Unification of height systems in the frame of GGOS

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Motivation

GGOS requires *a global gravity field-related height frame* with

- an *order of accuracy higher* than the magnitude of the phenomena 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 *existing height systems* exhibit

- more than *100 realizations* with *discrepancies up to dm ... m*;
- *static heights* $\rightarrow \dot{H} \equiv 0$ and *imprecise combination* with geometric heights $\left| h - H - N \right| \rightarrow \gg 0$;
- *1 ... 2 order of accuracy less* than the ITRS/ITRF coordinates.

However, these heights systems

- are the *reference* for the heights determined *in the last 150 years*;
- provide a *higher accuracy in contiguous areas* than the combination of ellipsoidal heights with (quasi-)geoid models, i.e. *H=h-N*.

If these systems are integrated into the global height system, *the existing vertical data can be updated and be useful for GGOS*.

Basics to establish a global vertical reference system

Main requirement: consistent combination of ellipsoidal and physical heights
$h - H^N - \zeta \approx h - H - N \rightarrow 0$ with high accuracy (mm ... cm) worldwide

Geometrical component

Definition:

Coordinates: $h(\mathbf{X}, t); dh(\mathbf{X})/dt$

Reference level: $U_0 = U(\mathbf{X}) = const.$

Realization:

1) referred to the ITRS/ITRF
2) conventional ellipsoid

Alignment of standards and conventions to guarantee the consistency between physical and geometrical parameters.

Physical component

Definition:

Coordinates: $C(\mathbf{X}, t) = W_0 - W(\mathbf{X}, t); dC(\mathbf{X})/dt$

Reference level: $W(\mathbf{X}) = W_0 = const.$

Realization:

1) Adoption of a suitable W_0 value;
2) Realization of the reference surface defined by W_0 (i.e. geoid modelling);
3) Connection of the local reference levels with the global one $\delta W_0^i = W_0 - W_0^i$ (i.e. vertical datum unification based on geopotential numbers);
4) Conversion into physical heights (H, H^N, ...)

Remarks on the vertical reference level W_0

- It is to be *defined arbitrarily by convention* (like any reference system);
- Basic convention:
  1) *Reference level*: potential value W_0 defining *the scale* of the global zero-height surface;
  2) *Reference surface*: realization (geometric description) of the surface with the potential value W_0 (e.g. *geoid computation*);
- To get consistency between definition (W_0) and realization (geoid modelling), *W_0 shall be estimated from the same observations applied for the geoid modelling*;
  1) *Global reference level* W_0: by solving the *fixed GBVP on ocean areas*
  2) *Local reference levels* W_0^i: by solving the *Molodenskii scalar-free GBVP on land areas* (vertical datum unification)
- Most appropriate W_0 value according to the *GGOS Working Group on Vertical Datum Standardization*:

$$W_0 = 62\,636\,853{,}4 \text{ m}^2\text{s}^{-2}$$

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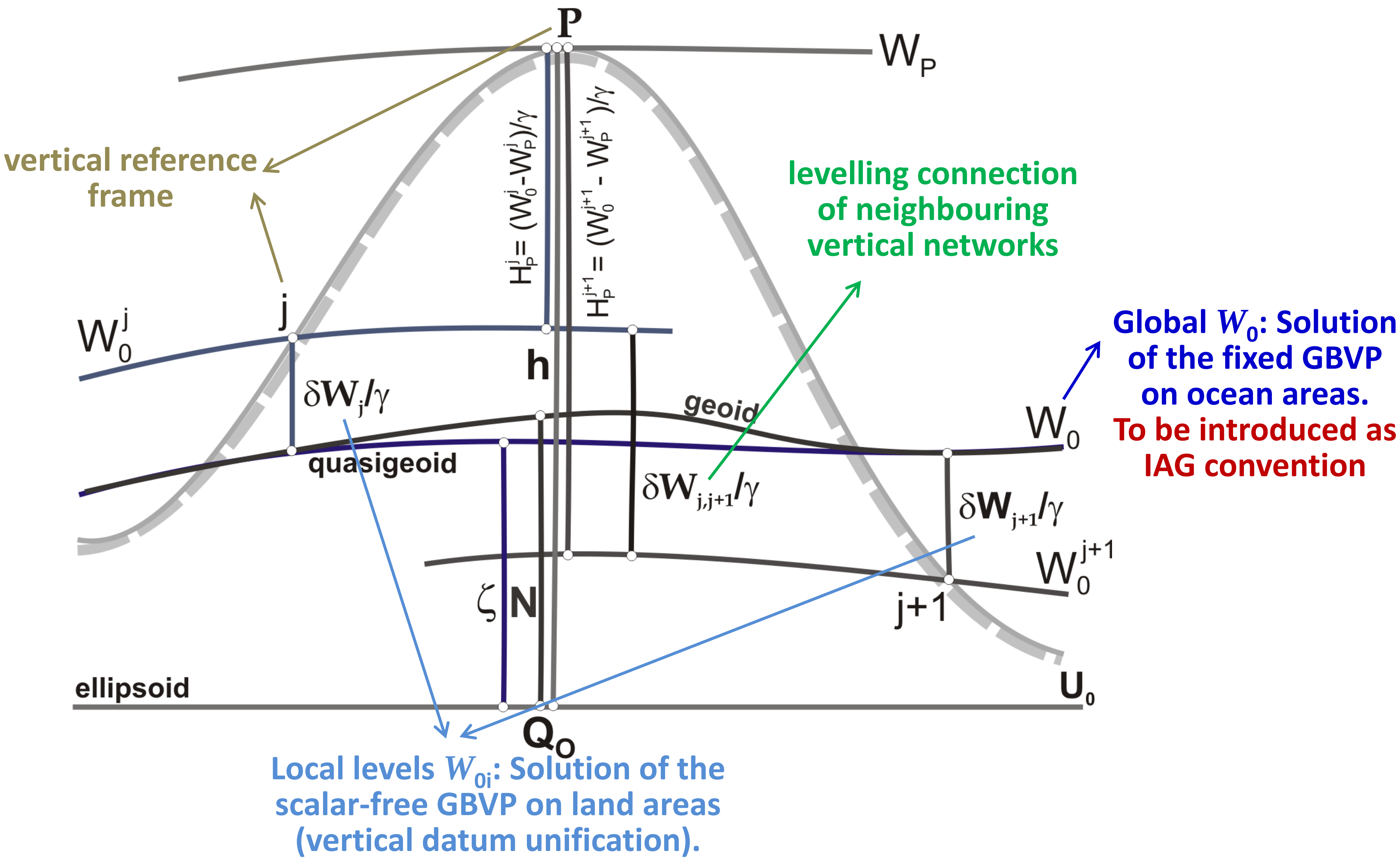
Remarks on the vertical reference level W_0



Realization in practice: vertical reference frame

- Like the ITRF: A *global network* with *regional/national densifications*.
- This network shall include:
  1) *reference tide gauges* (local vertical datum points);
  2) main *nodal points of the levelling networks*;
  3) geometrical reference stations (*ITRF* and densifications);
  4) fundamental *geodetic observatories* (connection between W_0 and TAI).
- These stations must be:
  1) *continuously monitored* to detect deformations of the reference frame;
  2) *referred to the ITRS/ITRF* to precisely know their geometric coordinates;
  3) *connected by levelling with the local vertical datum* to precisely know their local geopotential numbers.

Observation equations for the vertical datum unification

(after Rummel und Teunissen 1988, Heck and Rummel 1990)

- at border points connecting neighbouring vertical datum zones:

$$H^{N,i+1}(P) - H^{N,i}(P) = q\left(\delta W_0^{i+1} - \delta W_0^{i}\right)$$

- at tide gauges, levelling nodes, geometric reference stations

$$h(P) - H^{N,i}(P) - q\Delta W_0 - E\big(\zeta(P)\big) = e^{i}(P)\,\delta W_0^{i} + \sum_{\substack{j=1 \\ i\neq j}}^{J} f_0^{\,j}(P)\,\delta W_0^{\,j}(P)$$

$$\Delta W_0 = W_0 - U_0$$

GNSS positioning on land and satellite altimetry on sea areas around tide gauges ($h(P)$)

heights from geop. numbers on land and sea surface topography around tide gauges ($H^{N,i}(P)$)

height anomalies from GBVP [GGM (n=200) + terrestrial gravity + terrain models] ($E(\zeta(P))$)

vertical datum discrepancies (to be determined) (δW_0^{i})

indirect effects (negligible) ($\sum f_0^{\,j}(P)\,\delta W_0^{\,j}(P)$)

$$q := -\frac{1}{\gamma}, \quad e^{i}(P) := -q + f_0^{i}(P), \quad f_0^{i}(P) := \frac{1}{2\pi\gamma}\iint_{\sigma_i} S\left(\psi_{P,P_k}\right) d\sigma$$

Example: a global vertical reference frame with regional densifications (e. g. South America)

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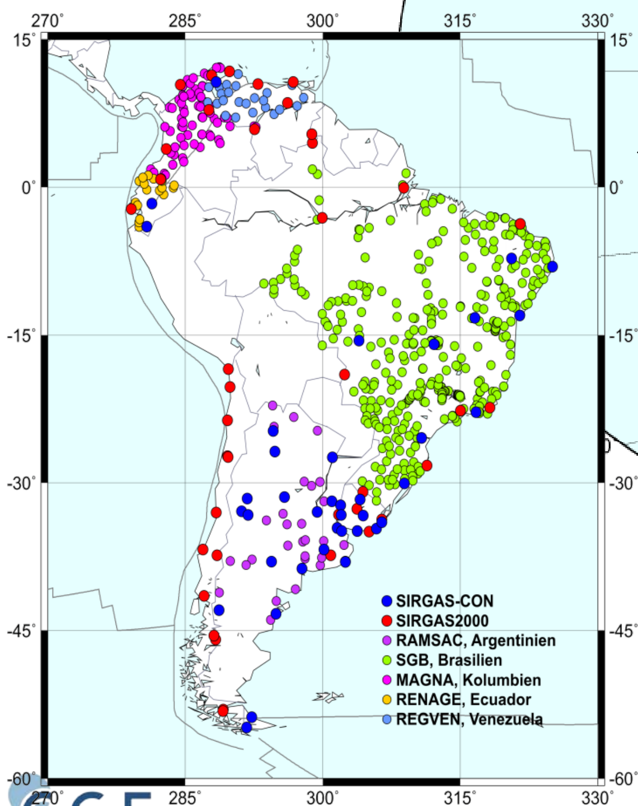
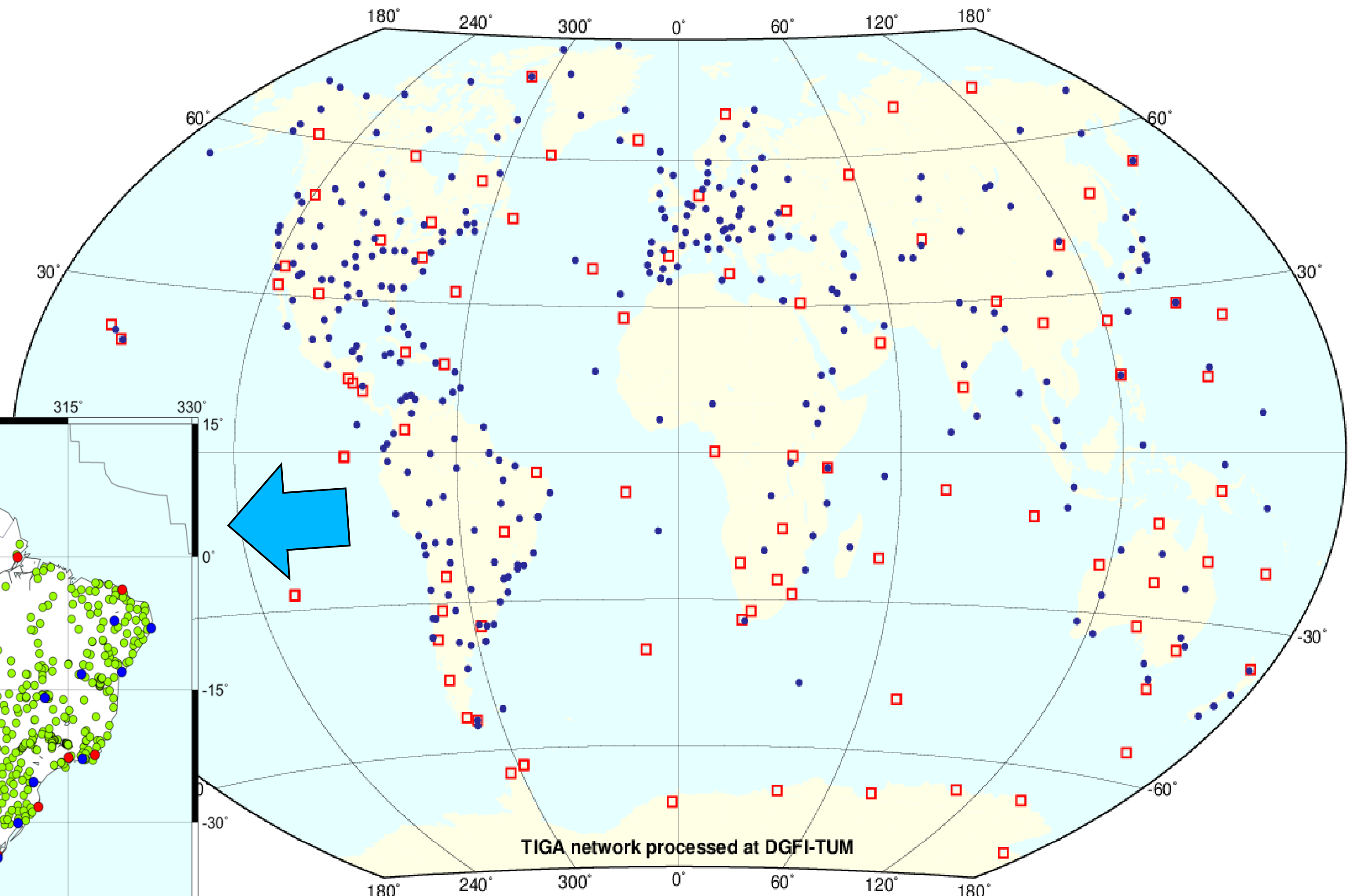
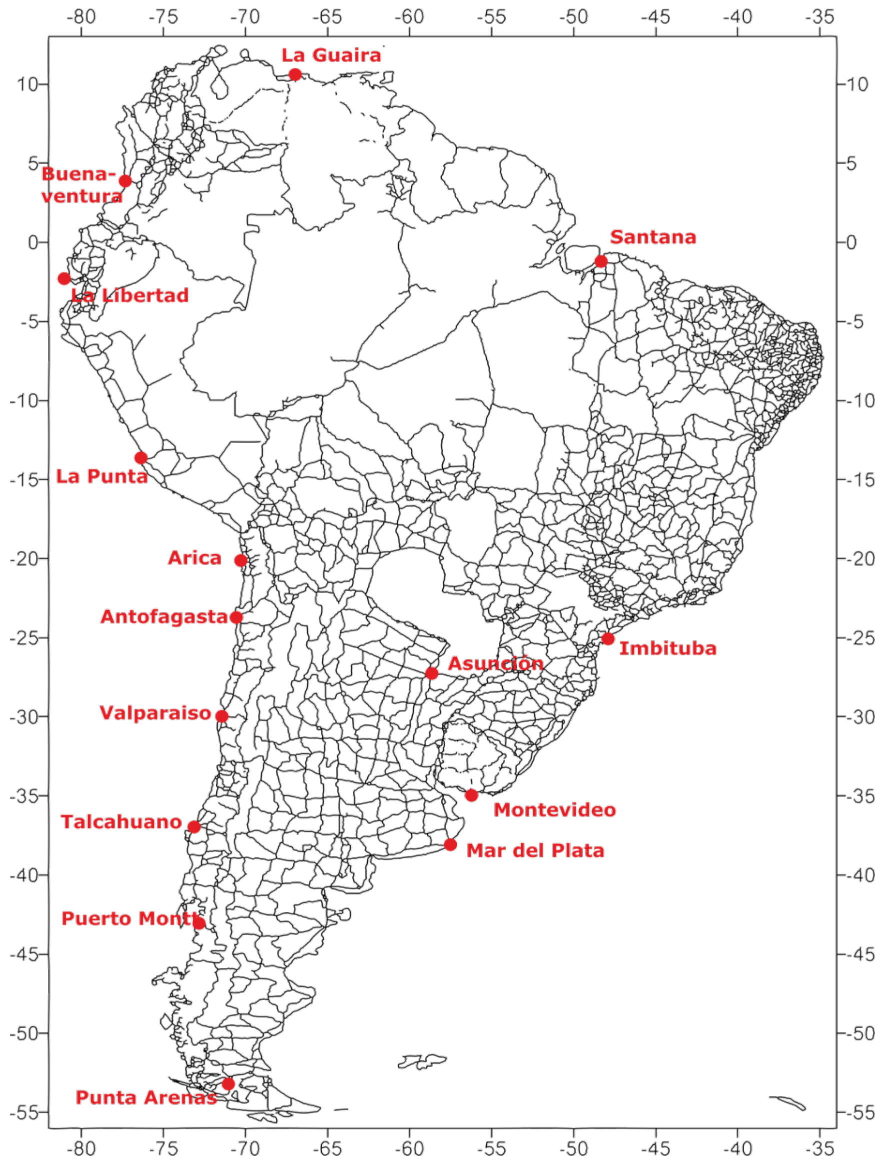




Example: vertical datum unification in South America

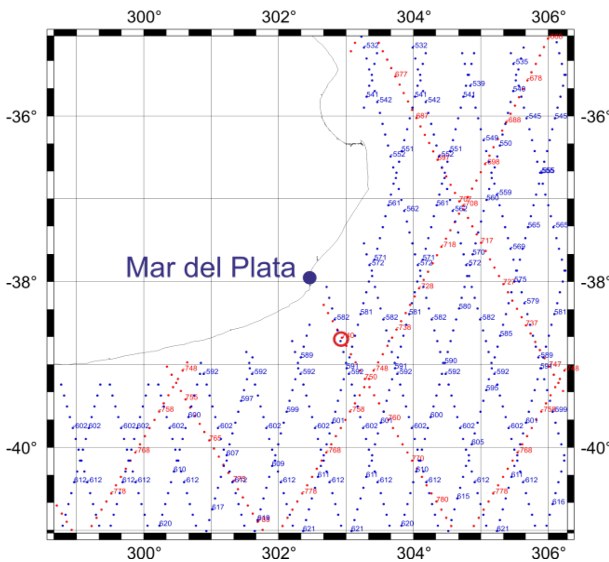


Existing height systems

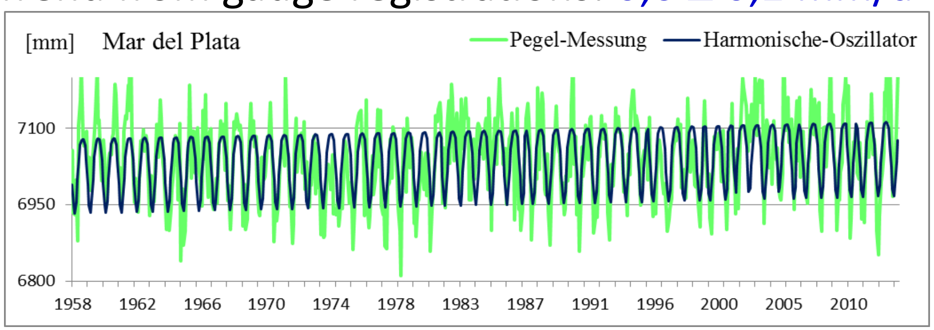
- *15 reference tide gauges*;
- mean sea surface level referred to a *different epochs* (some unknown);
- Levelling *since ~1940* with *dH/dt = 0*;
- in general *no gravity reductions applied*;
- *no common adjustment*;
- First and second order levelling networks comprise more than *360 000 km* and *200 000 bench marks*.

Example: vertical datum unification in South America

Trend from satellite altimetry: 2,4 ± 0,8 mm/a



Trend from gauge registrations: 0,6 ± 0,2 mm/a



Trend from GPS: 2,2 ± 2,2 mm/a

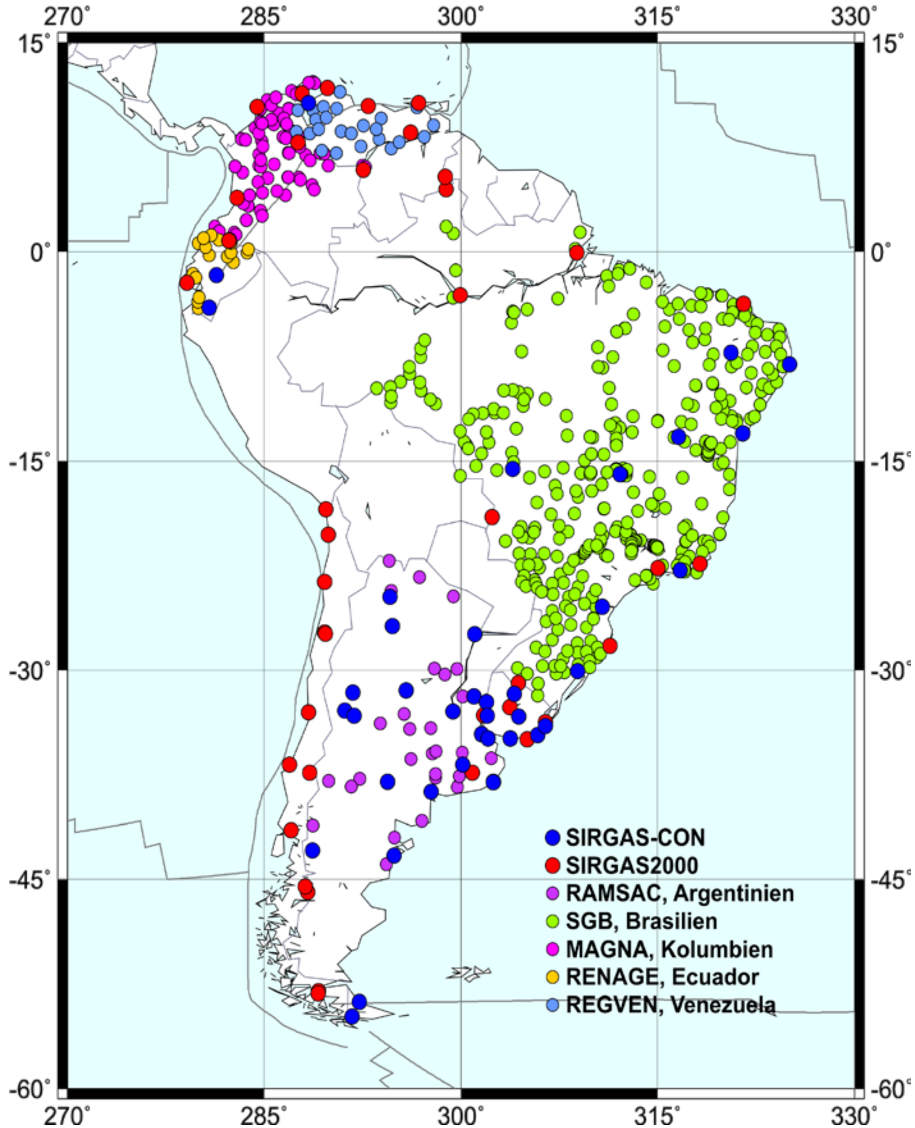
→ Discrepancy: 2,4 – (2,2 + 0,6) = 0,8 mm/a

Geometric heights in sea areas around tide gauges

- mean sea surface heights from satellite altimetry (OpenADB);
- Tide gauge registrations from PSMSL;
- GNSS positioning at tide gauges.
- *Data standardization* (TIGA objectives):
  - Determination of *vertical trends* from satellite altimetry, tide gauge registrations, and GPS;
  - It is assumed that the trends $(dh/dt)_{Altimetry} = (dh/dt)_{(Gauge + GPS)}$
  - Reduction of the reference sea levels to a common *epoch (2005.0)*.

OpenADB: Open altimetry database @ DGFI-TUM
PSMSL: Permanent Service for Mean Sea Level

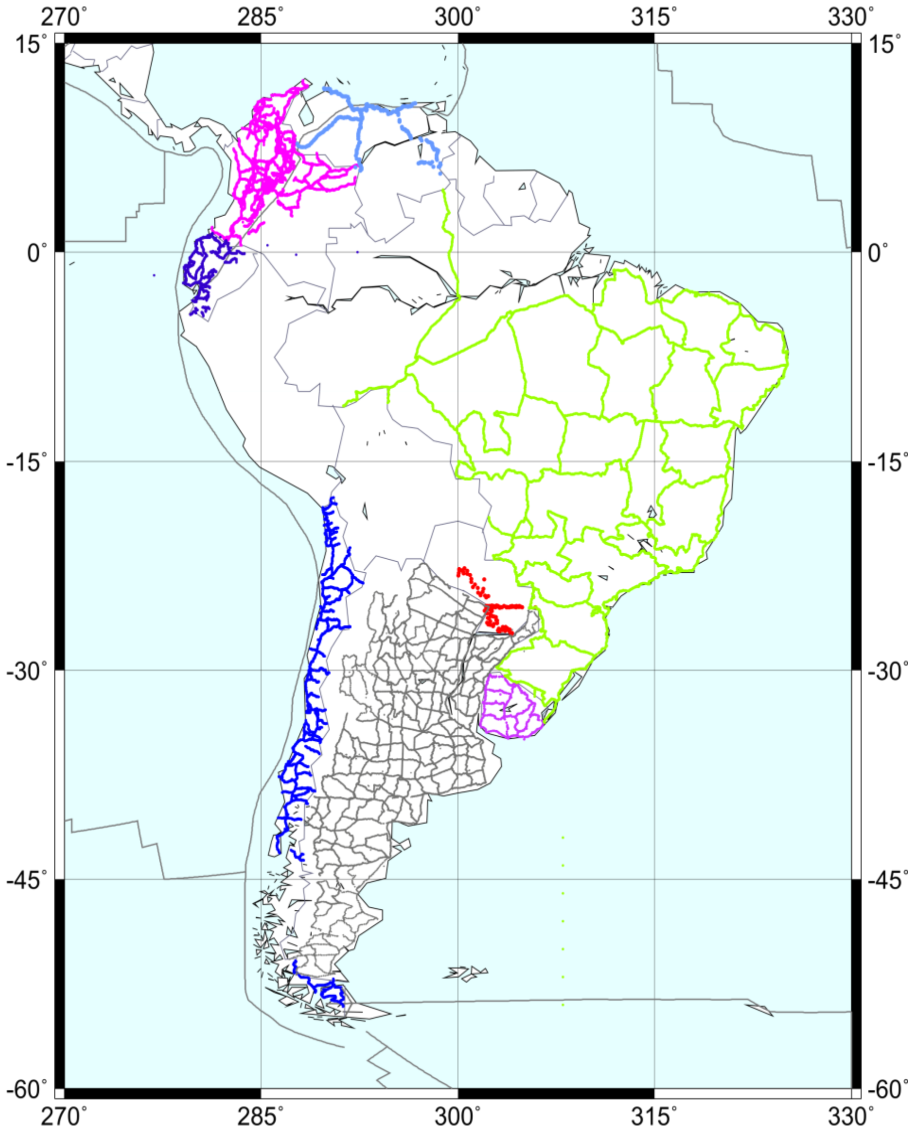
Example: vertical datum unification in South America



Geometrical heights on land areas

- Reference stations (663):
  ITRF stations (10) +
  SIRGAS stations (74) +
  national densifications (579);
- Data standardization:
  - Transformation of previous ITRF solutions to the IGb08;
  - Stations positions given at a *common epoch (2005.0)* (with station velocities or a kinematics model - VEMOS);
  - Transformation *from conventional tide-free to zero-tide.*

Example: vertical datum unification in South America



Observed height differences

- Levelling lines provided by the countries
- Data standardization:
  - least squares adjustment country by country to build *free normal equations for each vertical datum zone*;
  - astronomical correction + indirect effect (levelling in *zero-tide system*);
  - *kinematic adjustment* assuming dH/dt ≈ dh/dt;
  - *combination of free normal equations* for countries with international levelling connections

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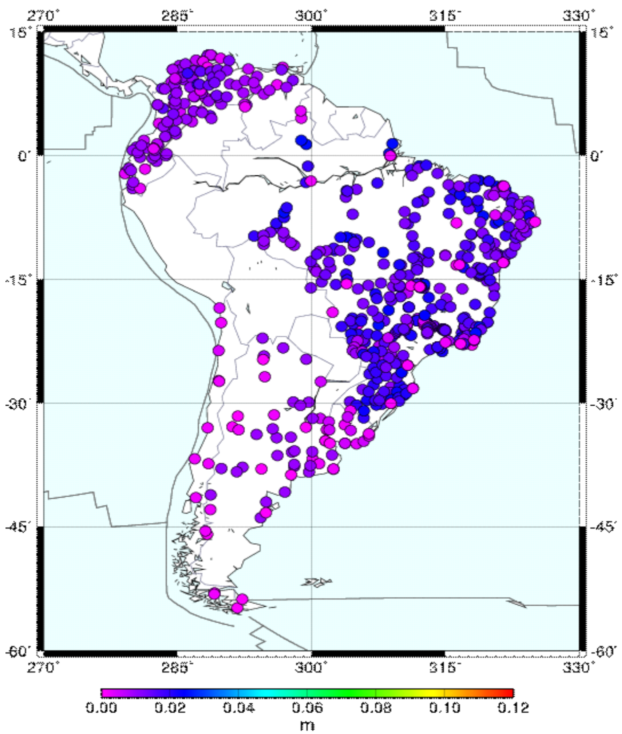
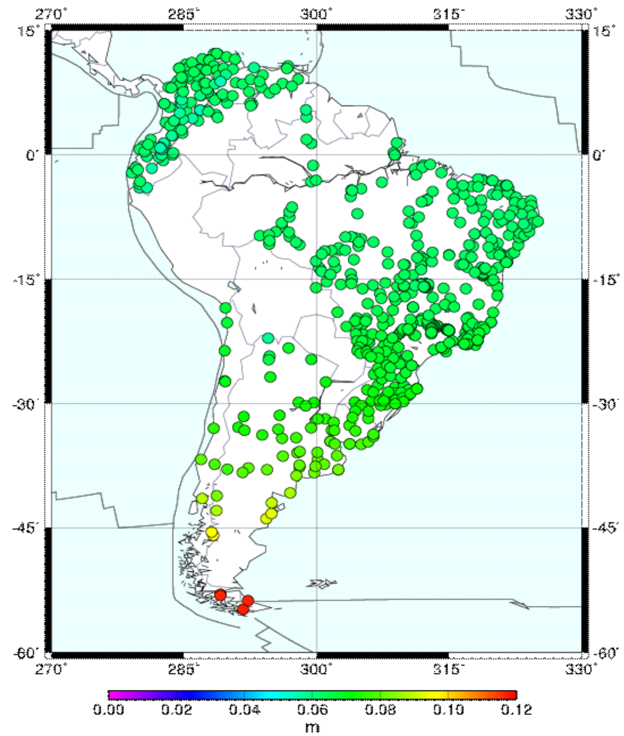
Example: vertical datum unification in South America

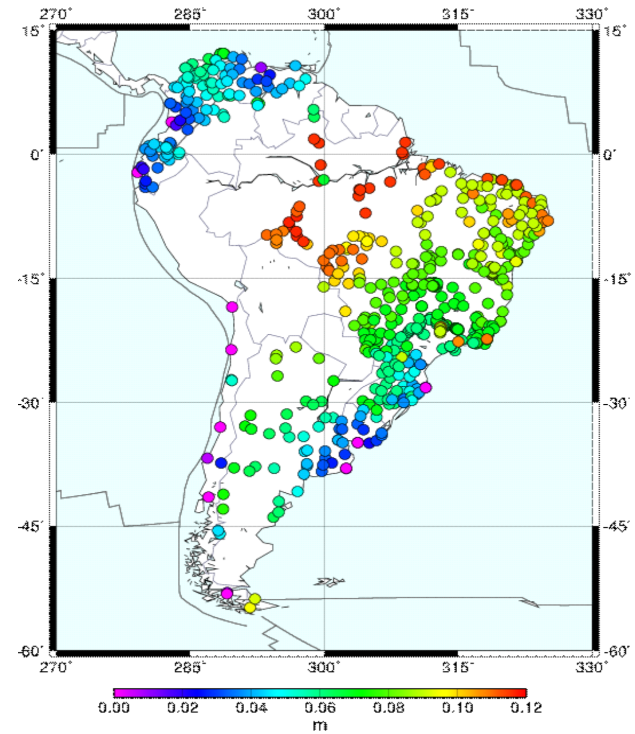
Uncertainty of the input data



Ellipsoidal heights



Height anomalies

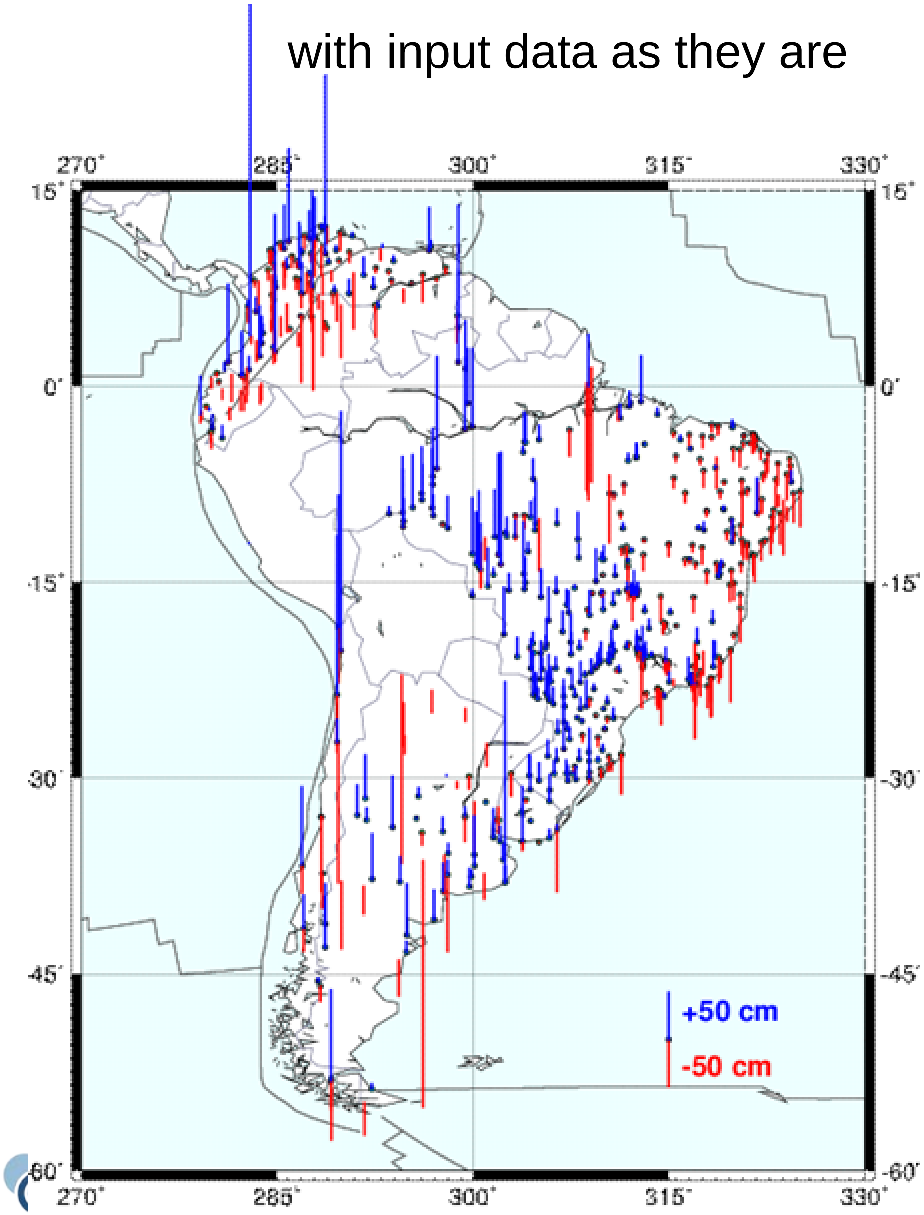


Normal heights

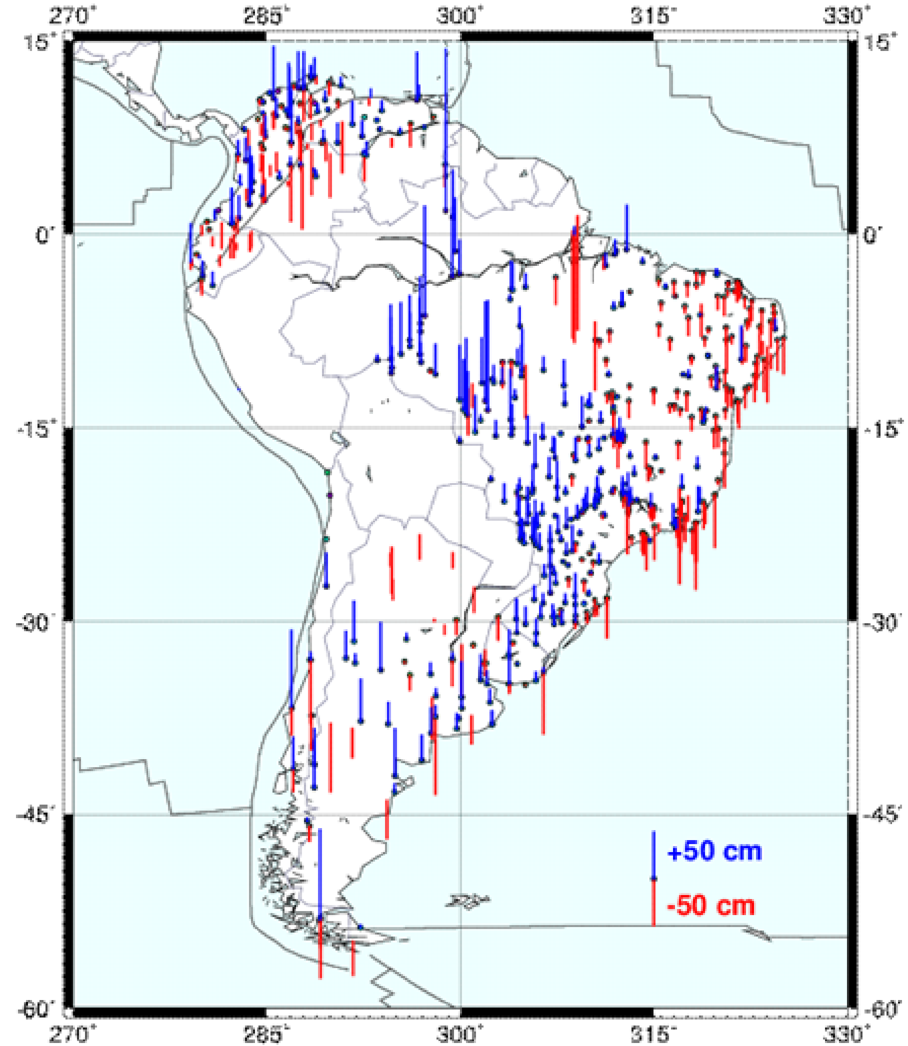
Example: vertical datum unification in South America

Residuals

with input data as they are

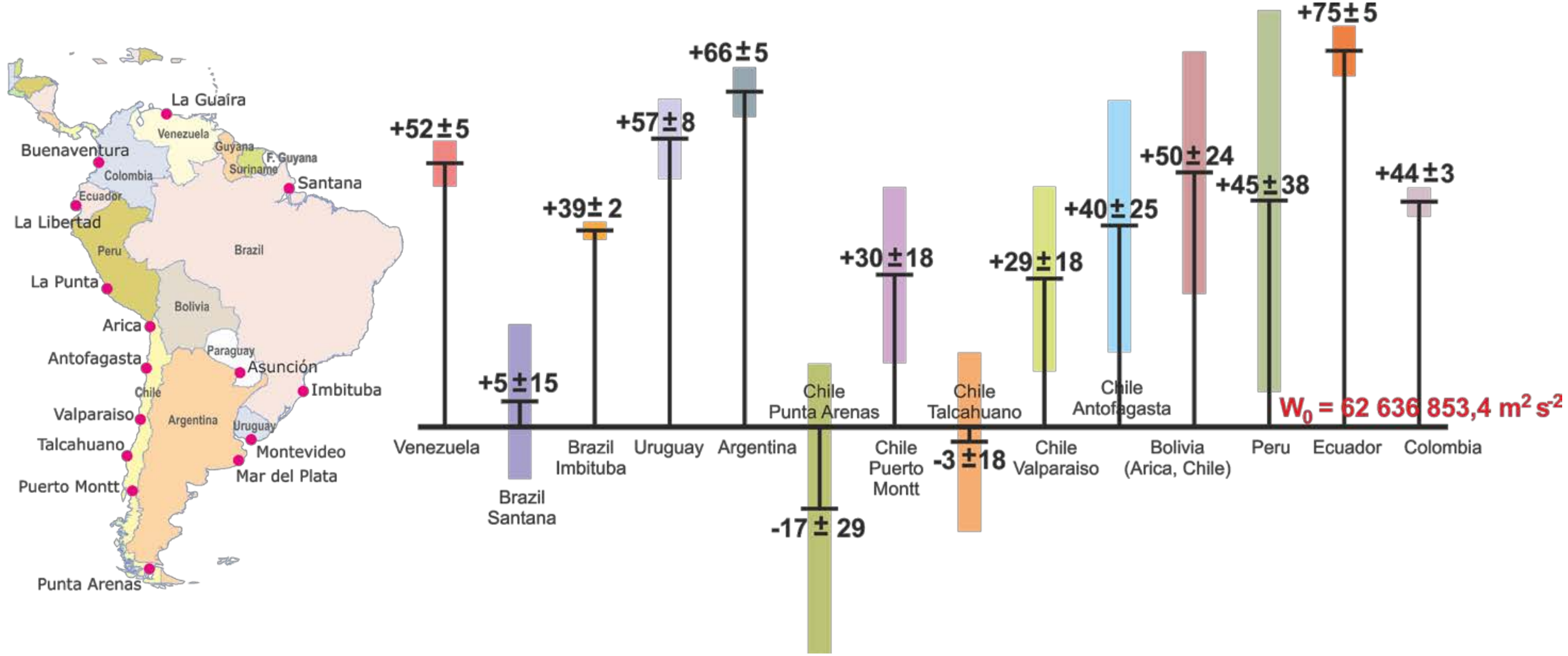


with input data standardized



Example: vertical datum unification in South America

Vertical datum parameters with respect to W_0= 62 636 853,4 m^2s^{-2}



- Uncertainty of about ±5 cm in those countries with *good data coverage*;
- Uncertainty of about ±20 ... 40 cm in those countries with poor data coverage (similar uncertainties have been found by other authors in other regions, e.g. Gruber et al. 2012 Rülke et al. 2014, Gerlach and Rummel 2013)

Closing remarks

- A global vertical reference system shall support the *unification of the existing height systems* in order *to be accepted and used worldwide*;
- The vertical datum unification requires essentially *levelling-based geopotential numbers* and *(quasi)-geoid models of high-resolution*;
- The precise combination of physical heights, ellipsoidal heights and (quasi-)geoid models requires *a standardization* of conventions, constants, and procedures (e.g. *tide system, reference epoch for vertical positions, etc.*).
- The establishment of a global unified vertical reference system of high-precision *is only possible under the umbrella of the IAG, GGOS and its services*.