Activities and plans of the GGOS Focus Area Unified Height System

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GGOS Focus Area Unified Height System

The GGOS Focus Area Unified Height System (formerly Theme 1) was established during the *GGOS Planning Meeting 2010* (February 1 - 3, Miami/Florida, USA) with the objective to *unify the existing height systems* through the *definition and realisation of a world height system* and with the following goals (as in Geodesist's Handbook 2012):

- Short-term goals:
  - To establish a *global vertical reference level* and its potential value W_0.
  - Refinement of standards and conventions for the *definition and realisation of a world height system*.
- Mid-term goals:
  - To develop *GGOS products* for the *realisation of a world height system*: reference frame, global height system unification, registry and metadata of existing height systems.
- Long-term goals:
  - To *maintain and use in practice* the world height system: temporal changes, update of definition and realisation according to new geodetic developments, servicing the vertical datum needs to other geosciences.

GGOS FA-UHS: activities 2011 – 2015

- Conventional global reference level:
  → WG *Vertical Datum Standardisation*: Estimation of a W_0 value based on the newest geodetic models and including reliability assessment (Sánchez et al. 2017)

- Standards and conventions for the definition and realization of a world height system.

  → Main contributions:
  - Recommendations of the *IAG Ad-hoc group on an International Height Reference System – IHRS* (Ihde et al. 2015, 2017)
  - *BPS Inventory of Standards and Conventions* used for the IAG Products (Angermann et al. 2016).
  - Activities under the *ESA project “HSU with GOCE”* (Rummel et al. 2014).

Main result: IAG Resolution for the Definition and Realization of an International Height Reference System (IHRS) released in July 2015.

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:

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

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

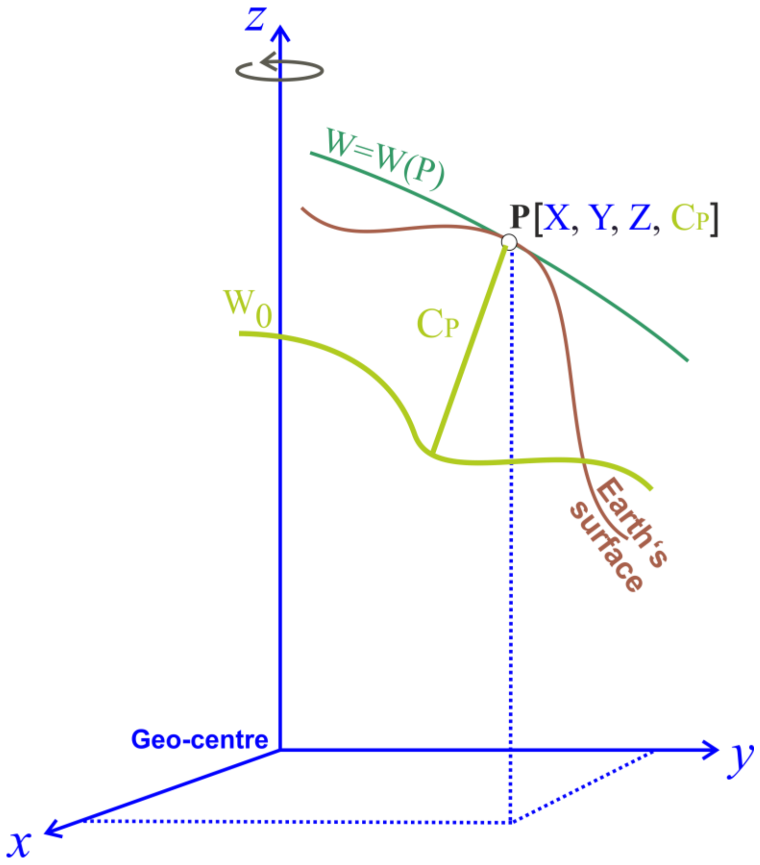
2) The position P is given in the ITRF

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

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

GGOS FA-UHS: activities 2015 – 2019 (1/5)

Objective: Realisation of the IHRS according to the IAG Resolution No. 1, 2015

- Establish a global *reference network* for the IHRS realisation: the International Height Reference Frame (IHRF)
- Evaluate different *strategies for the determination of reference coordinates* at the reference stations
- Identify *required standards, conventions and procedures* needed to ensure consistency between the definition (IHRS) and the realisation (IHRF).

GGOS FA-UHS: activities 2015 – 2019 (2/5)

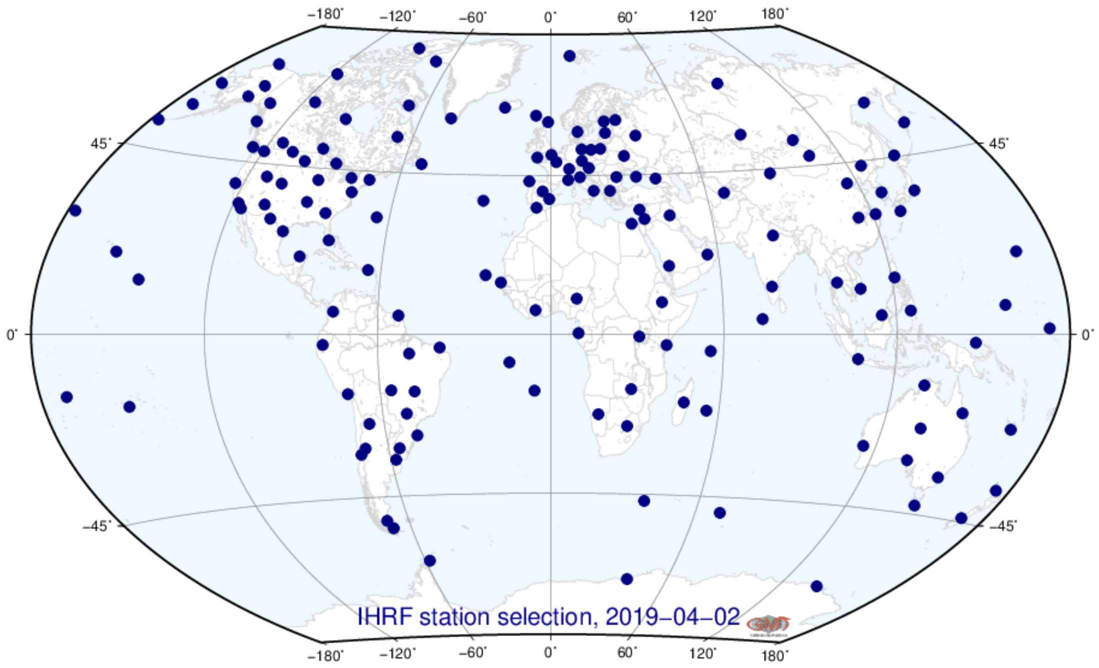
- Reference network

→ Criteria for the *station selection* (Sep 2016, GGHS2016, Thessaloniki)

→ *Proposed core reference network for the IHRF* based on the contribution of the GGOS-BNO, the IAG Services, and regional/national experts on reference frames and geoid modelling (started in Oct 2016, GGOS Days 2016, Cambridge, MA, still open)

→ The present proposal of the IHRF reference network is a start point of implementation; the station selection is not finished or closed. New stations can be added or some stations may be decommissioned.

→ This network is globally distributed and should be extended by means of regional and national densifications.



170 stations well-distributed world-wide, materialized by GNSS continuously operating stations and co-located with *VLBI (30 sites)*, *SLR (40 sites)*, *DORIS (35 sites)*, *absolute gravity – IGRF (77 sites)*, *tide gauges (26 sites)*, *national levelling networks (23 sites)*.

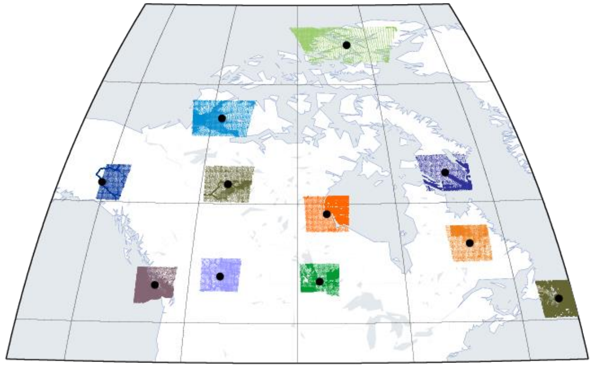
GGOS FA-UHS: activities 2015 – 2019 (3/5)

- Determination of potential values as IHRS/IHRF coordinates

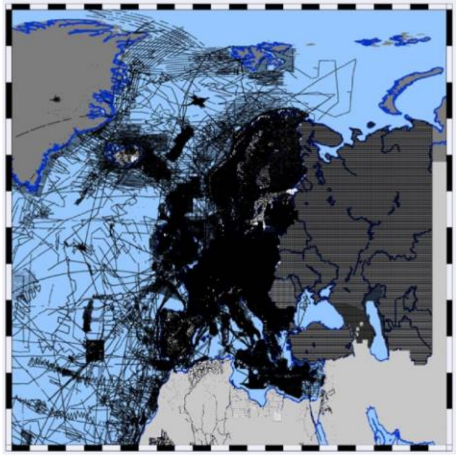
→ Sep 2016 to Mar 2017: Strategy for the integration (transformation) of existing vertical datums into the IHRS/IHRF (Sánchez and Sideris 2017)

→ 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) Further 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)

GGOS FA-UHS: activities 2015 – 2019 (4/5)

- Determination of potential values as IHRS/IHRF coordinates

→ Potential values W determined using *different approaches* present *discrepancies in the dm-level*.

→ To assess the consistency between different computation methods, *fifteen approaches* were evaluated by *computing potential values using exactly the same input data* (Colorado experiment)

→ To minimise discrepancies and to obtain as similar and compatible results as possible with the different methods, a *set of basic standards* was released (L Sánchez, J Ågren, J Huang, YM Wang, R Forsberg, 2019)

→ Action conducted by

- GGOS JWG: *Strategy for the realisation of the IHRS* (chair: L Sánchez)
- IAG JWG 2.2.2: *The 1 cm geoid experiment* (chair: YM 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)

GGOS FA-UHS: activities 2015 – 2019 (5/5)

- Determination of potential values as IHRS/IHRF coordinates
  - → The Colorado experiment *started in July 2017*
  - → *First results* were discussed GGHS2018 (Sep 2018, Copenhagen)
  - → A *second computation* was ready for the EGU2019 (Apr 2019, Vienna)
  - → Some refinements (*third computation*) were delivered in Jun 2019
  - → Results presented and extensively discussed at the *IUGG2019, Symposium G02: Static Gravity Field and Height Systems*
  - → Twelve of fifteen solutions agree within *±1 cm to ±2 cm in terms of standard deviation with respect to the mean value*

Journal of Geodesy, Special Issue on Reference Systems in Physical Geodesy

- Includes the *International Height Reference System (IHRS)*, the *International Gravity Reference System (IGRS)*, and *gravity field modelling within the Colorado experiment*.
- Paper submission from Oct 25, 2019 to Jan 31, 2020.
- Guest editors: L Sánchez, H Wziontek, YM Wang, G Vergos, L Timmen
- 13 manuscripts with Colorado results
- 11 manuscripts with absolute gravity matters
- 1 manuscript about the IGRS
- 1 manuscript about the IHRS
- 2 manuscripts about handling of tide effects (permanent tide, polar tides)
- 1 manuscript about a reference ellipsoid consistent with the IHRF W_0
- 1 introductory (general) manuscript on Reference Systems in Physical Geodesy

IAG Resolution No. 3, 2019: Establishment of the IHRF

Resolution 3: Establishment of the International Height Reference Frame (IHRF)

The International Association of Geodesy,

Considering,

- The IAG Resolution for the Definition and Realization of an International Height Reference System (IHRS) released at the 26th IUGG General Assembly in July 2015;

Acknowledging,

- The achievements of
  - GGOS Focus Area “Unified Height System” and its JWG 0.1.2 “Strategy for the Realization of the International Height Reference System (IHRS)”,
  - IAG JWG 2.2.2 “The 1 cm geoid experiment”,
  - IAG SC 2.2 “Methodology for geoid and physical height systems”,
  - ICCT JSG 0.15 “Regional geoid/quasi-geoid modelling - Theoretical framework for the sub-centimetre accuracy”;
- in realizing this resolution;

Noting,

- The need of an operational infrastructure to ensure the determination, maintenance and availability of an International Height Reference Frame (IHRF) in the long-term basis;

Urges,

- All countries to engage with the IAG and concerned components, in particular the International Gravity Field Service (IGFS), in order to promote and support the implementation of the IHRF by
  - Installing IHRF reference stations at national level,
  - Conducting the necessary gravimetric surveys to guarantee the precise determination of potential values,
  - Making data available open access,
  - Contributing to the development of analysis strategies to improve the estimation of reference coordinates and modelling of the Earth’s gravity field,
  - Describing, archiving and providing geodetic products associated to the IHRF.

GGOS FA-UHS: planned activities 2019 – 2023 (1/2)

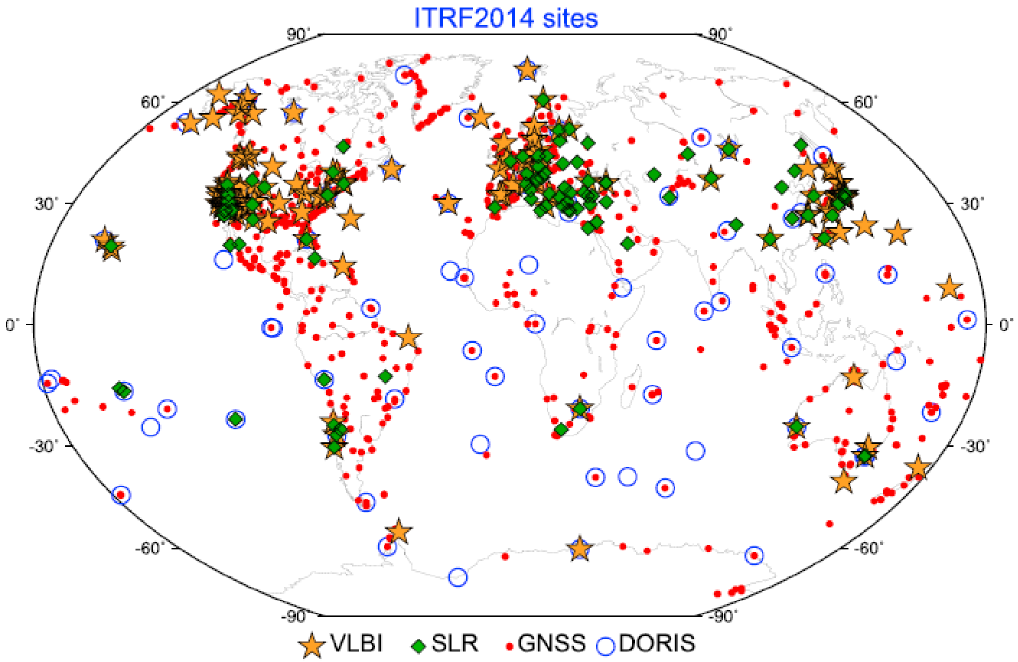
- Based on the Colorado experiment outcomes, to elaborate a document with *detailed standards and conventions* for the realisation and maintenance of the IHRS.
- To compute *a first static solution* for the IHRF to evaluate the achievable accuracy under the present conditions (data availability, computation methods, etc.) and to identify key actions to improve the determination of the IHRS/IHRF coordinates.
- With the support of the IAG Commission 2, the IGFS and the ICCT to promote the study of
  - quality assessment in the determination of potential values,
  - determination of potential changes with time $\dot{W}$,
  - realization of the IHRS in marine areas.
- Planned related working groups (WG) or study groups (SG):
  - ICCT SG: *Geoid/quasi-geoid modelling for realisation of the geopotential height datum*, chairs: J Huang (Canada), YM Wang (USA)
  - IAG Commission 2 WG: *Error assessment of the 1 cm geoid experiment*, chairs: M Willberg (Germany), T Jiang (China)
  - GGOS-FA-UHS WG: *Implementation of the International Height Reference Frame*, chair: L Sánchez (Germany)
  - GGOS-BPS WG: *Towards a consistent set of parameters for a new GRS*, chair U Martí (Switzerland)

GGOS FA-UHS: planned activities 2019 – 2023 (2/2)

- In agreement with the IGFS and the IAG Commission 2, to design a strategy *to install an operational infrastructure within the IGFS* to ensure the *maintenance and availability of the IHRF in a long-term basis*.
- Aspects to be considered are
  - Updates of the IHRS definition and realisation according to future improvements in geodetic theory and observations.
  - Regular updates of the IHRF (e.g. IHRFyyyy) according to new stations, coordinate changes with time, improvements in the estimation of reference coordinates and modelling of the Earth’s gravity field, etc.
  - Support in the realisation and utilisation of the IHRS/IHRF at regional and national level.
  - To guarantee an organizational and operational infrastructure to ensure the sustainability of the IHRF.

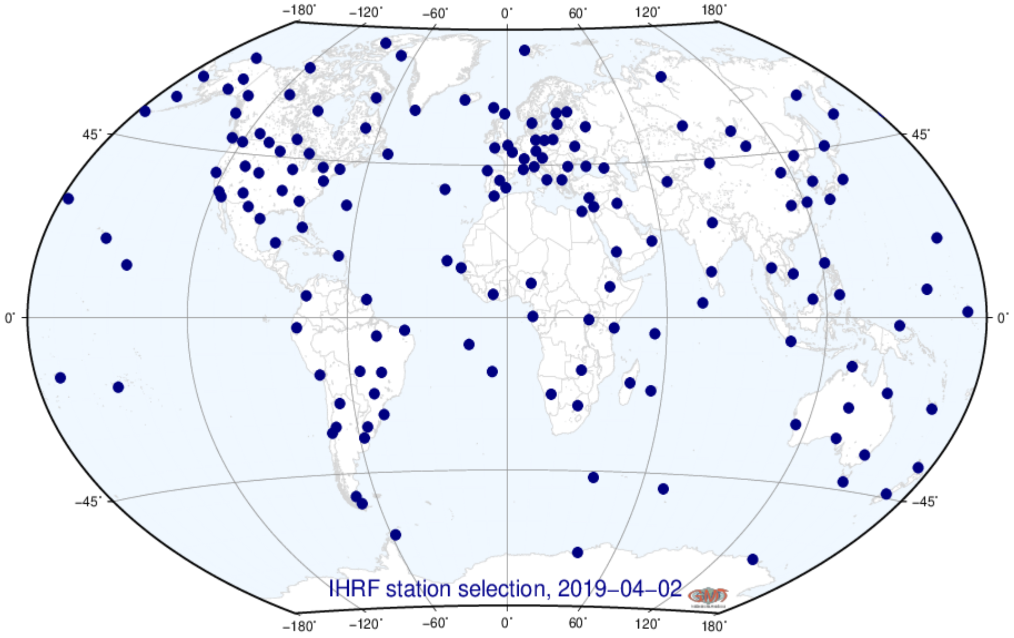
Major concerns: Reference network

ITRS/ITRF



- Expensive techniques (VLBI, SLR, DORIS) supported by space and geodetic agencies.
- Densification with GNSS based on contributions from the regional and national reference frames.
- Station selection in accordance to the station performance and quality (IVS, ILRS, IGS, IDS).

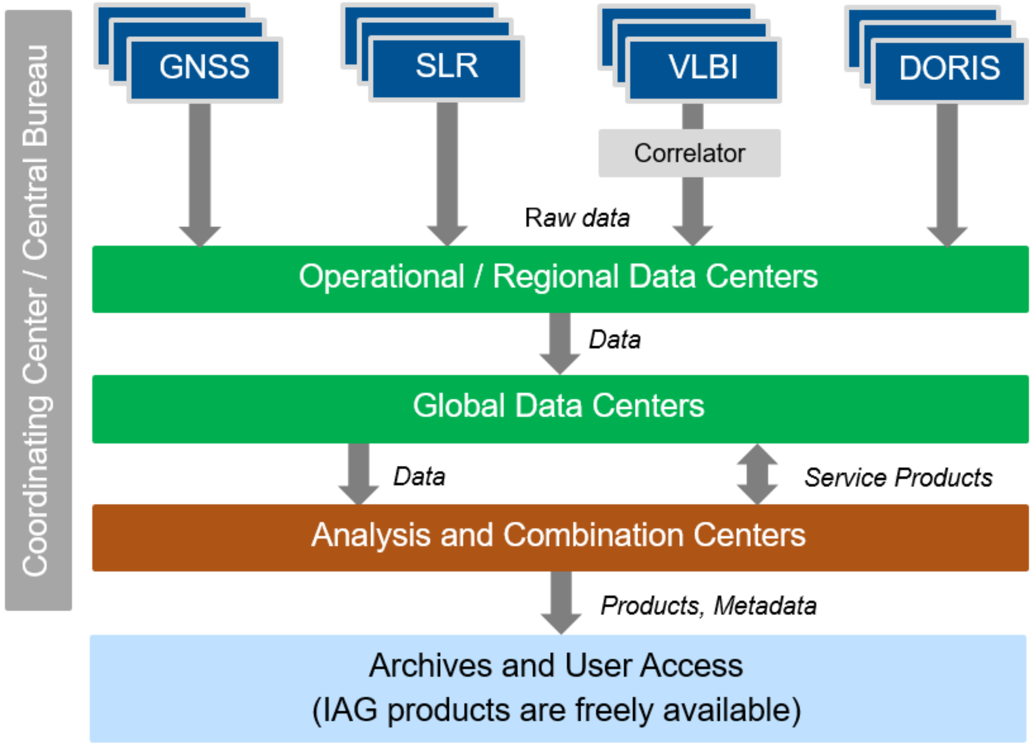
IHRS/IHRF



- Primary realisation with GNSS and co-located with VLBI, SLR, DORIS, absolute gravity, tide gauges and levelling networks.
- *Gravity data of high resolution for reliable determination of W*.
- Densification based on the recommendations from the regional and national reference frames.
- *Quality of* ***X*** *assessable, quality of W unknown or hard to be estimated*.

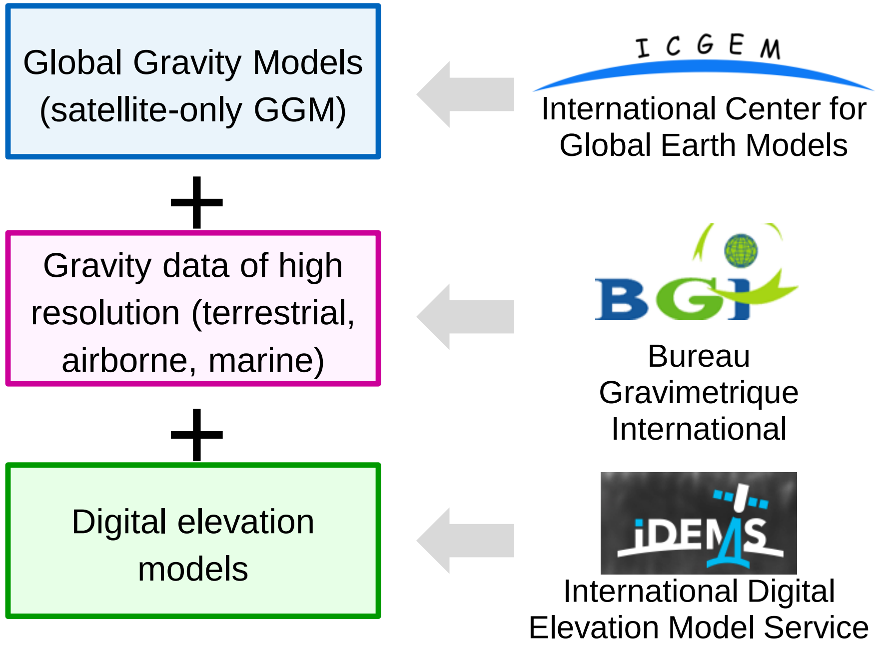
Major concerns: Input data and data flow

ITRS/ITRF



Angermann et al. 2019

IHRS/IHRF



- ICGEM: data freely available, quality assessment
- *BGI: historical gravity data freely available but uncertainty about reference system for gravity and positions, low accuracy. Recent gravity data with restricted access.*
- *IDEMS: elevation models of low resolution and accuracy freely available, better elevation models with costs. Software-dependent accessibility.*

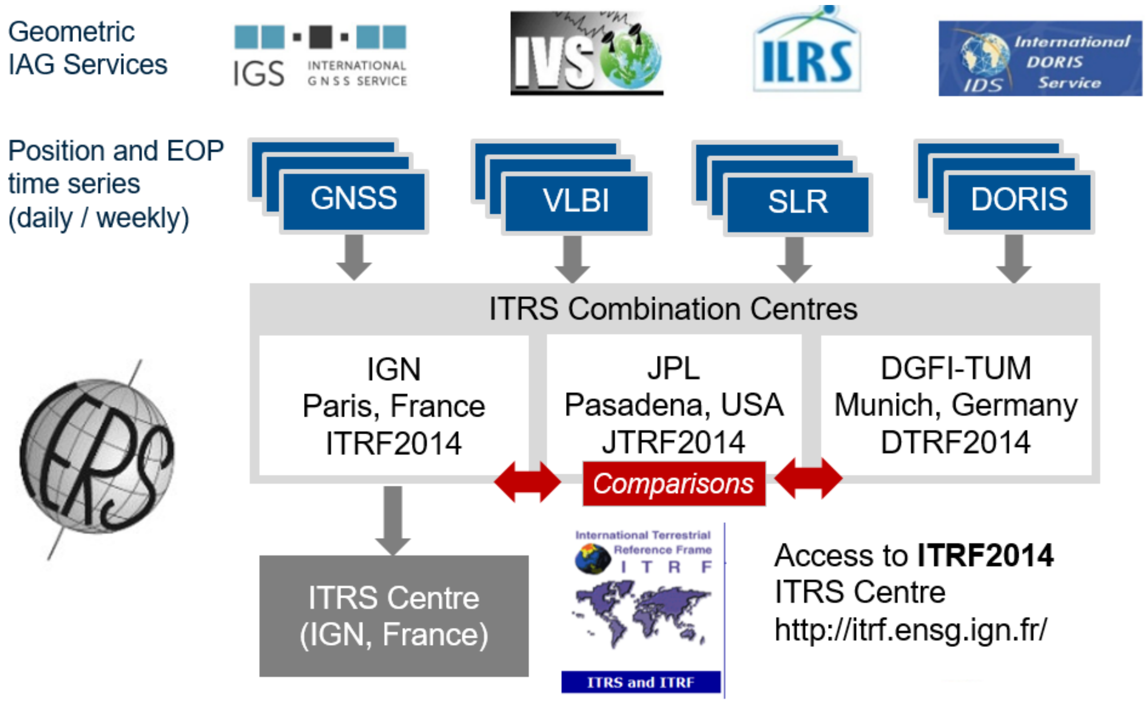
Possible solution

- To increase the reliability of the potential values the old gravity data sets have to be replaced with modern gravity data: referring to the Absolute Gravity Reference Frame (IGRF), with precise (~2 cm) 3D coordinates referring to the ITRF, and a high spatial resolution (ideal 3 to 5 km). *The IGFS is not able to pay for gravity surveys*.
- The commercial (private) character of many gravity data sets has been a point of discussion over many years. *The IGFS cannot obligate anybody to make freely available private gravity data*.

→ *To establish a direct link to the UN-GGRF Resolution to outline political and technical arguments oriented to convince policy makers about the necessity of getting access to these data at national level for the gravity field (geoid) modelling (outreach by the IGFS Central Bureau?).*

Major concerns: Organisational scheme for computation

ITRS/ITRF



- Consistency trough IERS standards and conventions
- Centralised estimation by combining the technique-based solutions at the combination centres
- Redundancy: three independent combinations.

IHRS/IHRF

- A *centralised computation* of W is (still) *unviable* due to the restricted accessibility to terrestrial gravity data and elevation models of high-resolution.
- To exploit at maximum the existing data to get as accurate as possible potential values, *national/ regional experts in the gravity field (or geoid) modelling should be involved* in the determination of the IHRS/IHRF coordinates.
- A *rigorous standardisation* seems to be not suitable because
  1) it exists *different data availability* and *different data quality* around the world and
  2) regions with *different characteristics* require *particular approaches*
- *Quality assessment* of the individual computations is very difficult because *redundancy is practically impossible*.

Possible solution

- National/regional experts on gravity field modelling should be involved in the determination of the IHRS/IHRF coordinates. They should utilise all the data they have available to determine the potential values using the computation approaches they have implemented for their regions. However, to minimise discrepancies and to obtain as similar and compatible results as possible

  → *a set of basic standards should be defined and updated in accordance with new models and procedures (start point: outcomes of the Colorado experiment)*

- To assess the reliability of the individual computations performed by the national/regional experts

  → *1) "Auxiliary" stations close (20 ... 50 km) to the core IHRF stations connected by levelling of high precision to have independent data (potential differences) for evaluation;*

  → *2) Redundancy in the computation should be ensured: an IGFS "analysis centre" or IGFS "associates" could be provided with local data to determine potential values to be compared with the local results, or*

  → *3) Computation methods used by national/regional experts should be calibrated: determination of potential values using a certain set of input data and comparison with results obtained by other approaches (like in the Colorado experiment)*

- Options (1) and (2) may be useful to support the evaluation of global gravity models (GGM)

Possible solution

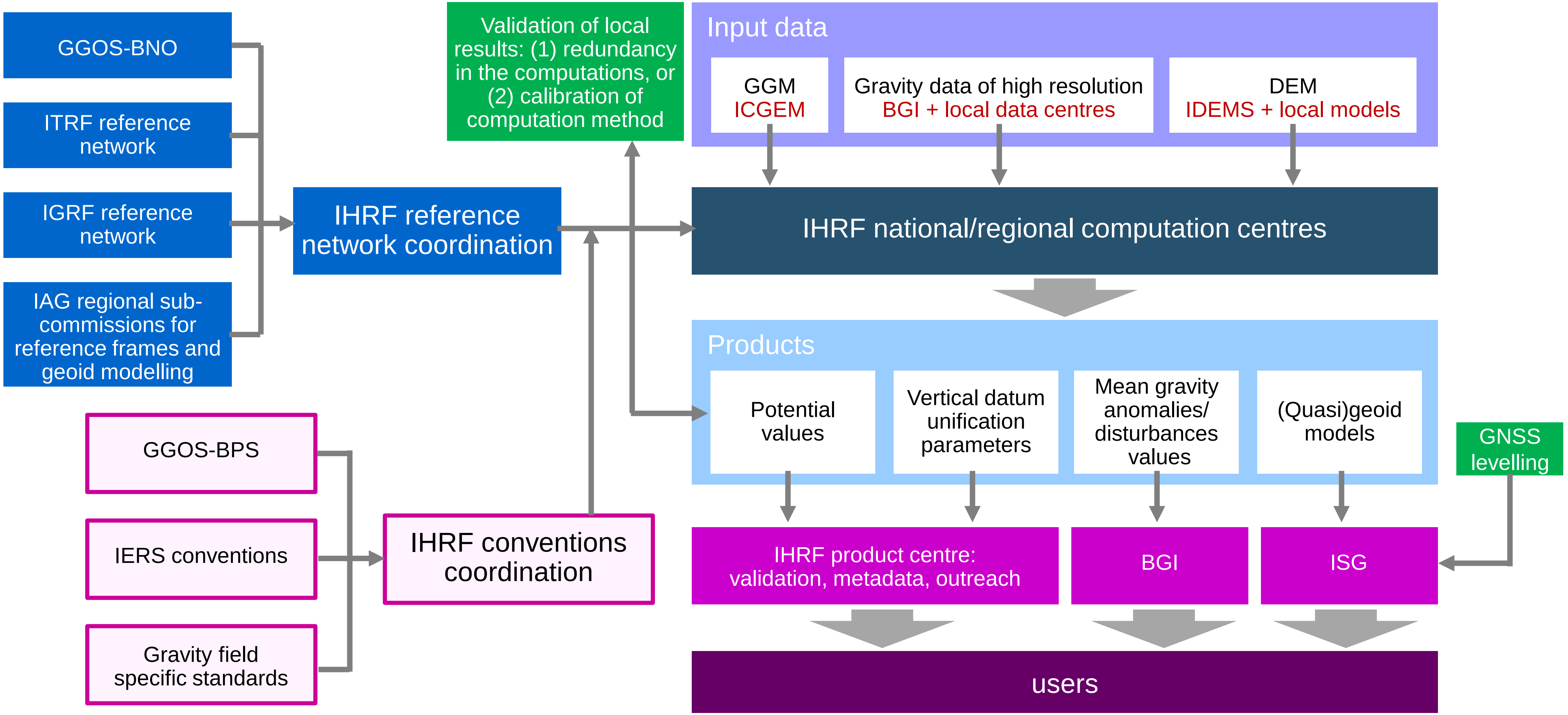
- To keep the IHRS realisation up-to-date, it would be necessary

  → *The interaction with the GGOS Bureau for Networks and Observations, the IERS (ITRF reference network), the BGI (IGRF network), and national/regional experts to maintain the reference network*

  → *Regular updates of the IHRFyyyy (synchronised with the release of new ITRF solutions) to take account for:*

    – *new stations;*
    – *coordinate changes with time $\dot{X}$, $\dot{W}$;*
    – *improvements in the estimation of X and W (new observations, better standards, better models, better computation algorithms, etc.).*

Possible IHRF “element” within the IGFS



Sánchez et al. (2019b)

Major concerns: Usability

ITRS/ITRF

- In scientific applications, the ITRF is the best available platform for the determination of geometric coordinates (positions, trajectories, velocities). It is well accepted and widely used.
- In practical and non-geodetic applications, the ITRF is “involuntarily” accepted and used by everyone using GNSS techniques and ITRF-based satellite orbits.
- Regional and national densifications of the ITRF have been necessarily established, because GNSS is the primary technique used today for the establishment of reference frames.

IHRS/IHRF

- Discussions about a world height system or a global vertical reference system *started 30 years ago*. Realisation for the first time possible after GRACE and GOCE. However, *accuracy one to two levels worse than by the ITRF*.
- To achieve a wide acceptance of the IHRS/IHRF, the *certainty of potential values (gravity field modelling at high resolution) has to be drastically improved*.
- In the best case, the IHRF will be “involuntarily” accepted and used by everyone using *GNSS in combination with a consistent geopotential model of high resolution*.
- Most probably, the existing height systems will continue in daily use and the IHRS/IHRF will be considered for selected applications only.