GOCE Gravity Field Models – Overview, Performance and Impact on Height Systems

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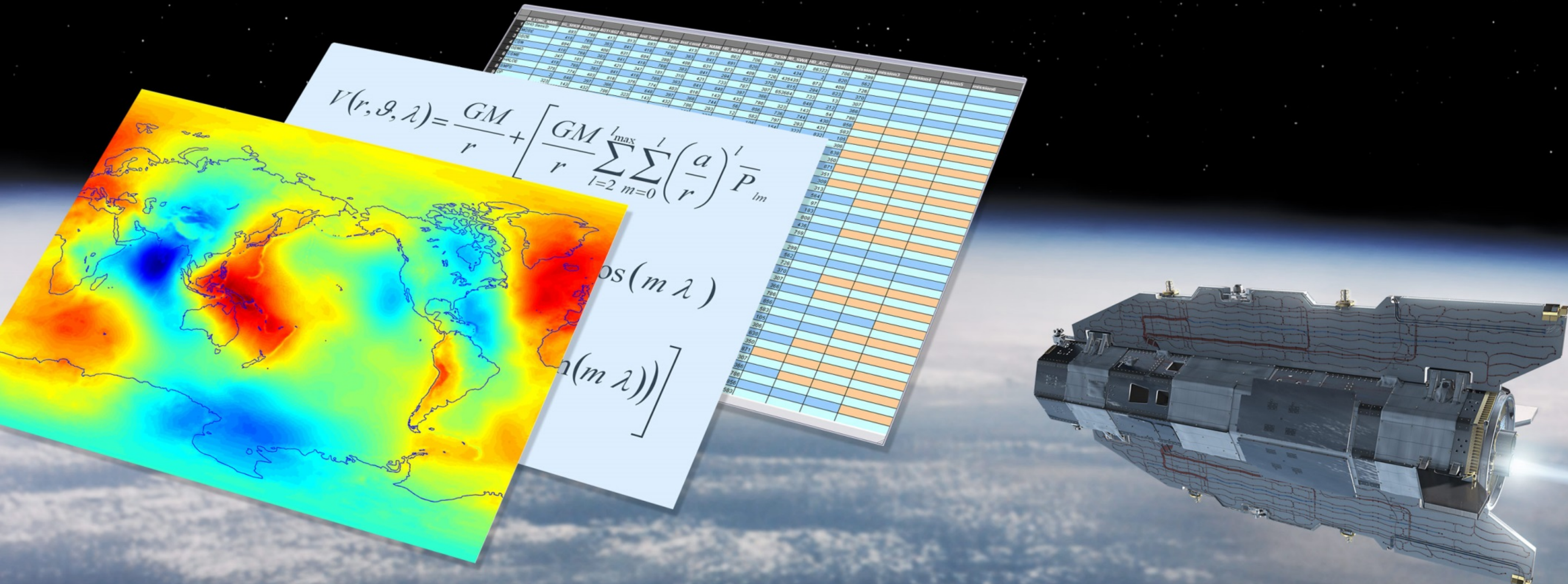
Technische Universität München

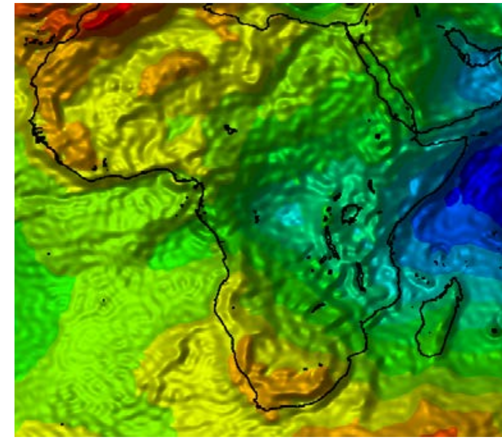


Tutorial Height and Gravity, Leipzig, 02.06.2015

Outline

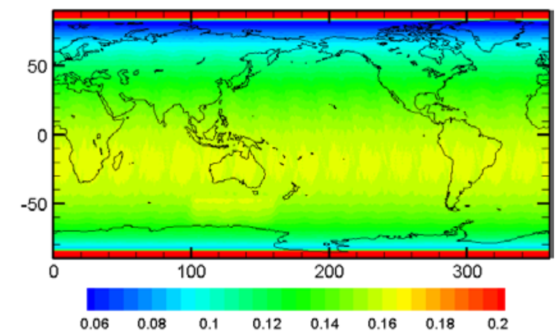
1. GOCE-based Gravity Field Models

- Overview
- Signal Characteristics



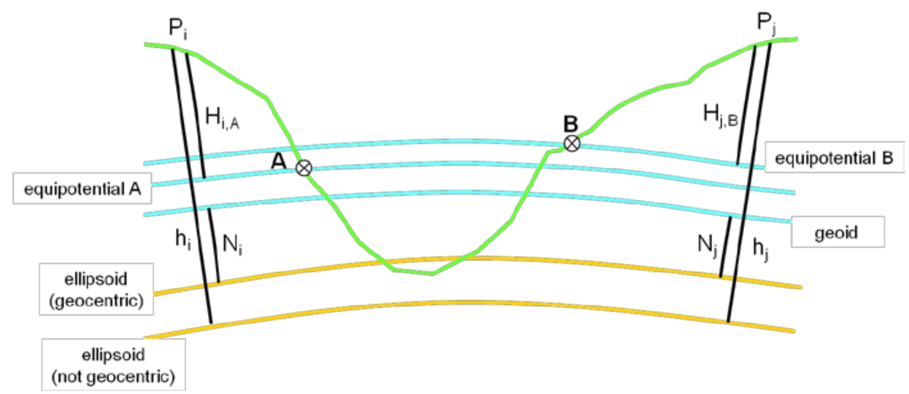
2. Performance Analysis

- Estimated Errors
- External Validation
- Geoid Accuracy



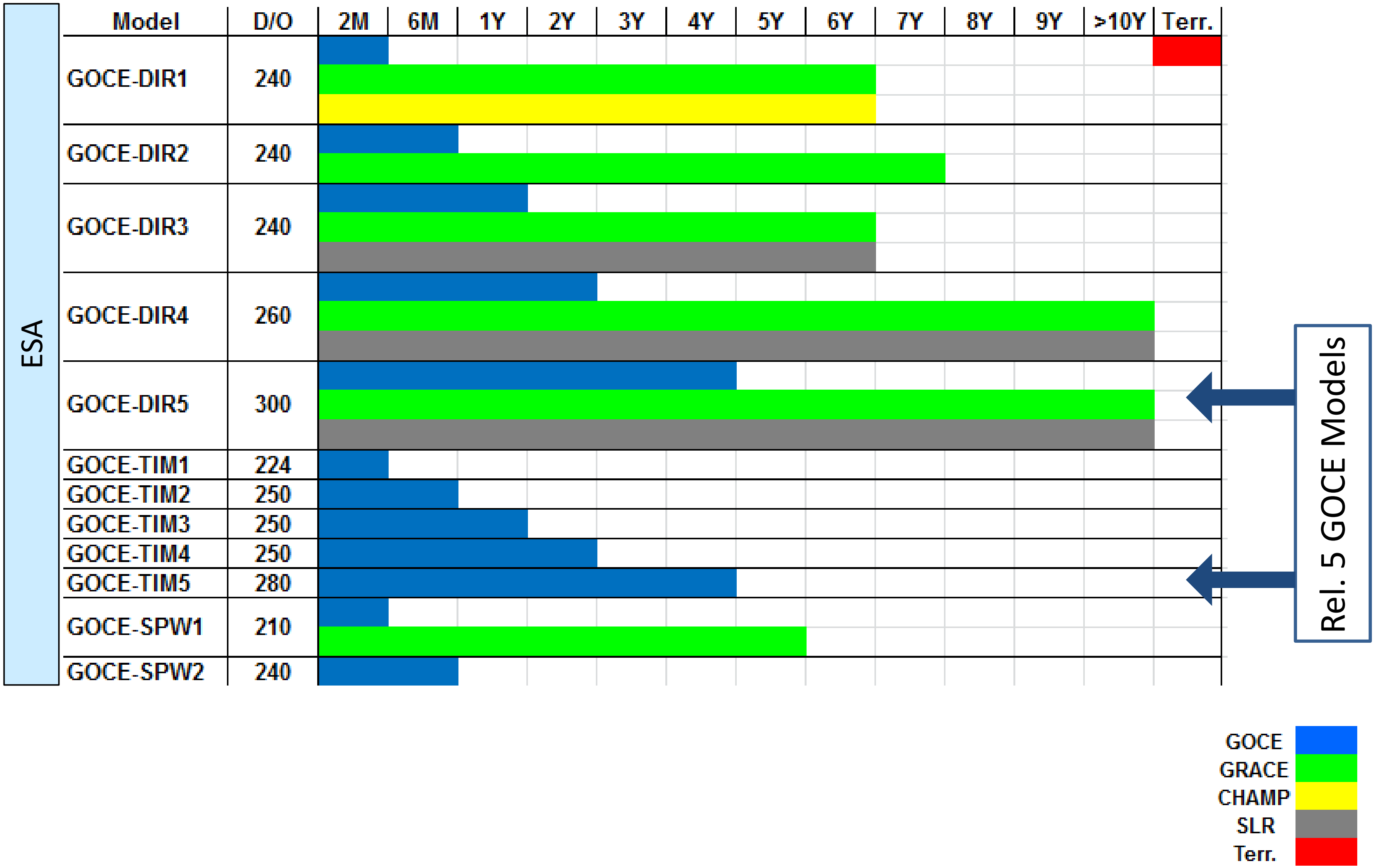
3. GOCE & Height System

- Overview
- Scientific Roadmap

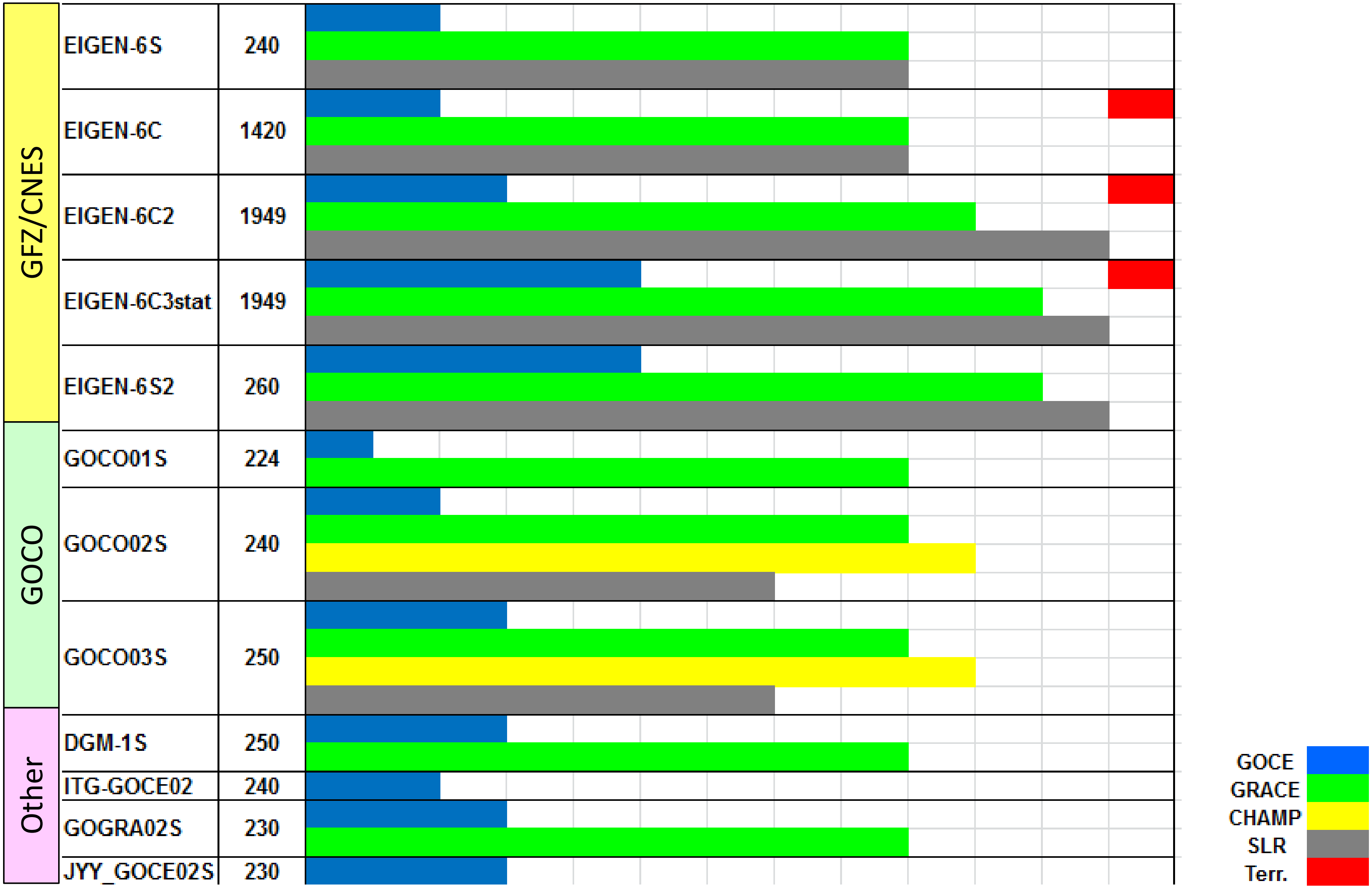


4. Summary

Overview of GOCE Models



Overview of GOCE Models



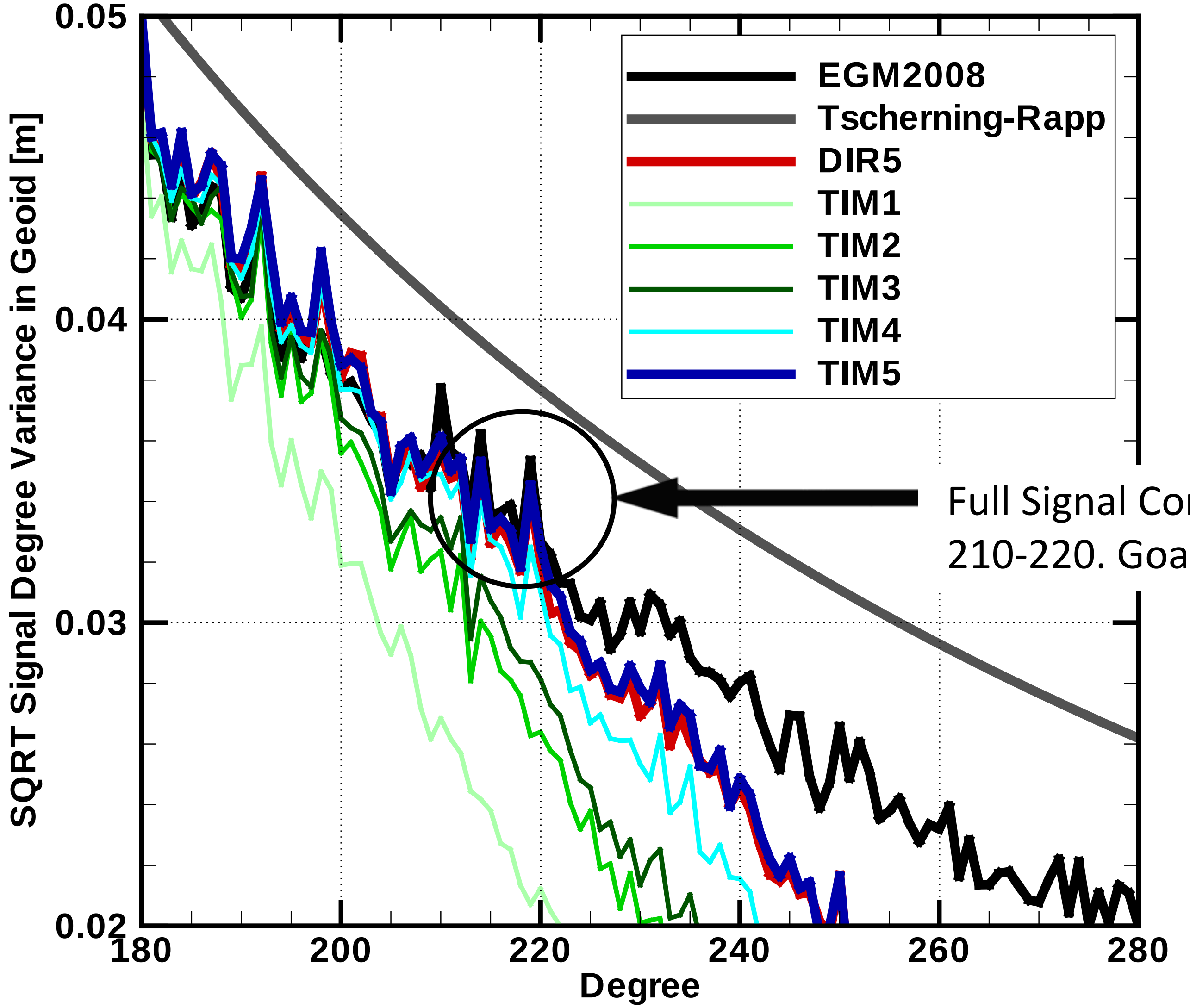
Overview of GOCE Models

ESA Release 5 GOCE Models Characteristics

	DIR5	TIM5
Maximum D/O	300	280
GOCE Data Volume	01.11.09-20.10.13; ~3.5 yrs (net)	01.11.09-20.10.13; ~3.5yrs (net)
Gravity Gradients	V_{xx}, V_{yy}, V_{zz}, V_{xz} >400 Mio. Obs.	V_{xx}, V_{yy}, V_{zz}, V_{xz} >439 Mio. Obs.
Gradient Filter	Band-pass filter	ARMA filter per segment (87)
GOCE SST (GPS)	-	Short arc approach (d/o 150)
GRACE SST (K-Band)	2003-2012 GRGS RL03 (d/o 130)	-
LAGEOS 1/2 (SLR)	1985-2010, ~25 yrs	-
Regularization	spherical cap based on GRACE/LAGEOS. Kaula zero constraint (d/o > 180)	Kaula zero constraint (near zonals and for d/o > 200)

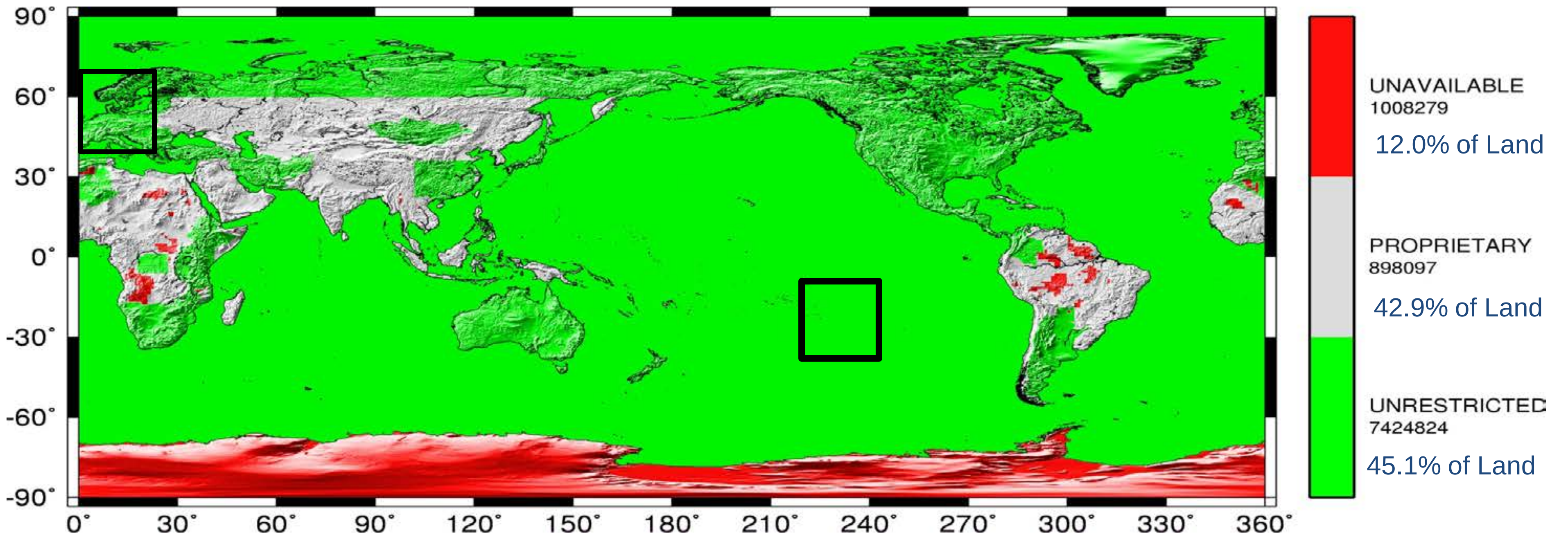
Signal Characteristic

Signal Degree Variances (GOCE RL5 vs. earlier Models)



Signal Characteristic

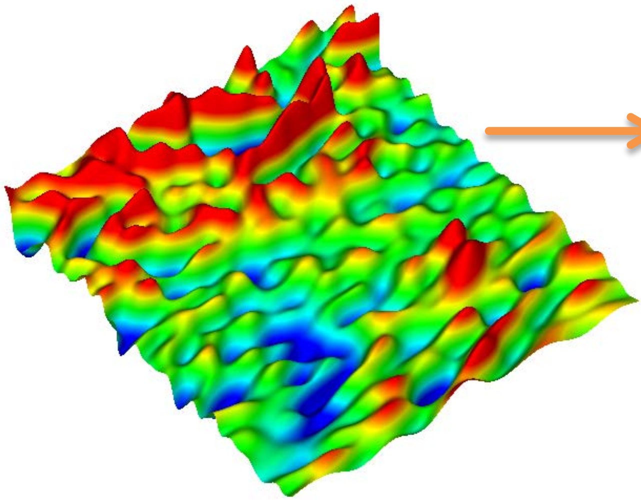
EGM2008 Data Coverage



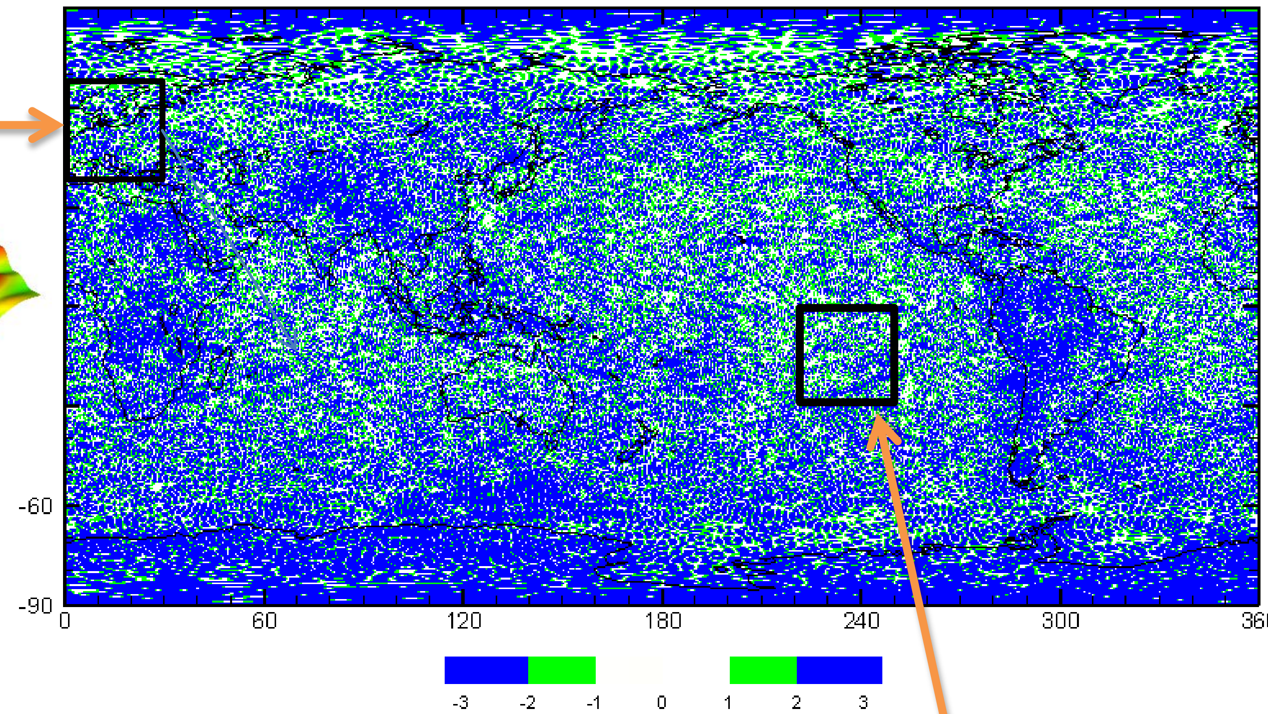
Map Source: Pavlis, N. K., Holmes, S., Kenyon, S., Factor, J. 2012. "The Development and Evaluation of the Earth Gravitational Model 2008 (EGM2008)." *Journal of Geophysical Research* 117

Signal Characteristic

Gravity Anomalies Signal



GOCE vs. EGM2008 Gravity Anomalies [mgal] (up to d/o 200)

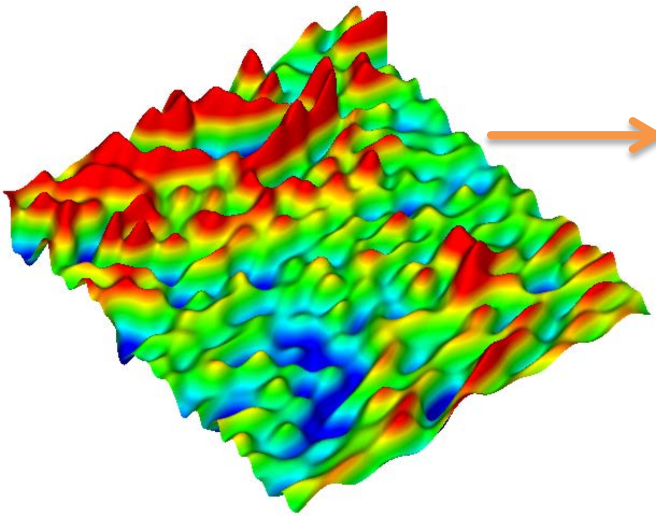


RMS of Differences in Test Area [mgal]

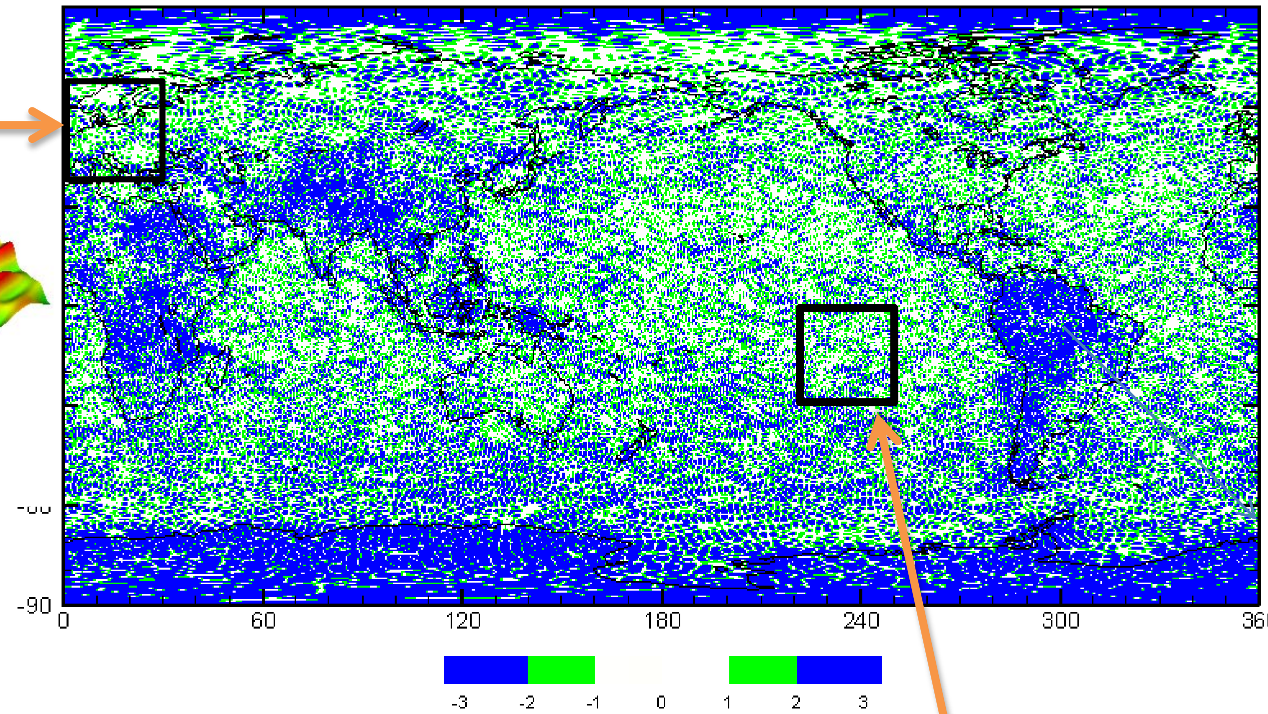
	Rel. 1	Rel. 2	Rel. 3	Rel. 4	Rel. 5
TIM	3.14				
DIR	1.07				

Signal Characteristic

Gravity Anomalies Signal



GOCE vs. EGM2008 Gravity Anomalies [mgal] (up to d/o 200)

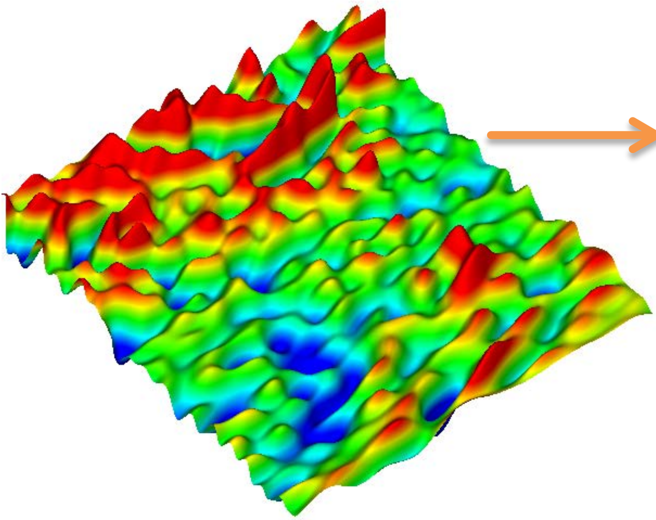


RMS of Differences in Test Area [mgal]

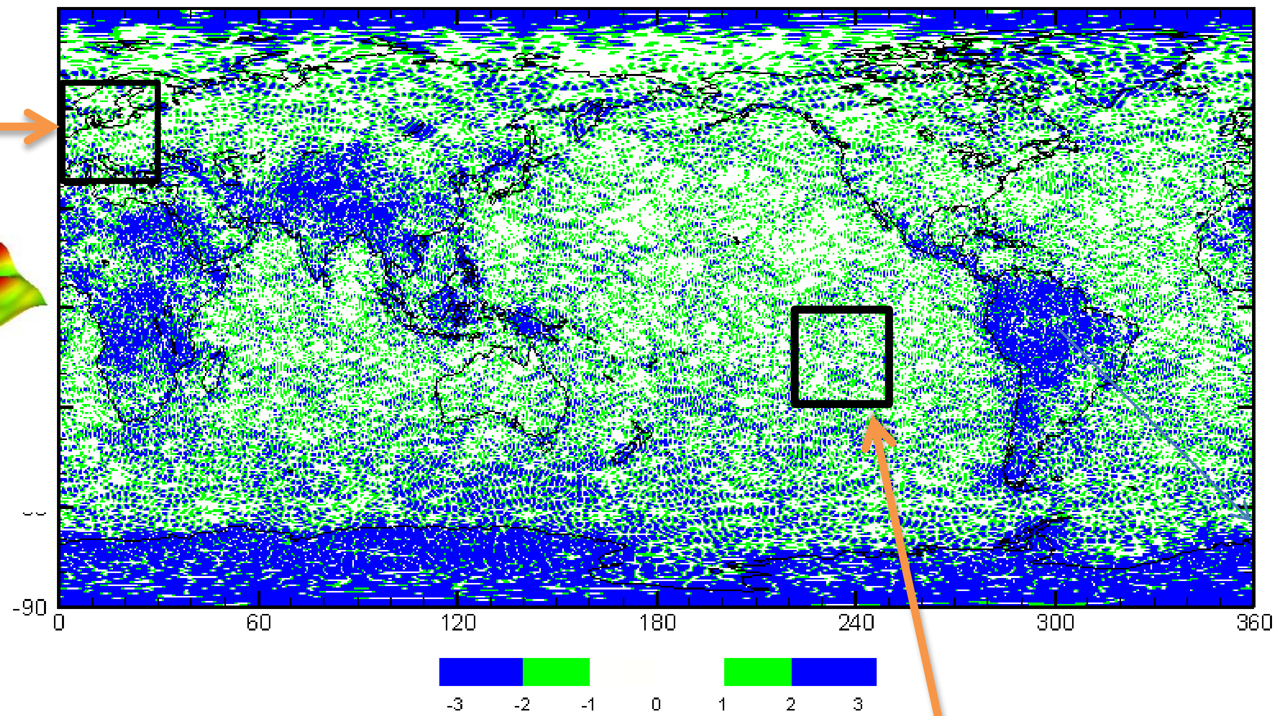
	Rel. 1	Rel. 2	Rel. 3	Rel. 4	Rel. 5
TIM	3.14	2.05			
DIR	1.07	2.28			

Signal Characteristic

Gravity Anomalies Signal



GOCE vs. EGM2008 Gravity Anomalies [mgal] (up to d/o 200)

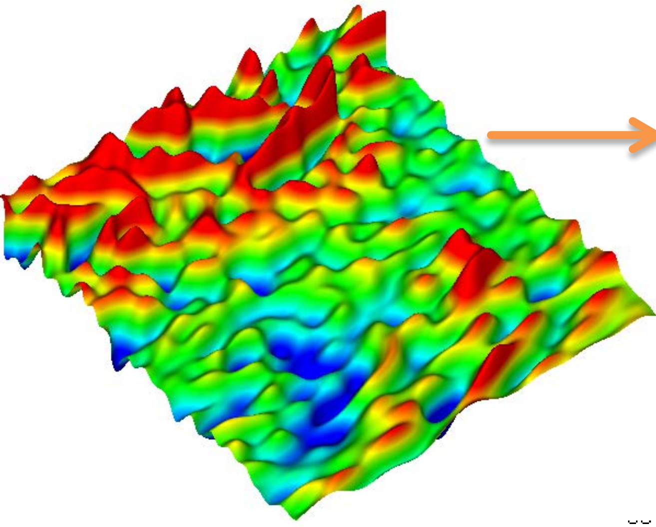


RMS of Differences in Test Area [mgal]

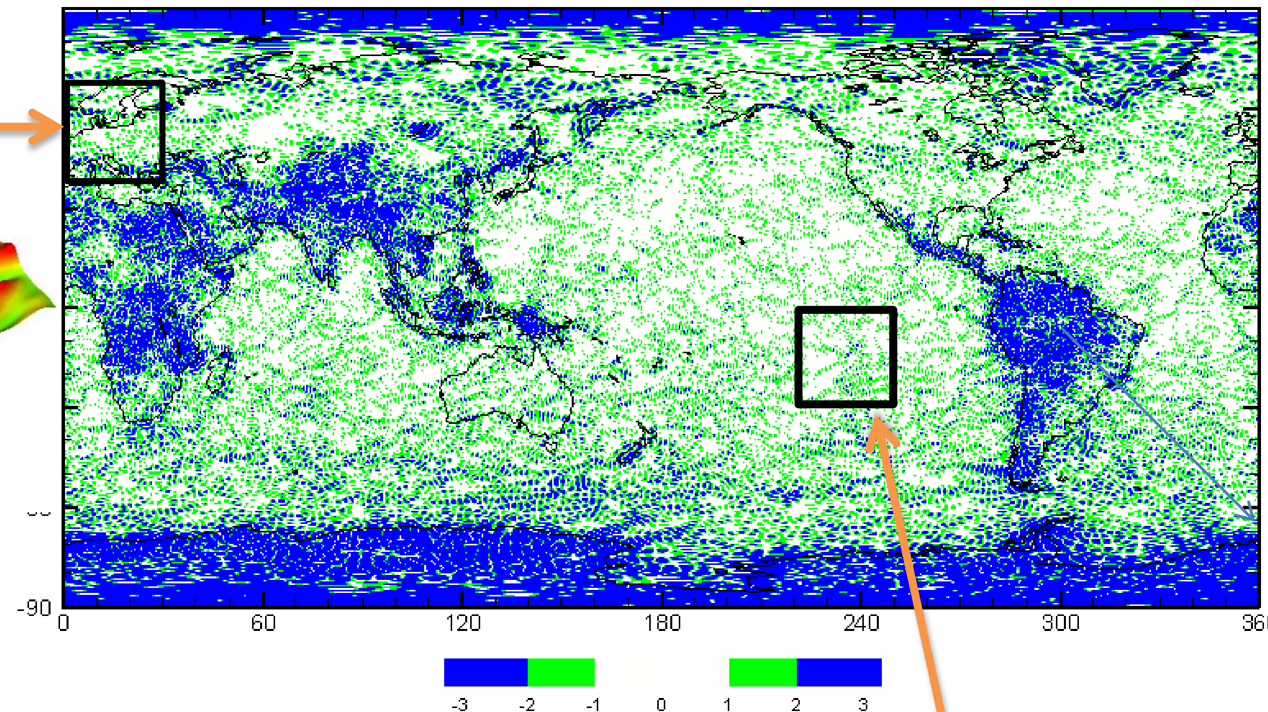
	Rel. 1	Rel. 2	Rel. 3	Rel. 4	Rel. 5
TIM	3.14	2.05	1.55		
DIR	1.07	2.28	1.85		

Signal Characteristic

Gravity Anomalies Signal



GOCE vs. EGM2008 Gravity Anomalies [mgal] (up to d/o 200)

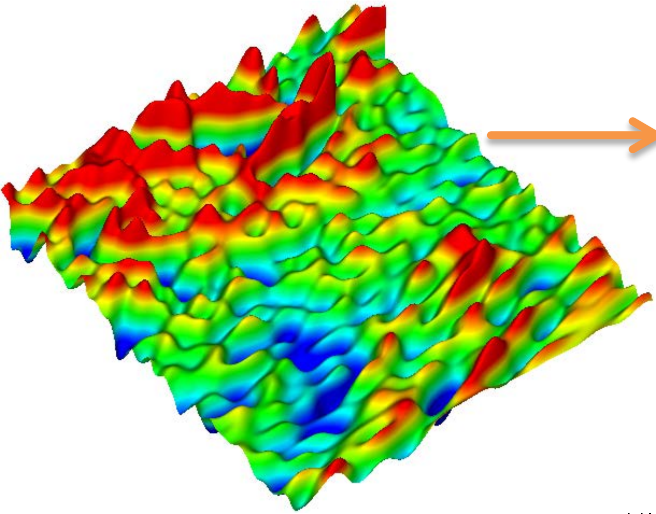


RMS of Differences in Test Area [mgal]

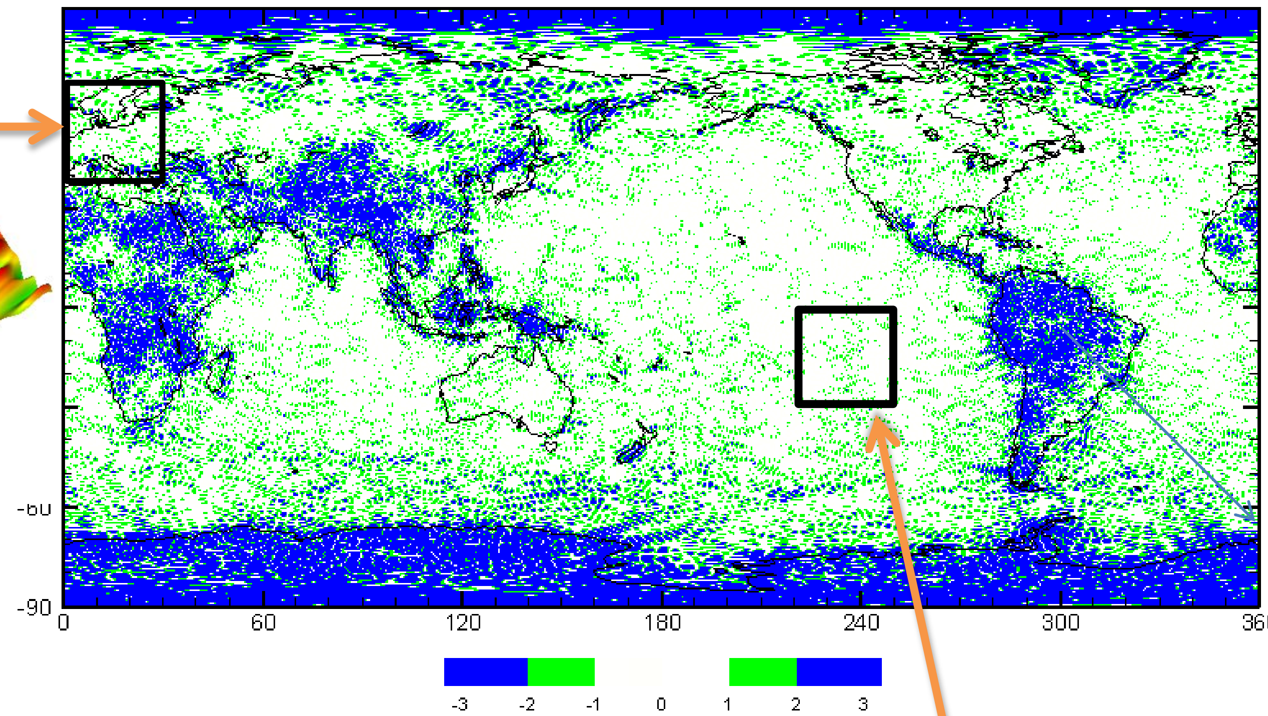
	Rel. 1	Rel. 2	Rel. 3	Rel. 4	Rel. 5
TIM	3.14	2.05	1.55	1.03	
DIR	1.07	2.28	1.85	1.00	

Signal Characteristic

Gravity Anomalies Signal



GOCE vs. EGM2008 Gravity Anomalies [mgal] (up to d/o 200)

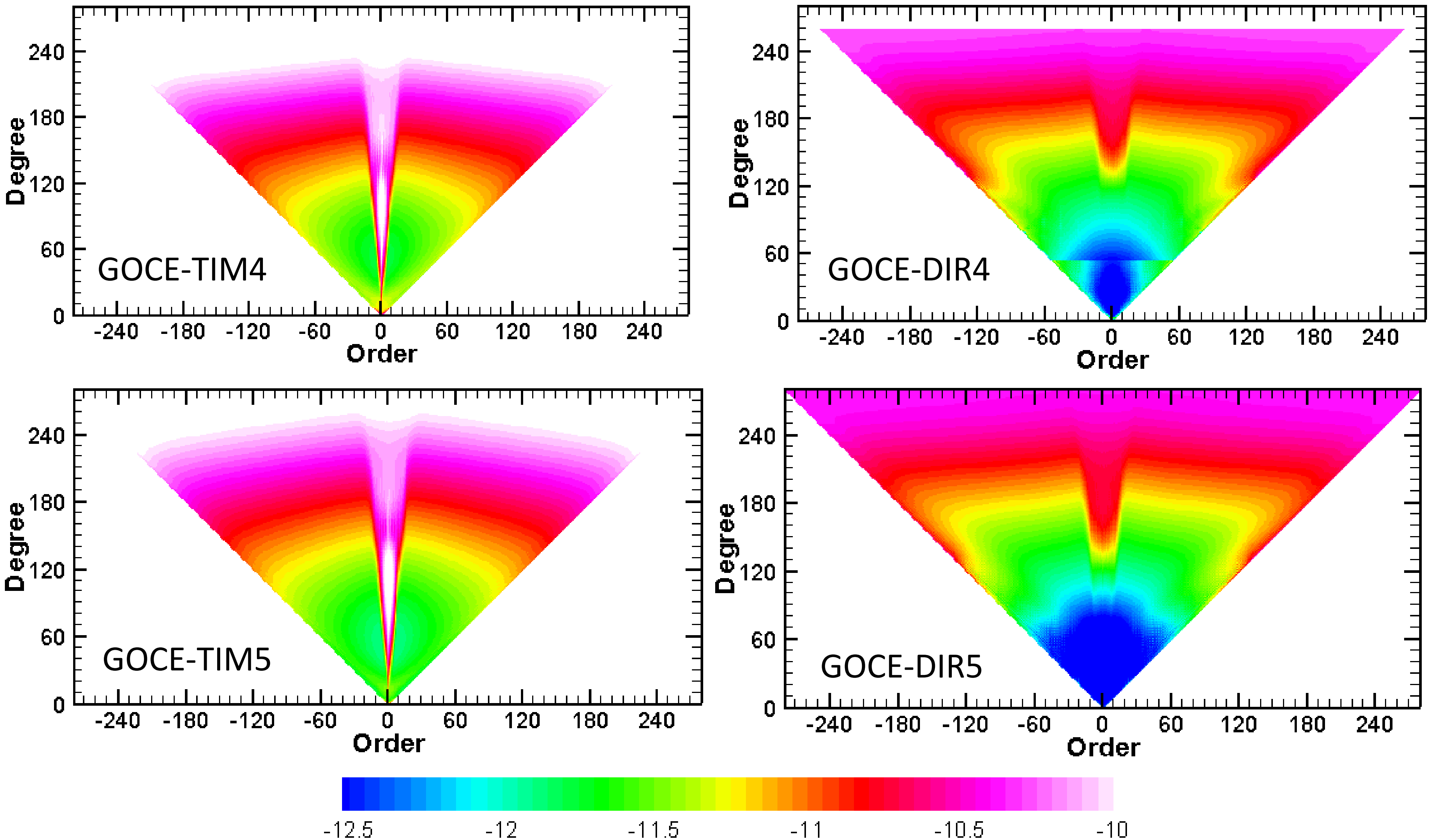


RMS of Differences in Test Area [mgal]

	Rel. 1	Rel. 2	Rel. 3	Rel. 4	Rel. 5
TIM	3.14	2.05	1.55	1.03	0.71
DIR	1.07	2.28	1.85	1.00	0.70

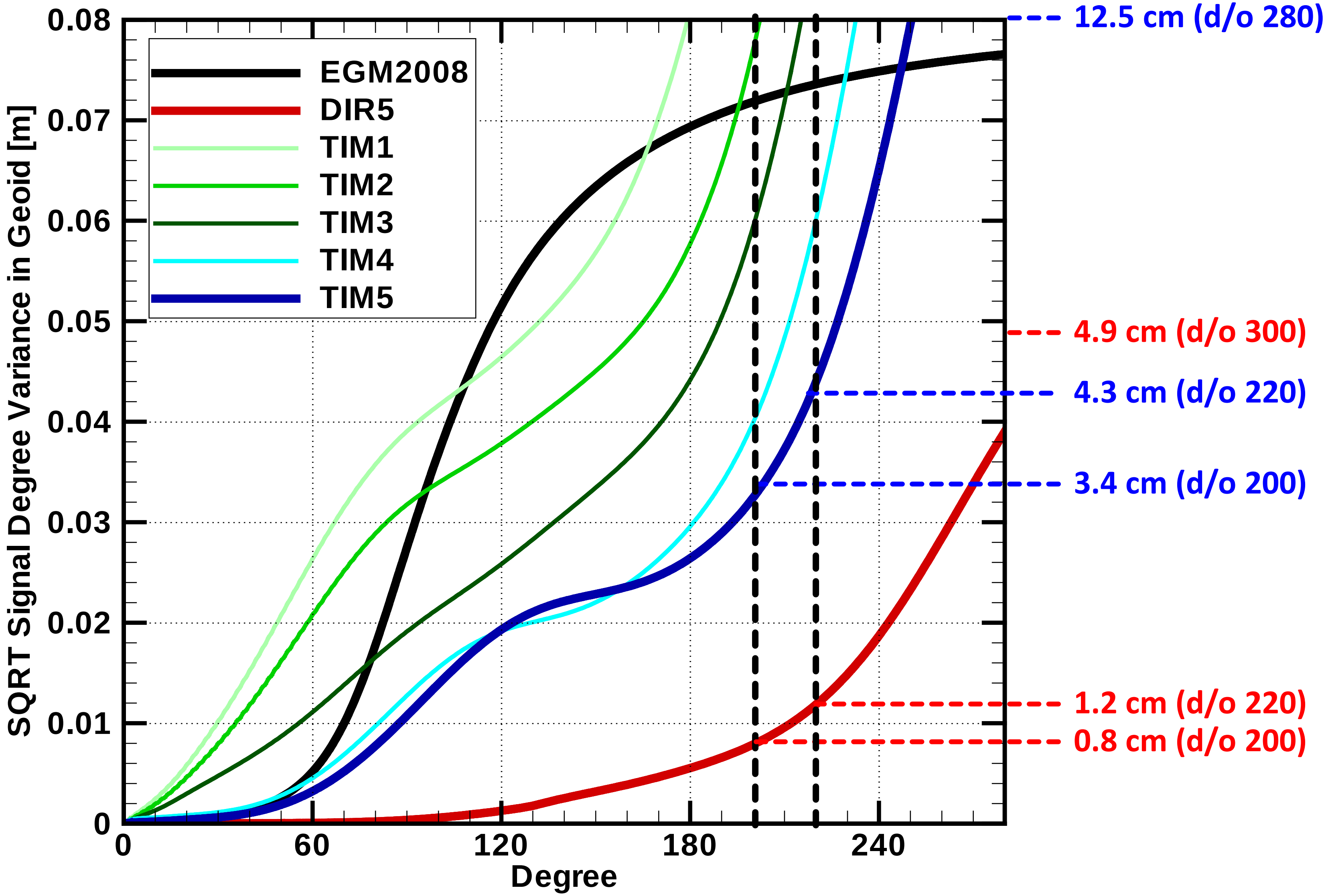
Estimated Errors

Coefficient Standard Deviations (log10)



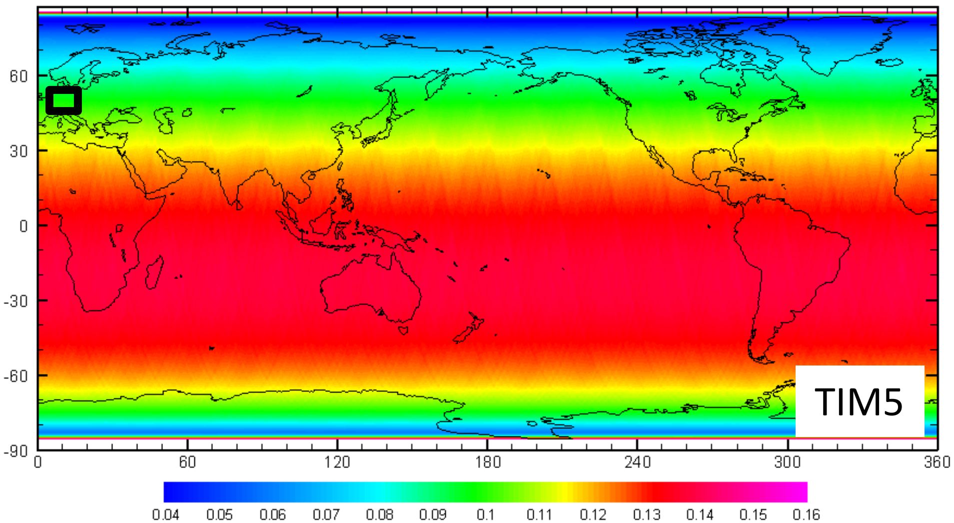
Estimated Errors

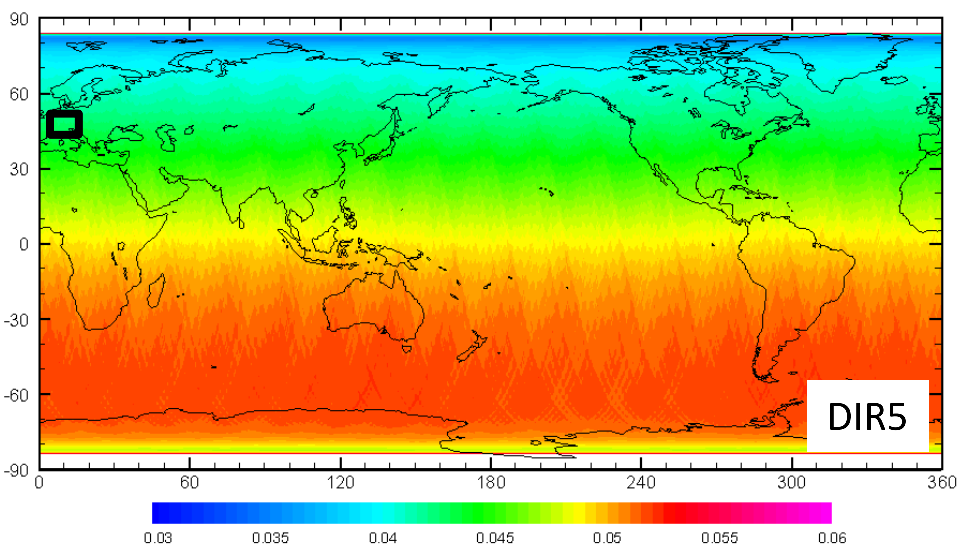
Cummulative Geoid Errors from Coefficient Errors



Estimated Errors

Maps of Geoid Error from VCM Propagation (Full Resolution)



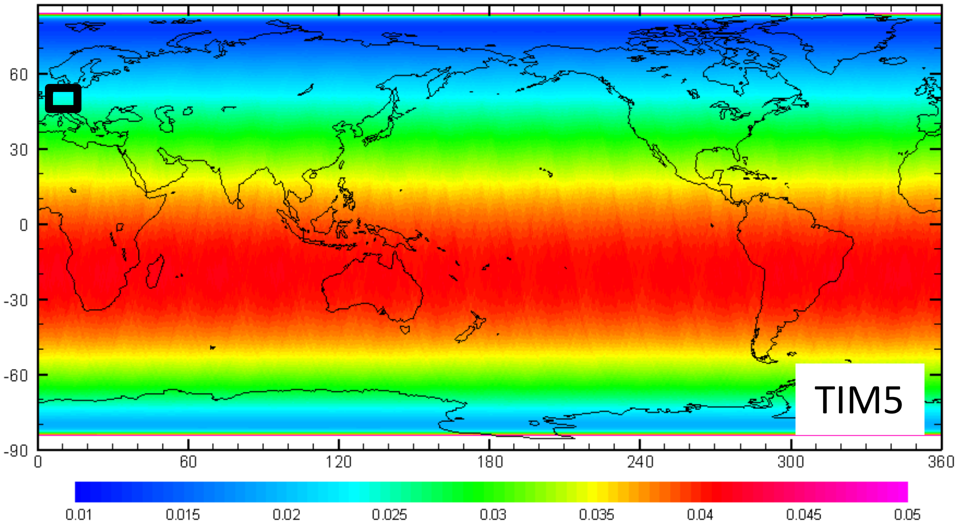


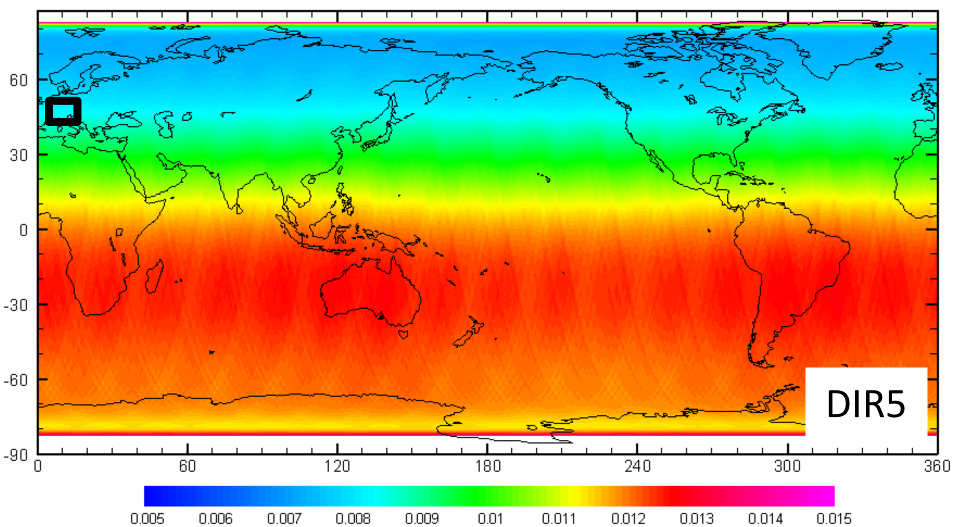
Geoid Error Comparison (Global from cum. Error Degree Variances, Germany from VCM Propagation)

Degree/Order & Area	TIM5 [cm]	DIR5 [cm]
200 Global		
200 Germany		
220 Global		
220 Germany		
Full Global	12.5	4.9
Full Germany	10.0	4.5

Estimated Errors

Maps of Geoid Error from VCM Propagation (Degree/Order 220)



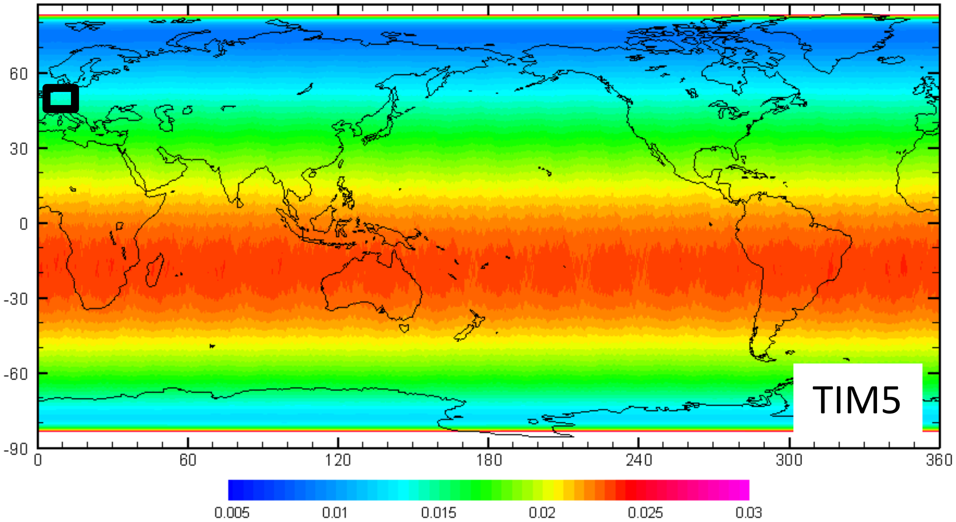


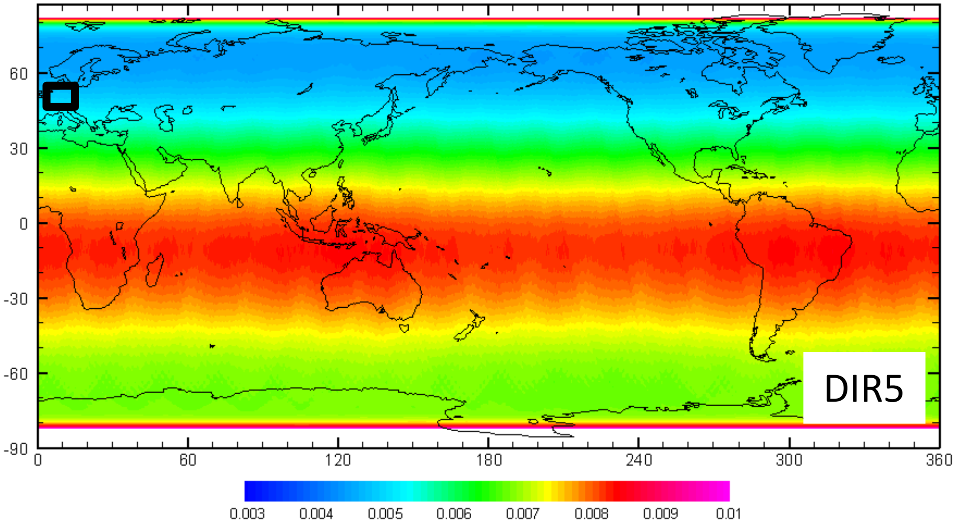
Geoid Error Comparison (Global from cum. Error Degree Variances, Germany from VCM Propagation)

Degree/Order & Area	TIM5 [cm]	DIR5 [cm]
200 Global		
200 Germany		
220 Global	4.3	1.2
220 Germany	2.4	0.8
Full Global	12.5	4.9
Full Germany	10.0	4.5

Estimated Errors

Maps of Geoid Error from VCM Propagation (Degree/Order 200)



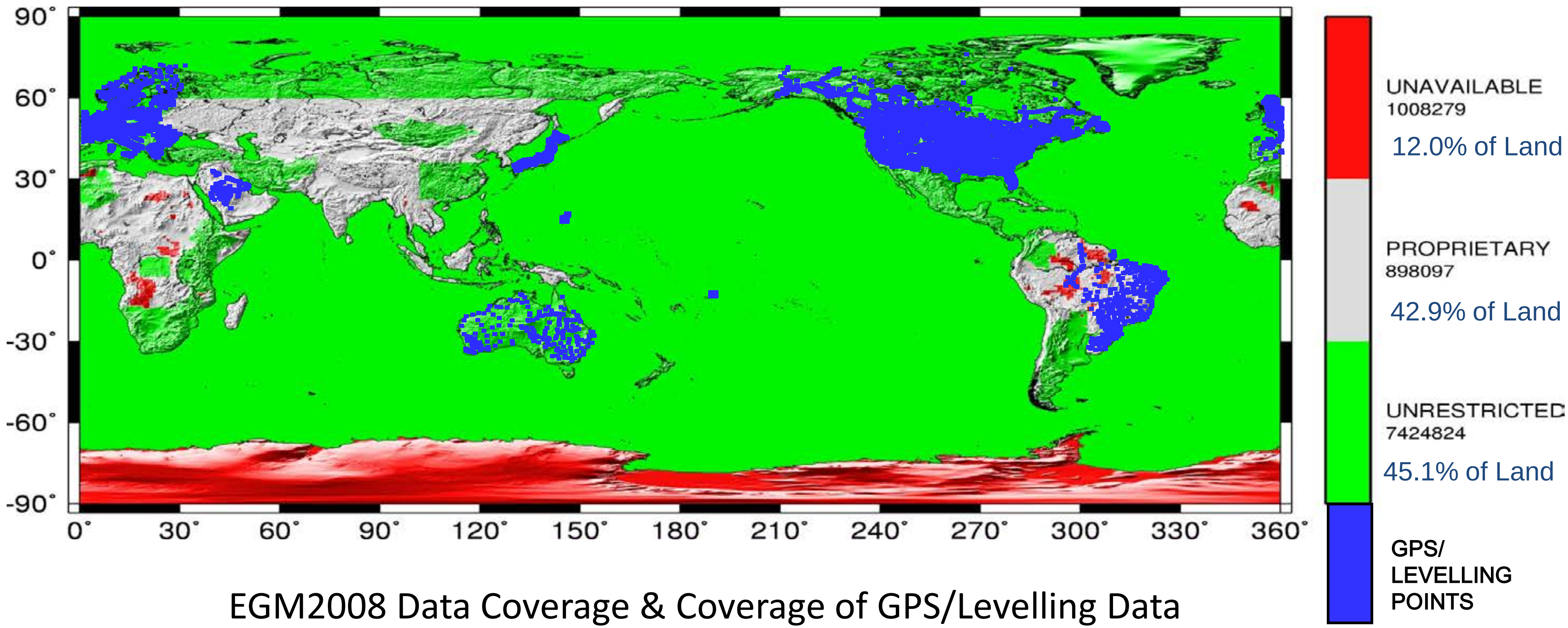


Geoid Error Comparison (Global from cum. Error Degree Variances, Germany from VCM Propagation)

Degree/Order & Area	TIM5 [cm]	DIR5 [cm]
200 Global	3.4	0.8
200 Germany	1.4	0.5
220 Global	4.3	1.2
220 Germany	2.4	0.8
Full Global	12.5	4.9
Full Germany	10.0	4.5

Model Validation

GPS Levelling Data for Gravity Field Validation

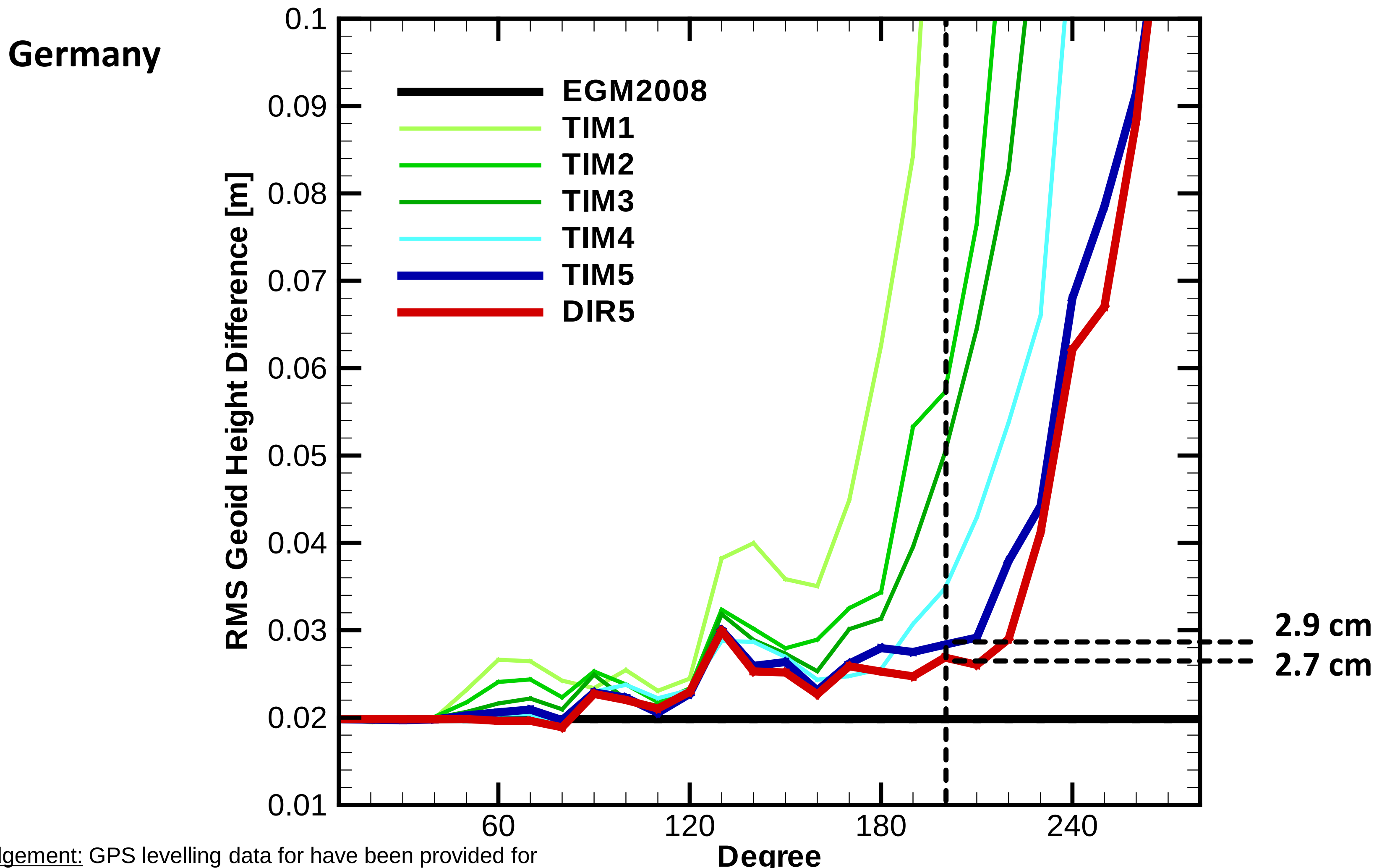


EGM2008 Data Coverage & Coverage of GPS/Levelling Data

Map Source: Pavlis, N. K., Holmes, S., Kenyon, S., Factor, J. 2012. “The Development and Evaluation of the Earth Gravitational Model 2008 (EGM2008).” *Journal of Geophysical Research* 117

Model Validation

RMS of Geoid Differences at GPS-Levelling Points after planar Fit
(Omission Error estimated from EGM2008)

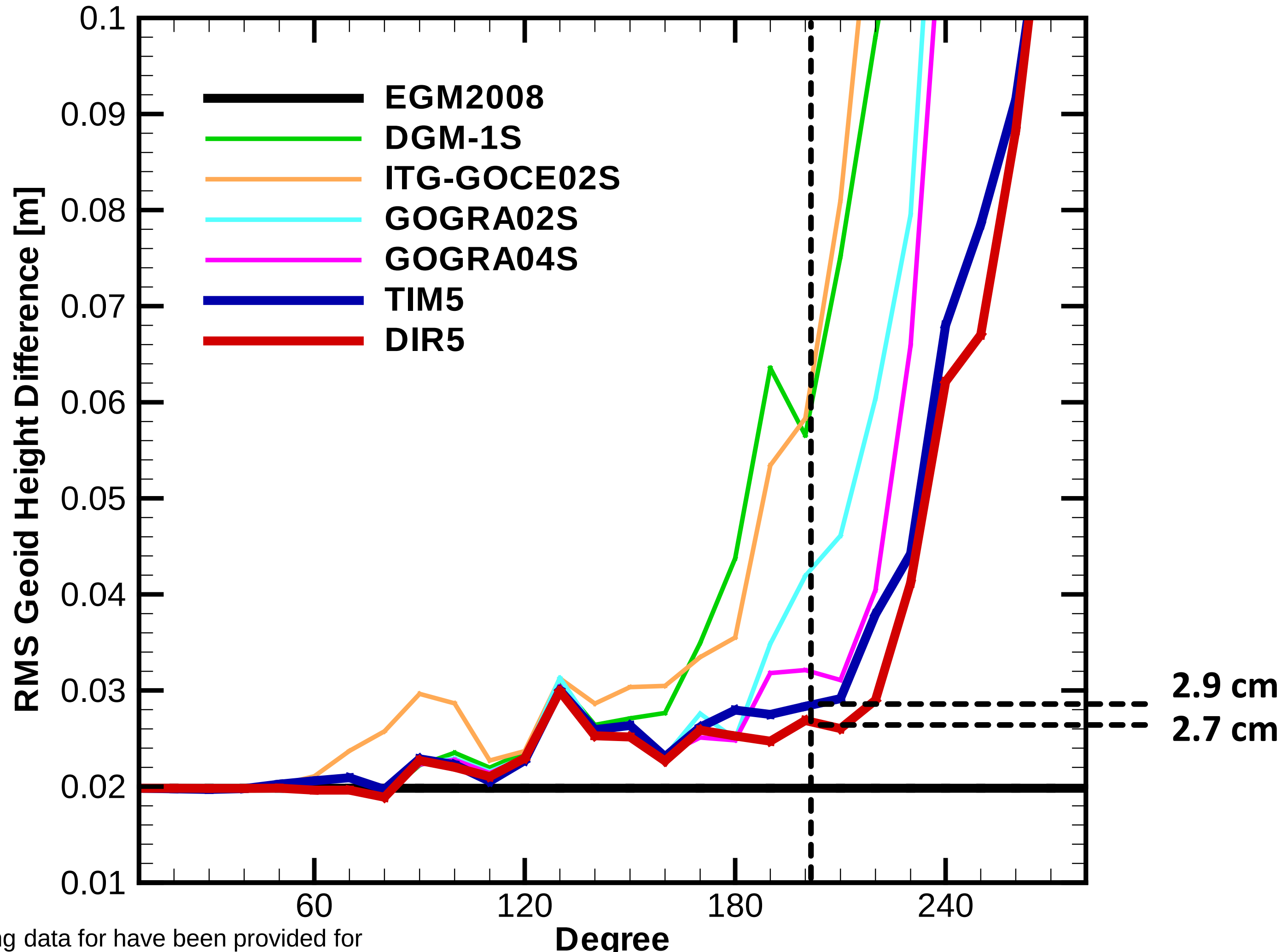


Acknowledgement: GPS levelling data for have been provided for validation purposes by BKG, Frankfurt/Main

Model Validation

RMS of Geoid Differences at GPS-Levelling Points after planar Fit
(Omission Error estimated from EGM2008)

Germany



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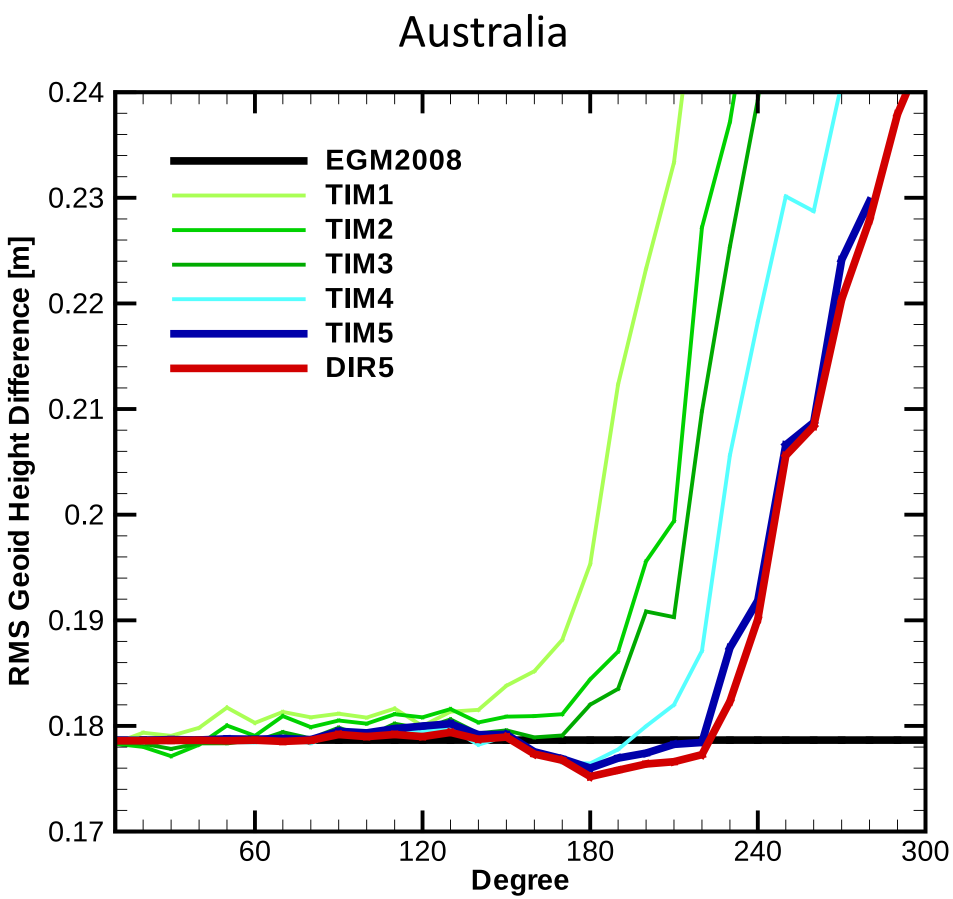
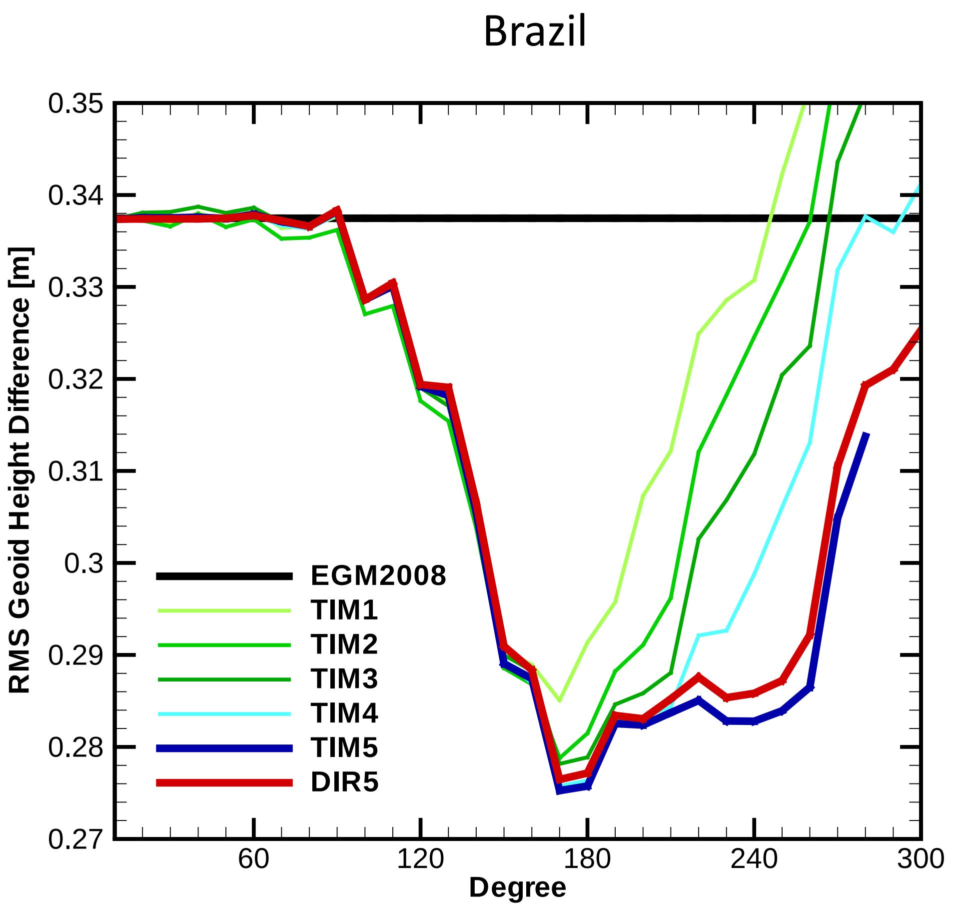




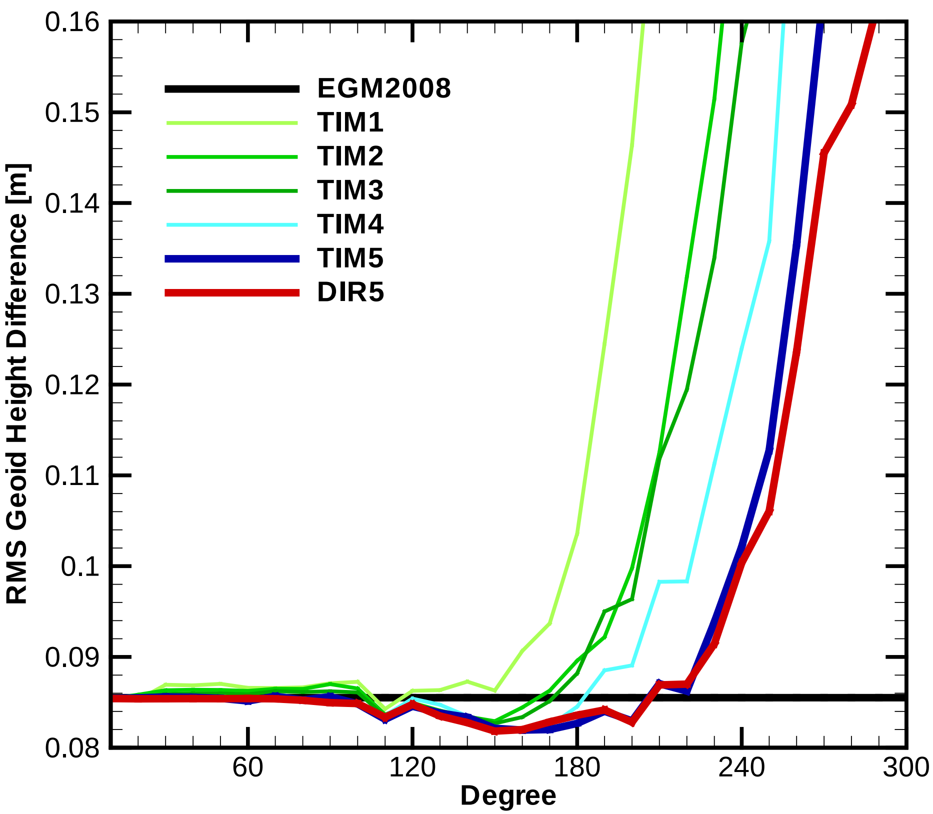
Acknowledgement: GPS levelling data for have been provided for validation purposes by AUSLIG.

Acknowledgement: GPS levelling data for have been provided for validation purposes by Brazilian Institute of Geography and Statistics - IBGE, Directorate of Geosciences - DGC, Coordination of Geodesy - CGED

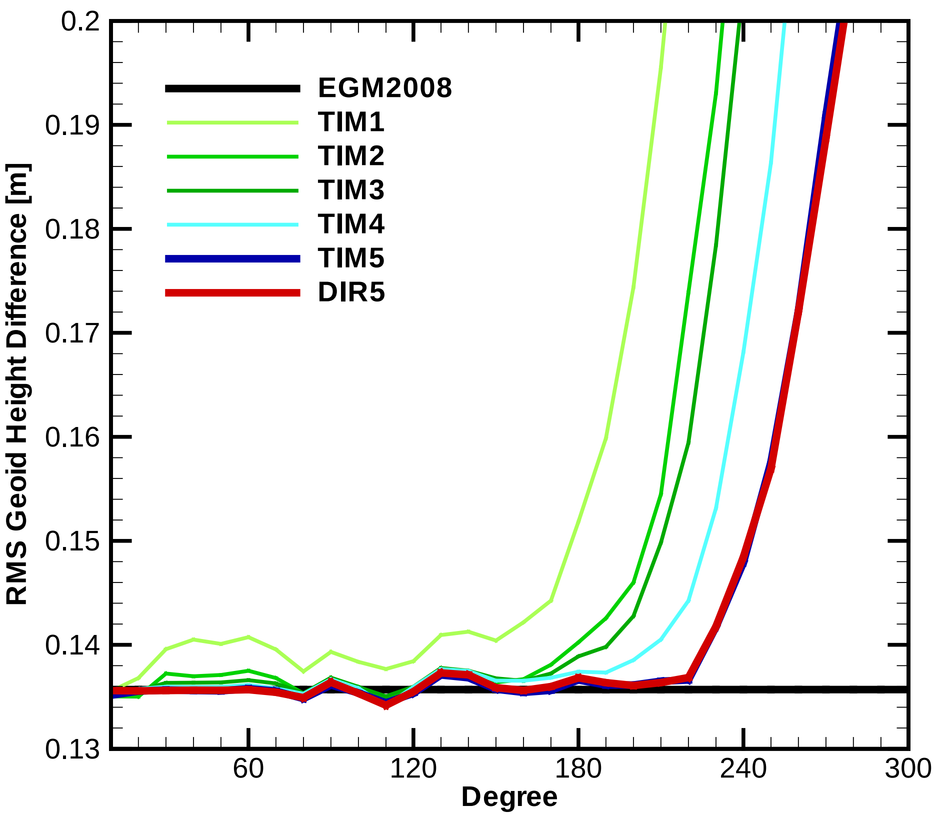
Model Validation

RMS of Geoid Differences at GPS-Levelling Points after planar Fit
(Omission Error estimated from EGM2008)

Canada



Europe (EUREF EUVN)

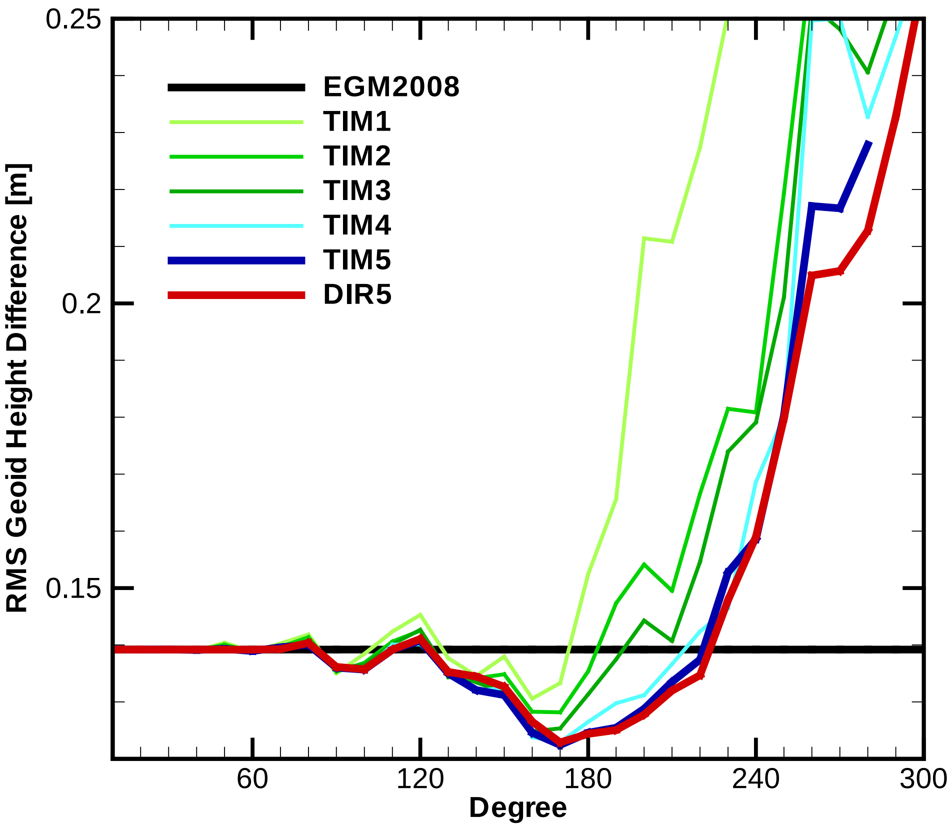


Acknowledgement: GPS levelling data for have been provided for validation purposes by National Resources of Canada (NRCan).

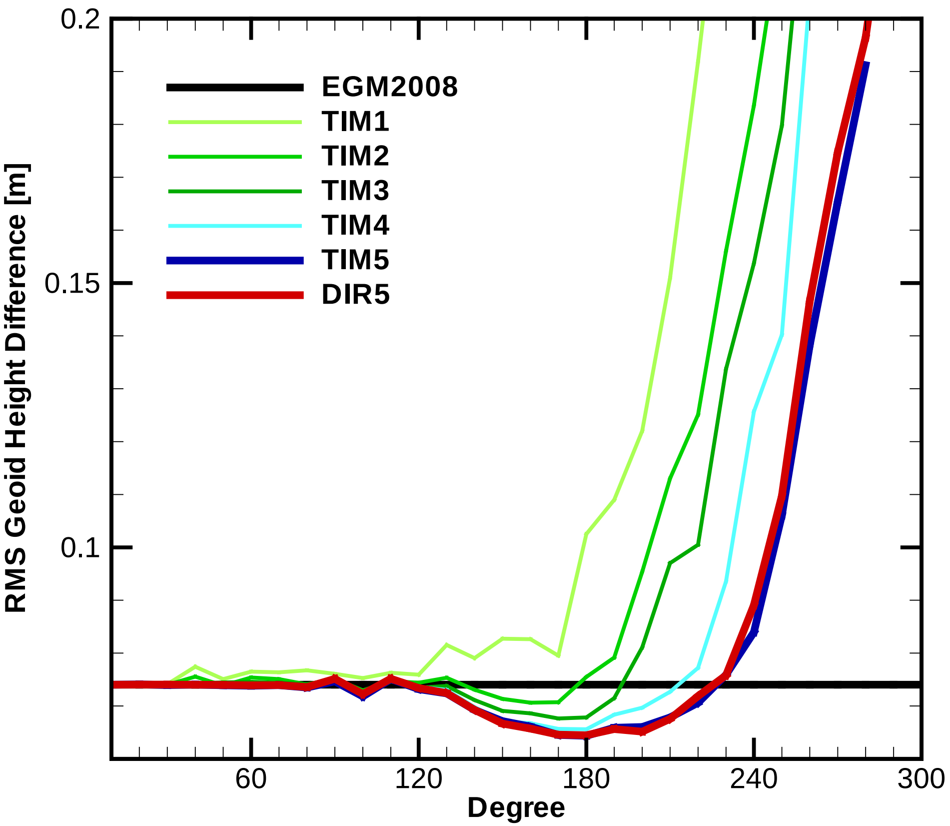
Model Validation

RMS of Geoid Differences at GPS-Levelling Points after planar Fit
(Omission Error estimated from EGM2008)

Greece



Japan



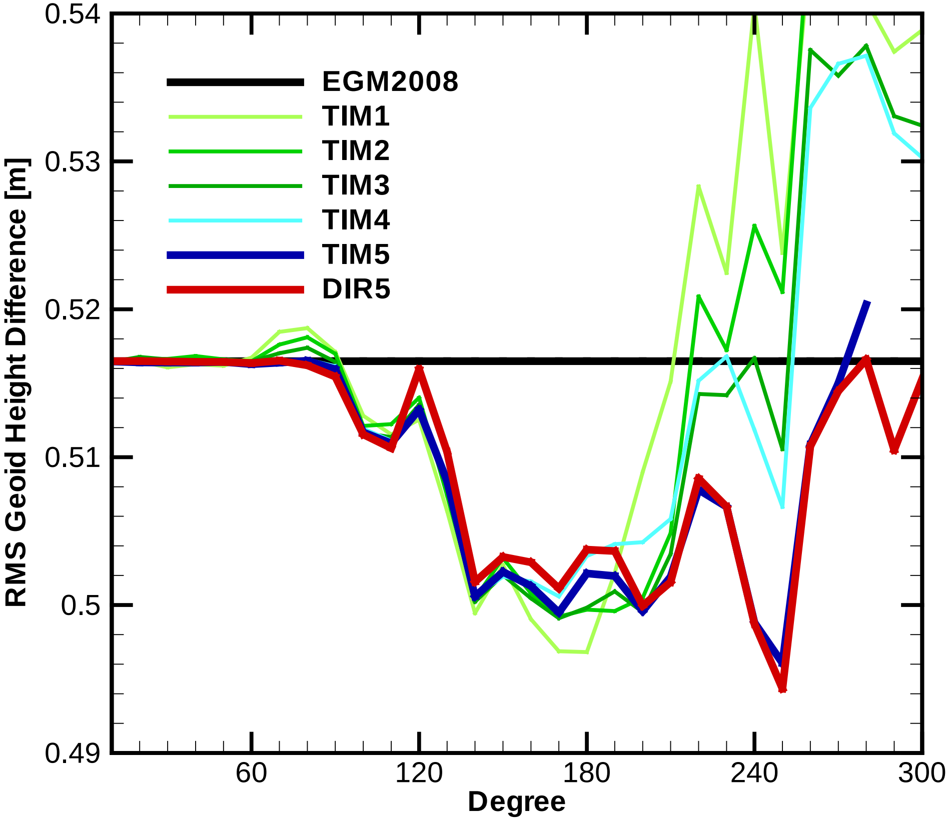
Acknowledgement: Access to GPS levelling data for GREECE has been provided by technical University Thesssaloniki.

Acknowledgement: GPS levelling data for Japan have been provided for validation purposes by the Japanese Geographical Survey Institute

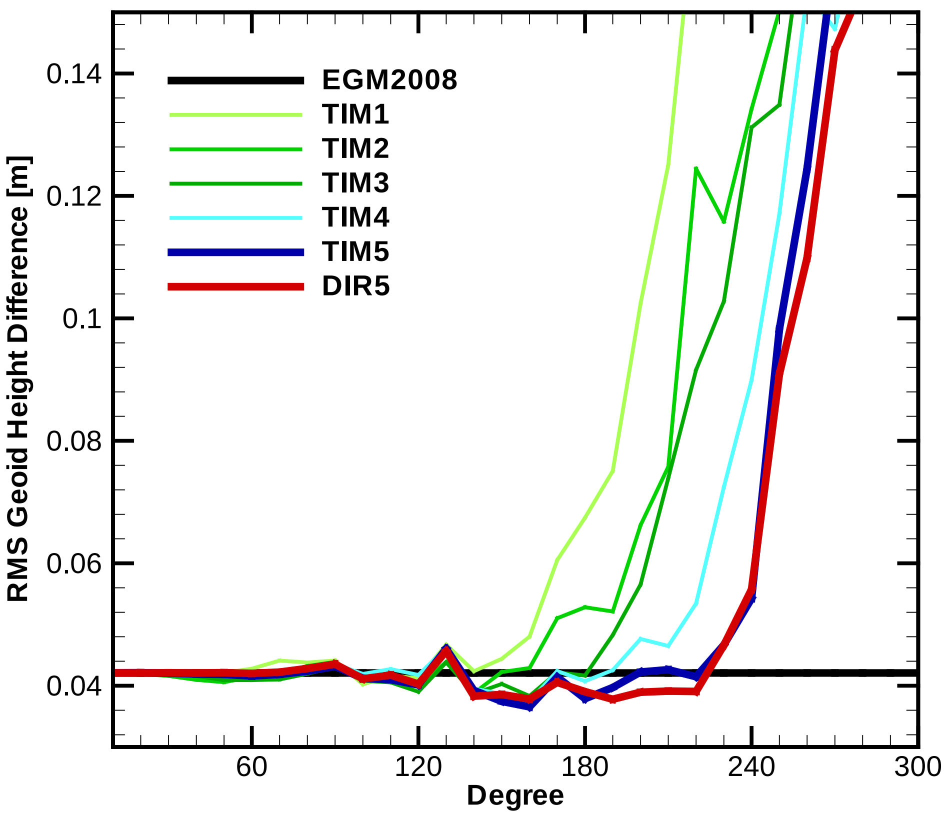
Model Validation

RMS of Geoid Differences at GPS-Levelling Points after planar Fit
(Omission Error estimated from EGM2008)

Saudi Arabia



United Kingdom

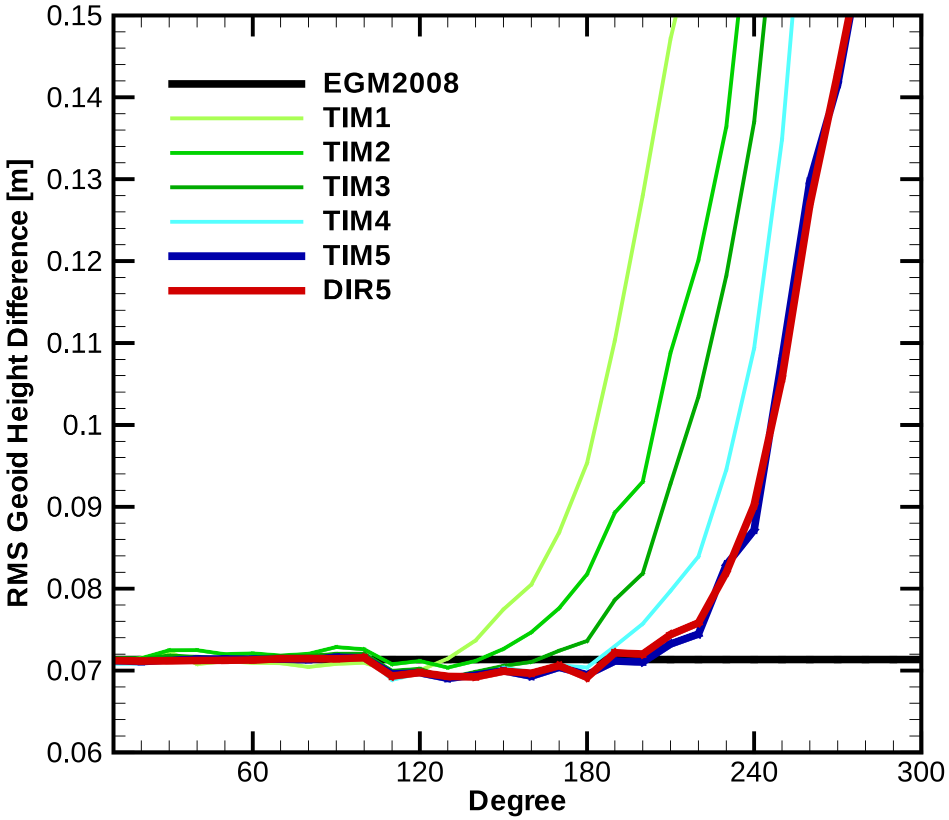


Acknowledgement: GPS levelling data for have been provided for validation purposes by King Abdulaziz City for Science and Technology KACST.

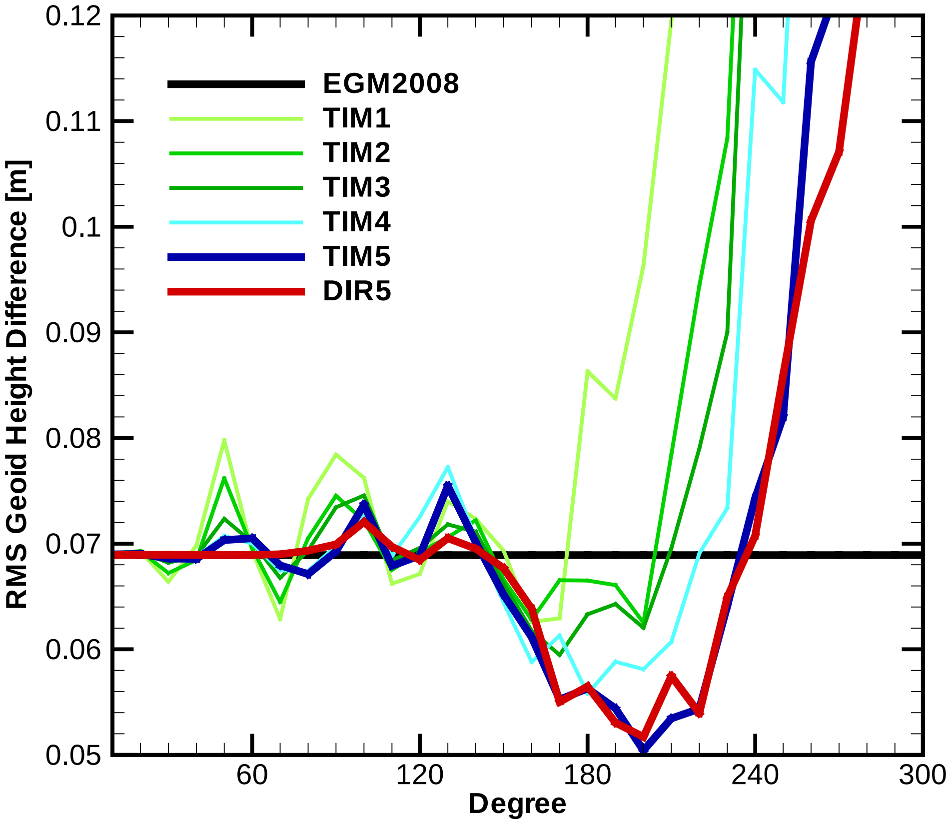
Model Validation

RMS of Geoid Differences at GPS-Levelling Points after planar Fit
(Omission Error estimated from EGM2008)

USA (2009 Data Set)



Finland (EUREF EUVN)



Model Validation

RMS of Geoid Differences at GPS-Levelling Points after planar Fit
(Omission Error estimated from EGM2008)

Areas with High Quality GPS/Levelling Data

Area	RMS [cm]	No. Points
Germany	2.8	675
UK	3.9	177
Netherlands (EUREF)	1.8	15
Sweden (EUREF)	2.6	84
USA2009 - DC	1.9	16
USA2009 – MD	2.4	511
USA2009 - NH	2.6	14
USA2009 - NJ	2.5	326
USA2009 - RI	2.2	29
USA2009 - MN	3.3	4089

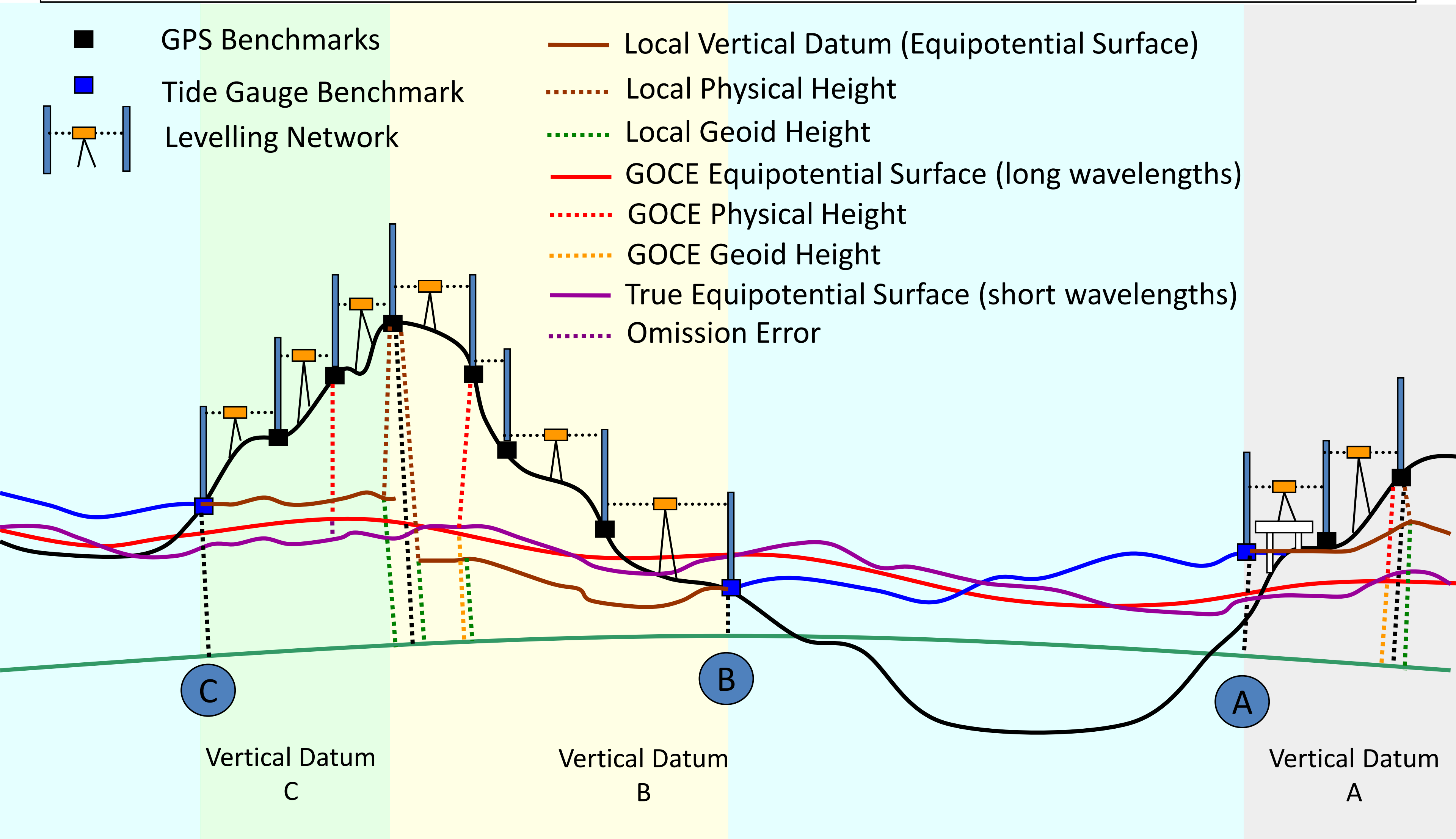
What is the GOCE Geoid Accuracy ?

- Estimated error from GOCE-DIR5 at D/O 200 in Germany (formal): **0.5 cm**
- Estimated error from GOCE-TIM5 at D/O 200 in Germany (calibrated based on gradient residuals): **1.4 cm**
- Differences at GPS/Levelling Stations in Germany for both models at D/O 200 (after planar fit) using EGM2008 for omission error: **2.8 cm**
- GPS/Levelling geoid error is composed by:
  - GPS height error: ≈ 1.5 cm
  - Normal height accuracy after planar fit: ≈ 1.5 cm
  - Error of EGM2008 used for omission error: ≈ 1.0 cm
  - Total after error propagation: **2.4 cm**
- Attempt to derive a realistic error:
  - GOCE geoid error (reverse error propagation) → **1.4 to 1.5 cm**

Summary GOCE Models

- Full signal of GOCE-based satellite-only model up to degree and order 210-220.
- Fit to “quiet” ocean area at a level of 0.7 mgal in terms of gravity anomaly or 2.6 cm in terms of geoid – geoid more sensitive to dynamic ocean topography.
- Estimated cumulative geoid error at d/o 200 for Germany, 0.5 and 1.4 cm respectively.
- GPS-leveling fits significantly improved wrt. release 4 models (now 2.8 cm RMS in Germany , about 1 cm better than rel. 4).
- Estimated absolute geoid error of rel. 5 models at d/o 200 roughly 1.8 cm or better.

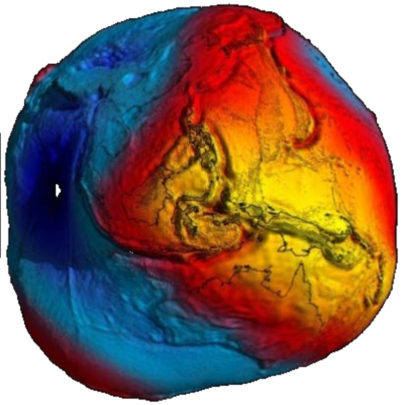
Height Systems - Problem Overview



Scientific Roadmap – Essential Tasks

The geopotential and geoid improvements resulting from GOCE are the basis of a reassessment of global height systems

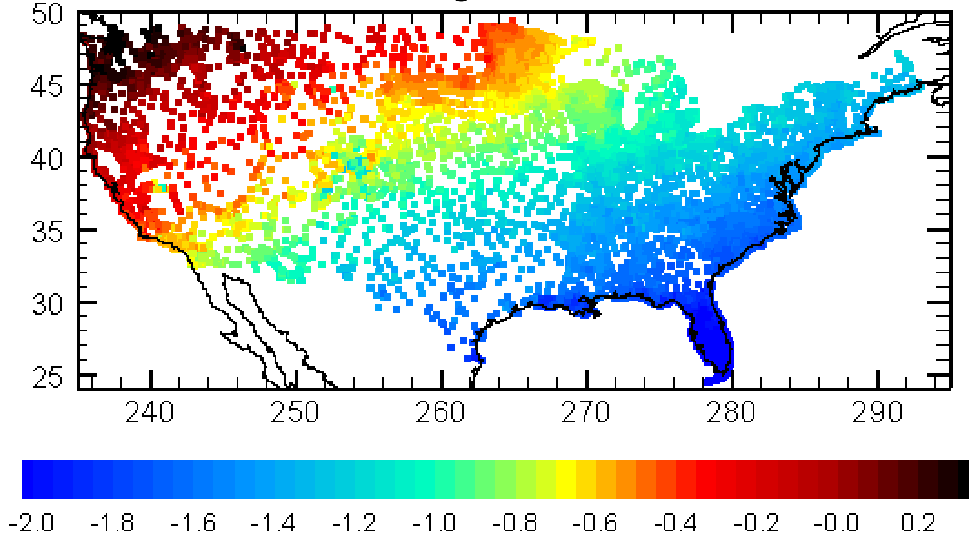
Diagnosis of existing height systems by comparison with GOCE geoid



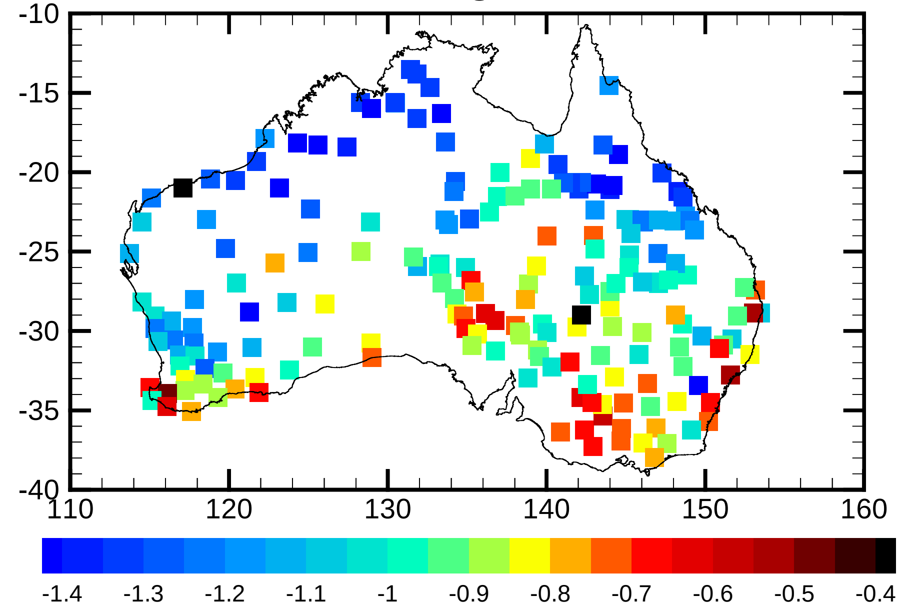
Scientific Roadmap – Diagnosis of Height Systems

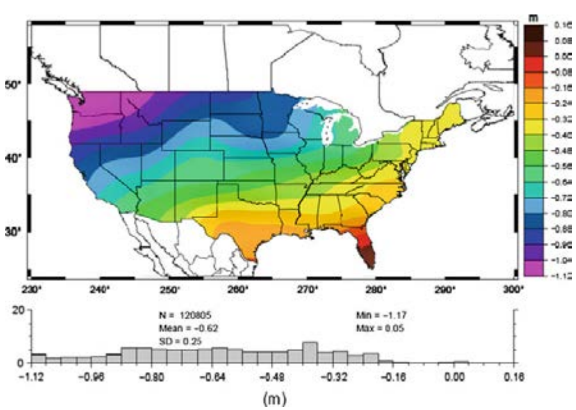
Diagnosis of existing Height Systems by Comparison of GPS/Levelling with GOCE Geoid

US GPS/Levelling vs. GOCE-TIM5 Geoid



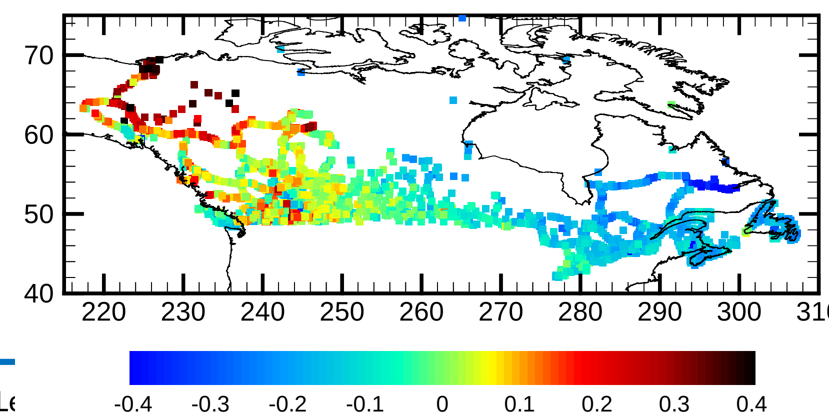
Australian GPS/Levelling vs. GOCE-TIM5 Geoid





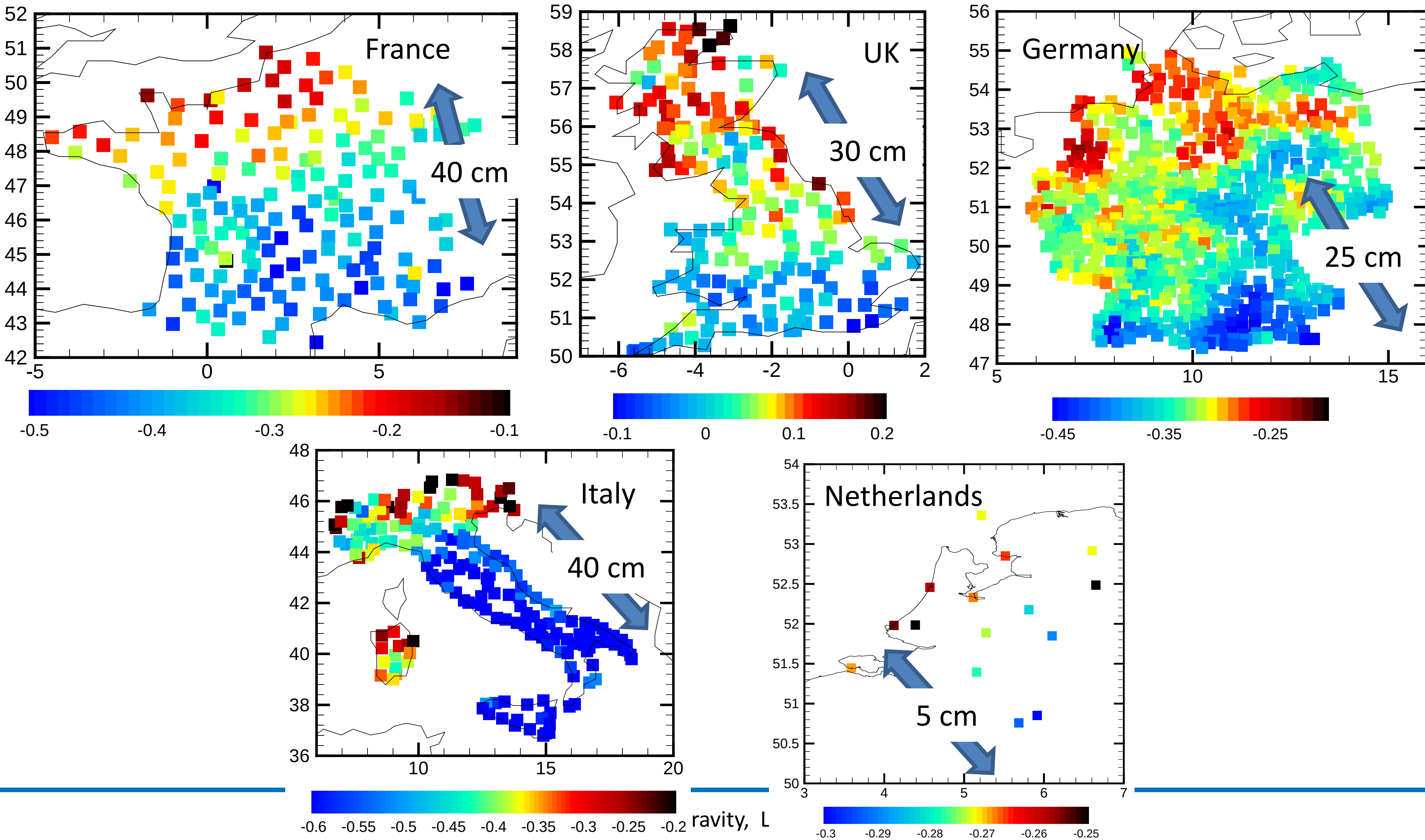
Reference:
Long-wavelength errors of the US vertical datum (Wang et al., 2012)

Canadian GPS/Levelling vs. GOCE-TIM5 Geoid

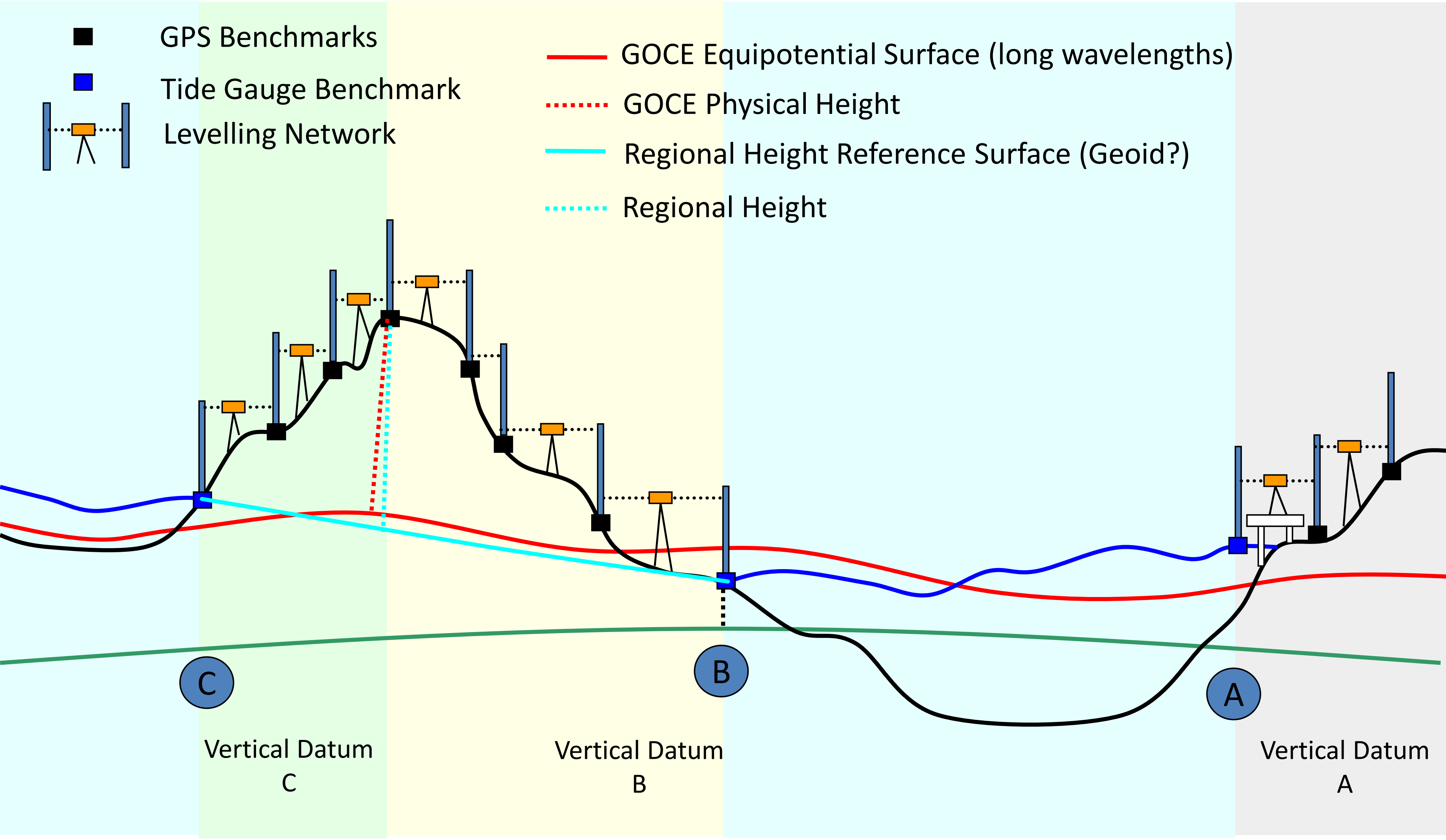


Scientific Roadmap – Diagnosis of Height Systems

Diagnosis of existing Height Systems by Comparison of GPS/Levelling with GOCE-TIM5 Geoid for some European Countries

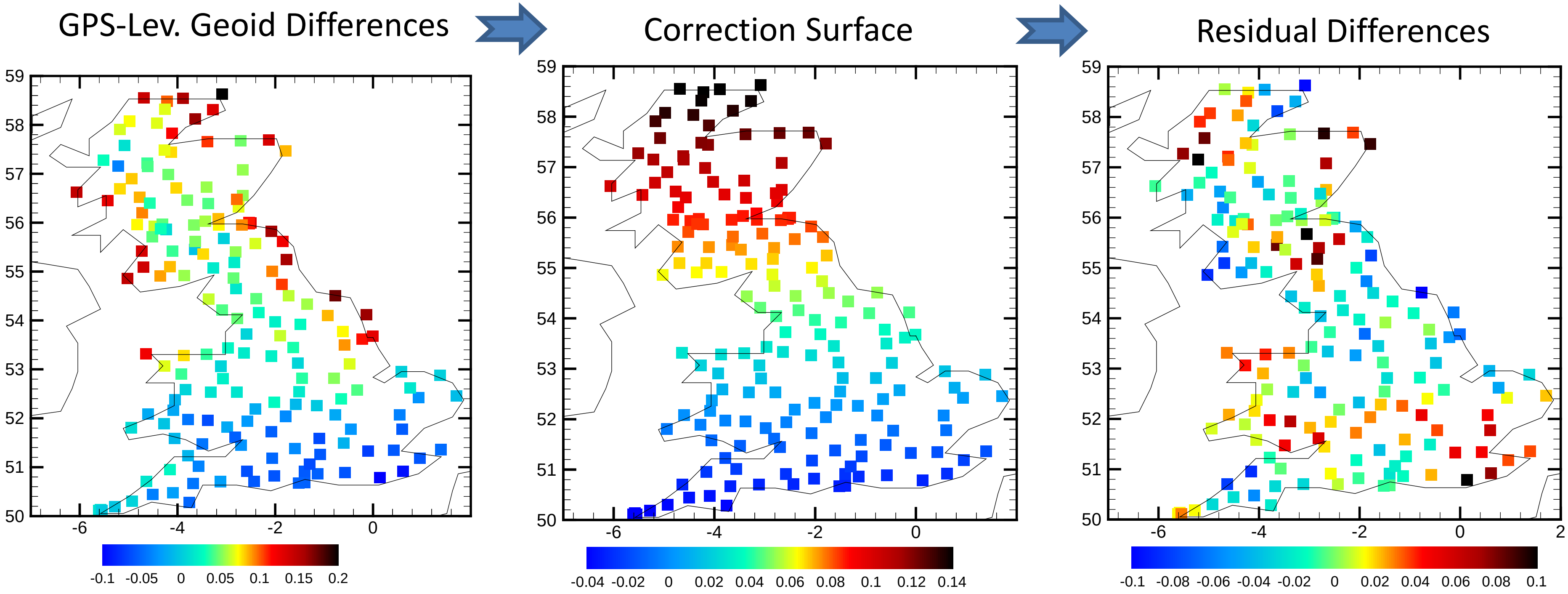


Scientific Roadmap – Diagnosis of Height Systems



Scientific Roadmap – Diagnosis of Height Systems

Diagnosis of existing Height Systems by Comparison of GPS/Levelling with GOCE-TIM5
- before and after subtracting a regional Correction Surface

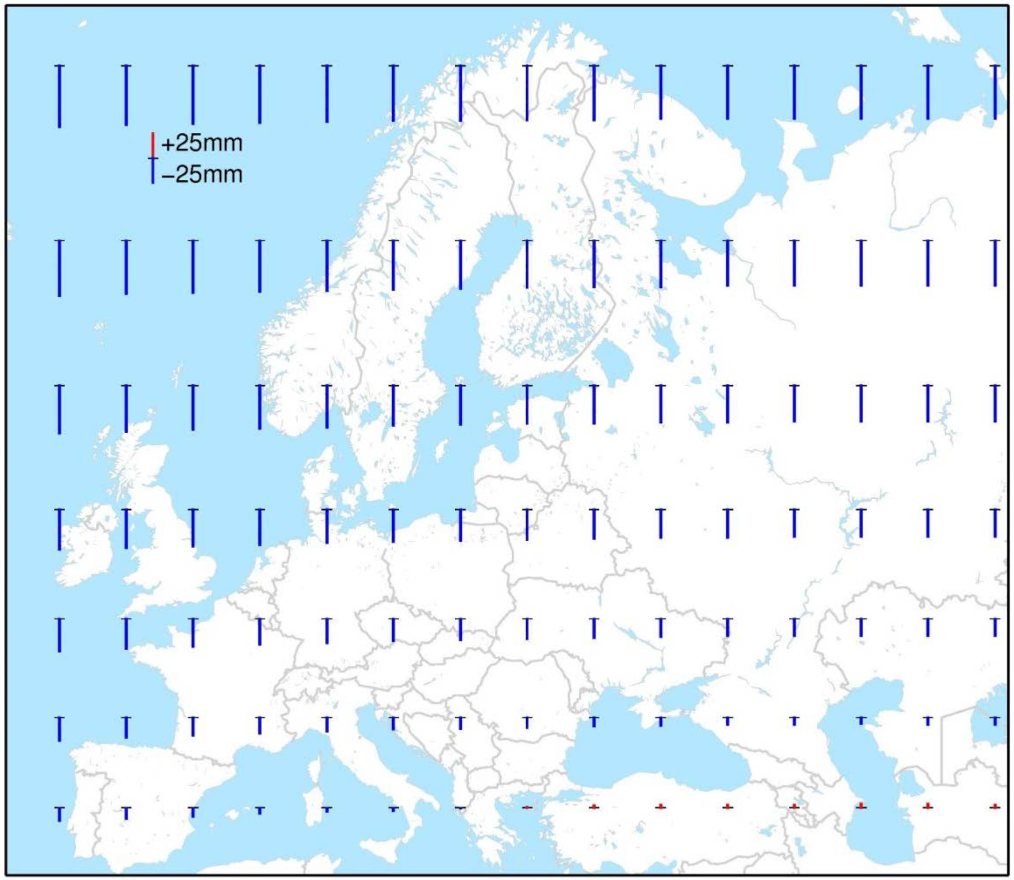


What causes these systematic differences: GOCE geoid, Levelling or GPS Heights?

- GOCE geoid error is below 2 cm globally – cannot be the reason.
- Levelling is sensitive to systematic distortions – most likely the main reason.
- Observation GPS height error 1-2 cm randomly distributed – cannot be the reason.
- But what about the coordinate frames?

Scientific Roadmap – Diagnosis of Height Systems

Impact of Coordinate Frame Transformations on GPS Heights
(Study performed by G. Liebsch, BKG)



- GPS and geoid heights need to be in a consistent frame.
- GOCE geoid heights refer to CoM.
- GPS heights refer to an ITRFxxxx with a center of origin which is not consistent to CoM.
- ITRF2008 is known to be close to CoM.
- ITRF1989 (ETRF1989) to ITRF2008 offset is (x,y,z): 2.8 - 3.9 - 10.1 cm
- 7 parameter Helmert transformation (plus linear trends) result in height change of up to 7 cm in Europe (see figure).
- When GPS and GOCE geoid heights are jointly used in GPS-Levelling this needs to be taken into account.

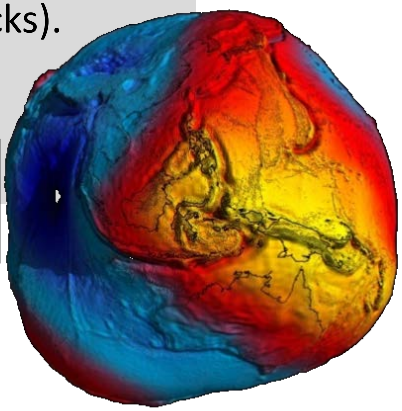
Scientific Roadmap – Essential Tasks

The geopotential and geoid improvements resulting from GOCE are the basis of a reassessment of global height systems

Global Height System Unification

Realization of a globally unified height system but confined to a **global set of primary stations** (national datum points, fundamental stations, primary tide gauges, primary clocks).

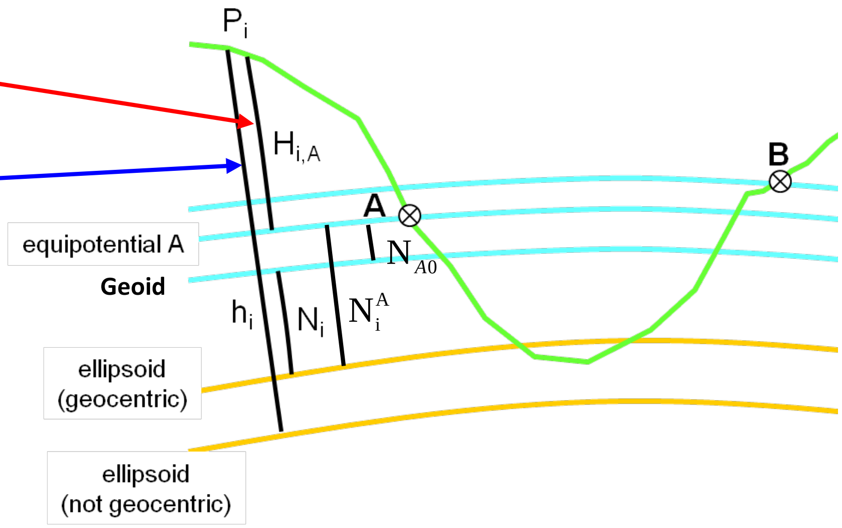
Diagnosis of existing height systems by comparison with GOCE geoid (100 km)



Scientific Roadmap – Global Height System Unification

H_{iA} from spirit levelling referring to height datum A (e.g. tide gauge)

h_i from GNSS positioning referring to a specific ellipsoid



Observed Geoid Height referring to vertical Datum A

$$N_i^A = h_i - H_{iA}$$

Computed Geoid Height referring to "mean" Geoid

$$N_i = N_i^{GOCE} + N_i^{res}$$

N_i^{GOCE} Geoid height from GOCE model

N_i^{res} Residual geoid height (omission)

N_{A0} Geoid Height Offset of vertical Datum A wrt. "mean" Geoid.

Observation Equation

$$\Delta N = N_i^A - (N_i^{GOCE} + N_i^{res})$$

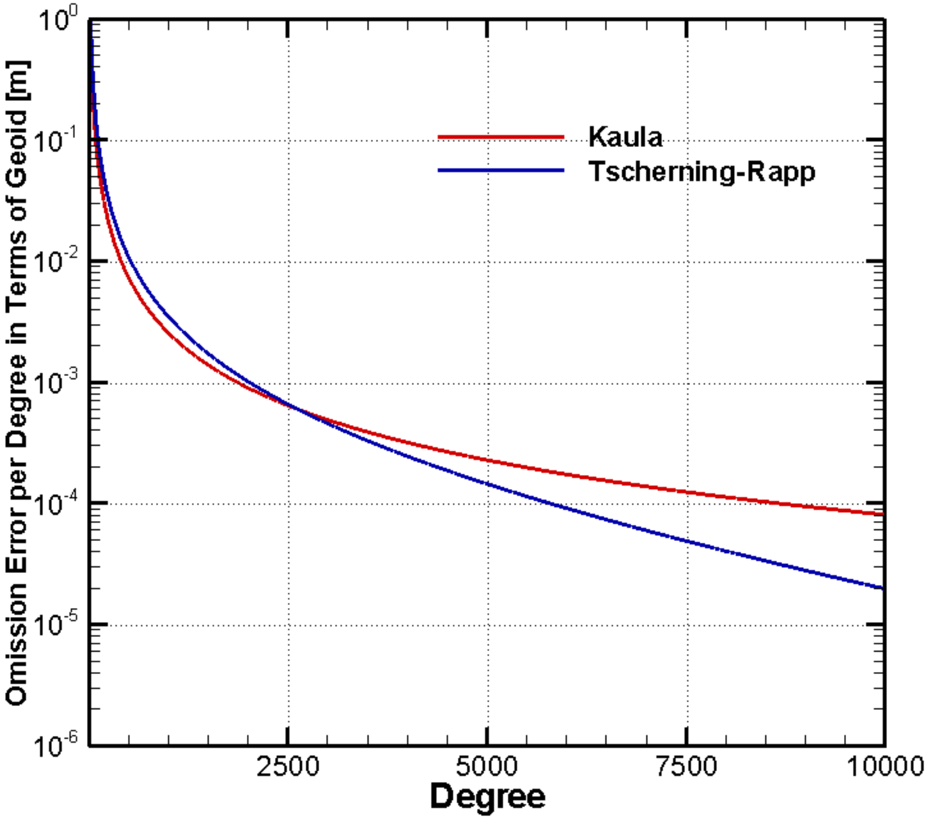
Height System Offset wrt. Geoid

$$N_{A0} = Mean(\Delta N)$$

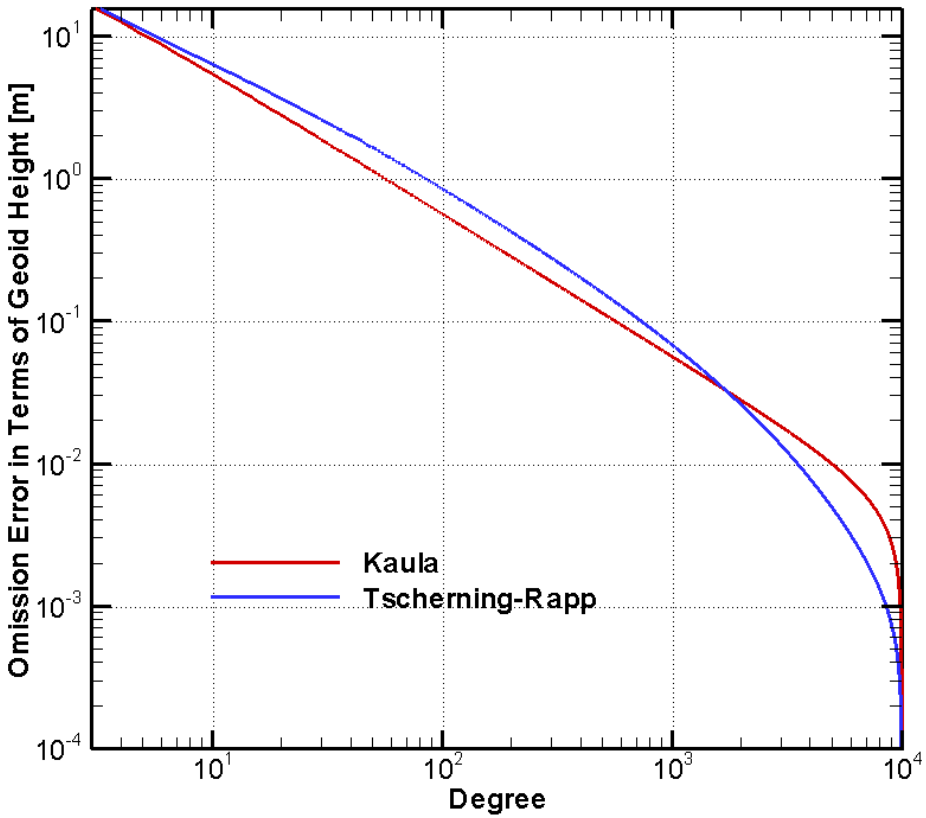
Scientific Roadmap – Global Height System Unification

Omission Error

per degree



from degree (to infinity)

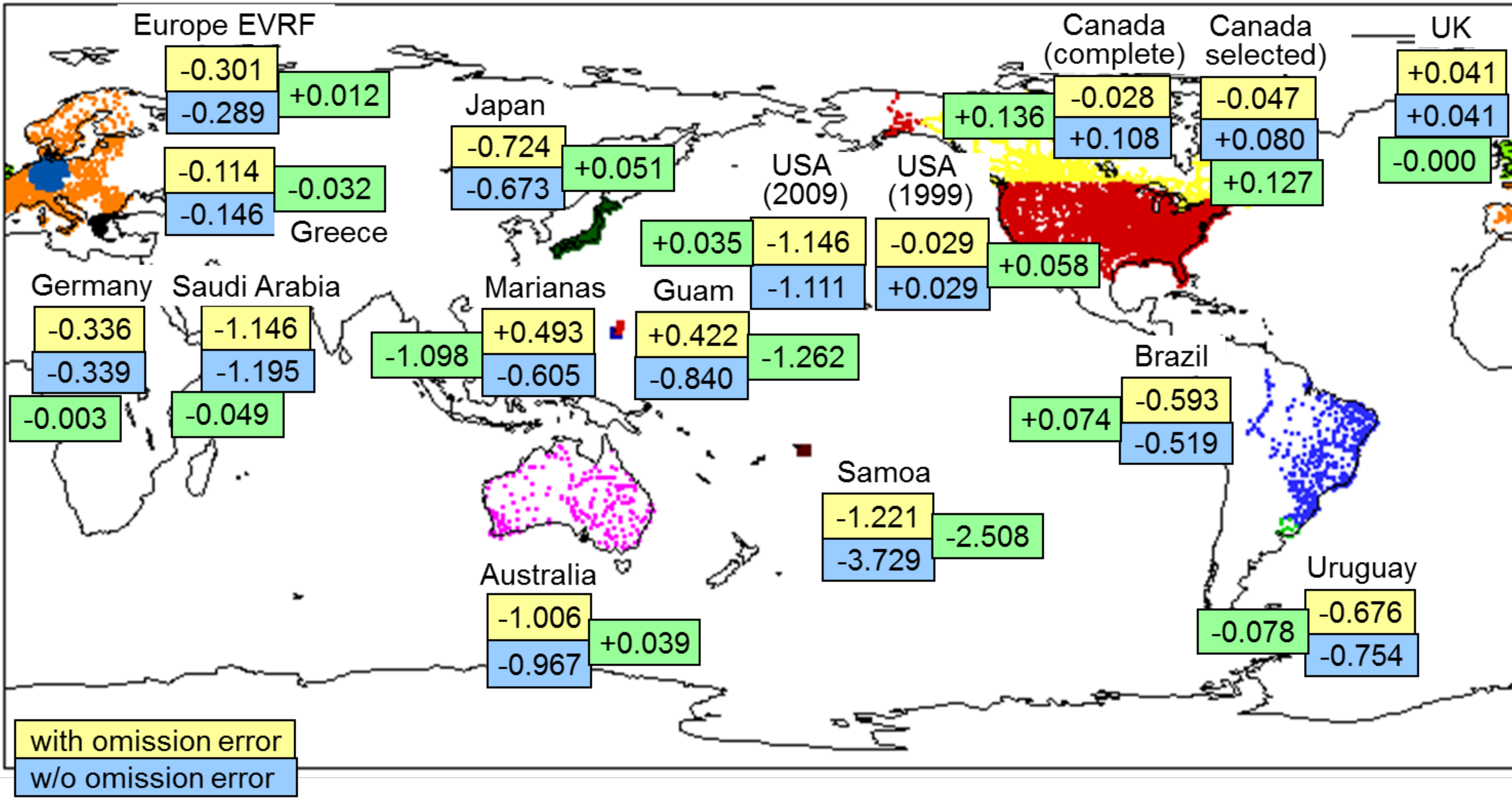


Omission error can be estimated from EGM2008 and/or residual terrain modelling

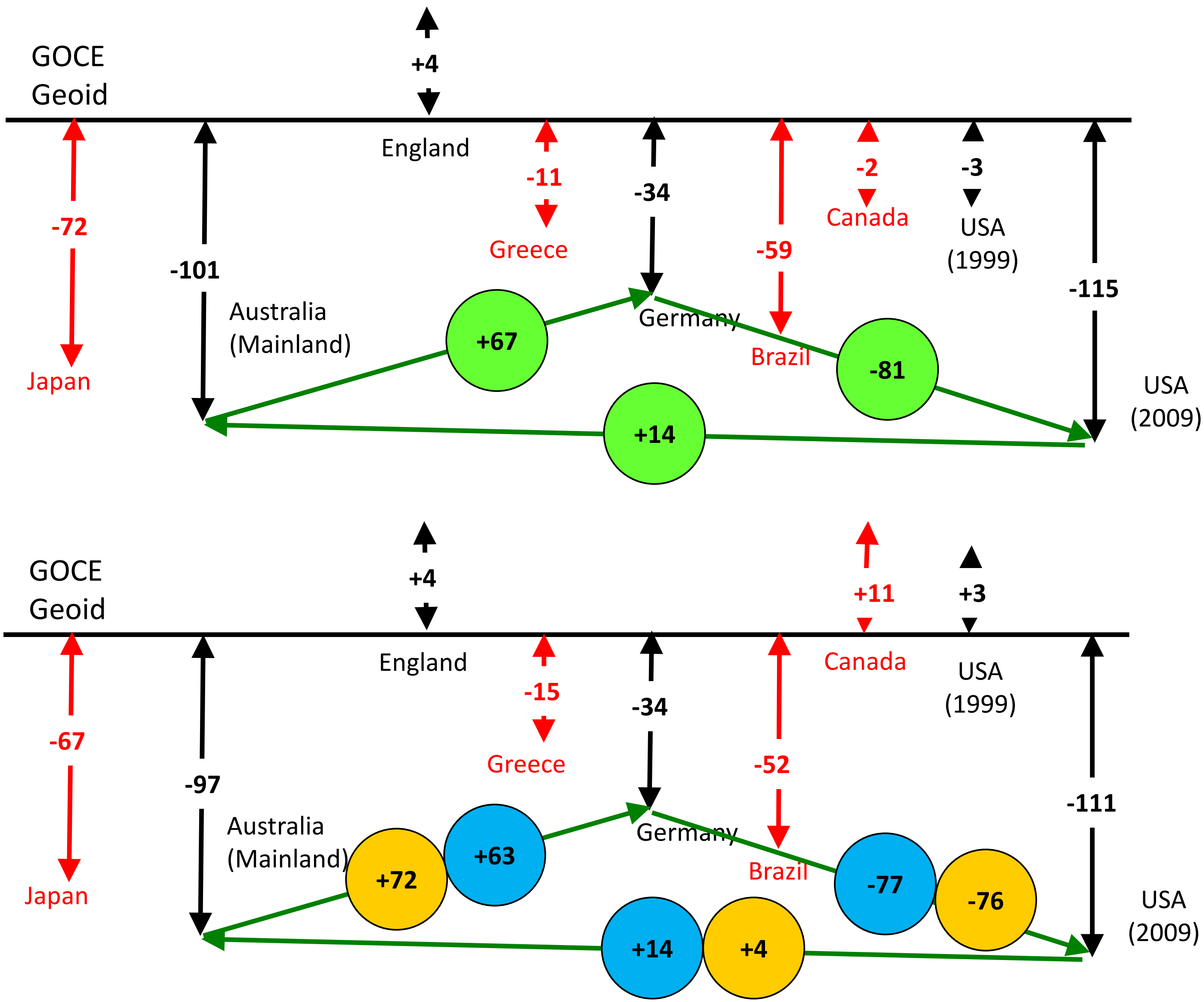
Scientific Roadmap – Global Height System Unification

GOCE –TIM5 Model truncated at D/O 200

$$N_{A0} = Mean(\Delta N)$$



Scientific Roadmap – Global Height System Unification



GOCE-TIM5 (0-200) & EGM2008 (201-2190)

GOCE-TIM5 (0-200)

Results from Rapp (1994) (Bulletin Geodesique 69, p.26-31) based on JGM-2 / OSU91A and Geoid Heights on Doppler Stations.

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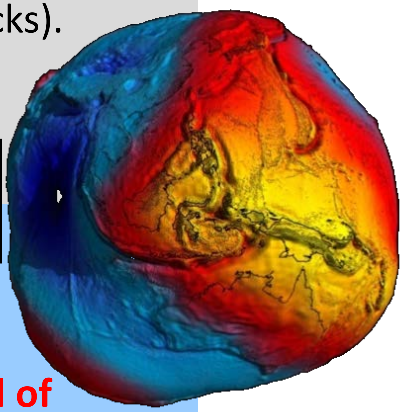
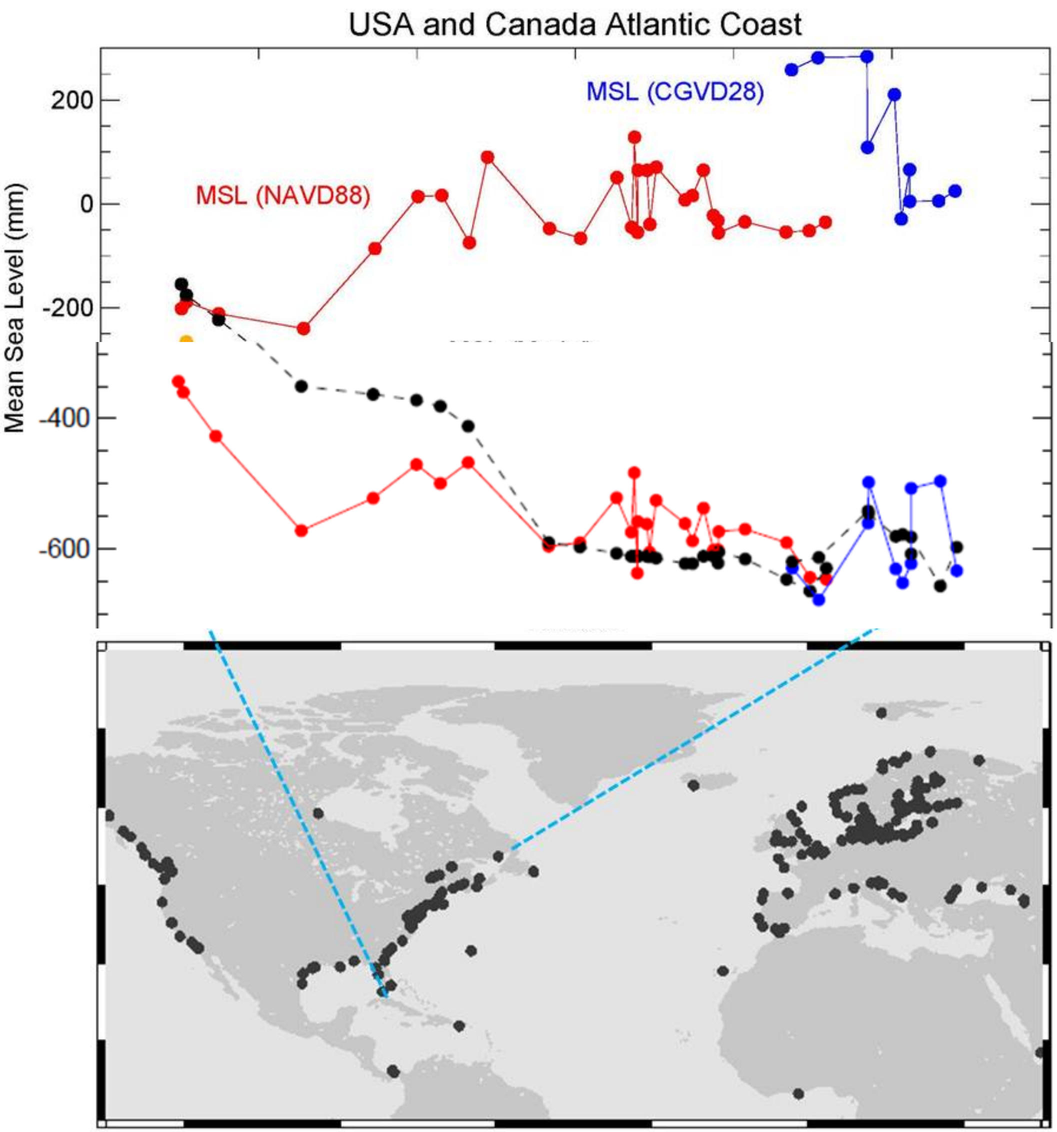


Realization of a **globally consistent model of mean dynamic ocean topography** at tide gauges and at sea (**Ocean Levelling**).

Open Oceans and Coastal Zones

Scientific Roadmap – Ocean Levelling



(Study performed by Phil Woodworth, NOC)

Sea level slope at tide gauges along the east coast of North America from

- classical geodetic leveling (**top**: **USA in red**, **Canada in blue**),
- from an ocean circulation model (**black**) and
- from GNSS-Levelling based on GOCE DIR5 & EGM2008 (**bottom: red & blue**)

Scientific Roadmap – Essential Tasks

The geopotential and geoid improvements resulting from GOCE are the basis of a reassessment of global height systems

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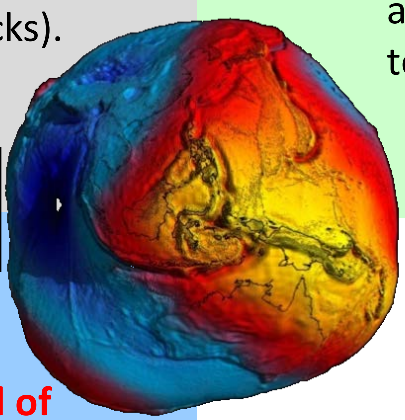


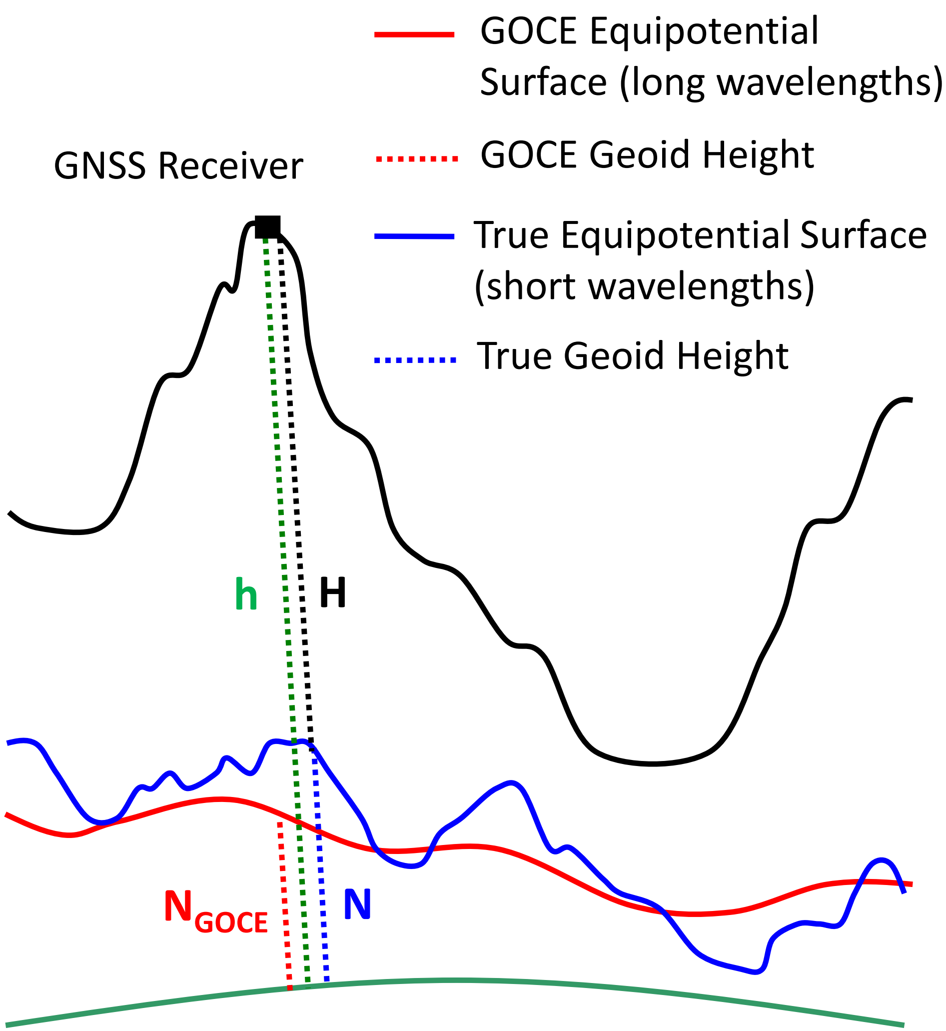
Well Surveyed Areas (Land)

Regional geoid based on GOCE model. Establishment of **national or regional height systems at primary points** (first and second order) based on the technique of "**GNSS-leveling**".

Realization of a **globally consistent model of mean dynamic ocean topography** at tide gauges and at sea.

Open Oceans and Coastal Zones

Scientific Roadmap – Well Surveyed Areas



Assumptions:

(1) Network of permanent, high quality GNSS stations. Observation of h

(2) GOCE geopotential/geoid model. Determination of N_{GOCE}

(3) Regional gravity and topographic data.

(4) Refined GOCE geoid model leading to a regional geoid. Determination of N

(5) Consistent reference frames for h and N_{GOCE} / N

$$H = h - N$$

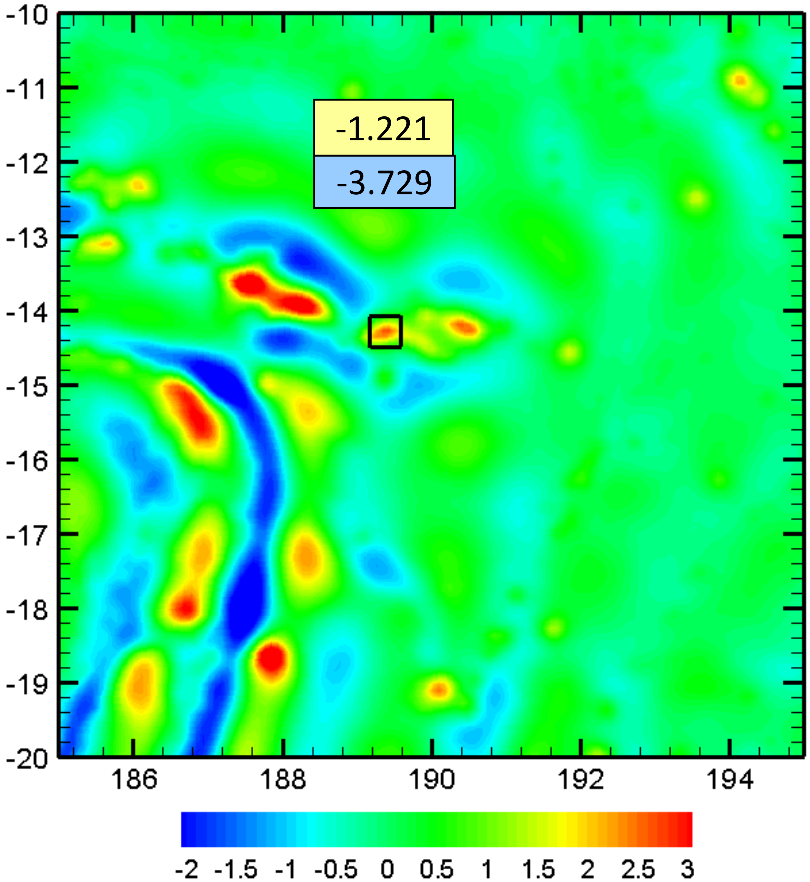
$$H = h - N_{GOCE}$$

$$\text{Omission Error} = N - N_{GOCE}$$

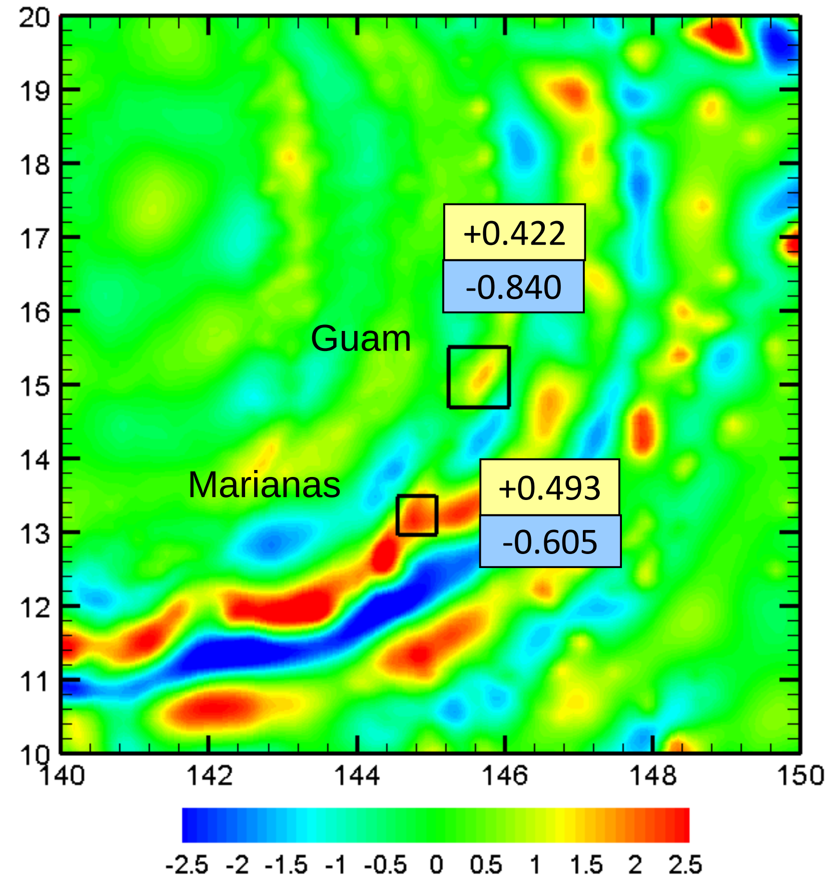
Scientific Roadmap – Well Surveyed Areas

Mean Differences of GOCE TIM5 and GPS-Levelling Geoid Heights &
Omission Error from EGM2008 from D/O 181 to 2190

Samoa



Guam & Marianas



w/o omission error (signal) | with omission error (signal)

Scientific Roadmap – Essential Tasks

The geopotential and geoid improvements resulting from GOCE are the basis of a reassessment of global height systems

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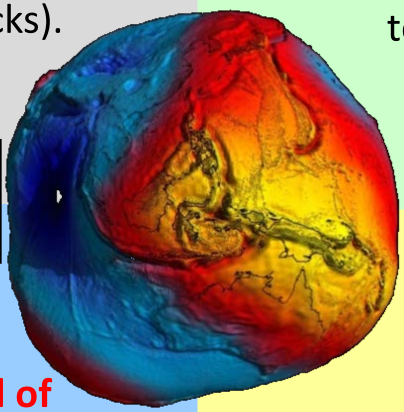
Well Surveyed Areas (Land)

Establishment of **national or regional height systems at primary points** (first and second order) based on the technique of "**GNSS-leveling**".



Realization of a **globally consistent model of mean dynamic ocean topography** at tide gauges and at sea.

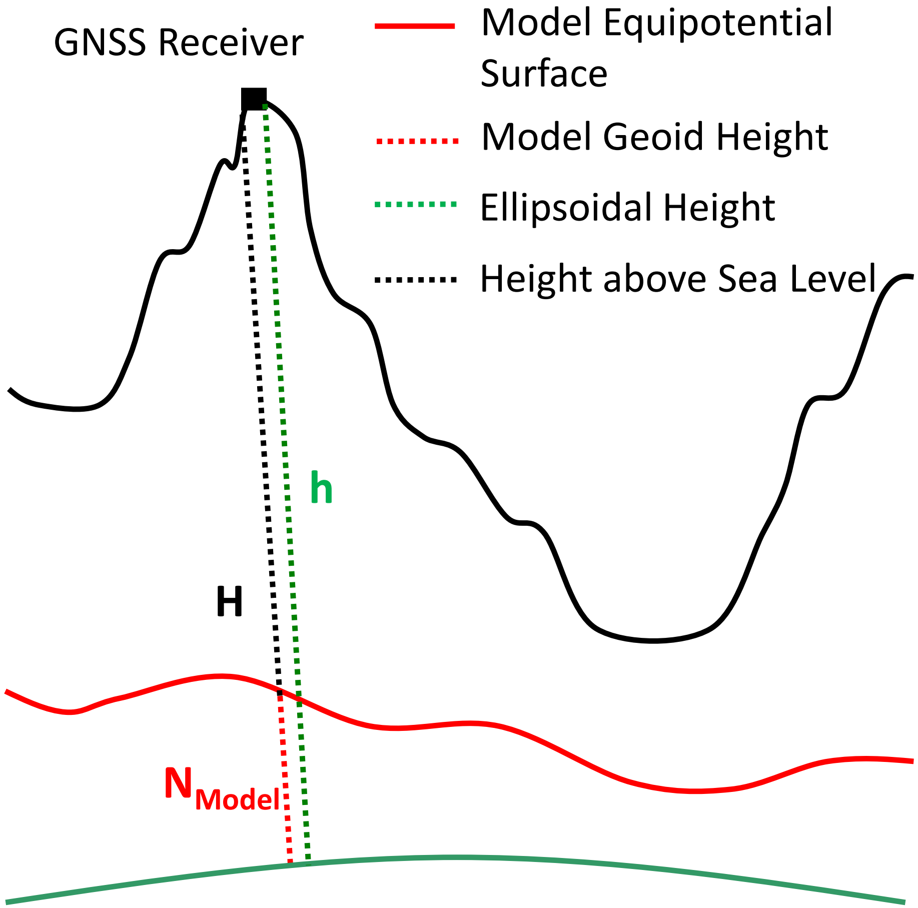
Open Oceans and Coastal Zones

Establishment of a master plan:

- realization of datum point
- first-order **GNSS reference points**
- diagnosis of **regional** gravity and/or leveling and/or topographic **data base**

Sparsely Surveyed Areas (Land)

Scientific Roadmap – Sparsely Surveyed Areas



Large uncertainty in omission error estimate due to lack of gravimetric data.

Height of Mount Everest:

h = 8821.47 m (average from GPS and classical techniques for snow surface)

(Chen, J. et al, 2006, Science in China; doi: 10.1007/s11430-006-0531-1

Model geoid height for H=0

N_{GOCE}	= -26.58 m	(GOCE-TIM5 d/o 280)
N_{EGM}	= -22.90 m	(EGM2008 d/o 2190)
$N_{GOCE/EGM}$	= -22.19 m	(GOCE-TIM5 d/o 200 & EGM2008 d/o 201-2190)

Model geoid height from height anomaly and correction terms (c.f. Rapp, 1997, JoG).

$N_{EGM/Rapp}$ = -28.50 m (EGM2008 d/o 2190)

this leads to heights above sea level:

H_{GOCE}	= 8848.05 m	
H_{EGM}	= 8844.37 m	
$H_{EGM/Rapp}$	= 8849.97 m	
H_{Chen}	= 8847.93 m	(based on local geoid)

Summary Height Systems

- The GOCE geoid represents a reference for global and regional height systems with unprecedented spatial resolution.
- GOCE enables the diagnosis of systematic distortions in existing height systems.
- GOCE enables global height system unification if the omission error at height reference stations can be quantified.
- The GOCE geoid supports results obtained from ocean models at tide gauges.
- GOCE supports GNSS/Levelling.
  - In well surveyed areas a GOCE based regional geoid and consistent reference frames shall be used.
  - In sparsely surveyed areas the GOCE geoid in many cases represents the best possible reference surface. Data for regional geoid modelling have to be acquired.

Final Remarks on Height Systems

Project results are available at the following web-site:

http://www.goceplushsu.eu