Strategy for the establishment of the International Height Reference System (IHRS)

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Outline

1) Motivation

2) The International Height Reference System (IHRS)

3) 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)

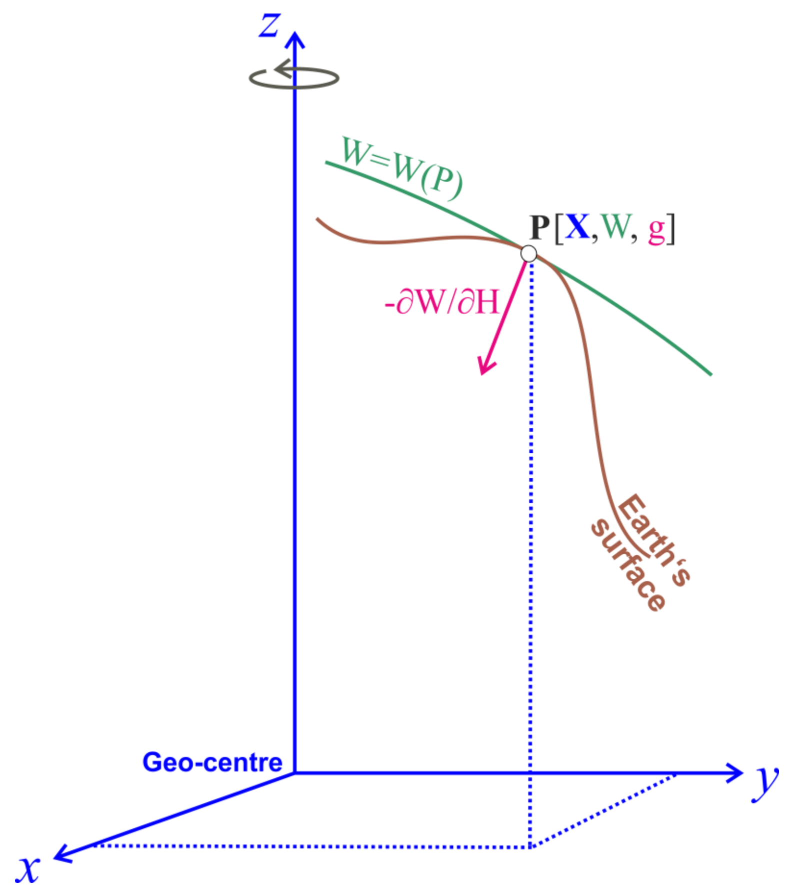
4) Next steps

Motivation

A main objective of the International Association of Geodesy (IAG) and its Global Geodetic Observing System (GGOS) is the implementation of an integrated Global Geodetic Reference Frame (GGRF) that supports the consistent determination and monitoring of the Earth's geometry, rotation and gravity field with high accuracy worldwide.

The GGRF includes:

- Geocentric Cartesian coordinates $\mathbf{X}$, $\dot{\mathbf{X}}$
- Gravity vector $\mathbf{g}$, $\dot{\mathbf{g}}$
- Potential of the Earth's gravity field W, $\dot{W}$
- Physical height H, $\dot{H}$



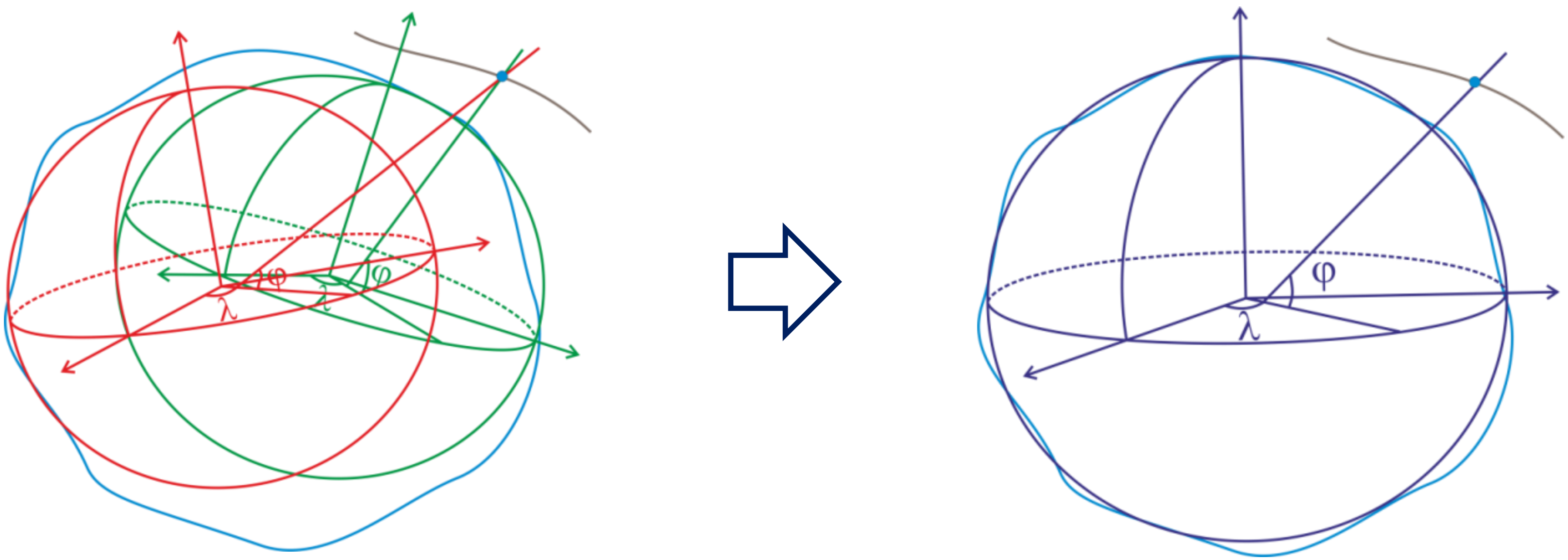
GGRF coordinates according to the IAG

See: *Description of the Global Geodetic Reference Frame*; position paper adopted by the IAG Executive Committee, April, 2016, http://iag.dgfi.tum.de/fileadmin/IAG-docs/GGRF_description_by_the_IAG_V2.pdf

Geocentric Cartesian coordinates

refer to the International Terrestrial Reference System (ITRS) and Frame (ITRF)

- Standardized computation through the IERS (International Earth Rotation and Reference Systems' Service);
- Worldwide unified reference frame;
- Reliability at the cm-level.

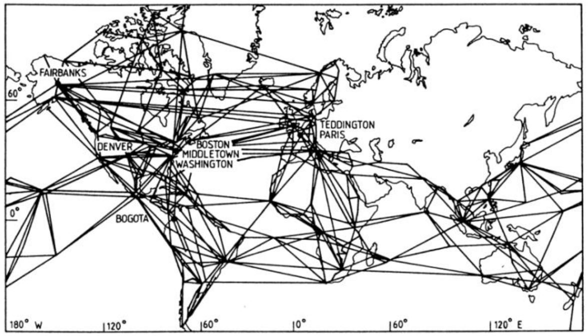


Before the ITRS/ITRF: many individual (local) horizontal reference systems

Today: one global unified geocentric reference system

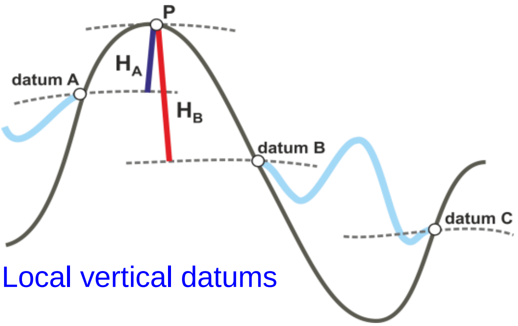
References for physical coordinates

1) Gravity observations refer to the International Gravity Standardization Net 1971 (IGSN71)
   - Accuracy: 1μms-2 (100 μGal)
   - 10 absolute gravity stations
   - 1,200 pendulum and 24,000 relative observations
   - Potsdam datum correction -14mGal



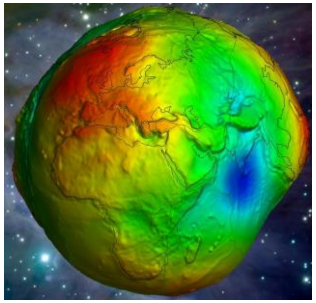
IGSN71 (after Morelli et al. 1976)

2) Physical heights refer to more than 100 vertical datums
   - Different reference levels (many [dm] of discrepancy);
   - Different types of heights (normal, orthometric, etc.);
   - Omission of (sea and land) vertical variations with time;
   - Unprecise combination of h-H-N



Local vertical datums

3) (Static) geoid
   - Accuracy at the cm-level at the long wavelengths (~ 100 km) thanks to the satellite gravity missions, but more than 150 models since 2008
   - Accuracy at the short wavelengths depends on the availability of terrestrial (airborne, marine) gravity data and terrain models
   - Different geoid modelling approaches lead to different results (discrepancies of some dm).



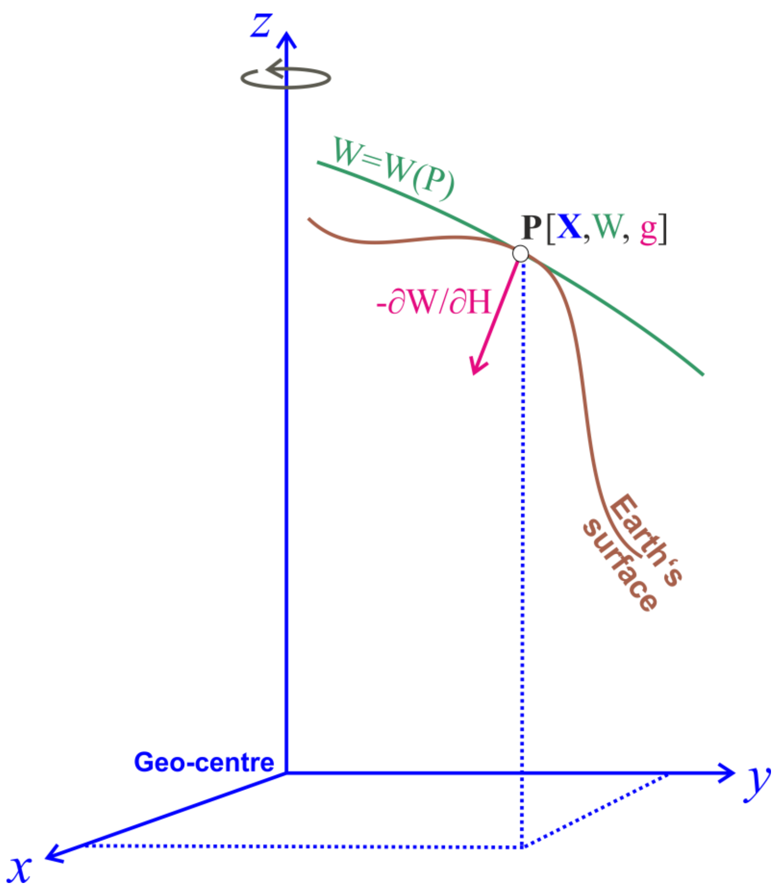
EIGEN-6C4 geoid model, ICGEM

IAG Resolutions 2015

The establishment of an integrated GGRF demands the implementation of a worldwide-unified (standardized) physical reference system able to support the high precision provided by the current geodetic observation techniques.

A first concrete step oriented to this purpose was the release of two IAG resolutions during the IUGG2015 General Assembly (Prague, July 2015):

- one for the definition and realization of an International Height Reference System (IHRS), and
- the second one for the establishment of an International Gravity Reference System (IGRS) based on absolute gravity measurements (as replacement of the IGSN71).



GGRF coordinates according to the IAG

See: Drewes et al.: *The Geodesist's Handbook 2016*, Journal of Geodesy. 2016.

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:

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

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

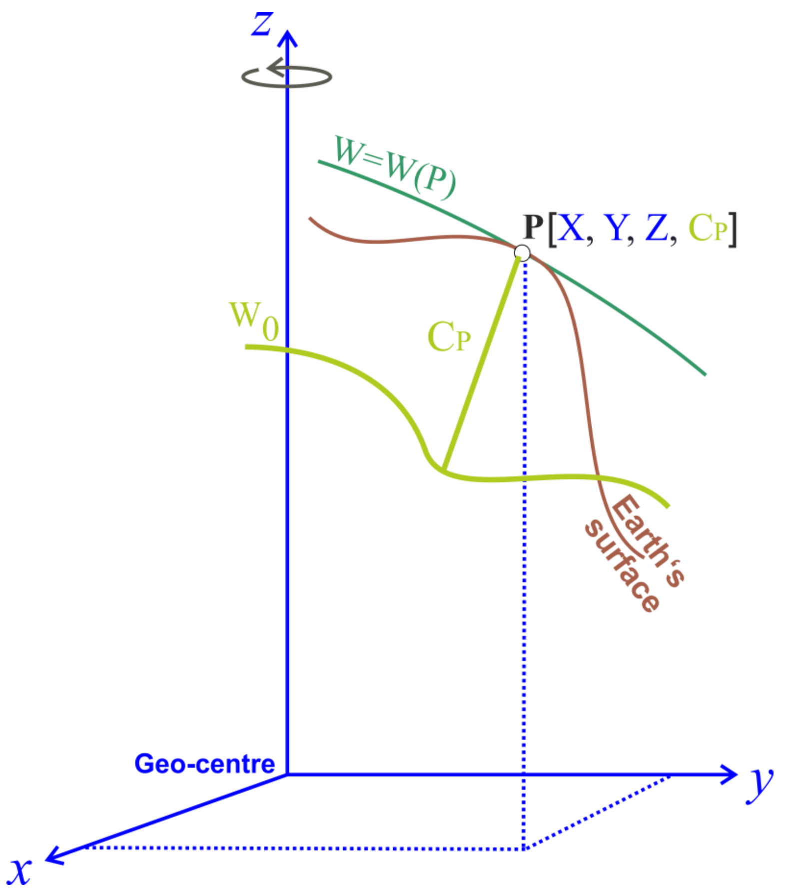
2) The position P is given in the ITRF

$\mathbf{X}_P\ (X_P, Y_P, Z_P)$; 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).



IHRS coordinates according to the IAG Resolution No. 1, 2015

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). During the Gravity Symposium GGHS2018 (Copenhagen, Sep 17-21, 2018) initial contact with Israel, Nepal and Saudi Arabia to identify potential IHRF stations in those countries.

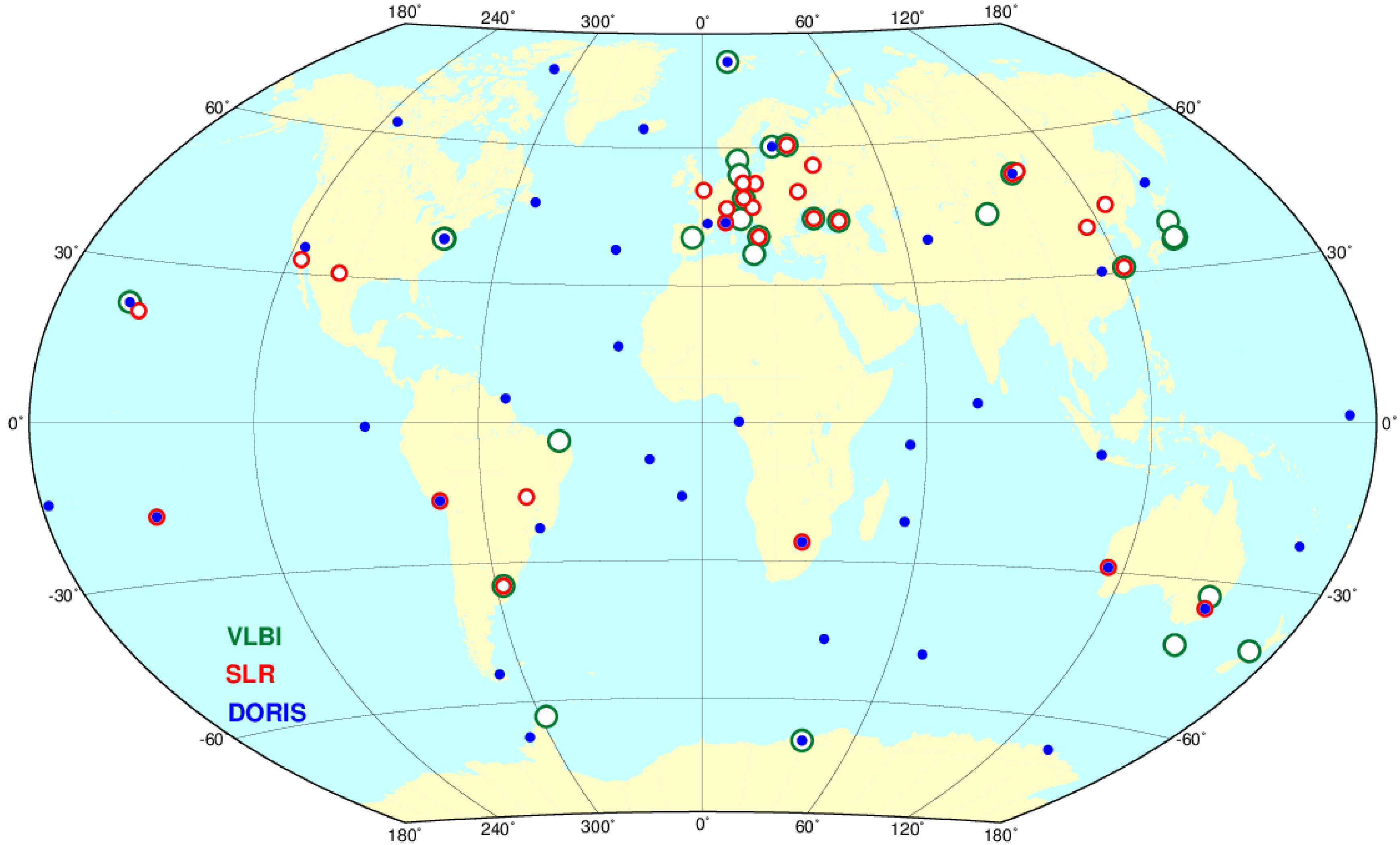
Criteria for the IHRF reference network configuration

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

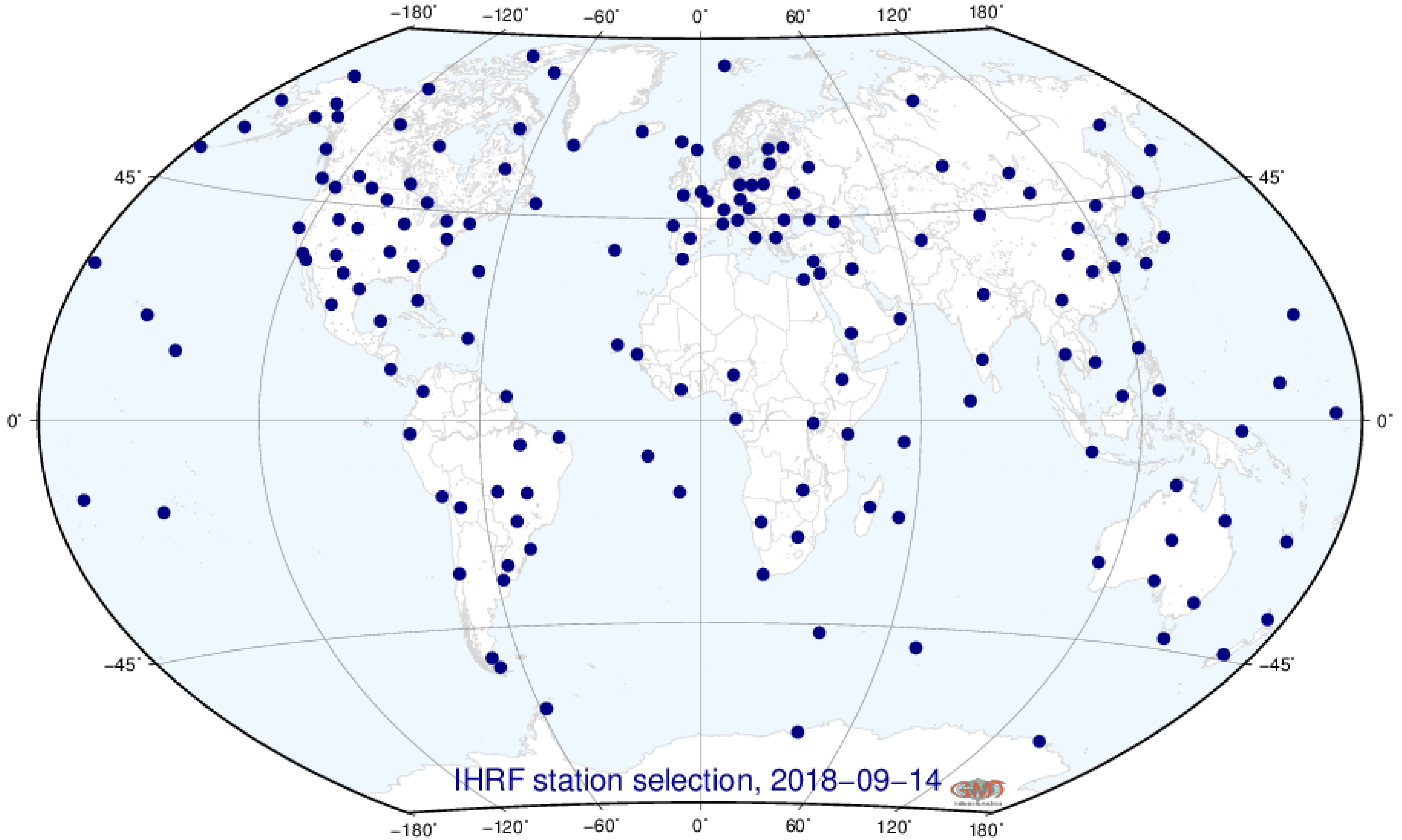
2) Collocated with:
   - fundamental geodetic observatories → connection between $\mathbf{X}$, W, $\mathbf{g}$ and time realization (reference clocks) → to support the GGRF;
   - continuously operating reference stations → to detect deformations of the reference frame (preference for ITRF and regional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

Preliminary station selection for the IHRF (Oct. 2016)



First proposal for the IHRF reference network: 165 selected sites



Interaction with regional/national experts for the IHRF station selection

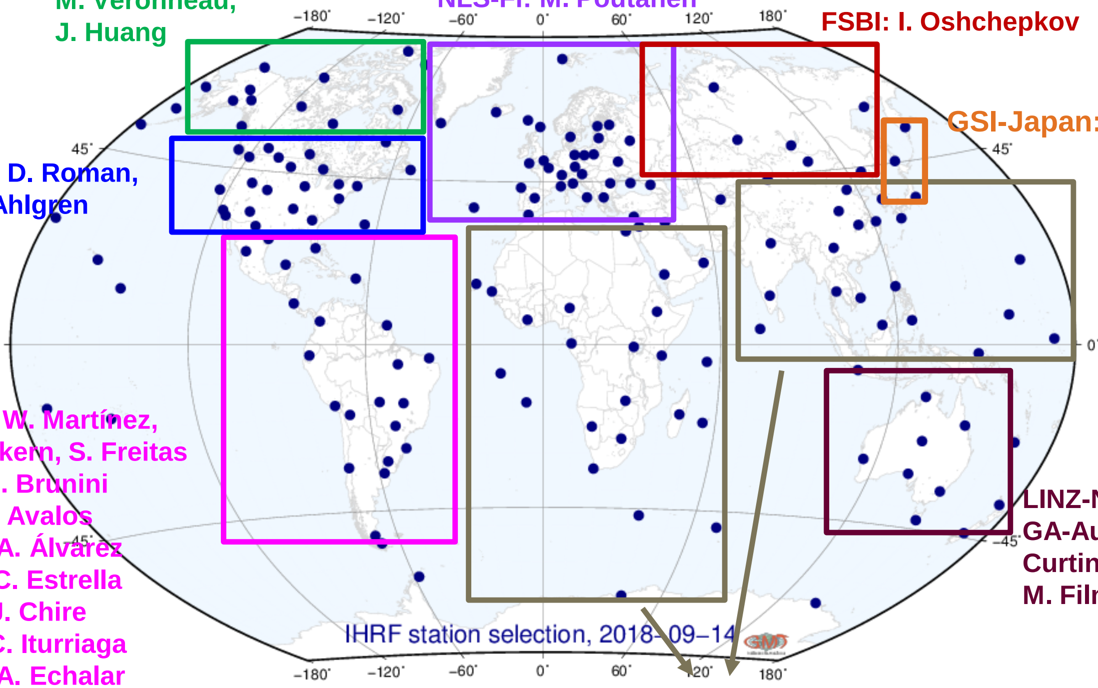
IGIK-Pl: J. Krinsky
DTU-Dk: R. Forsberg
AUTH-Gr: G. Vergos
LGIA-LV: I. Liepins
LM-Se: J. Ågren, Nordic Geodetic Commission (NGK)
Swisstopo-Ch: U. Martí
IGN-Es: P. Vaquero
NLS-Fi: M. Poutanen

NRCan:
M. Véronneau,
J. Huang

FSBI: I. Oshchepkov

GSI-Japan: K. Matsuo

NGS/NOAA: D. Roman,
K. Choi, K. Ahlgren

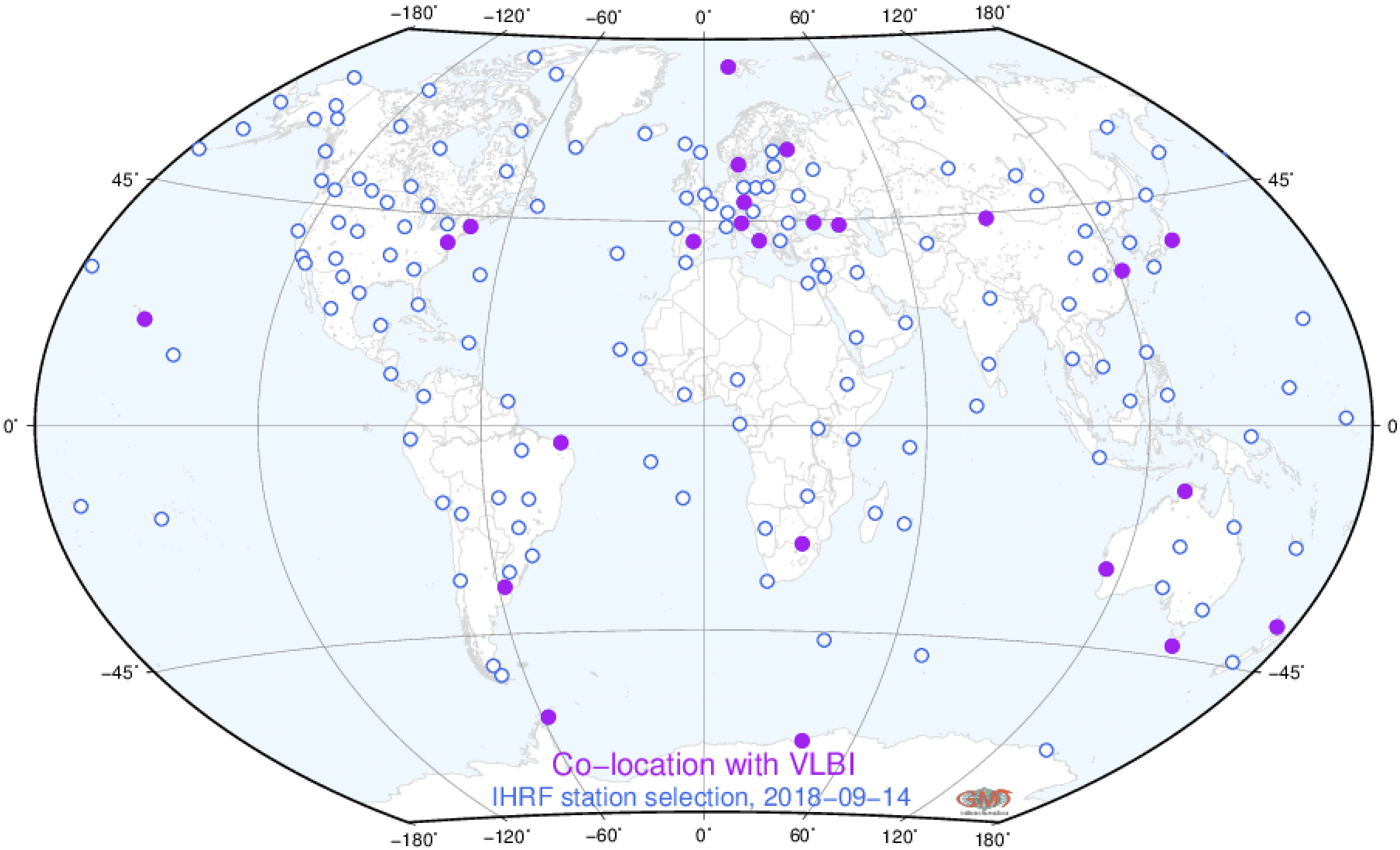


SIRGAS: W. Martínez,
M.V. Mackern, S. Freitas
AGGO: C. Brunini
INEGI: D. Avalos
IGN-CR: A. Álvarez
IGM-Ec: C. Estrella
IGN-Pe: J. Chire
IGM-Cl: C. Iturriaga
IGM-Bo: A. Echalar
IGN-Ar: D. Piñon
SGM-Uy: N. Suárez
IBGE: S. Costa, R. Luz
EPUSP: D. Blitzkow, A.C.O.C. Matos

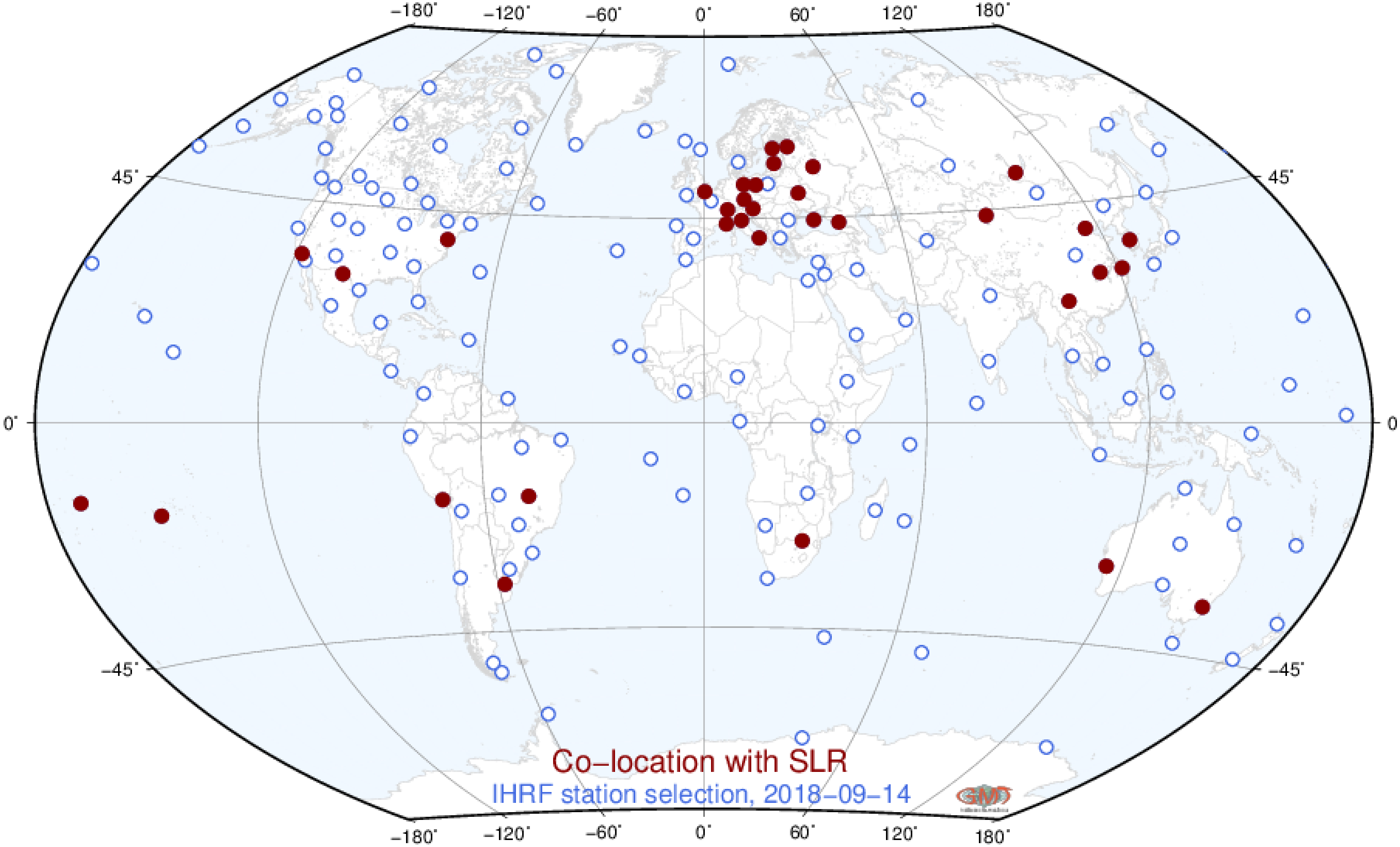
LINZ-Nz: M. Amos
GA-Au: R Ruddick
Curtin-Au: W. Featherstone
M. Filmer, S. Claessens

IGS stations
H.A. Abd-Elmotaal (Egypt)

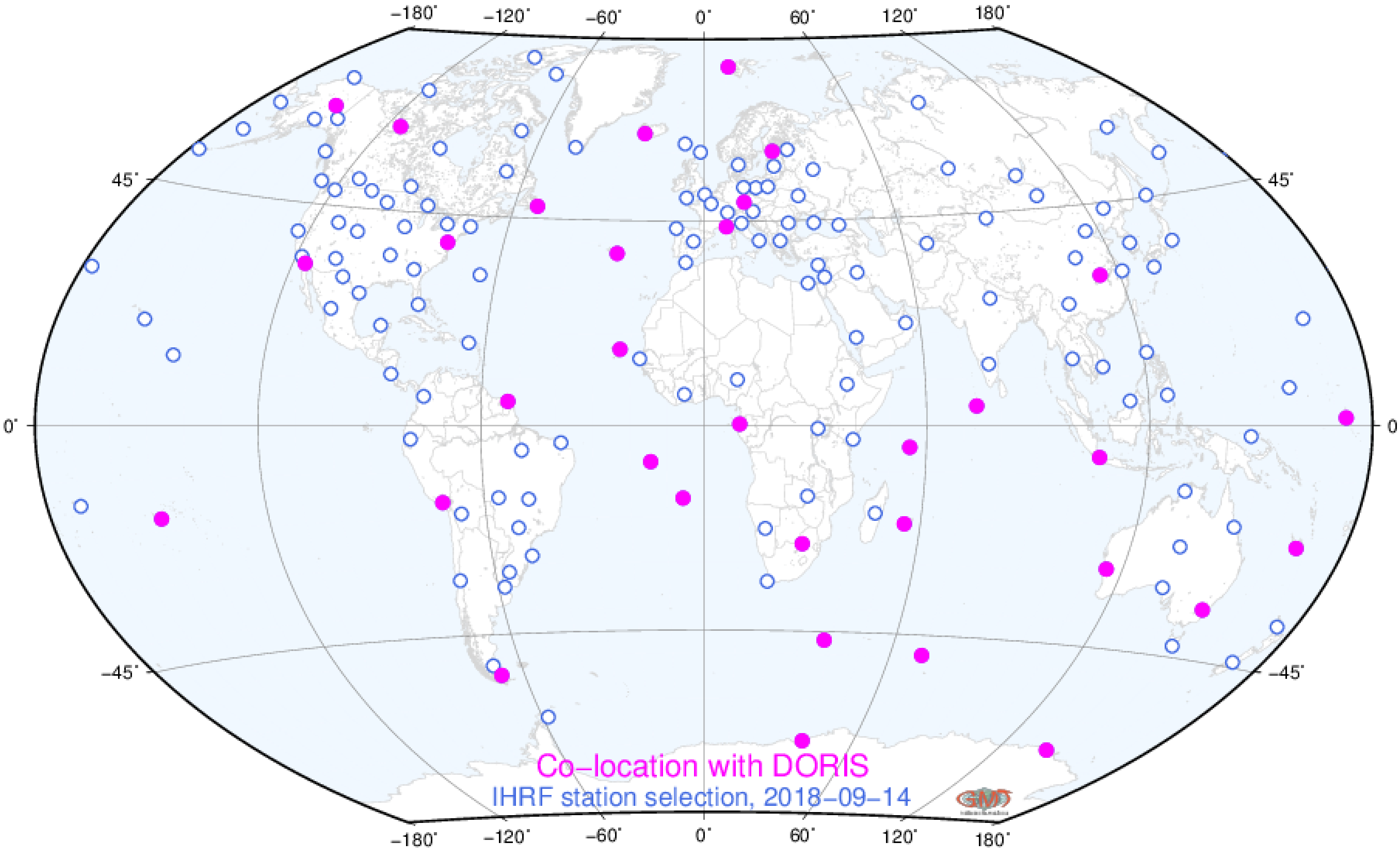
Co-location with VLBI (25 sites)



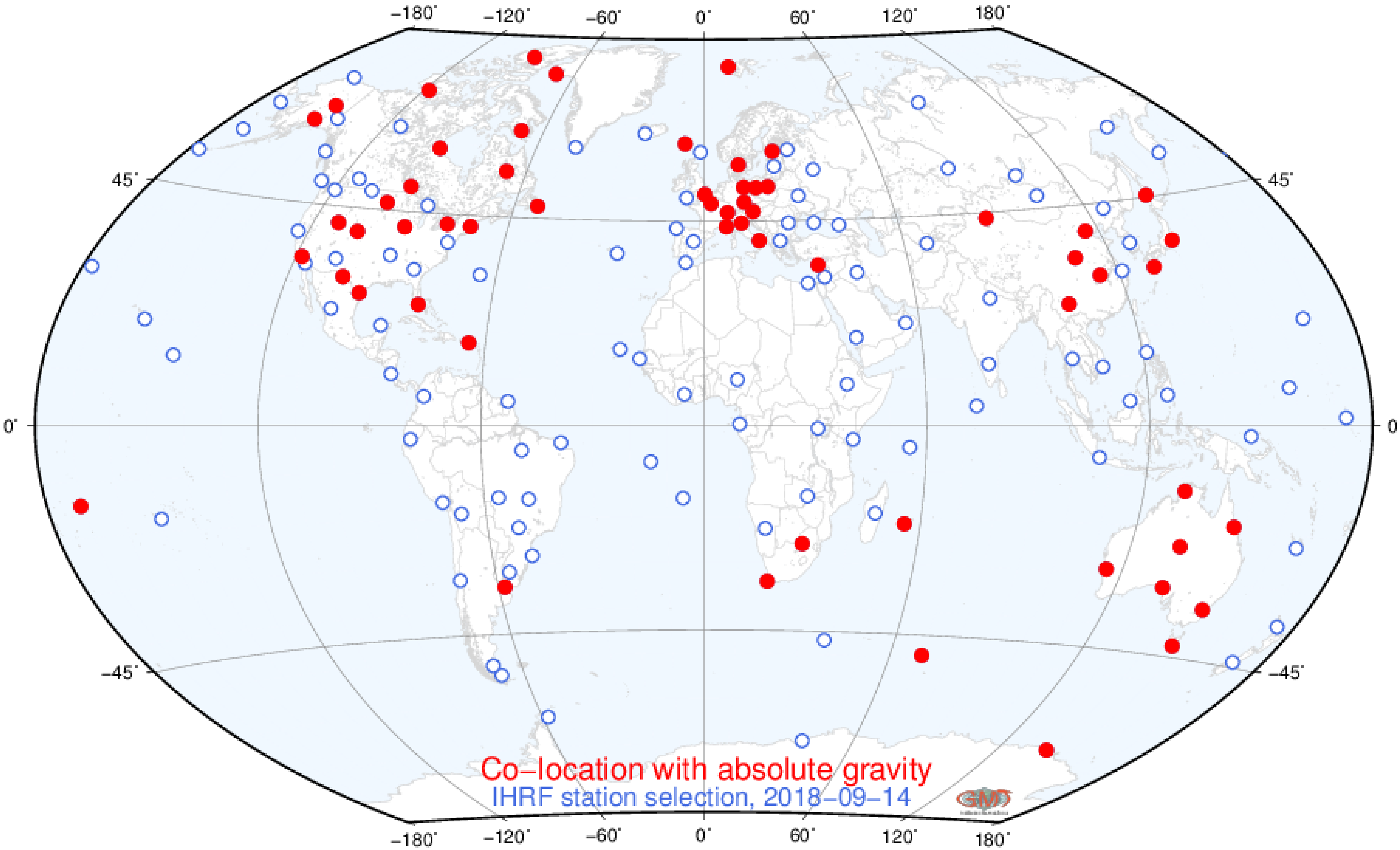
Co-location with SLR (35 sites)



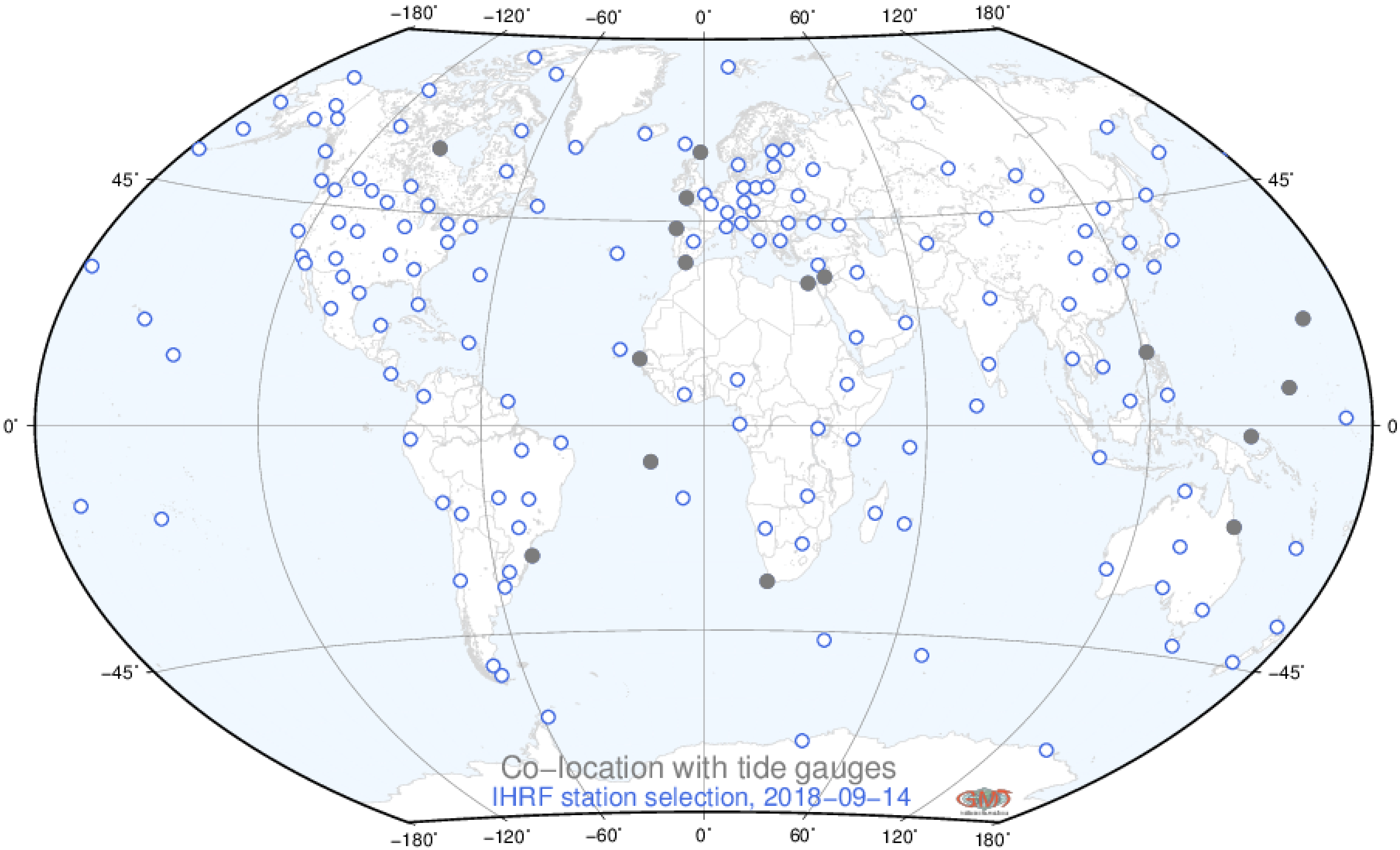
Co-location with DORIS (34 sites)



Co-location with absolute gravity (59 sites)



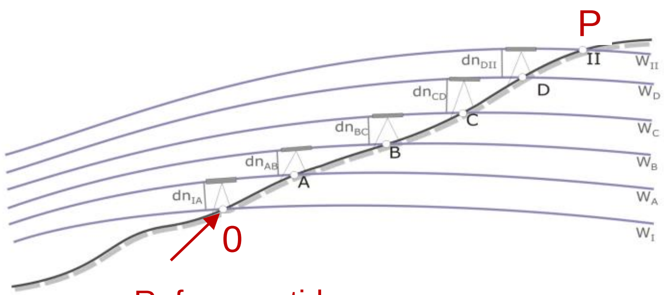
Co-location with tide gauges (15 sites)



Gravity-related vertical coordinates

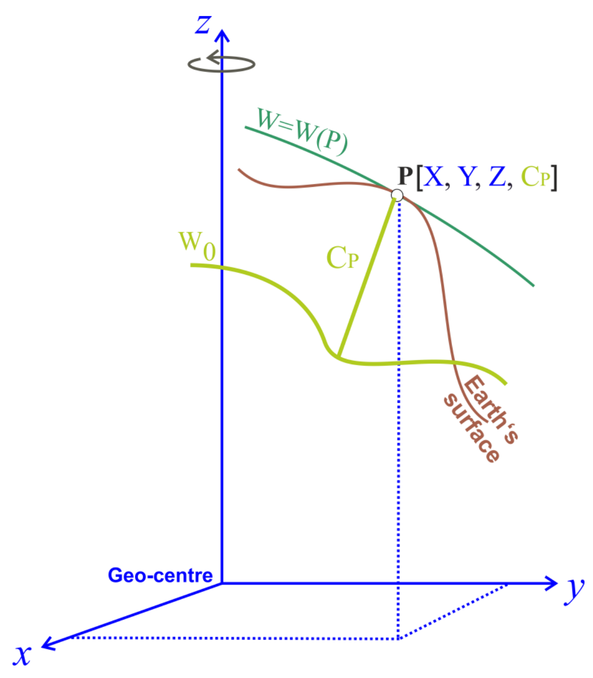
- In levelling, we determine geopotential numbers with respect to a reference tide gauge (local vertical datum)

$$H_P^{local} = \frac{W_0^{local} - W_{\mathbf{P}}}{\hat{g}} = \frac{C_P^{local}}{\hat{g}} \quad ; \quad C_P = \cong \sum_0^P g\ dn$$



- Within the IHRS, we aim at determining (global) geopotential numbers with respect to a global conventional reference potential W_0. As W_0 is a convention, known and fixed, the primary vertical coordinates are potential values W_P directly:

$$-\Delta W_P = C_P = W_0 - W_P$$



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	+	High-resolution gravity field modelling: Stokes or Molodenskii approach
Satellite tracking from ground stations (SLR) Satellite-to-satellite tracking (CHAMP, GRACE) Satellite gravity gradiometry (GOCE) *Satellite altimetry (oceans only)*		*Satellite altimetry (oceans only)* Gravimetry, astro-geodetic methods, levelling, etc. Terrain effects

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

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

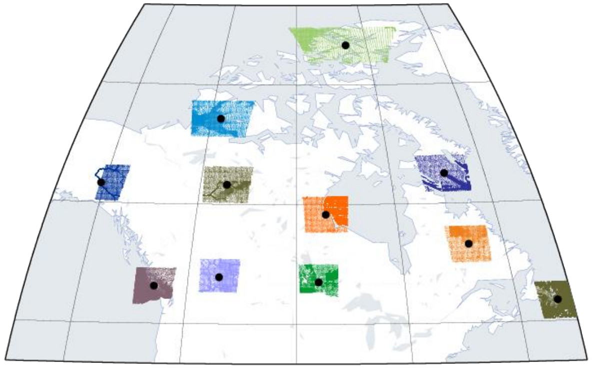
4) Levelling + gravimetry (after vertical datum unification):

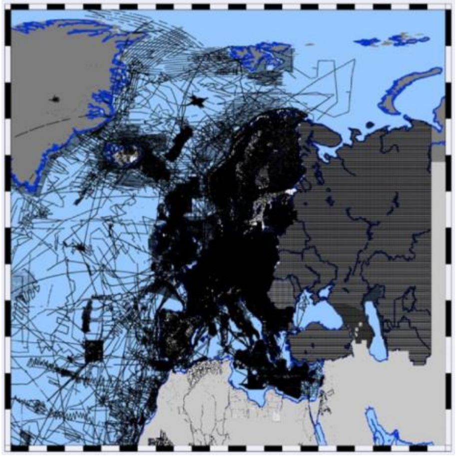
$$W_P = \left(W_0^{local} + \delta W\right) - C_P; \quad \delta W = W_0^{IHRF} - W_0^{local}$$

Activities related to the IHRF coordinates (1/2)

1) Sep. 2016 to Mar. 2017: Strategy for the integration (transformation) of existing vertical datums into the IHRS/IHRF

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 for the computation of potential values 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 500 km x 800 km in Colorado, USA → Colorado experiment

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

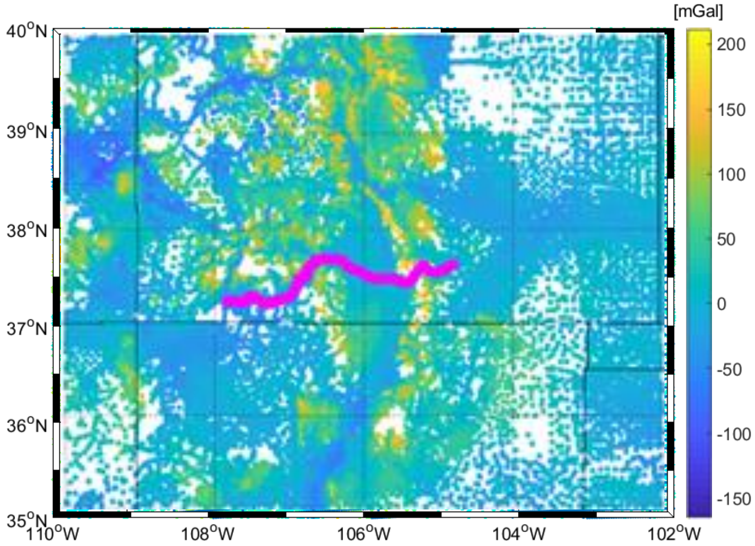
3) This experiment is performed within:
   - GGOS JWG: Strategy for the realisation of the IHRS (chair: L. Sánchez)
   - IAG JWG 2.2.2: The 1 cm geoid experiment (chair: Y.M. Wang)
   - IAG SC 2.2: Methodology for geoid and physical height systems (chair: J. Ågren)
   - ICCT JSG 0.15: Regional geoid/quasi-geoid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

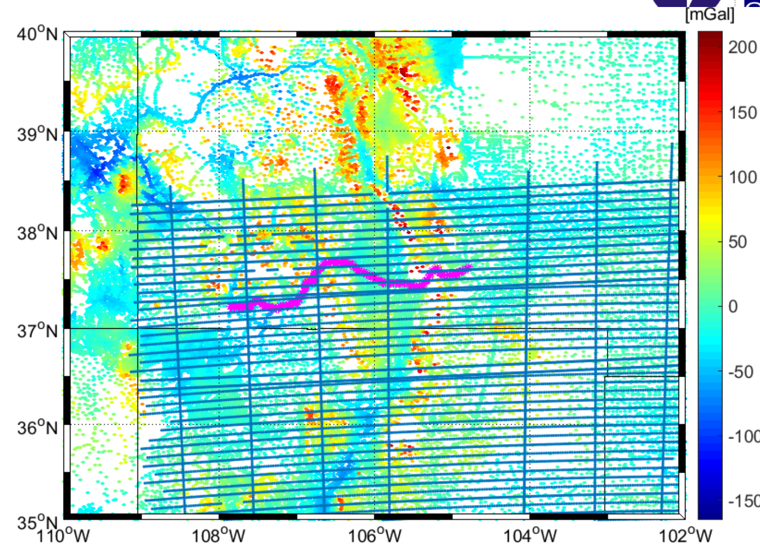
5) Feb. 2018: The Colorado data was distributed

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

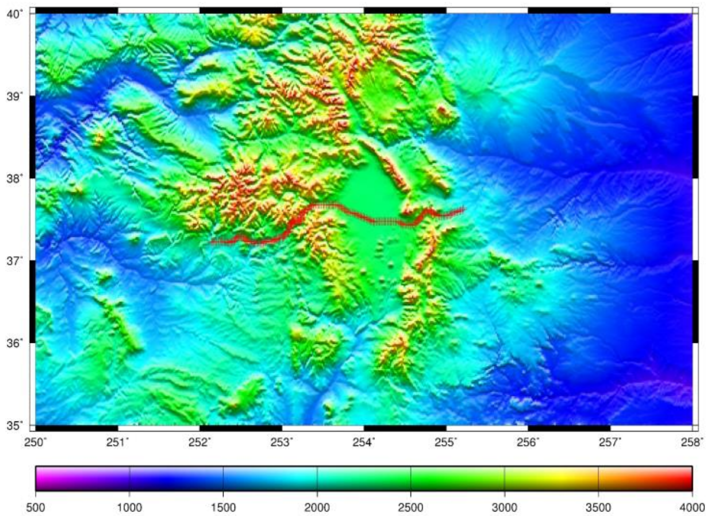
Colorado data



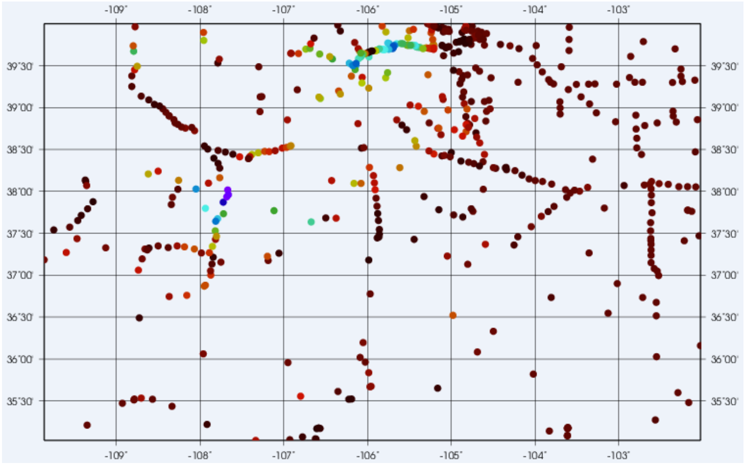
Surface gravity data (59,303 points)



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	

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

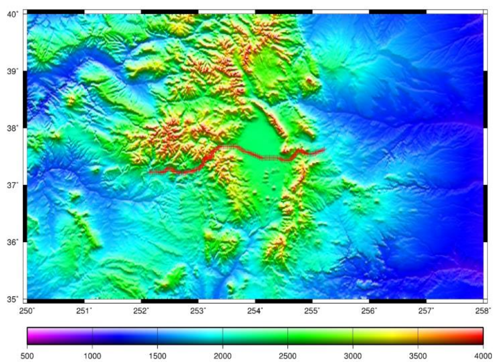
2) Participants in the experiment got φ, λ, h; levelling is not available (yet).

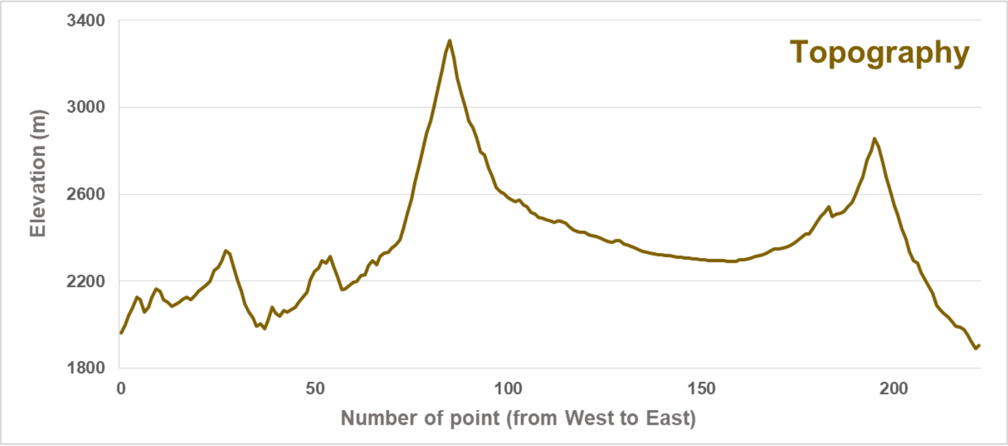
3) The potential values provided by the different solutions are converted to geopotential numbers with respect to the IHRS W_0 value

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

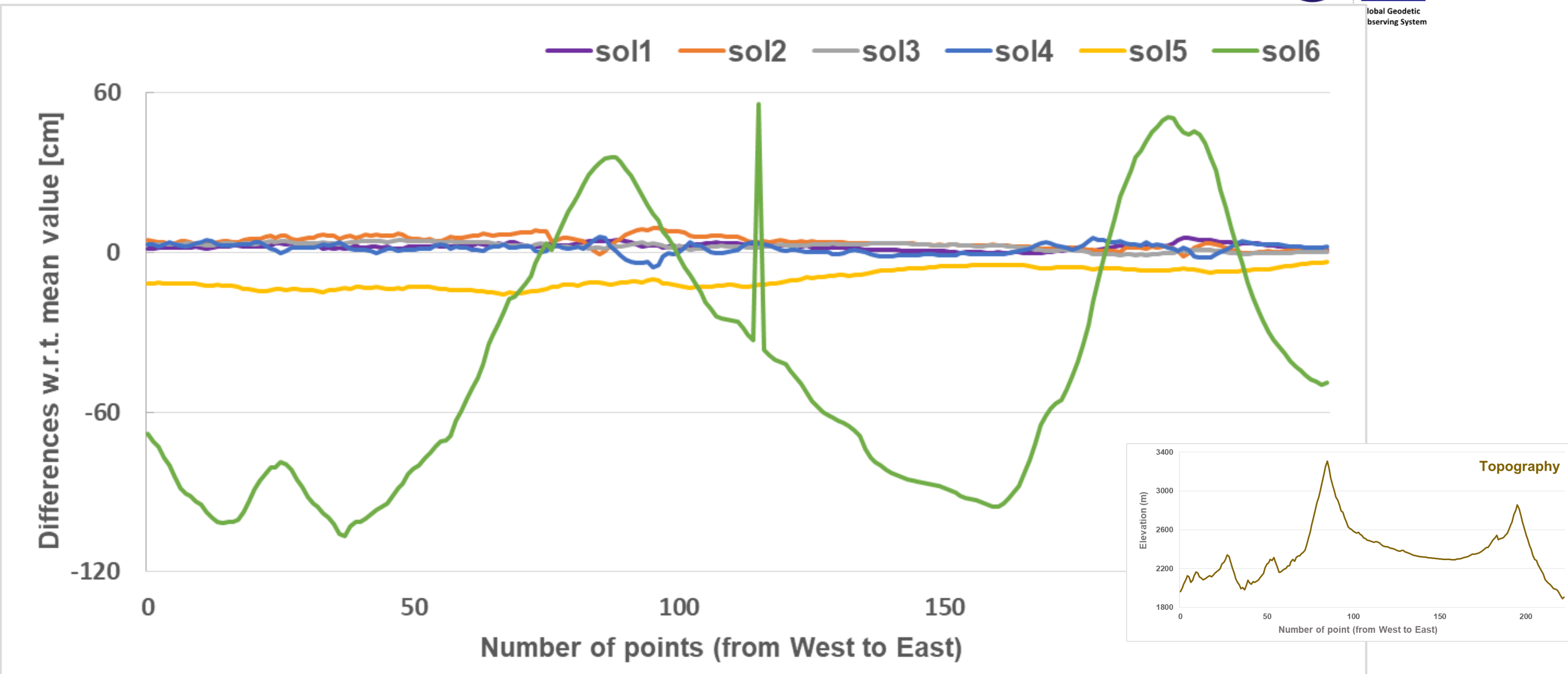
2) and further transformed to normal heights (to see the differences in meters):

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





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



sol1: $\zeta \rightarrow W$

sol2: $N \rightarrow W$

sol3: W

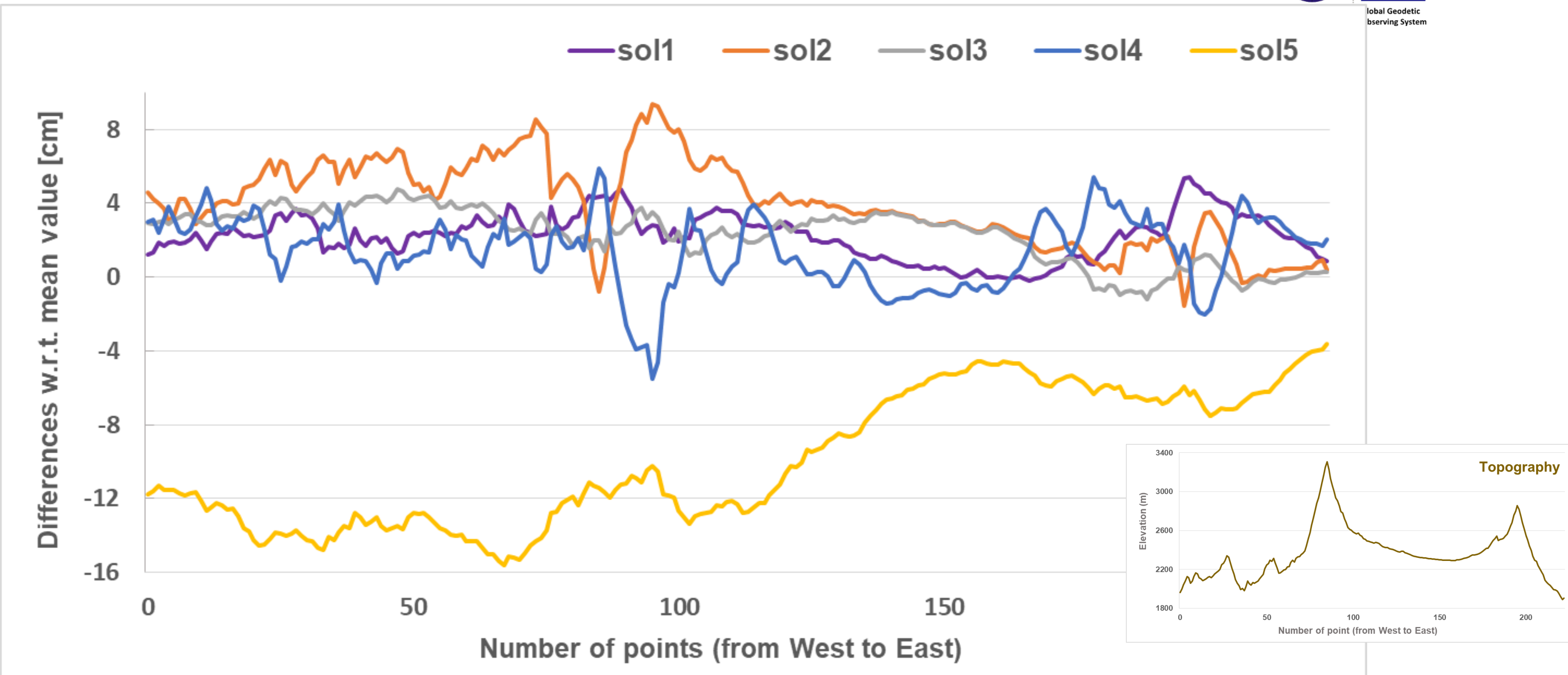
sol4: $N \rightarrow W$

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: $N \rightarrow W$

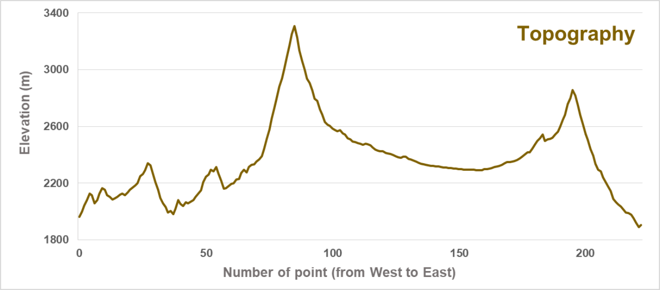
sol3: W

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

Main conclusions from the Colorado experiment

1) Four (of seven) solutions are consistent in the 1 dm level, with agreement within 1 cm to 2 cm in terms of standard deviation with respect to the mean value
2) Discrepancies present a strong correlation with the topography
3) To be the first (preliminary) results, they are very promising
4) A convergence of the results at the 1 cm level may be reachable

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".

Outlook

1) The first version of "the IHRS standards and conventions" should be ready for discussion before the next IUGG General Assembly in Montreal, July, 2019
2) A first (static) solution for the IHRF will be presented at the IUGG General Assembly: it should be preliminary and it is to identify drawbacks and required improvements
3) For the next term 2019-2023, a joint working group of the GGOS FA-UHS, IAG Commission 2 and the IGFS should investigate the best way to establish an 'IHRS/IHRF element' within the IGFS to ensure the maintenance and availability of the IHRF:
    - Regular updates of the IHRF*yyyy* to take account for:
        - new stations;
        - coordinate changes with time $\dot{\mathbf{X}}$, $\dot{W}$;
        - improvements in the estimation of $\mathbf{X}$ and W (more observations, better standards, better models, better computation algorithms, etc.)
    - Geodetic products associated to the IHRF (description and metadata).
    - Organizational and operational infrastructure to ensure the IHRF sustainability.

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