not yet released coordinates for AUT100GRC (Thessaloniki, Greece).

3. POSITIONS/VELOCITIES PUBLISHED BY THE IERS

LATEST RELEASE

ETRF2000(14R) not yet ready

-

ITRF2014_GNSS.SSC.txt (January 21, 2016)

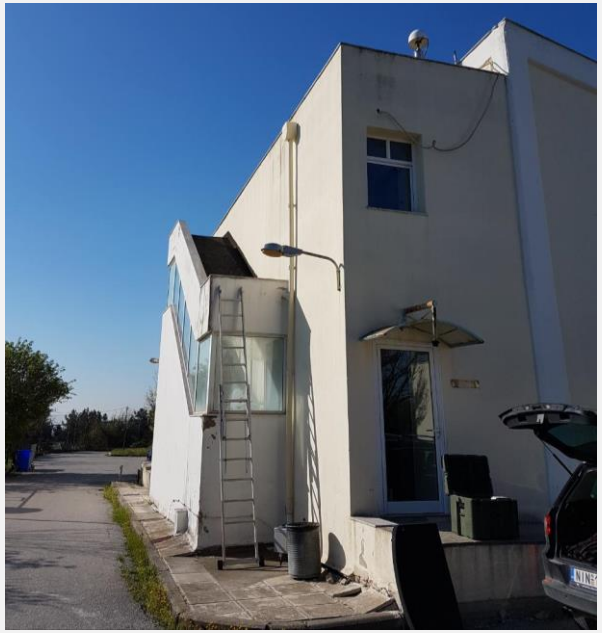
ITRF2014	epoch t_0	Position (m)			Velocity (m/y)		
		X	Y	Z	V_X	V_Y	V_Z
048/2006 - 365/2014	001/2010	4466283.353 ± 0.001	1896166.980 ± 0.001	4126096.805 ± 0.001	-0.0148 ± 0.0000	0.0208 ± 0.0000	0.0041 ± 0.0000
start - 048/2006	001/2010	4466283.351 ± 0.001	1896166.980 ± 0.001	4126096.808 ± 0.001	-0.0148 ± 0.0000	0.0208 ± 0.0000	0.0041 ± 0.0000

AUT1 ellipsoidal height from DGS/AUTH

Data availability

$$h_{AUT1} = 150.0785 \pm 0.0020\ m$$

$$H_{AUT1} = 108.8291 \pm 0.0021\ m$$



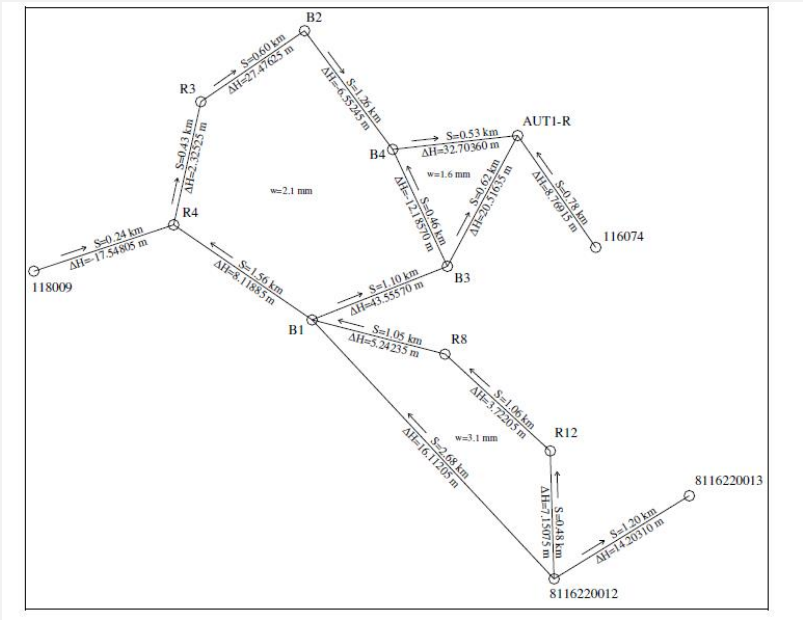
AUT1 dedicated spirit leveling from AUT1 leveling BM to the ARP

Data availability

$$h_{AUT1} = 150.0785 \pm 0.0020\ m$$

$$H_{AUT1} = 108.8291 \pm 0.0021\ m$$

AUT1 dedicated spirit leveling



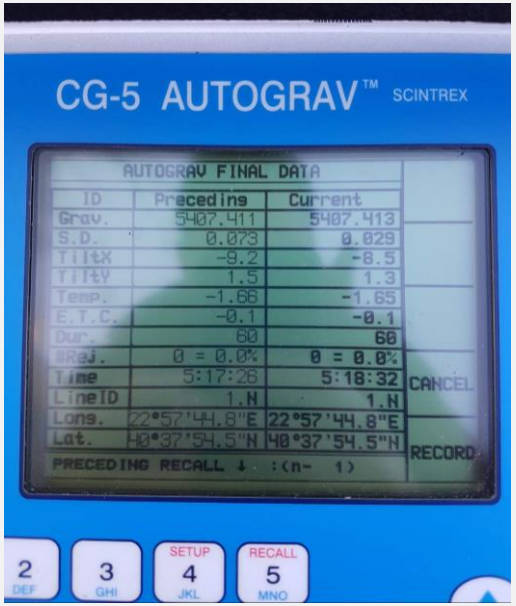
AUT1 1st order spirit leveling to connect to HVRF (Vlachakis et al. 2005)

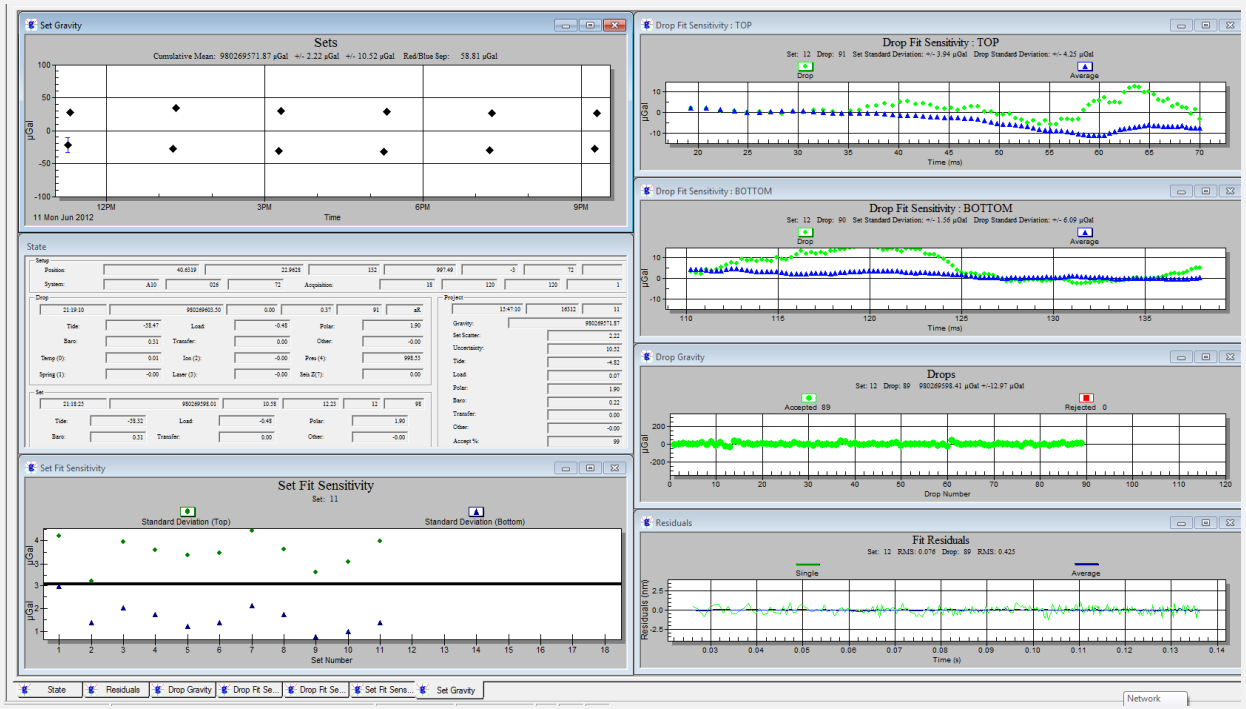
Data availability

$$h_{AUT1} = 150.0785 \pm 0.0020\ m$$

$$H_{AUT1} = 108.8291 \pm 0.0021\ m$$

$$g_{AUT1} = 980234905.23 \pm 19.98\ \mu Gal$$





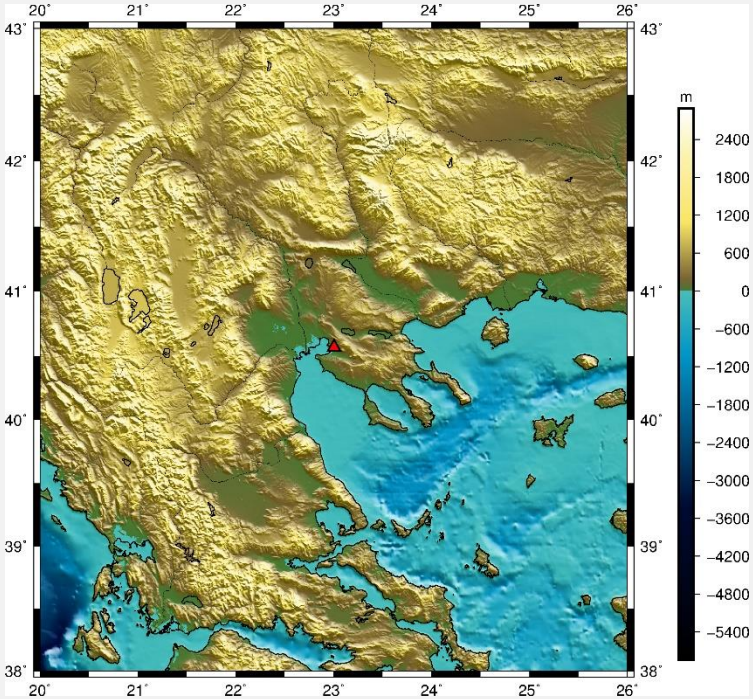
GravLab dedicated gravity survey connecting A10(#027) with AUT1

Data availability

$N_{RTM}|_{n_{1+1}}^{216,000}$

SRTM3″ DTM for the wider Hellenic area

	max	min	mean	std
DTM/DBM	3041.7	-5250.00	-768.10	1478.99



The generated SRTM3″ DTM/DBM around AUT1 for the evaluation of RTM

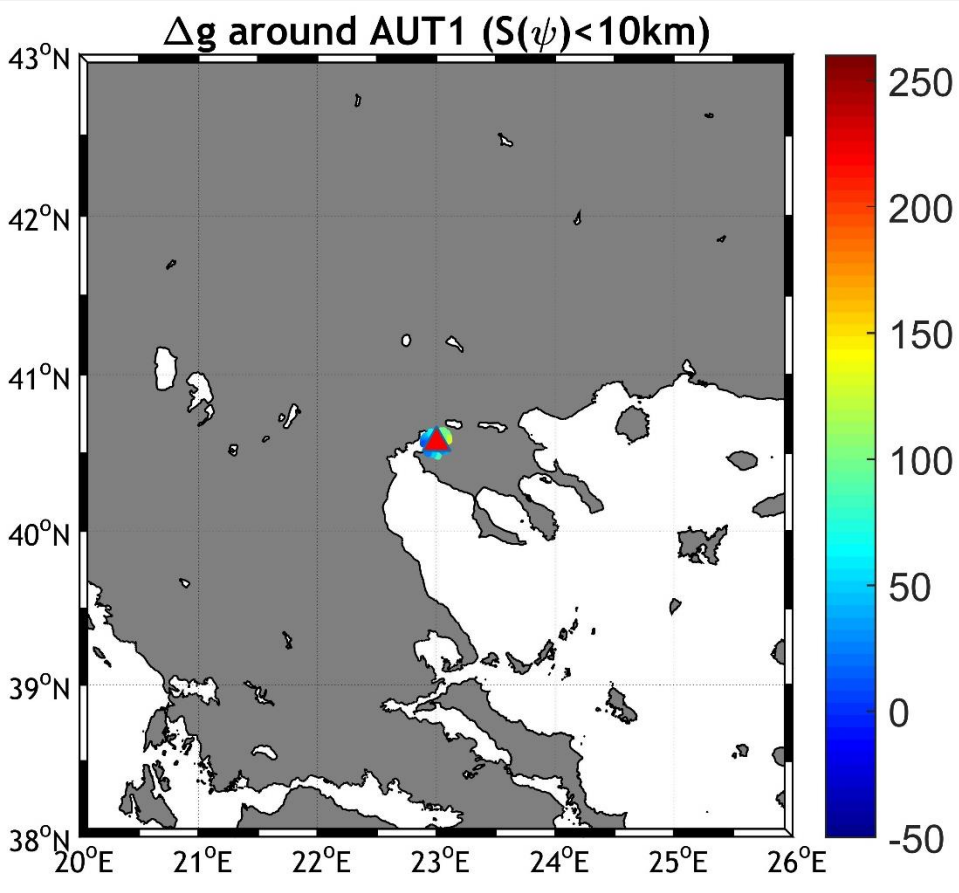
Data availability

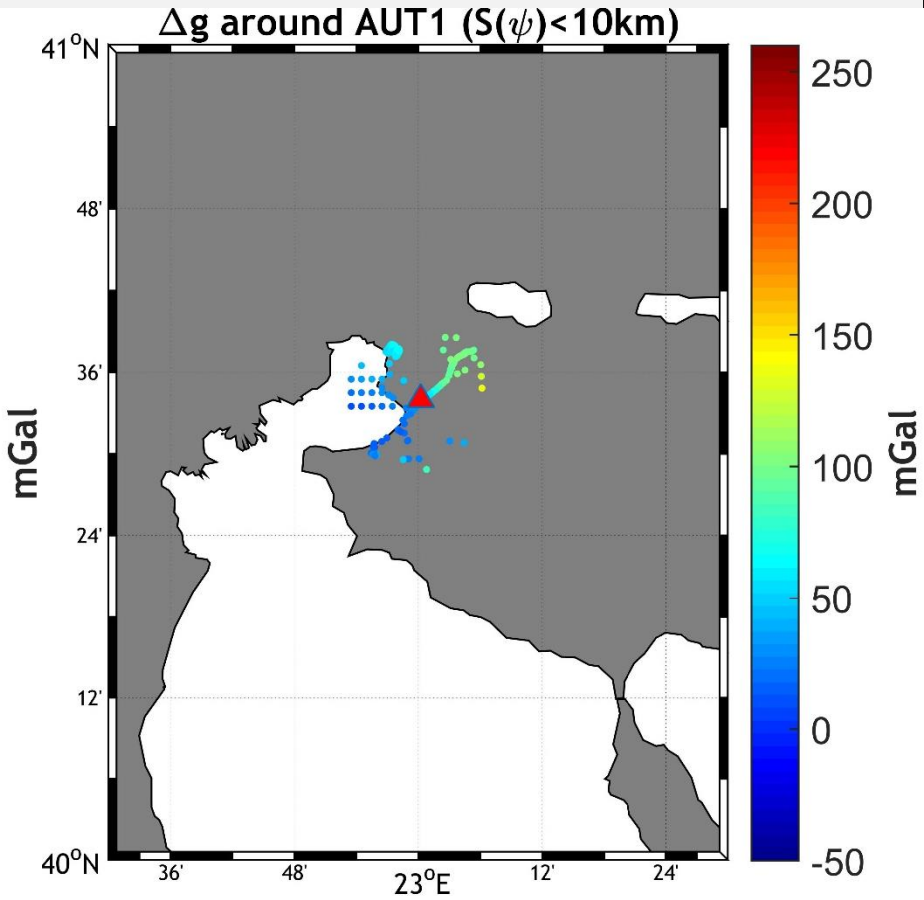
Select local gravity data based on the JWG0.1.2 concept

Statistics of the available local free-air gravity anomalies around AUT1. Unit: [mGal]

	nr. pts.	max	min	mean	std
S∈[0,10]	**460**	137.739	11.111	58.057	17.929
S∈(10,50]	**2209**	180.365	-20.643	31.579	37.364
S∈(50,110]	**6319**	192.130	-44.743	13.411	28.892
S∈(110,210]	**16221**	258.979	-107.127	23.252	32.643
all S∈[0,210]	**25205**	258.979	-107.127	22.150	32.775

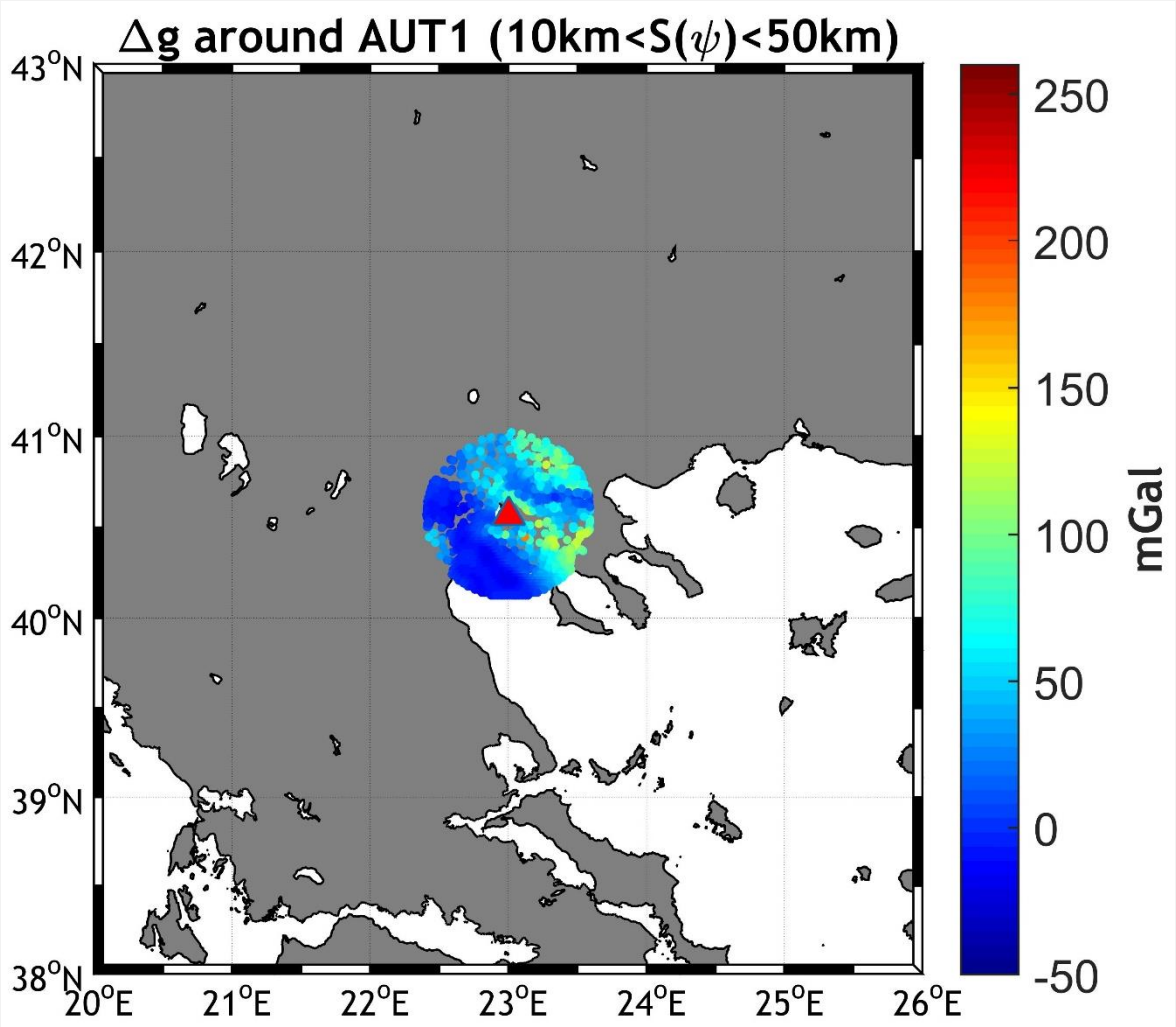
Data availability





Distribution of local gravity data around AUT1

Data availability



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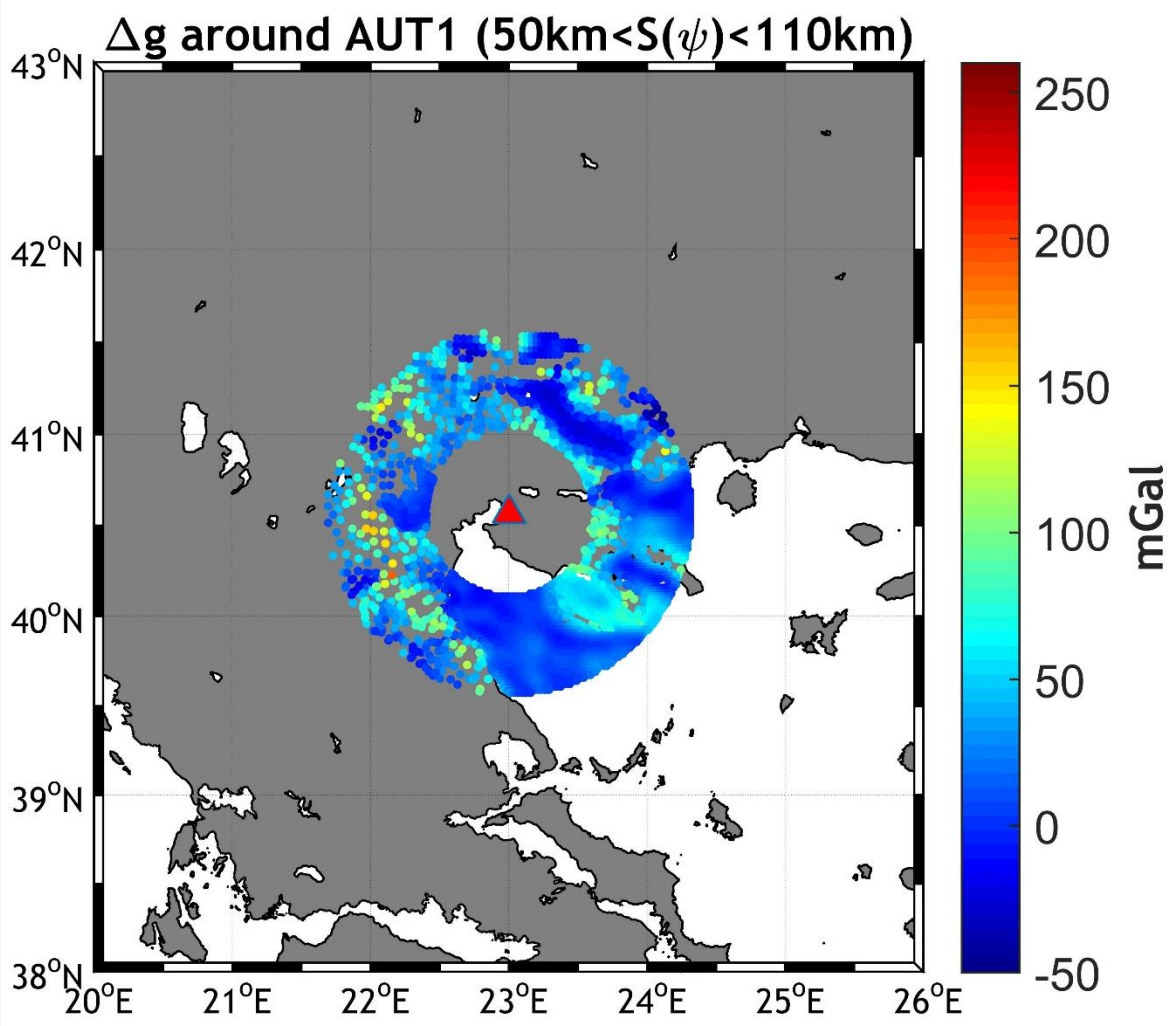

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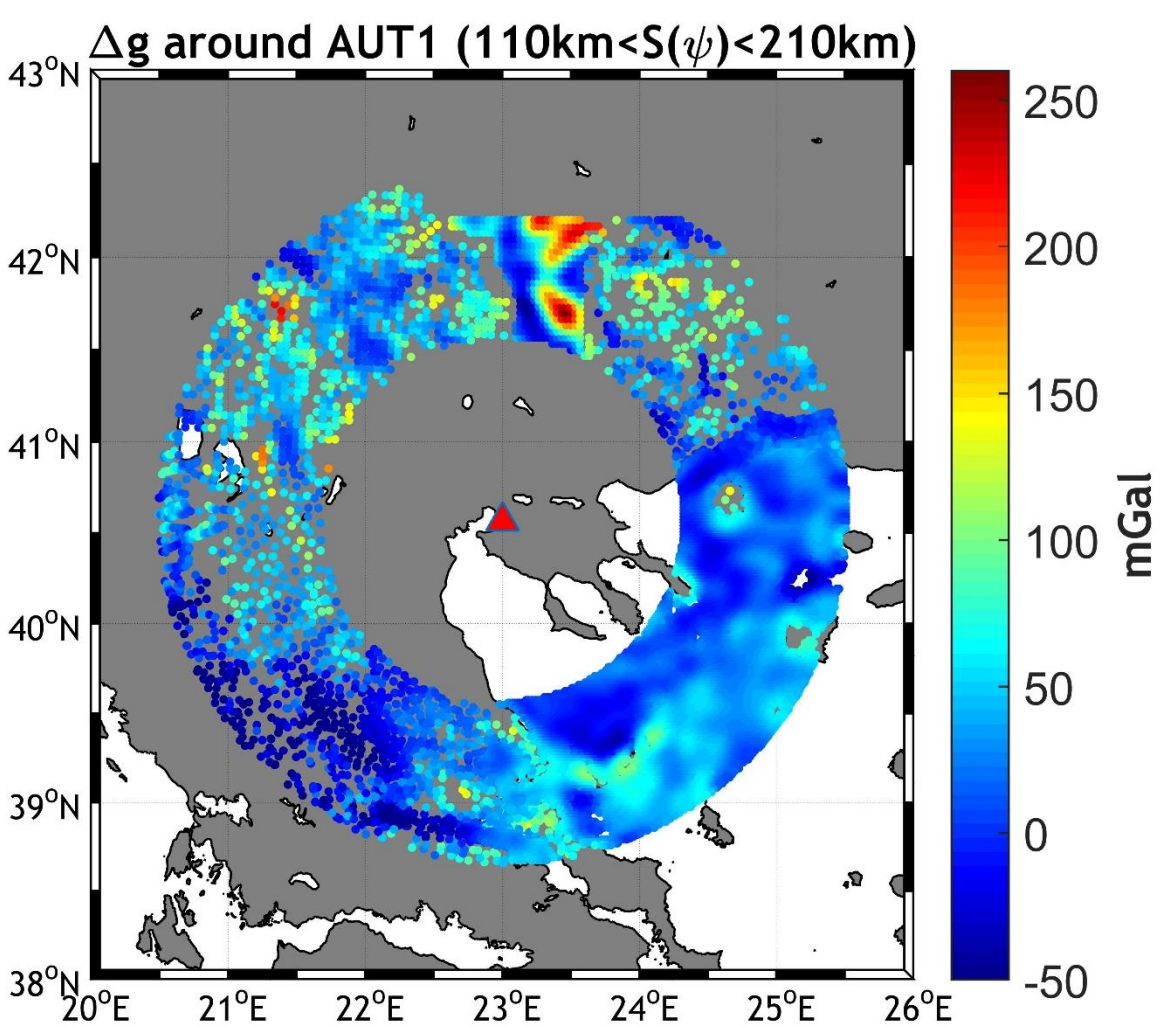

Distribution of local gravity data around AUT1

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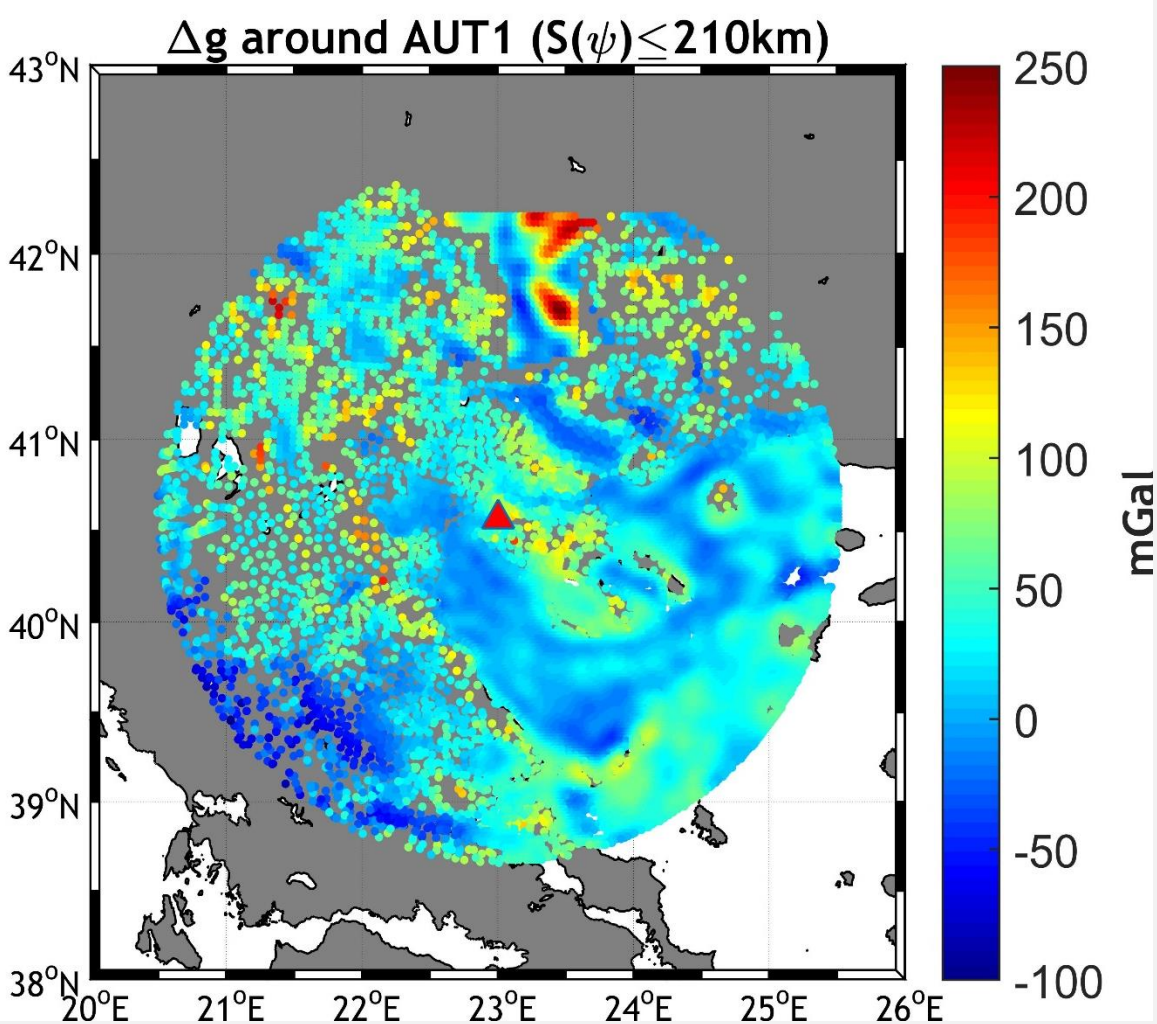
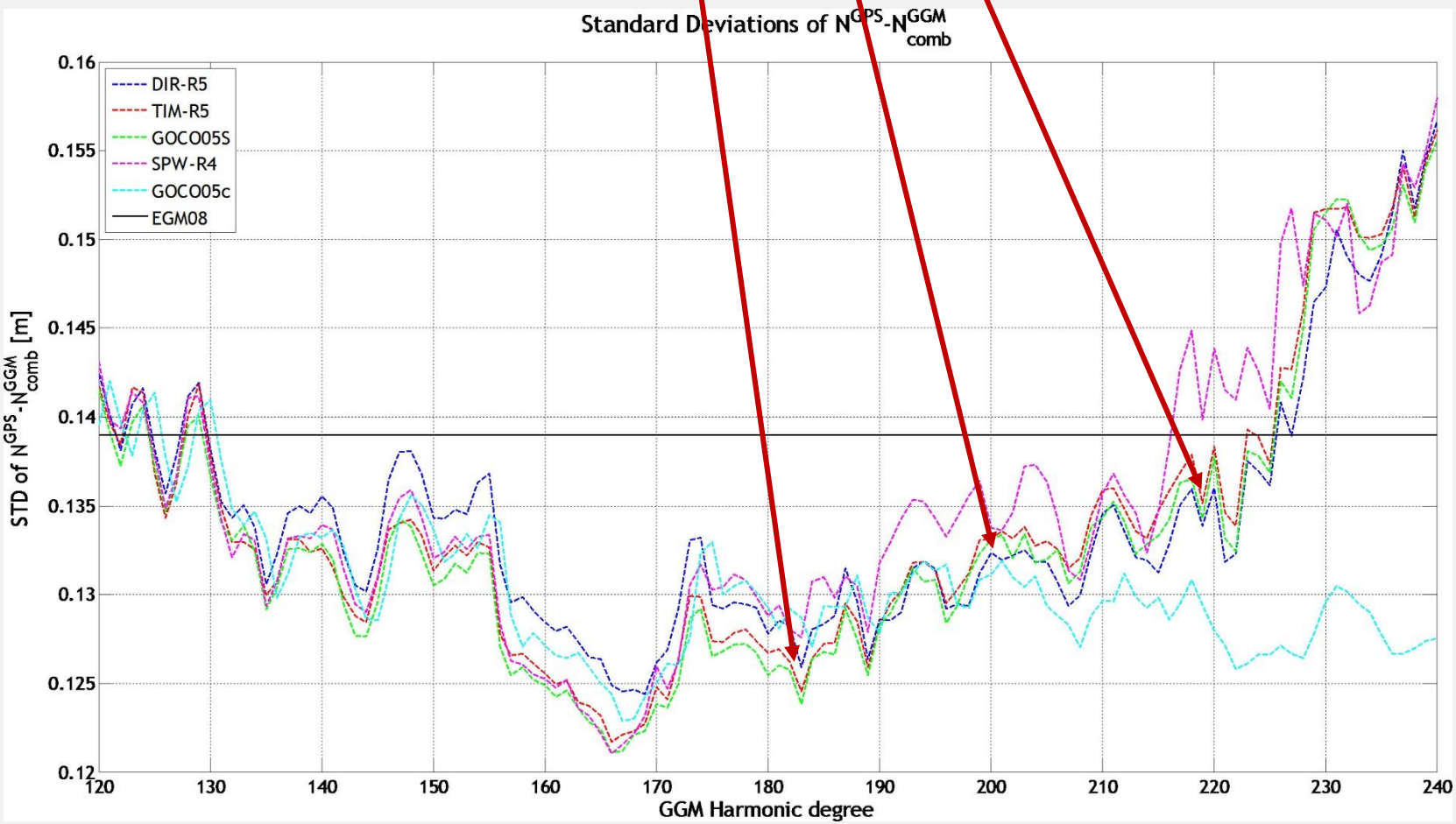


Distribution of local gravity data around AUT1

Data pre-processing

Reduction to GOCO05s (n_{max}=183, 200, 220)



GOCE GGM evaluation over Greece

Reduction to GOCO05s (n_{max}=183, 200, 220)

Statistics of the original and reduced free-air gravity anomalies. Unit: [mGal]

	max	min	mean	std
Δg_f	258.979	-107.127	22.150	32.775
Δg_{red} (d/o 183)	200.782	-107.907	-10.068	32.971
Δg_{red} (d/o 200)	195.579	-110.758	-9.798	32.475
Δg_{red} (d/o 220)	201.558	-111.594	-10.459	30.699

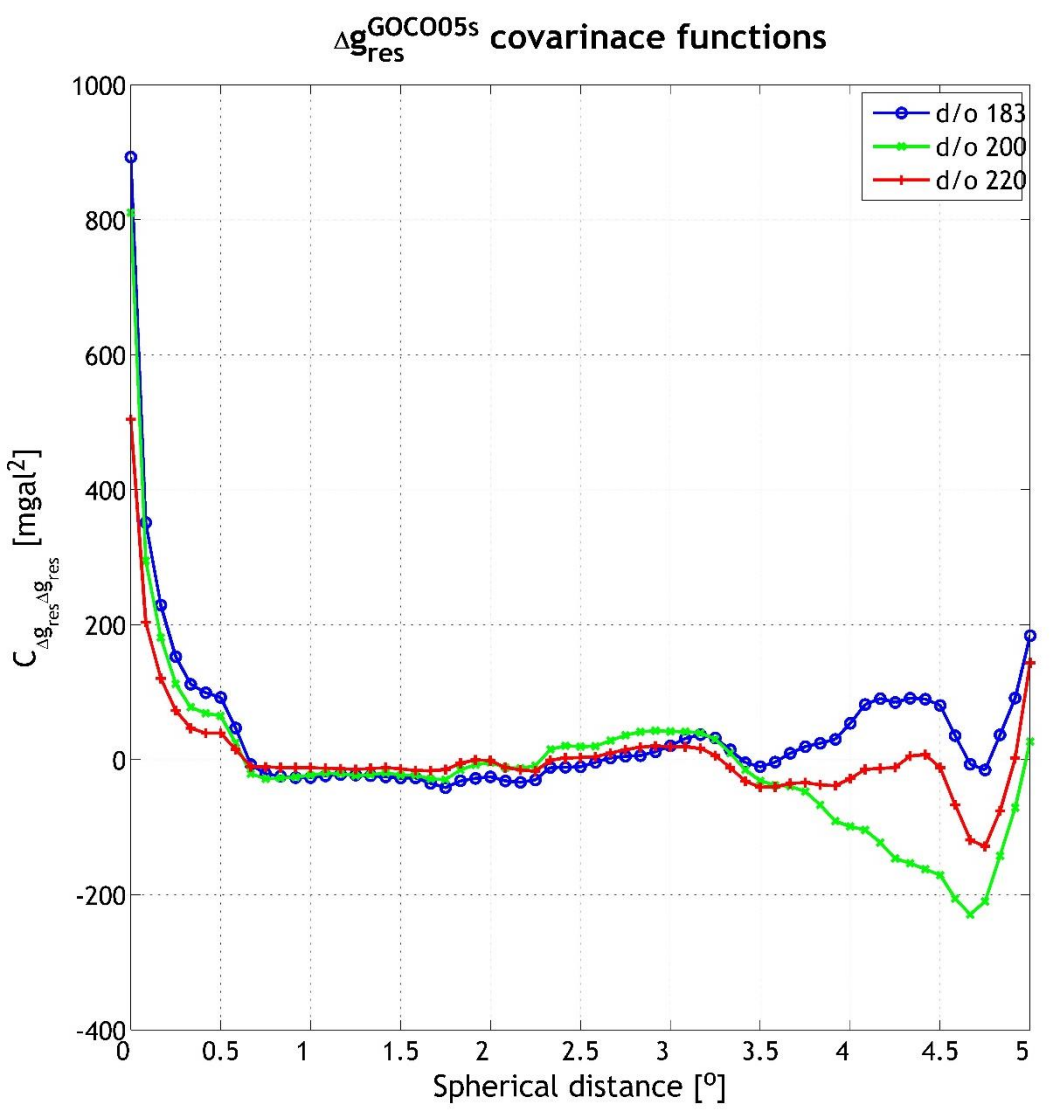
Data pre-processing

Compute RTM effects on gravity the usual way *(terrain effects relative to a smooth but varying surface generated from the fine-detail DTM)*

Statistics of the original and reduced free-air gravity anomalies. Unit: [mGal]

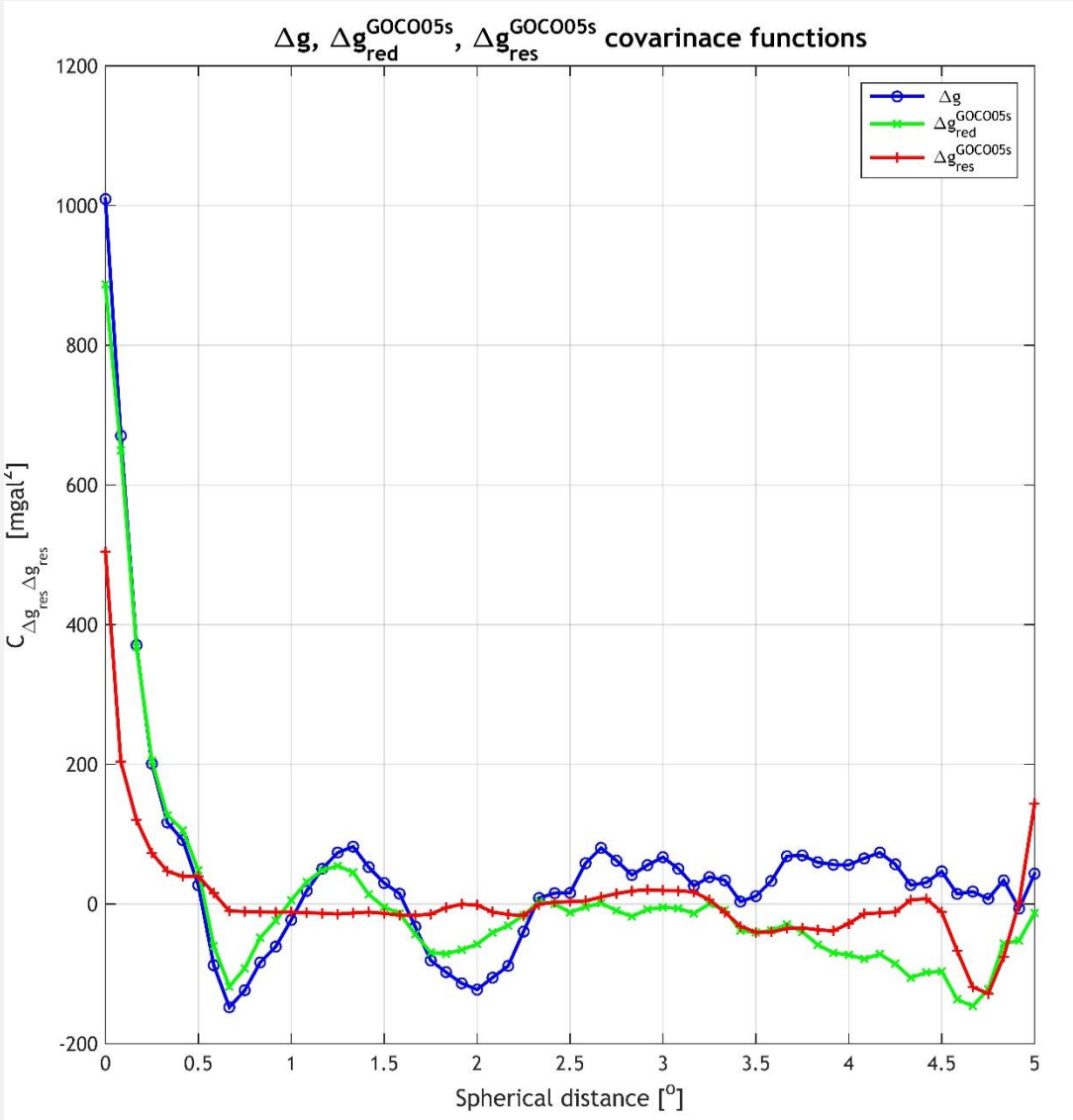
	max	min	mean	std
Δg_f	258.979	-107.127	22.150	32.775
Δg_{red} (d/o 183)	200.782	-107.907	-10.068	32.971
Δg_{res} (d/o 183)	141.590	-90.568	6.562	21.604
Δg_{red} (d/o 200)	195.579	-110.758	-9.798	32.475
Δg_{res} (d/o 200)	138.192	-89.915	5.804	20.279
Δg_{red} (d/o 220)	201.558	-111.594	-10.459	30.699
Δg_{res} (d/o 220)	121.683	-88.945	4.151	18.328

Data pre-processing



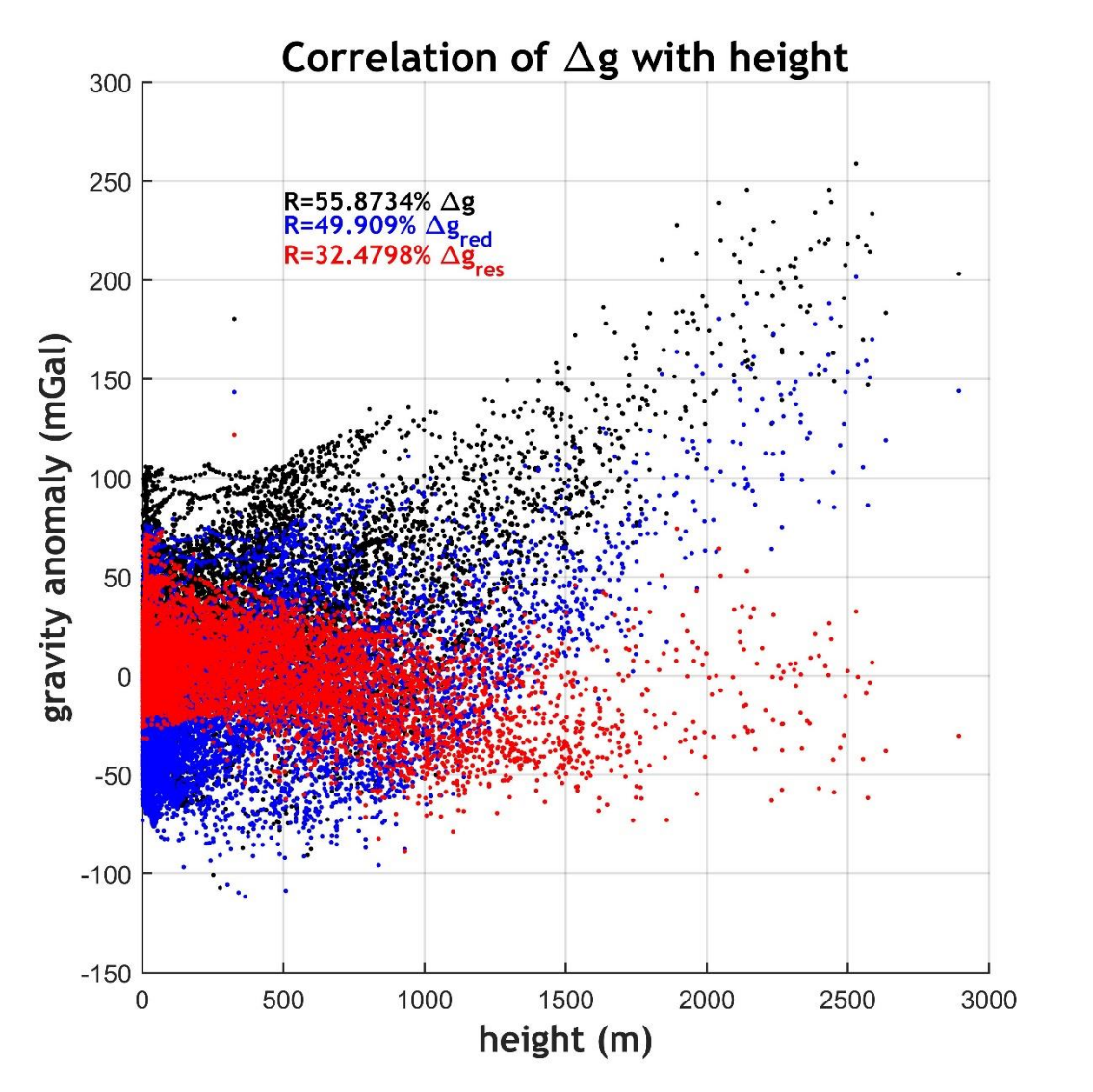
Δg_{res} empirical covariance functions

Data pre-processing

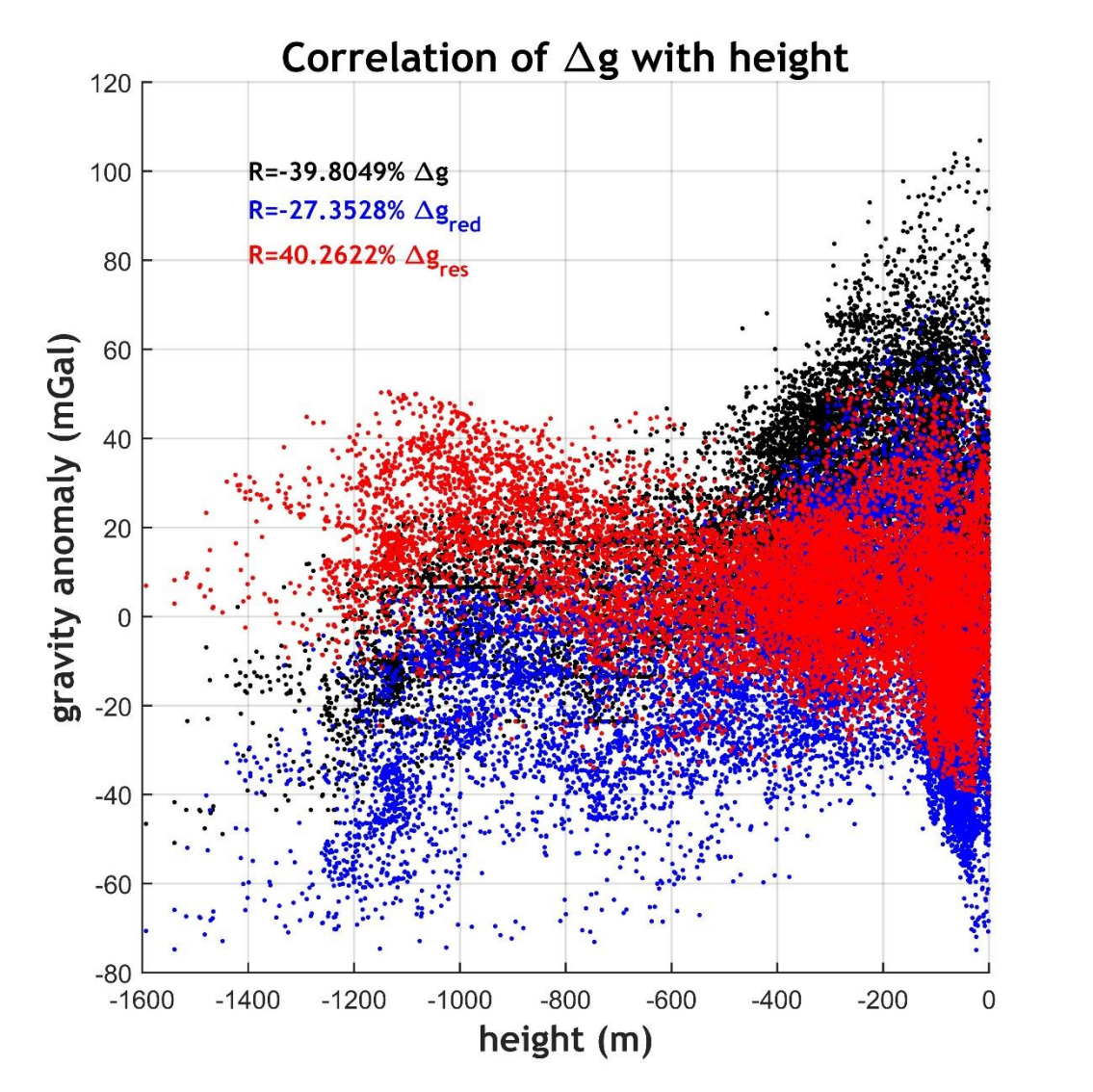


Δg, Δg_{red} and Δg_{res} empirical covariance functions

Data pre-processing



Data pre-processing



✗ RTM does not work well over marine areas due to the limited resolution/accuracy of current bathymetry models

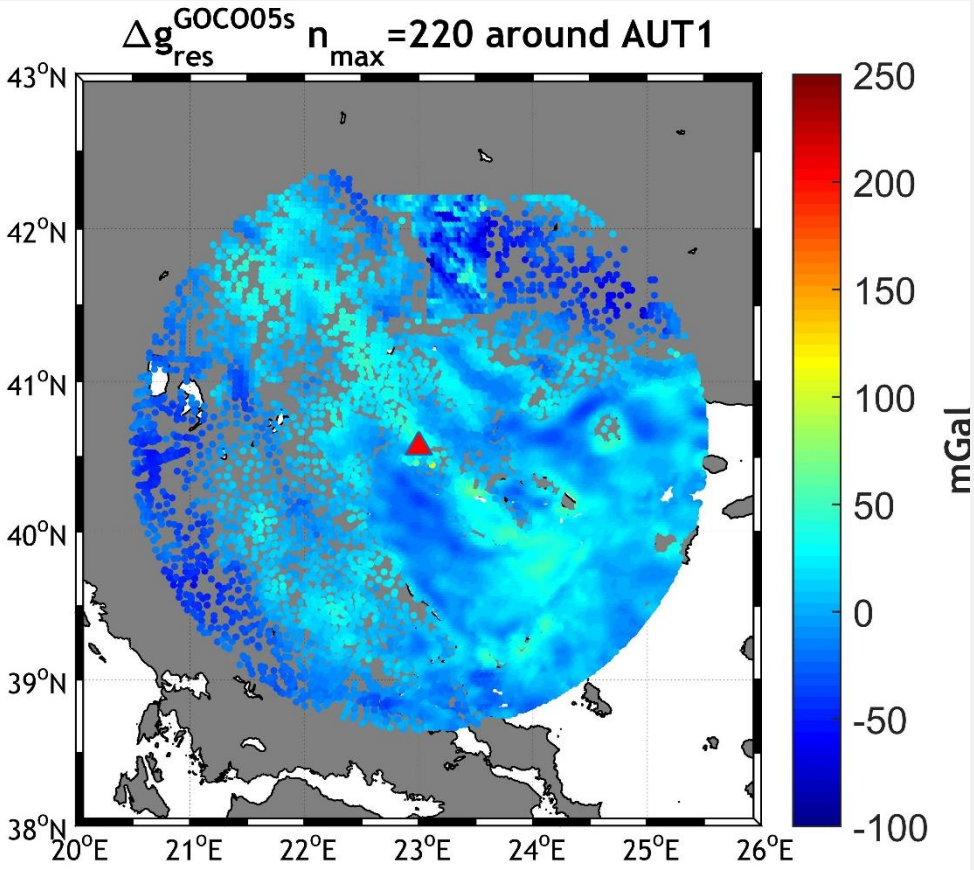
Data pre-processing

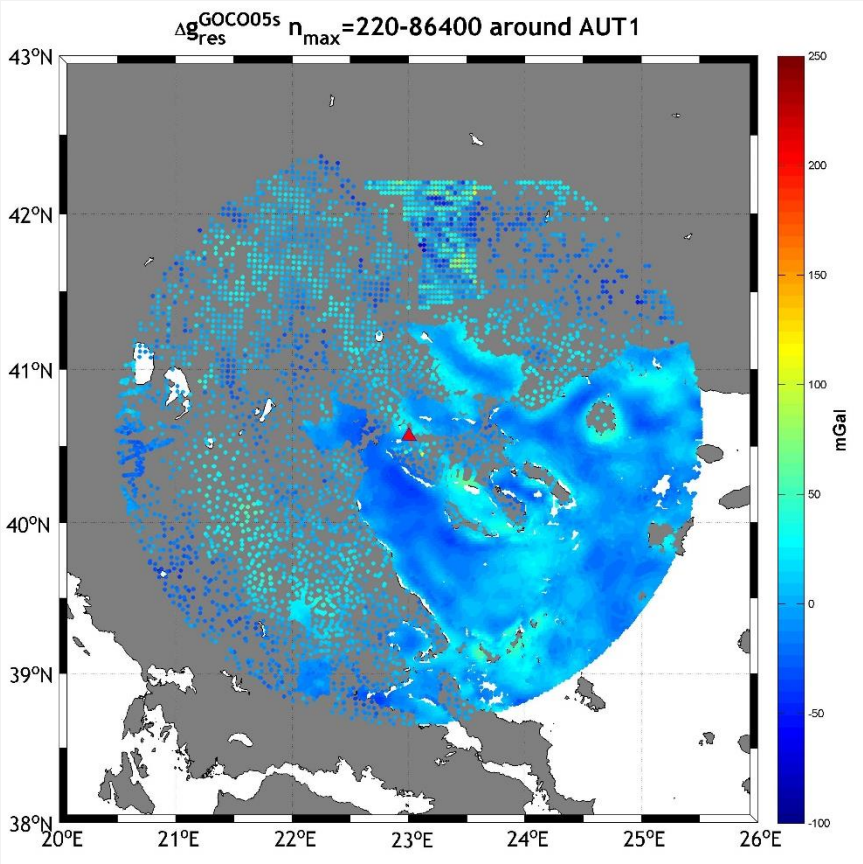
Compute RTM effects as a synthesis of **dv_ell2014** (d/o 221 to 2160) and **ERTM2160** (Hirt et al. 2016) (from d/o 2160 to 99,000)

Statistics of the original and residual free-air gravity anomalies. Unit: [mGal]

	max	min	mean	std
Δg_f	258.979	-107.127	22.150	32.775
Δg_{red} (d/o 220)	201.558	-111.594	-10.459	30.699
Δg_{res} (d/o 220)	121.683	-88.945	4.151	18.328
Δg_{res} (dv_ell&ERTM)	114.401	-66.380	0.354	15.846

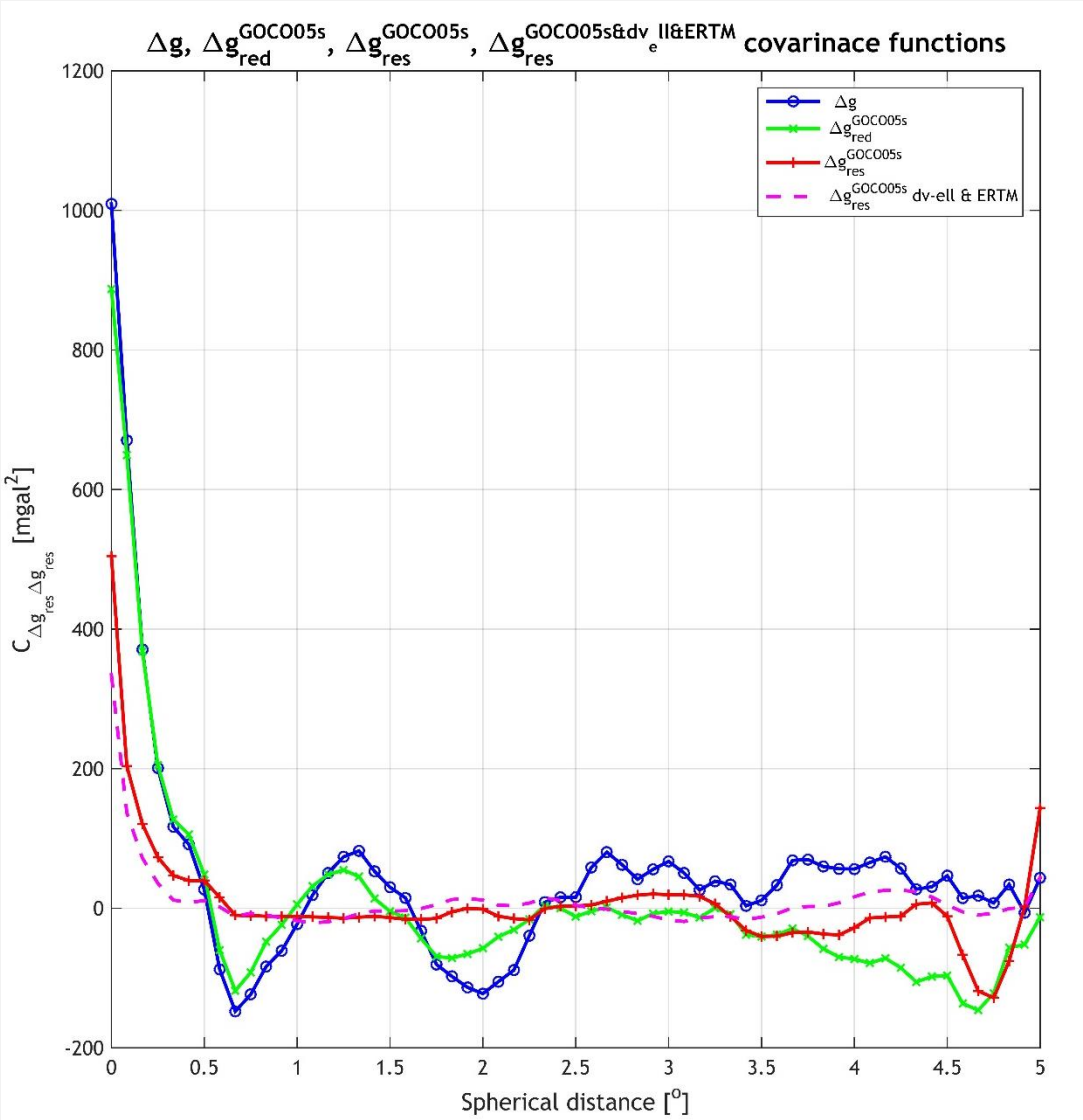
Data pre-processing





Δg_{res} with the classical (left) and dv_ell&ERTM approach (right)

Data pre-processing



Data pre-processing

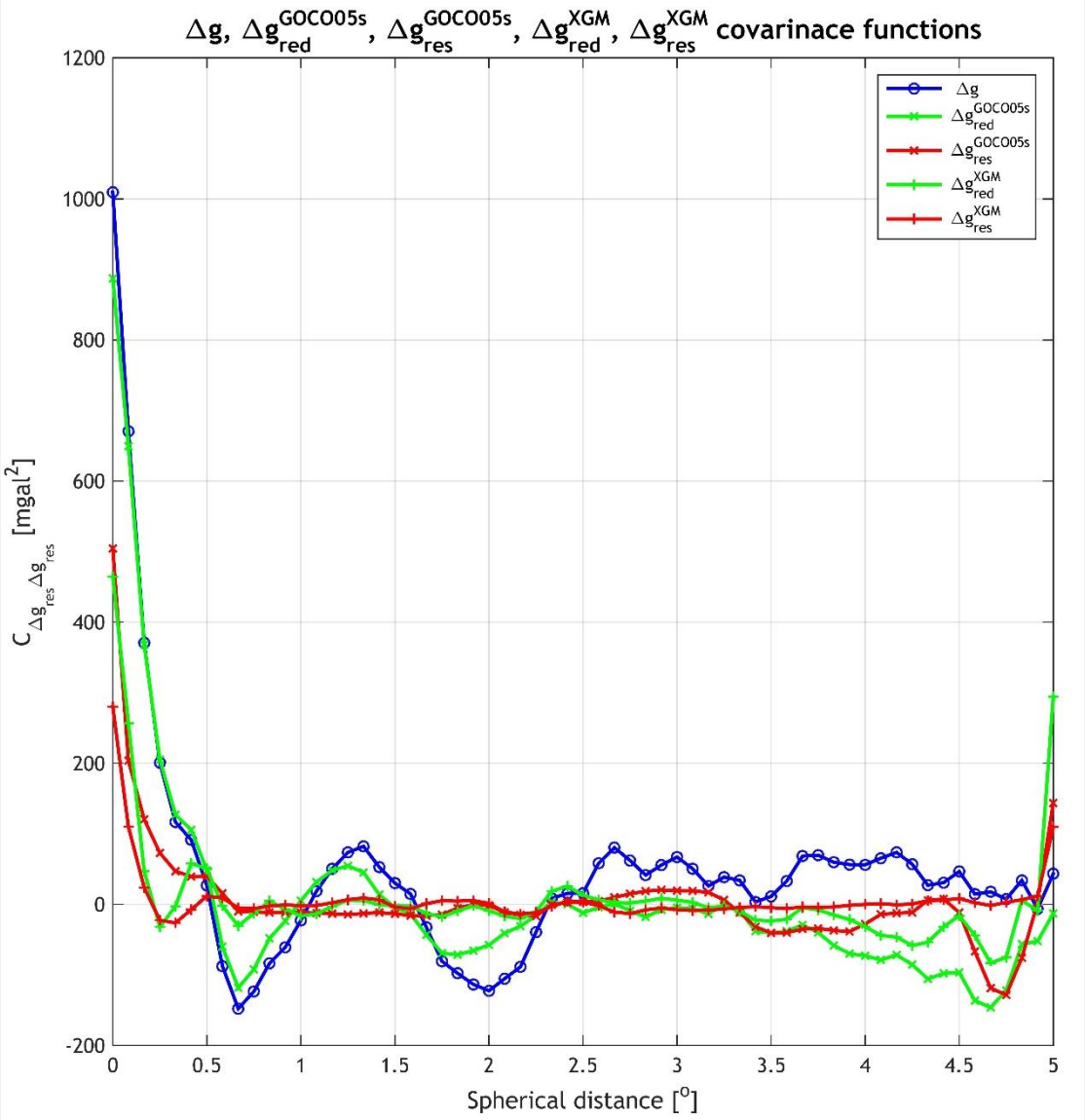
Reduction to XGM2016 *(n_{max}=719)*

Compute RTM effects on gravity the usual way

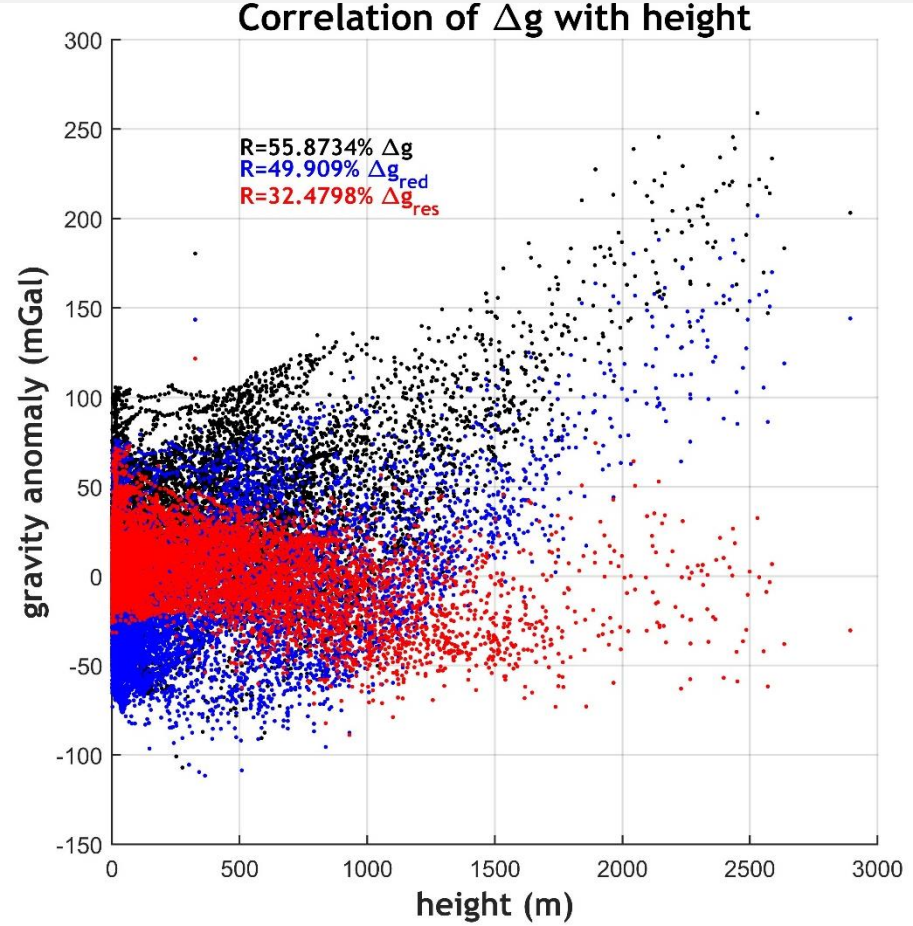
Statistics of the original and residual free-air gravity anomalies. Unit: [mGal]

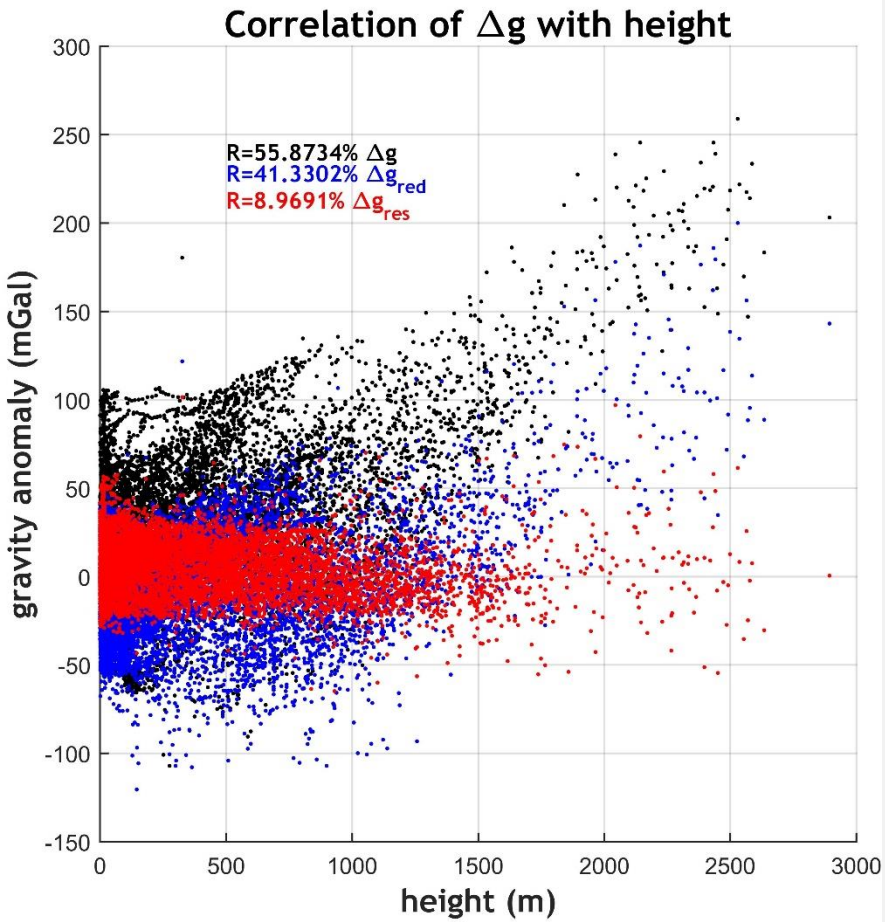
	max	min	mean	std
Δg_f	258.979	-107.127	22.150	32.775
Δg_{red} (d/o 220)	201.558	-111.594	-10.459	30.699
Δg_{res} (d/o 220)	121.683	-88.945	4.151	18.328
Δg_{res} (dv_ell&ERTM)	114.401	-66.380	0.354	15.846
Δg_{red} (d/o 719)	200.017	-120.424	-5.468	23.876
Δg_{res} (d/o 719)	101.551	-64.925	3.118	14.854

Data pre-processing



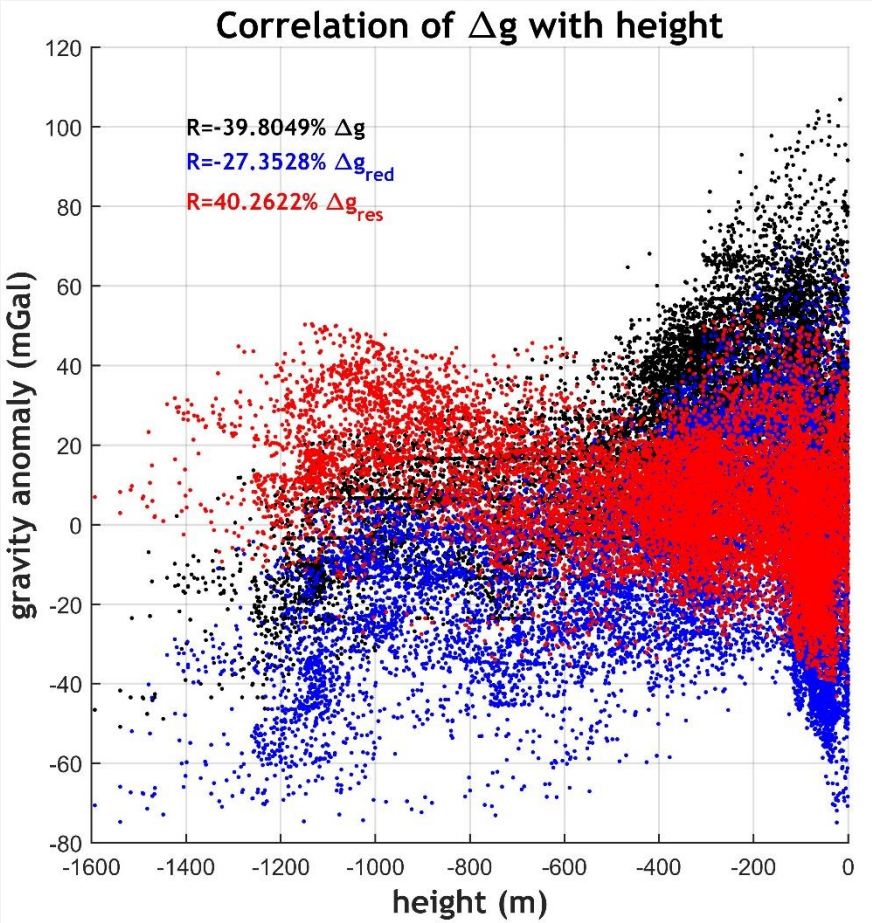
Data pre-processing

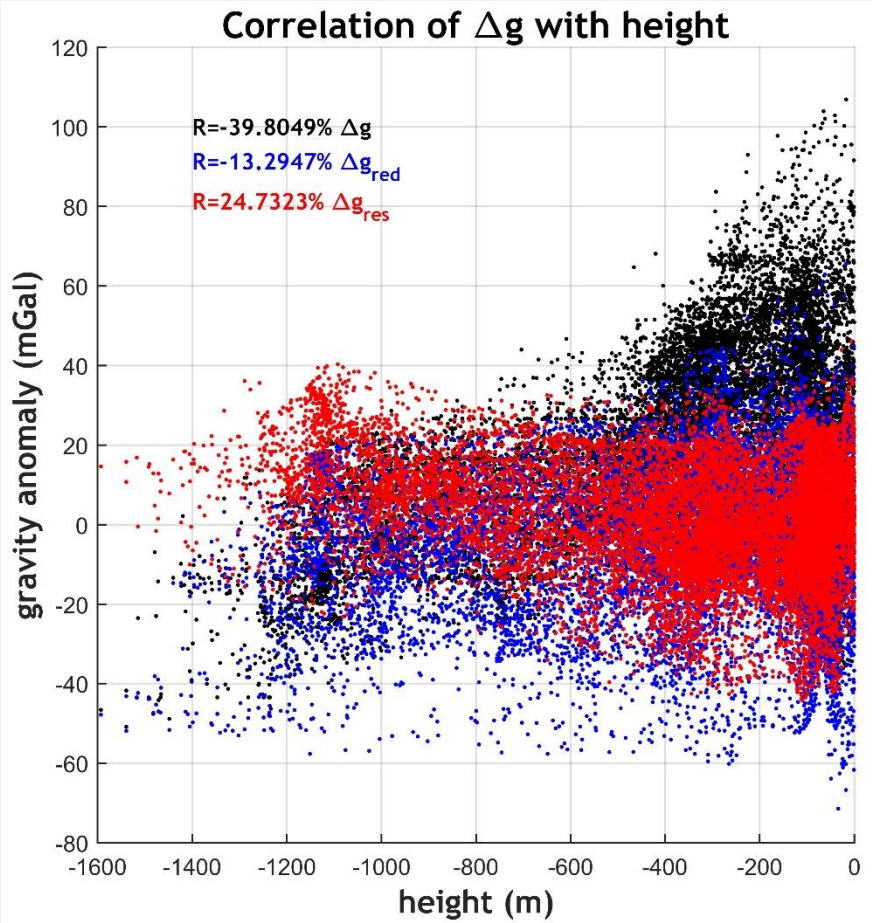




Δg_{res} relative to GOCO (left) and relative to XGM2016 (right)

Data pre-processing





Δg_{res} relative to GOCO (left) and relative to XGM2016 (right)

Effect of estimation method

Statistics of the estimated geoid and potential at AUT1

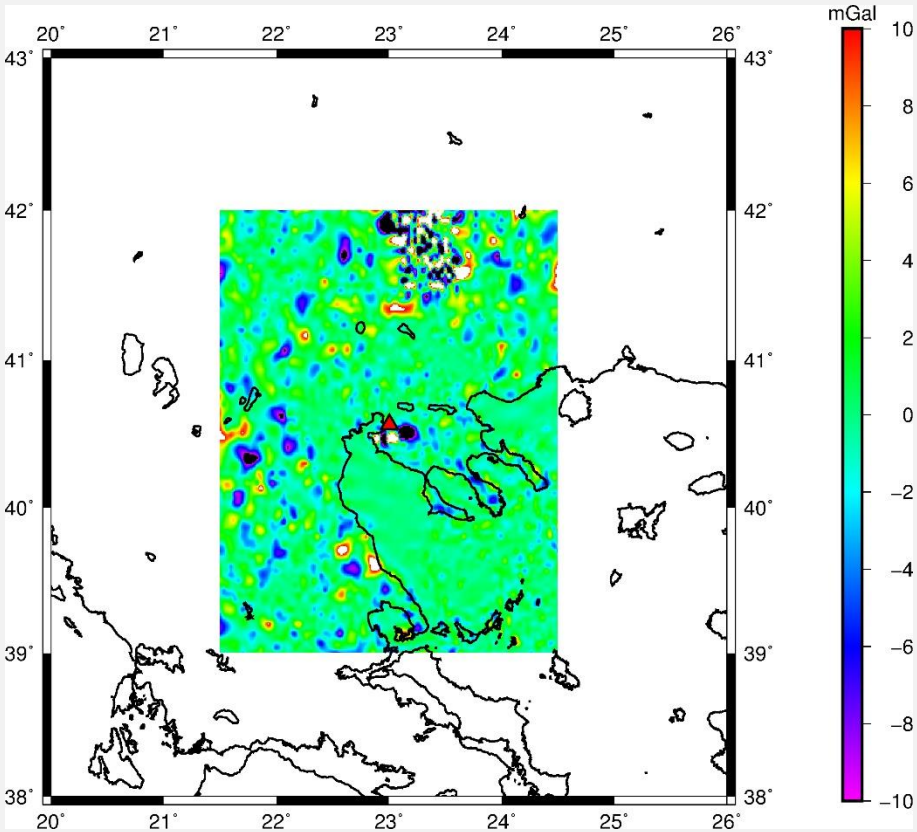
	N_{AUT1} $[m]$	N_{AUT1}^{err} $[m]$	W_{AUT1} $[m^2/s^2]$
EGM2008	42.5621	0.0035	64.4393
XGM2016	42.5091	0.0063	63.9198
GOCO05s ^{LSC} (RTM)	42.2413	0.0189	61.2947
GOCO05s ^{LSC} (dv_ell & ERTM)	42.3647	0.0168	62.5043
FFT 1d (1° cap)	42.1410	----------	60.3125
FFT WG (d/o 220)	42.1041	----------	59.9498
Stokes (1.5° cap)	42.1921	----------	60.8124
SBFs (smooth)	42.4528	0.0198	63.3679
SBFs (no smooth)	42.4494	0.0186	63.3346

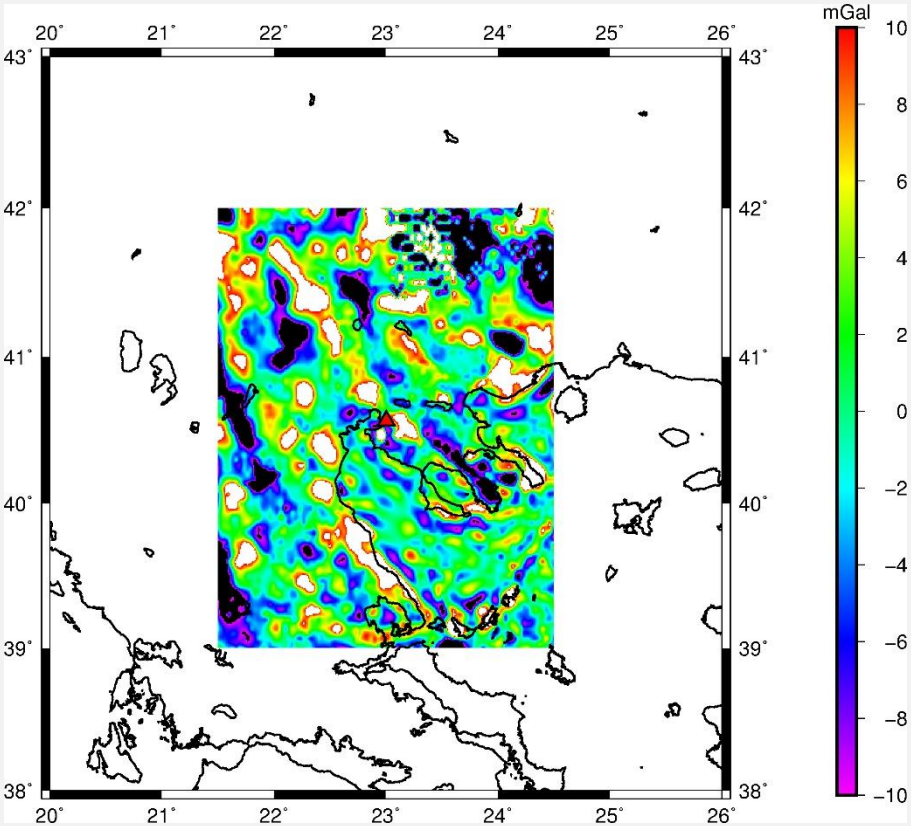
Effect of gridding (splines, krigging, bilinear)

Statistics of the estimated geoid and potential at AUT1

	N_{AUT1} $[m]$	N_{AUT1}^{err} $[m]$	W_{AUT1} $[m^2/s^2]$
GOCO05s ^{LSC} (RTM)	42.2413	0.0189	61.2947
FFT 1d (1° cap)	42.1410	----------	60.3125
FFT WG (d/o 220)	42.1041	----------	59.9498
Stokes (1.5° cap)	42.1921	----------	60.8124
FFT 1d (1° cap)	-0.0029	----------	60.2831
FFT WG (d/o 220)	-0.0200	----------	59.7537
Stokes (1.5° cap)	-0.0261	----------	60.5575
FFT 1d (1° cap)	-0.0259	----------	60.0576
FFT WG (d/o 220)	-0.0240	----------	59.7533
Stokes (1.5° cap)	-0.0590	----------	60.2341

Effect of gridding (splines, krigging, bilinear)





Gravity residuals differences between spline/kringging (left) and spline/bilinear (right). σ_{dif}=1.5 mGal and 8.5 mGal respectively

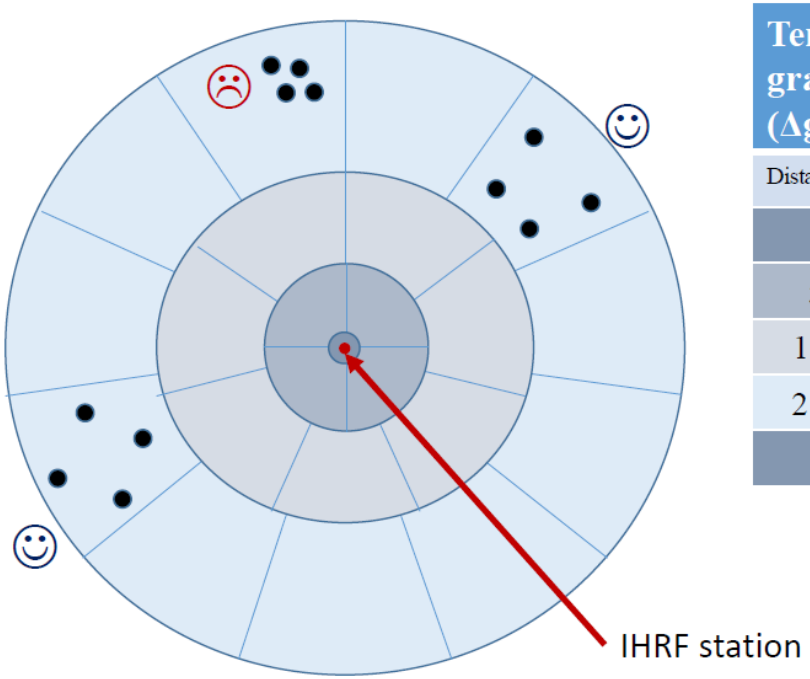
N_{AUT1} & W_{AUT1} modeling

Effect of data distribution and density

Use the GOCO5s LSC-based solution employing all data as reference and then evaluate the impact of data distribution and sampling

Minimum requirements on the terrestrial gravity data

- Gravity points with ±20 µGal accuracy needed to estimate the residual (quasi-)geoid height with ±5 mm uncertainty.
- Uncertainties of GGM and DTM must be added.



Template according to the gravity effect on the geoid ($\Delta g = 1 \cdot 10^{-6}$ ms^{-2} → 1 mm)

Distance	Compartments	# of points	Rounded values
10 km	1	4	5
50 km	4	16	15
110 km	7	28	30
210 km	11	44	45
Sum	23	92	95

See comments at the splinter meeting in the next slide.

Splinter meeting of the WG on Strategy for the IHRS realization
Sept. 21, 2016. GGHS2016, Thessaloniki, Greece

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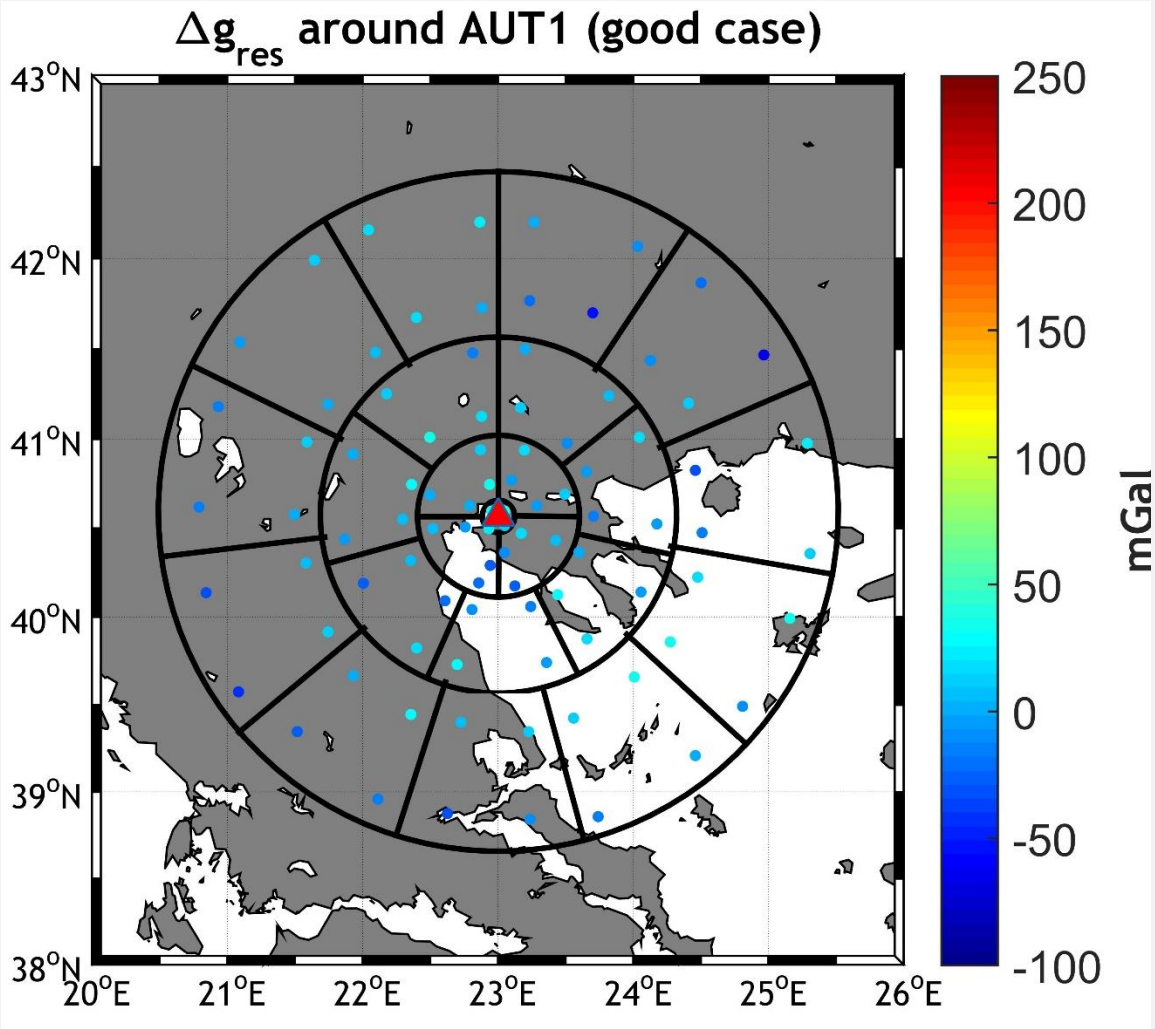
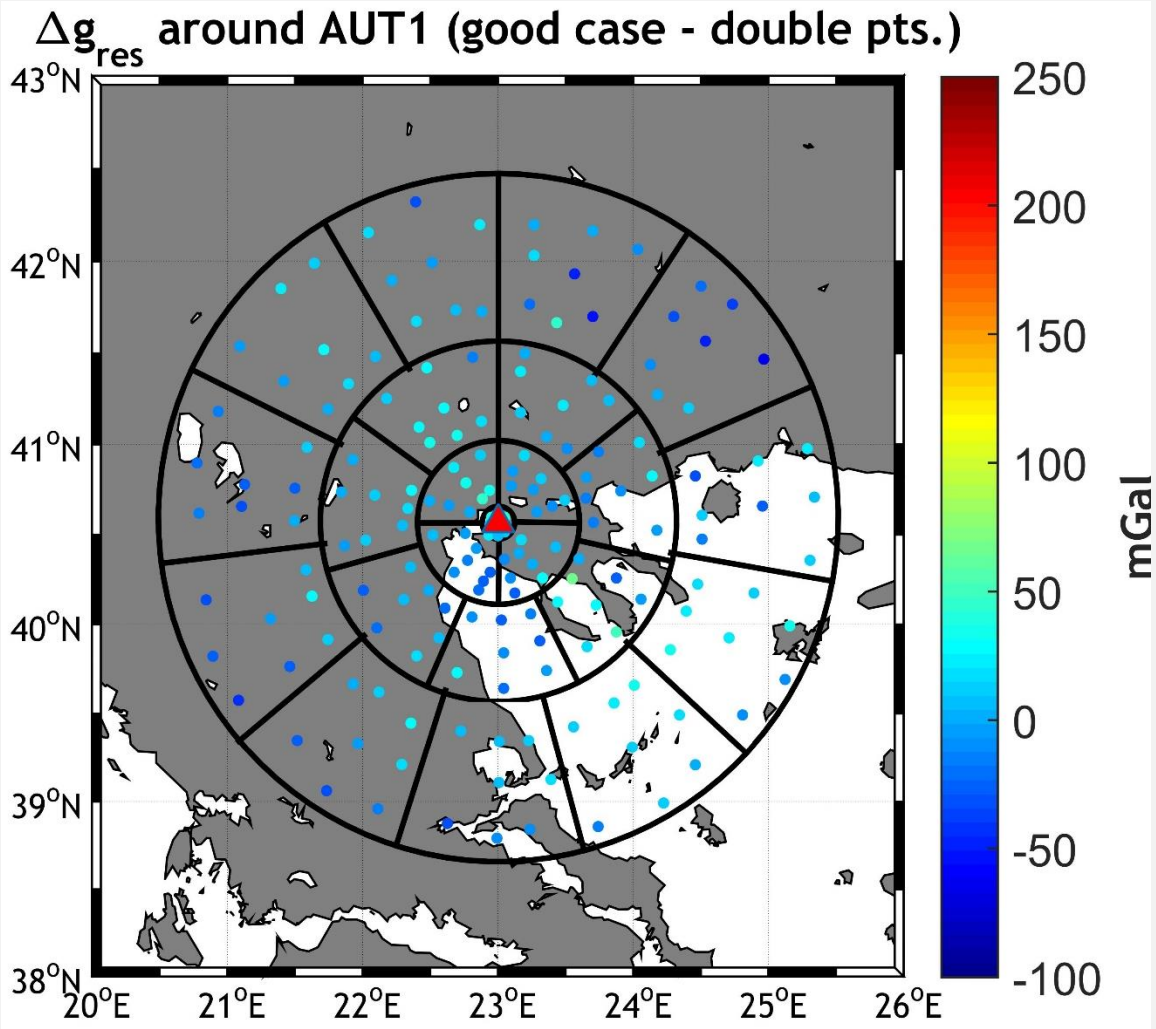
Splinter Meeting IAG JWG0.1.2 GGHS2016 Thessaloniki, Greece (© Sánchez, 2016)

N_{AUT1} & W_{AUT1} modeling



Good distribution as per the JWG0.1.2 recommendation

N_{AUT1} & W_{AUT1} modeling



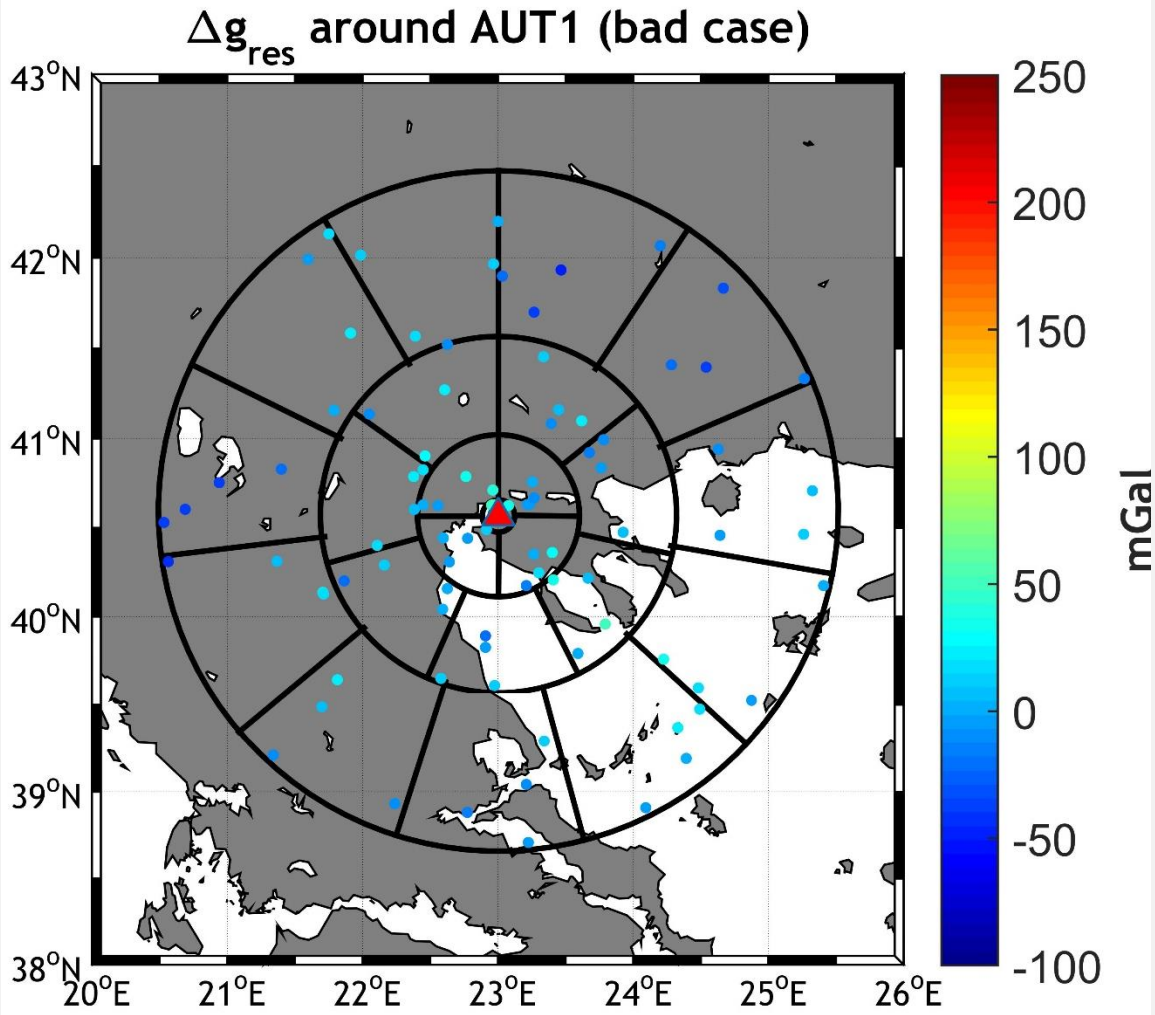
Good distribution as per the JWG0.1.2 recommendation (x2)

N_{AUT1} & W_{AUT1} modeling

Statistics of the estimated geoid and potential at AUT1

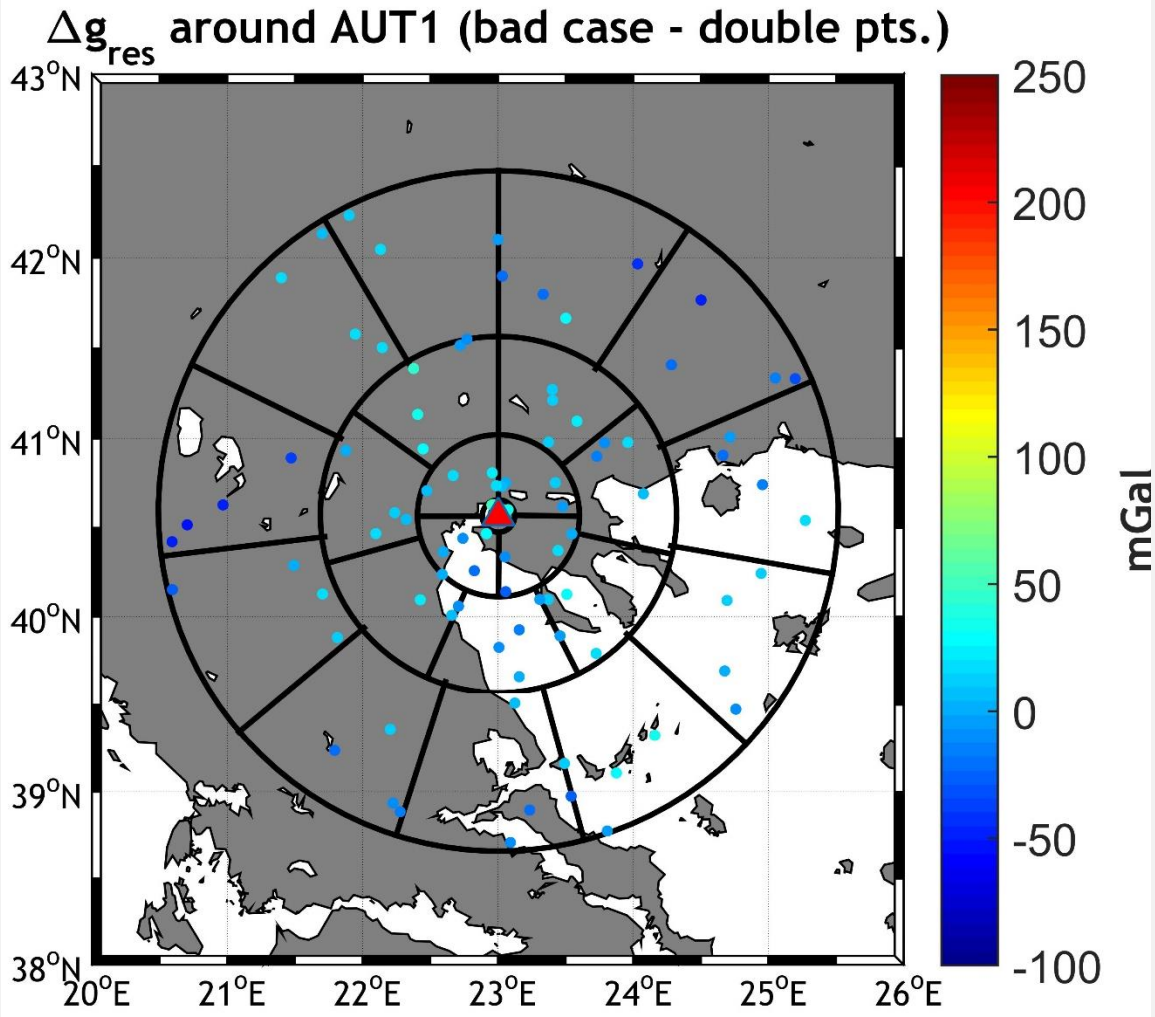
	N_{AUT1} $[m]$	N_{AUT1}^{err} $[m]$	W_{AUT1} $[m^2/s^2]$
GOCO05s ^{LSC} (RTM)	42.2413	0.0189	61.2947
Select data	42.0292	0.1053	59.2156
Select data (x2)	42.0425	0.0769	59.3460
Spline interp.	42.0798	0.1020	59.7116
Spline interp. (x2)	42.0890	0.0759	59.8018
Bilinear interp.	42.0767	0.1052	59.6812
Bilinear interp. (x2)	42.0806	0.0760	59.7194

N_{AUT1} & W_{AUT1} modeling



Bad distribution contrary to the JWG0.1.2 recommendation

N_{AUT1} & W_{AUT1} modeling



Bad distribution contrary to the JWG0.1.2 recommendation (x2)

N_{AUT1} & W_{AUT1} modeling

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Bilinear interp.	42.0767	0.1052	59.6812
Bilinear interp. (x2)	42.0806	0.0760	59.7194
~~Random~~	~~42.1258~~	~~0.1399~~	~~60.1625~~
~~Random (x2)~~	~~42.1273~~	~~0.1174~~	~~60.1772~~

N_{AUT1} & W_{AUT1} modeling

Effect of data distribution and density

Use the GOCO5s LSC-based solution employing all data as reference and then evaluate the impact of data distribution and sampling

But use RTM from dv_ell2016 and ERTM2016

N_{AUT1} & W_{AUT1} modeling

Statistics of the estimated geoid and potential at AUT1

	N_{AUT1} $[m]$	N^{err}_{AUT1} $[m]$	W_{AUT1} $[m^2/s^2]$
GOCO05s ^{LSC} (RTM)	42.2413	0.0189	61.2947
GOCO05s ^{LSC} (dv_ell & ERTM)	42.3647	0.0168	62.5043
Select data	42.3433	0.1053	62.2945
Select data (x2)	42.3174	0.0769	62.0406
Spline interp.	42.3979	0.1020	62.8297
Spline interp. (x2)	42.3650	0.0759	62.5072
Bilinear interp.	42.3984	0.1052	62.8346
Bilinear interp. (x2)	42.3226	0.0760	62.0916
Random	42.3413	0.1399	62.2749
Random (x2)	42.3157	0.1174	62.0240

N_{AUT1} & W_{AUT1} modeling

Prediction accuracy w.r.t. the observed gravity @AUT1

GOCO05s^{LSC} (RTM)	$\varepsilon_{AUT1}^{\Delta g} = 0.8815\ mGal$
GOCO05s^{LSC} (dv_ell&ERTM)	$\varepsilon_{AUT1}^{\Delta g} = 0.2839\ mGal$
GOCO05s^{LSC} (dv_ell&ERTM - JWG)	$\varepsilon_{AUT1}^{\Delta g} = 2.043\ mGal$
GOCO05s^{LSC} (dv_ell&ERTM – JWGx2)	$\varepsilon_{AUT1}^{\Delta g} = 1.1303\ mGal$
EGM2008 ^{LSC} (RTM)	$\varepsilon_{AUT1}^{\Delta g} = 1.7961\ mGal$
XGM2016^{LSC} (RTM)	$\varepsilon_{AUT1}^{\Delta g} = 0.5719\ mGal$
SBFS (smooth)	$\varepsilon_{AUT1}^{\Delta g} = 0.7711\ mGal$

N_{AUT1} & W_{AUT1} modeling

The final, recommended, potential of the AUT1 IHRF station, using LSC, all data and dv_ell&ERTM

$$N_{AUT1} = 42.3647 \pm 0.0168\, m$$

$$W_{AUT1} = 62636862.5043 \pm 0.0017\ {}^{m^2}/_{s^2}$$

with spline interpolation and 2x the points

$$N_{AUT1} = 42.3650 \pm 0.0759\, m$$

$$W_{AUT1} = 62636862.5072 \pm 0.0076\ {}^{m^2}/_{s^2}$$

N_{AUT1} & W_{AUT1} modeling

The final, recommended, potential of the AUT1 IHRF station, using LSC, all data and dv_ell&ERTM (WGS84 & TF)

$$N_{AUT1} = 42.3647 \pm 0.0168\, m$$

$$W_{AUT1} = 62636862.5043 \pm 0.0017\ {}^{m^2}/_{s^2}$$

To GRS80 and MT

$$N_{AUT1}^{GRS80\ MT} = 41.3987 \pm 0.0168\, m$$

$$W_{AUT1}^{GRS80\ MT} = 62636853.0347 \pm 0.0017\ {}^{m^2}/_{s^2}$$

N_{AUT1} & W_{AUT1} modeling

The final, recommended, potential of the AUT1 IHRF station, using LSC, all data and dv_ell&ERTM (WGS84 & TF)

$$N_{AUT1} = 42.3647 \pm 0.0168\, m$$

$$W_{AUT1} = 62636862.5043 \pm 0.0017\ {}^{m^2}/_{s^2}$$

To GRS80 and MT

$$N_{AUT1}^{GRS80\ MT} = 41.3987 \pm 0.0168\, m$$

$$W_{AUT1}^{GRS80\ MT} = 62636853.0347 \pm 0.0017\ {}^{m^2}/_{s^2}$$

To GRS80 ZT

$$N_{AUT1}^{GRS80\ ZT} = 41.4248 \pm 0.0168\, m$$

$$W_{AUT1}^{GRS80\ MT} = 62636853.2914 \pm 0.0017\ {}^{m^2}/_{s^2}$$

CONCLUSIONS

- The use of a satellite only model and then (classic) RTM is not sufficient, given the problems (still) in bathymetry.
- Using dv_ell2016 coupled by ERTM2016 (scales up to 200 m) seems promising.
- It provides the most consistent results with errors up to 5 cm in the geoid prediction, irrespective of the data distribution.
- If interpolation/gridding is needed, then splines are to be preferred.
- Other modifications of Stokes kernel need to be checked as well as the GBVP approach

Sincere thanks to (誠にありがとう):

- Verena Lieb and Michael Schmidt for the SBFs computations
- Christian Hirt and Martin Willberg for the discussions on the evaluation of RTM through dv_ell2016 and ERTM2016
- Roland Pail and Thomas Gruber for the XGM2016 coefficients