

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

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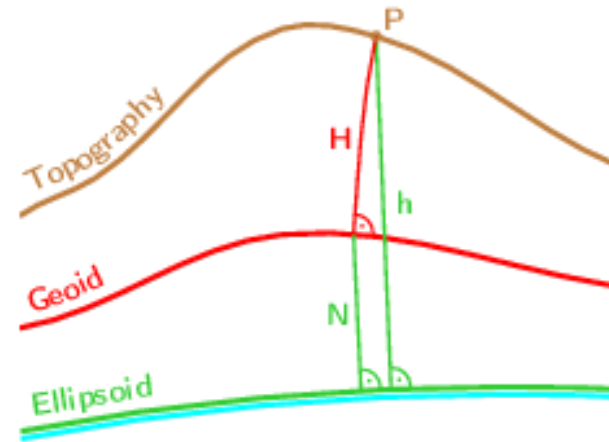
Quito, Ecuador, November 16 - 18, 2016



Motivation

1) Vertical coordinates used in practice:

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



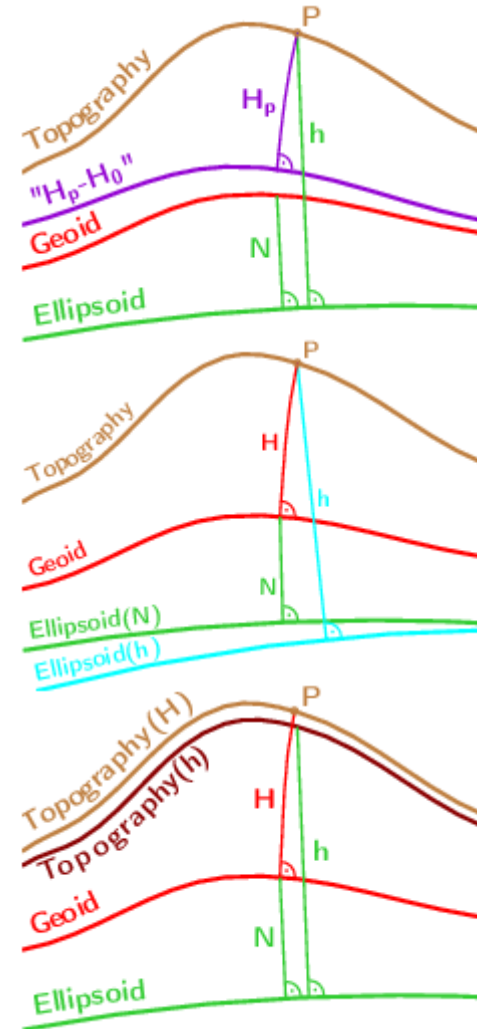
2) Everyone using GNSS positioning and requiring physical heights demands

$$H = h - N$$

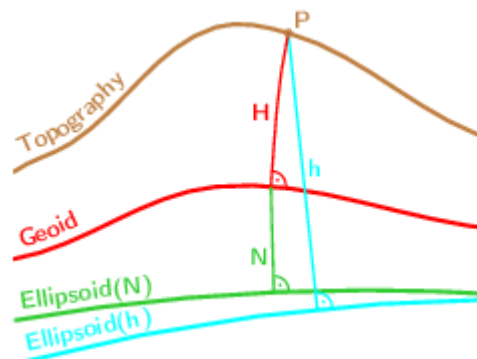
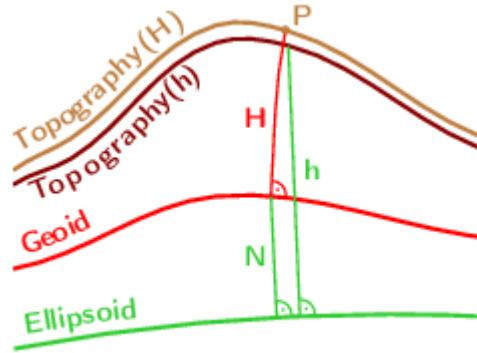
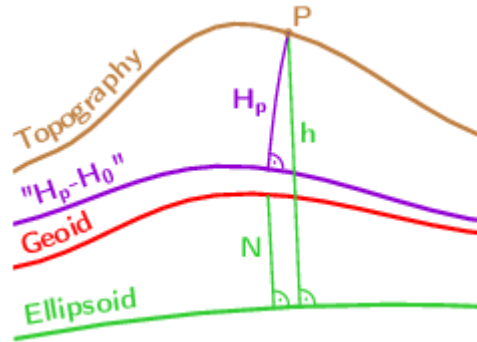
with consistency at the cm-level and worldwide.

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

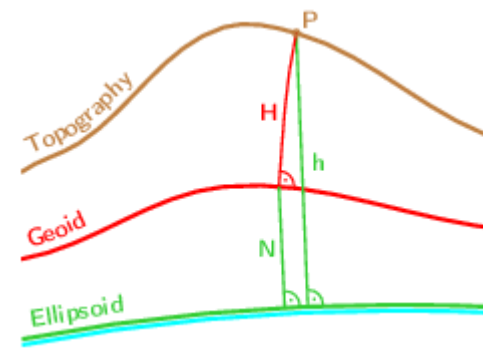
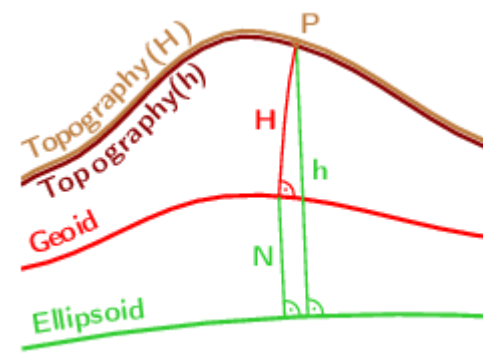
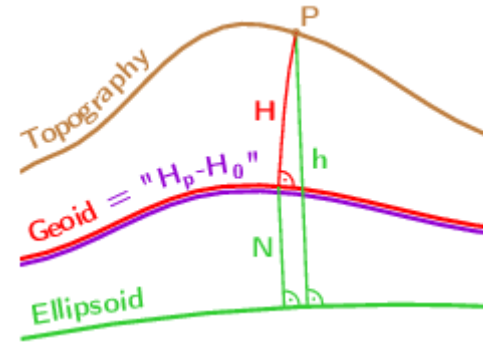
- Physical heights H usually refer to different local vertical reference levels (more than 100 worldwide).
- Different ellipsoid parameters (a , GM) are used in geometry and gravity.
- H and h are given in different reference epochs (usually dH/dt is unknown).
- Different solid Earth tide systems for 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.).
- ...



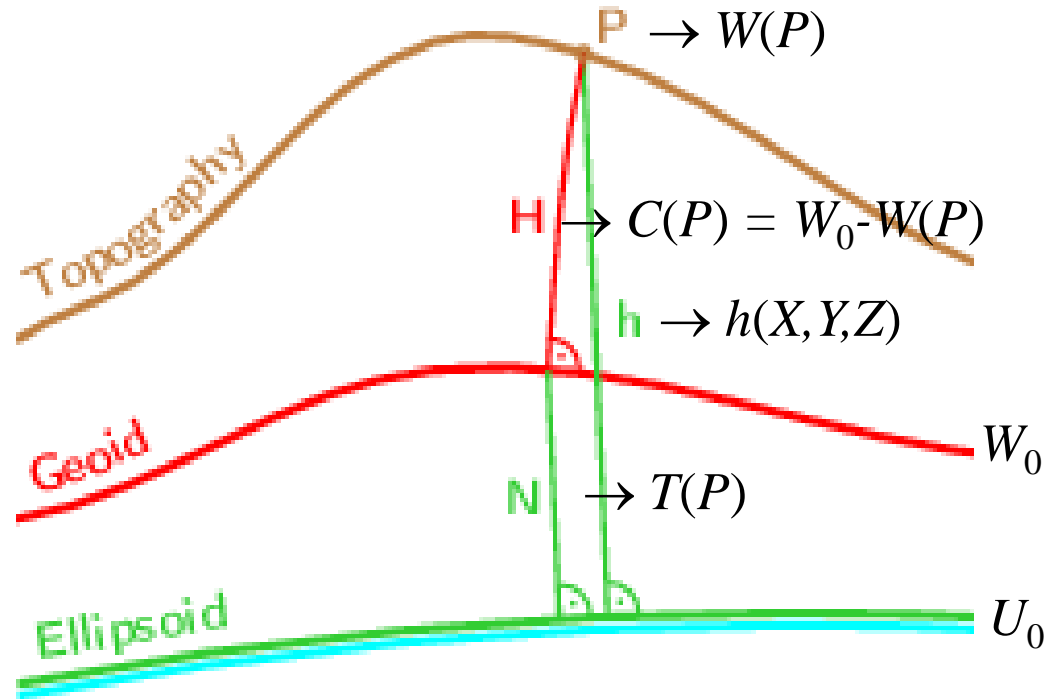
A global unified height system is needed to ensure consistency between h , H , N , worldwide and at the cm-level



- 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 (IHR)

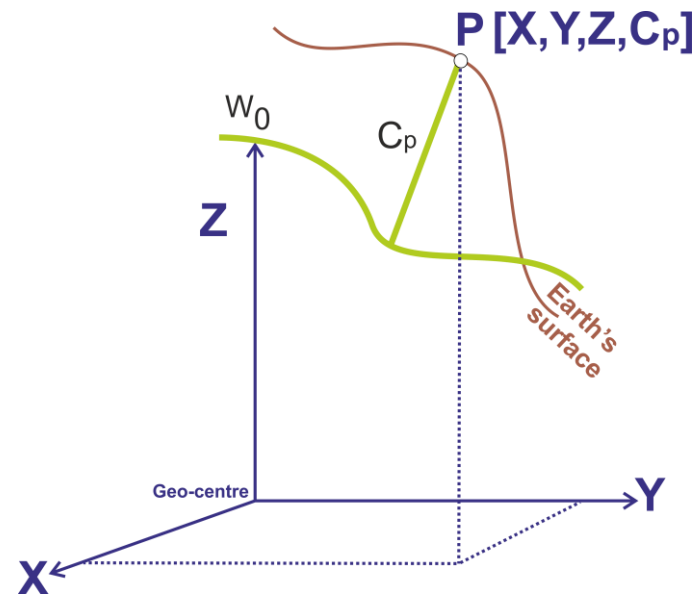
IAIG Resolution No. 1, Prague, July 2015

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

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 IHR 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.

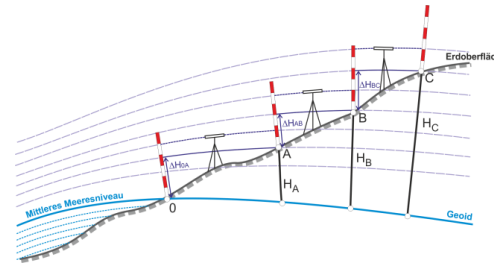
Immediate objectives regarding the IHRS:

- 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: $\sim 3 \times 10^{-2} \text{ m}^2\text{s}^{-2}$ (about 3 mm). Velocities: $\sim 3 \times 10^{-3} \text{ m}^2\text{s}^{-2}$ (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

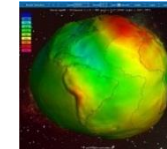
1) Levelling + Gravimetry:

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



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

$$W_P = f(X_P, GGM)$$



3) High-resolution gravity field modelling:

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

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)



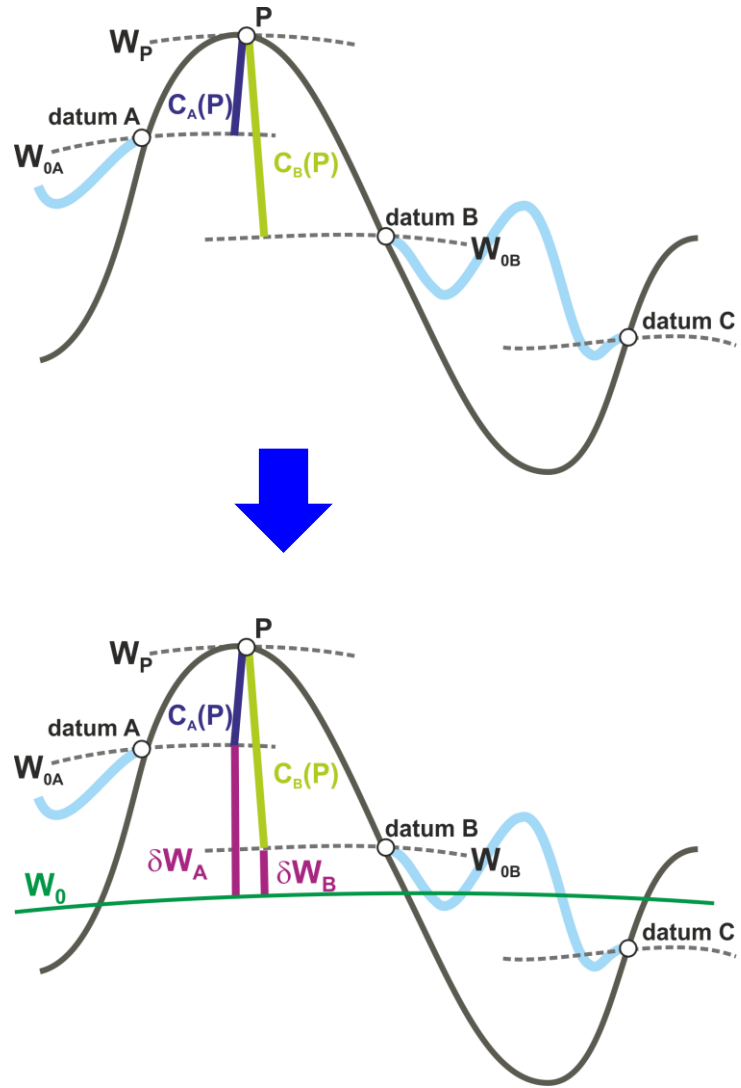
High-resolution gravity field modelling:
 Stokes or Molodensky approach
 Satellite altimetry (oceans only)
 Gravimetry, astro-geodetic methods, levelling, etc.
 Terrain effects

1) W_P from Levelling + Gravimetry

- Refer to **local vertical datums** with unknown potential value $W_{0,local} = ?$
- To determine W_P , it is necessary to estimate the **level difference** between the global W_0 and the local $W_{0,local} \rightarrow \delta W = W_0 - W_{0i}$

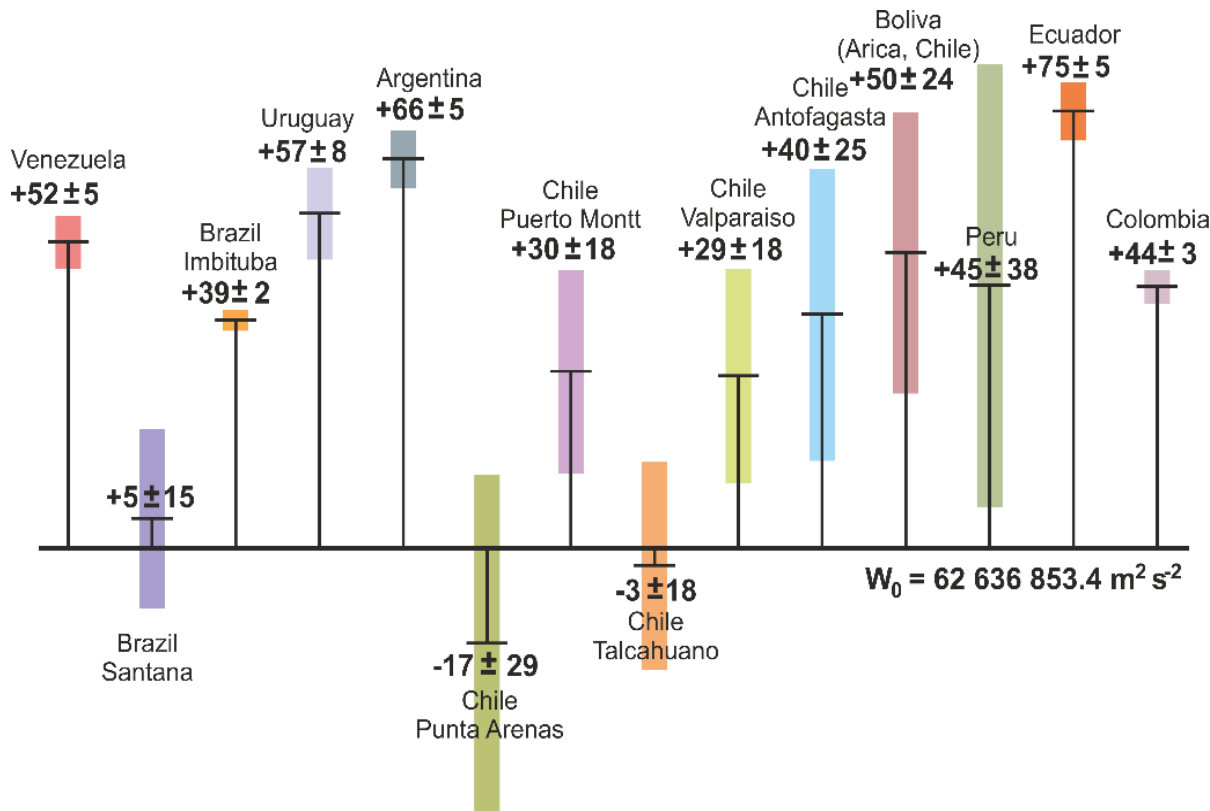
$$W_P = (W_{0,local} + \delta W) - C_P;$$

- 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.



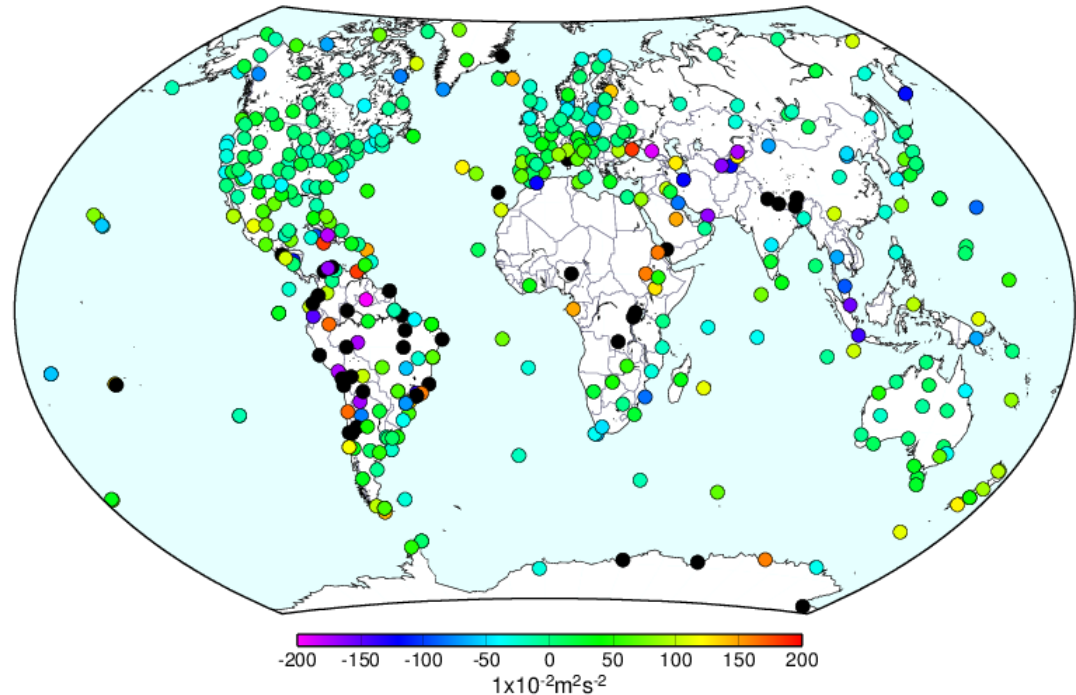
➤ This strategy is needed to integrate the existing height systems into the IHRs, but its accuracy is not enough for establishing the core network of the IHRs realisation.

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 $\pm 200 \times 10^{-2} \text{ m}^2\text{s}^{-2}$ (up to $\pm 20 \text{ m}^2\text{s}^{-2}$)
- Desired accuracy for W_P : $\pm 3 \times 10^{-2} \text{ m}^2\text{s}^{-2}$



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 IHR

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

Satellite-only gravity field modelling:
Satellite orbits and gradiometry analysis

Satellite tracking from ground stations (SLR)
Satellite-to-satellite tracking (CHAMP, GRACE)
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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

$$W_P = U_P + T_P$$



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

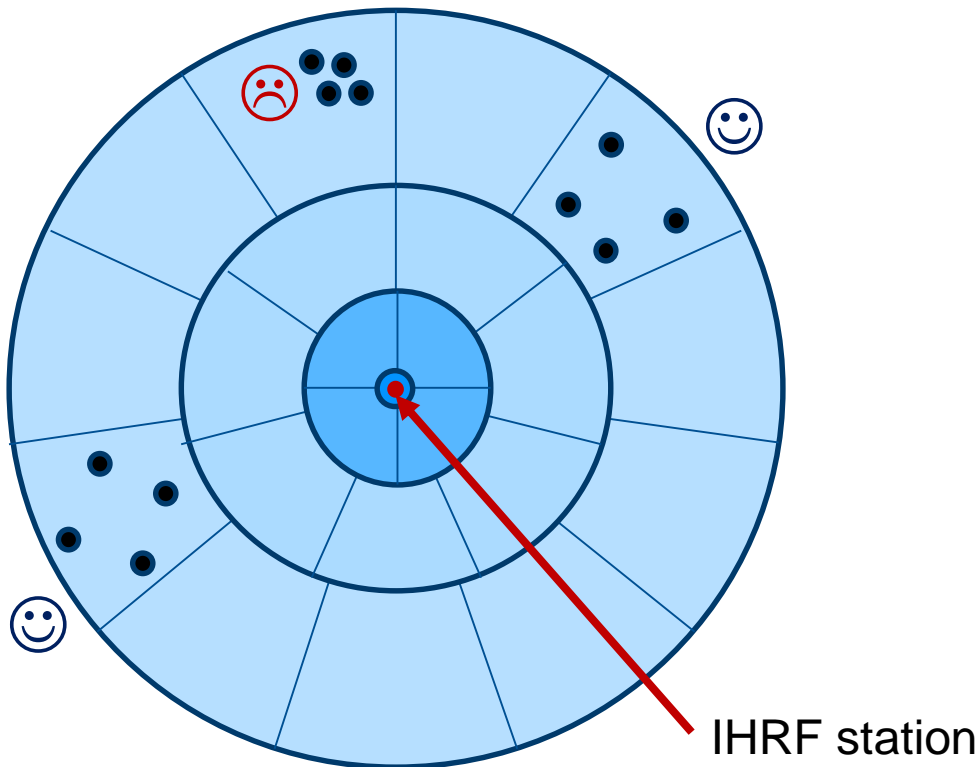
One GGM

Terrestrial
gravity
data

One DTM

Requirements on the terrestrial gravity data

- Homogeneously distributed gravity points around the IHRF reference stations up to 210 km ($\sim 2^\circ$). The gravity data may exist or have to be observed.
- Minimum accuracy of the gravity values: $\pm 20 \mu\text{Gal}$.
- Gravity point positions with GPS.
- In mountain areas $\sim 50\%$ more gravity points.
- Uncertainties of GGM and DTM must be added.



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

Distance	Compart ments	# 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:

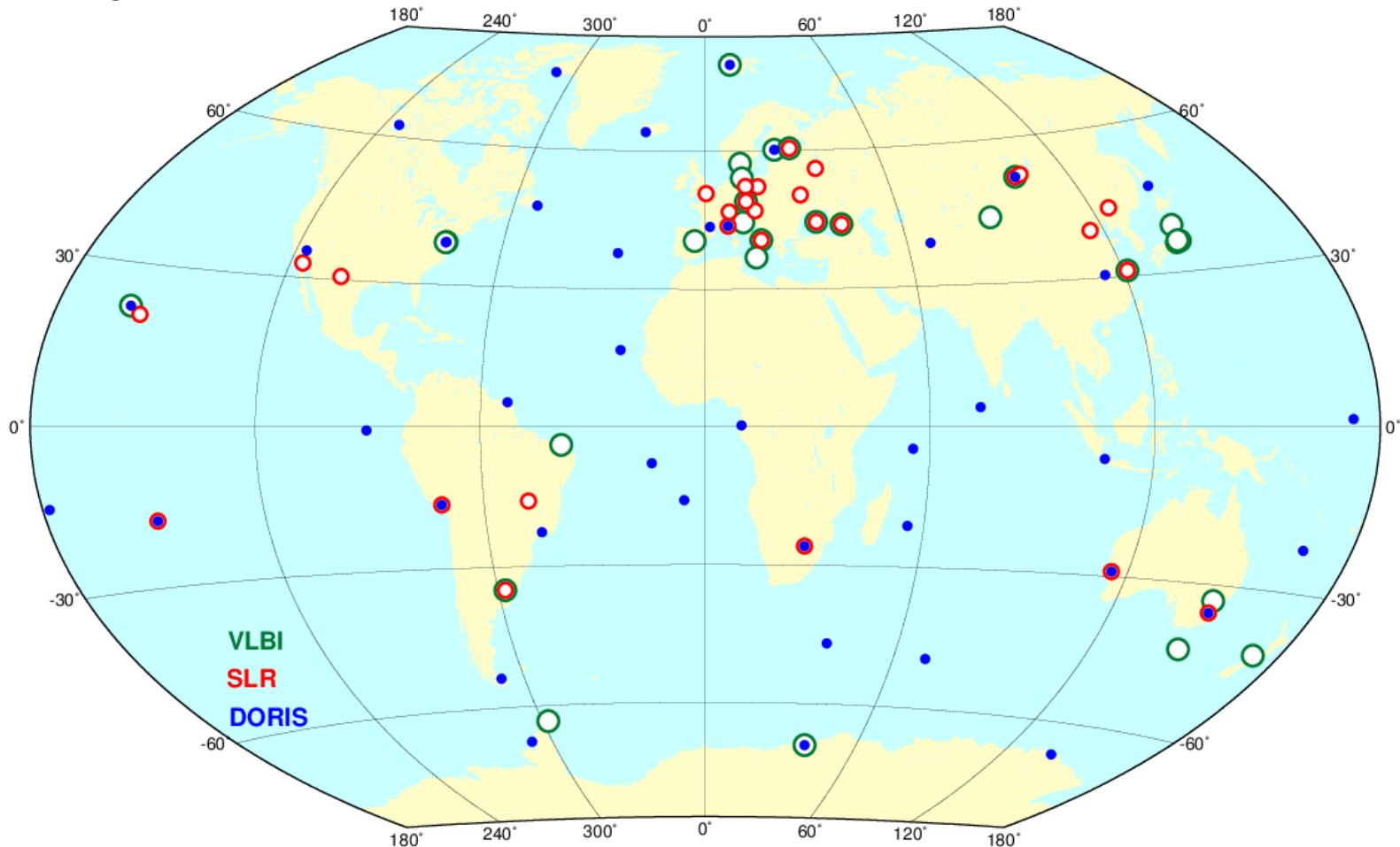
- A **global network** → worldwide distribution, including
- A **core network** → to ensure perdurability and long term stability
- **Regional and national densifications** → local accessibility

2) Collocated with:

- fundamental **geodetic observatories** → connection between \mathbf{X} , W , 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



Selection of possible IHRF reference stations

- 1) Geodetic observatories (GGOS core stations).
- 2) Existing VLBI stations collocated with GPS.
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In progress (expected to be ready by the end of the year):

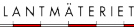
- 1) Tide gauges connected to the vertical networks (in coordination with TIGA).
- 2) Reference stations of the new Global Absolute Gravity Reference System (in coordination with H. Wziontek).
- 3) Densification with continuously operating GNSS stations in cooperation with the regional IAG sub-commissions (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 IHRIS/IHRF

1) Establishment of IHRIS stations in the SIRGAS region

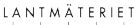
- To select some (1 to 5) continuously operating SIRGAS reference stations in each country (well distributed and materialized by a monument on the ground; stations on the top of buildings are not welcome).
- To survey gravity data around the selected SIRGAS reference stations (about 150 gravity points well distributed around each station up to a distance of about 200 km).
- Coordinates of gravity points determined with GNSS positioning (± 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 IHRIS/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 IHRIS/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 requirements 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 \(IHRF\)](http://ihrs.dgfi.tum.de), more information at <http://ihrs.dgfi.tum.de>

