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Advances in the establishment of the International Height Reference Frame (IHRF)

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International Symposium on Gravity, Geoid and Height Systems 2018 (GGHS2018)
Sep. 17-21, 2018, Copenhagen, Denmark

Outline

1) Definition of the International Height Reference System (IHRS)

2) Realization of the IHRS: the International Height Reference Frame (IHRF):
   a) Physical realization: solid materialization by means of reference stations
      - Criteria for the station selection
      - Preliminary reference network for the IHRF
   b) Mathematical realization: determination of reference coordinates in agreement with the definition of the IHRS (preliminary computation of vertical coordinates)

3) Conclusions and next steps

International Height Reference System (IHRS)
IAG Resolution No. 1, Prague, July 2015

1) Vertical coordinates are potential differences with respect to a conventionally fixed W_0 value:

$$C_P = C(P) = W_0 - W(P) = -\Delta W(P)$$

$$W_0 = const. = 62\,636\,853.4\ \mathrm{m^2 s^{-2}}$$

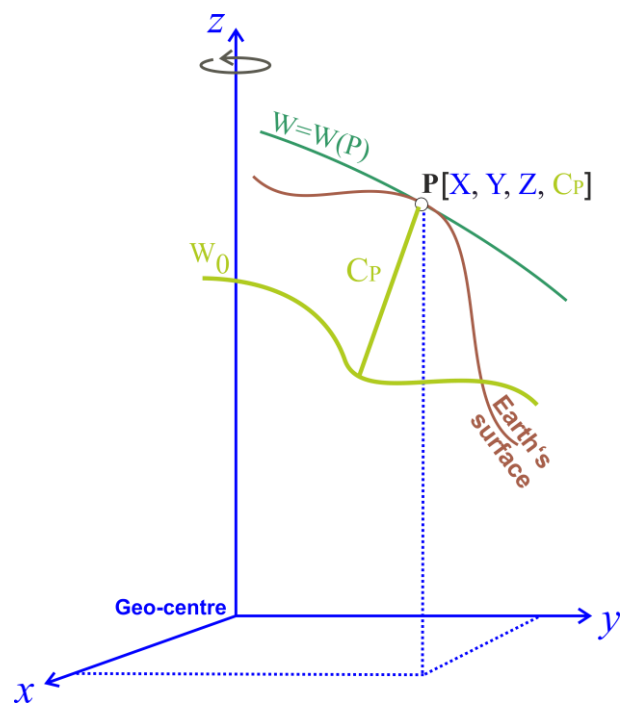
2) The position P is given in the ITRF

$\mathbf{X}_P\,(X_P, Y_P, Z_P)$; i.e., $W(P) = W(\mathbf{X}_P)$

3) The estimation of $\mathbf{X}(P)$, $W(P)$ (or $C(P)$) includes their variation with time; i.e., $\dot{\mathbf{X}}(P)$, $\dot{W}(P)$ (or $\dot{C}(P)$).

4) Coordinates are given in mean-tide system / mean (zero) crust.

5) The unit of length is the meter and the unit of time is the second (SI).



See: Ihde J. et al.: *Definition and proposed realization of the International Height Reference System (IHRS)*. Surv Geophy 38(3), 549-570, 10.1007/s10712-017-9409-3, 2017

Primary actions to implement the IHRS and its realization IHRF

1) Station selection for the IHRF reference network
2) Strategy for the determination of high-precise primary coordinates $\mathbf{X}_P$, $\dot{\mathbf{X}}_P$, W_P, $\dot{W}_P$ at the IHRF reference stations
3) Identification and preparation of standards and conventions to ensure consistency between the definition (IHRS) and the realization (IHRF); i.e., an equivalent documentation to the IERS conventions is needed for the IHRS/IHRF.

Activities related to the IHRF reference network

1) Sep. 2016 (GGHS2016, Thessaloniki): Criteria for the selection of IHRF stations

2) Oct. 2016 (GGOS Days 2016, Cambridge, MA): Preliminary IHRF station selection

3) Nov. 2016 – Mar. 2017: Interaction with regional and national experts about the preliminary station selection and proposal for further geodetic sites

4) Apr. 2017 (EGU2017, Vienna): First proposal for the IHRF reference network

5) At present: refinement of the station selection with contributions from Japan, Africa and the IAG JWG 2.1.1 (Establishment of a global absolute gravity reference system).

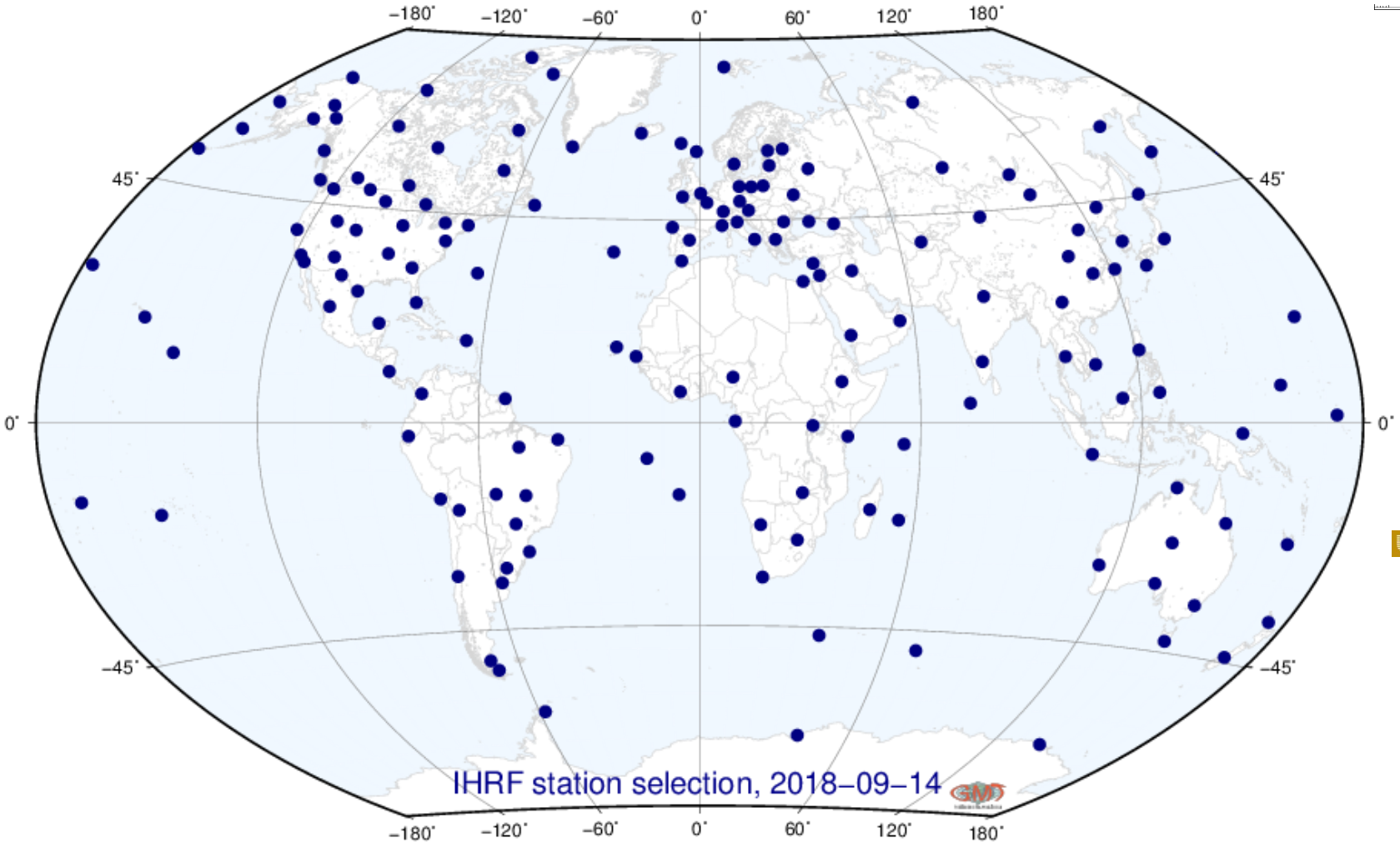
Criteria for the IHRF reference network configuration

1) Hierarchy:
   - A global network → worldwide distribution, including
   - A core network → to ensure sustainability and long term stability
   - Regional and national densifications → local accessibility

2) Collocated with:
   - fundamental geodetic observatories → connection between $\mathbf{X}$, W, $\mathbf{g}$ and time realization (reference clocks) → to support the GGRF;
   - continuously operating reference stations → to detect deformations of the reference frame (preference for ITRF and regional reference stations, like SIRGAS, EPN, APREF, etc.);
   - reference tide gauges and national vertical networks → vertical datum unification;
   - reference stations of the new Global Absolute Gravity Reference System (see IAG Resolution 2, Prague 2015).

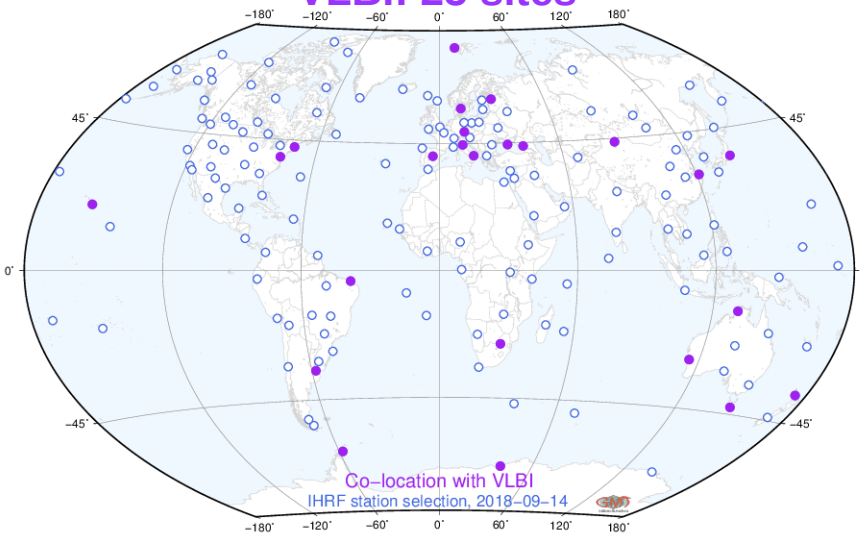
3) Main requirement: availability of terrestrial gravity data around the IHRS reference stations for high-resolution gravity field modelling (i.e., precise estimation of W).

First proposal for the IHRF reference network: 165 selected sites

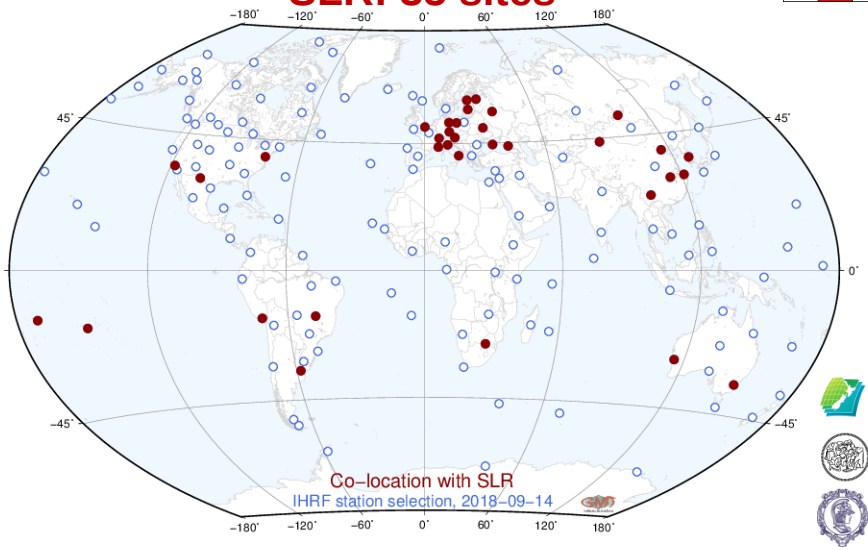


Co-location with VLBI, SLR, DORIS, and absolute gravity stations

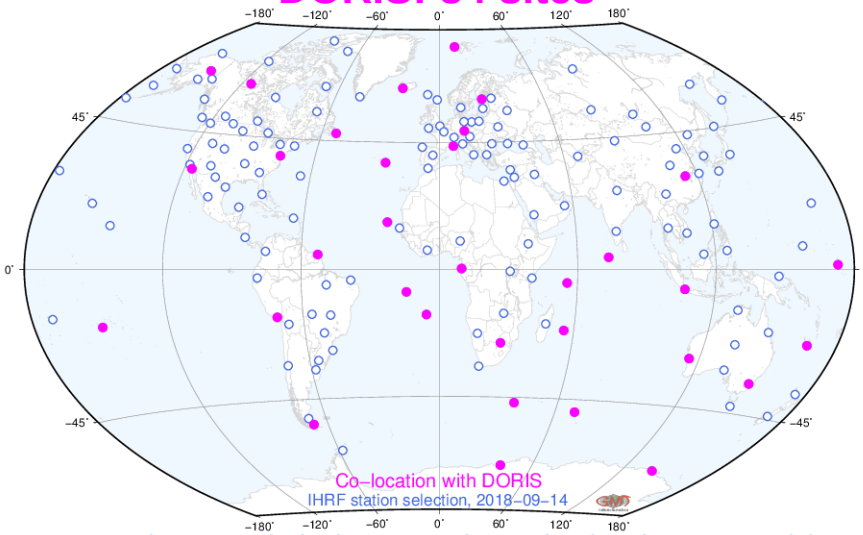
VLBI: 25 sites



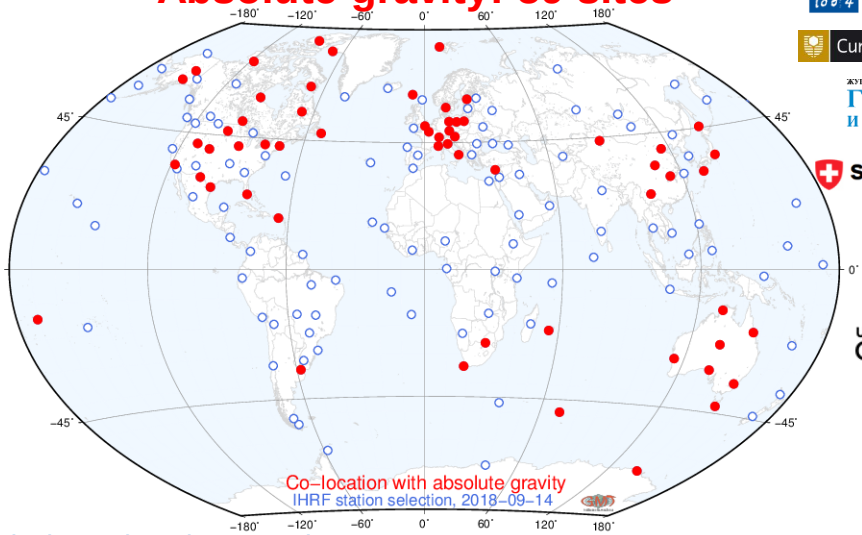
SLR: 35 sites



DORIS: 34 sites



Absolute gravity: 59 sites



Computation of potential values $W(P)$

1) Global gravity models of high-degree (with RTM)

$$W_P = f\left(X_P, GGM\right)$$

2) High-resolution gravity field modelling:

$$W_P = W_{P,satellite-only} + W_{P,high-resolution}$$

Satellite-only gravity field modelling:
Satellite orbits and gradiometry analysis
Satellite tracking from ground stations (SLR)
Satellite-to-satellite tracking (CHAMP, GRACE)
Satellite gravity gradiometry (GOCE)
Satellite altimetry (oceans only)

+

High-resolution gravity field modelling:
Stokes or Molodenskii approach
Satellite altimetry (oceans only)
Gravimetry, astro-geodetic methods, levelling, etc.
Terrain effects

3) Potential values recovered from existing (quasi)-geoid models:

$$W_P = U_P + \gamma\,\zeta_P + \left(W_0 - U_0\right)$$

4) Levelling + gravimetry (after vertical datum unification):

$$W_P = \left(W_0^{local} + \delta W\right) - C_P; \quad \delta W = W_0^{IHRF} - W_0^{local}$$

Activities related to the IHRF coordinates (1/2)

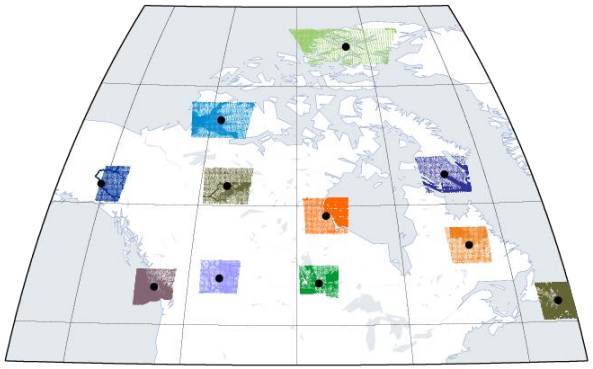
1) Sep. 2016 to Mar. 2017: Strategy for the integration (transformation) of local vertical datums into the IHRS/IHRF → M. Sideris' talk on Thursday 10:00 am

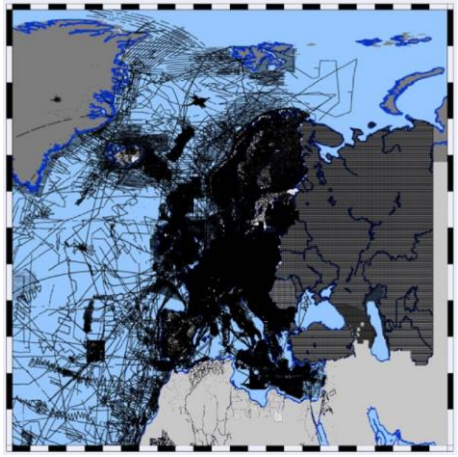
2) May to Aug. 2017:

   a) Computation of potential values using the latest GGMs of high-resolution:
      - EGM2008 (Pavlis et al., 2012), lmax = 2190
      - EIGEN-6C4 (Förste et al., 2014), lmax = 2190
      - XGM2016 (Pail et al., 2017), lmax = 719, extended to lmax = 2190 with EIGEN-6C4

   b) Comparison with potential values inferred from high-resolution gravity field modelling in Canada (NRCan, M. Véronneau, J. Huang) and Europe (IFE/LUH, Germany H. Denker)

   c) Futher numerical experiments in Greece (AUTH, G. Vergos), Brazil (EPUSP, D. Blitzkow, A.C.O.C. Matos) and Ecuador (UFPR, S. Freitas and J.L. Carrión-Sánchez)





After Denker (2015)

Conclusions from the activities in 2017

1) The use of GGMs is (at present) not suitable for the estimation of precise potential values. GGMs may be used if „no other way“.

2) Results obtained from high-resolution gravity field modelling present discrepancies up to the dm-level.

3) A “standard” procedure may be not appropriate as
   - different data availability and different data quality exist around the world
   - regions with different characteristics require particular approaches (e.g. modification of kernel functions, size of integration caps, geophysical reductions like GIA, etc.)

4) A “centralized” computation (like in the ITRF) is complicated due to the restricted accessibility to terrestrial gravity data

5) What should we do? - Discussions at the IAG-IASPEI Assembly (Aug. 2017):
   - To compute IHRF coordinates using exactly the same input data and the own methodologies (software) of colleagues involved in the gravity field modelling
   - Based on the comparison of the results, to identify a set of standards that allow to get as similar and compatible results as possible.

Activities related to the IHRF coordinates (2/2)

1) Aug. 2017: YM Wang (NGS/NOAA), chair of the IAG JWG 2.2.2 (The 1 cm geoid experiment) proposes the distribution of gravity data, terrain model and GNSS/levelling data for an area of about 700 km^2 in Colorado, USA → Colorado experiment

2) Participants in the Colorado experiment should compute geoid, quasi-geoid, and potential values at selected points

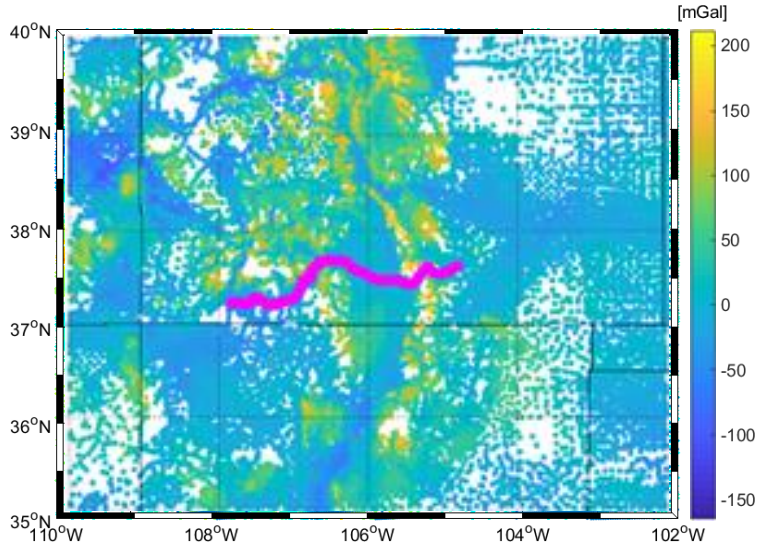
3) This experiment is performed within:
   - IAG JWG 2.2.2: The 1 cm geoid experiment (chair: Y.M. Wang)
   - GGOS JWG: Strategy for the realisation of the IHRS (chair: L. Sánchez)
   - IAG SC 2.2: Methodology for geoid and physical height systems (chair: J. Ågren)
   - ICCT JSG 0.15: Regional geoid/quasi-geoid modelling - Theoretical framework for the sub-centimetre accuracy (chair: J. Huang)

4) Dec. 2017 - Jan. 2018: A set of basic (minimum) standards/requirements for the computation of potential values was prepared

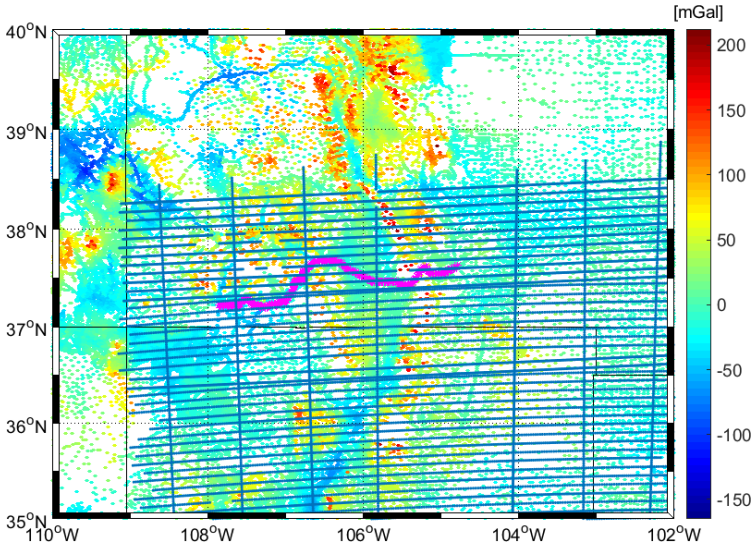
5) Feb. 2018: The Colorado data was distributed

6) Since Feb. 2018: Different computation groups are working with these data.

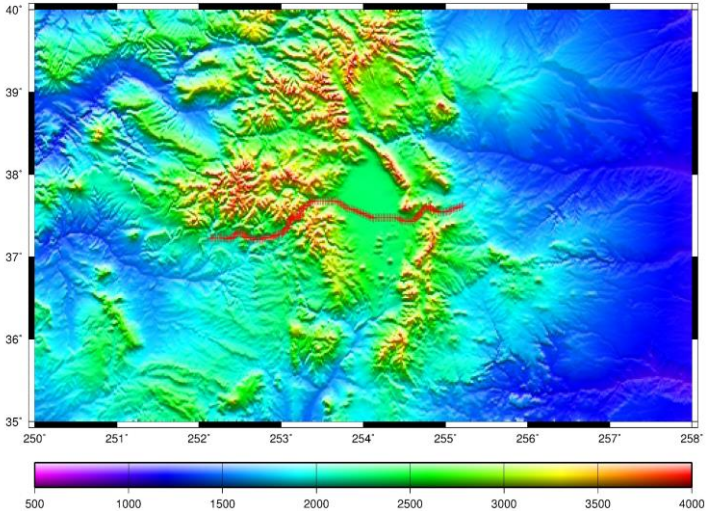
Colorado data



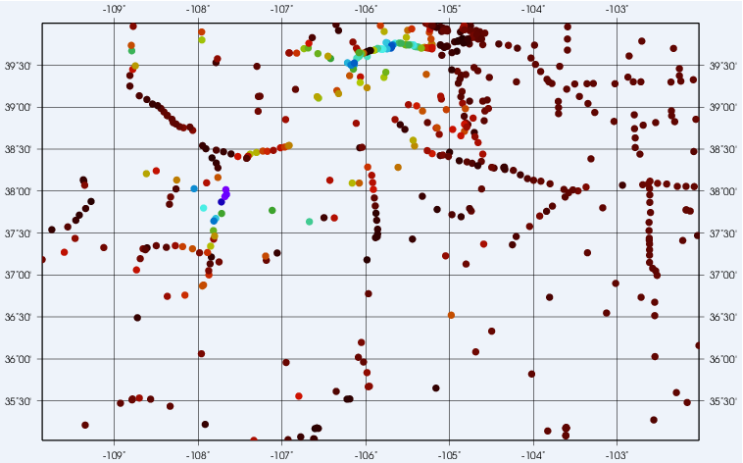
Surface gravity data (59,303 points)



Airborne gravity data
(41 lines E-W, 7 lines N-S)



Terrain model: SMRT V4.1



NGS *historical* GPS/levelling (510 points)

Contributing solutions

Faculty of Engineering, Minia University, Egypt	→	N			
İstanbul Teknik Üniversitesi, Istambul, Turkey	→	N	ζ		
Department of Geodesy and Surveying, Aristotle University of Thessaloniki, Thessaloniki, Greece	→	N	ζ	W	
National Geodetic Survey, USA	→	N	ζ	W	
Natural Resources Canada, Canada	→	N	ζ	W	
Lantmäteriet, Swedish mapping, cadastral and land registration authority, Sweden	→	N	ζ	W	
School of Earth and Planetary Sciences and The Institute for Geoscience Research, Curtin University, Australia	→	N	ζ	W	
Universidade Federal do Parana, Brazil	→	N	ζ	W	
Escola Politécnica, Universidade de São Paulo; Centro de Estudos de Geodesia, Brazil	→				T
Deutsches Geodätisches Forschungsinstitut, Technische Universität München, Germany	→			W	

Contributing solutions

YM Wang's talk S3-O6 on Wed. 9:15

Faculty of Engineering, Minia University, Egypt	→	N			
İstanbul Teknik Üniversitesi, Istambul, Turkey	→	N	ζ		
Department of Geodesy and Surveying, Aristotle University of Thessaloniki, Thessaloniki, Greece	→	N	ζ		
National Geodetic Survey, USA	→	N	ζ	W	
Natural Resources Canada, Canada	→	N	ζ	W	
Lantmäteriet, Swedish mapping, cadastral and land registration authority, Sweden	→	N	ζ	W	
School of Earth and Planetary Sciences and The Institute for Geoscience Research, Curtin University, Australia	→	N	ζ	W	
Universidade Federal do Parana, Brazil	→	N	ζ	W	
Escola Politécnica, Universidade de São Paulo; Centro de Estudos de Geodesia, Brazil	→				T
Deutsches Geodätisches Forschungsinstitut, Technische Universität München, Germany	→			W	

Contributing solutions

YM Wang's talk S3-O6 on Wed. 9:15

Faculty of Engineering, Minia University, Egypt	→	N			
İstanbul Teknik Üniversitesi, İstanbul, Turkey (Erol and Işik, S3-P4)	→	N	ζ		
Department of Geodesy and Surveying, Aristotle University of Thessaloniki, Thessaloniki, Greece (Grigoriadis et al., S3-P10)	→	N	ζ		
National Geodetic Survey, USA (Wang et al., S3-O5)	→	N	ζ	W	
Natural Resources Canada, Canada	→	N	ζ	W	
Lantmäteriet, Swedish mapping, cadastral and land registration authority, Sweden	→	N	ζ	W	
School of Earth and Planetary Sciences and The Institute for Geoscience Research, Curtin University, Australia	→	N	ζ	W	
Universidade Federal do Paraná, Brazil (Nicacio et al., S5-P7)	→	N	ζ	W	
Escola Politécnica, Universidade de São Paulo; Centro de Geodesia, Brazil (Blitzkow et al., S5-P1)	→				T
Deutsches Geodätisches Forschungsinstitut, Technische Universität München, Germany	→			W	

Comparison of potential values W(P) (1/4)

1) The comparison is carried out at 223 GSVS17 marks (Geoid Slope Validation Survey 2017) selected by NGS

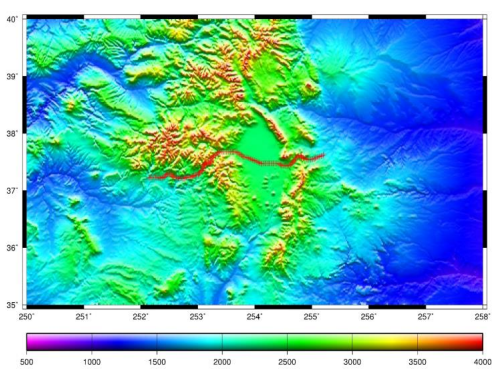
2) Participants in the experiment got φ, λ, h; levelling is not available (yet).

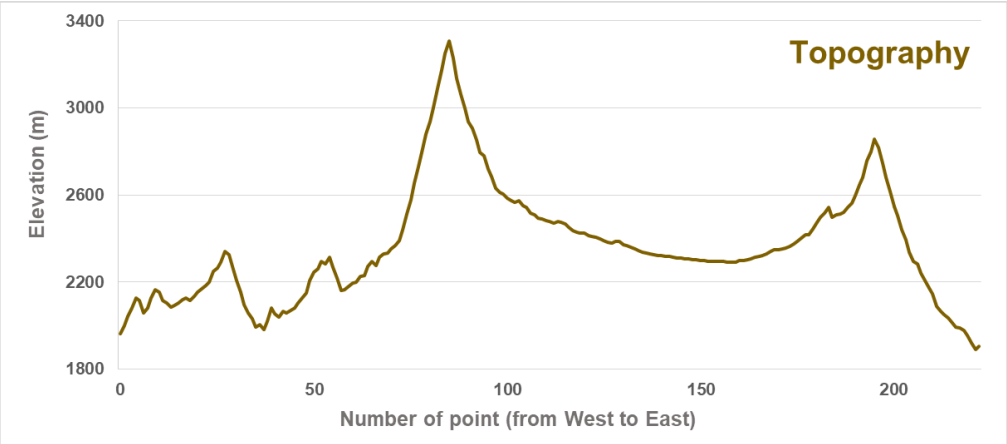
3) The potential values provided by the different solutions are converted to geopotential numbers with respect to the IHRS W_0 value

$$C(P) = W_0 - W(P) \quad ; \quad W_0 = 62\,636\,853.4 \text{ m}^2\text{s}^{-2}$$

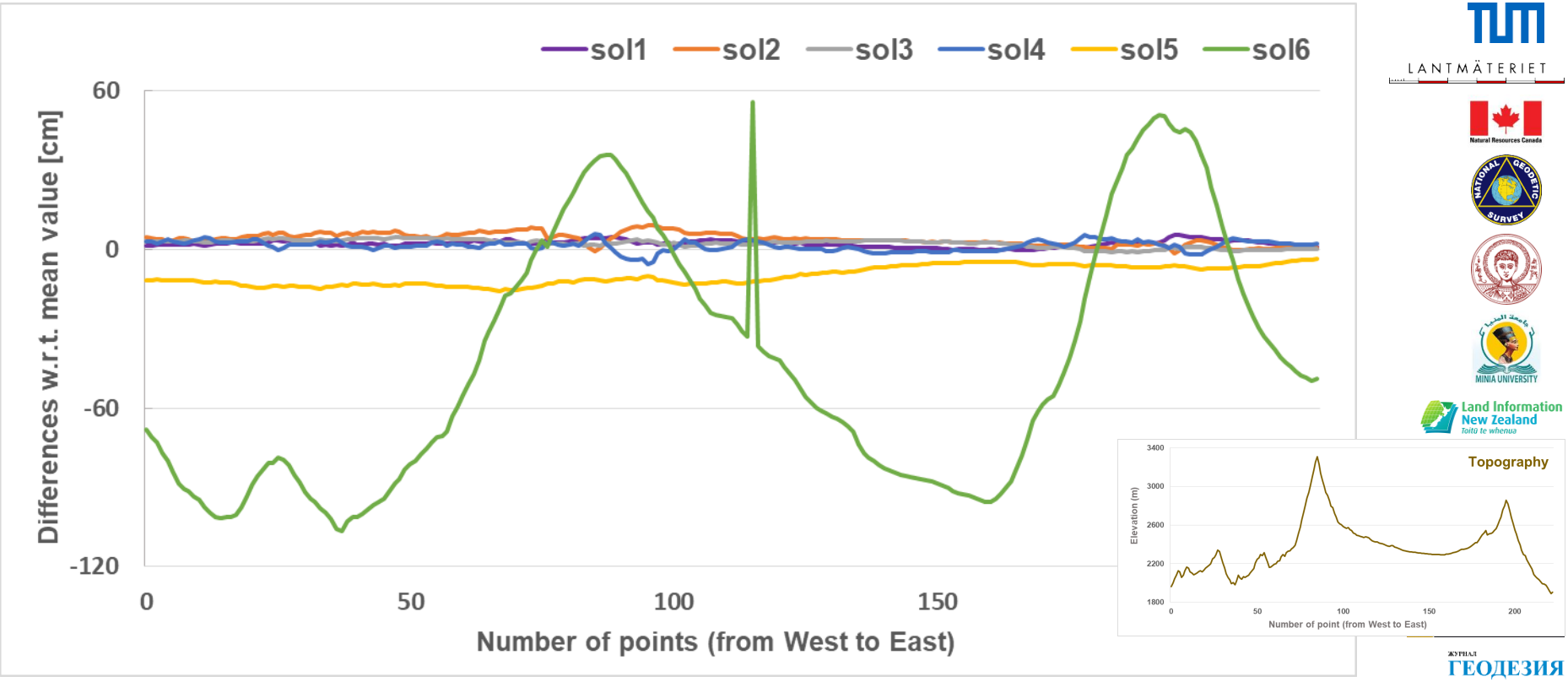
2) and further transformed to normal heights (to see the differences in meters):

$$H^*(P) = C(P)/\gamma(P)$$





Comparison of potential values W(P) (2/4)



sol1: $\zeta \rightarrow$ **W**

sol2: **N** $\rightarrow$ **W**

sol3: **W**

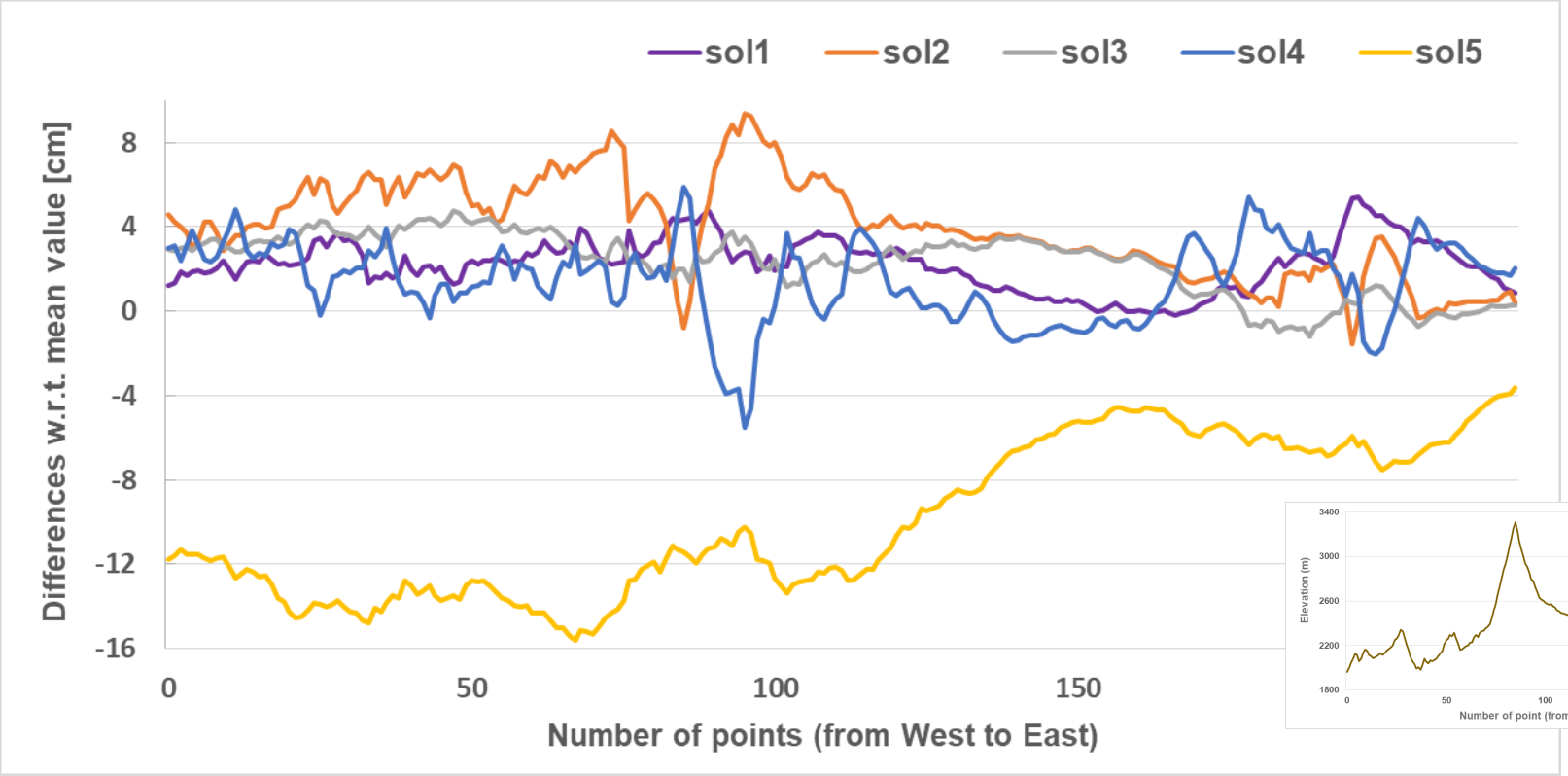
sol4: **N** $\rightarrow$ **W**

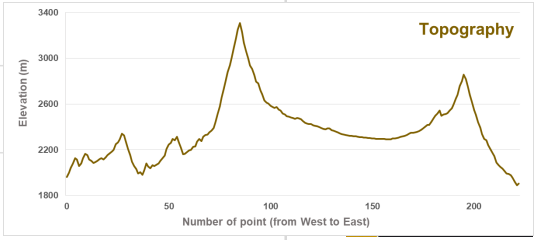
sol5: $\zeta \rightarrow$ **W**

sol6: $\zeta \rightarrow$ **W**

	sol1	sol2	sol3	sol4	sol5	sol6
mean [cm]	2.2	3.9	2.3	1.4	-9.9	-42.9
std [cm]	1.2	2.3	1.5	1.9	3.6	47.0
max [cm]	5.4	9.4	4.8	5.9	-3.6	55.8
min [cm]	-0.2	-1.6	-1.2	-5.5	-15.6	-106.6
range [cm]	5.6	11.0	6.0	11.4	19.2	162.4

Comparison of potential values W(P) (3/4)





sol1: $\zeta \rightarrow$ **W**

sol2: **N** $\rightarrow$ **W**

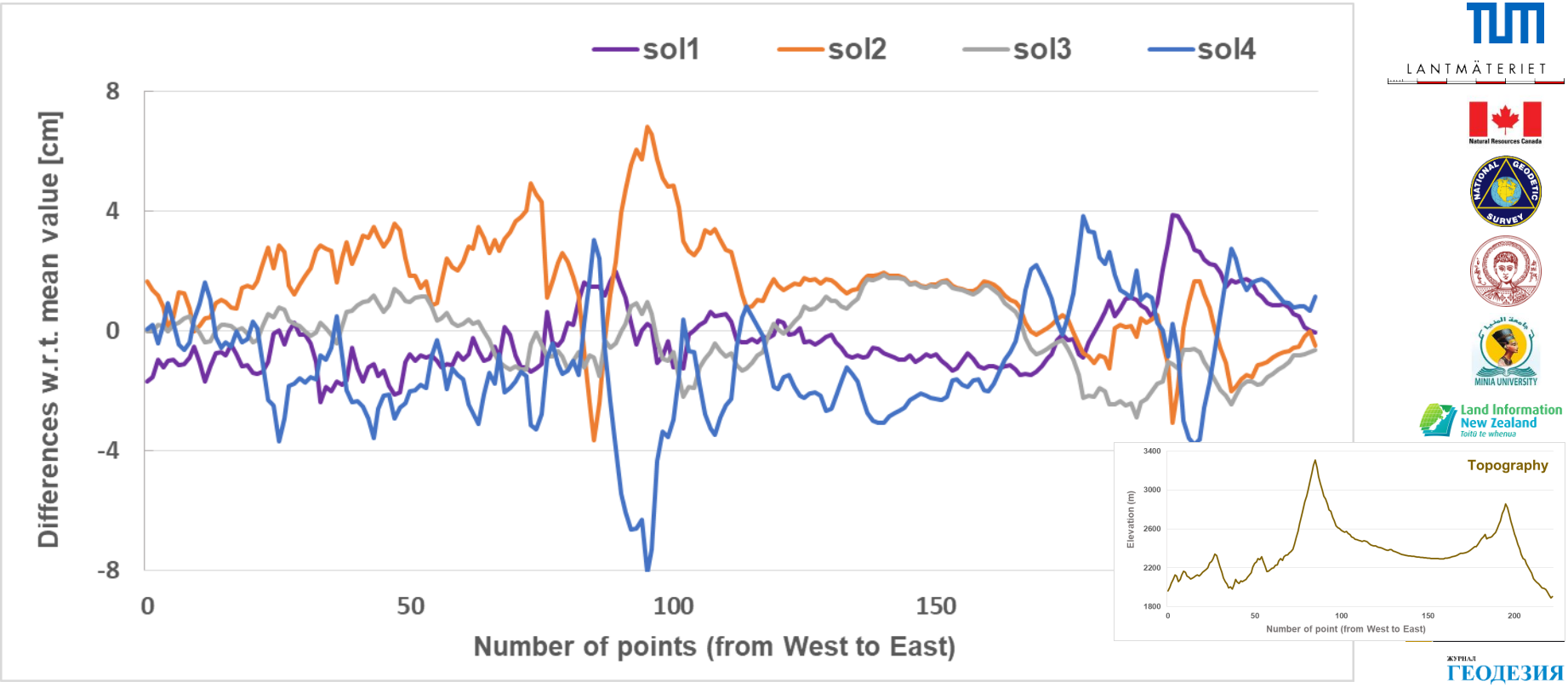
sol3: **W**

sol4: **N** $\rightarrow$ **W**

sol5: $\zeta \rightarrow$ **W**

	sol1	sol2	sol3	sol4	sol5
mean [cm]	2.2	3.9	2.3	1.4	-9.9
std [cm]	1.2	2.3	1.5	1.9	3.6
max [cm]	5.4	9.4	4.8	5.9	-3.6
min [cm]	-0.2	-1.6	-1.2	-5.5	-15.6
range [cm]	5.6	11.0	6.0	11.4	19.2

Comparison of potential values W(P) (4/4)



sol1: $\zeta \rightarrow$ **W**

sol2: **N** $\rightarrow$ **W**

sol3: **W**

sol4: **N** $\rightarrow$ **W**

	sol1	sol2	sol3	sol4
mean [cm]	-0.2	1.5	-0.2	-1.1
std [cm]	1.2	1.7	1.1	2.0
max [cm]	3.9	6.8	1.9	3.8
min [cm]	-2.4	-3.6	-2.9	-8.1
range [cm]	6.3	10.5	4.7	11.9

Conclusions

1) We compare the potential values estimated in six independent solutions: two solutions are geoid-based, three solutions are quasi-geoid-based and one solution computes potential values directly at the test marks.

2) Four solutions are consistent in the 1 dm level.

3) Discrepancies present a strong correlation with the topography, especially those solutions based on the geoid (discrepancies up to 15 cm). We suspect that this may be caused by the handling of orthometric hypothesis in the transformation from geoid heights to potential values.

4) The quasi-geoid-based solution and the direct computation of potential values agree quite well (discrepancies up to 4 cm).

5) To be the first (preliminary) results, they are very promising.

Next steps

1) To identify sources of discrepancy between the different solutions
2) To compute refined solutions (two o more iterations)
3) To compare potential differences with geopotential values derived from levelling and gravimetry (when NGS releases these data)
4) To compile a first version of “the IHRS standards and conventions”.

This work is possible thanks to the contribution of many colleagues. Their support is deeply acknowledged:

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More information at **http://ihrs.dgfi.tum.de**, **www.ggos.org**