# Definition and realisation of a global vertical reference system under the umbrella of the Global Geodetic Observing System - GGOS

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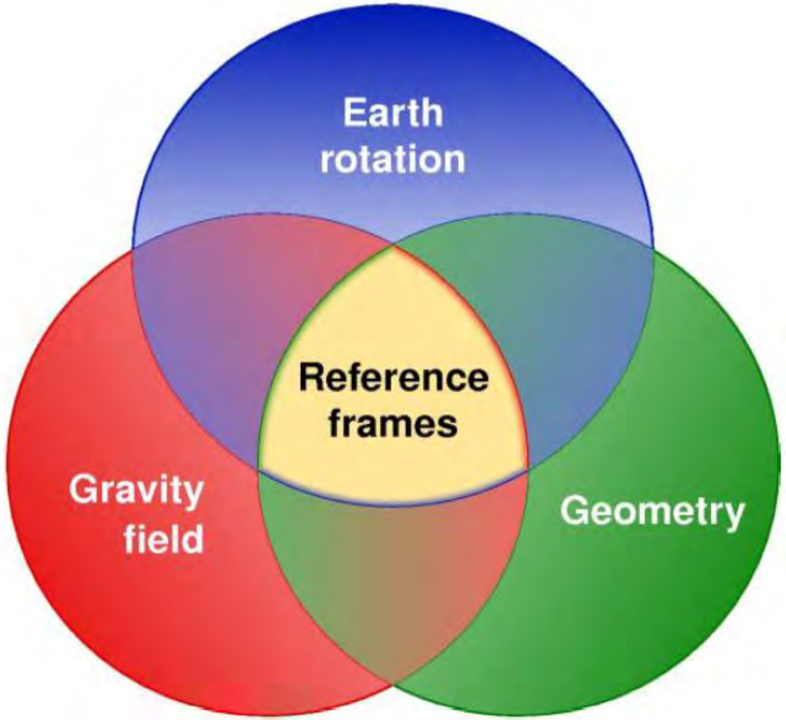
# GGOS: Global Geodetic Observing System

- GGOS is the contribution of Geodesy to a global Earth monitoring system;
- It was installed (2003) by the International Association of Geodesy (IAG) and participates in the Group on Earth Observation (GEO) and in the Global Earth Observation System of Systems (GEOSS).
- Main objectives:
  1) To provide the observations needed to monitor, map and understand changes in the Earth's shape, rotation and mass distribution;
  2) To provide the **global frame of reference** for measuring and consistently interpreting global change processes.



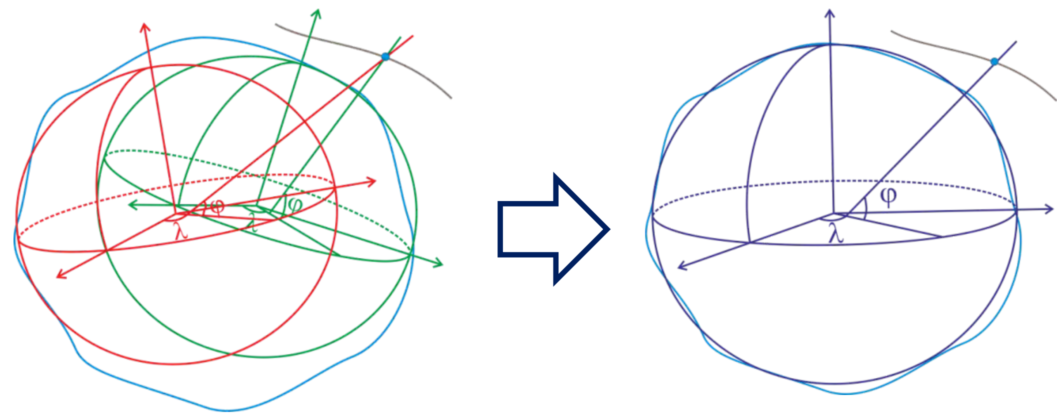

Integration of geometry, gravity field and Earth rotation, from Plag and Pearlman 2009

# Existing reference systems/frames



## In geometry

- **ITRS/ITRF**;
- Standardised realisation through IERS;
- Worldwide unified reference frame;
- Reliability in the cm-level.

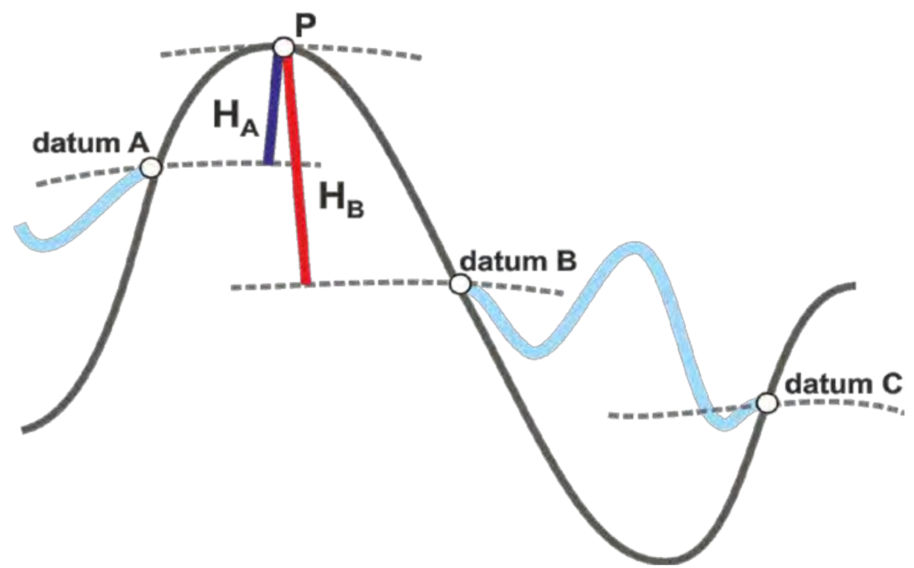


Before: many individual (local) horizontal reference systems

Today: one global unified geocentric reference system

## In gravity field-related height systems

- **Different reference levels** (many [dm] of discrepancy);
- **Different types of heights** (normal, orthometric, etc.);
- Omission of (sea and land) **vertical variations** with time;
- Imprecise combination of **h-H-N**

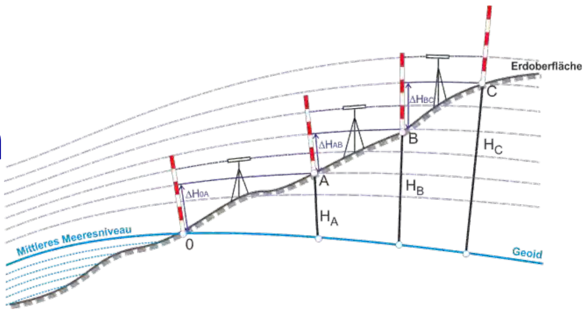


# New methods for height determination



**Today**

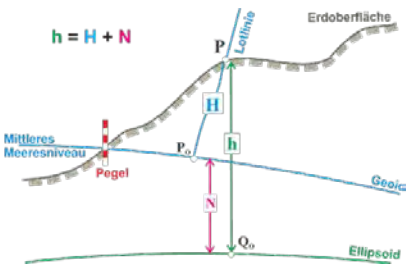
Levelling in combination with gravity reductions




$$C(g,dn) = W_0 - W_P = \int_0^P g\,\delta n \cong \sum_0^P g\,dn$$

**Desired**

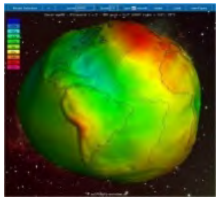
Disturbing potential in combination with a reference ellipsoid




$$C(U_0,T) = -(U_0 - W_0) + \bar{\gamma}(\varphi)h - T(\varphi,\lambda,h)$$

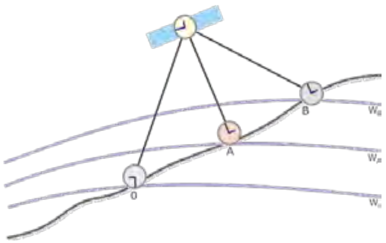
**In the future**

Global gravity field models in combination with ITRS/ITRF coordinates



$$C(\bar{C}_{nm},\bar{S}_{nm}) = W_0 - [V(r,\theta,\lambda) + Z(r,\theta)]$$

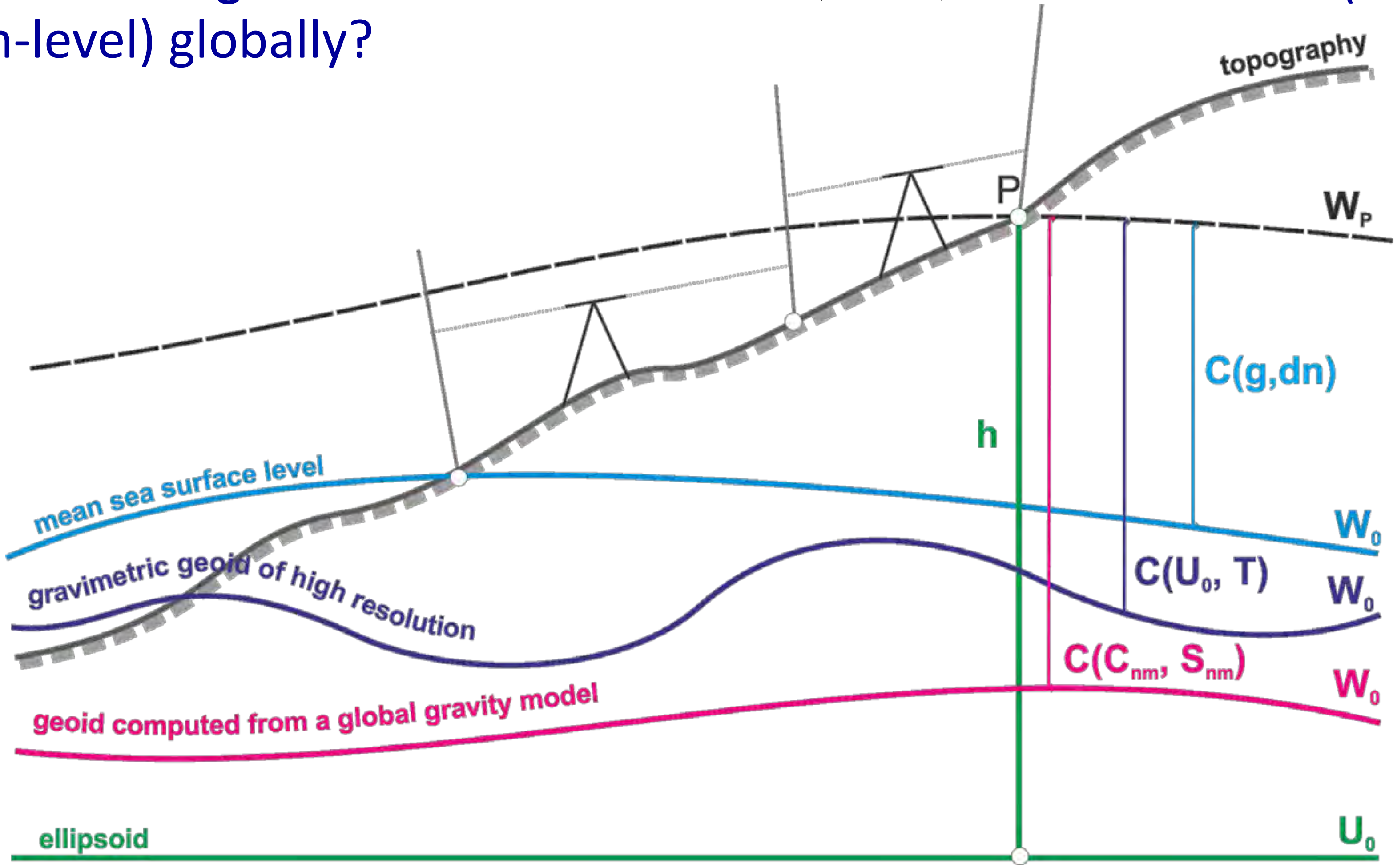
Comparison of clock frequencies of high-precision




$$C(f) = c^2\left(\frac{f - f_0}{f_0}\right)$$

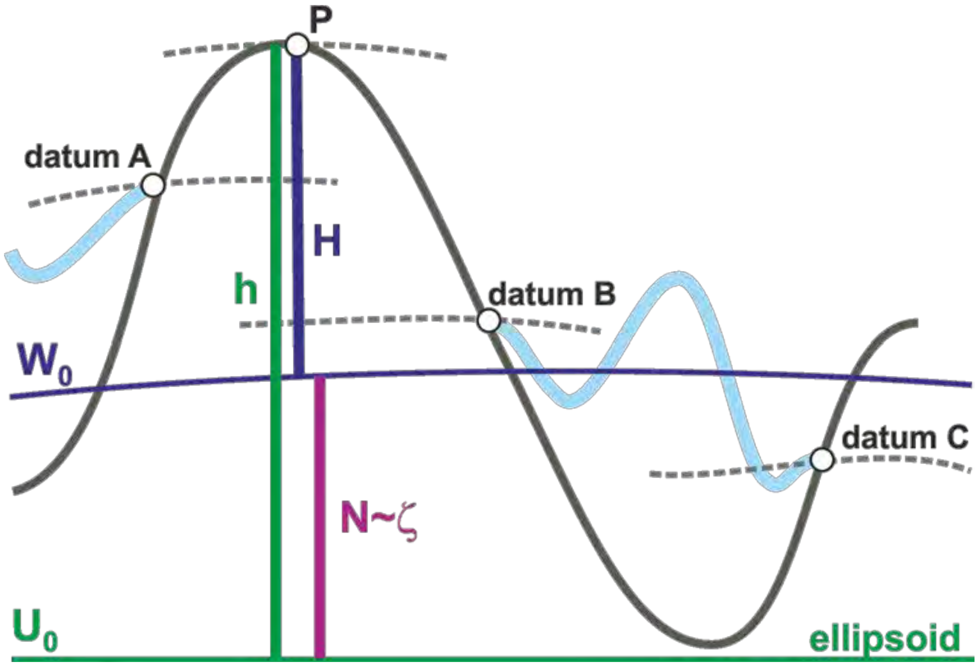
# Reference level depending on input data?

- Vertical coordinates from the different methods refer to different geoids.
- Discrepancies between those geoids can reach some metres (2m).
- How can we guarantee $C(g,dn) \approx C(U_0,T) \approx C(\overline{C}_{nm},\overline{S}_{nm}) \approx C(f)$ in cm-level (better in mm-level) globally?



# A global vertical reference system: a GGOS challenge






**Main objectives:**

- To solve **discrepancies** between the **existing height systems**;
- To support the **different** techniques for **height determination**;
- To guarantee the same accuracy everywhere and at any time.

**Implicit characteristics:**

- One reference level ($W_0$ or geoid) to be used globally;
- All existing geo-potential numbers (physical heights) referring to one and the same global level;
- Precise combination with geometric heights and geoid models of high resolution, i.e. h-H-N=0.

# Basic approach for the vertical datum unification globally



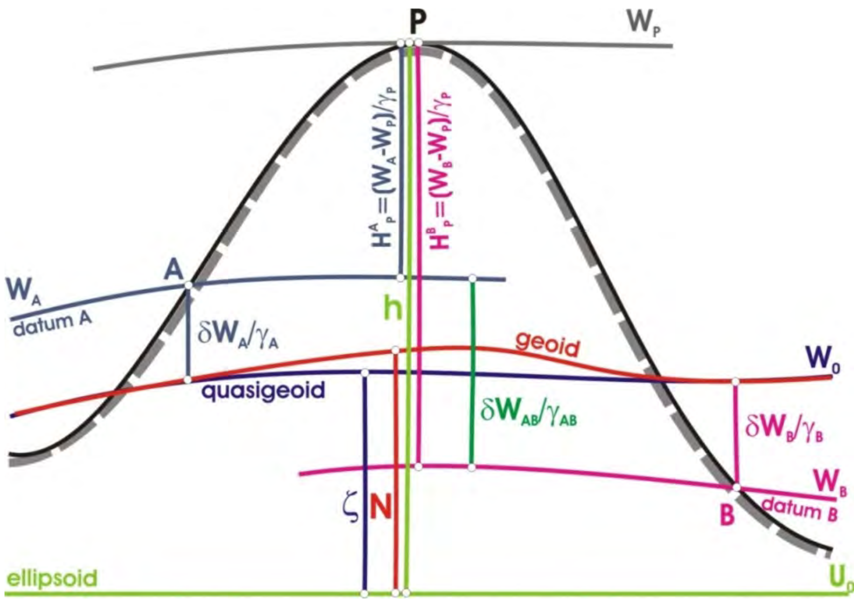
Geoid undulations $N$ (or height anomalies $\zeta$) can be computed in two ways:

- By comparing geometric heights $h$ with physical heights $H$ (derived from levelling + gravity)

$$N_j^{GNSS}(P) = h(P) - H_j(P)$$

- By solving the GBVP

$$N_j^{GBVP}(P) = -\frac{\Delta W_0}{\gamma} + \frac{\delta W_j}{\gamma} + \frac{R}{4\pi\gamma}\iint_\sigma \Delta g_j S(\psi)\,d\sigma + \frac{1}{2\pi\gamma}\iint_\sigma \delta W_j S(\psi)\,d\sigma$$




The comparison of these two estimates allows the formulation of the observation equation for the datum unification, e.g. between two neighbouring countries:

$$N_j^{GNSS}(P) - N_j^{GBVP}(P) = \frac{1}{\gamma}\Delta W_0 + \left(-\frac{1}{\gamma} + f_i\right)\delta W_j + \sum_{\substack{i=1\\ j\neq i}}^{I} f_i \delta W_i \quad ; \quad f_i := \frac{1}{2\pi\gamma}\iint_{\sigma_j} S(\psi)\,d\sigma$$

$$\delta W_j = W_0 - W_0^j \qquad \Delta W_0 = W_0 - U_0 \qquad \Delta W_0^j = W_0^j - U_0$$

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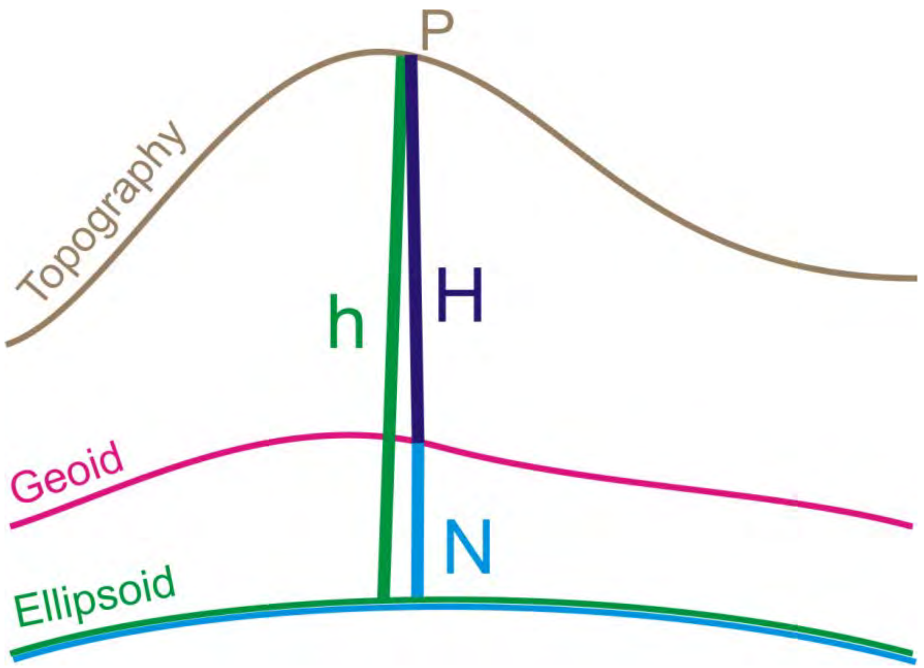
# How to bring h, N, H together consistently?



1) Ellipsoidal heights *h* and (quasi)geoid undulations *N* must be given w.r.t. the same ellipsoid:
   - [X, Y, Z] ⇔ [φ, λ, h]
   - Reference field (surface) for solving the GBVP and for scaling global gravity models (GGM)

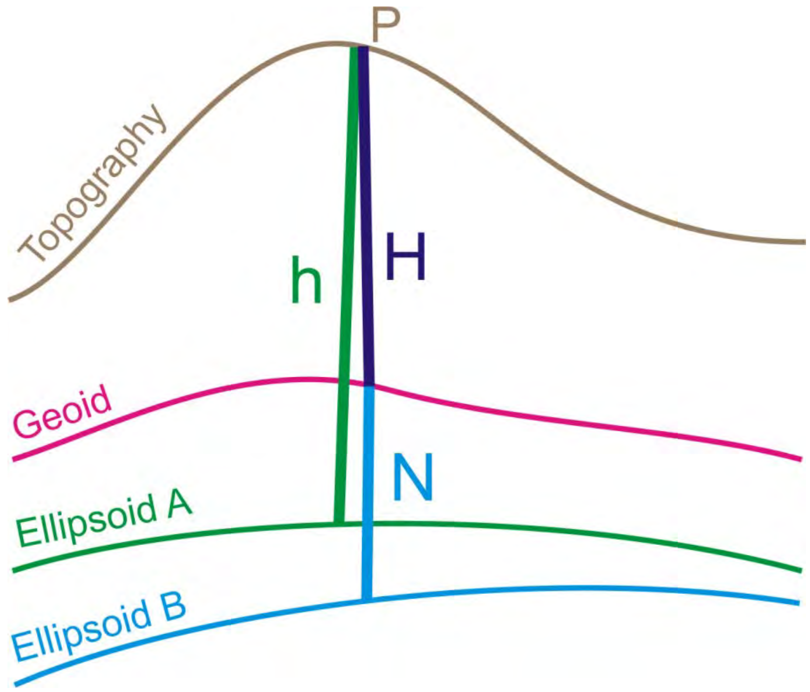


# How to bring h, N, H together consistently?

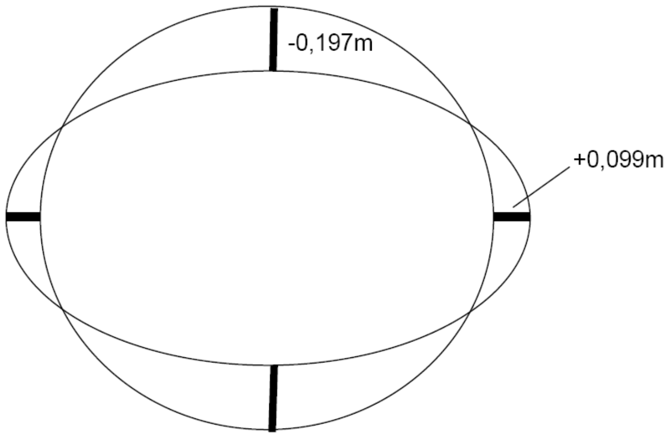


In practice, e.g.:

- ❑ Different ellipsoid parameters (a, GM) in geometry and gravity
- ❑ Different tide systems for *h* and *N*
  - Oceanography, satellite altimetry, levelling in mean tide system
  - ITRF positions, GRS80, some geoids in tide free system
  - Some geoids, terrestrial gravity data in zero tide system



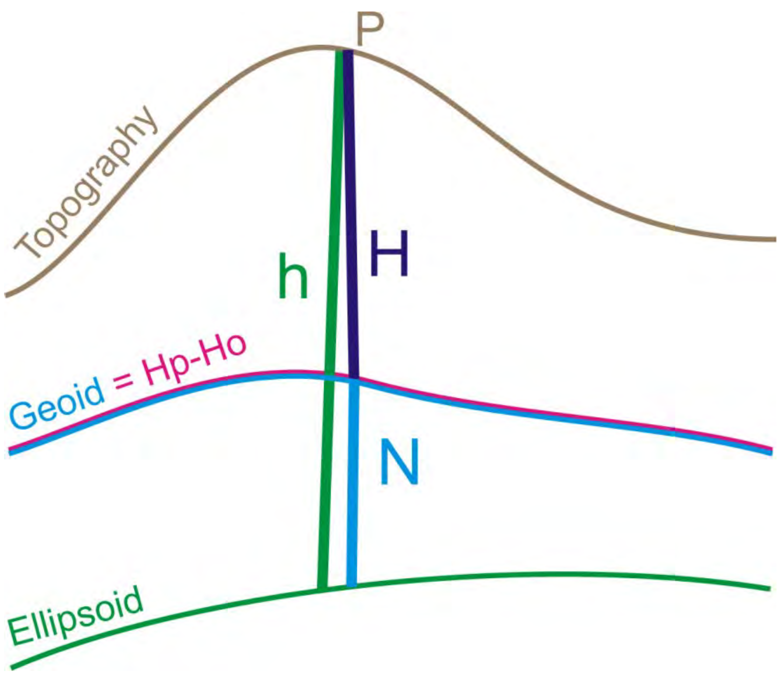

Differences between mean and zero geoids (Heck 2010)



# How to bring h, N, H together consistently?



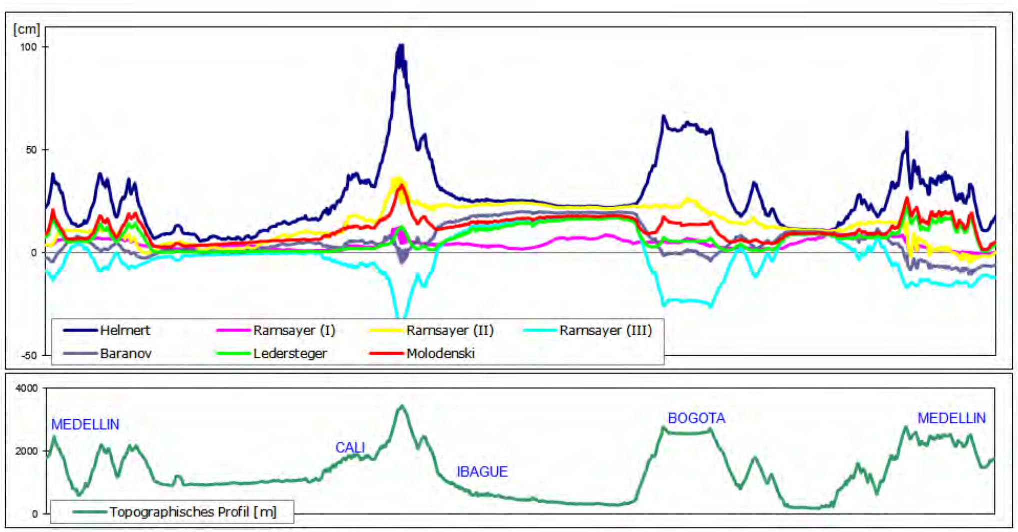
2) Physical heights *H* and (quasi)geoid undulations *N* must reflect the same reference surface:
   - $H_p$ (from levelling) – $H_0$ (datum point) $\rightarrow$ geoid from geometry
   - N (from the GBVP) $\rightarrow$ geoid from gravity



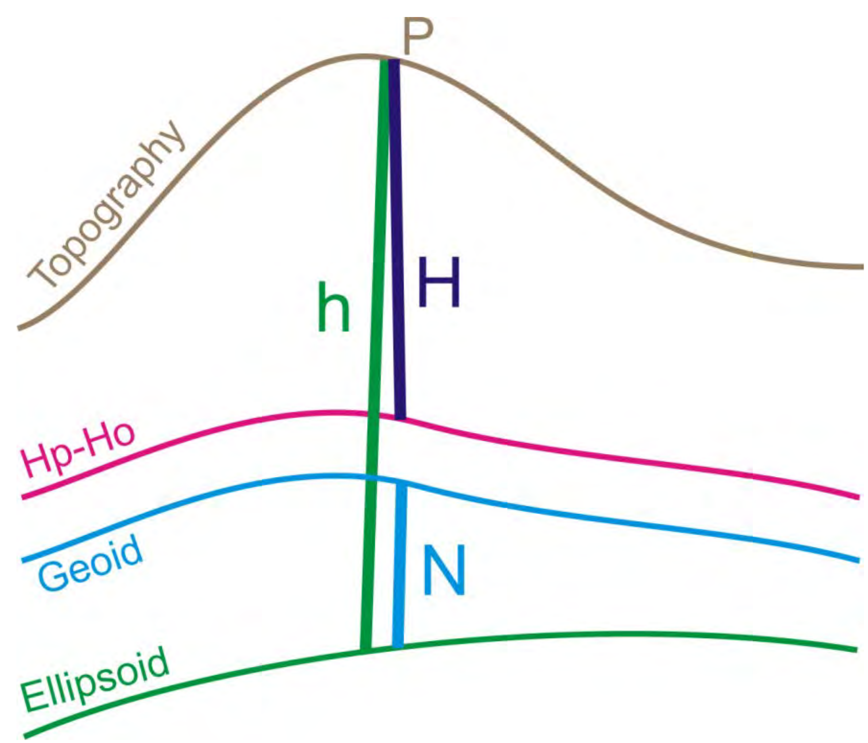
# How to bring h, N, H together consistently?

In practice, e.g.:

- Orthometric heights and geoid from GBVP with different hypotheses
- Different tide systems for H and N
- Systematic errors over long distances in levelling (reliability of $H_p$-$H_0$)



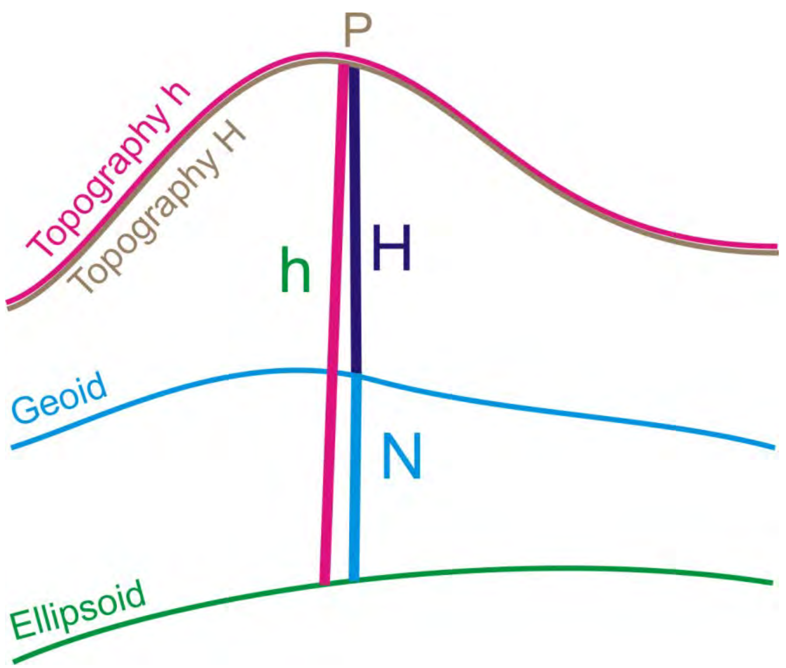

Physical heights using different gravity reductions to levelling.



# How to bring h, N, H together consistently?



3) Physical heights *H* and ellipsoidal heights *h* must represent the same Earth's surface

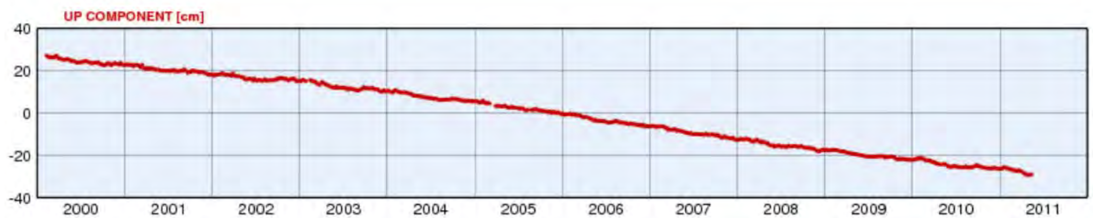


# How to bring h, N, H together consistently?

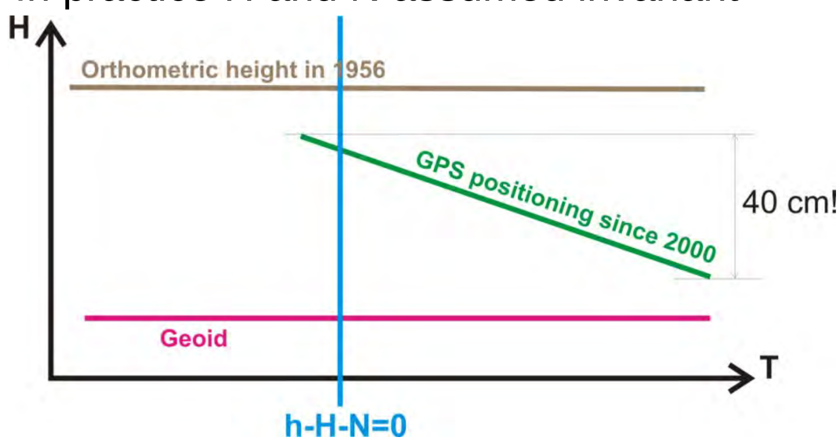
In practice, e.g.:

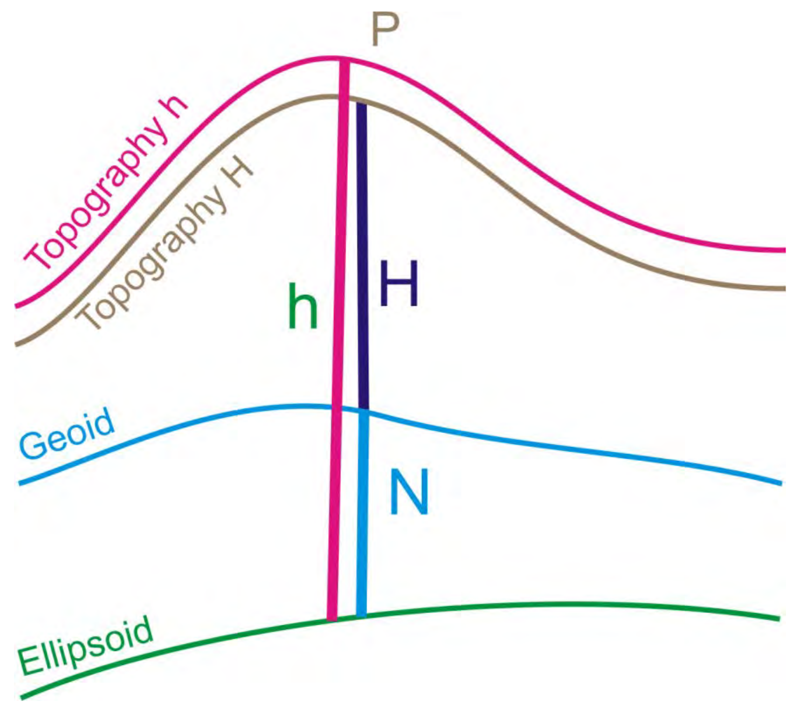
- ❑ Different reference epochs (with unknown dH/dt)
- ❑ Different reductions (Earth-, ocean-, atmospheric tides, ocean and atmospheric loading, post-glacial rebound, etc.)

Time series of the GNSS station BOGA (Bogotá, CO)




In practice H and N assumed invariant

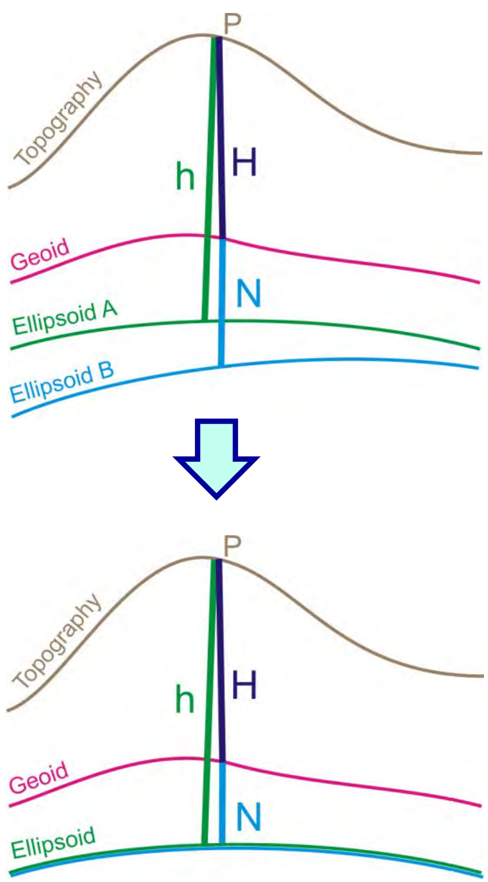


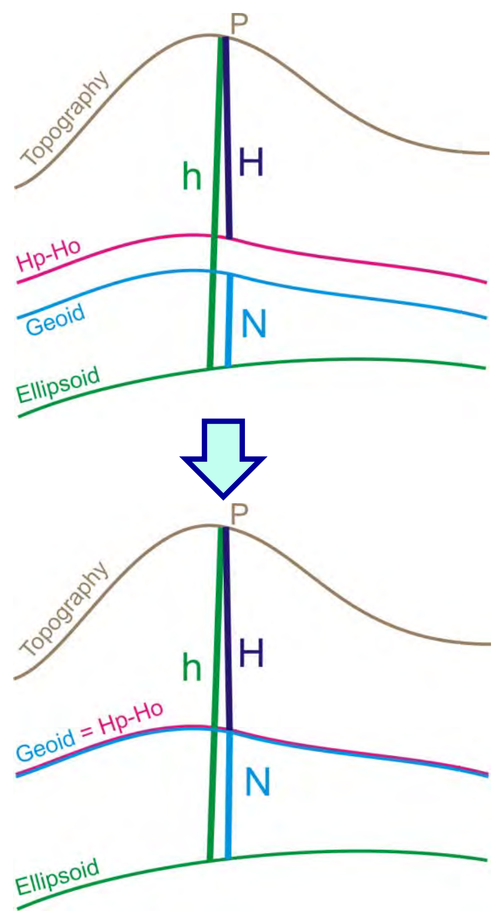
# Challenge for a global unified vertical reference system



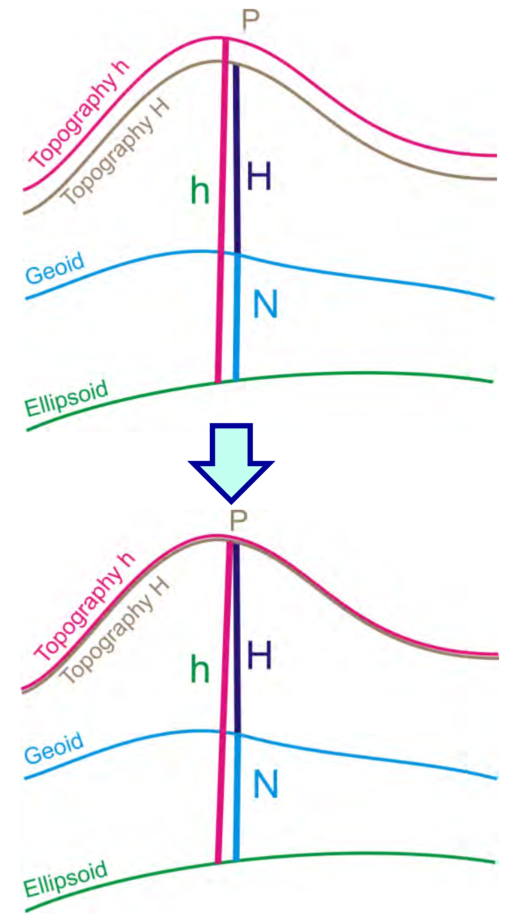
**Consistency between h, N to get H**




**Consistency between H, N to get h**




**Consistency between h, H to get N**




1. at cm-level
2. worldwide

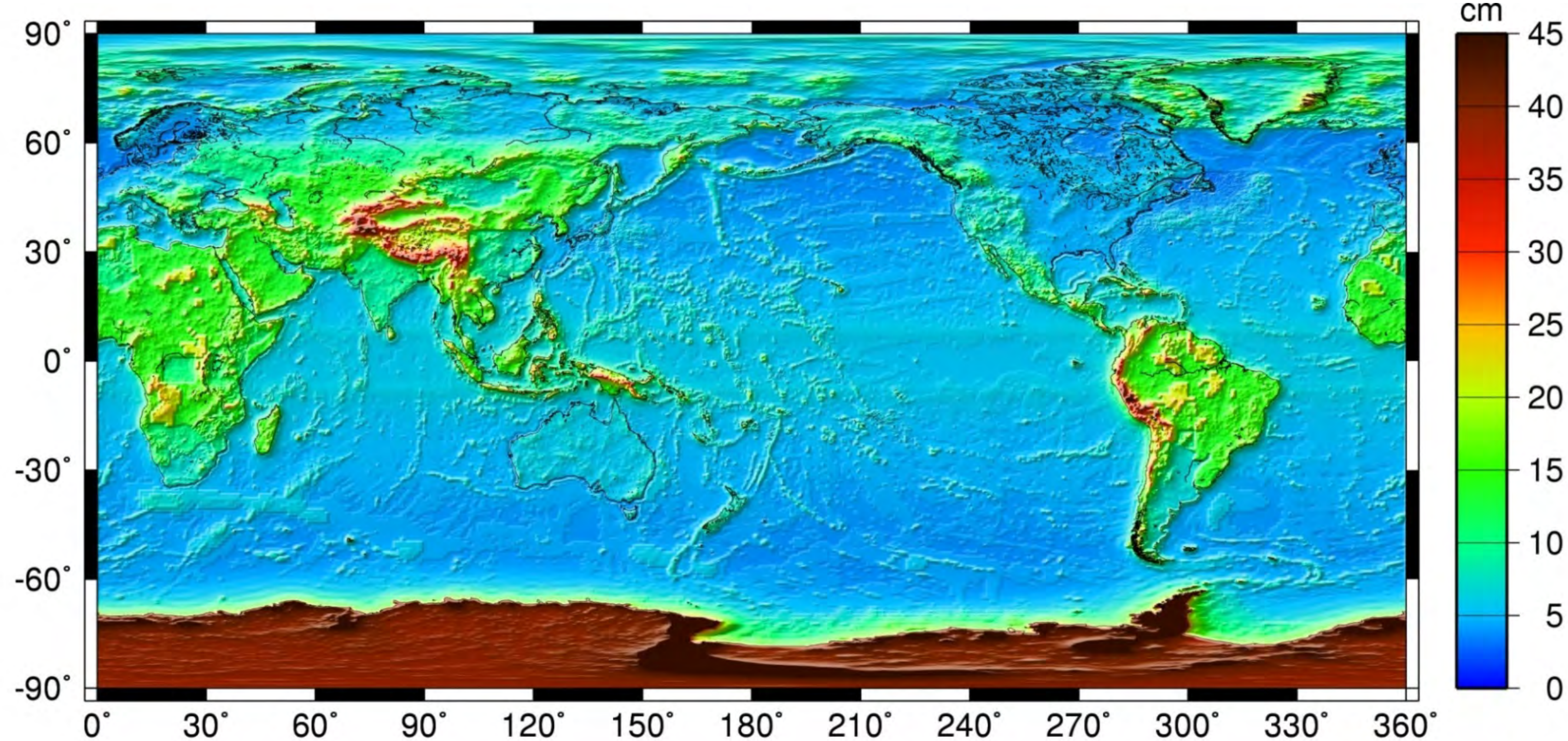
# How to bring h, N, H together consistently?



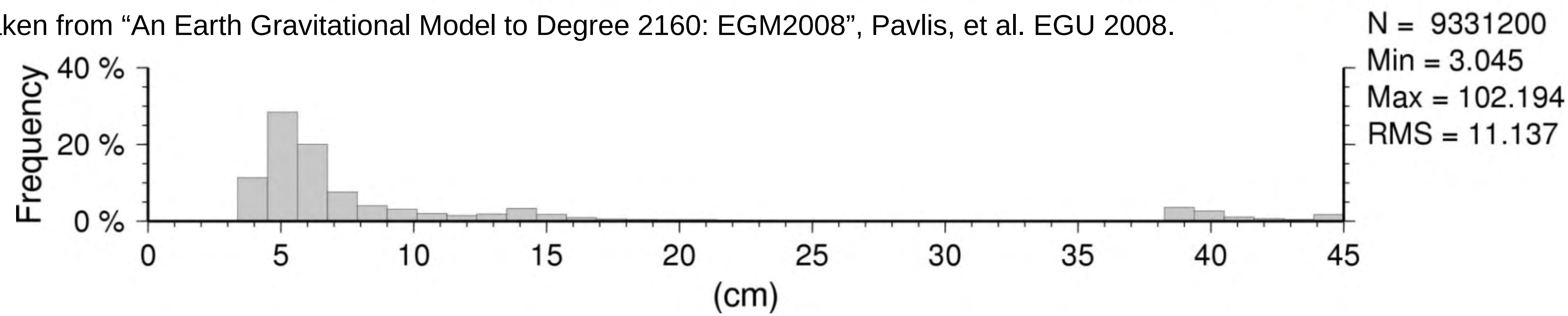
- At present, the only data with high consistency [mm-level] in a global frame are the ellipsoidal heights obtained from continuously GNSS positioning and post-processing strategies.
- Physical heights from levelling (+ gravity reductions) are very precise relatively; but systematic errors growing with the distance, the use of different gravity reductions, and neglecting vertical displacements reduce their reliability behind local applications.
- Geoid models are still too inaccurate to be combined with ellipsoidal heights for replacement of levelling.

# Uncertainties in the geoid EGM2008



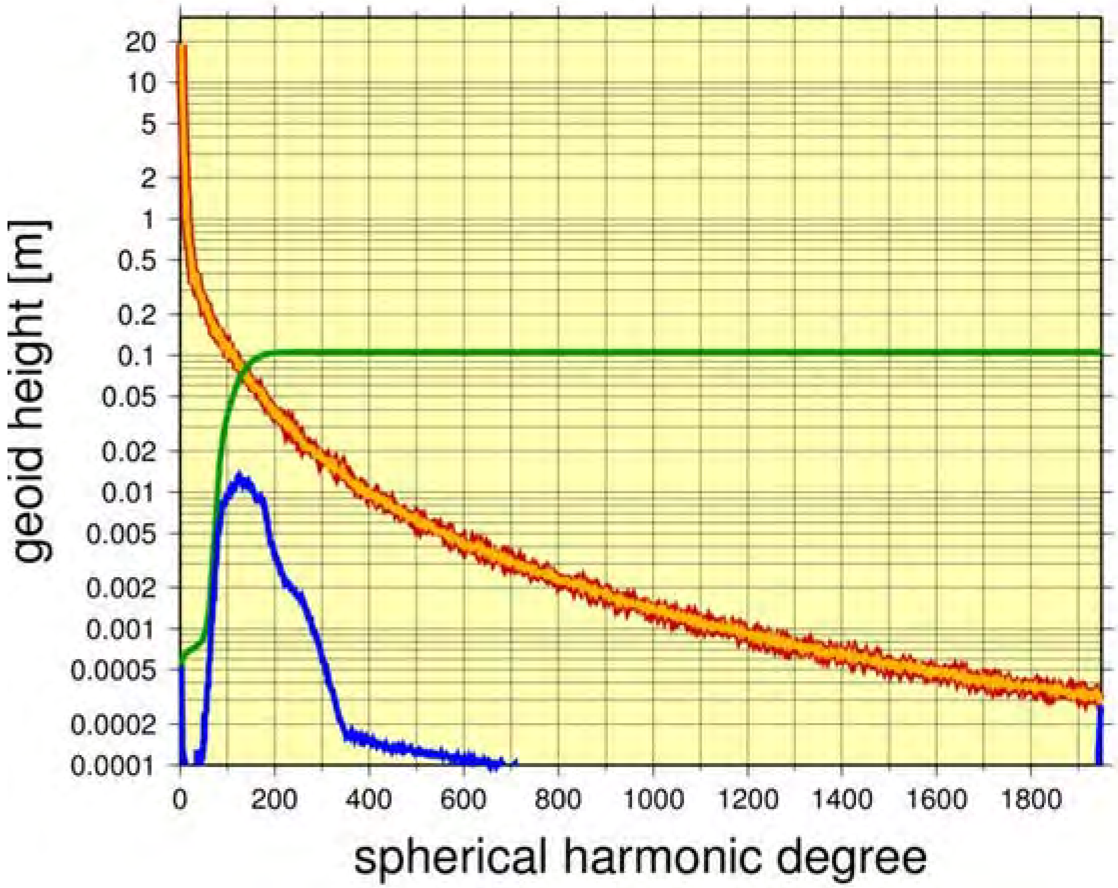



Taken from “An Earth Gravitational Model to Degree 2160: EGM2008”, Pavlis, et al. EGU 2008.



# Uncertainties in the geoid EGM2008






**EGM2008**

**spectral comparison with the model EIGEN–6C2**

**The graphs show:**

**Signal amplitudes per degree of EGM2008**

**Signal amplitudes per degree of EIGEN–6C2**

**Difference amplitudes per degree of EGM2008 vs. EIGEN–6C2**

**Difference amplitudes as a function of maximum degree of EGM2008 vs. EIGEN–6C2**

http://icgem.gfz-potsdam.de/ICGEM/

# Requirements for a reliable vertical datum unification



- Only ellipsoidal heights of highest precision shall be considered. The ***so-called*** GPS-levelling including ***any*** GPS positioning provides accuracies in dm-level due to the strong influence of the radial errors on the vertical coordinate.

  **For vertical datum unification, only continuously operating GPS stations (ITRF, SIRGAS, EPN reference stations) are suitable. These stations must include (reference) tide gauges, levelling main points (nodes) and connection points at the borders between datum zones.**

- Physical heights derived from levelling + gravity reductions must be homogeneous: the same reductions, the same reference epoch, consistent with each other.

  **For vertical datum unification, only vertical networks of first order can be considered. They must be adjusted as a unified block, including time dependency of heights.**

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# Requirements for a reliable vertical datum unification



- Precise geoid models remain as a main problem:
  - The geoid computation is not a unified/standardised procedure. **There are as many reference surfaces (vertical datums) as geoid computations**.
  - The sate-of-the-art allows the computation of geoid models with a maximum accuracy in dm-level. This could satisfy some practical applications, but what about **measuring, understanding and modelling global change effects**?
- **Basic requirements in the geoid determination**:
  - GBVP is solved following the Molodenskii theory, without orthometric hypotheses to avoid misrepresentations in $\Delta W$ caused by inconsistencies between different assumptions.
  - All datum zones shall apply the same global gravity model (GGM) by solving the mixed GVBP (GGM + terrestrial data). This GGM should be a satellite-only model including satellite laser ranging, GRACE and GOCE data.

# Requirements for a reliable vertical datum unification



- **Basic requirements (continued...)**:
  - All datum zones shall apply the same reference surface and normal gravity (and potential) field for the linearization of the GBVP. It should correspond to the conventional ellipsoid of the geometrical reference system (e.g. GRS80).
  - All observations shall refer to the ITRF and to the same epoch to avoid misrepresentations caused by horizontal local datums or temporal changes.
  - In all datum zones, the long wavelength component must be combined with terrestrial gravity data to improve the resolution and accuracy of the geoid model.

# Major open issues in the SIRGAS vertical problem



- **Continental adjustment** (free normal equations) of the levelling networks in South America. Present related tasks are:
  - Identification of levelling gaps (especially between neighbouring countries)
  - Standardization of gravity values for computation of geopotential numbers
  - GNSS positioning at tide gauges
- Treatment of **time-dependent components** (parameters), i.e. a reference epoch and dh/dt, dC/dt, dN/dt;
- Identification (correction) of uncertainties in $\delta W_j$ due to systematic errors (in levelling networks, GNSS at tide gauges, etc.);
- Reliable combination of **satellite-only GGMs** and **terrestrial gravity data**.