EIGEN-6C4
The latest combined global gravity field model including GOCE data up to degree and order 2190 of GFZ Potsdam and GRGS Toulouse

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Introduction

- GFZ Potsdam and GRGS/CNES Toulouse have a long-time close cooperation in the field of global gravity field determination which presently focuses among others on:
  - GOCE gravity field determination ("Direct Approach"): behalf of ESA and in the framework of the GOCE High Level Processing Facility" (GOCE-HPF), the latest release is **GO_CONS_GCF_2_DIR_R5** (Bruinsma et al. 2014)
  - Computation of high resolution global gravity field models incl. GOCE SGG data:

    EIGEN*-6C (2011, Shako et al. 2013, max. d/o 1420)
    EIGEN-6C2 (2012, Förste et al. 2012, max. d/o 1949)
    EIGEN-6C3 (2013, Förste et al. 2013, max d/o 1949), was taken as basis for the new Canadian Hight Reference System: **Canadian Gravimetric Geoid CGG2013**

- Subject of this presentation: **EIGEN-6C4** (max d/o 2190), the latest release of the EIGEN-6C-Series, containing the complete SGG data of the GOCE-Mission

* EIGEN = "European Improved Gravity model of the Earth by New techniques"

Data used for EIGEN-6C4

LAGEOS-1/2 SLR data:

1985 – 2010 of GRGS release 2 normal equations to degree/order 30

GRACE GPS-SST and K-band range-rate data:

Feb 2003 – Dec 2012 of GRGS release 3 normal equations to degree 175

GOCE data:

- **SGG data (Txx, Tyy, Tzz, Txz) from 01 November 2009 – 20 October 2013**
- **weighting per measurement (based on RMS of residual), cos-latitude weighting**
- **individual normal equations for each SGG component (4) up to degree/order 300**
- **application of a (120 – 8) s band-pass filter for all four SGG components**

Surface data:

DTU 2'x2' global gravity anomaly grid (Anderson, 2010)

= altrimetry over the oceans, EGM2008 (Pavlis et al. 2012) over continents

Block diagonal solution for degrees 371-2190

The combination of the different satellite and surface parts is done by a band-limited combination of normal equations, as a function of their resolution and accuracy (c.f. Förste et al. 2008**).**

Combination scheme of the normal equations for EIGEN-6C4

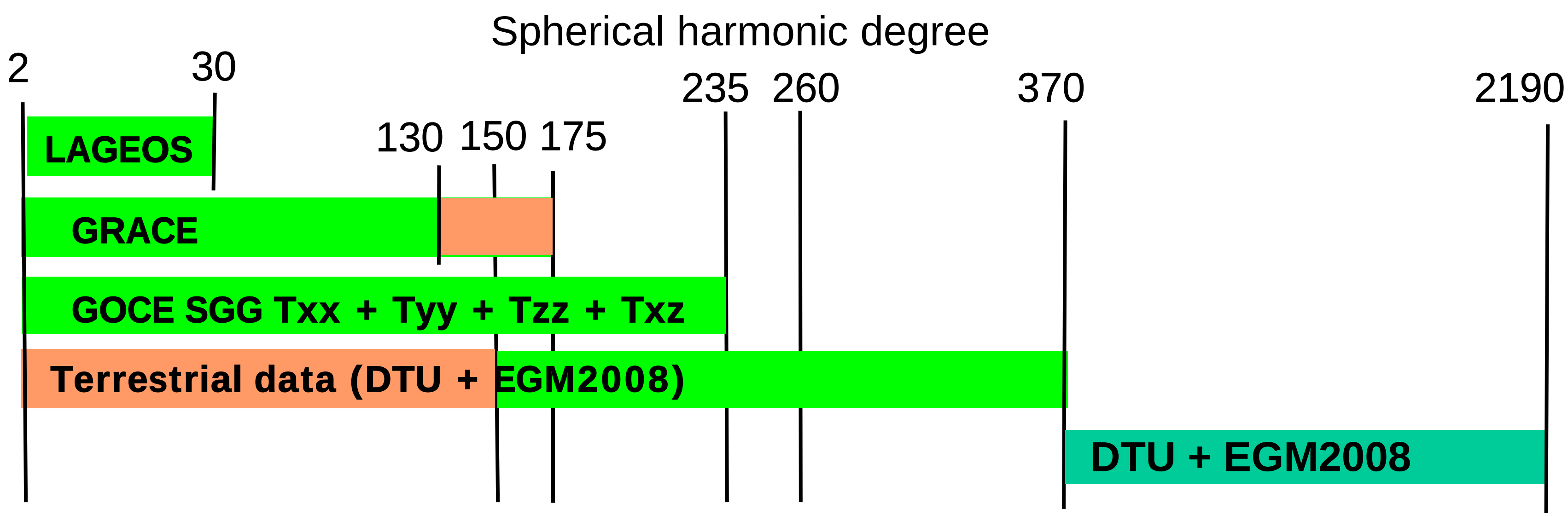
Accumulation of a full normal matrix up to d/o 370:

~200.000 parameters, ~ 250 GByte

contribution to the solution EIGEN-6C4:

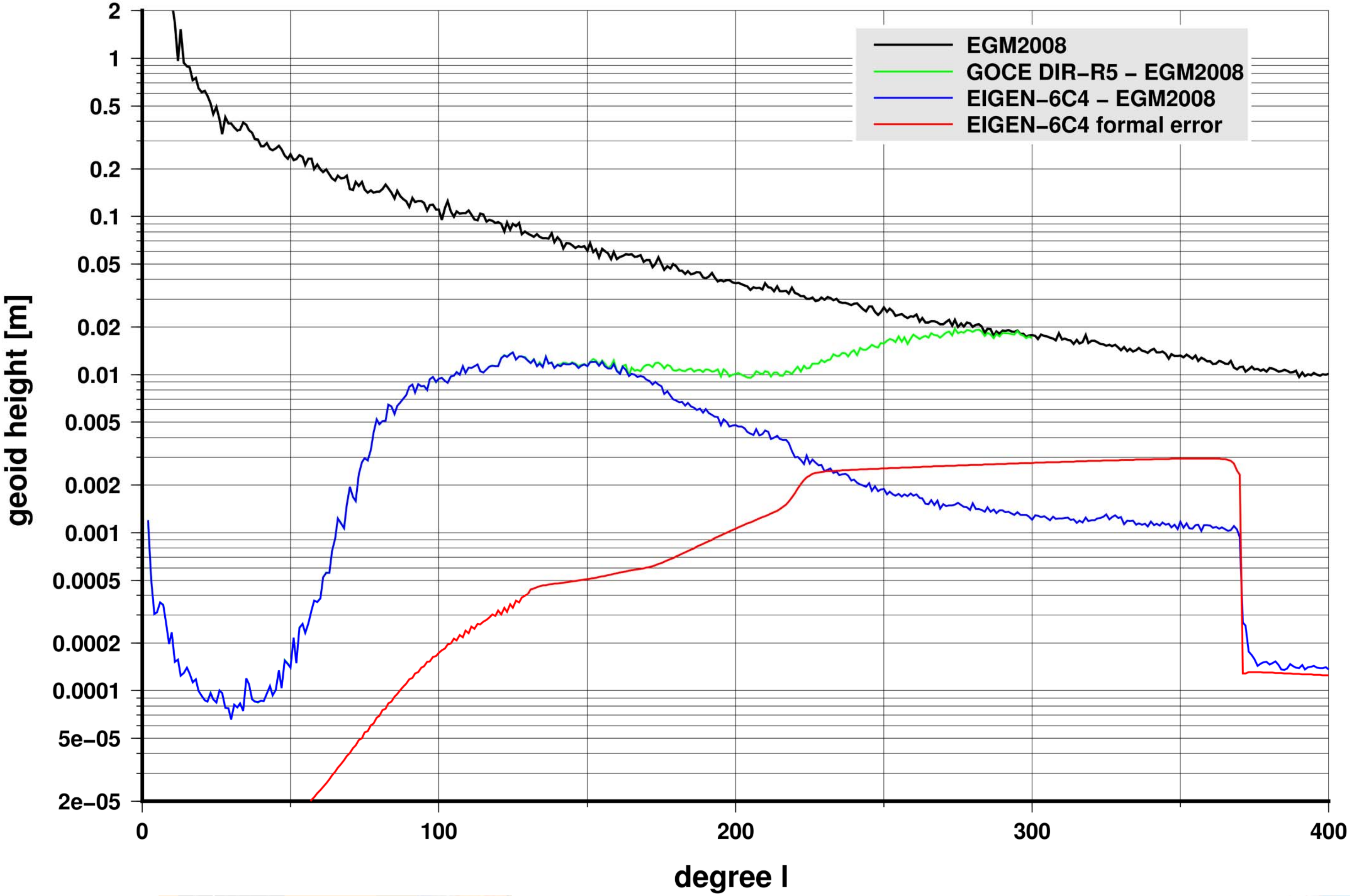
elminated beforehand (block matrix reduction):

Separate block diagonal solution:

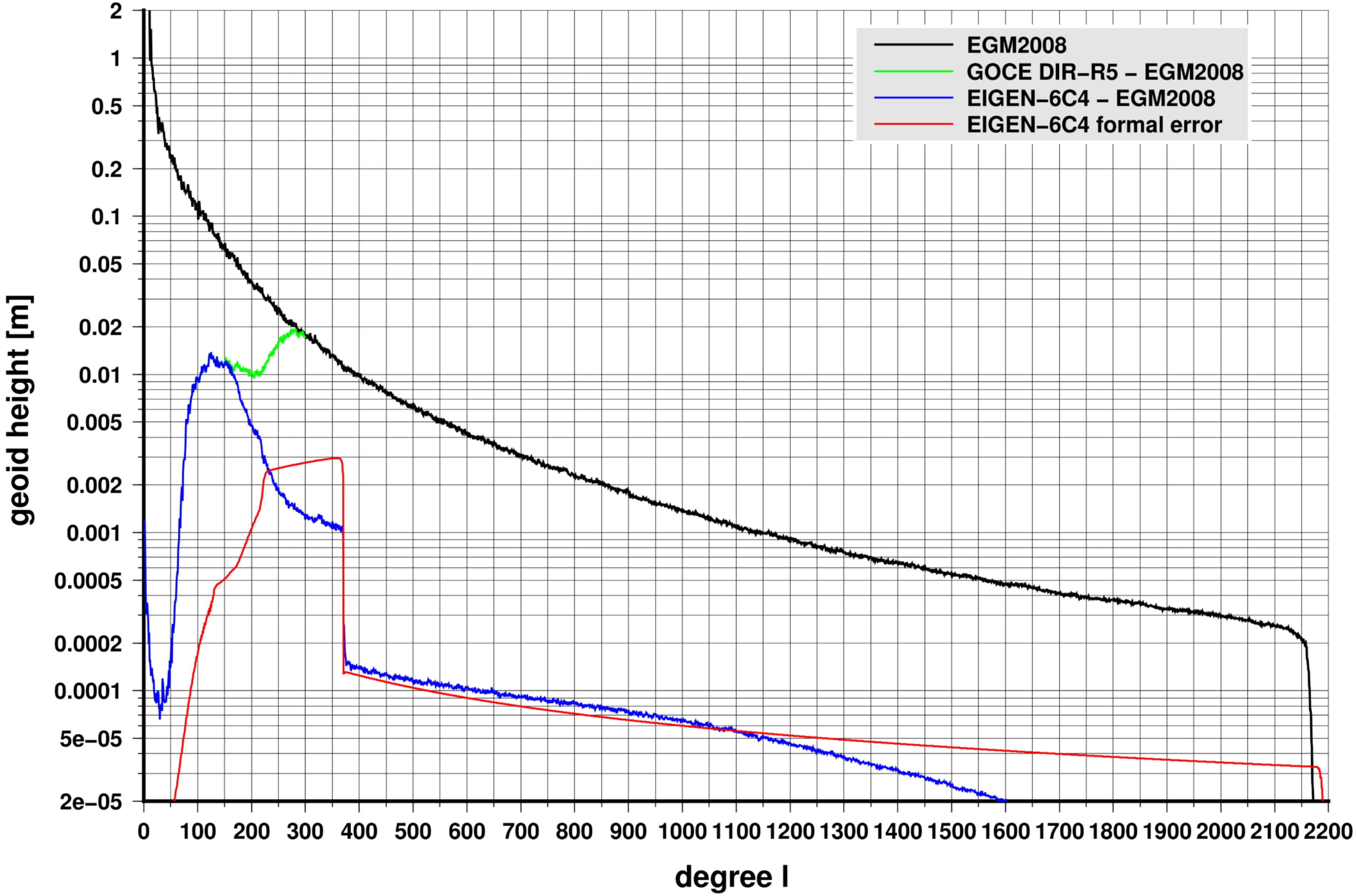


EIGEN-6C4 – Spectral behaviour

Spectral evaluation – difference degree amplitudes to EGM2008 (1)



Spectral evaluation – difference degree amplitudes to EGM2008 (2)



Helmholtz Centre Potsdam

Christian-Albrechts-Universität zu Kiel

GRGS

EIGEN-6C4 – Evaluation

GPS/Levelling test with EIGEN-6C4

Comparison with geoid heights determined point-wise by GPS positioning and levelling:

- Root mean square (**cm**) about mean of GPS-Levelling minus model-derived geoid heights (number of points in brackets).

GPS/Leveling fit in cm up to d/o 2190

	EGM2008	EIGEN-6C4
Europe (1234)	20.7	20.9
Germany (675)	4.3	4.8
Canada (1930)	12.6	12.4
USA (6169)	24.6	24.5
Australia (201)	21.5	21.1
Japan (816)	8.2	7.8
Brasil (672)	36.6	30.6

Sources/References for the used GPS/Lev data:

- **USA**: (Milbert, 1998)
- **Canada:** (M. Véronneau, personal communication 2003, Natural Resources Canada)
- **Europe/Germany:** (Ihde et al., 2002)
- **Australia:** (G. Johnston, Geoscience Australia and W. Featherstone, Curtin University of Technology, personal communication 2007)
- **Japan**: (Tokuro Kodama, Geospatial Information Authority of Japan, personal communication 2013)
- **Brazil**: Denizar Blitzkow and Ana Cristina Oliveira Cancoro de Matos, Centro de Estudos de Geodesia (CENEGEO), personal communication, the data belongs to the Brazilian Institute of Geography and Statistics (IBGE)

GOCE and CHAMP Orbit adjustment tests

- Observations: Kinematic GOCE (Bock et al. 2011) and CHAMP (Prange et al. 2010) orbit positions
- Dynamic orbit computation
- **GOCE: 60 arcs** (01.11. – 31.12.2009), Arclength = **1.25 days**
- **CHAMP: 75 arcs** (01.02. – 01.05.2008), Arclength = **1.0 day**
- Parametrization for GOCE (this is similar for CHAMP):
  - Accelerometer **biases**: 2/rev for cross track / radial / along track
  - Accelerometer **scaling factor**: along track fixed (set to 1.0), 1/arc for cross track / radial

Rms values [cm] of the orbit fit residuals (mean values for the 75/60 arcs)

Gravity Field Model	GOCE Max d/o 180 x 180	CHAMP Max d/o 150 x 150
EGM2008 (Pavlis et al. 2012)	2.79	2.68
GIF48 (Ries et al. 2011)	1.64	2.52
GOCO03S (Mayer-Gürr et al. 2012)	1.64	2.55
GO_CONS_GCF_2_DIR_R3	1.60	2.50
GO_CONS_GCF_2_DIR_R4 (Bruinsma et al. 2013)	1.58	2.50
GO_CONS_GCF_2_TIM_R4	1.52	8.84
GO_CONS_GCF_2_TIM_R5 (Brockmann et al. 2014)	1.52	7.18
GO_CONS_GCF_2_DIR_R5 (Bruinsma et al. 2014)	1.51	2.50
EIGEN-6C3stat	1.55	2.50
EIGEN-6C4	1.50	2.50

- **EIGEN-6C4 gives the best orbit fits for GOCE**
- **The best CHAMP orbit fits for EIGEN-6C4, EIGEN-6C3 and the three GOCE models of the Direct Approach**
- **Worse CHAMP orbit fit results for the timewise models due to the GOCE polar gaps**
  → the TIM-models are not good for orbit computations in general

EIGEN-6C4

Comparison with GEOHALO Airborne Gravimetry

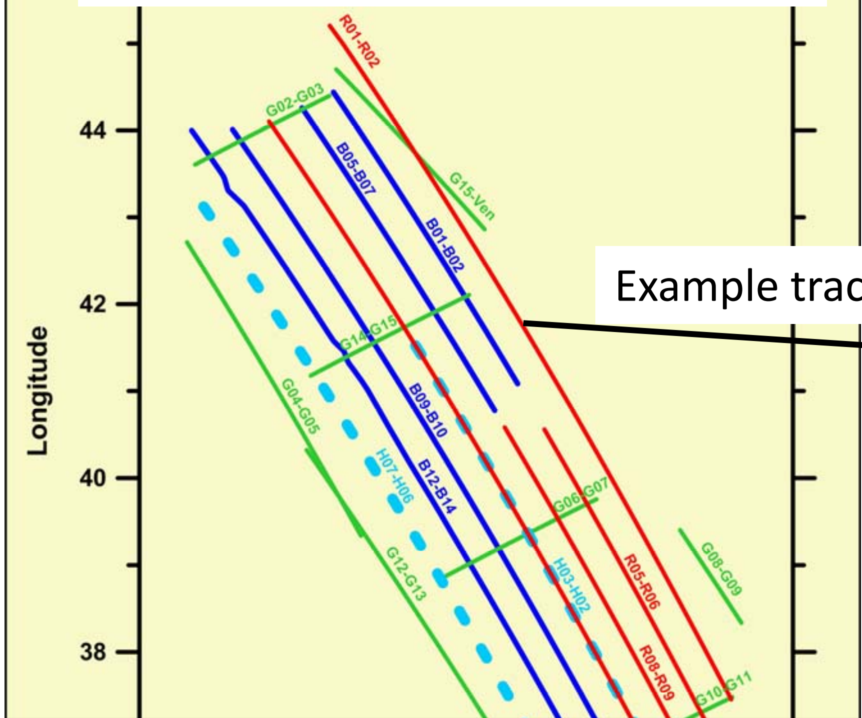
HALO – the German High Altitude and LOng Range Research Aircraft (HALO).

GEOHALO –
Multidisciplinary geoscientific airborne mission on the HALO aircraft over Italy
June 2012

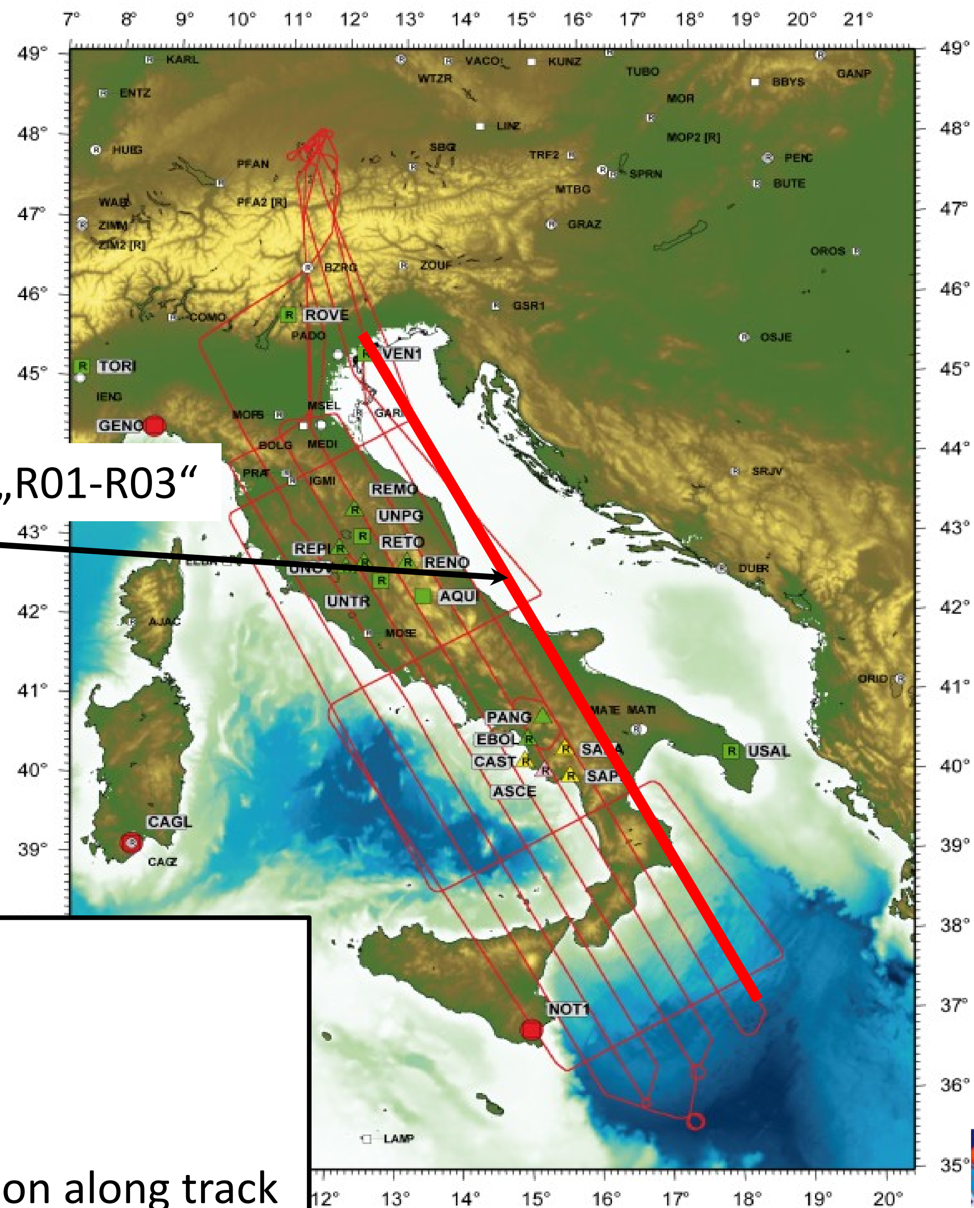
GFZ‘s airborne gravimeter on HALO:
CHEKAN - AM

The GEOHALO flight tracks over Italy (June 2012)

The GEOHALO flight tracks where gravimetry has been processed



Example track „R01-R03“



GEOHALO flight characteristics

Flight altitude: 3500 m

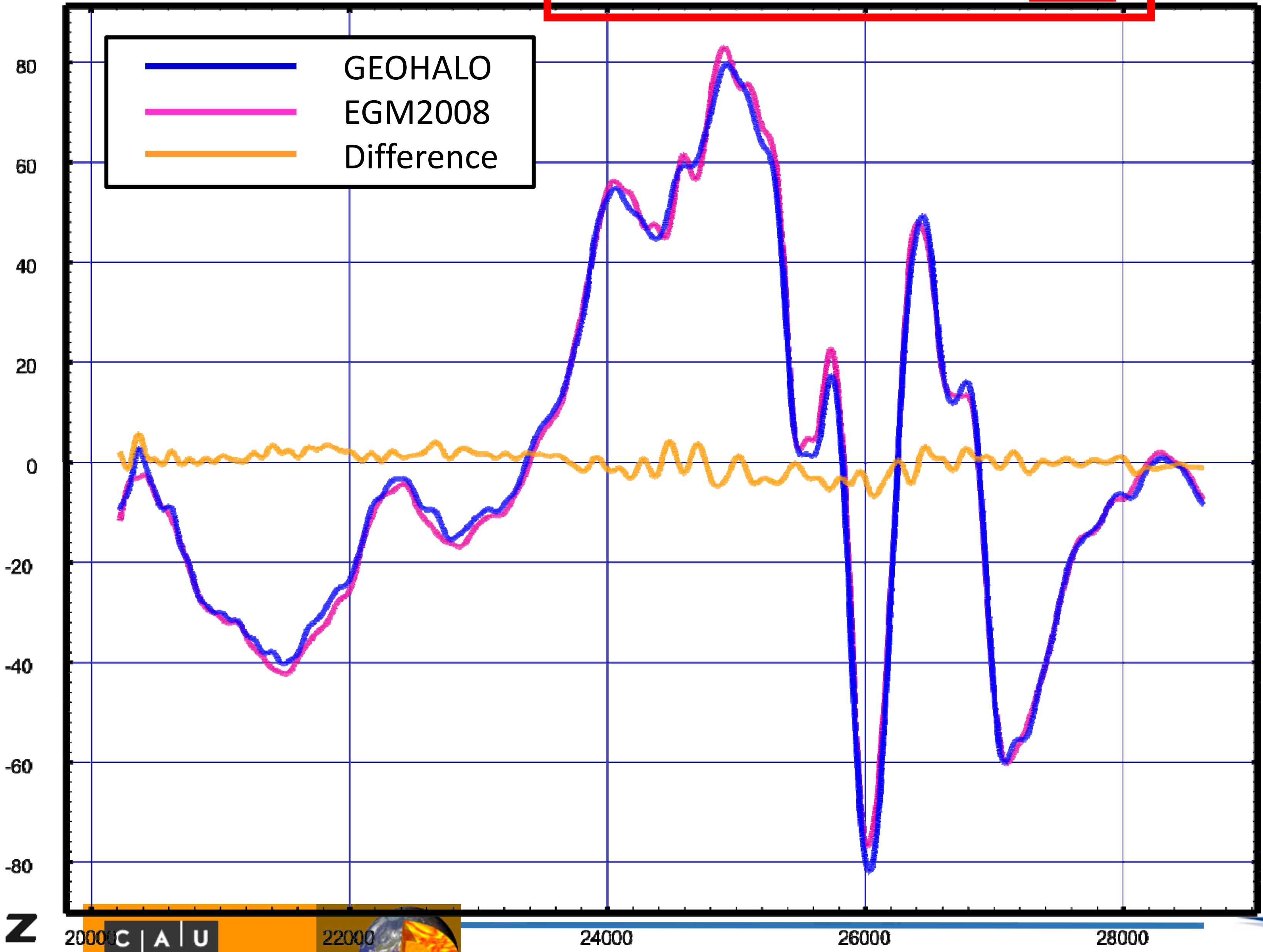
Speed: 120 m/s (425 km/h)

Application of a low-pass filter:

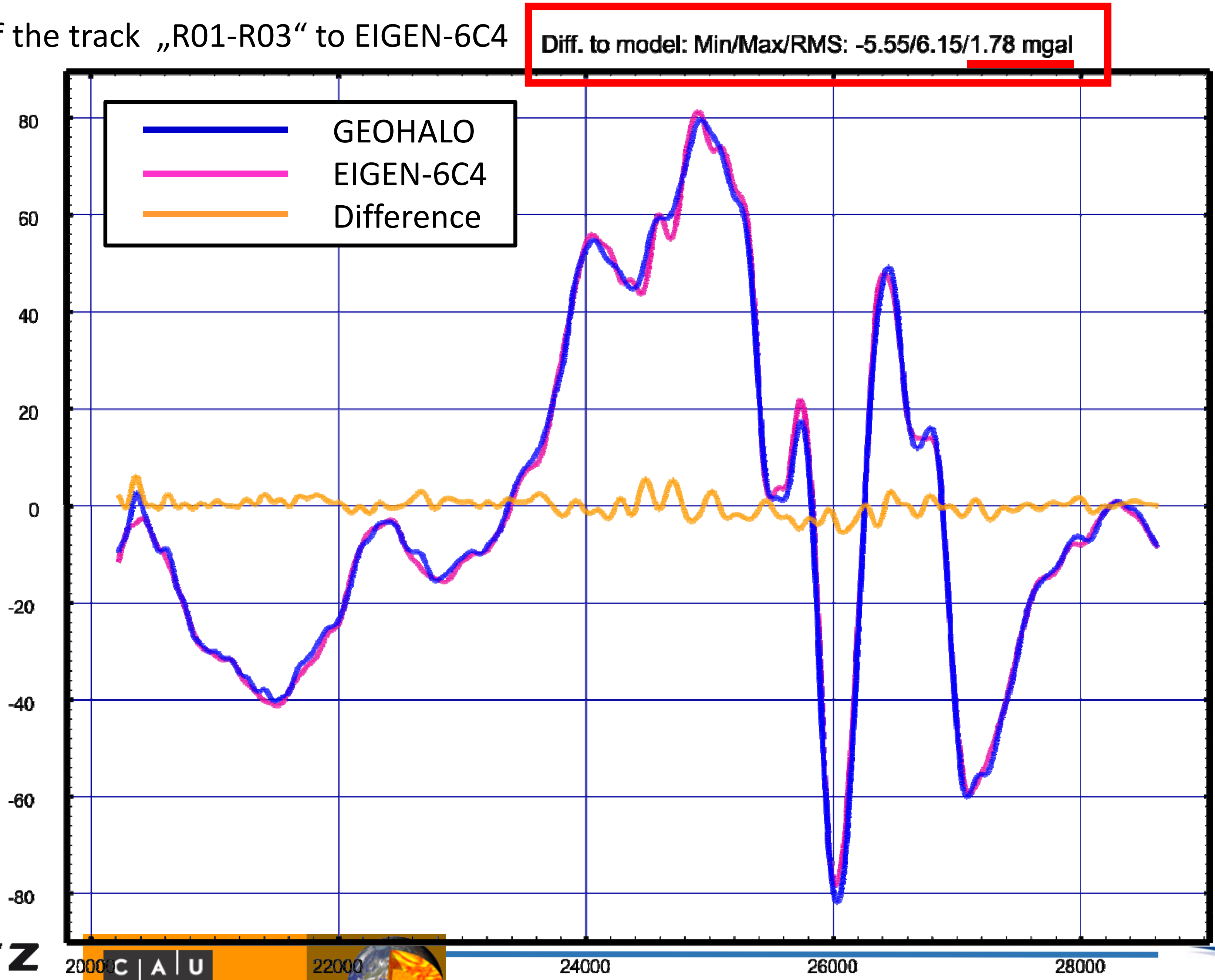
cut-off period 260s → ~15 km spatial resolution along track

Fit of the track „R01-R03“ to EGM2008

Diff. to model: Min/Max/RMS: -6.80/5.75/2.13 mgal



Fit of the track „R01-R03“ to EIGEN-6C4



Statistics (mGal) of all GEOHALO airborne gravimetry tracks:

Fit of the measured gravity at flight altitude
to EGM2008 and EIGEN-6C4

Profile	#obs	Track length[km]	Min	Max	RMS	Min	Max	RMS
			---- eigen-6c4 ----			----- egm2008 -----		
G04-G05	3001	360	-4.54	3.33	**1.54**	-3.00	3.98	1.32
G06-G07	2101	250	-7.32	3.09	1.83	-7.58	3.01	1.97
G08-G09	1081	130	-6.47	4.13	1.63	-6.53	4.10	1.59
G10-G11	1921	230	-2.35	3.99	1.14	-3.20	3.06	1.06
G12-G13	3421	410	-4.31	8.76	1.98	-5.09	8.15	1.98
G14-G15	1981	240	-6.71	5.98	2.65	-7.22	5.52	2.66
G15-Ven	2101	250	-6.08	5.76	2.03	-7.17	5.83	2.11
R01-R03	8401	1010	-5.55	6.15	1.78	-6.80	5.75	2.13
R05-R06	3901	468	-12.61	8.85	2.82	-14.78	7.63	2.72
R08-R09	3961	470	-6.78	7.61	2.69	-7.02	7.08	2.63
B01-B03	4201	504	-9.96	13.72	3.24	-11.43	11.09	3.39
B09-B10	5101	612	-7.17	11.82	2.82	-6.24	11.80	2.67
B12-B14a	5161	619	-11.81	11.32	2.96	-12.99	9.68	3.09
B12-B14b	1201	144	-8.23	8.94	3.71	-7.93	9.76	3.81
H07-H06	6661	800	-13.52	9.68	2.73	-14.84	8.38	2.77
H03-H02	4681	562	-9.82	8.66	2.48	-9.24	8.81	2.57
Overall RMS (58876 points/7065 km):					**2.50**			**2.55**

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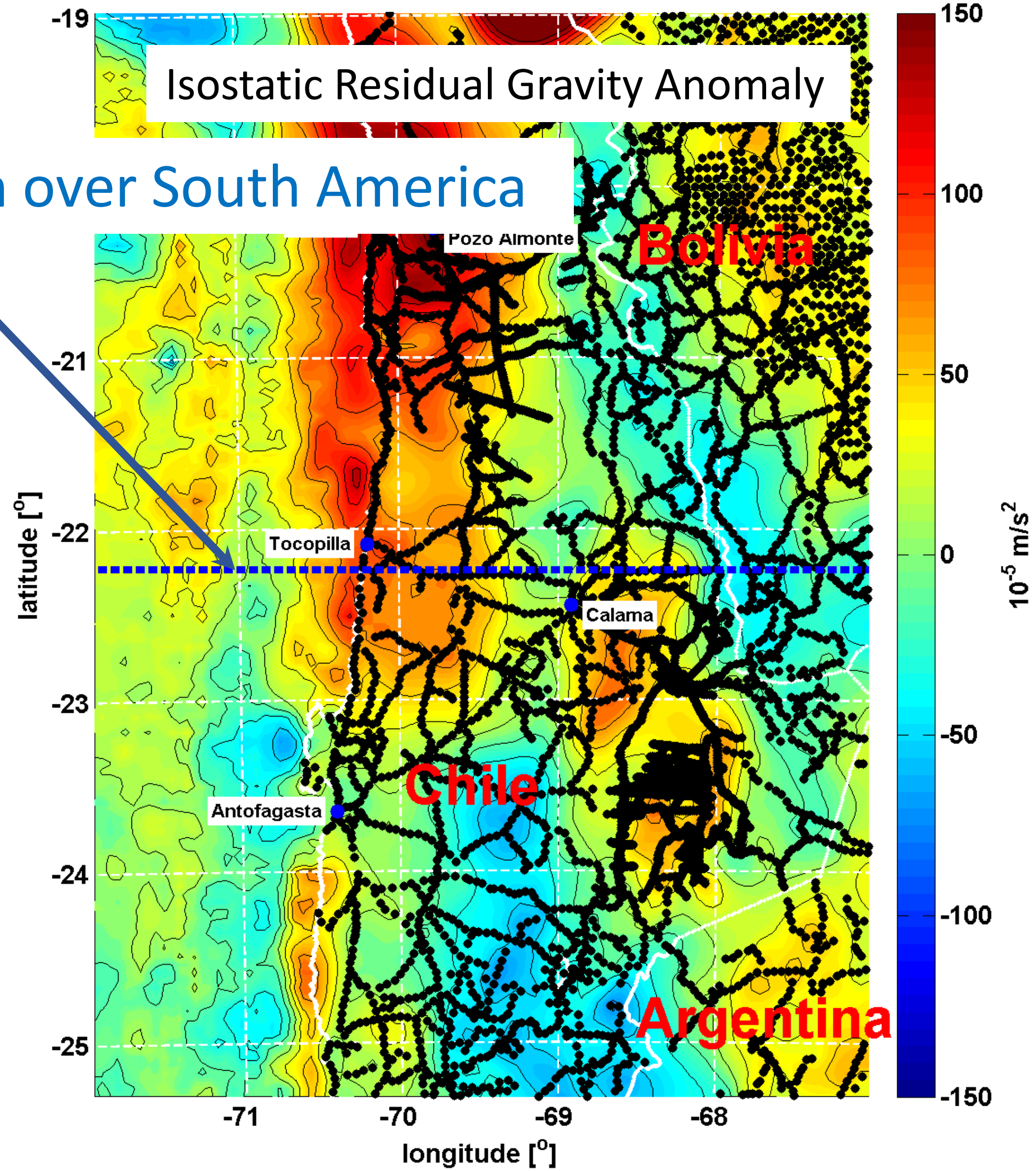
EIGEN-6C4
Application in 3D density modelling

Application of EIGEN-6C4 in density modelling for the Earth‘s crust and mantle

3D-Density modelling over South America

Example: Profile at 22.2° South over South America



Input Gravity Data:

- Terrestrial Gravimetry (black dots, Götze et al. 1988 - 2006)
- Satellite Altimetry (Anderson & Knudsen 1998))

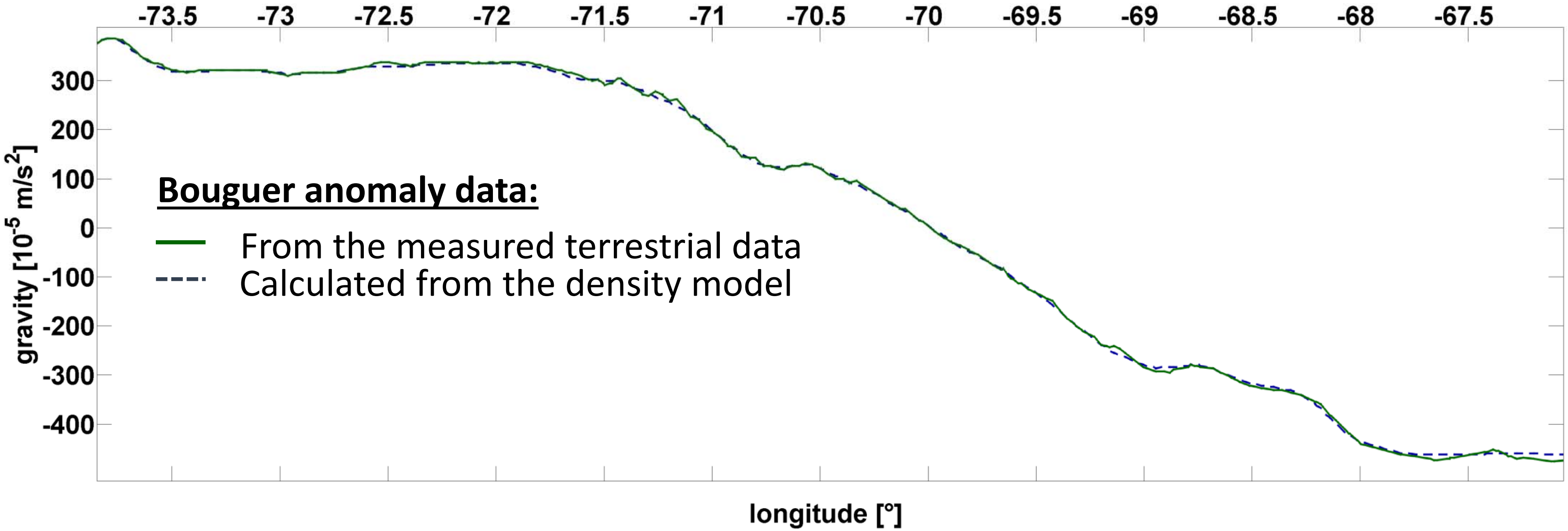
Constraining Data:

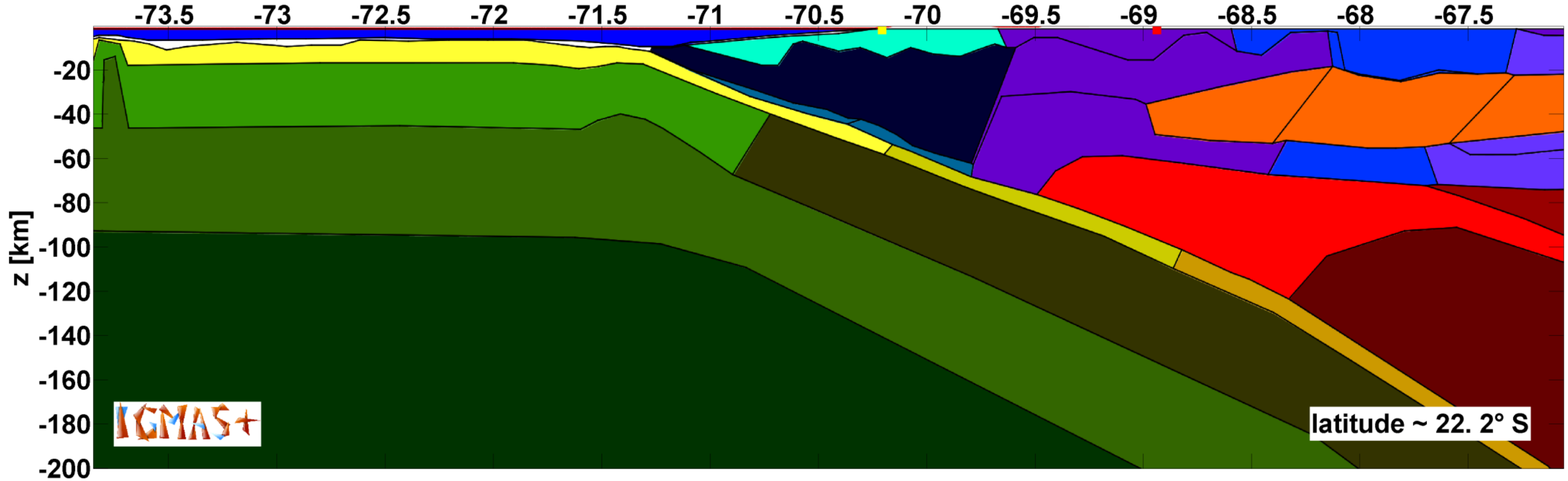
- Magnetotelluric
- Seismic (refraction & reflexion)
- Earthquake hypocentres
- Heat flow data
- Geological information

Modelling Software:

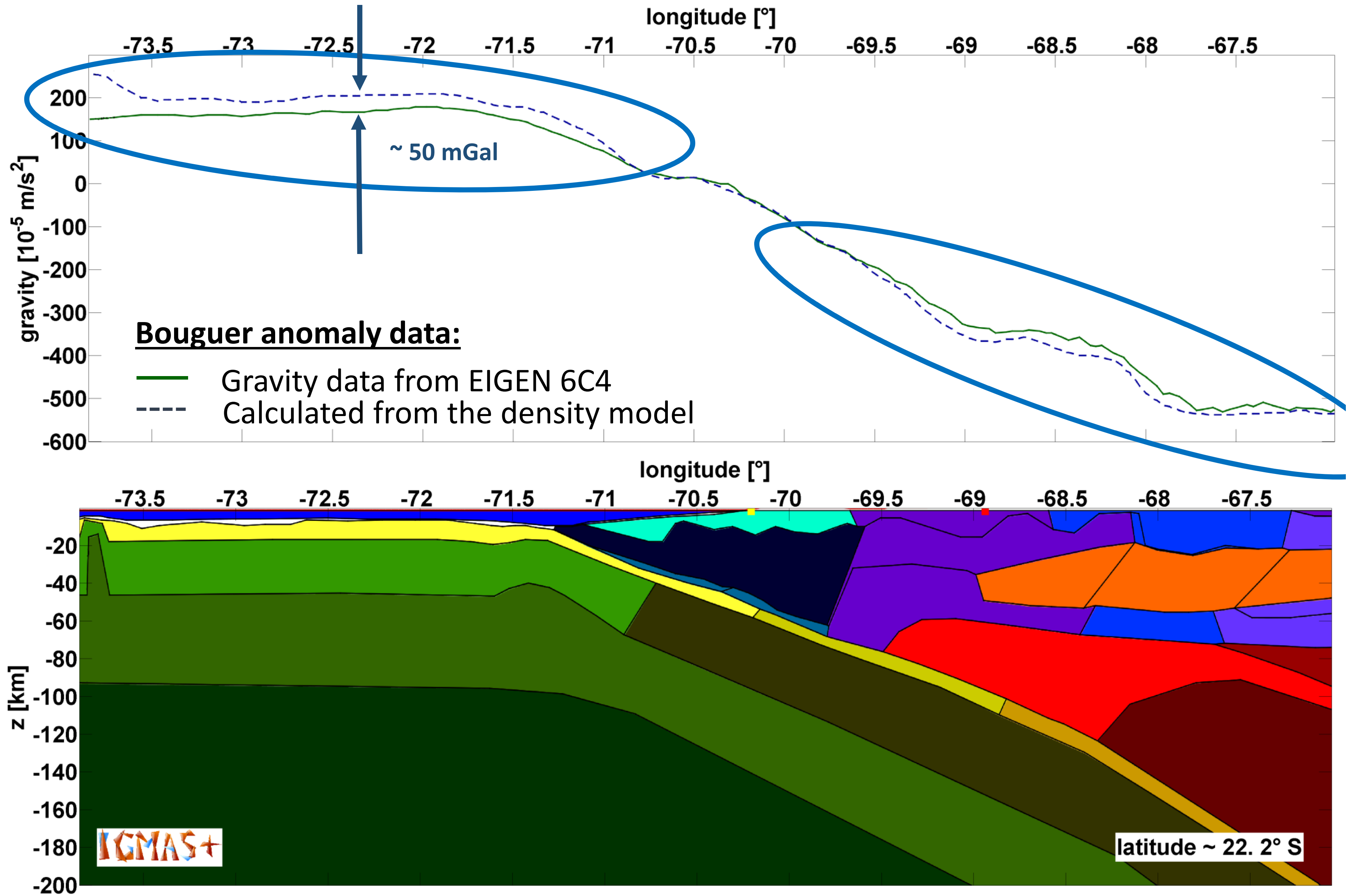
- IGMAS+ (Schmidt & Götze Univ. Kiel together with Transinsight Dresden)

Previous density model from terrestrial data (Schaller, 2013; Diploma thesis)

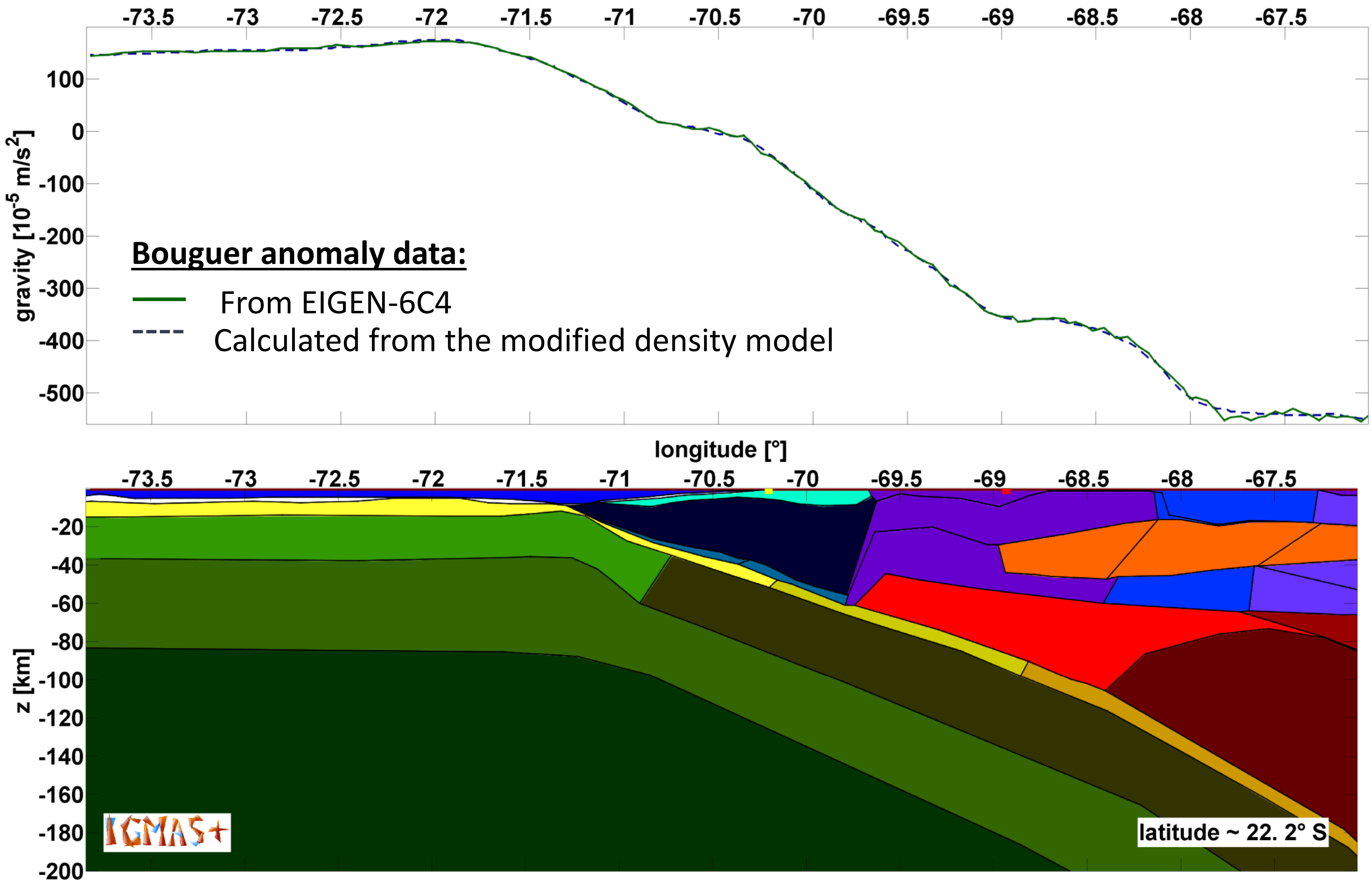




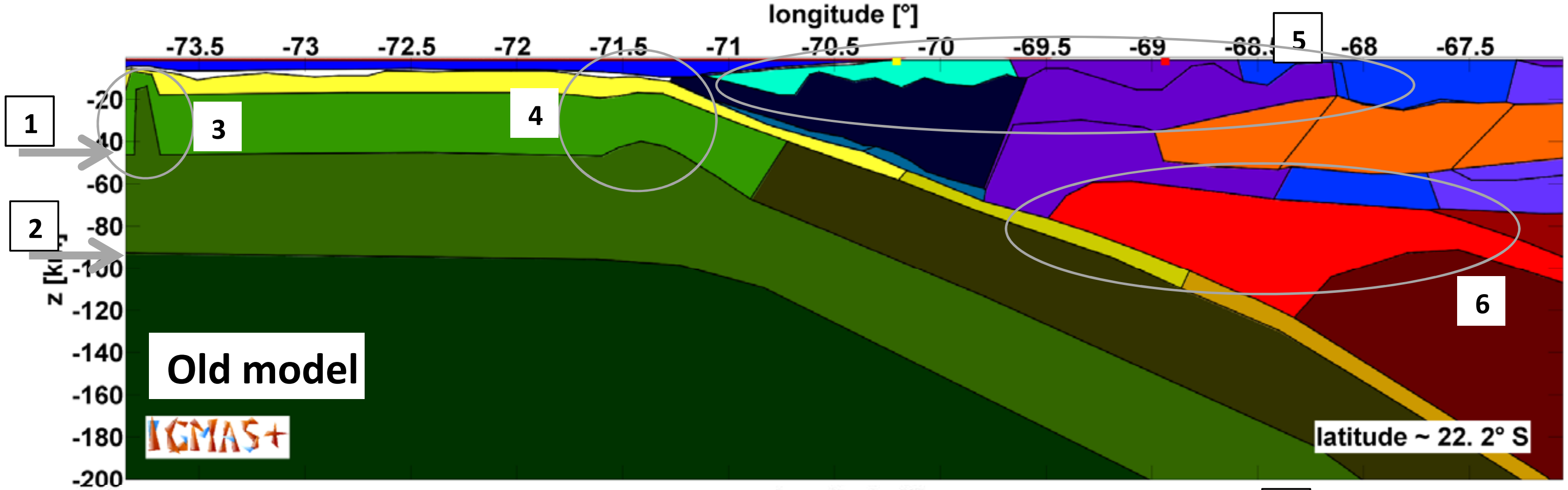
Previous density model – Gravity calculated for EIGEN-6C4 data

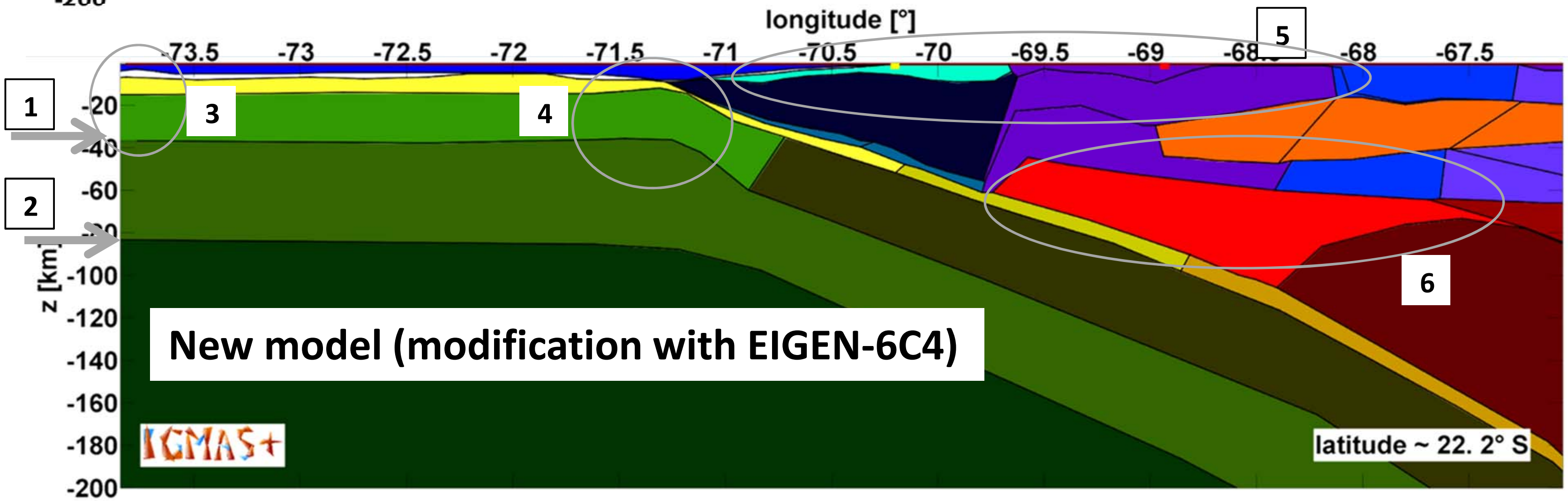


Modified density model fitted to EIGEN-6C4



Comparison: Previous and modified density models





Modifications:

1 Depth of the boundary between upper and lower oceanic mantle lithosphere

2 Depth of the boundary between oceanic mantle lithosphere and asthenosphere

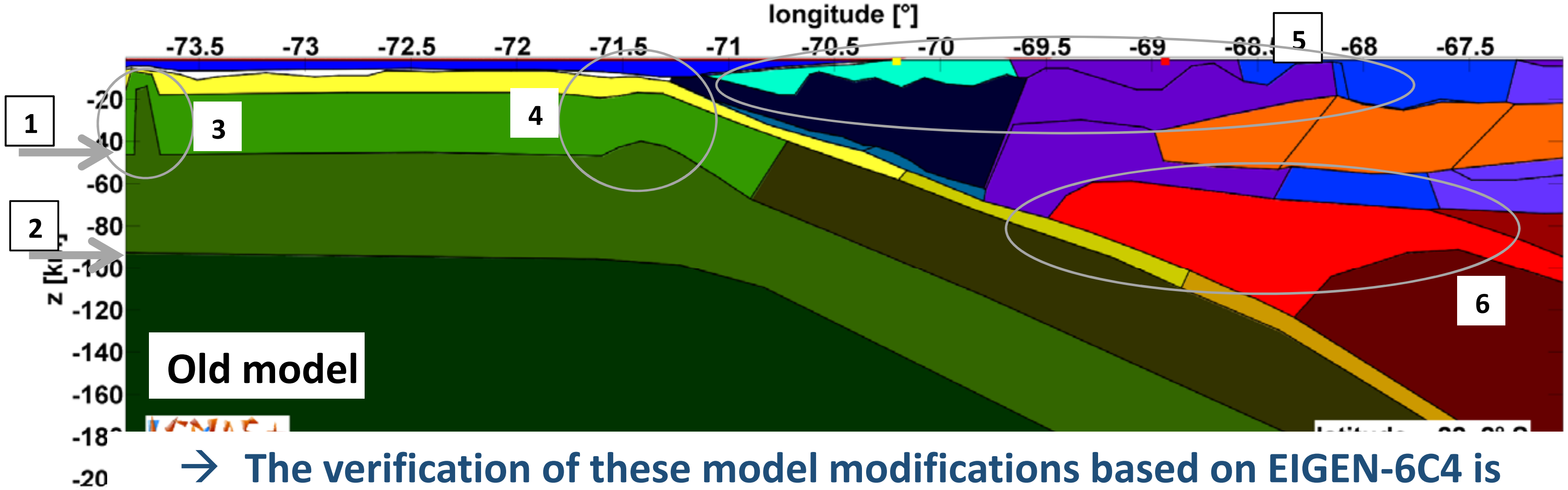
3 Strong inhomogenity in mantle lithsosphere of the old model

4 Geometry of the upward bulge of the downgoing plate

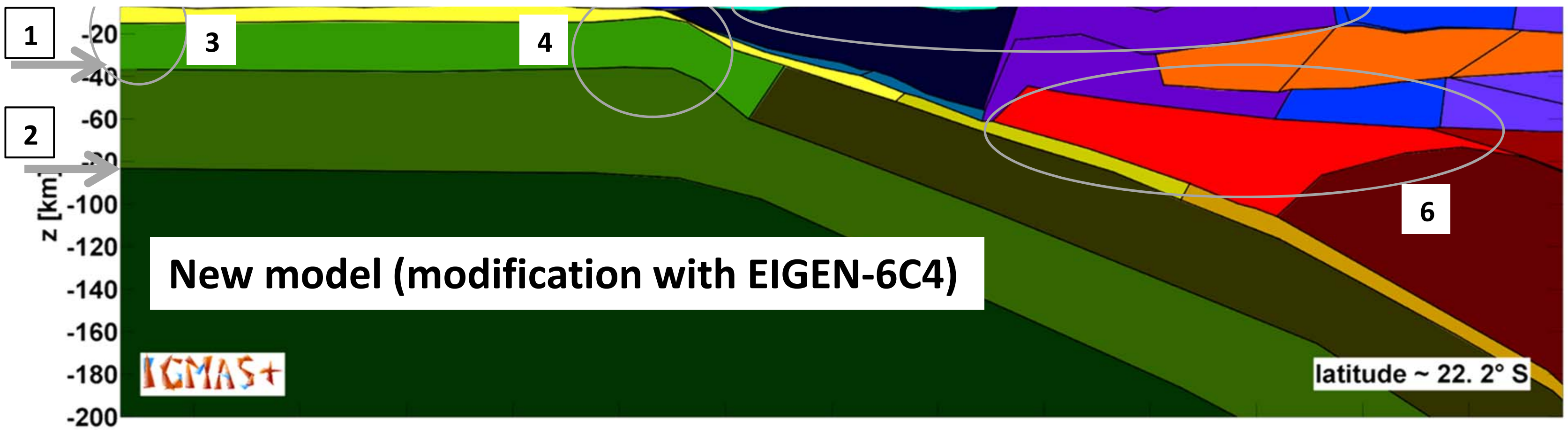
5 Smoothing of the boundary between upper and middle continental crust

6 Geometry of the asthenospheric wedge (on some model sections the size changed significantly)

Comparison: Previous and modified density models



→ **The verification of these model modifications based on EIGEN-6C4 is subject for further investigations, mainly by using seismological data**



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Conclusion/Summary

- **EIGEN-6C4** is a new Global Combined Gravity Field model to degree/order 2190
- This model has been inferred from the combination of LAGEOS, GRACE, GOCE and DTU ground data
- EIGEN-6C4 contains the complete SGG data of the GOCE mission.
- On the continents for wavelengths beyond spher. harm. degree 235, EIGEN-6C4 is basically a reconstruction of EGM2008
- The final version of EIGEN-6C4 is downloadable at the ICGEM data base at GFZ Potsdam

http://icgem.gfz-potsdam.de

Thank you for your attention!

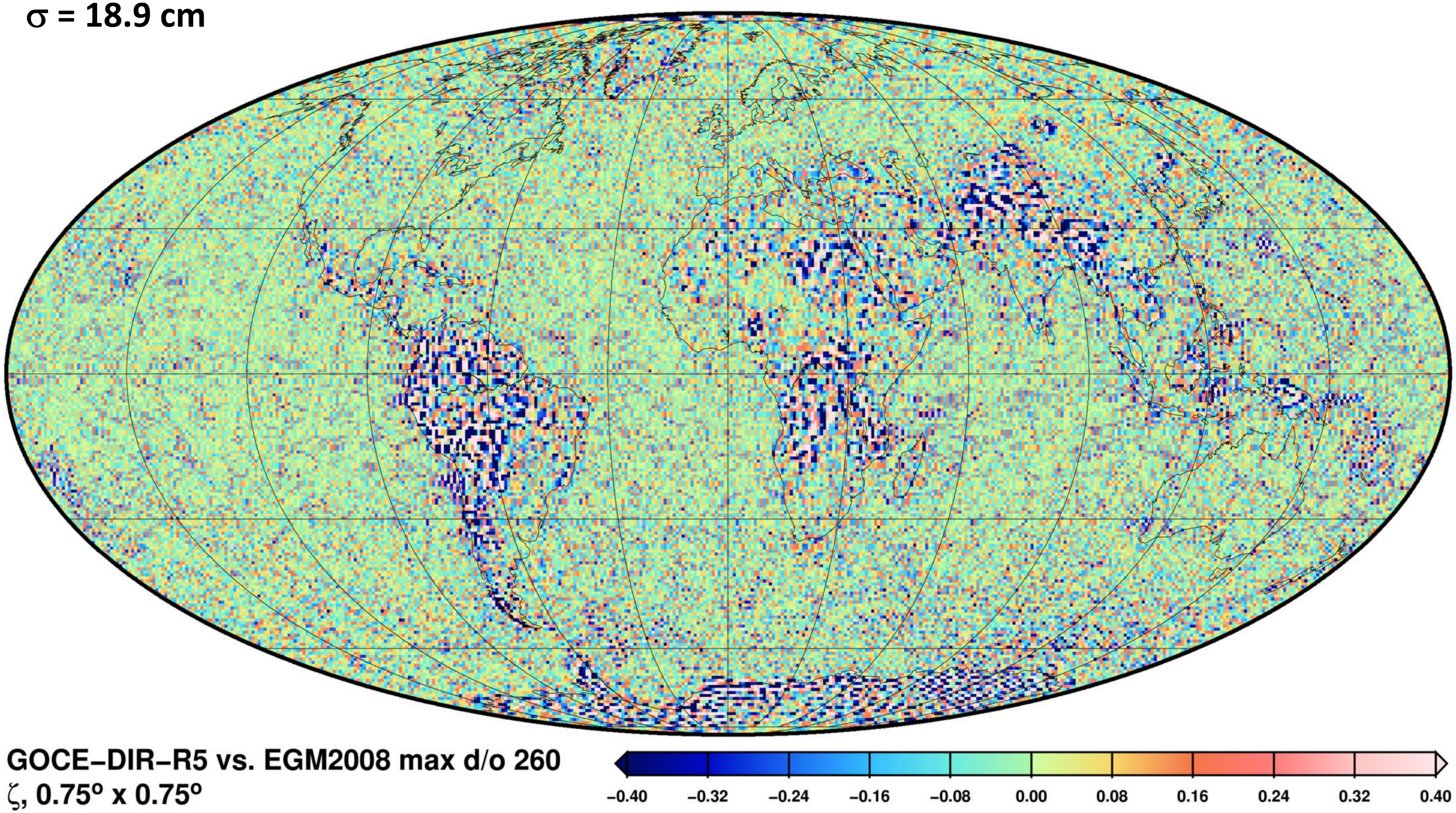
Main characteristics/differences of EIGEN-6C, EIGEN-6C2, EIGEN-6C3stat and EIGEN-6C4

	EIGEN-6C (2011)	EIGEN-6C2 (2012)	EIGEN-6C3stat (2013)	EIGEN-6C4 (2014)
Max d/o	1420	1949	1949	2190
LAGEOS	GRGS 200301 - 200906	GRGS, 1985 - 2010	GRGS, 1985 - 2010	GRGS, 1985 - 2010
GRACE	GRGS RL02 200301 - 200906	GRGS RL02 200303 - 201012	GRGS RL02 (deg. 2 – 100) 200302 – 201101 + GFZ RL05 (deg. 55 – 180) 200310 - 201209	GRGS RL03 10 years 2003 – 2012
Max d/o GRACE	130	130	180	130
GOCE SGG data	200 days T_{xx} T_{yy} T_{zz} out of 20091101 – 20100630	350 days T_{xx} T_{yy} T_{zz} out of 20091101 – 20110419	nominal orbit altitude: 837 days T_{xx} T_{yy} T_{zz} T_{xz} out of 20091101 – 20120801 + lower orbit phases: 225 days T_{xx} T_{yy} T_{zz} out of 20120901 – 20130524	nominal orbit altitude: 837 days T_{xx} T_{yy} T_{zz} T_{xz} out of 20091101 – 20120801 + lower orbit phases: 422 days T_{xx} T_{yy} T_{zz} T_{xz} out of 20120801 – 20131020
Max d/o GOCE	210	210	235	235
Terrestrial data	DTU Global gravity anomalies	DTU Global gravity anomalies DTU Ocean geoid + EGM2008 geoid grid	DTU Global gravity anomalies DTU Ocean geoid + EGM2008 geoid grid	DTU Global gravity anomalies DTU Ocean geoid + EGM2008 geoid grid

EGM-DIR-5 compared with EGM2008: spatial

Satellite-only minus EGM2008, Max degree=260

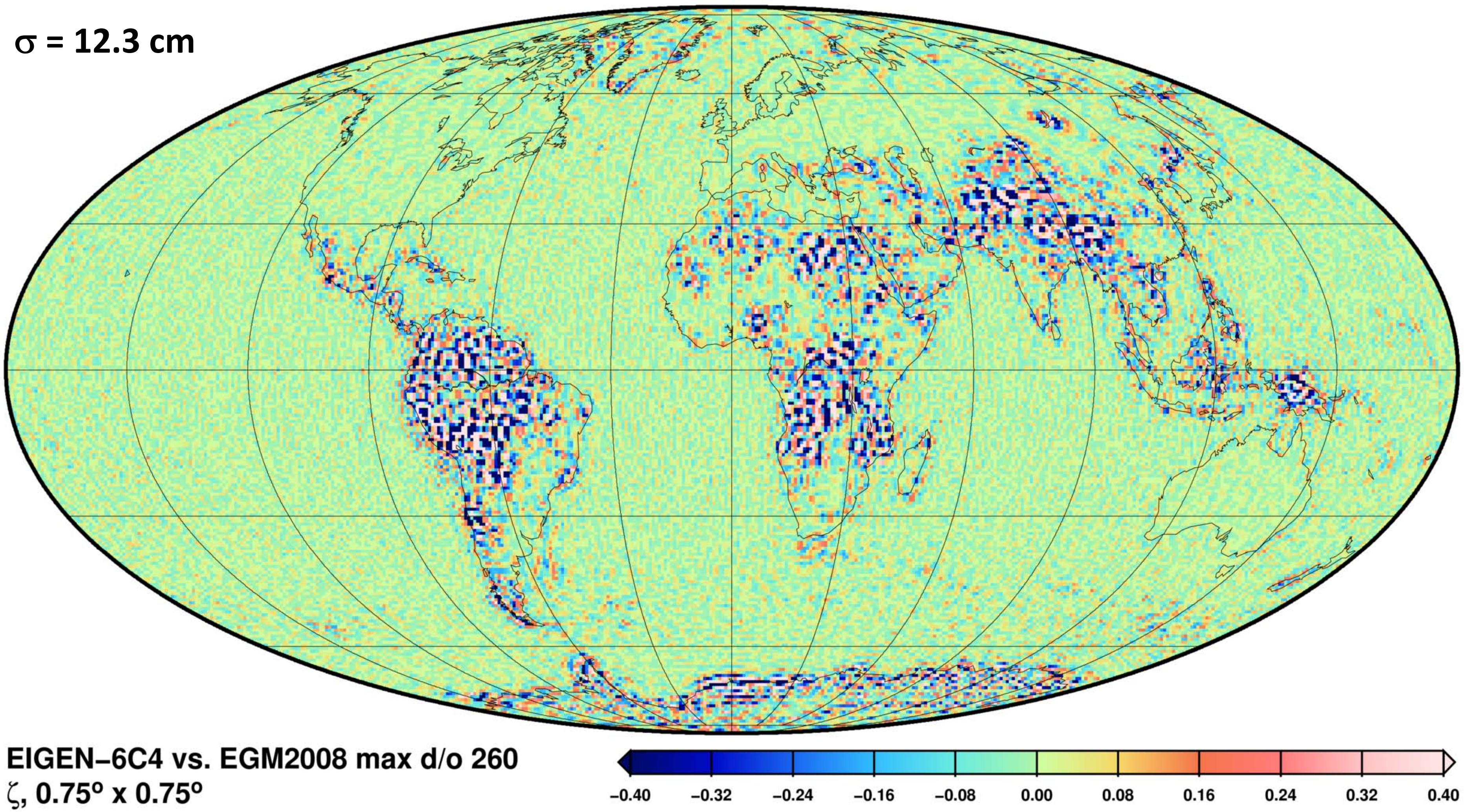
σ = 18.9 cm



EIGEN-6C4 compared to EGM2008: spatial

EGM2008 minus EIGEN-6C4, max. degree = **260** (as for the GOCE-only model)

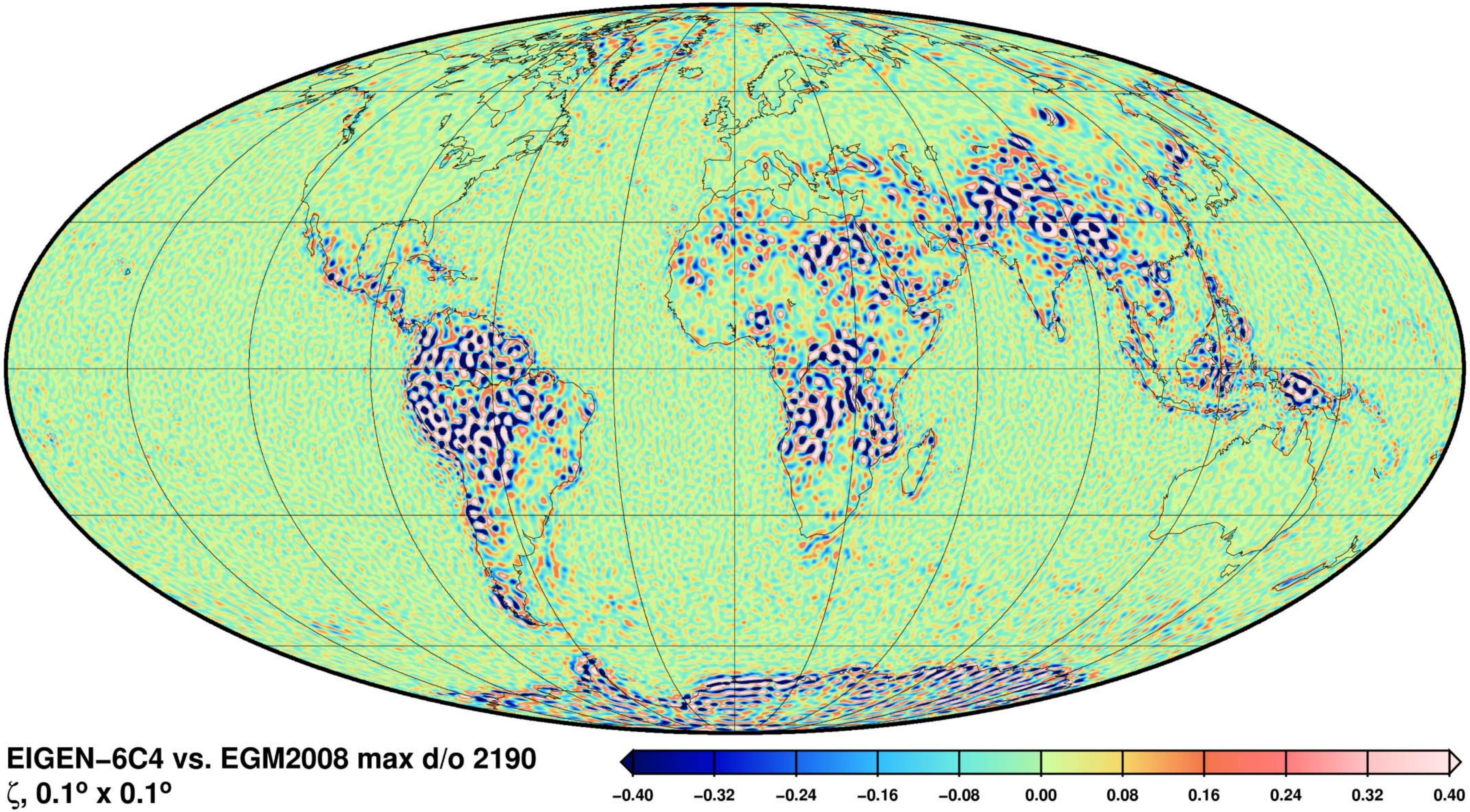
σ = 12.3 cm



EIGEN-6C4 compared to EGM2008: spatial

EGM2008 minus EIGEN-6C4, max. degree = **2190** (full resolution)

σ = 12.4 cm → the same as for max degree 260



References:

Andersen, O. B. and Knudsen, P. (1998), Global marine gravity field from the ERS-1 and Geosat geodetic mission Altimetry J. Geophys. Res., 103/C4, pp 8129 – 8137

Andersen O. B. P. Knudsen and P. Berry. (2009): DNSC08 mean sea surface and mean dynamic topography models, Journal of Geophysical Research, Vol. 114, c11001 12 pp., 2009, doi:10.1029/2008JC005179

Andersen, O. B.,(2010): The DTU10 Gravity field and Mean sea surface (2010), Second international symposium of the gravity field of the Earth (IGFS2), Fairbanks, Alaska

Bock H, Jäggi A, Meyer U, Visser P, van den Ijssel J, van Helleputte T, Heinze M and Hugentobler U (2011), GPS-derived orbits for the GOCE satellite, J Geod (2011) 85:807–818, DOI 10.1007/s00190-011-0484-9

Bruinsma, S. L., J. M. Lemoine, R. Biancale, and N. Vales (2010), CNES/GRGS 10-day gravity field models (release 2) and their evaluation, Adv. Space Res., 45(4), 587–601, doi:10.1016/j.asr.2009.10.012.

Bruinsma, S.-L., Förste,C., Abrikosov, O., Marty, J.-C., Rio, M.-H., Mulet, S., Bonvalot, S. (2013): The new ESA satellite-only gravity field model via the direct approach, Geoph. Res. Lett., DOI 10.1002/grl.50716

Sean L. Bruinsma, Christoph Förste, Oleg Abrikosov, Jean-Michel Lemoine, Jean-Charles Marty, Sandrine Mulet, Marie-Helene Rio, and Sylvain Bonvalot (2014), ESA's satellite-only gravity field model via the direct approach based on all GOCE data, Geoph. Res. Lett., DOI 10.1002/2014GL062045

Dahle, C., F. Flechtner, C. Gruber, R. König, G. Michalak, and K. H. Neumayer (2012), GFZ GRACE level-2 processing standards document for level-2 product release 0005, Sci. Tech. Rep., Data, 12/02, Potsdam, Germany

Förste, C.; Schmidt, R.; Stubenvoll, R.; Flechtner, F.; Meyer, U.; König, R.; Neumayer, H.; Biancale, R.; Lemoine, J.-M.; Bruinsma, S.; Loyer, S.; Barthelmes, F.; Esselborn, S. (2008): The GeoForschungsZentrum Potsdam / Groupe de Recherche de Géodésie Spatiale satellite-only and combined gravity field models: EIGEN-GL04S1 and EIGEN-GL04C. Journal of Geodesy, 82, 6, 331-346, DOI 10.1007/s00190-007-0183-8

Förste C, S. L. Bruinsma, R. Shako, O. Abrikosov, F. Flechtner, J.-C. Marty, J.-M. Lemoine, C. Dahle, H. Neumeyer, F. Barthelmes, R. Biancale, G. Balmino and R. König (2012), A new release of EIGEN-6: The latest combined global gravity field model including LAGEOS, GRACE and GOCE data from the collaboration of GFZ Potsdam and GRGS Toulouse, Geophysical Research Abstracts Vol. 14, EGU2012-2821-2, EGU General Assembly 2012

Ch. Förste, F. Flechtner, Ch. Dahle, O. Abrikosov, H. Neumayer, Franz Barthelmes, R. König, S.L. Bruinsma, J.C. Marty, J.-M. Lemoine, R. Biancale

EIGEN-6C3 - The latest Combined Global Gravity Field Model incl. GOCE data up to d/o 1949 of GFZ Potsdam and GRGS Toulouse, Abstracts, AGU 2013 Fall Meeting (San Francisco, USA 2013)

Götze H.-J. and MIGRA-Group (1996), Group updates Gravity Database for central Andes, EOS Trans. Am. Geophys. Un., 1996, VOLUME 77, number 19, pages 181--181, DOI = 10.1029/96EO00121

Mayer-Gürr, T. and the GOCO consortium (2012), The new combined satellite only model GOCO03s, paper presented at International Symposium on Gravity, Geoid and Height Systems GGHS 2012, Venice, Italy

Prange, L., A. Jäggi, R. Dach, H. Bock, G. Beutler, L. Mervart; 2010: AIUB-CHAMP02S: The influence of GNSS model changes on gravity field recovery using spaceborne GPS. Advances in Space Research, vol.45(2), pp. 215-224, DOI:10.1016/j.asr.2009.09.020

Ries, J.C., S. Bettadpur, S. Poole, and T. Richter (2011): Mean Background Gravity Fields for GRACE Processing, GRACE Science Team Meeting, Austin, TX, 8-10 August 2011

Pavlis, N.K., Holmes, S.A., Kenyon, S.C., and Factor, J.K. (2012), The development and evaluation of the Earth Gravitational Model 2008 (EGM2008), Journal of Geoph. Res., Vol. 117, B04406, doi:10.1029/2011JB008916, 2012

Schmidt, S. and Götze, H.-J. Bouguer and Isostatic Maps of the Central Andes (2006), in: The Andes, pages 559—562, Springer, doi=10.1007/978-3-540-48684-8_28

Shako R, Förste C, Abrikosov O, Bruinsma SL, Marty J - C, Lemoine J - M, Flechtner F, Neumayer KH and Dahle C. (2013), EIGEN-6C: A High-Resolution Global Gravity Combination Model Including GOCE Data, in F. Flechtner et al. (eds.), Observation of the System Earth from Space – CHAMP, GRACE, GOCE and future missions, Advanced Technologies in Earth Sciences, DOI: 10.1007/978-3-642-32135-1_20, Springer-Verlag Berlin Heidelberg 2013