Scientific Roadmap towards Height System Unification with GOCE

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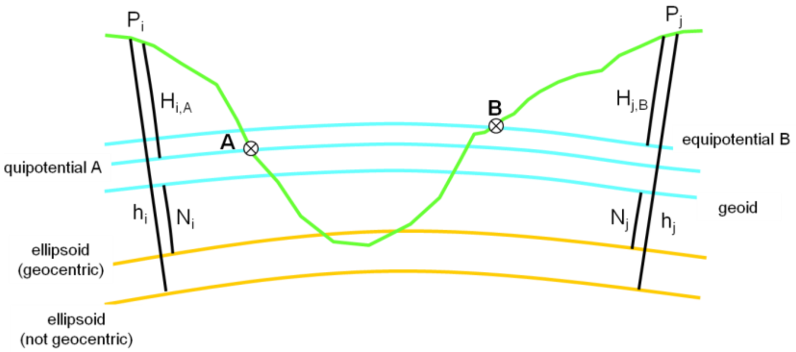
ESA Project:
Support to Science Element (STSE) GOCE+
Theme 1: Height System Unification (HSU)

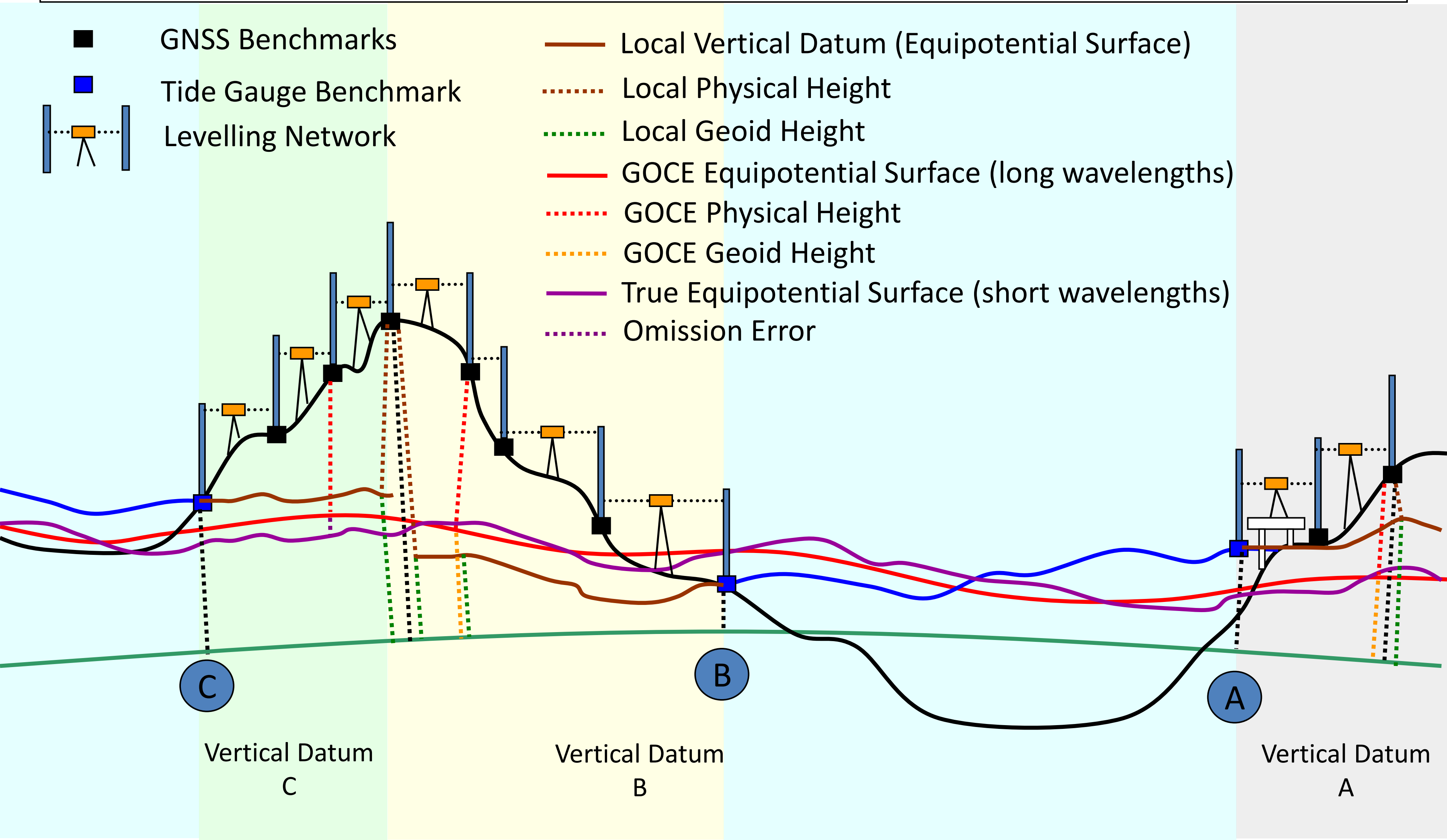
Outline

- Problem Overview
- Essential Tasks (Scientific Roadmap)
  - Diagnosis of Height Systems
  - Global Height System Unification
  - Ocean Levelling
  - GNSS/Levelling in well surveyed Land Areas
  - GNSS/Levelling in sparsely surveyed Land Areas
- Conclusions

Upper-Rhine Bridge; Germany – Switzerland:
27 cm height offset applied with wrong sign



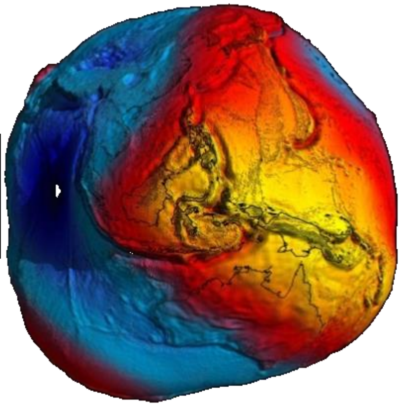
Problem Overview



Scientific Roadmap – Essential Tasks

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

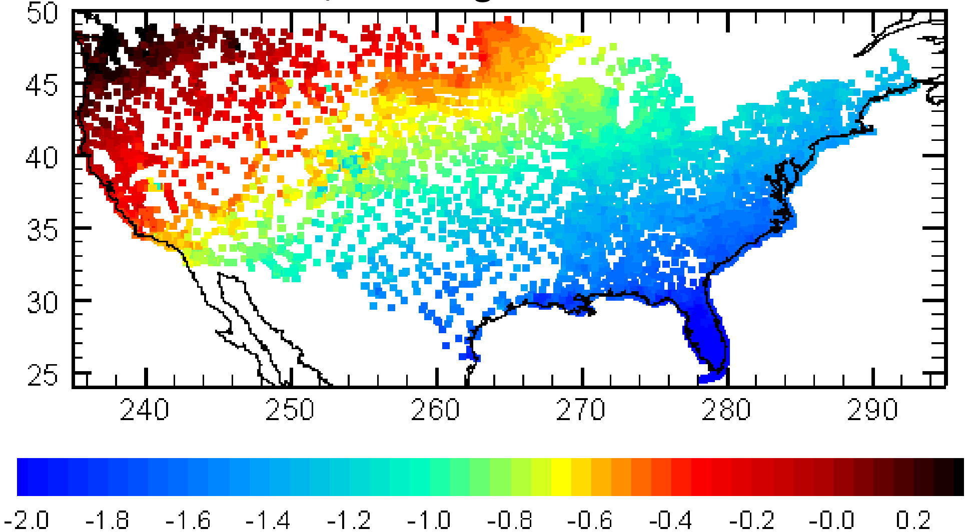
Diagnosis of existing height systems by comparison with GOCE geoid



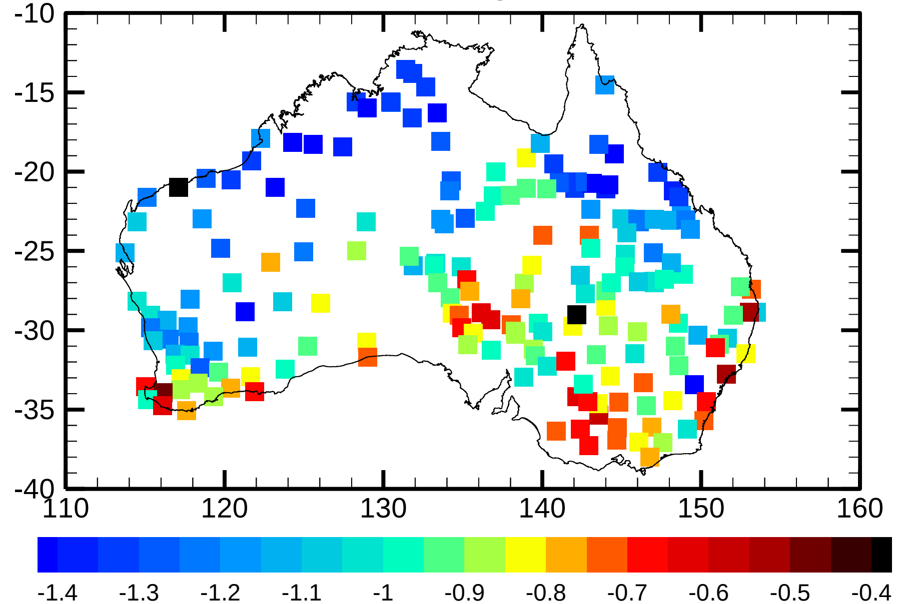
Scientific Roadmap – Diagnosis of Height Systems

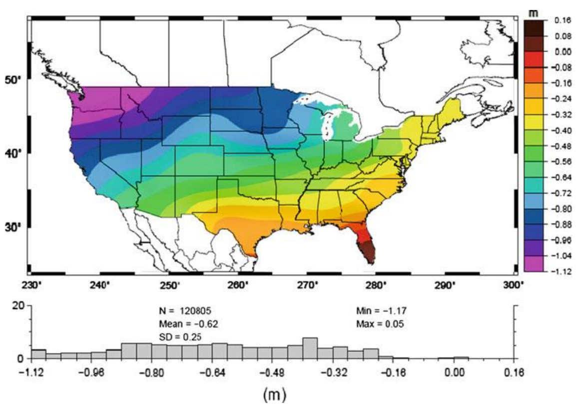
Diagnosis of existing Height Systems by Comparison of GNSS/Levelling with GOCE Geoid

US GNSS/Levelling vs. GOCE-TIM5 Geoid



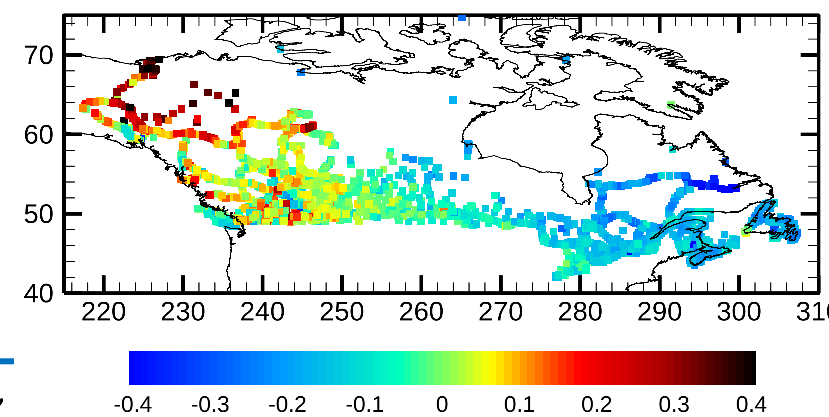
Australian GNSS/Levelling vs. GOCE-TIM5 Geoid





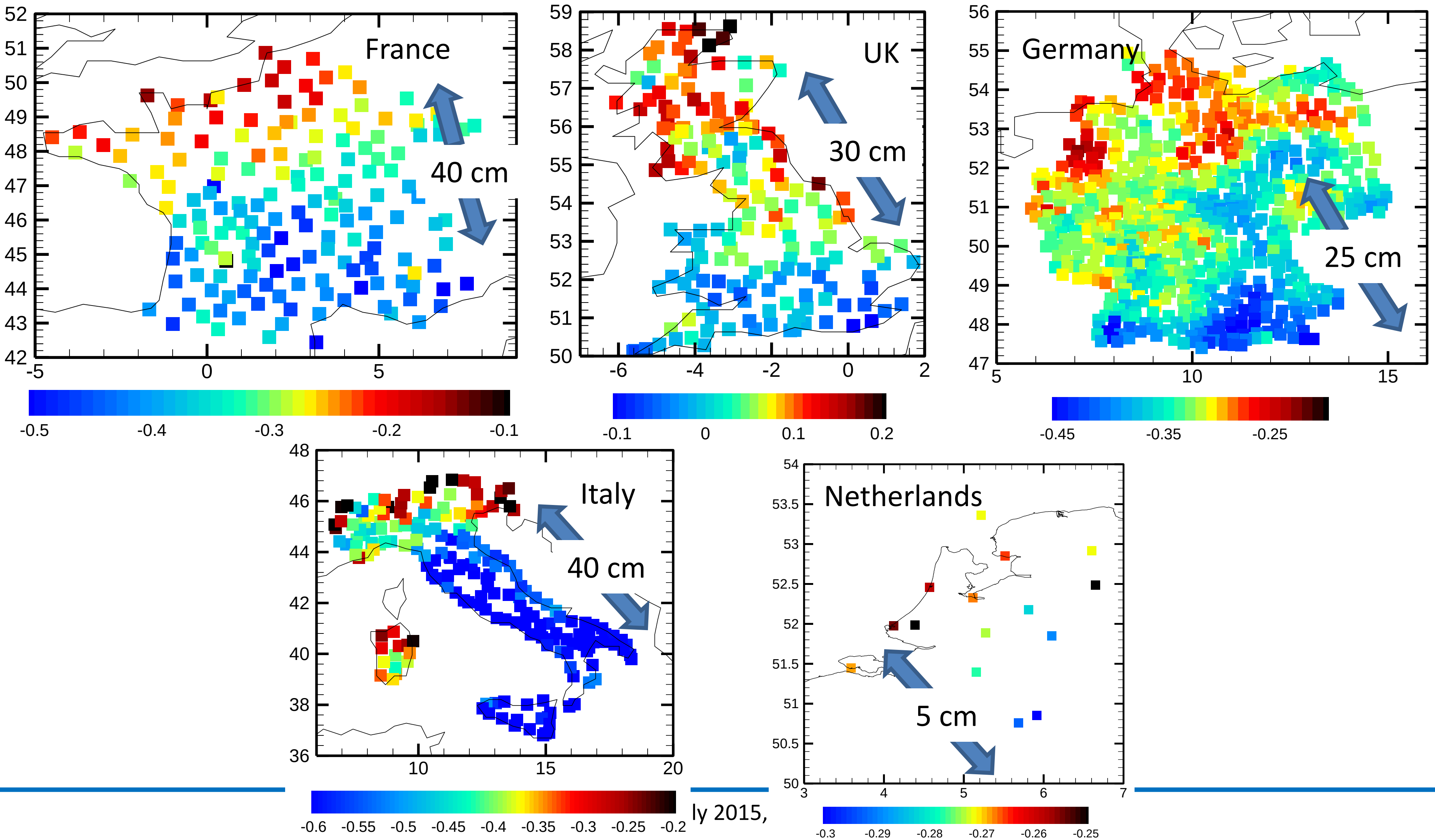
Reference:
Long-wavelength errors of the US vertical datum (Wang et al., 2012)

Canadian GNSS/Levelling vs. GOCE-TIM5 Geoid

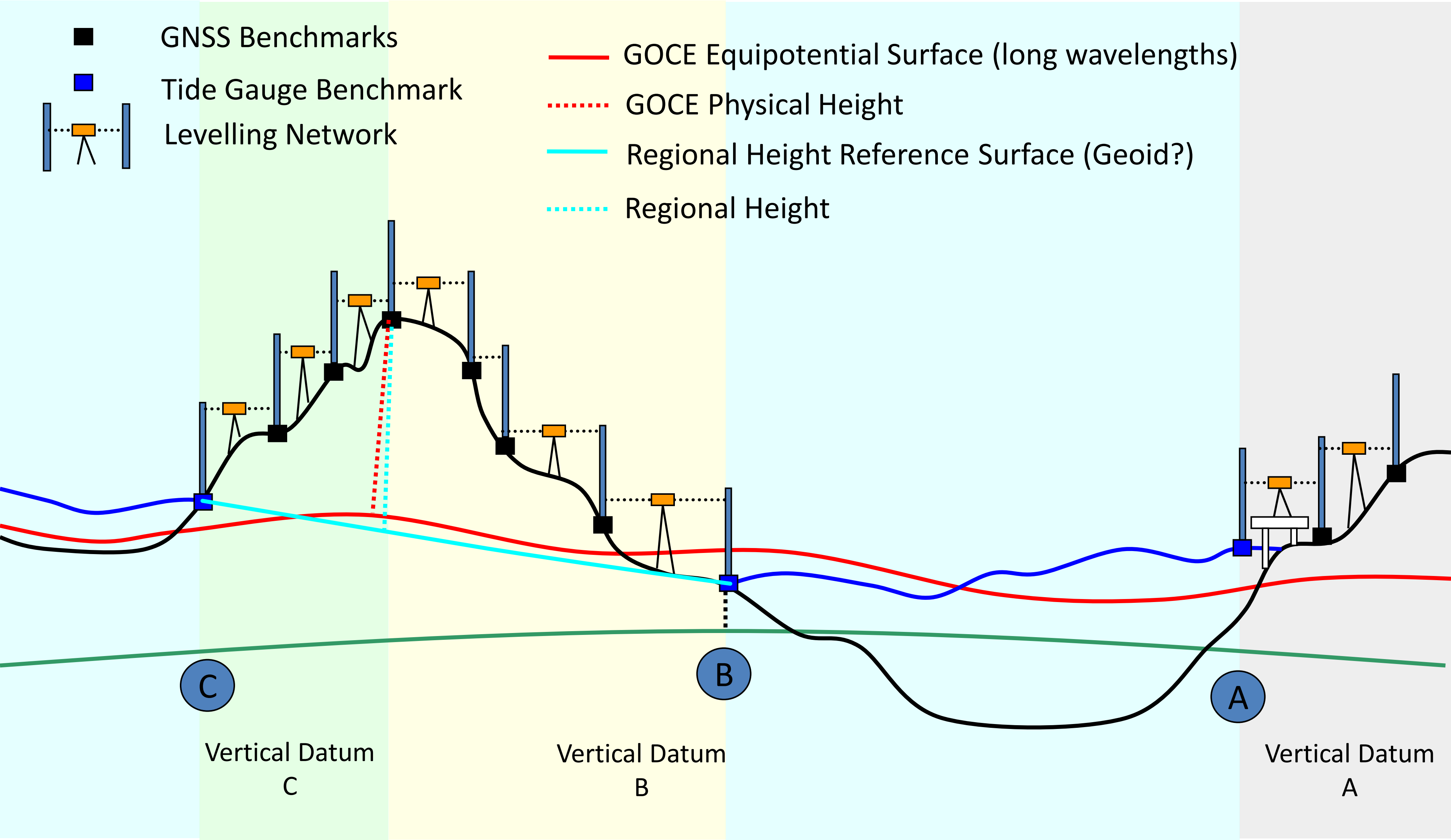


Scientific Roadmap – Diagnosis of Height Systems

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



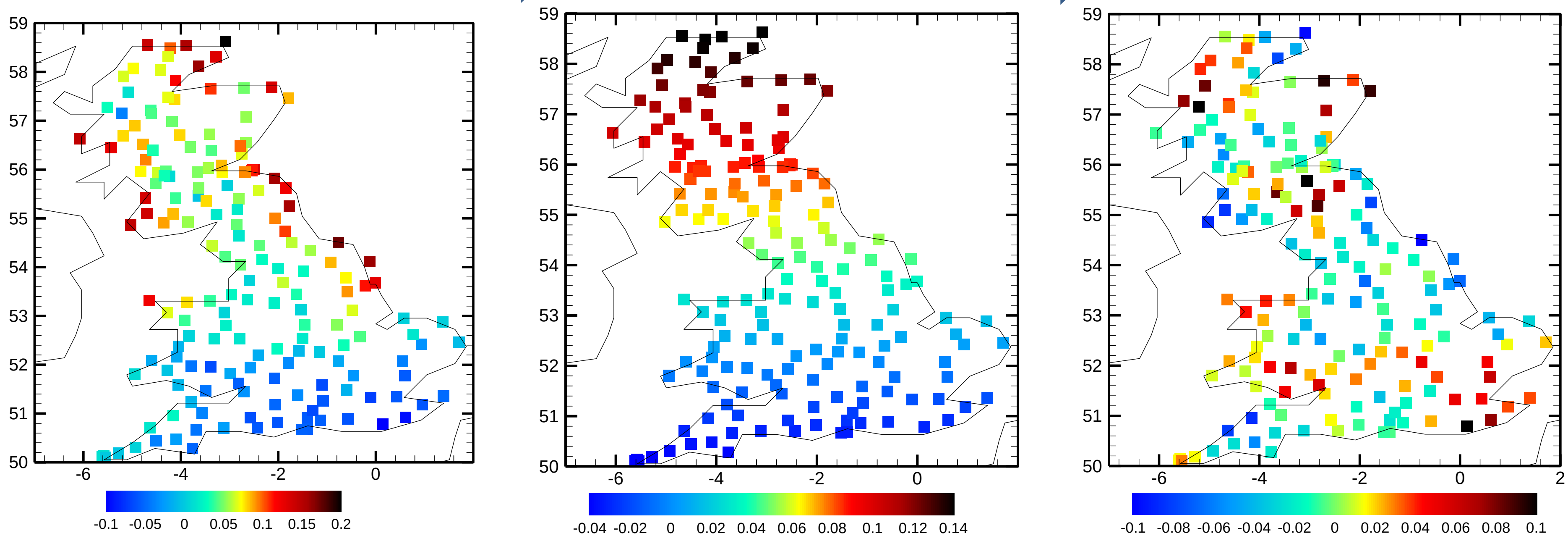
Scientific Roadmap – Diagnosis of Height Systems



Scientific Roadmap – Diagnosis of Height Systems

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

GPS-Lev. Geoid Differences → Correction Surface → Residual Differences



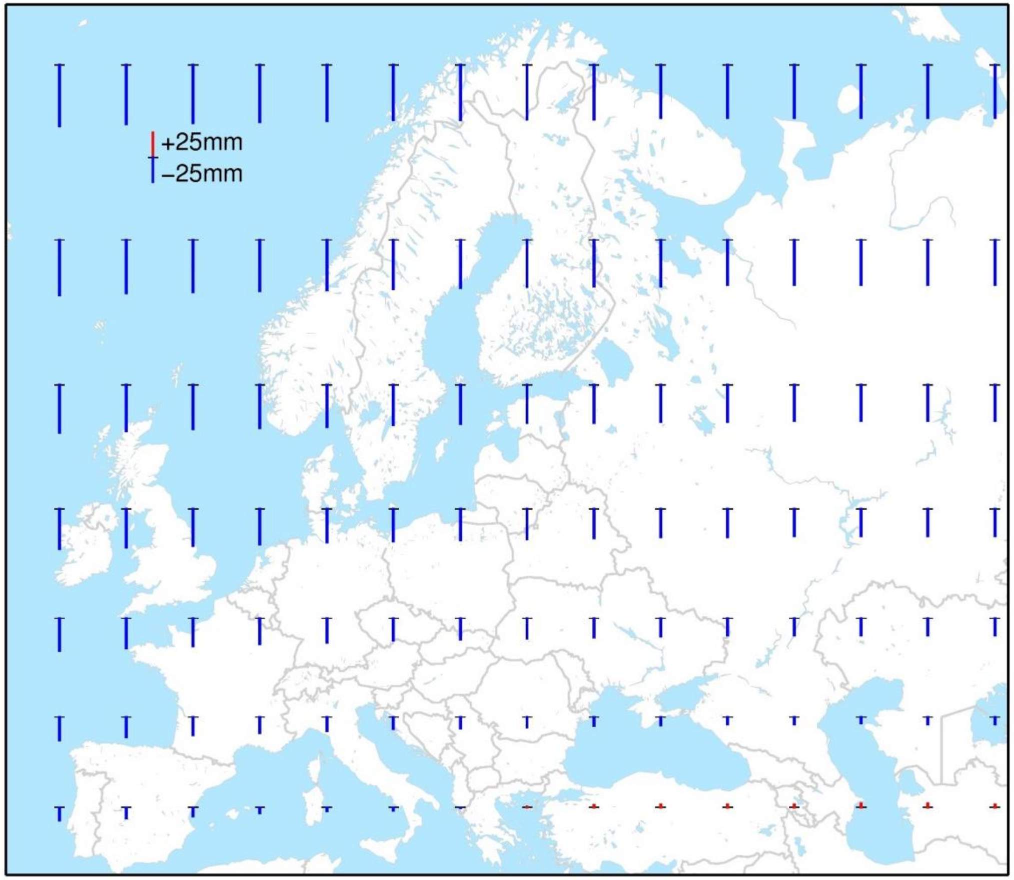
What causes these systematic differences: GOCE geoid, Levelling or GNSS Heights?

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

Scientific Roadmap – Diagnosis of Height Systems

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

ITRF1989 – ITRF2008



- GNSS and geoid heights need to be in a consistent frame.
- GOCE geoid heights refer to CoM.
- GNSS 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 GNSS and GOCE geoid heights are jointly used in GNSS-Levelling this needs to be taken into account.

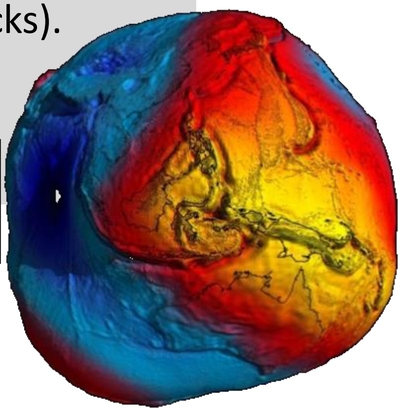
Scientific Roadmap – Essential Tasks

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).

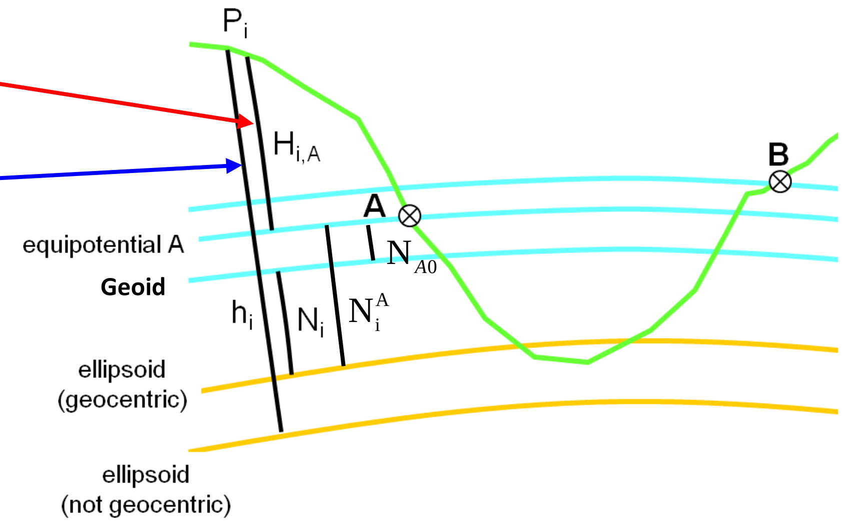
Diagnosis of existing height systems by comparison with GOCE geoid (100 km)



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

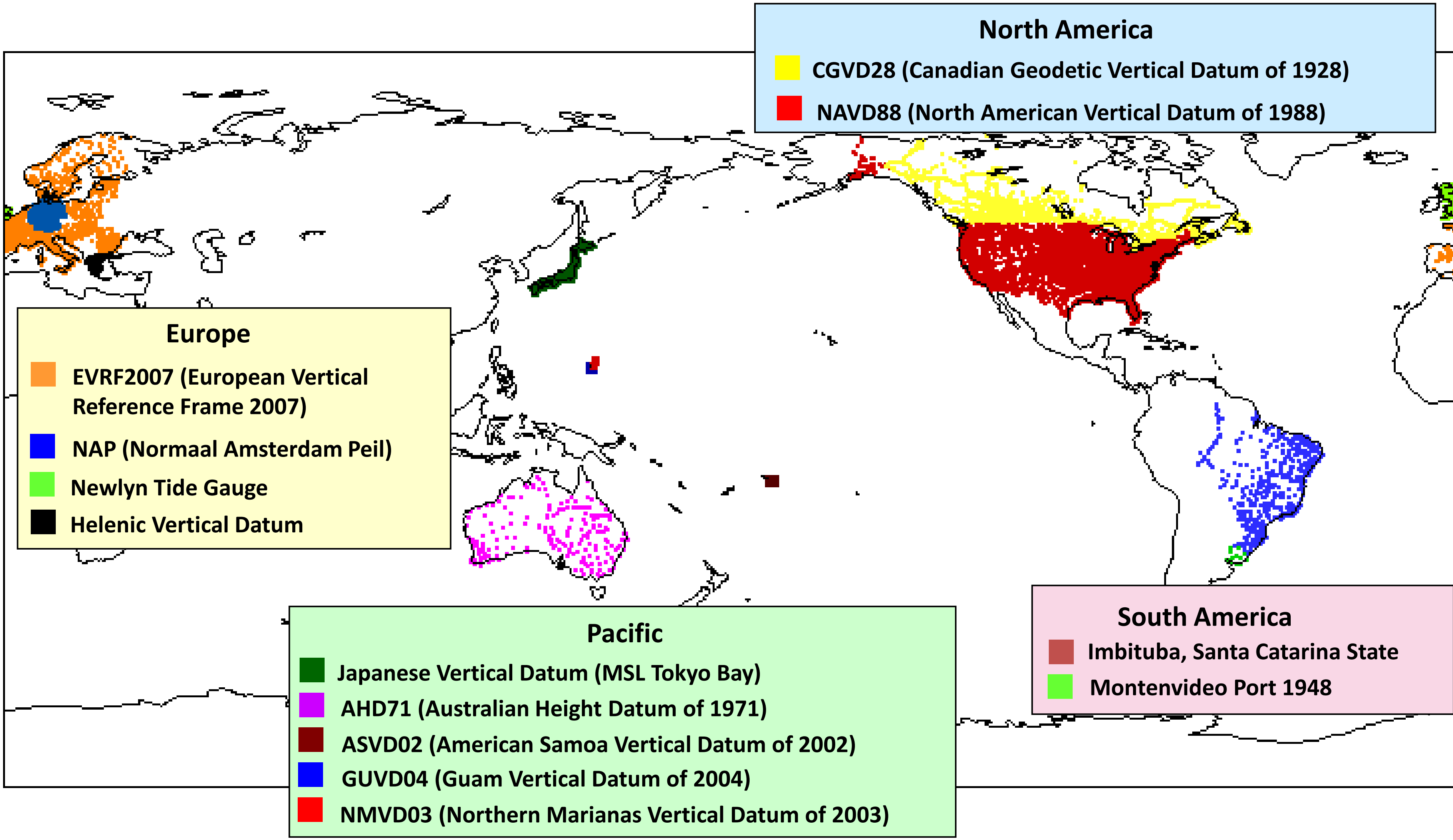
$$\Delta N = N_i^A - (N_i^{GOCE} + N_i^{res})$$

Height System Offset wrt. Geoid

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

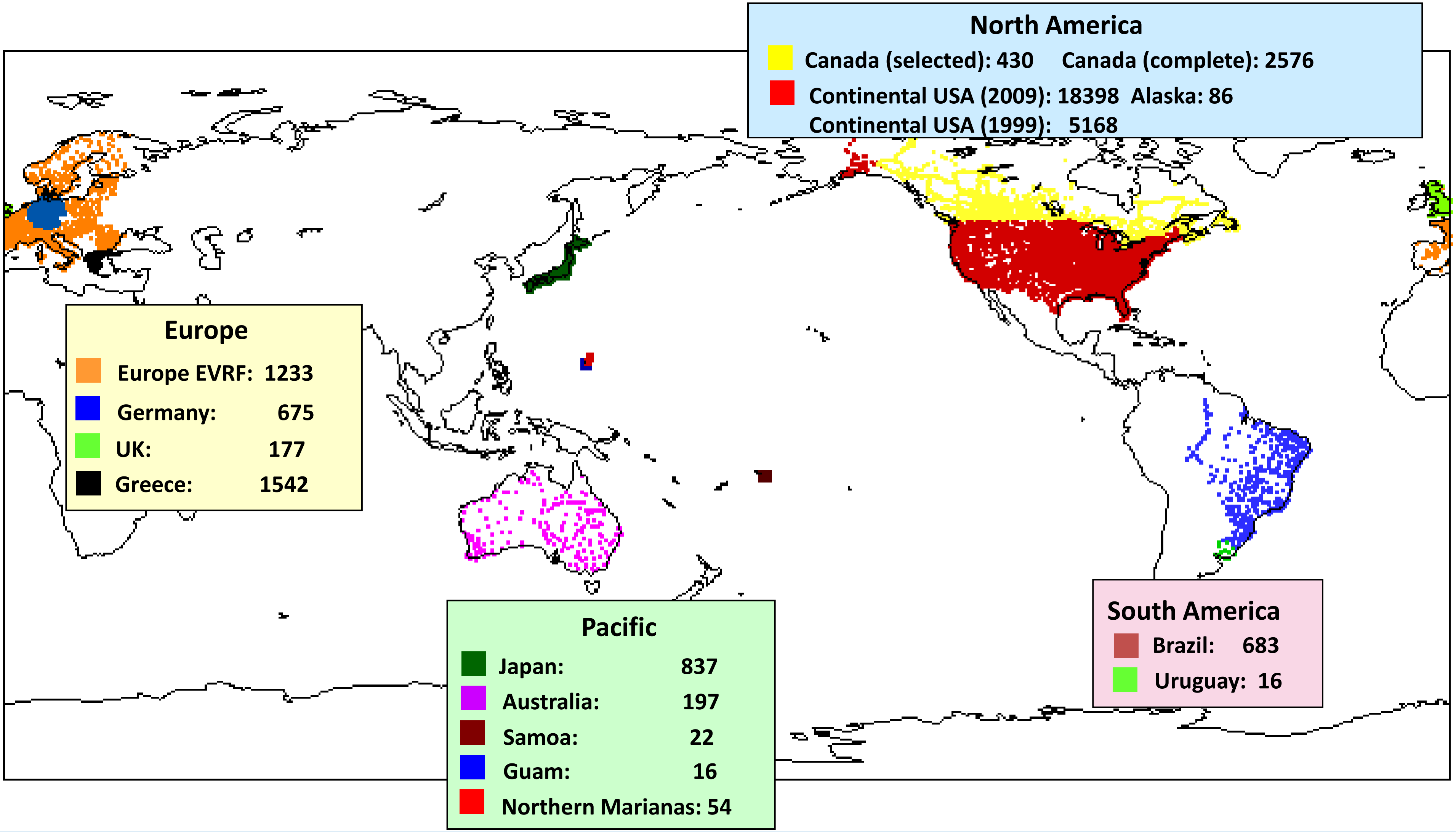
Scientific Roadmap – Global Height System Unification

GNSS-Levelling Vertical Datums



Scientific Roadmap – Global Height System Unification

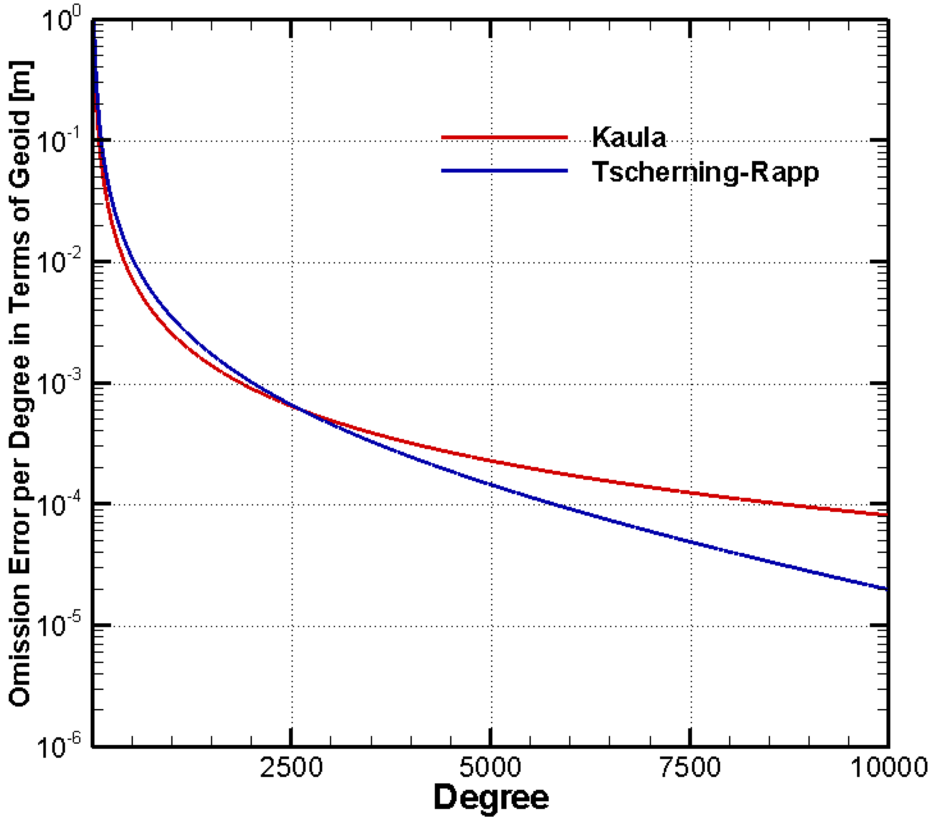
GNSS-Levelling Number of Points



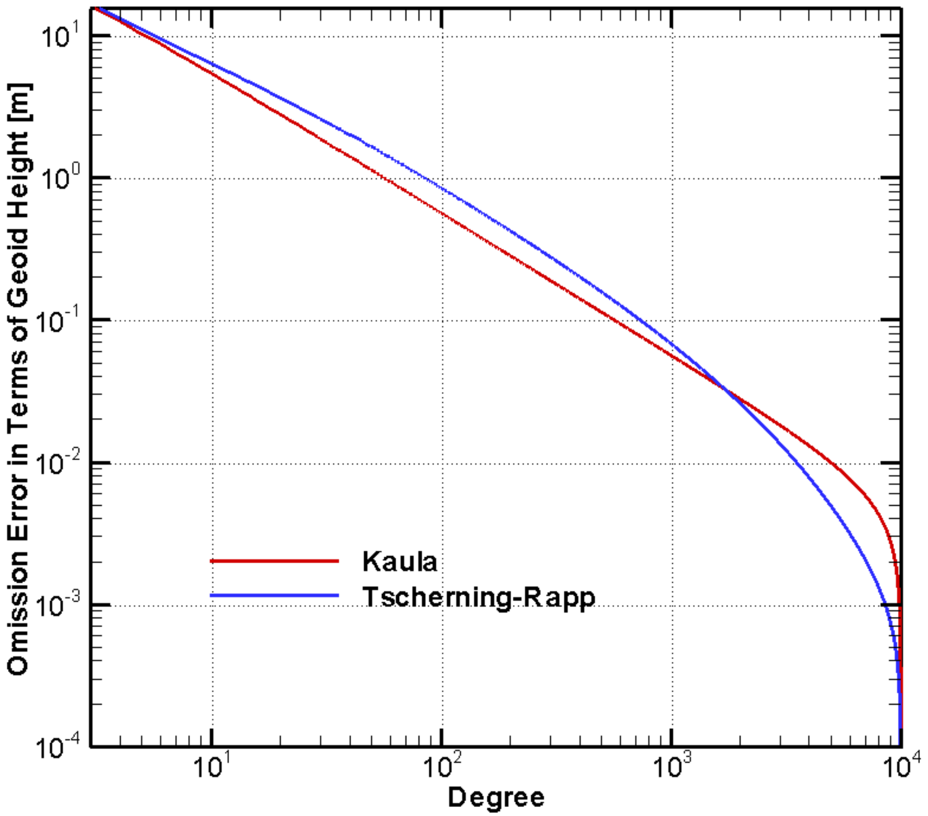
Scientific Roadmap – Global Height System Unification

Omission Error

per degree



from degree (to infinity)

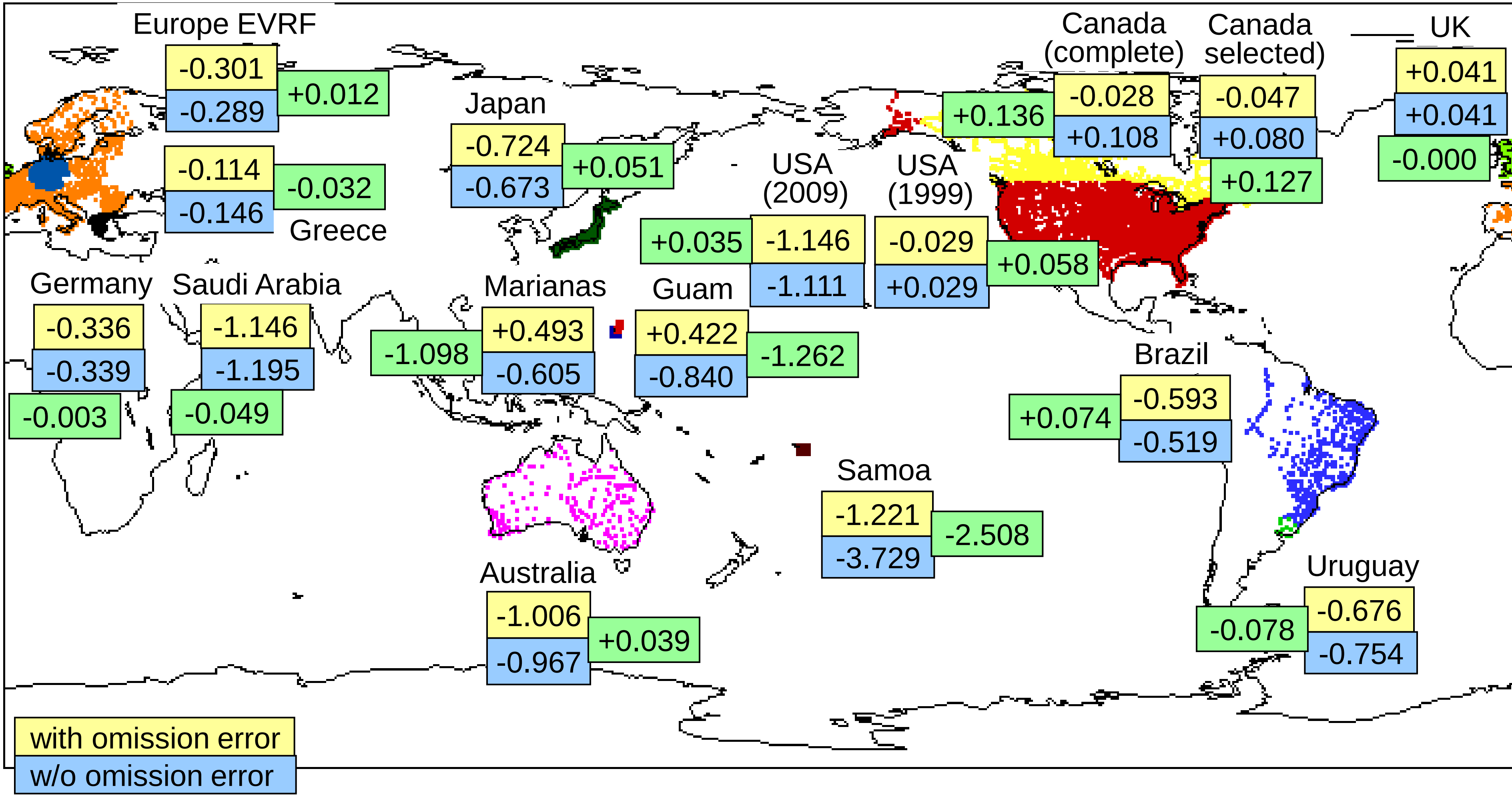


Omission error can be estimated from EGM2008 and/or residual terrain modelling

Scientific Roadmap – Global Height System Unification

GOCE –TIM5 Model truncated at D/O 200

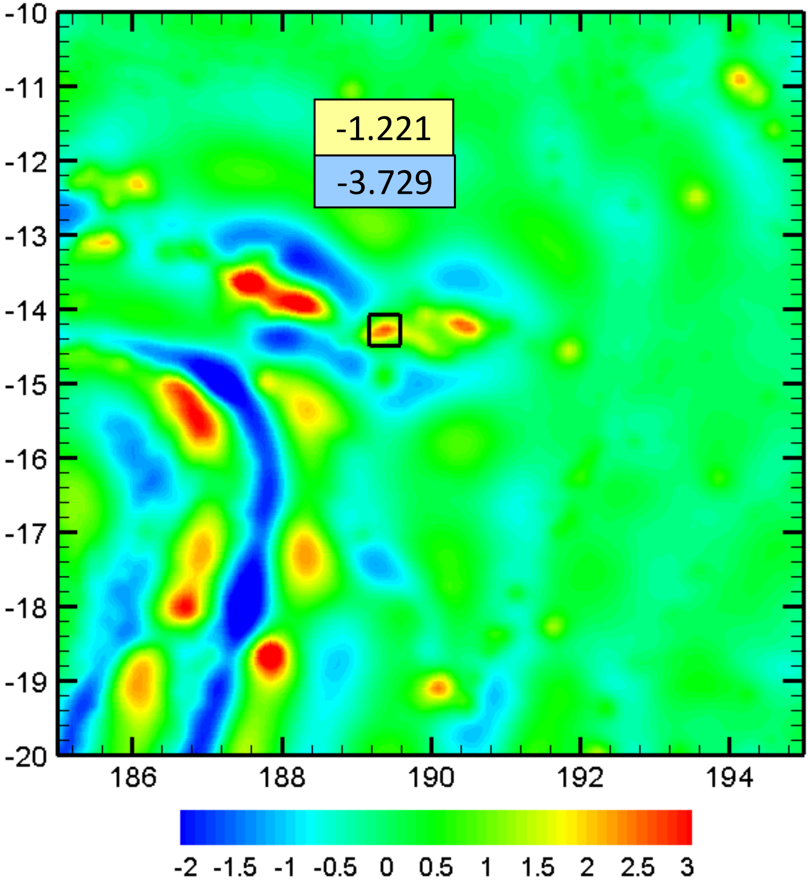
$$N_{A0} = Mean(\Delta N)$$



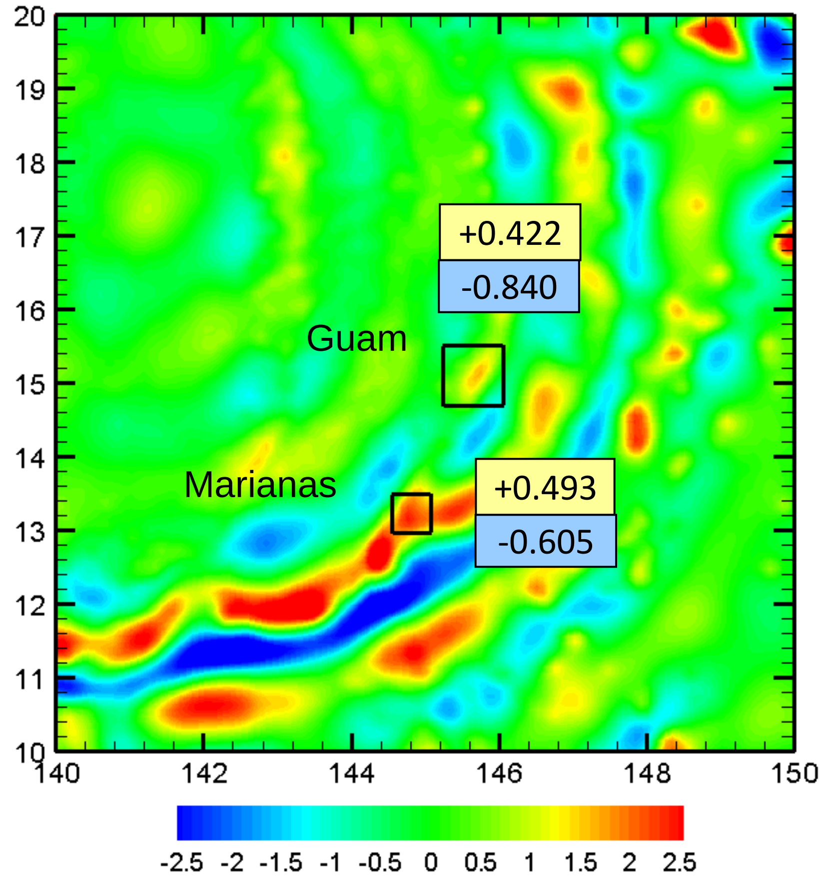
Scientific Roadmap – Global Height System Unification

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

Samoa



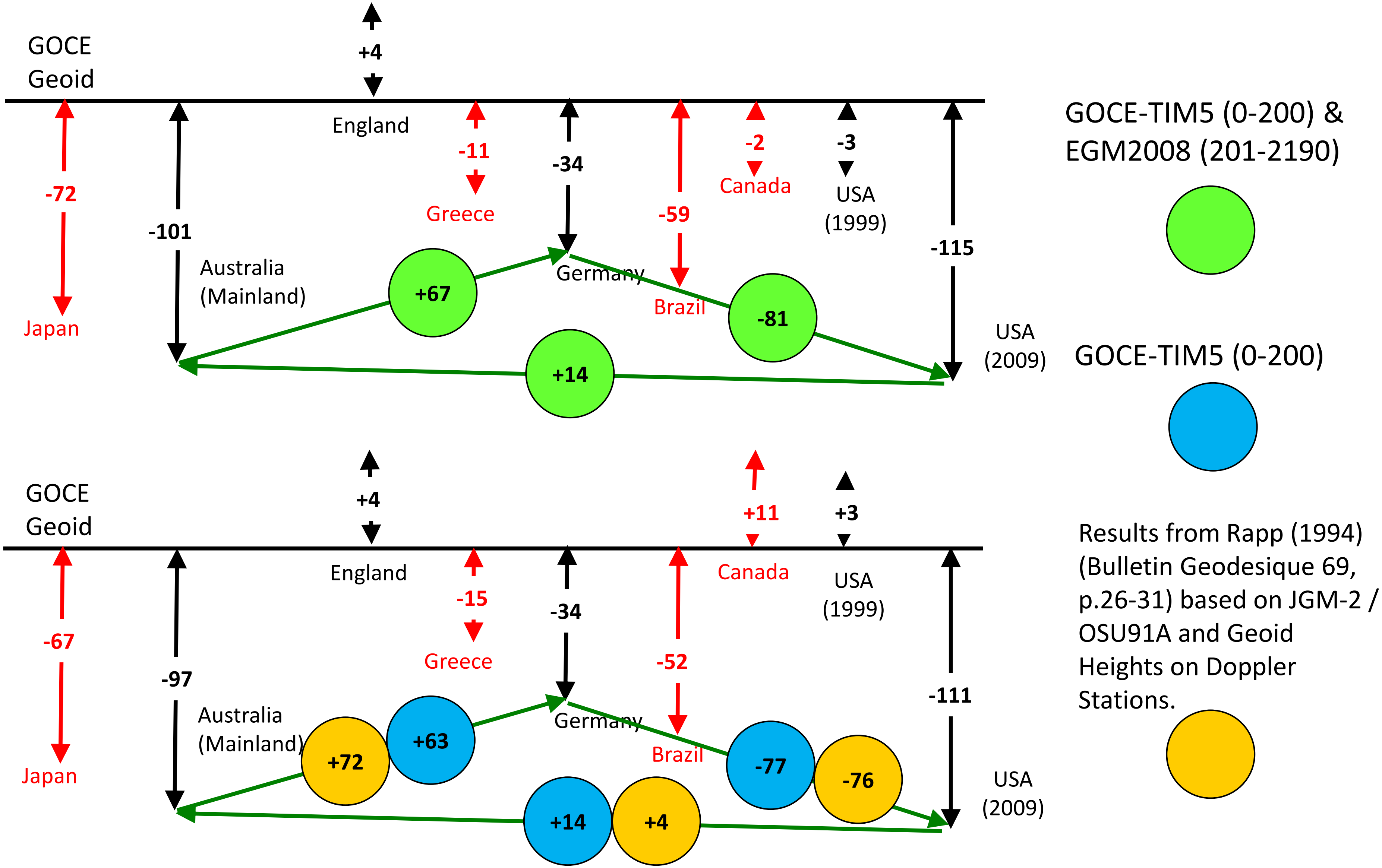
Guam & Marianas



w/o omission error (signal)

with omission error (signal)

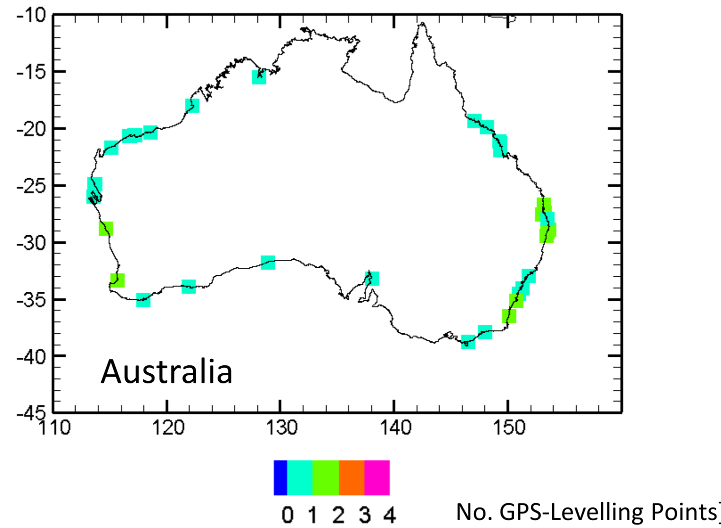
Scientific Roadmap – Global Height System Unification

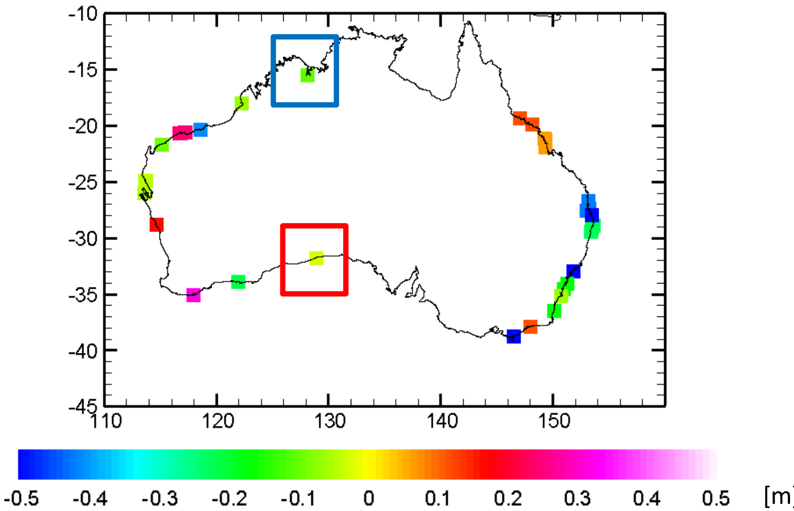


Scientific Roadmap – Global Height System Unification

GNSS-Levelling Offsets close to Tide Gauges - Procedure

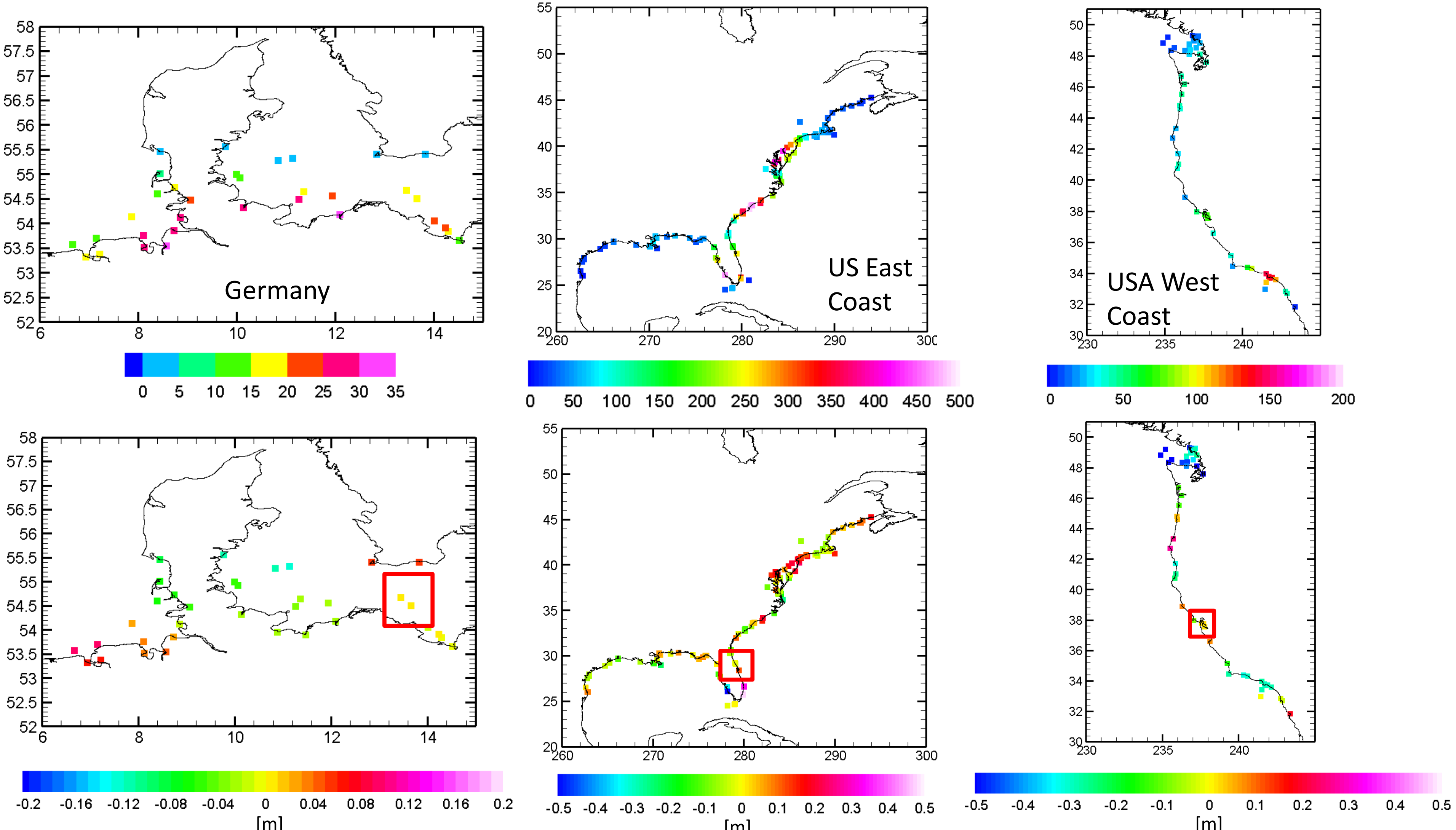
1. Identification of GNSS-Levelling points close to PSMSL tide gauge stations. Limit: Distance corresponding to d/o 200 (100km).
2. Computation of mean offsets of the GOCE geoid to the selected GNSS-Levelling geoid for each tide gauge.
3. Identification of tide gauges, where the omission error has minor impact (either due to the geoid signal characteristic in this area or due to the distribution of GNSS Levelling stations).
4. Use quasi omission error free geoid heights determined from GNSS-Levelling to estimate offsets to the GOCE geoid.
5. Use these tide gauges to connect them across the oceans.





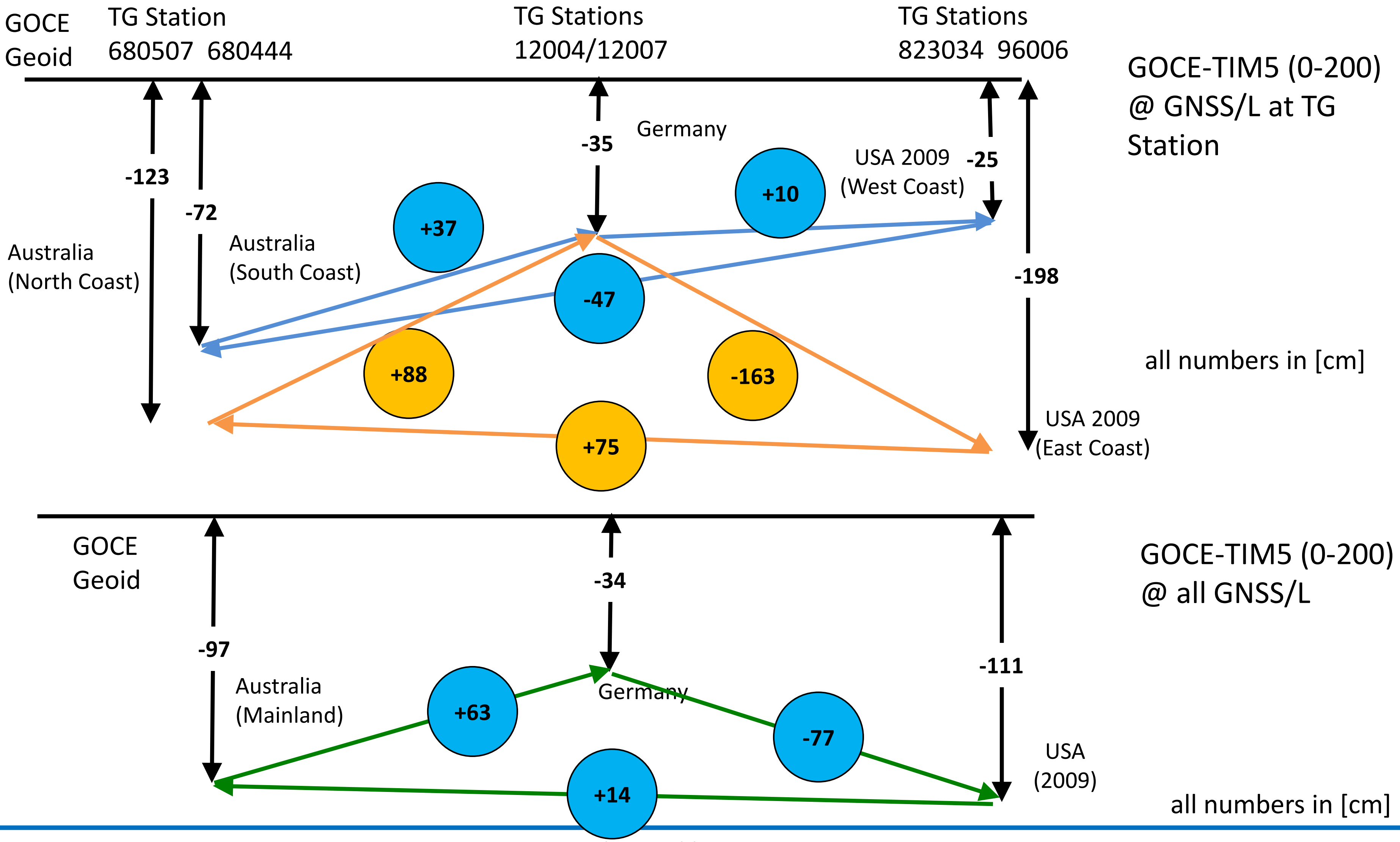
Scientific Roadmap – Global Height System Unification

GNSS-Levelling Offsets close to Tide Gauges - Procedure



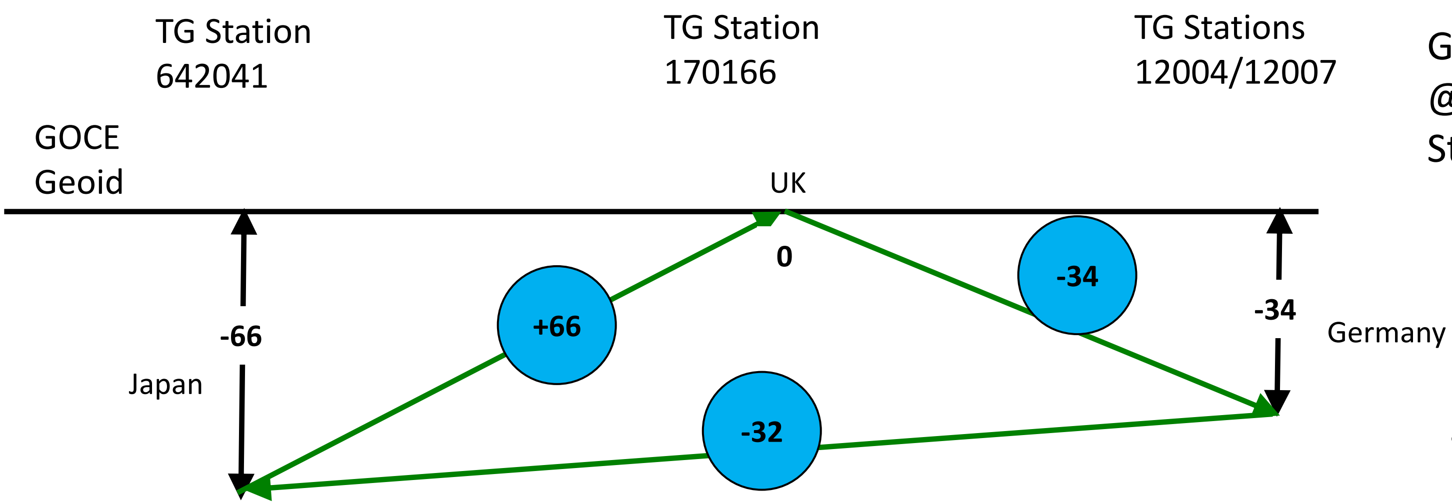
Scientific Roadmap – Global Height System Unification

Height System Connection via GNSS/Levelling at Selected Tide Gauges



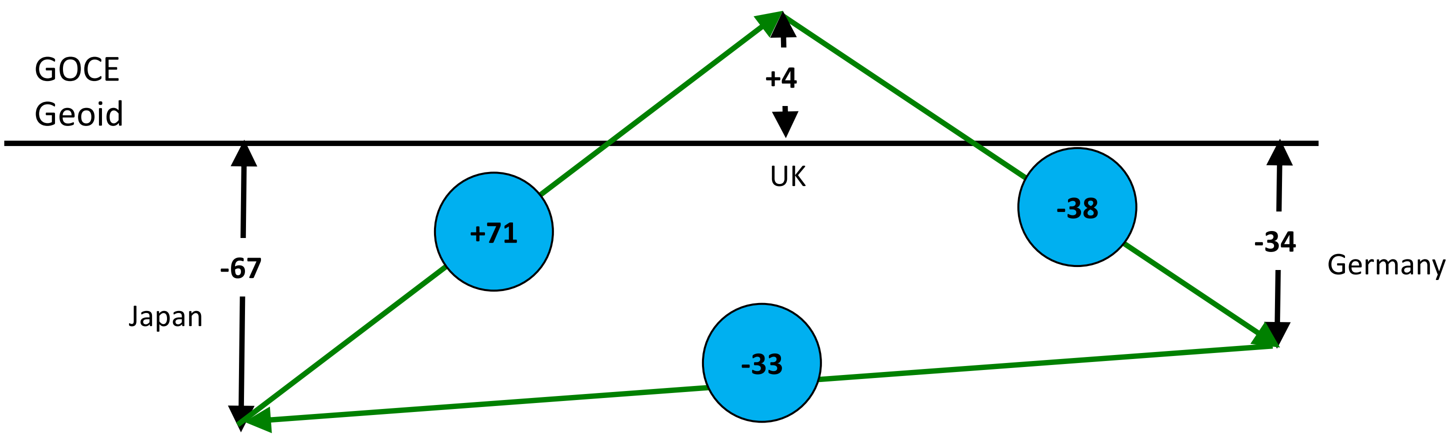
Scientific Roadmap – Global Height System Unification

Height System Connection via GNSS/Levelling at Selected Tide Gauges



GOCE-TIM5 (0-200) @ GNSS/L at TG Station

all numbers in [cm]



GOCE-TIM5 (0-200) @ all GNSS/L

all numbers in [cm]

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).

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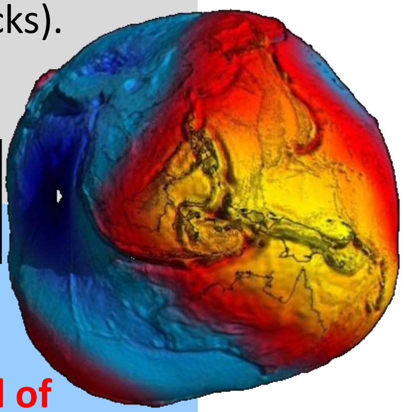
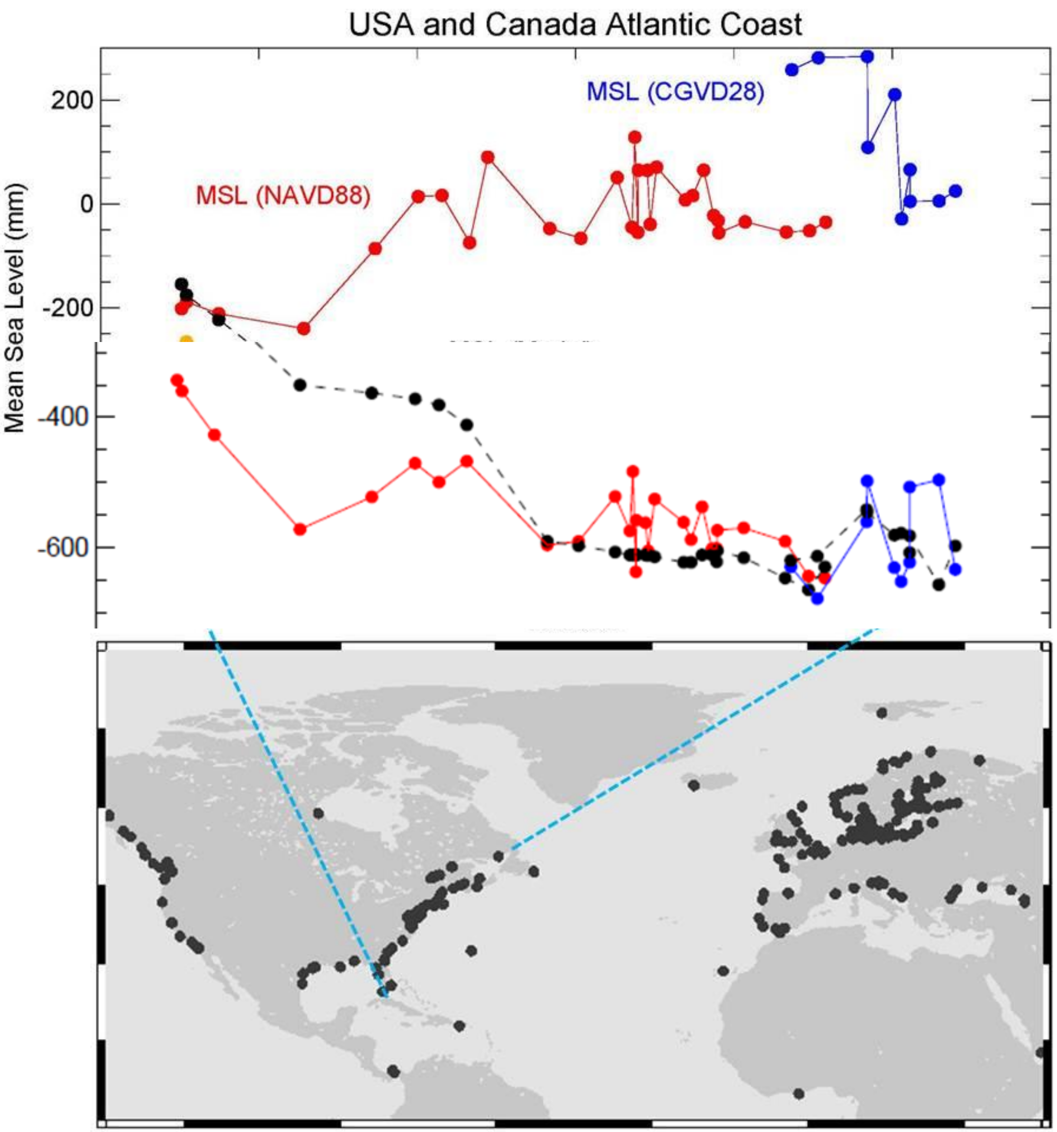


Realization of a **globally consistent model of mean dynamic ocean topography** at tide gauges and at sea (**Ocean Levelling**).

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

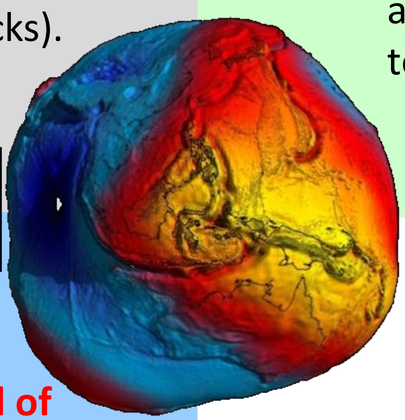
Global Height System Unification

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)

Well Surveyed Areas (Land)

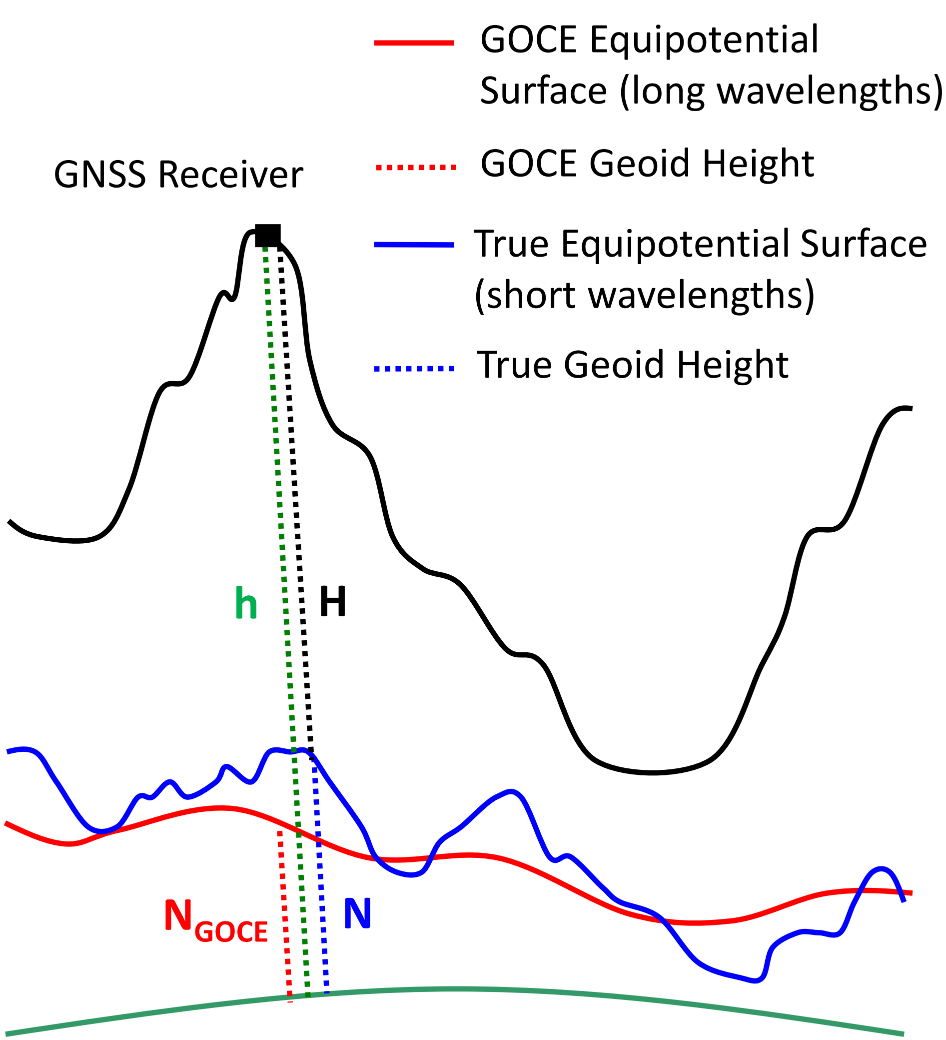
Regional geoid based on GOCE model. Establishment of **national or regional height systems at primary points** (first and second order) based on the technique of “**GNSS-leveling**”.



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



<u>Assumptions</u>:

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

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

(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 $\mathbf{N_{GOCE}}$ / **N**

$$\mathbf{H = h - N}$$

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

$$\textbf{Omission Error} = \mathbf{N - N_{GOCE}}$$

Scientific Roadmap – Essential Tasks

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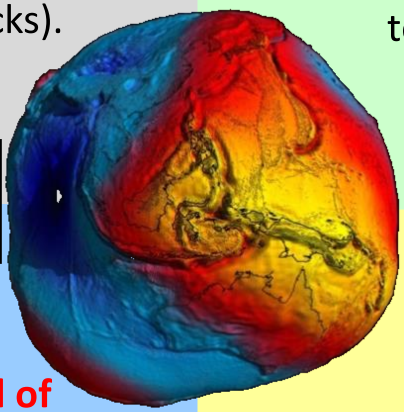
Establishment of **national or regional height systems at primary points** (first and second order) based on the technique of "**GNSS-leveling**".



Open Oceans and Coastal Zones

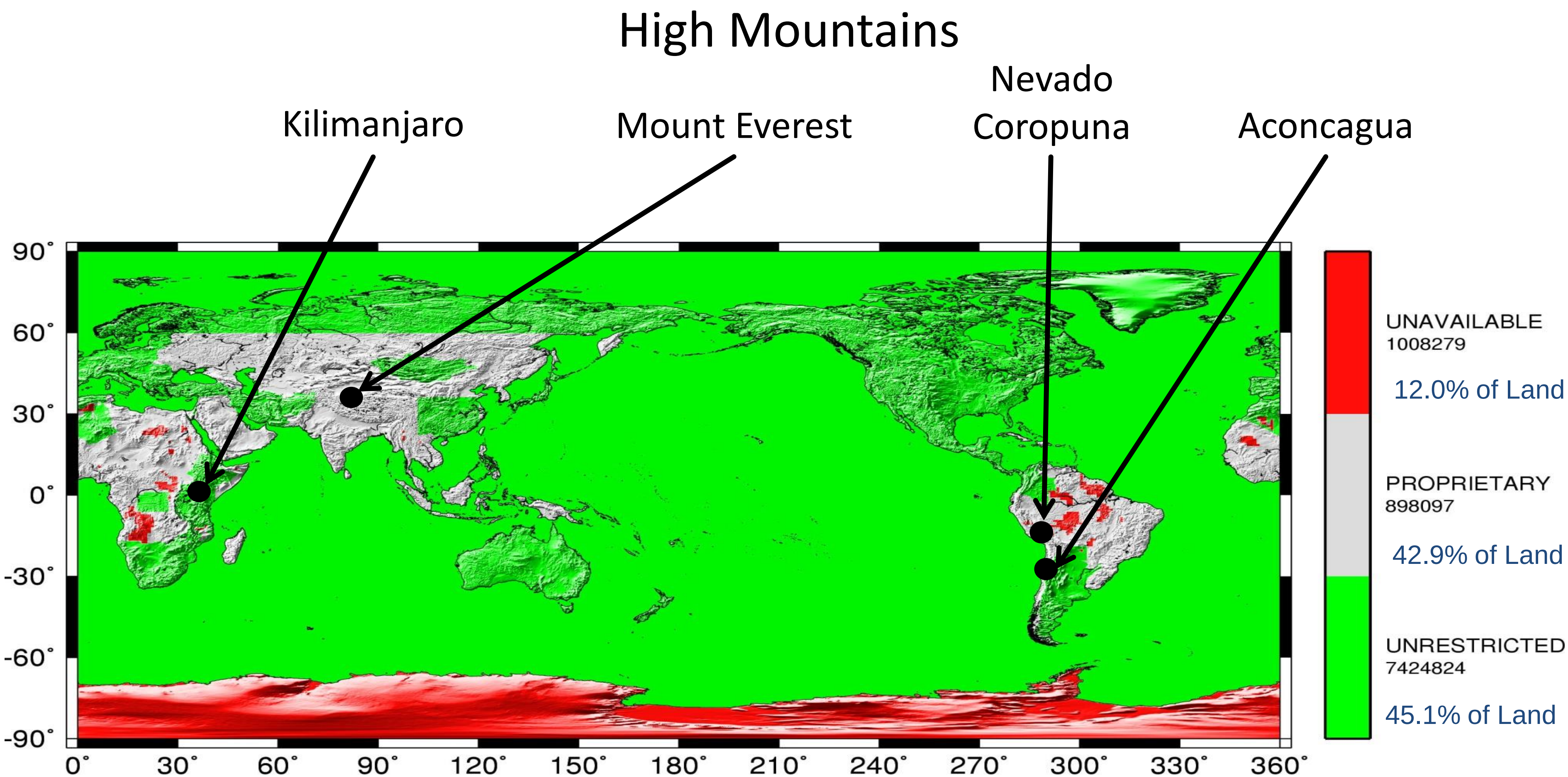
Realization of a **globally consistent model of mean dynamic ocean topography** at tide gauges and at sea.

Sparsely Surveyed Areas (Land)

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**

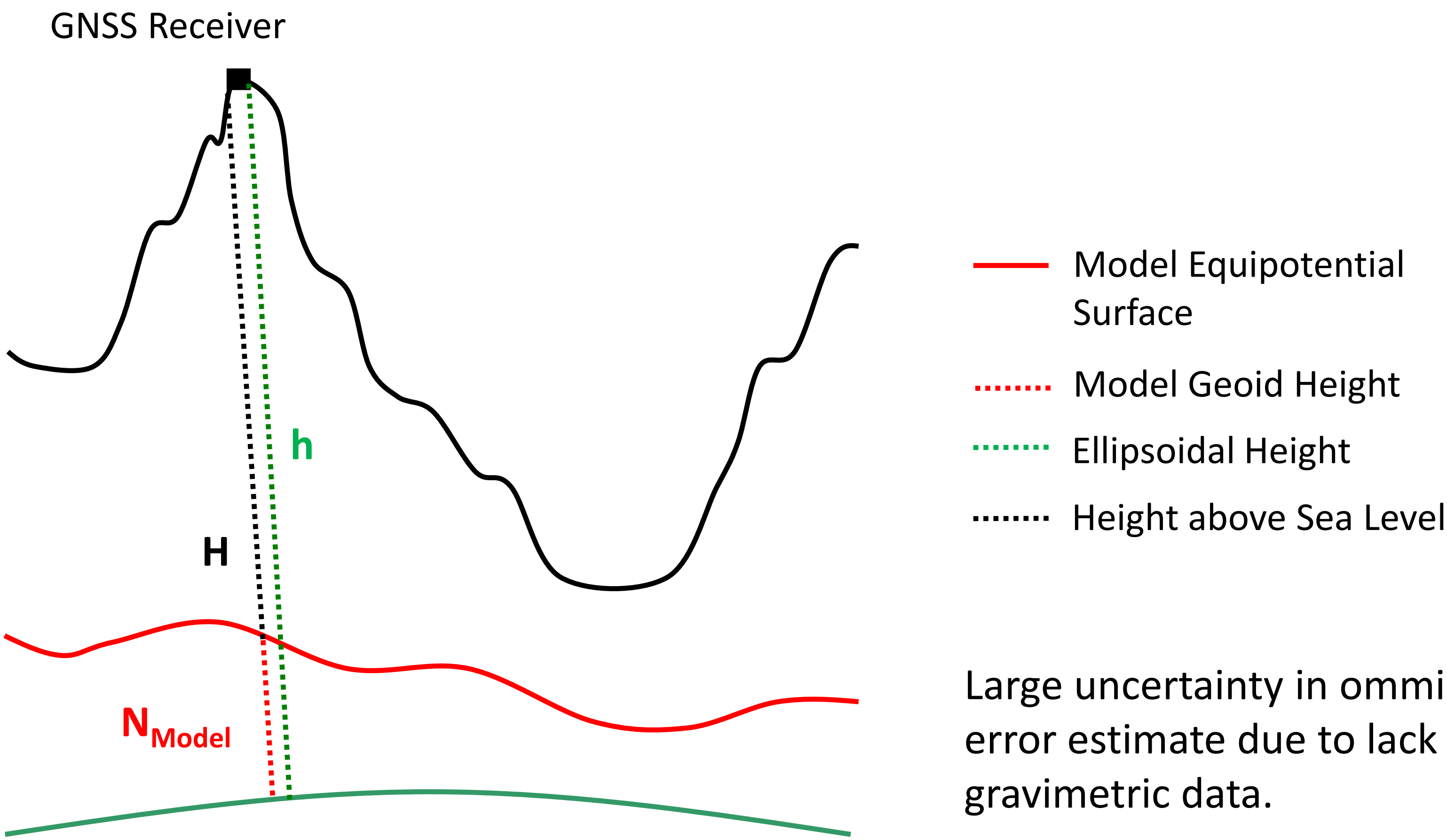
Scientific Roadmap – Sparsely Surveyed Areas



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

Scientific Roadmap – Sparsely Surveyed Areas

Mountain Heights from GNSS and GOCE Geoid



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

Scientific Roadmap – Sparsely Surveyed Areas

GOCE-TIM5 to d/o 280 solved at height h=0

EGM2008 to d/o 2190 solved at height h=0

GOCE-TIM5 d/o 200 & EGM2008 d/o 201-2190 solved at h=0

EGM/Rapp: EGM2008 to d/o 2190 solved at height h and correction term applied

	GNSS Height	Geoid	Height above Sea Level
Mount Everest	h = 8821.47 m Average from GPS and classical techniaues for snow surface [1]	$N_{GOCE-TIM5}$ = -26.58 m (h=0) $N_{EGM2008}$ = -22.90 m (h=0) $N_{GOCE/EGM}$ = -22.19 m (h=0) $N_{EGM/Rapp}$ [2] = -28.50 m $N_{local\ geoid}$ [1] = -26.46 m	**$H_{GOCE-TIM5}$ = 8848.05 m** $H_{EGM2008}$ = 8844.37 m $H_{GOCE/EGM}$ = 8843.66 m $H_{EGM/Rapp}$ = 8849.97 m **H_{local} = 8847.93 m**

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

[2] Rapp, 1997, Journal of Geodesy, Vol. 71, p. 282-289

Scientific Roadmap – Sparsely Surveyed Areas

GOCE-TIM5 to d/o 280 solved at height h=0

EGM2008 to d/o 2190 solved at height h=0

EGM/Rapp: EGM2008 to d/o 2190 solved at height h and correction term applied

	GNSS Height	Geoid	Height above Sea Level
Uhuru Peak Kilimanjaro	5875.43 m KILI2008 Survey GIPSY [1]	$N_{GOCE\text{-}TIM5}$ = -17.39 m (h=0) $N_{EGM2008}$ = -12.44 m (h=0) $N_{EGM/Rapp}$ [2] = -14.70 m $N_{local\ geoid}$ [1] = -14.08 m	$H_{GOCE-TIM5}$ = 5892.82 m $H_{EGM2008}$ = 5887.87 m **$H_{EGM/Rapp}$ = 5890.13 m** **H_{local} = 5889.51 m**

[1] Team KILI2008, FIG Working Week, 2009, Eilat, Israel 3-8 May 2009

[2] Rapp, 1997, Journal of Geodesy, Vol. 71, p. 282-289

Scientific Roadmap – Sparsely Surveyed Areas

GOCE-TIM5 to d/o 280 solved at height h=0

EGM2008 to d/o 2190 solved at height h=0

EGM/Rapp: EGM2008 to d/o 2190 solved at height h and correction term applied

	GNSS Height	Geoid	Height above Sea Level
Aconcagua	6995.10 m [1]	$N_{GOCE\text{-}TIM5}$ = 33.96 m (h=0) $N_{EGM2008}$ = 36.98 m (h=0) $N_{EGM/Rapp}$ [2] = 34.32 m $N_{local\ geoid}$ [1] = 34.67 m	$H_{GOCE-TIM5}$ = 6961.14 m $H_{EGM2008}$ = 6958.12 m **$H_{EGM/Rapp}$ = 6960.78 m** **H_{local} = 6960.43 m**

[1] Pacino, Jäger, Forsberg, Olesen, Miranda, Lenzano, U. Marti (ed.), *Gravity, Geoid and Height Systems*, International Association of Geodesy Symposia 141, DOI 10.1007/978-3-319-10837-7_23, Springer

[2] Rapp, 1997, Journal of Geodesy, Vol. 71, p. 282-289

Scientific Roadmap – Sparsely Surveyed Areas

GOCE-TIM5 to d/o 280 solved at height h=0

EGM2008 to d/o 2190 solved at height h=0

EGM/Rapp: EGM2008 to d/o 2190 solved at height h and correction term applied

	GNSS Height	Geoid	Height above Sea Level
Nevado Coropuna	6425 m [1]	$N_{GOCE-TIM5}$ = 41.09 m (h=0) $N_{EGM2008}$ = 44.86 m (h=0) $N_{EGM/Rapp}$ [2] = 41.55 m $N_{local\ geoid}$ [1] = ?? m	$H_{GOCE-TIM5}$ = 6383.91 m $H_{EGM2008}$ = 6380.14 m **$H_{EGM/Rapp}$ = 6383.45 m** **H_{local} = ?? m**

[1] Wikipedia (type of height not indicated)

[2] Rapp, 1997, Journal of Geodesy, Vol. 71, p. 282-289

Conclusions

- 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 Remark

Project results are available at the following web-site:

http://www.goceplushsu.eu