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Advances in the determination of a global unified reference frame for physical heights

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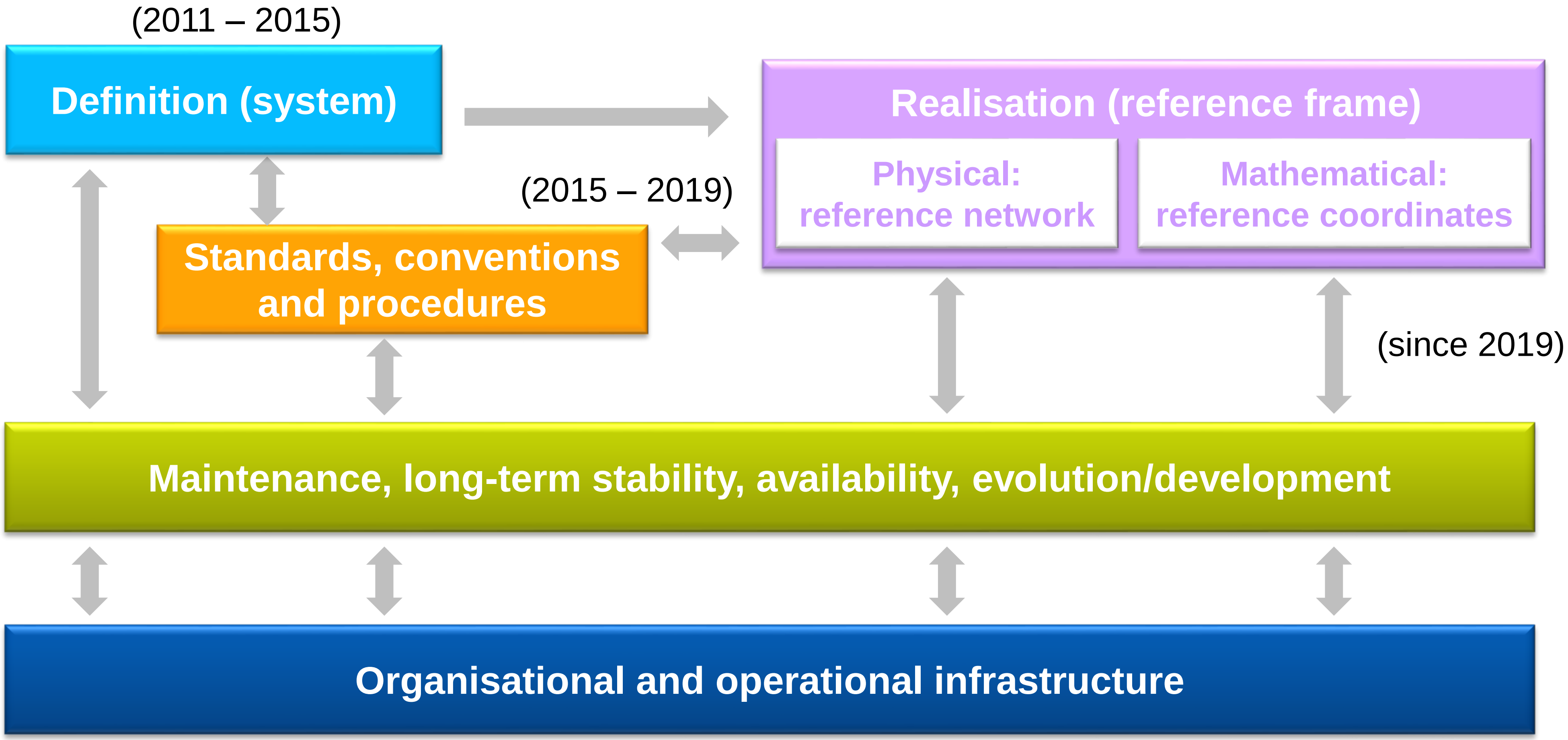
Motivation

- Physical heights are required for positioning depending on the gravity field (e.g. water flow, absolute sea level monitoring, dams, bridges, tunnels, large engineering projects, …).
- With no international standard for physical height determination, existing physical height systems were established individually and locally:
  - local mean sea level, local levelling networks
  - more than 100 realizations worldwide;
  - discrepancies of dm ... m (different vertical datums, different physical heights, missing standardisation);
  - static heights $\rightarrow \dot{H} \equiv 0$;
  - imprecise combination with geometric heights, i.e. the ITRF, $|h - H - N| \rightarrow >> 0$;
  - 1 ... 2 order of accuracy less than $(\mathbf{X}, \dot{\mathbf{X}})$.
- Since the 1970s, the installation of a global unified height system has been discussed within the International Association of Geodesy (IAG): world height system, global vertical datum, global vertical network, etc.
- In 2010, IAG's Global Geodetic Observing System (GGOS) installed the Focus Area Unified Height System to develop an international standard for precise determination of physical heights worldwide,
  - the **International Height Reference System (IHRS)**

Motivation



(2011 – 2015)
Definition (system)
(2015 – 2019)
Standards, conventions and procedures
Realisation (reference frame)
Physical: reference network
Mathematical: reference coordinates
(since 2019)
Maintenance, long-term stability, availability, evolution/development
Organisational and operational infrastructure

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:

$$C_P = C(P) = W_0 - W(P) = -\Delta W(P) \rightarrow H = C(P)/\gamma$$

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

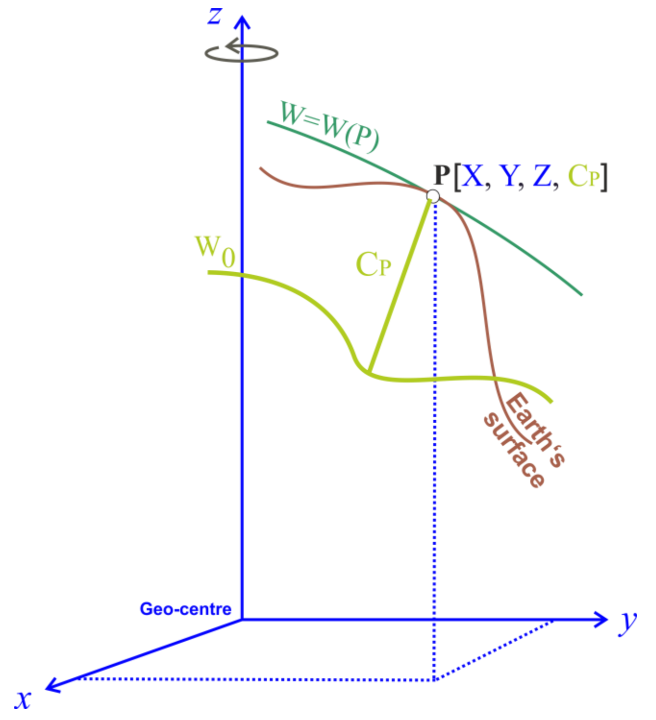
2) The position P is given in the ITRF

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



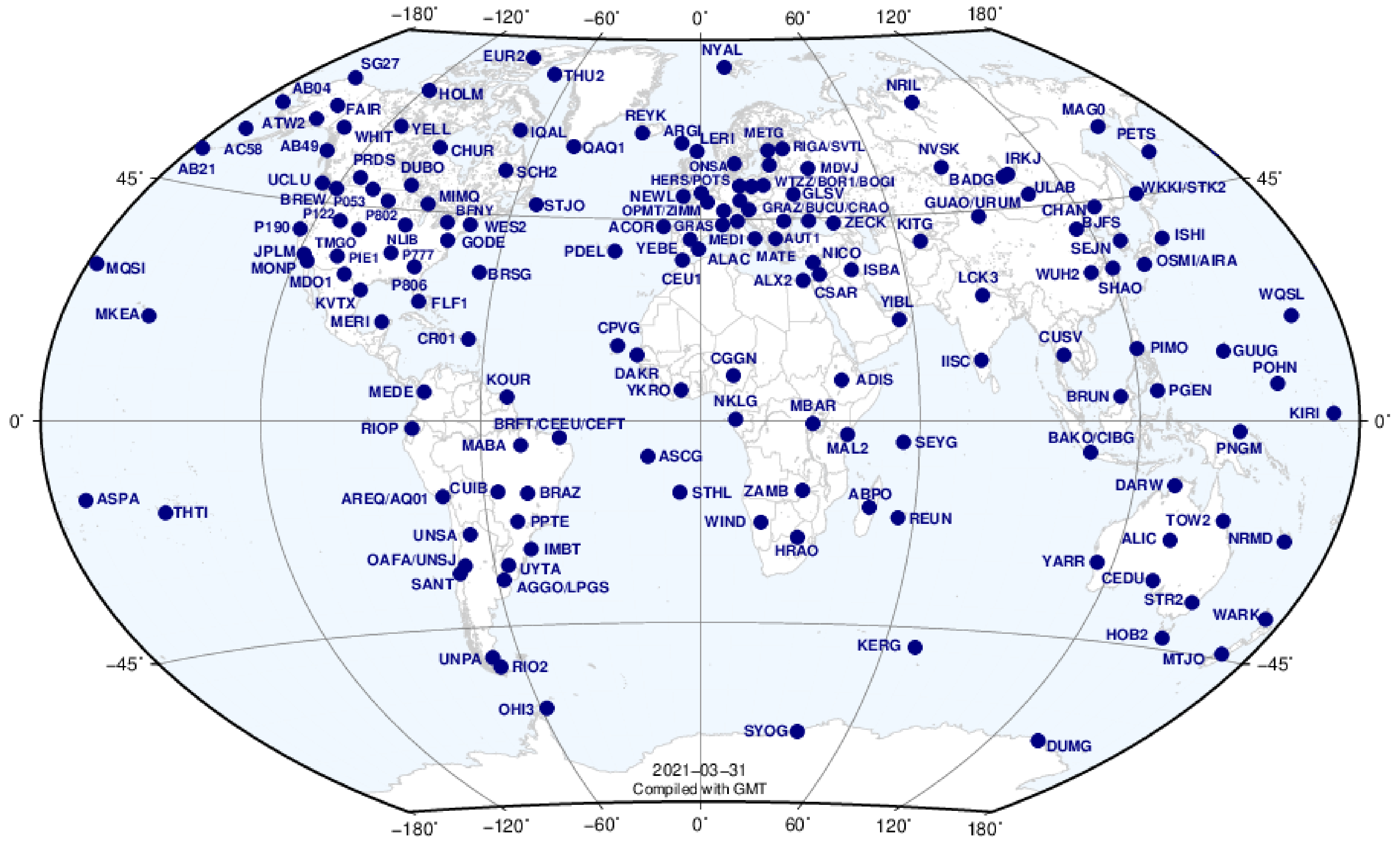
→ For the IAG resolutions, see Drewes et al. (2016), *The Geodesist's Handbook 2016*, J Geod, https://doi.org/10.1007/s00190-016-0948-z

→ 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,

Realisation: the International Height Reference Frame – IHRF

Reference network (first proposal ~170 stations)



- Global network with regional/national densifications
- Materialised by GNSS continuously operating stations (ITRF and regional frames' stations)
- Co-location with
  - VLBI: 30 sites
  - SLR: 40 sites
  - DORIS: 35 sites
  - Absolute gravimetry: 77 sites
  - Tide gauges: 26 sites
  - Levelling networks: 23 sites

Realisation: the International Height Reference Frame - IHRF

Reference coordinates (1/3)

1) The IHRS/IHRF is based on the combination of
   - a geometric component given by the coordinate vector $\mathbf{X}$ in the ITRS/ITRF and
   - a physical component given by the determination of potential values W at $\mathbf{X}$.
2) The determination of $\mathbf{X}$ follows the IERS Conventions and it is well-stablished in practice (IERS and associated data, analysis, combination and product centres).
3) The determination of W is only possible by means of gravity field modelling:

$$W = U + T \quad \rightarrow \quad \Delta g = \delta g + \frac{1}{\gamma}\frac{\partial \gamma}{\partial h}T = -\frac{\partial T}{\partial h} + \frac{1}{\gamma}\frac{\partial \gamma}{\partial h}T \quad \rightarrow \quad N = \frac{T}{\gamma}$$

U, γ : Normal gravity field
Δg, δg : Gravity observables
T : Disturbing potential
N : Geoid height

Realisation: the International Height Reference Frame - IHRF

Reference coordinates (2/3)

$$W = U + T \quad \rightarrow \quad \Delta g = \delta g + \frac{1}{\gamma}\frac{\partial \gamma}{\partial h} T = -\frac{\partial T}{\partial h} + \frac{1}{\gamma}\frac{\partial \gamma}{\partial h} T$$

- W can be determined up to a constant only $\rightarrow$ Gravitational potential vanishing at ∞
- W is nonlinear and not harmonic $\rightarrow$ Linearization (reference level ellipsoid)
- Valid in “mass-free” external space $\rightarrow$ Removal of gravitational effects due to Sun, Moon, topography, etc.
- Adaptability to available surface gravity data coverage and quality $\rightarrow$ Integral formulas-based computation with different analytical approximations (spherical, planar, constant radio approximation, etc.)
- Mathematical evaluation with different formulations (fast Fourier transformation, least-squares collocation, spherical basis functions, etc.)

$\rightarrow$ **A very large variety of possibilities and each possibility produces different results, i.e. different W values.**

Realisation: the International Height Reference Frame - IHRF

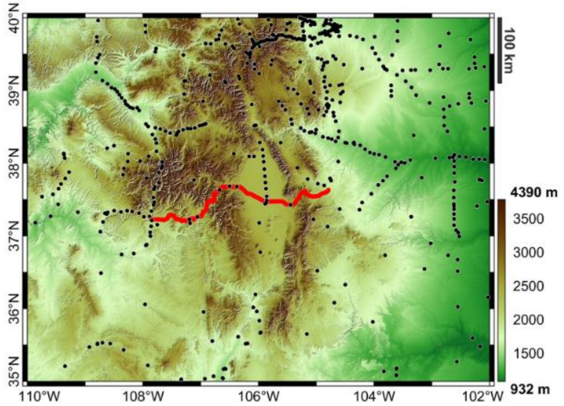
Reference coordinates (3/3)

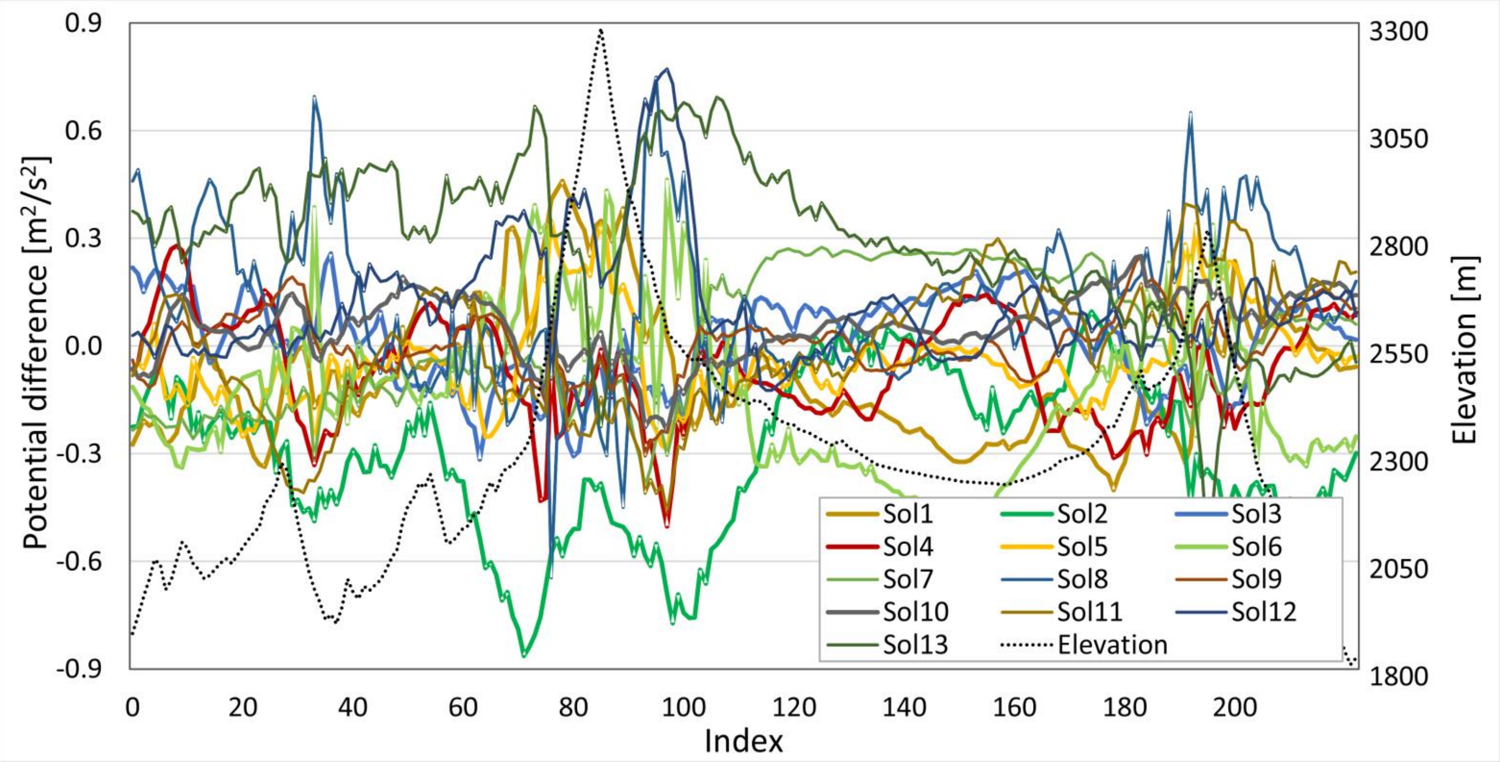
- A “centralised” computation (like in the ITRF) is quite complicated due to the restricted accessibility to surface gravity data. So, regional/national experts have to be involved in the determination of the potential coordinates in their regions/countries
- A “standard” computation procedure may be 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.)
- Pragmatic solution: To standardise as much as possible in a world-wide distributed computation.

Realisation: the International Height Reference Frame - IHRF

Comparison/Calibration of computation approaches

- Computation of potential values using the same input gravity data (in Colorado, USA, provided by NGS, Wang et al. 2021)
- 13 different computation strategies
- 3 iterations between 2017 and 2019 with participation of about 50 colleagues
- Comparison between solutions and validation using first-order levelling and GNSS data (vanVestrum et al. 2021)





Standard deviation of the differences between $C(P)$ from gravity field modelling and $C(P)$ from levelling varies from 0.12 m^2s^{-2} (~1.2 cm) to 0.78 m^2s^{-2} (7.8 cm) with maximum ranges of 1.41 m^2s^{-2} (14.1 cm).

Realisation: Standardisation and strategy

→ Catalogue of basic standards and conventions including
  - → numerical constants, reference ellipsoid
  - → degree zero and mass centre convention
  - → handling of permanent tide effects.

→ Guidelines for determination and evaluation of IHRF coordinates depending on the data availability and quality
  - → regions with good surface gravity data coverage and quality
  - → regions without (or with very few) surface gravity
  - → regions with some surface gravity data

→ Strategies for
  - → improvement of the input data required for the determination of IHRF coordinates
  - → IHRF station selection in regional and national densifications
  - → ensuring the usability and long-term sustainability of the IHRF

→ With the contribution/consensus of GGOS FA-UHS, IAG Commission 2, IAG ICCT, IGFS.

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

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

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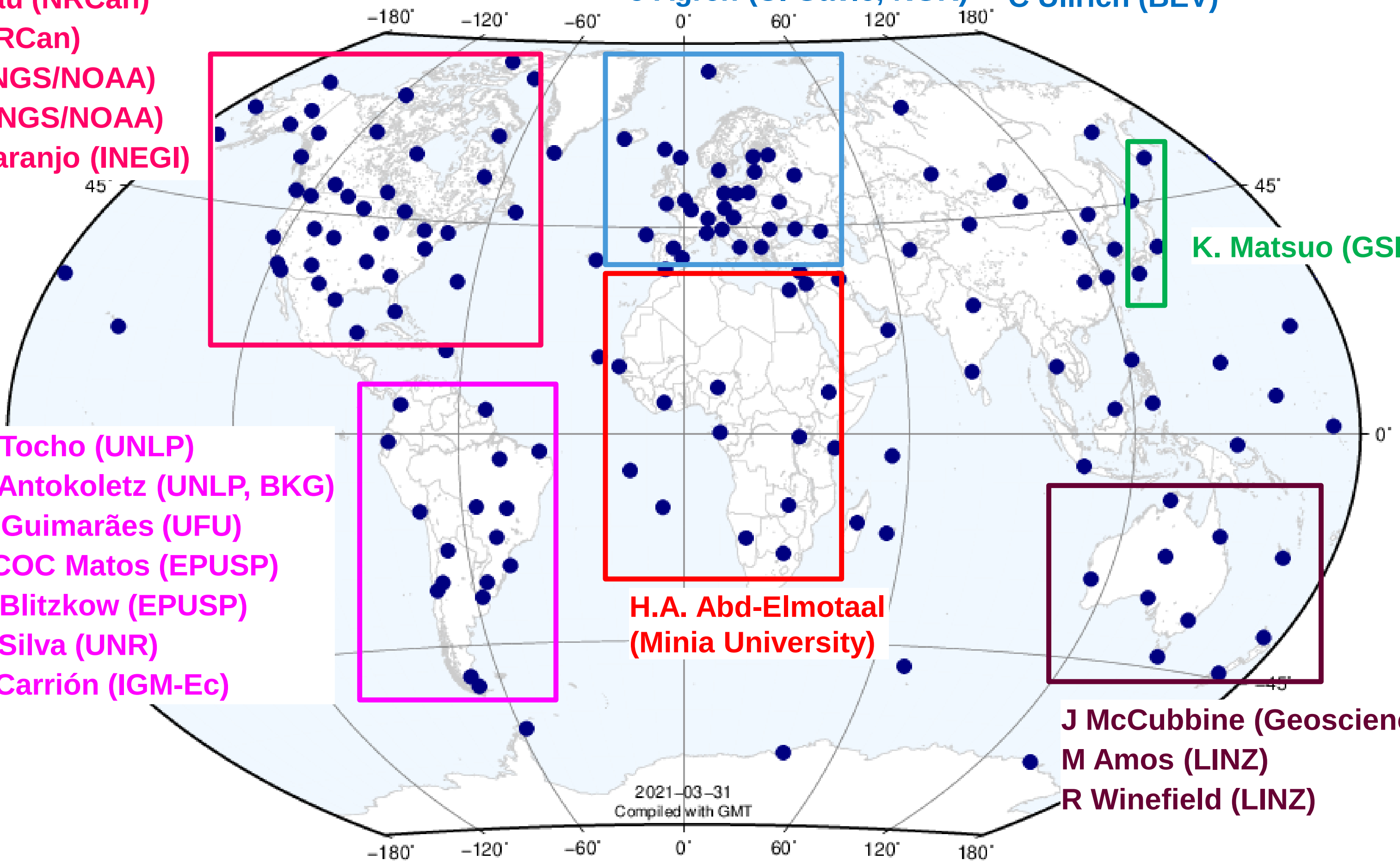

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On going activities: Computation of a first solution for the IHRF

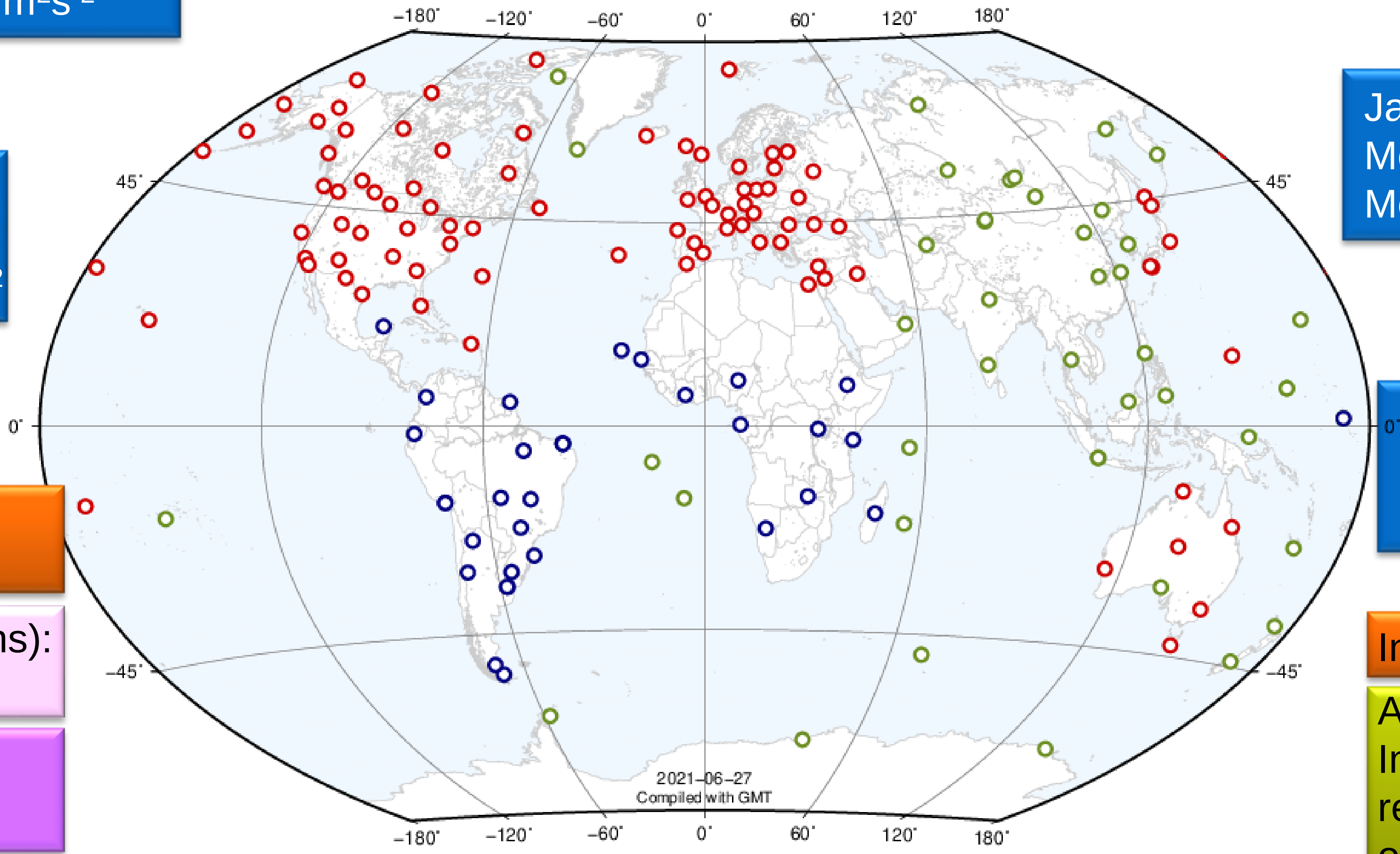
US main territory (30 stations):
Model NAPGD2022 - xG20B
Mean accuracy 0.45 m^2s^{-2}

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}



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

In progress:
Accuracy assessment in

South America (22 stations):
Model GEOIDE2021

Africa (13 stations):
Model AFRgeo2019

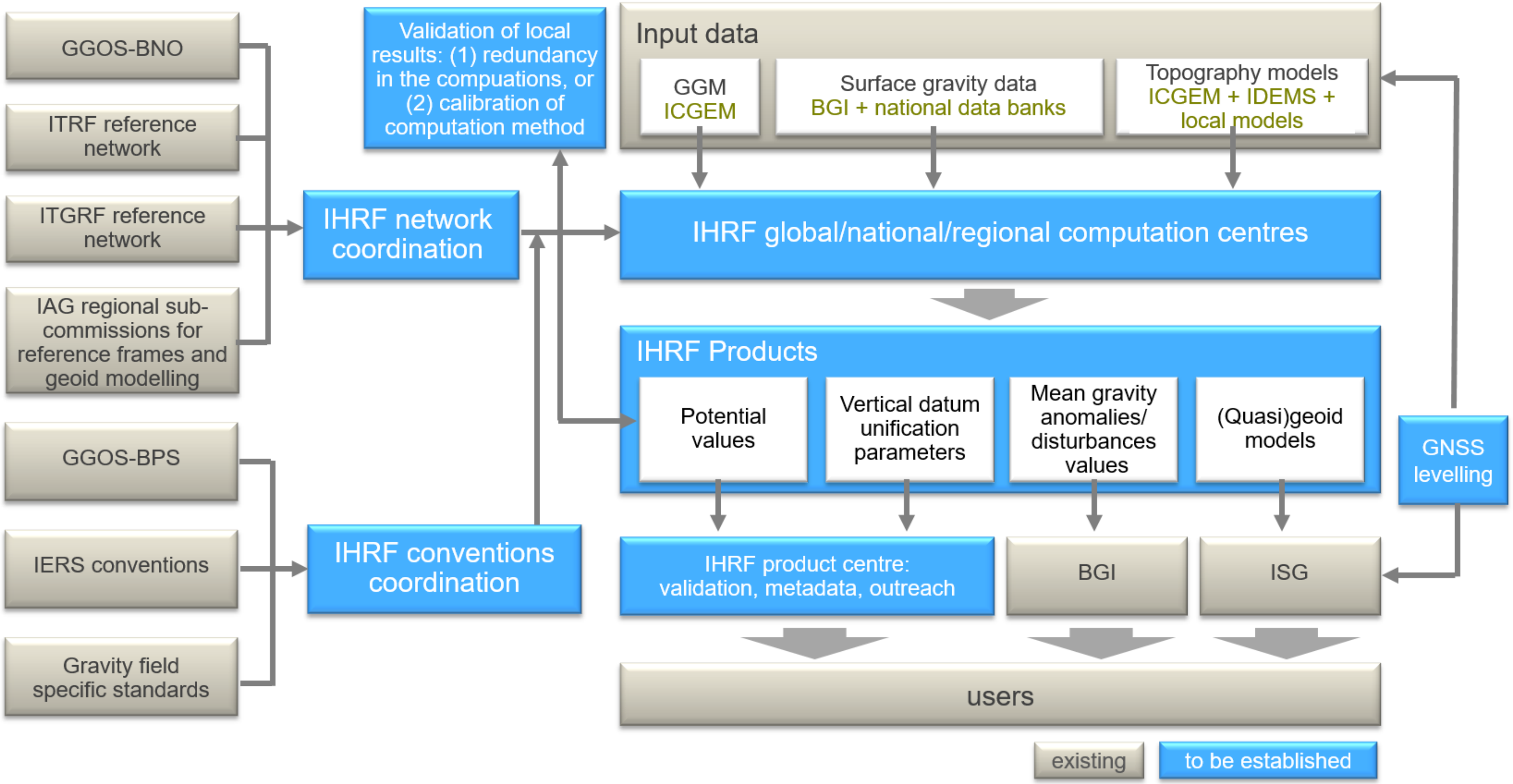
In progress:

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

On-going activities: Operational maintenance

Design of an **IHRF Product Centre** within the International Gravity Field Service (IGFS) to ensure the maintenance and availability of the IHRF:

- Regular updates of the IHRF 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.).



Outlook

1) Present efforts concentrate on
   - Evaluation of discrepancies between different (quasi-)geoid computation methods
   - Quality assessment in the determination of potential values
   - Methods to determine potential changes with time
2) The first IHRF solution should be completed for the next IUGG general assembly (Berlin, July 2023)
3) Terms of reference for the IHRF product centre under the umbrella of IGFS are in preparation

Thanks to the support of

- About *50 colleagues* responsible for the geoid/quasi-geoid modelling in different countries/regions worldwide
- 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)