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

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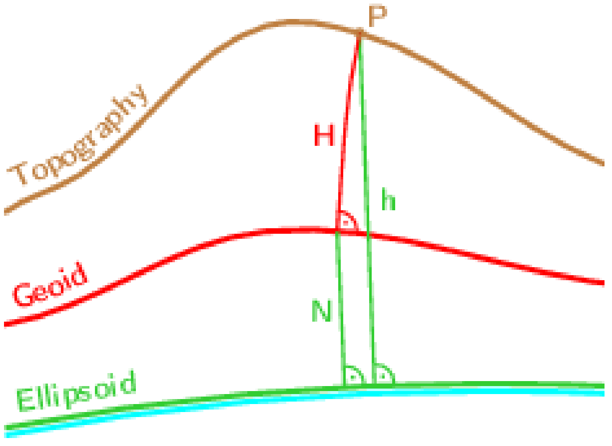
Motivation

1) Vertical coordinates used in practice:

- $h \rightarrow$ ellipsoidal heights (GNSS positioning);
- $H \rightarrow$ Physical heights (levelling + gravity reductions);
- $N \rightarrow$ (Quasi-)geoid undulations (gravity field modelling).



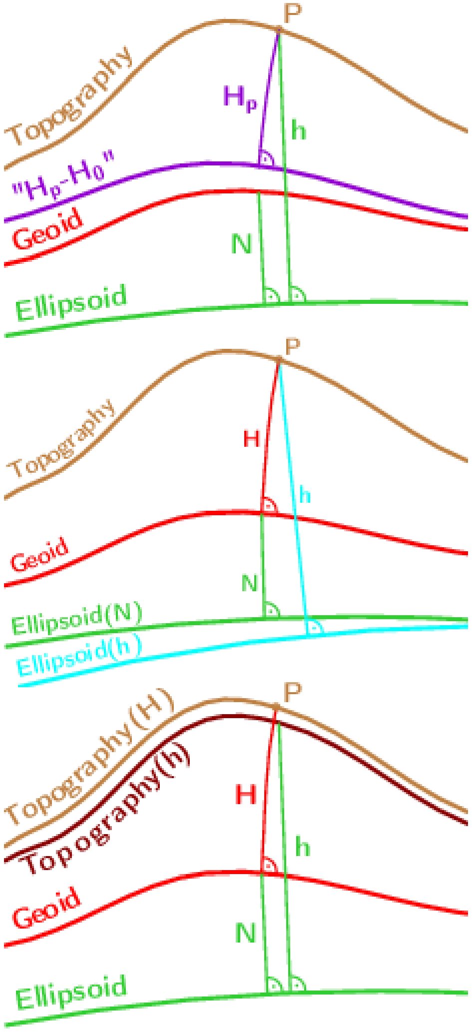
2) Everyone using GNSS positioning and requiring physical heights demands

$$H = h - N$$

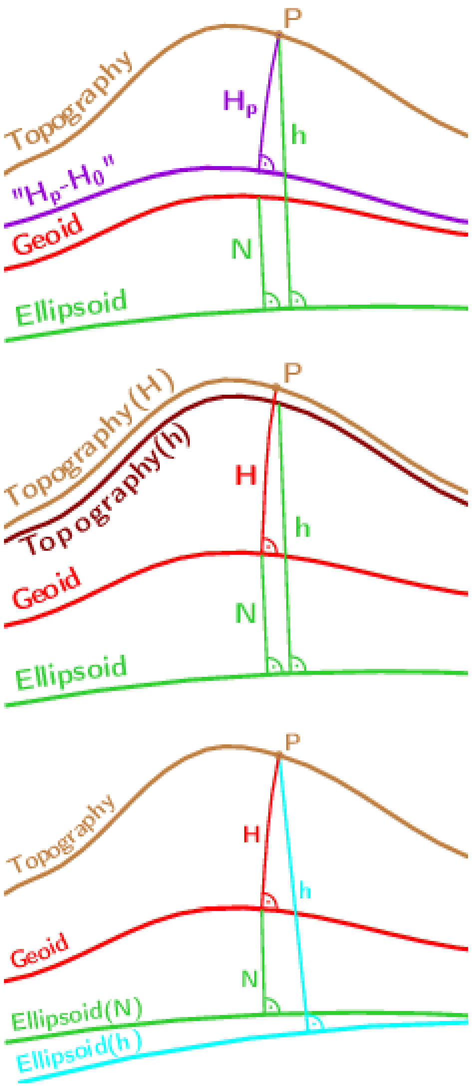
with consistency at the cm-level and worldwide.

$H = h - N$ in theory, but in practice, e.g.

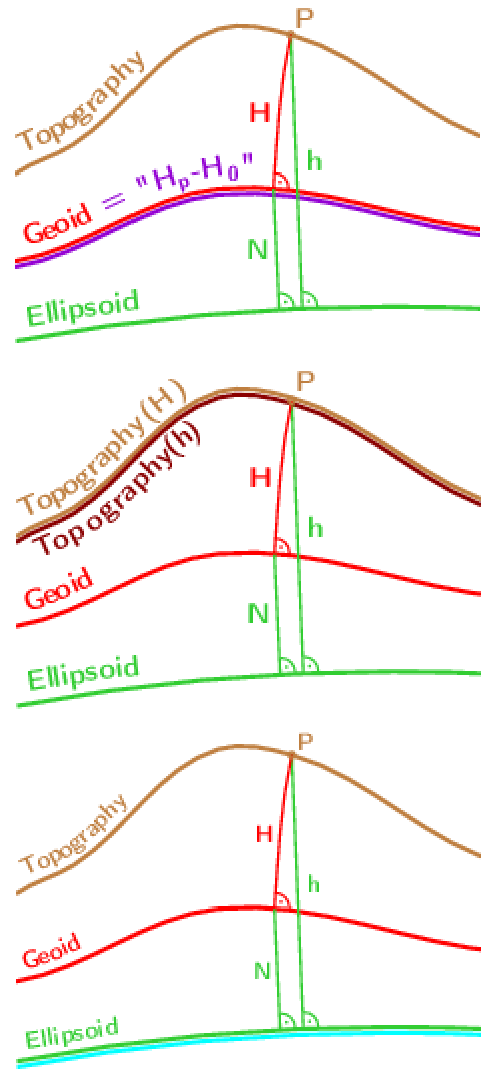
- Physical heights H usually refer to different local vertical reference levels (more than 100 worldwide).
- Different ellipsoid parameters (a, GM) are used in geometry and gravity.
- H and h are given in different reference epochs (usually dH/dt is unknown).
- Different solid Earth tide systems for H, h and N are used.
- Different reductions are applied to H, h and N (ocean and atmospheric tides, ocean, atmospheric and hydrologic loading, post-glacial rebound, etc.).
- …



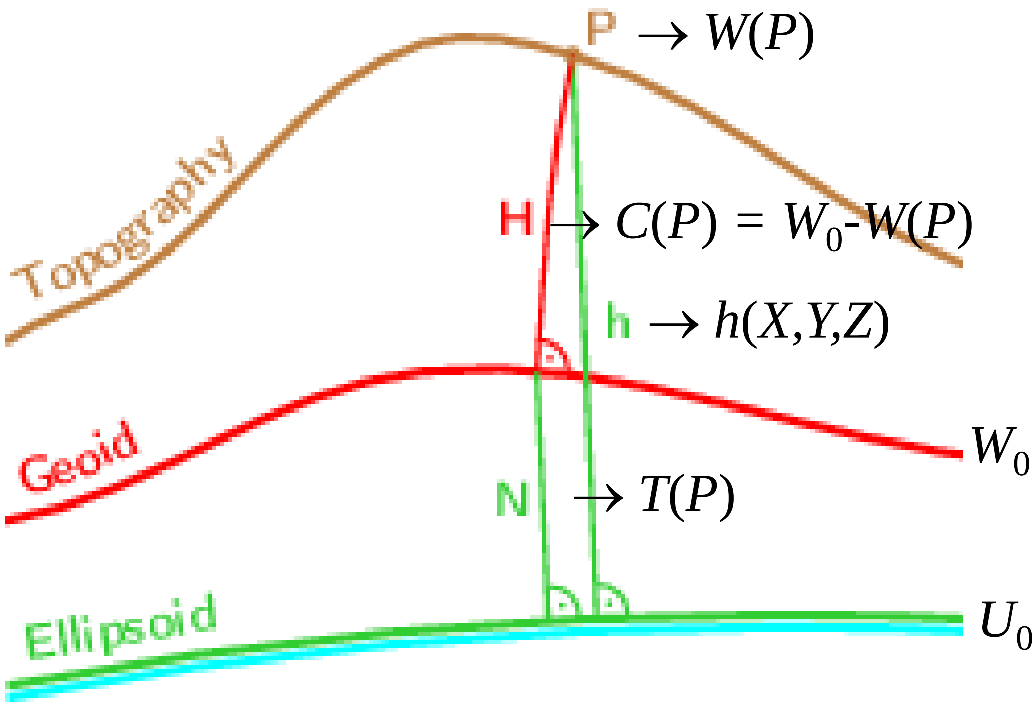
A global unified height system is needed to ensure consistency between h, H, N, worldwide and at the cm-level



- A unified reference level for physical heights.
- H, h and N in the same tide system.
- The same models to reduce time-dependent changes in H, h, N.
- The same reference epoch for H and h.
- The same ellipsoidal parameters in gravity and geometry.
- …



Vertical coordinates in terms of potential



Requirements

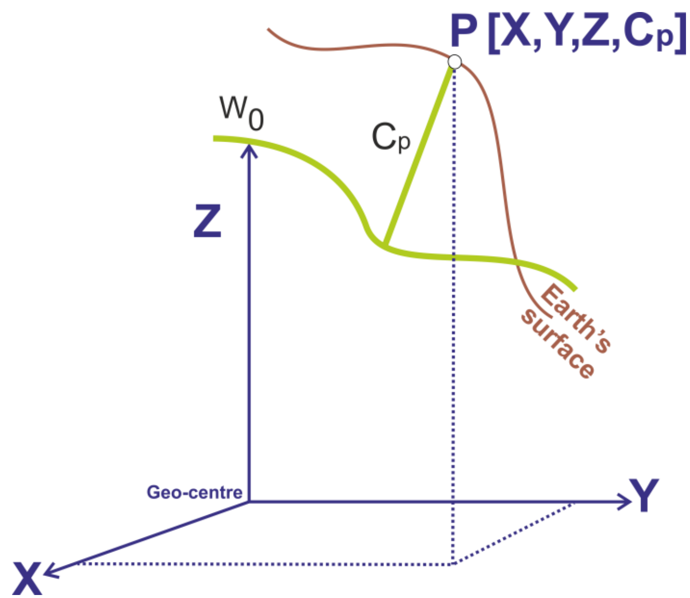
- $W_0 = U_0$
- Additional parameters: GM, ω, J_2

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

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

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

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



2) The position P is given by the coordinate vector $\mathbf{X}_P\ (X_P, Y_P, Z_P)$ in the ITRF, i.e. $W(P) = W(\mathbf{X}_P)$

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

The realization of the IHRS is understood to be a component of the Global Geodetic Reference Frame (UN GGRF resolution 2015).

Realization of the IHRS

A reference frame realizes a reference system in two ways:

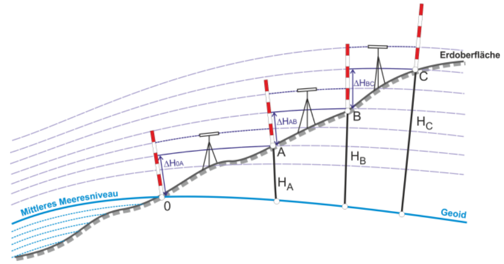
- physically, by a solid materialization of points (or observing instruments),
- mathematically, by the determination of coordinates referring to that reference system.
- The coordinates of the points are computed from the measurements, but following the definition of the reference system.

Immediate objectives regarding the IHRS:

- Establishment of an International Height Reference Frame (IHRF) with high-precise primary coordinates X_P, $\dot{X}_P$, W_P, $\dot{W}_P$.
- Expected accuracy for W_P: Positions: ~ $3\times10^{-2}\ m^2s^{-2}$ (about 3 mm). Velocities: ~ $3\times10^{-3}\ m^2s^{-2}$ (about 0.3 mm/a).
- Identification and compilation/outlining of the required standards, conventions and procedures 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.

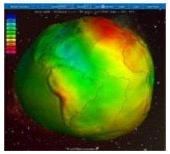
Possibilities for the determination of W_P

1) Levelling + Gravimetry:



$$W_P = W_0 - C_P; \quad C_P = \int_0^P g\, dn$$

2) Combined (high-resolution) gravity field models:



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

3) 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 Molodensky approach
Satellite tracking from ground stations (SLR)		*Satellite altimetry (oceans only)*
Satellite-to-satellite tracking (CHAMP, GRACE)		Gravimetry, astro-geodetic methods, levelling, etc.
Satellite gravity gradiometry (GOCE)		Terrain effects
Satellite altimetry (oceans only)		

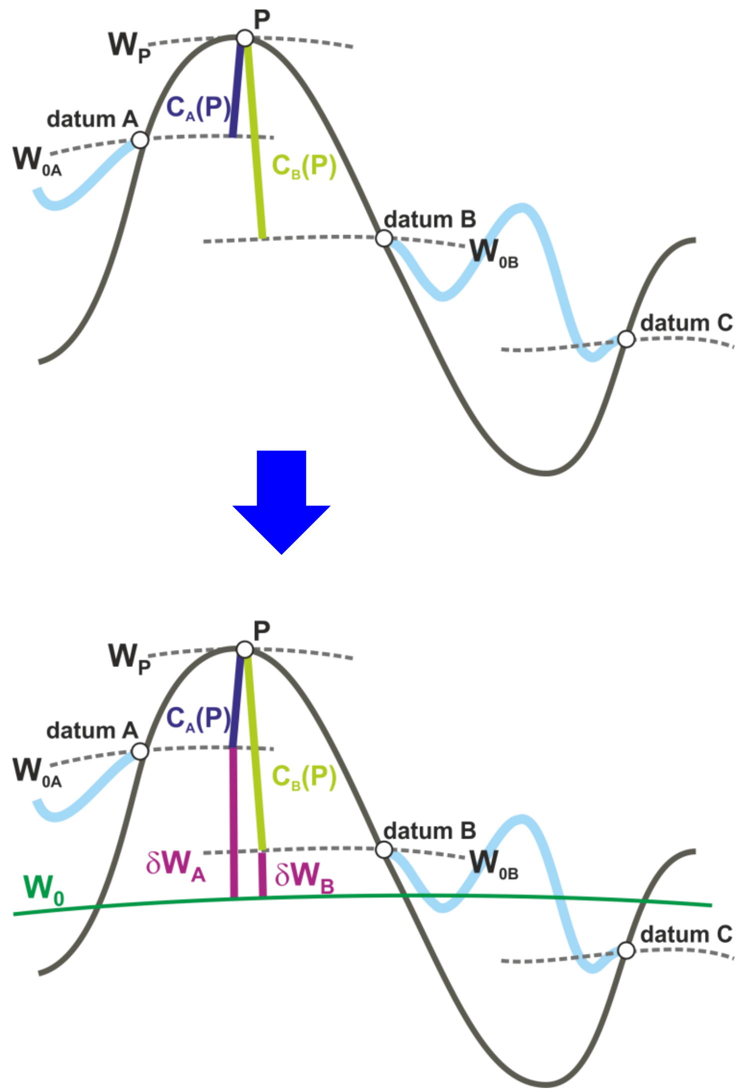
1) W_P from Levelling + Gravimetry

- Refer to local vertical datums with unknown potential value $W_{0,\mathrm{local}} = ?$

- To determine W_P, it is necessary to estimate the level difference between the global W_0 and the local $W_{0,local} \rightarrow \delta W = W_0 - W_{0i}$

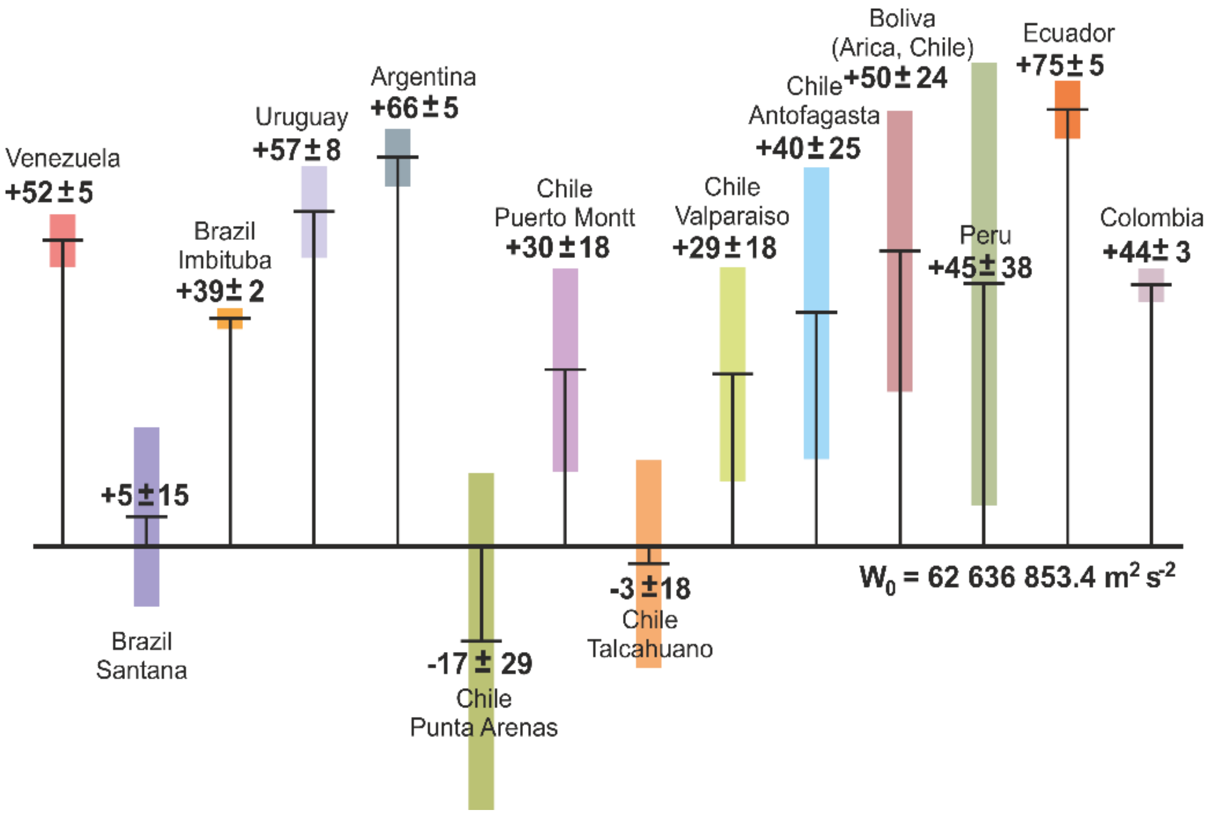
$$W_P = \left(W_{0,local} + \delta W\right) - C_P;$$

- Expected accuracy of δW: cm in well-surveyed regions, dm in sparsely surveyed regions, extreme cases up to 1 m.



1) W_P from Levelling + Gravimetry

Example: δW (in cm) for the South American height systems w.r.t. the IHRS W_0 value.



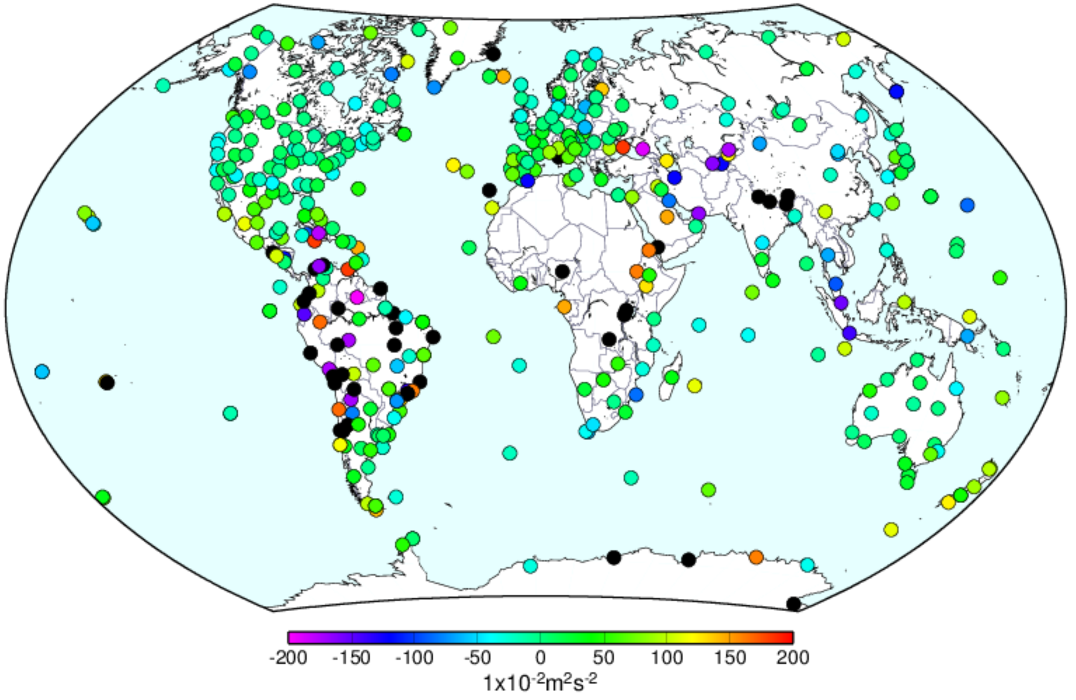
➢ This strategy is needed to integrate the existing height systems into the IHRS, but its accuracy is not enough for establishing the core network of the IHRS realisation.

2) W_P from combined (high-resolution) GGMs

- This method is not (yet) suitable.
- Main drawback: incomplete gravity signal due to lack of data and restricted accessibility to terrestrial gravity data.

Example:

- Global network with known $\mathbf{X}$ coordinates
- Differences between the W_P values derived from EGM2008 (Pavlis et al. 2008) and EIGEN6C4 (Förste et al. 2014), both at n=2190
- Differences larger than $\pm 200 \times 10^{-2}\ m^2s^{-2}$ (up to $\pm 20\ m^2s^{-2}$)
- Desired accuracy for W_P: $\pm 3 \times 10^{-2}\ m^2s^{-2}$



3) W_P from high-resolution gravity field modelling

At present, the only possibility to get closer to the accuracy required for the realisation of the IHRS

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

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 Molodensky approach
Satellite altimetry (oceans only)
Gravimetry, astro-geodetic methods, levelling,etc.
Terrain effects

$$W_P = U_P + T_P$$

$$T_P = T_{P,satellite-only} + T_{P,residual} + T_{P,terrain}$$

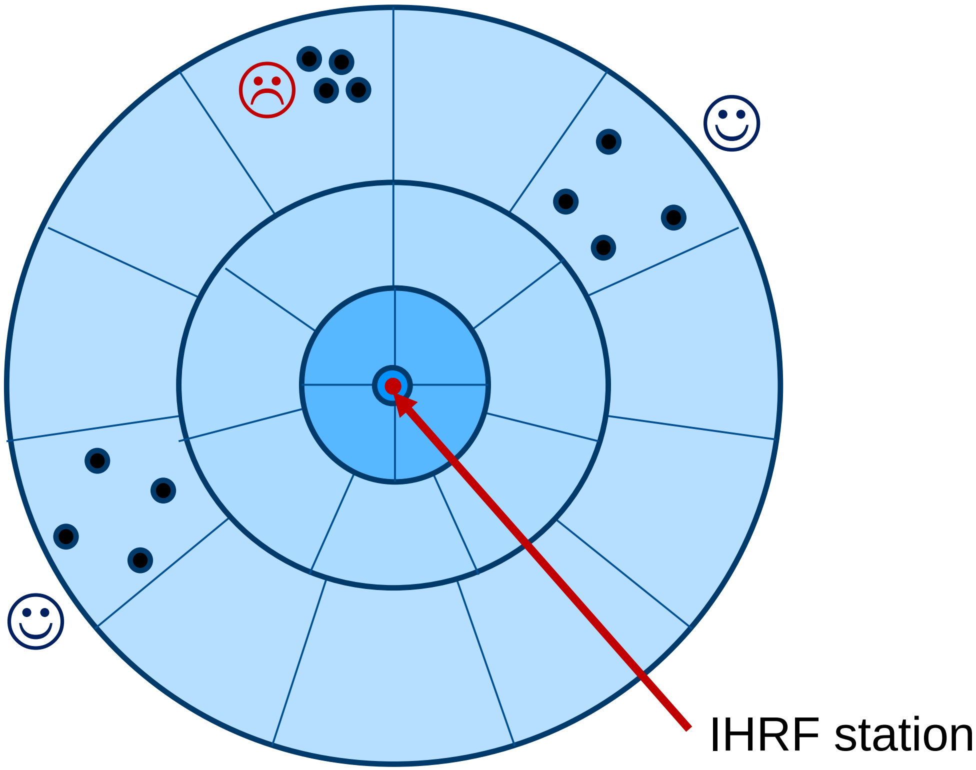
One GGM

Terrestrial gravity data

One DTM

Requirements on the terrestrial gravity data

- Homogeneously distributed gravity points around the IHRF reference stations up to 210 km (~ 2°). The gravity data may exist or have to be observed.
- Minimum accuracy of the gravity values: ±20 μGal.
- Gravity point positions with GPS.
- In mountain areas ~50% more gravity points.
- Uncertainties of GGM and DTM must be added.



Template according to the gravity effect on the geoid ($\Delta g = 1 \cdot 10^{-6}\ ms^{-2} \rightarrow 1$ mm)

Distance	Compartments	# of points **flat**/**mountain**
10 km	1	**4**/**8**
50 km	4	**20**/**30**
110 km	7	**30**/**45**
210 km	11	**50**/**75**
Sum	23	**100**/**150**

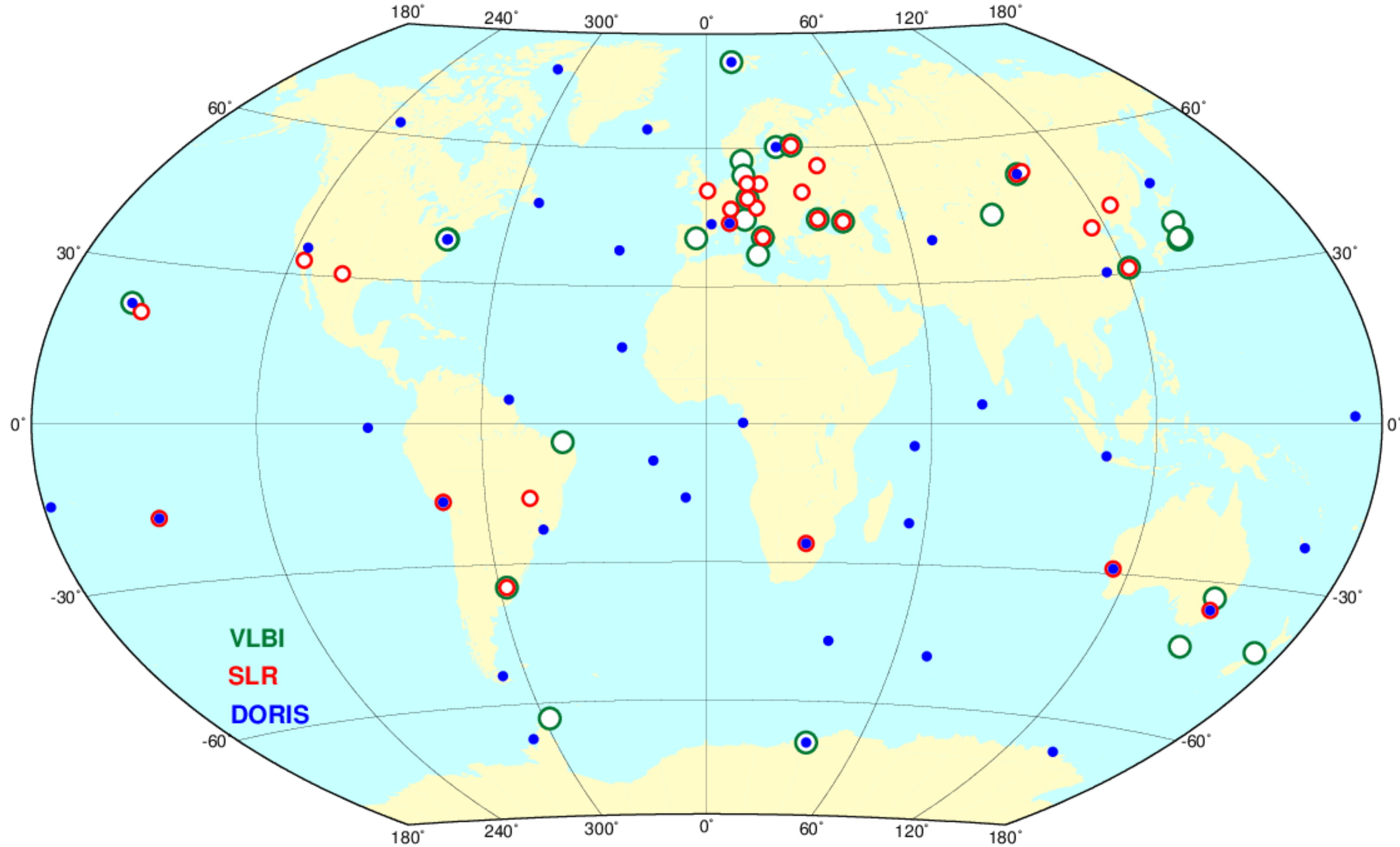
Reference network

1) Hierarchy:
   - A global network → worldwide distribution, including
   - A core network → to ensure perdurability 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 → to support the GGRF;
   - continuously operating reference stations → to detect deformations of the reference frame;
   - 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).

Selection of possible IHRF reference stations

1) Geodetic observatories (GGOS core stations)
2) Existing VLBI stations collocated with GPS
3) Existing SLR stations collocated with GPS
4) Existing DORIS stations collocated with GPS



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2) Existing VLBI stations collocated with GPS.
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In progress (expected to be ready by the end of the year):

1) Tide gauges connected to the vertical networks (in coordination with TIGA).
2) Reference stations of the new Global Absolute Gravity Reference System (in coordination with H. Wziontek).
3) Densification with continuously operating GNSS stations in cooperation with the regional IAG sub- commissions (e.g. SIRGAS and the Sub-commission for the geoid in South America).

Still open:

1) Collocation with time laboratories (to provide high-precise potential values for reference clocks).

Once the reference stations are selected, next steps are:

1) To contact local experts to collect the gravity data.
2) To compute a preliminary IHRF solution (first results expected to be presented during IAG2017).

SIRGAS and the IHRS/IHRF

1) Establishment of IHRS stations in the SIRGAS region
   - To select some (1 to 5) continuously operating SIRGAS reference stations in each country (well distributed and materialized by a monument on the ground; stations on the top of buildings are not welcome).
   - To survey gravity data around the selected SIRGAS reference stations (about 150 gravity points well distributed around each station up to a distance of about 200 km).
   - Coordinates of gravity points determined with GNSS positioning ($\pm$2 cm).
   - It is desirable that the gravity surveys refer to absolute gravity stations.

2) Integration of the existing Latin American height systems into the IHRS/IHRF
   - First order levelling (with gravity data) of SIRGAS reference stations (optimal if IHRF stations are levelled).
   - Reference tide gauges connected to SIRGAS.
   - Combination of ellipsoidal heights, levelling-based physical heights, tide gauge registrations, satellite altimetry observations and height-resolution gravity field modelling.

3) SIRGAS member countries should take advantage of the SIRGAS-WG3 activities:
   - Capacity building and software for the processing of gravity data
   - Capacity building and software for the adjustment of levelling networks and computation of geopotential numbers
   - Until now: Rio (2012), La Paz (2014), Curitiba (2015), Quito (2016), San José (2017)
   - Once the levelling networks are properly adjusted, a workshop about the integration of the existing height systems into the IHRS/IHRF can be planned.

On-going activities

Coordinated work between:

- GGOS Focus Area Unified Height System
- International Gravity Field Service (IGFS)
- IAG Commission 2 (Gravity field)
- IAG Commission 1 (Reference Frames)
- IAG Inter-commission Committee on Theory (ICCT)
- Regional/national vertical reference systems

1) Selection of core stations for the IHRF
   - in agreement with the GGOS Bureau for Networks and Observations, main requirement are gravity data around (~200 km) core stations for high-resolution gravity field modelling.

2) Identification of required standards and conventions
   - in agreement with the GGOS Bureau for Products and Standards, main requirement is the harmonization with the IERS conventions.

3) Estimation of potential values
   - Evaluation of different methodologies and compilation of guidelines for high-resolution gravity field modelling.

4) Vertical datum unification
   - Roadmap for the integration of the existing local height systems into the IHRF.

Working Group on the Strategy for the Realization of the International Height Reference System (IHRS), more information at **http://ihrs.dgfi.tum.de**