Deutsches Geodätisches Forschungsinstitut (DGFI-TUM)
Technische Universität München

Status of the International Height Reference Frame (IHRF)

L Sánchez, R Barzaghi, J Huang, GS Vergos, J Ågren, J Mäkinen, M Véronneau, YM Wang, H Denker, J Schwabe, M Bilker-Koivula, H Abd-Elmotaal, C Tocho, E Antokoletz, D Avalos-Naranjo, M Amos, R Winefield, ACOC Matos, D Blitzkow, G Guimarães, V Silva, J McCubbine, S Claessens, M Filmer, T Jiang, Q Liu, K Matsuo, R Pail, K Ahlgren, U Marti, C Ullrich, J Carrión

Symposium SIRGAS2021, November 30, 2021

Motivation

Earth System research requires unified geodetic reference frames with

- an order of accuracy higher than the magnitude of the effects to be observed (e.g. global change);
- consistency and reliability worldwide (the same accuracy everywhere);
- long-term stability (the same accuracy at any time).

The ITRS and its realization (ITRF) provide

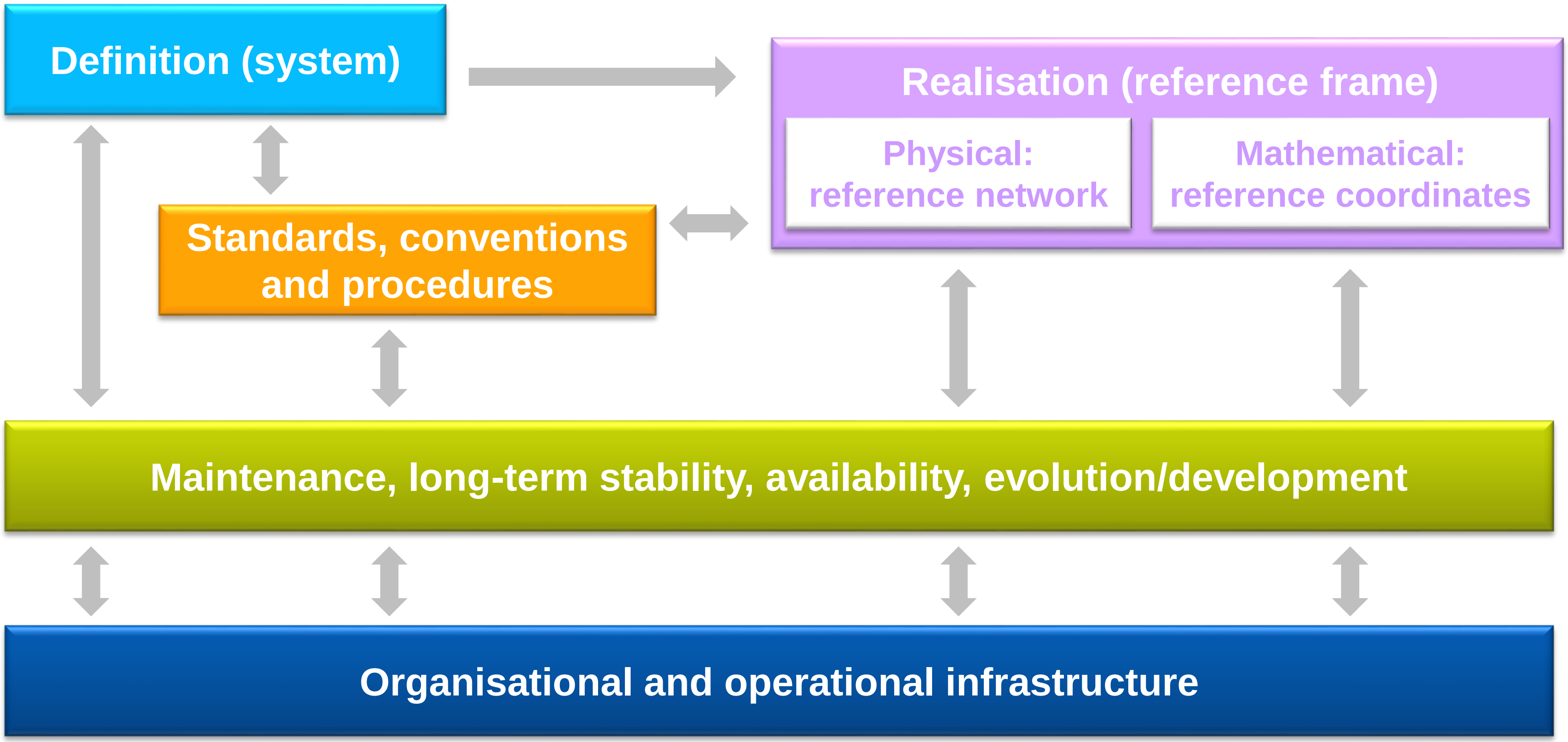
- geometric coordinates ($\mathbf{X}, \dot{\mathbf{X}}$) consistent globally;
- accuracy at mm ... cm level.

The existing physical height systems exhibit

- more than 100 realizations worldwide;
- discrepancies of dm ... m (different vertical datums, different physical heights, missing standardization);
- static heights $\rightarrow \dot{H} \equiv 0$;
- imprecise combination with geometric heights $|h - H - N| \rightarrow >> 0$;
- 1 ... 2 order of accuracy less than ($\mathbf{X}, \dot{\mathbf{X}}$).

$\rightarrow$ A core objective of the International Association of Geodesy (IAG) is to provide an international standard for precise determination of physical heights.

Core aspects for the establishment of a geodetic reference frame



Definition of the 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:

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

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

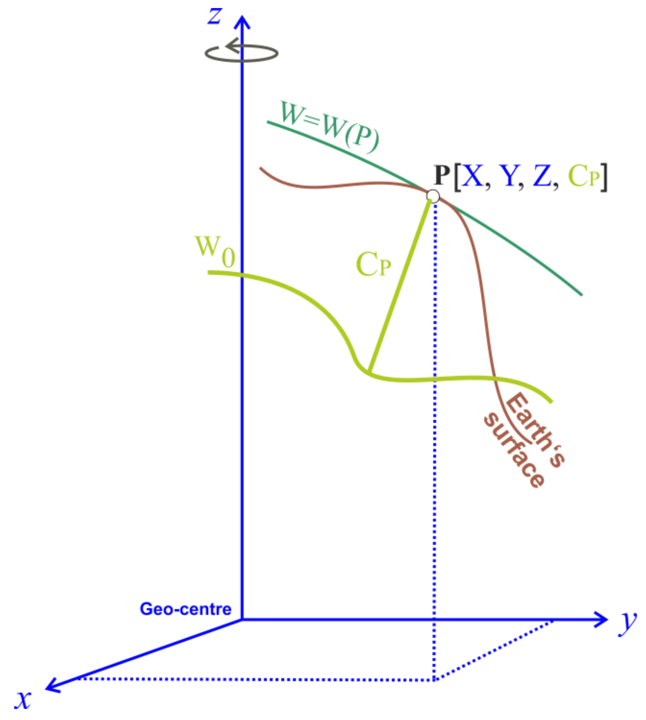
2) The position P is given in the ITRF

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

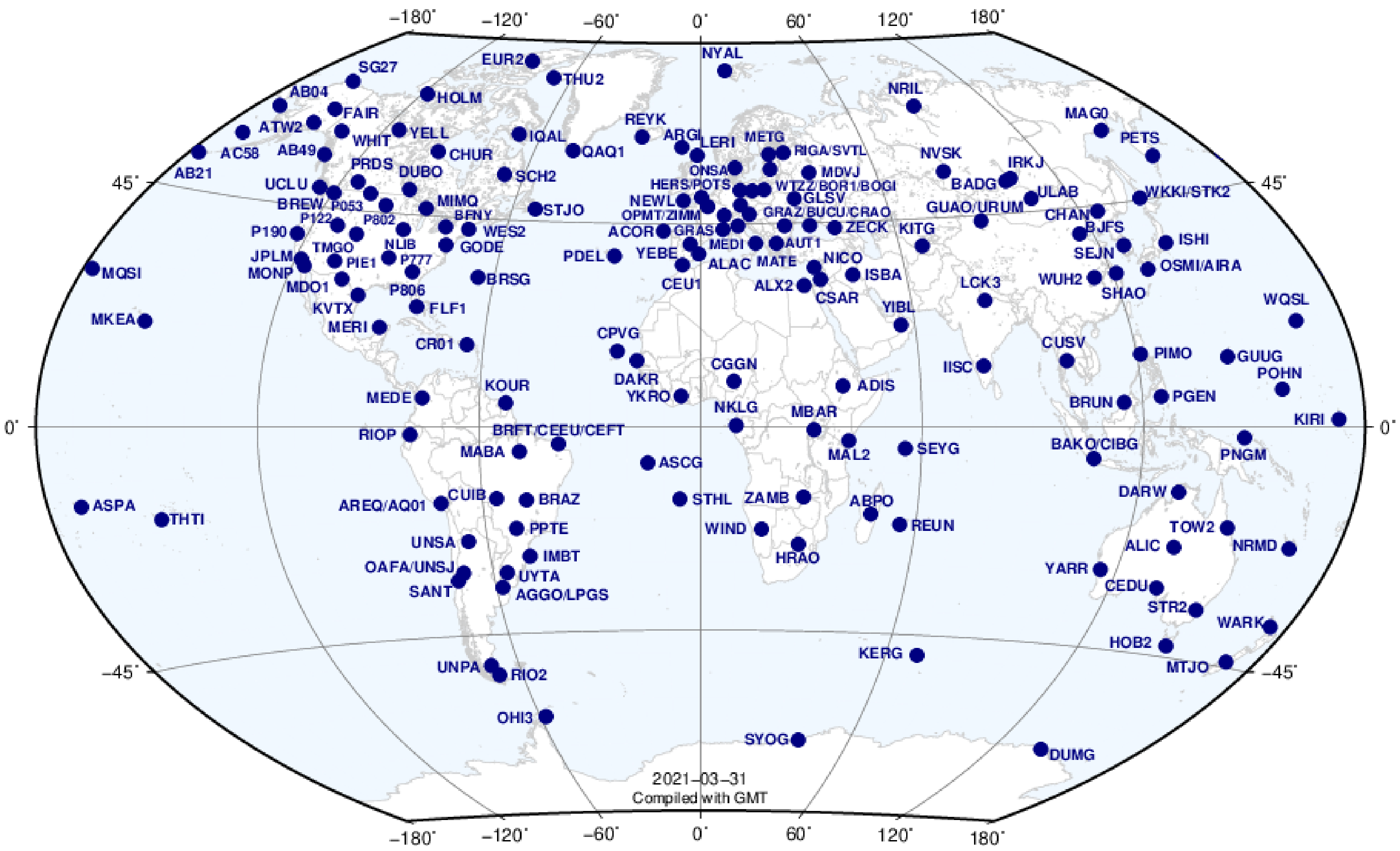


→ For the IAG resolutions, see Drewes et al. (2016), *The Geodesist's Handbook 2016*, J Geod, https://doi.org/10.1007/s00190-016-0948-z

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

→ Sánchez et al. (2016), *A conventional value for the geoid reference potential* W_0, J Geod, 90(9): 815-835, https://doi.org/10.1007/s00190-016-0913-x,

IHRF reference network: first proposal



1) Global network with regional/national densifications
2) Core network materialised by GNSS continuously operating stations and co-located with the ITRF (and its regional densifications), IGRF, reference clocks, national vertical frames
3) First proposal for the IHRF reference network (~170 stations) in coordination with the GGOS-BNO, IERS, BGI/IGFS and the IAG regional sub-commissions for reference frames and gravity field modelling.
4) A living network: new stations and decommission of stations.

Reference coordinates: determination approaches

1) To be in agreement with the reliability of the ITRF, the expected accuracy of W is

   Positions: $\approx \pm 3\times10^{-2}$ m^{2}s^{-2} (about 3 mm), velocities: $\approx \pm 3\times10^{-3}$ m^{2}s^{-2}/a (about 0.3 mm/a)

   $\rightarrow$ For the moment, the goal is $\pm 1\times10^{-1}$ m^{2}s^{-2} (about 1 cm)

2) Global gravity models of high resolution (GGM-HR)

$$W(X,Y,Z) = \frac{GM}{r}\left[1+\sum_{n=1}^{\infty}\left(\frac{a}{r}\right)^{n}\sum_{m=0}^{n}\left[C_{nm}\cos m\lambda + S_{nm}\sin m\lambda\right]P_{nm(\cos\theta)}\right] + \frac{1}{2}\omega^2 r^2 \cos(90° - \theta)$$

3) Precise regional gravity field modelling (methods for the geoid/quasi-geoid determination – GBVP)

$$W(P) = U(P) + T(P) \quad [\mathrm{m^2s^{-2}}]$$

Quasi-geoid $W(P) = U(P) + \zeta(P)\cdot\gamma_Q + \Delta W_0 \quad [\mathrm{m^2s^{-2}}] \rightarrow \quad W(P) = W_0 - \left(h(P) - \zeta(P)\right)\cdot\bar{\gamma}_{QQ_0} \quad [\mathrm{m^2s^{-2}}]$

Geoid $W(P) = W_0 - \left(h(P) - N(P)\right)\cdot\bar{g}(P) \quad [\mathrm{m^2s^{-2}}]$ with

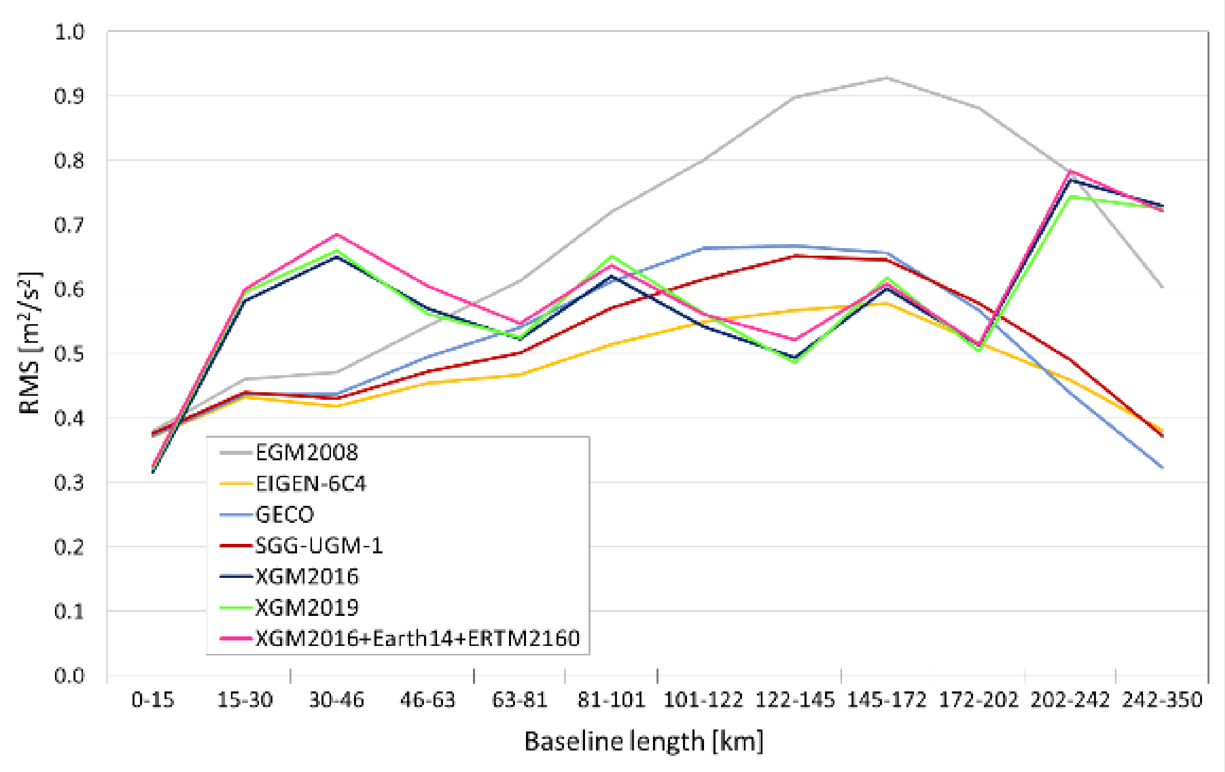
$$\bar{g}(P) = g(P) + 0.424\times10^{-6}\cdot\left(h(P) - N(P)\right) + TC(P) \quad [\mathrm{ms^{-2}}]$$

4) Vertical datum unification of the local height systems into the IHRF (see Sánchez and Sideris (2017), https://doi.org/10.1093/gji/ggx025)

$$W(P) = \left(W_0^{local} + \delta W\right) - C_P^{local} \quad \text{with} \quad \delta W = W_0^{IHRF} - W_0^{local}$$

Evaluation/calibration of different procedures for the determination of potential values (Colorado experiment)

1) Geoid, quasi-geoid and potential values computation using exactly the same input data, a set of basic standards, and the own methodologies (software) of colleagues involved in the gravity field modelling.
2) Validation with respect to a GNSS/levelling profile of high precision (gravity and GNSS/levelling data provided by the US National Geodetic Survey)



The RMS values of the ΔC_{ij} differences for each interval indicates the consistency between the model-based and levelling-based potential values as a function of the distance.

Sánchez et al. (2021), *Strategy for the realisation of the IHRS*, J Geod 95, 33 (2021). https://doi.org/10.1007/s00190-021-01481-0

Wang et al. (2021) *Colorado geoid computation experiment: overview and summary*. J Geod, 95(12), https://doi.org/10.1007/s00190-021-01567-9.

Special Issue on *Reference Systems in Physical Geodesy* of the Journal of Geodesy with computation methods and comparison of geoid and quasi-geoid models, see https://link.springer.com/journal/volumesAndIssues/190?tabName=topicalCollections

Standardisation and strategy

- Based on the Colorado outputs, we prepared an extensive guideline for the realisation of the IHRS. It Includes:

  → Basic standards on numerical constants, reference ellipsoid, degree zero and mass centre convention, handling of permanent tide effects.

  → Strategy for the determination and evaluation of IHRF coordinates depending on the data availability and quality (specially surface gravity data and topography models)

  → For regions with good surface gravity data coverage and quality, use precise (quasi-)geoid regional models

  → For regions without (or with very few) surface gravity, data use GGM + topographic gravity signals,

  → For regions with some surface gravity data, but with poor data coverage or unknown data quality, improve data availability and quality and solve the GBVP

  → Strategy to improve the input data required for the determination of IHRF coordinates

  → Strategy for the IHRF station selection in regional and national densifications

  → Strategy to ensure the usability and long-term sustainability of the IHRF

  → Authors: L Sánchez, J Ågren, J Huang, YM Wang, J Mäkinen, R Pail, R Barzaghi, GS Vergos, K Ahlgren, Q Liu – GGOS FA-UHS, IAG Commission 2, IAG ICCT, IGFS.

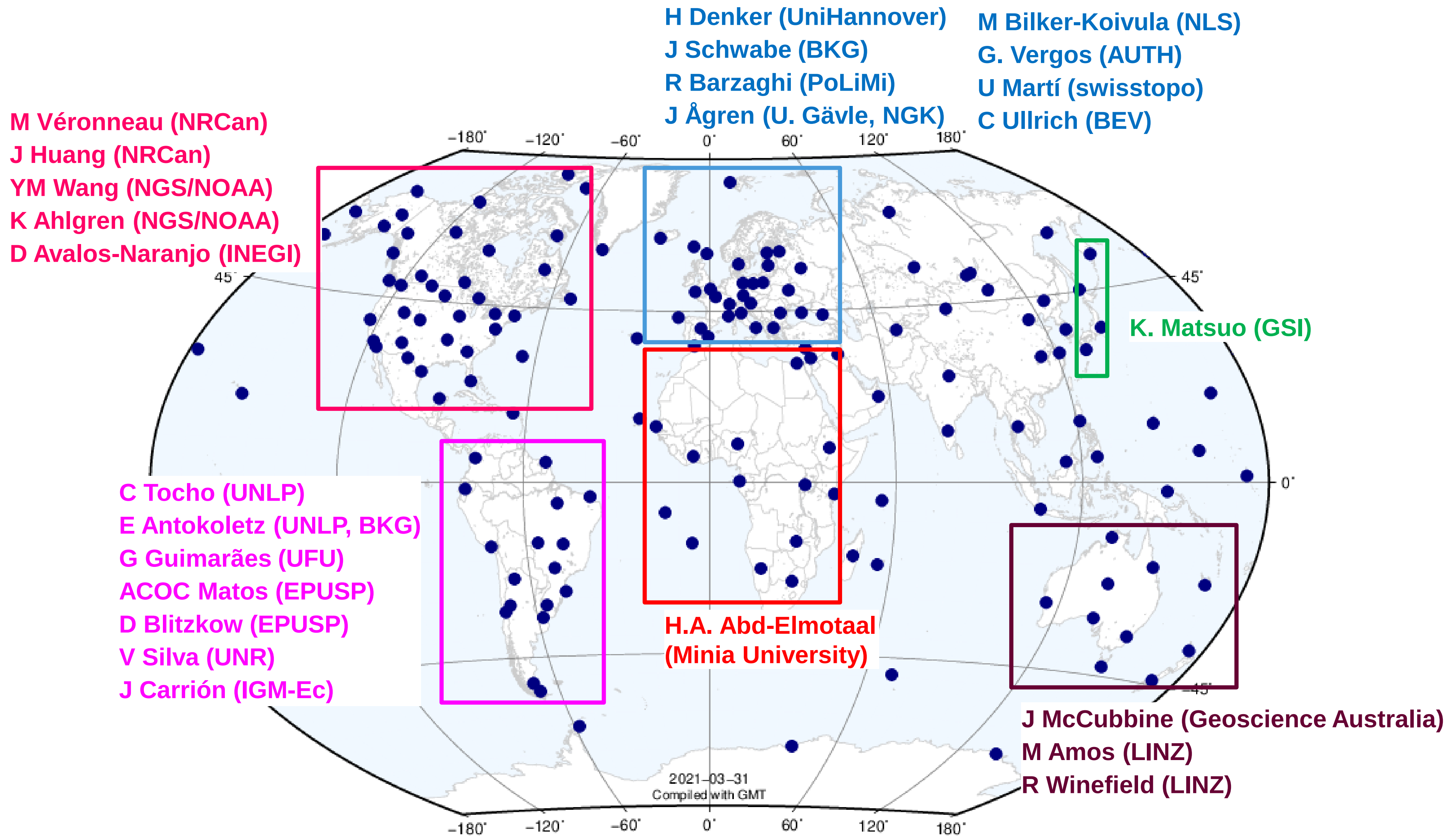
On going activities: Computation of a first solution for the IHRF

1) Recovering of IHRF potential values from national and regional (quasi-)geoid models with the support of IAG regional sub-commissions, national/regional experts in geoid modelling, and the geoid repository of the International Service for the Geoid (ISG)

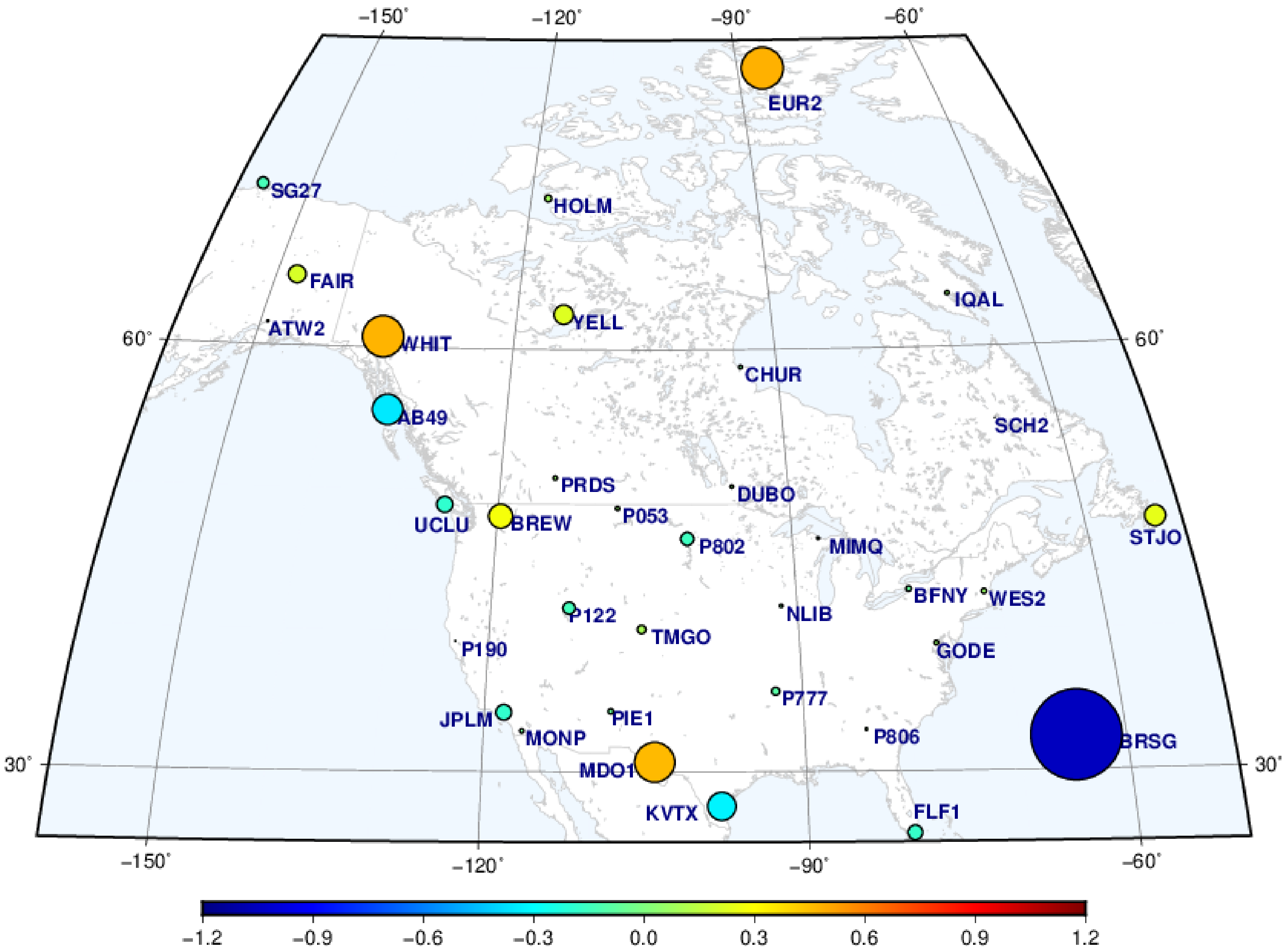
2) Computation of potential values using the latest GGM + topography signals from Earth2014 and ERTM2160

3) Comparison of (1) and (2)
   - to decide on the GGM to be used in regions with no (quasi-)geoid model available and
   - to evaluate the reliability of regional models with poor gravity data distribution

On going activities: Computation of a first solution for the IHRF



On going activities: Computation of a first solution for the IHRF



Differences between the potential values inferred from the Canadian geoid model PCGG20_21A and the US quasi-geoid model xG20B **(thanks to M Véronneau, J Huang, YM Wang and K Ahlgren)**:

Mean: -0.01 m^2s^{-2}
STD: 0.26 m^2s^{-2}
Min.: -1.05 m^2s^{-2}
Max.: 0.48 m^2s^{-2}

On going activities: Computation of a first solution for the IHRF

EGG2016	GCG2016	Difference
18032.74	18032.81	0.07
15946.68	15946.73	0.05
15381.77	15381.78	0.02
1019.01	1018.97	-0.04
16690.78	16690.73	-0.04
6070.26	6070.18	-0.08

IHRF geopotential numbers inferred from the European quasi-geoid model EGG2016 and the German quasi-geoid model GCG2026 **(thanks to H Denker and J Schwabe)**

Differences (@ 6 points)
Mean: -0.006 m^2s^{-2}
STD: 0.050 m^2s^{-2}
Min.: -0.080 m^2s^{-2}
Max.: 0.065 m^2s^{-2}

On going activities: Computation of a first solution for the IHRF

Geoid A	Geoid B	Difference
232.39	235.83	3.44
137.93	140.98	3.05
6884.95	6880.58	-4.37
192.03	195.81	3.79
6811.51	6810.58	-0.94
245.38	251.43	6.05
11980.35	11981.14	0.79
6707.59	6703.69	-3.90
1683.67	1686.87	3.21

IHRF geopotential numbers inferred from two different regional/national geoid models in South America **(thanks to C Tocho, E Antokoletz, D Avalos-Naranjo, D Blitzkow, G Guimarães, V Silva)**

Differences (@ 9 points)
Mean: 1.24 m^2s^{-2}
STD: 3.41 m^2s^{-2}
Min.: -4.37 m^2s^{-2}
Max.: 6.36 m^2s^{-2}

On going activities: Computation of a first solution for the IHRF

US main territory (30 stations):
Model NAPGD2022 - xG20B
Mean accuracy 0.45 m^2s^{-2}

Canada (11 stations):
Model PCGG20_21A
Mean accuracy 0.35 m^2s^{-2}

Europe (40 stations):
Model EGG2016
Mean accuracy 0.50 m^2s^{-2}

Mexico (1 station):
Model GGM-CA 2015
Mean accuracy 2.0 m^2s^{-2}

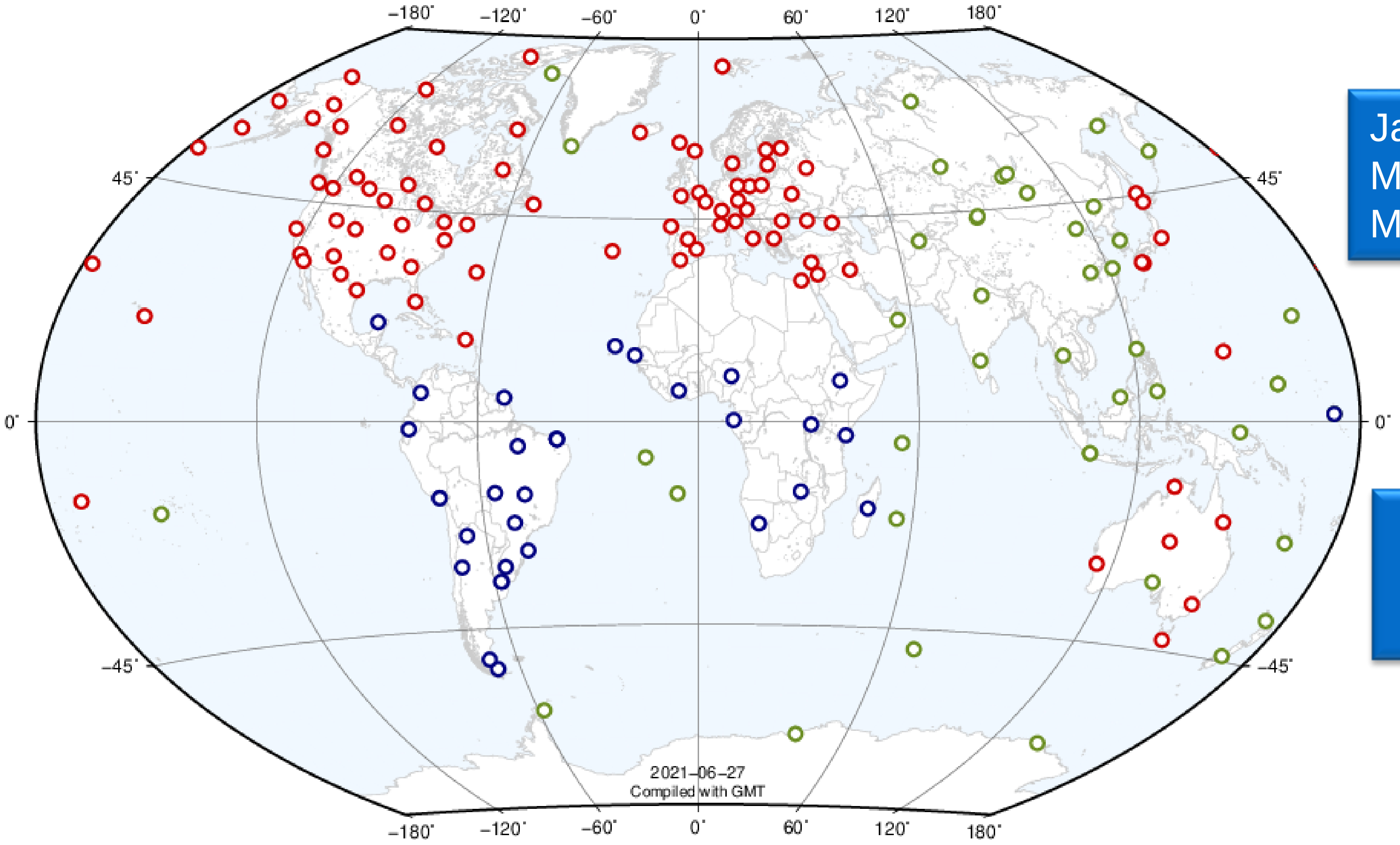
Japan (5 stations):
Model JGEOID2019
Mean accuracy 0.57 m^2s^{-2}

In progress:

South America:
Comparison of regional and national solutions

Africa: computation of potential values

Asia and Oceania:
Inventory of ISG geoid repository or selection of GGM



Australia (6 stations):
Model AGQG2017
Mean accuracy 0.62 m^2s^{-2}

On-going activities: Research/developing activities

- Evaluation of discrepancies between different (quasi-)geoid computation methods
- Quality assessment in the determination of potential values
- Methods to determine potential changes with time
- Design of a “IHRS/IHRF element” to be established within the International Gravity Field Service (IGFS)
- With the support of
  - GGOS-FA-UHS WG: *Implementation of the International Height Reference Frame*, chairs: L Sánchez (Germany), R. Barzaghi (Italy)
  - *International Gravity Field Service* (IGFS), chair: R Barzaghi (Italy), IGRF-CB G Vergos (Greece)
  - IAG Sub-Comm. 2.2: *Methodology for geoid and physical height systems*, chair: G Vergos (Greece), RS Grebenitcharsky (Saudi Arabia)
  - IAG Comm. 2 WG: *Error assessment of the 1 cm geoid experiment*, chairs: T Jiang (China), VN Grigoriadis (Greece), M Varga (Hungary)
  - ICCT SG: *Geoid/quasi-geoid modelling for realisation of the geopotential height datum*, chairs: J Huang (Canada), YM Wang (USA)

Closing remarks

1) The determination of the gravity potential $W(P) = U(P) + T(P)$ is the core element for the establishment of the IHRS/IHRF.

2) The comparison of different computation strategies (the Colorado experiment) proves that we can reach an agreement of about 0.2 m^2s^{-2} (~ 2 cm). However, this depends on the availability of surface gravity data. When no gravity data is available, the uncertainty may reach 10 m^2s^{-2} (~ 1 m).

3) Surface gravity data (terrestrial, airborne) acquisition and the precise determination of the (quasi-)geoid belong to the primary geodetic infrastructure. They are the counterpart of the geometric reference frame. Both IHRF and ITRF have to be consistent, be correspondingly developed and provide similar accuracy.