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Cartography and Geodesy

Unification of height reference frames in Europe

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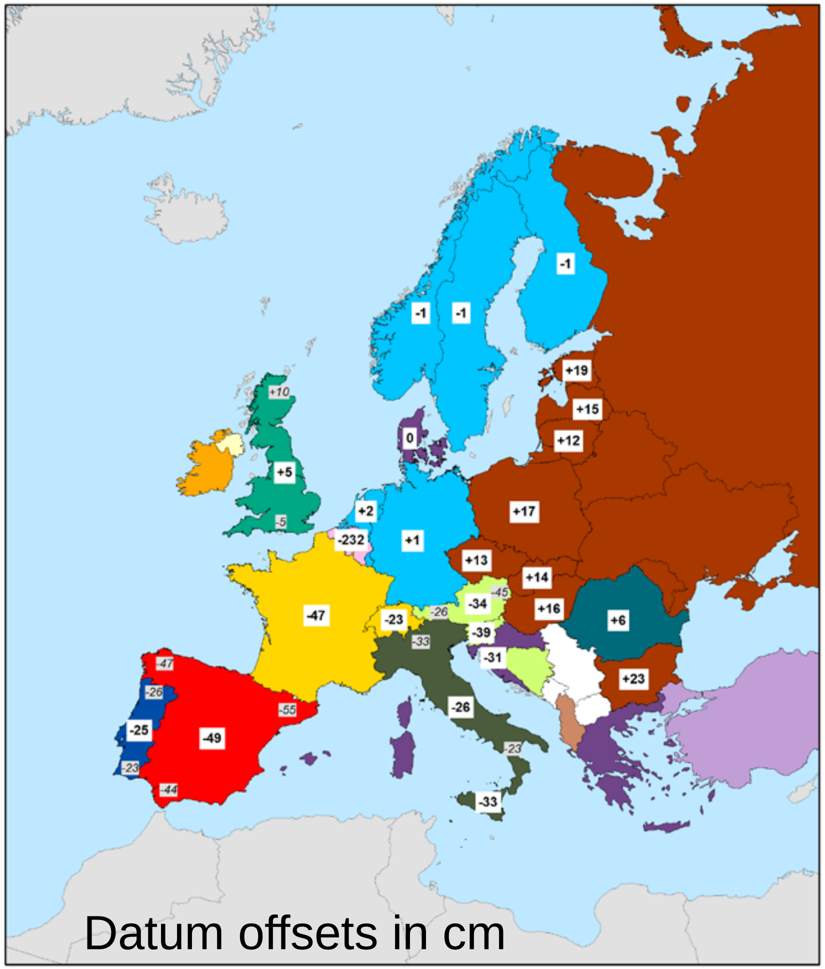
Current situation of height unification in Europe

- Unification of national height reference frames in Europe is based on
  - the European Vertical Reference System (EVRS),
  - the European Vertical Reference Frame (EVRF2007),
  - the United European Leveling network (UELN)
- Comparison of height in EVRF2007 with the heights of the national height reference frames
- Datum of EVRS is related to Normaals Amsterdams Peil and the national height reference frames to different tide gauges in Baltic, North Sea, Atlantic Ocean and the Mediterranean
- Estimation of datum parameter (offset for a point in the center of the country) and a tilt in N-S and E-W direction)
- Publication of the parameter on EVRS website (http://www.bkg.bund.de/evrs) and the website for Coordinate Reference Systems in Europe (CRS-EU, http://www.crs-geo.eu)

Transformation parameter



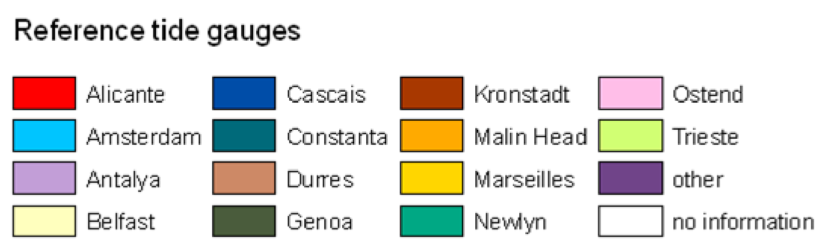
Datum offsets in cm

Estimation of 3 parameters (plane) as transformation parameters between the national vertical reference frames and EVRF2007

$$H_{EVRF\,2007} - H_{NVRF} = m_1 - e + \left[m_2 M_0 (\varphi_i - \varphi_0) + m_3 N_0 (\lambda_i - \lambda_0) \right]$$

m_1 height offset
m_2, m_3 tilt (North-South, West-East)
φ_0, λ_0 coordinates of reference point P_0
M_0, N_0 radius of curvature in meridian and perpendicular to the meridian in P_0

http://www.crs-geo.eu



Comparison of heights

	EVRS / EVRF2007	National HRS / HRF
Datum definition (zero level)	Noormals Amsterdams Peil (NAP) – approximately mean high water summer 1682/83 in Amsterdam	Different, e.g. NAP, Kronstadt, Ostend, Marseilles, Trieste, Newlyn
Permanent solid earth tide convention	Zero tide	Different (mean tide, zero tide, non tide)
Kind of heights	Geopotential differences, normal heights (GRS80)	Different, e.g. normal, normal-orthometric, orthometric
epoch	2000.0 for postglacial uplift in the Scandinavian part of EVRF2007 otherwise different	Different, usually mean epoch of observations

Difference of heights is not only a constant value (datum shift) and may vary !

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Data set description: GNSS and leveling data Europe

Country	Reference tide gauge	Permanent solid earth tide	Kind of heights
AT Austria	Trieste	mean tide	normal-orthometric
BG Bulgaria	Kronstadt	mean tide	normal
CH Switzerland	Marseilles	mean tide	Orthometric (scientific)
CZ Czech Republic	Kronstadt	mean tide	normal
DE Germany	Amsterdam (NAP)	mean tide	normal
DK Denmark	10 different tide gauges	tide free	orthometric
ES Spain	Alicante	mean tide	orthometric
FI Finland	Amsterdam (NAP)	zero tide	normal
FR France	Marseilles	mean tide	normal
GB Great Britain	Newlyn	mean tide	normal-orthometric
HR Croatia	Trieste	mean tide	normal-orthometric
HU Hungary	Kronstadt	mean tide	normal
IT Italy	Genoa	mean tide	Orthometric? / no gravity correction?
LT Lithuania	Kronstadt	mean tide	normal
LV Latvia	Kronstadt	mean tide	normal
NL The Netherlands	Amsterdam (NAP)	tide free	no gravity correction
NO Norway	Amsterdam (NAP)	zero tide	normal
PL Poland	Kronstadt	tide free	normal
PT Portugal	Cascais	mean tide	orthometric
RO Romania	Constanta	mean tide	normal
SE Sweden	Amsterdam (NAP)	zero tide	normal
SI Slovenia	Trieste	mean tide	normal-orthometric
SK Slovakia	Kronstadt	mean tide	normal

Drawbacks of the current leveling approach for the unification of height reference frames

- Different national standards and conventions for the national height systems and their realizations influence the UELN and the EVRF2007
  - Different accuracy of the national leveling networks
  - Different epochs of leveling observations ➔Very long observation period in EVRF2007
  - No information about height changes ➔ No common epoch of adjustment in EVRF2007 (except for the most dominant height changes due to the postglacial rebound in the Scandinavian part)
- Different number and quality of leveling lines connecting neighboring countries in UELN
- The replacement of the leveling network of one country may influence the estimation of the datum parameter for all other countries (example replacement of the German part in UELN)
- Some countries do not renew their leveling networks anymore
- Comparison of heights in the national height system and EVRF2007 does not handle the different conventions for permanent solid earth tides and the different kind of heights properly

Alternative Method: gravity field approach

- Comparison of height anomalies from
  - GNSS and leveling observations h-H (ellipsoidal height h minus physical height H with respect to a certain national height reference frame, e.g. NAP, Kronstadt, Ostend, Marseilles, Trieste, Newlyn)
  - Gravimetric geoid respectively quasigeoid model ζ^{grav} with a uniform zero level, e.g. Noormals Amsterdams Peil
- Investigation of the differences $m+r=(h\text{-}H)\text{-}\zeta^{grav}$
  - m… datum offset (mean value)
  - r … residuals
- Advantage:
  - Comparison of independent data
  - Information about accuracy
  - Determination of possible error sources (systematic and random)

Data sets

- Quasigeoid model
  - European Gravimetric Geoid, EGG08
  - EGG08 + TIM R5 (EGG08 combined by a simple filter technique with a global gravity field model which base on the satellite gravity mission GOCE)

Meta data	EGG08	EGG08 + TIM R5
Normal Gravity field	GRS80	GRS80
Reference level	W_{NAP}	$U_{0(GRS80)}$
Permanent solid earth tide	Zero tide	Zero tide
Heights anomalies	$W_{(NAP)}$ above GRS80 level ellipsoid	$W = U_{0(GRS80)}$ above GRS80 level ellipsoid

- GNSS and leveling data
  - New German height reference frame 2016 (presentation this morning by M. Sacher)
  - Europe (EUVN-DA) (Kenyeres et al., IAG Symposia 135, 2010)

Data set description: GNSS and leveling data Germany

Germany_ITRF2005/ETRF2000_DHHN2016, 359 points

	ellipsoidal coordinates h	physical heights H
Reference frame	ITRF2005, ETRF2000	DHHN2016
Geodetic datum	GRS80 reference ellipsoid	NAP
Kind of heights	Ellipsoidal height	Normal height
Permanent solid earth tide	Non tide	Mean tide
epoch	June 2008 (2008.39)	2006-2012

Transformation from ITRF2005, epoch 2008.39 to ETRF2000, epoch 2008.39 according to Memo 8 from Boucher and Altamimi

Data set description: GNSS and leveling data Europe

EUVN/DA_ETRS89/ITRF2008_EVRF2007/national height system, 1316 points

	ellipsoidal coordinates h	physical heights H
Reference frame	ETRS89 (country-specific), ITRF2008	EVRF2007, National height reference frames
Geodetic datum	GRS80 reference ellipsoid	NAP, Different reference tide gauges
Kind of heights	Ellipsoidal height	Normal height, different
Permanent solid earth tide	zero tide	zero tide, different
epoch	different	Different (2000.0 for the Scandinavian part) , different

Transformation from ETRF2000, epoch 2000.0 (assumed) to ITRF2008, epoch 2000.0

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Standards and Conventions for this investigation

- Permanent earth tides correction: zero tide (all ellipsoidal and physical heights were transformed if necessary)
- But:
  - No correction for the different kinds of physical heights
  - No correction for different observation epochs (ellipsoidal and physical heights, quasigeoid models)
- GRS80 normal gravity field for global geopotential model
- Comparisons with respect to
  - NAP (EGG08)
  - $U_{0(GRS80)} = 62636860.850\ m^2s^{-2}$ (EGG08 + TIM R5)

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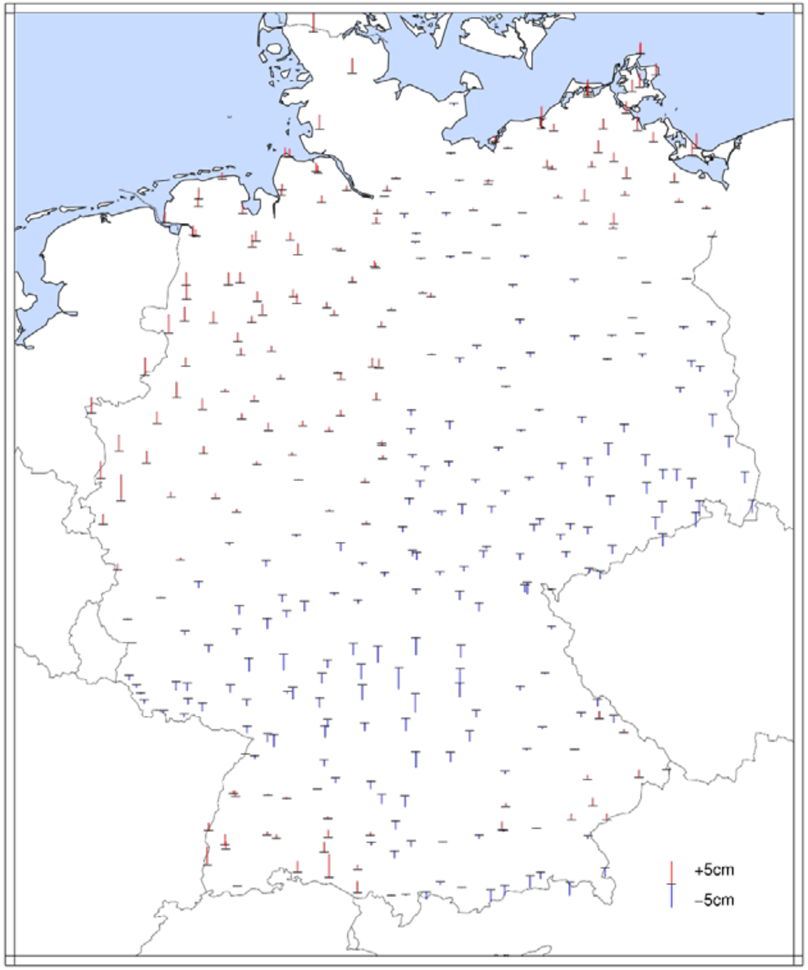
Results: Germany

- GNSS/leveling dataset (*h*, *H*): Germany_ITRF2005_DHHN2016 (NAP above GRS80, zero tide)
- Geoid model (ζ): EGG08 (NAP above GRS80, zero tide)

Quasigeoid model	TRF of *h*	s_r [cm]	m_r [cm]
EGG08	ITRF05	1,78	-0,6



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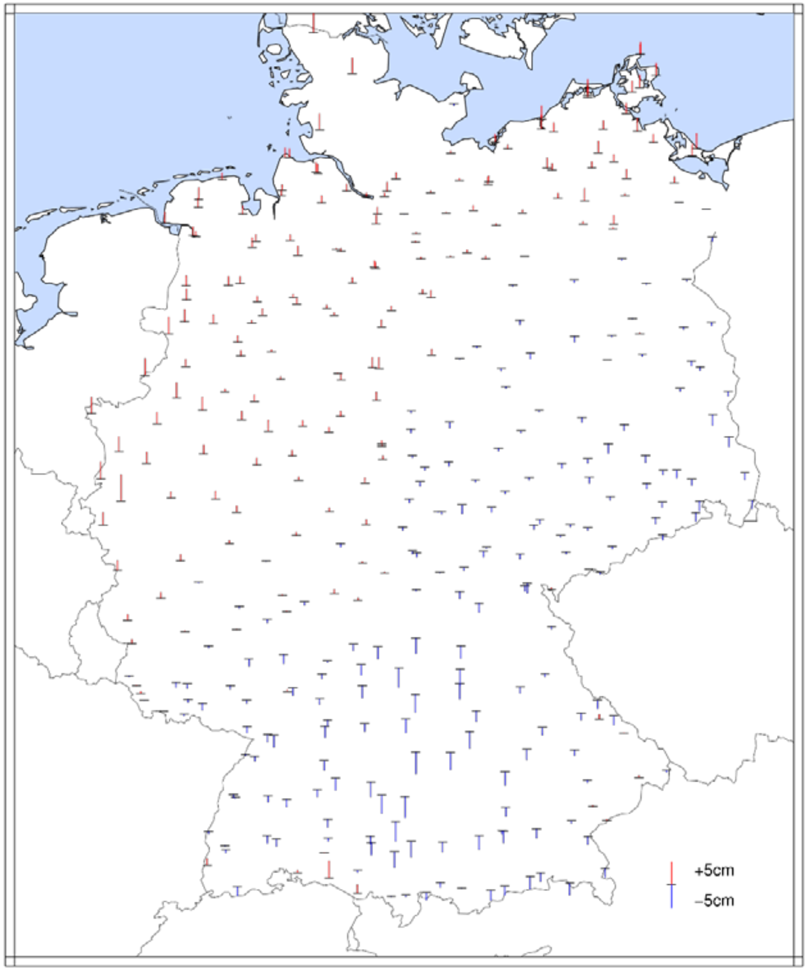
Results: Germany

- GNSS/leveling dataset (*h*, *H*):
  Germany_ITRF2005_DHHN2016
  (NAP above GRS80, zero tide)
- Geoid model (ζ): TIM_R5 + EGG08
  (W=$U_{0(GRS80)}$ above GRS80 ellipsoid, zero-tide)

Geoid model	TRF of *h*	s_r [cm]	m_r [cm]
EGG08	ITRF05	1,78	-0,6
TIM_R5 + EGG08	ITRF05	1,75	-31,1

- TIM_R5 + EGG08 is slightly better
- EGG08 performs quite well over Germany



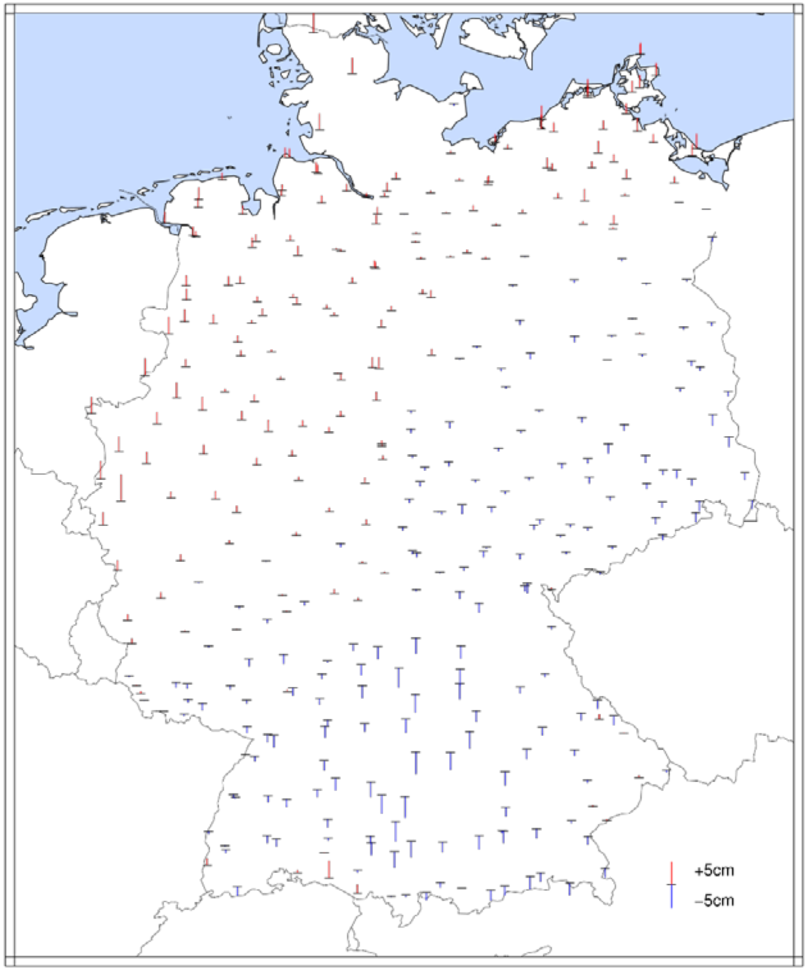
Geoid model „TIM_R5 + EGG08“:
Combined using a 390 km Gauss filter, relates to
77 km half-weight (half-response), 347 km half-gain (half-transfer)

Results: Germany

- GNSS/leveling dataset (h, H): Germany_ITRF2008_DHHN2016 (NAP above GRS80, zero tide)
- Geoid model (ζ): TIM_R5 + EGG08 ($W=U_{0(GRS80)}$ above GRS80 ellipsoid, zero-tide)

Geoid model	TRF of h	s_r [cm]	m_r [cm]
EGG08	ITRF05	1,78	-0,6
TIM_R5 + EGG08	ITRF05	1,75	-31,1
TIM_R5 + EGG08	ITRF08	1,74	-30,9

- Almost no difference (offset difference in the millimeter level)



Transformation of TRF at epoch of observations t ~ 2008.39 yr

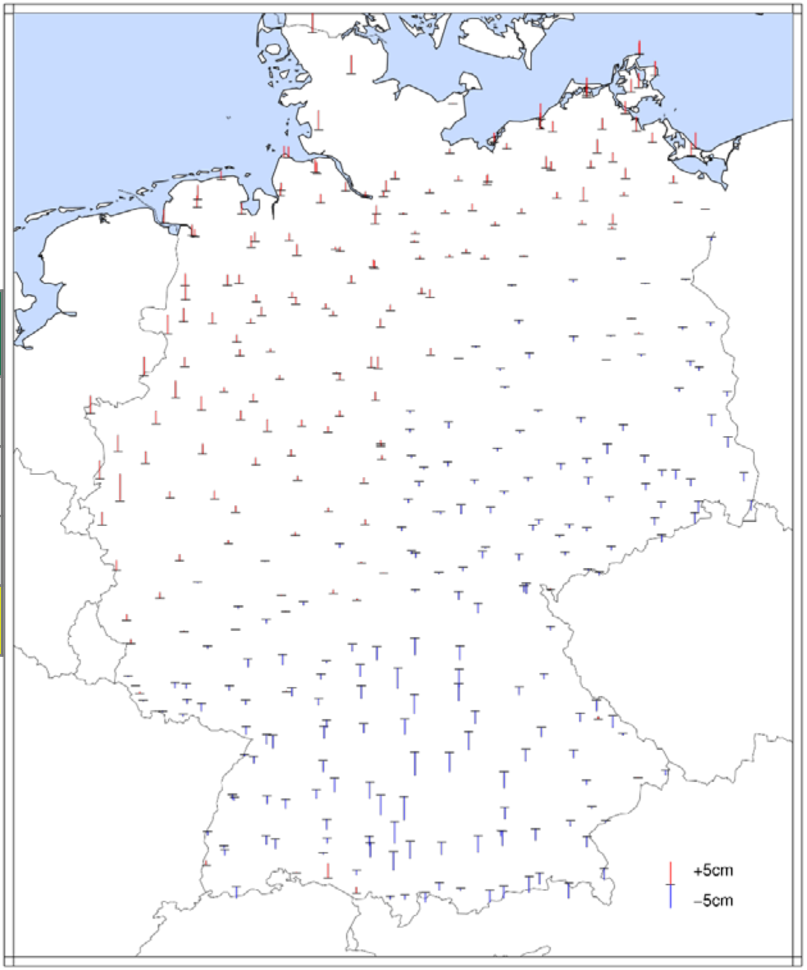
Geoid model „TIM_R5 + EGG08“:
Combined using a 390 km Gauss filter, relates to
77 km half-weight (half-response), 347 km half-gain (half-transfer)

Results: Germany

- GNSS/leveling dataset (h, H): Germany_ETRF2000_DHHN2016 (NAP above GRS80, zero tide)
- Geoid model (ζ): TIM_R5 + EGG08 ($W=U_{0(GRS80)}$ above GRS80 ellipsoid, zero-tide)

Geoid model	TRF of *h*	s_r [cm]	m_r [cm]
EGG08	ITRF2005	1,78	-0,6
TIM_R5 + EGG08	ITRF2005	1,75	-31,1
TIM_R5 + EGG08	ITRF2008	1,74	-30,9
TIM_R5 + EGG08	ETRF2000	1,99	-30,2

- ETRF2000 fits about 13% worse than ITRFxxxx
- height offset changes by about 1 cm



Review: ETRS89 datum transformation

- Recommendation of EUREF Technical Working Group for the transformation from ITRFxxxx into ETRF2000
  - Transformation from current ITRFxxxx → ITRF2000 using the 14 parameters published in the memo of Boucher and Altamimi
  - Transformation ITRF2000 → ETRF2000 using a 6 parameter transformation (3 rotation rates and 3 translations estimated from 14 transformation parameters between ITRF2000 and ITRF89 for the barycenter of the European network)

$$X^{E}(t_c) = X^{I}_{YY}(t_c) + T_{YY} + \begin{pmatrix} 0 & -\dot{R}3_{YY} & \dot{R}2_{YY} \\ \dot{R}3_{YY} & 0 & -\dot{R}1_{YY} \\ -\dot{R}2_{YY} & \dot{R}1_{YY} & 0 \end{pmatrix} \cdot X^{I}_{YY}(t_c) \cdot (t_c - 1989.0)$$

- Transformation can be carried out using the corresponding 14 transformation parameters

Transformation parameters from ITRFxxxx to ETRF2000

at a common epoch (Memo 8, Boucher/Altamimi)

parameter rate	T1 [mm] [mm/y]	T2 [mm] [mm/y]	T3 [mm] [mm/y]	D [10^{-9}] [10^{-9}/yr]	R1 [mas] [mas/y]	R2 [mas] [mas/y]	R3 [mas] [mas/yr]	t [yr]
ITRF2008	**52,1** 0,1	**49,3** 0,1	**-58,5** -1,8	**1,34** 0,08	**0,891** 0,081	**5,390** 0,490	**-8,712** -0,792	2000,0
ITRF2005	**54,1** -0,2	**50,2** 0,1	**-53,8** -1,8	**0,40** 0,08	**0,891** 0,081	**5,390** 0,490	**-8,712** -0,792	2000,0
ITRF2000	**54,0** 0,0	**51,0** 0,0	**-48,0** 0,0	**0,00** 0,00	**0,891** 0,081	**5,390** 0,490	**-8,712** -0,792	2000.0
ITRF97/96/94	**47,3** 0,0	**46,7** 0,6	**-25,3** -1,4	**-1,58** -0,01	**0,891** 0,081	**5,390** 0,490	**-8,712** -0,792	2000.0
ITRF93	**76,1** 2,9	**46,9** 0,2	**-19,9** 0,6	**-2,07** -0,01	**2,601** 0,191	**6,870** 0,680	**8,412** -0,862	2000.0
ITRF92	**39,3** 0,0	**44,7** 0,6	**-17,3** 1,4	**-0,87** -0,01	**0,891** 0,081	**5,390** 0,490	**-8,712** -0,812	2000.0
ITRF91	**27,3** 0,0	**30,7** 0,6	**-11,3** 1,4	**-2,27** -0,01	**0,891** 0,081	**5,390** 0,490	**-8,712** -0,812	2000.0
ITRF90	**29,3** 0,0	**34,7** 0,6	**4,7** 1,4	**-2,57** -0,01	**0,891** 0,081	**5,390** 0,490	**-8,712** -0,812	2000.0
ITRF89	**24,3** 0,0	**10,7** 0,6	**42,7** 1,4	**-5,97** -0,01	**0,891** 0,081	**5,390** 0,490	**-8,712** -0,812	2000.0

EVRS Conventions

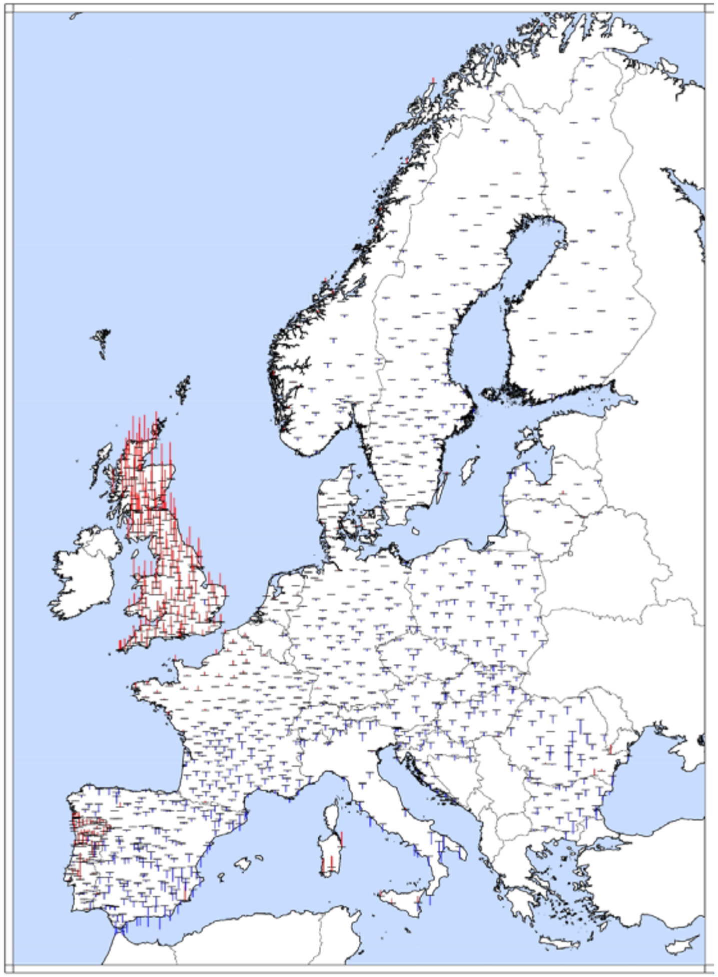
Impact of the reference frame on ellipsoidal heights

- Transformation between different ITRF and ETRF2000 realizations does affect ellipsoidal heights!
- Systematic spatial differences of the ellipsoidal heights over Europe even if coordinate sets refer *to the same epoch* in both frames
- Differences depend on the epoch
- Systematic differences between ellipsoidal height in ITRF2005 and ETRF2000 of up to 5 cm over Europe today

Results: Europe, NAP

- GNSS/leveling dataset: EUVN-DA
  h … ETRF????
  H … EVRF2007
  (NAP above GRS80, zero tide)
- Geoid model (*ζ*): EGG08
  (NAP above GRS80, zero tide)

➔ Datum offsets should be zero for all countries ! (deviations indicate systematic errors of EVRF2007, EGG08 or ETRF?????)



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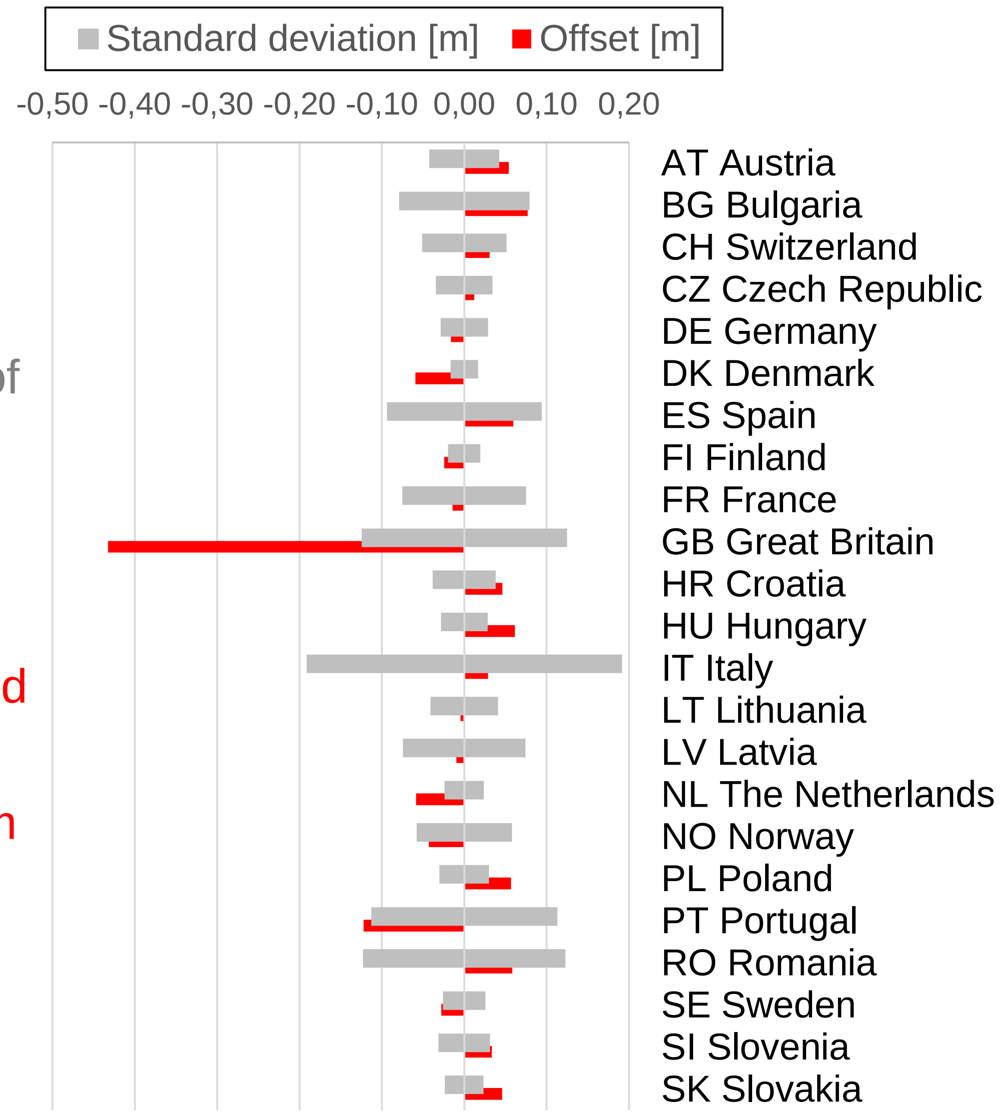
Results: Europe, NAP

- GNSS/leveling dataset: EUVN-DA
- Geoid model (ζ): EGG08

➔ Standard deviations reflect errors of the ETRF2007, the national ETRF realizations and of the EGG08

➔ Datum offsets are less than 10cm (except GB, PT, RO, IT) and not significant according to the standard deviation

➔ Mean value over all countries: 6mm standard deviation: 59mm (without GB, PT, RO, IT)



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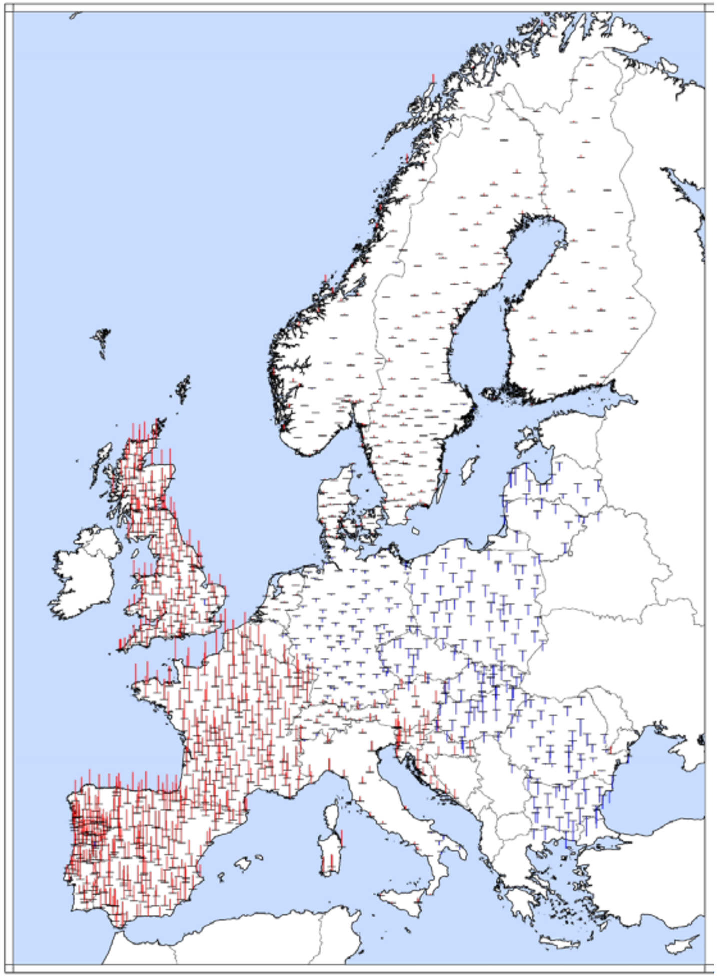
Results: Europe, national zero level above NAP

- GNSS/leveling dataset: EUVN-DA
  h … ETRF????, zero tide
  H … national height reference frames, converted to zero tide
  (national zero level above GRS80, zero tide)
- Geoid model (ζ): EGG08
  (NAP above GRS80, zero tide)

➔ Zero level of the national height systems above NAP (zero tide)



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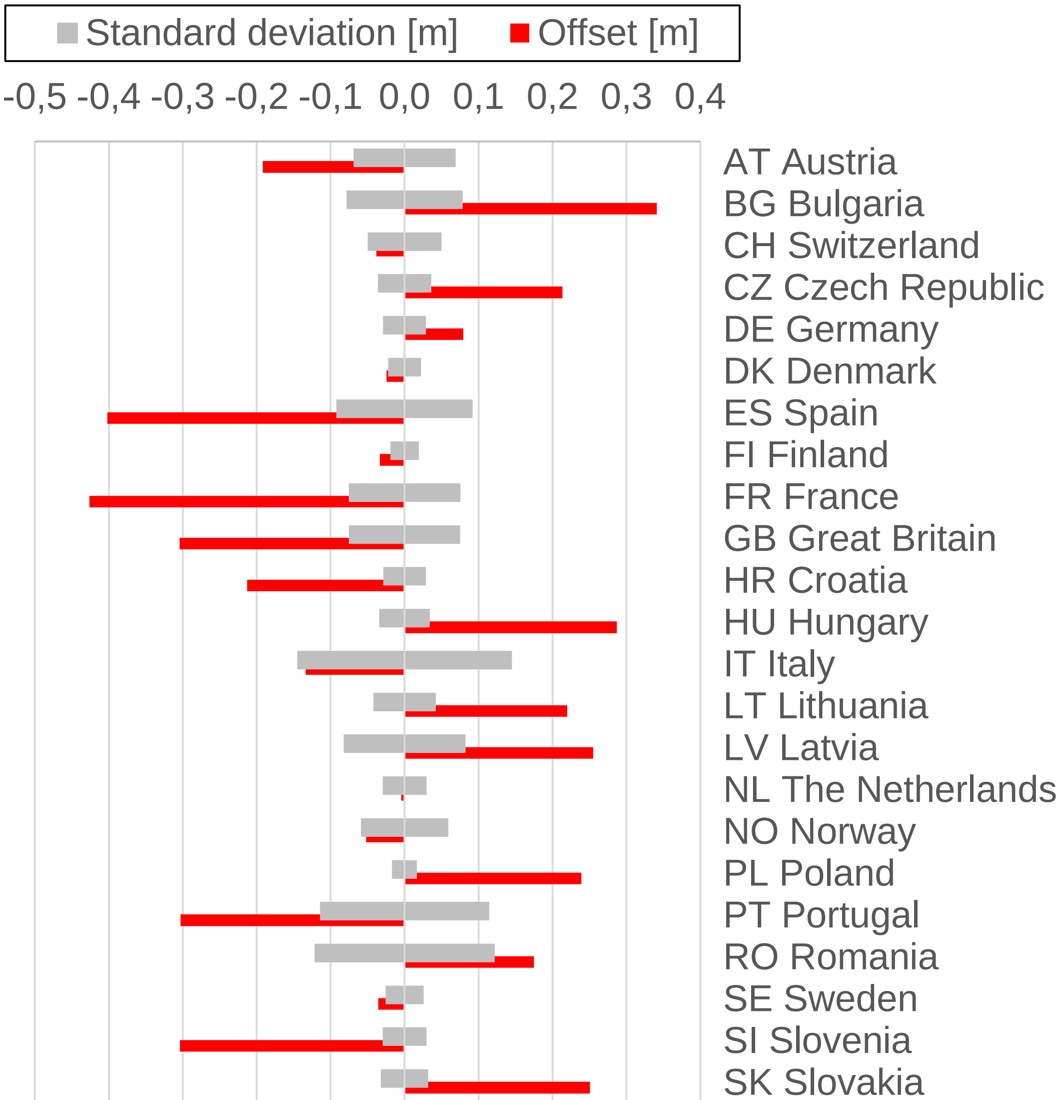
Europe (nat. heights)



- GNSS/leveling dataset: EUVN-DA (national height reference frames)
- Geoid model (ζ): EGG08

➔ Zero level of the national height systems above NAP (zero tide)

➔ for some countries the fit of EVRF2000 is either better or worse compared to national heights

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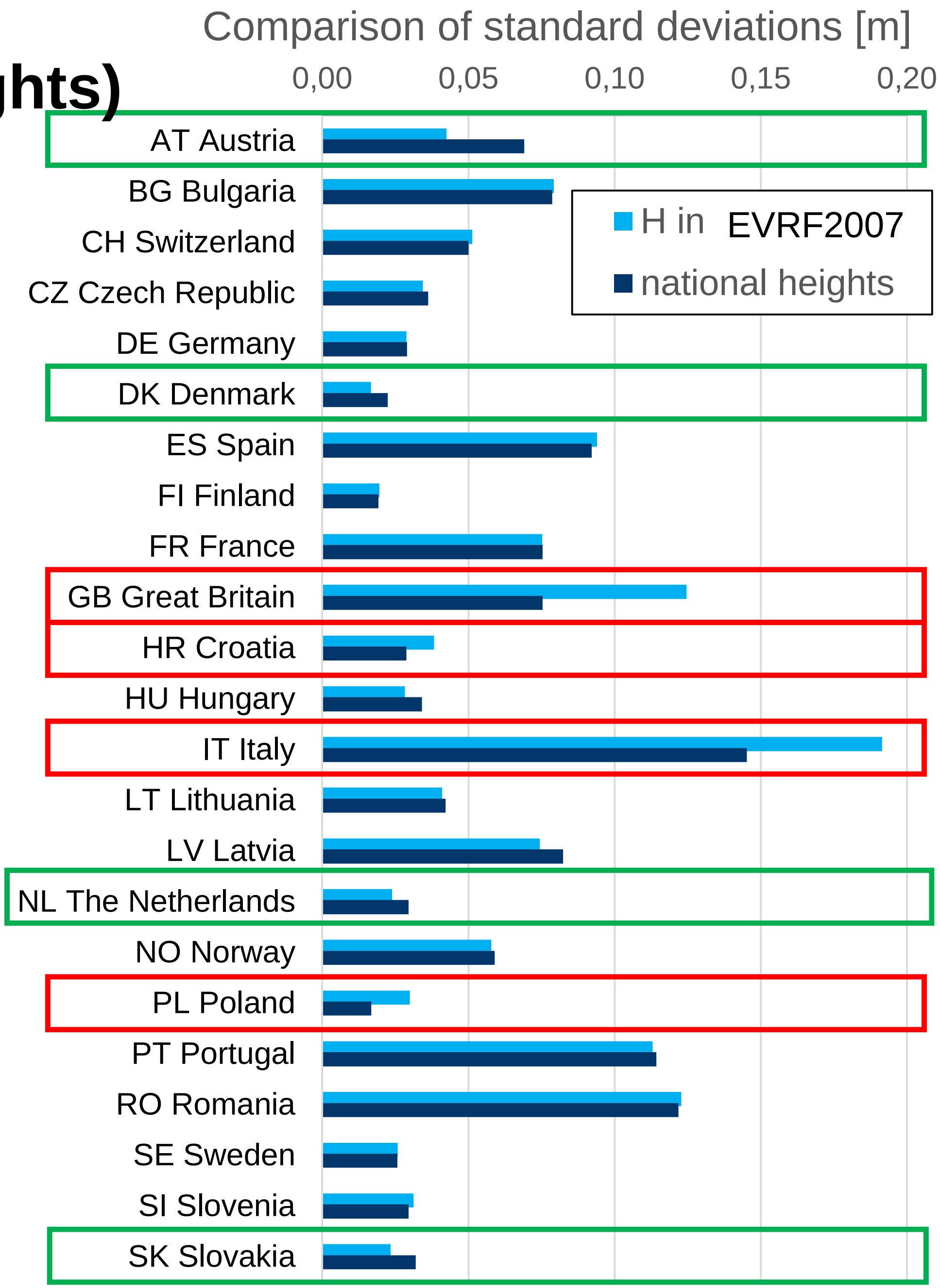
Europe (EVRF vs. nat. heights)

- GNSS/leveling dataset: EUVN-DA
  h ETRF????, zero-tide
  H **national height reference frames**, converted to zero-tide versus **EVRF2007**
- Geoid model (ζ): EGG08 (zero-tide)
- the fit of EVRF2007 is either **better** or **worse** compared to national heights

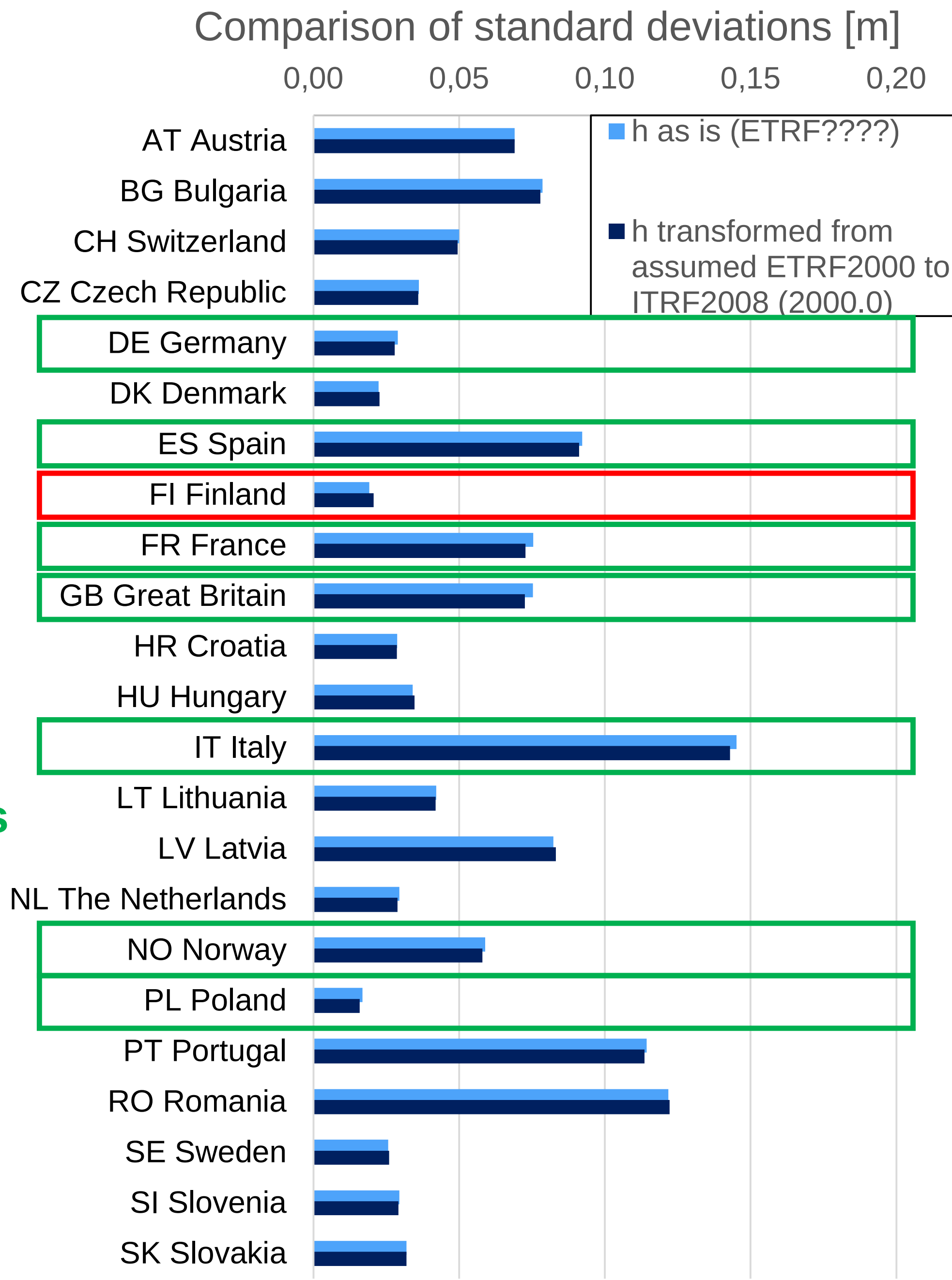
➔ Possible reasons:
  - Comparison using the same kind of physical heights, e.g. Austria
  - different adjustment approaches, e.g. Great Britain
  - constraints from cross-border leveling lines in EVRF2007



Europe (ETRF vs. ITRF)

- GNSS/leveling dataset: EUVN-DA
  h **ETRF????** versus **ITRF2008 (transformed from assumed ETRF2000 epoch 2000.0)**
  H national reference frames, converted to zero-tide
- Geoid model (ζ): EGG08 (zero-tide)

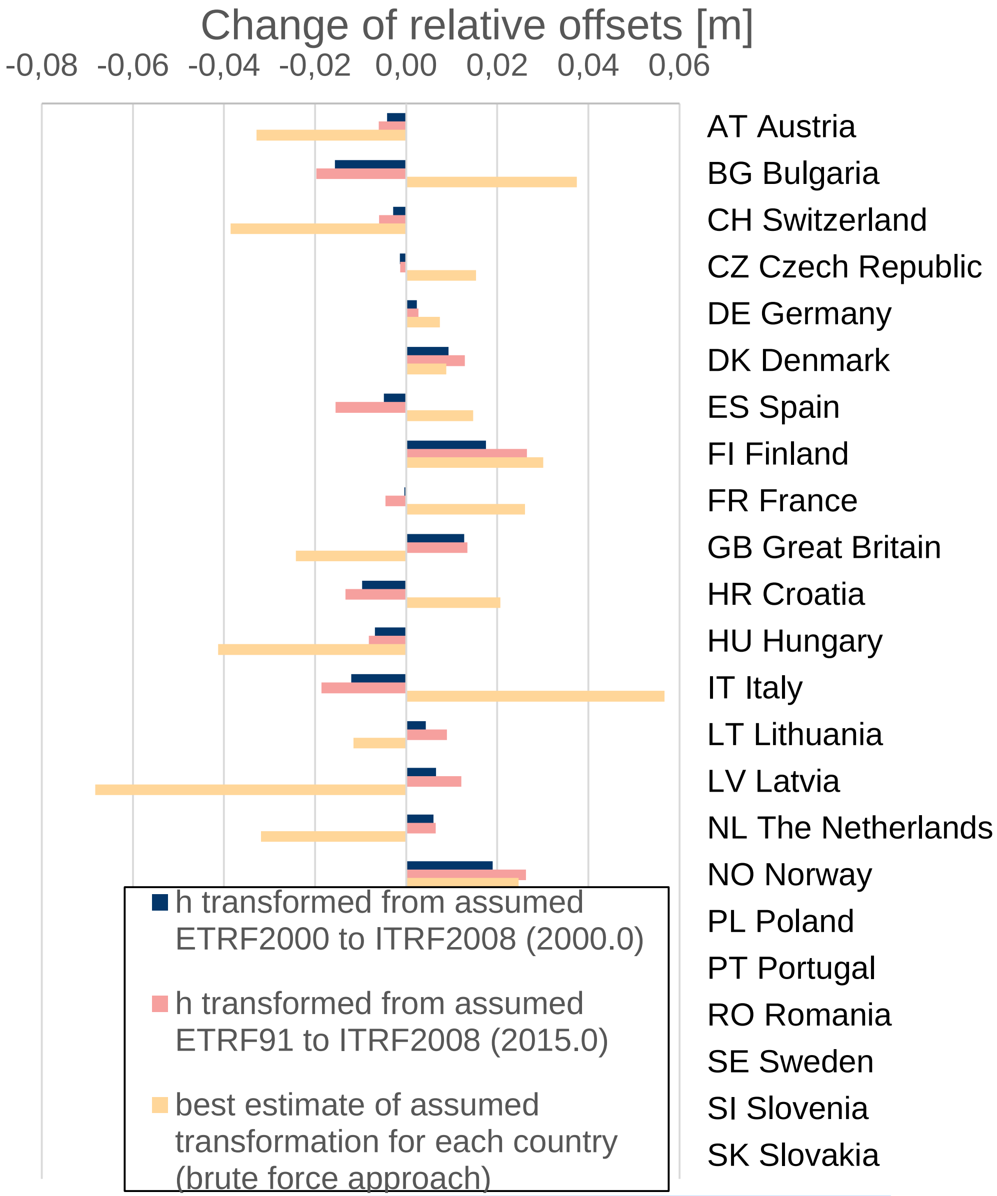
→ **Small improvements of the standard deviation in the order of a few percent in 16 of 23 countries after the assumed transformation into ITRF2000,**
e.g.
Germany -3,8 % SD
Poland -5,4 % SD



Europe (ETRF vs. ITRF)

- GNSS/leveling dataset: EUVN-DA
  h ETRF???? versus **ITRF2008 (transformed from assumed ETRF2000 epoch 2000.0)**
  H national reference frames, converted to zero-tide
- Geoid model (ζ): EGG08 (zero-tide)

➔ **But, the choice of the ETRF realization affects the ellipsoidal heights and therefore the datum offsets by a couple of centimeter !**



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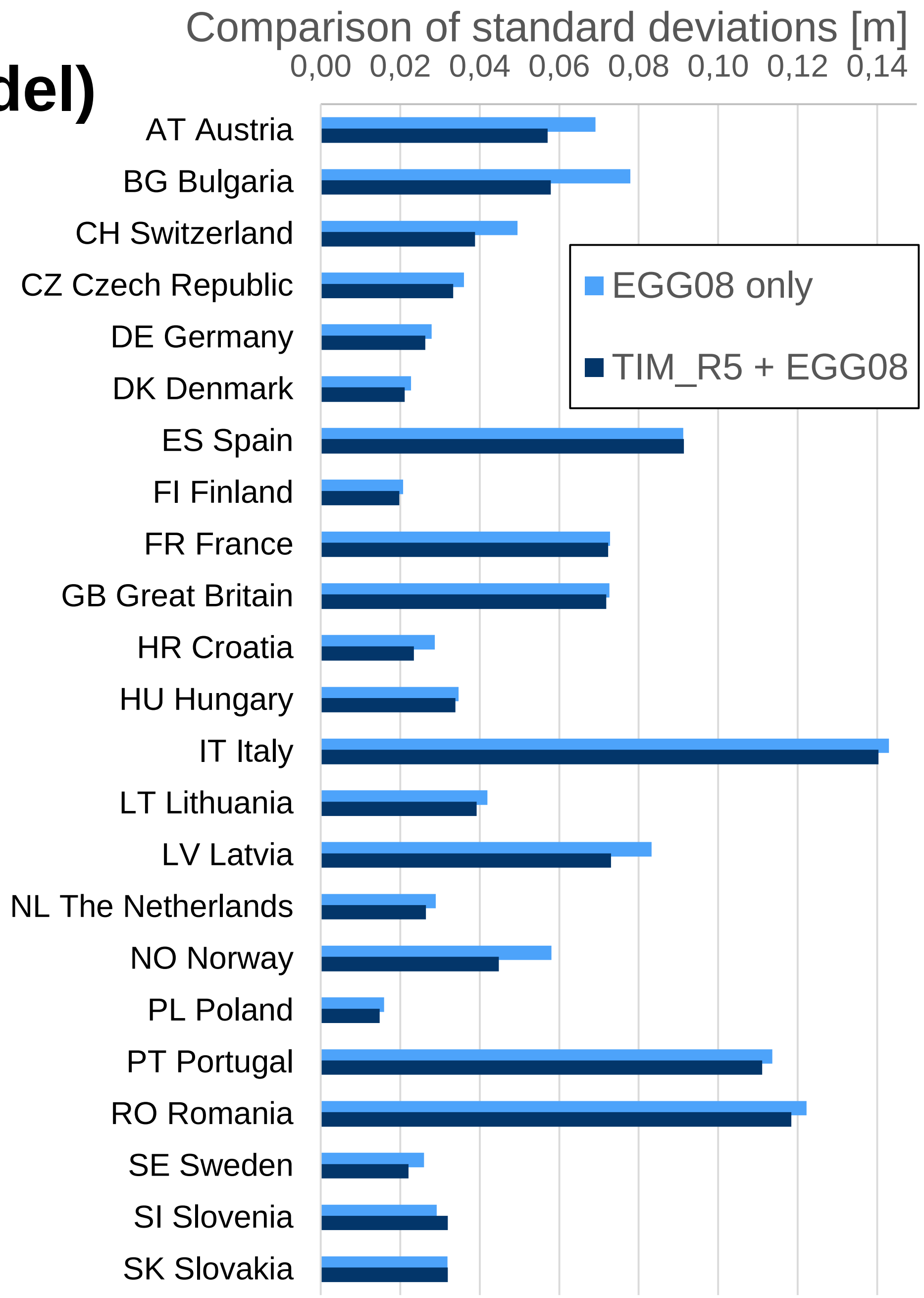
Results: Europe (geoid model)

- GNSS/leveling dataset: EUVN-DA
  h ETRF???? versus ITRF2008 (transformed from assumed ETRF2000 epoch 2000.0)
  H national reference frames, converted to zero-tide

- Geoid model (ζ): **EGG08 (zero-tide)** versus **TIM_R5 + EGG08 (zero tide) combined using Gauss filter approach (77 km half-response)**

➔ **improvements in almost all countries when using information from GOCE**



Summary

1. The unification of the national height reference frames in Europe based on GNSS/leveling data and a European quasigeoid model is an interesting and suitable approach.
2. Further improvements can be expected using a new version of the European quasigeoid model due to the data of the GOCE satellite gravity mission.
3. The European quasigeoid model, ellipsoidal heights and physical heights are in fairly good agreement for many European countries (standard deviations below the 5cm level).
4. The current inconsistencies in the international geodetic standards and conventions for the geometric (positioning) and physical (height and gravity) reference systems and frames become a limiting factor if they are not taken into account properly because they affect systematically the ellipsoidal heights over Europe, e.g. handling of permanent solid earth tide, transformation ITRF⇔ETRF.
5. Consistency of the geometric and physical reference systems and frames will become more important for practical applications (e.g. GNSS heighting, unification of height reference frames using the gravity field approach) in future.

Conclusion (I)

1. The planning of a next realization of EVRS should be started, EVRF20??
2. Next version of the EVRF could / should
   - take into account more prior information from the national leveling networks in the adjustment of the United European Leveling Network, e.g. handling of systematic errors of the last leveling epoch in Great Britain
   - include the European quasigeoid model as an equal realization of EVRS. This enables the use of EVRS also for maritime applications, e.g. as a reference surface for bathymetric surveys in hydrography.
   - information from up-to-date national GNSS / leveling data including all necessary meta information about the national reference frames and systems. This would be a valuable contribution to the unification of the European height systems (Update of information in CRS-EU) as well as the verification of global geopotential models.
3. Standards and conventions for the next EVRF should be revisited
   - Epoch of the realization?
   - Is the current correction for the permanent solid earth tides in the EVRS standards (zero tide) really the best decision for our costumers? The IAG convention of 1983 was never realized for the spatial reference system (positioning).

Conclusion (II)

4. The current inconsistencies of the international geodetic reference frames has to be taken into account by a corrector surface for European gravimetric quasigeoid model. This surface can be computed based on the knowledge of the inconsistencies only, e.g. permanent solid earth tides, ITRF⇔ETRF transformation (no adaption to GNSS/leveling data is necessary).
5. The comparison of the national geoid/quasigeoid models along the national borders as well as with respect to the European quasigeoid would provide additional valuable information for the unification of the European height reference frames.
6. Geoid and quasigeoid models become more and more important for the realization of the national and the European height reference frames. Therefore, the gravimetric data base should be further improved. One good example for the cooperation between the Baltic coastal states in this field is the activity 2 of the FAMOS project (which hopefully will be confirmed by EU this year). The major goal of this activity is the collection of gravity data over the Baltic Sea in order to improve the quasigeoid model which will serve as the height reference surface in bathymetric surveys (chart datum).

Thank you for your attention!

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