International Height Reference System (IHRS):
Required measurements and expected products

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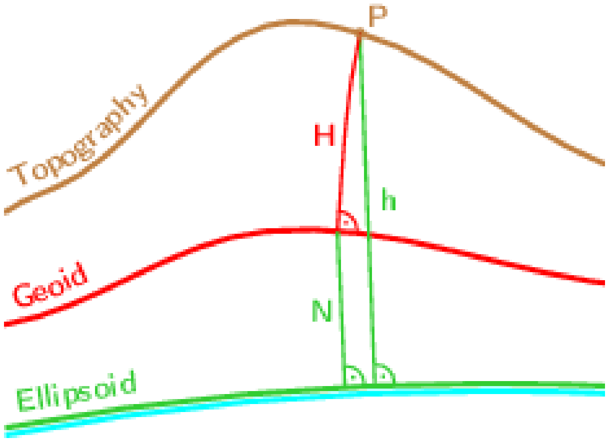
1) Motivation: Consistent combination of vertical coordinates.
2) Definition of the IHRS (IAG Resolution 1, 2015).
3) Realization of the IHRS: the International Terrestrial Height Reference Frame (IHRF).
4) Measurements required for the establishment of the IHRF.
5) Products associated to the IHRS/IHRF.
6) Report about GGOS-FA1 activities and future plans.

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).



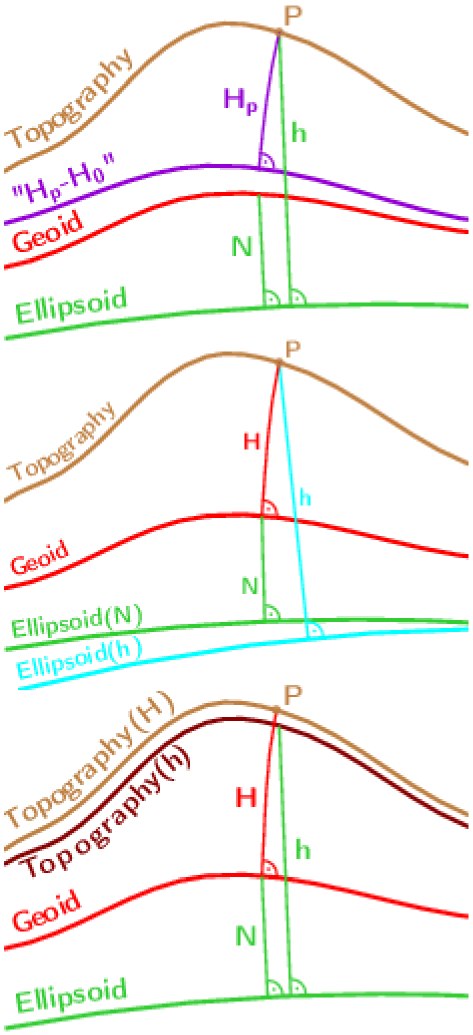
2) Everyone using GNSS positioning and requiring physical heights demands

$$H = h - N$$

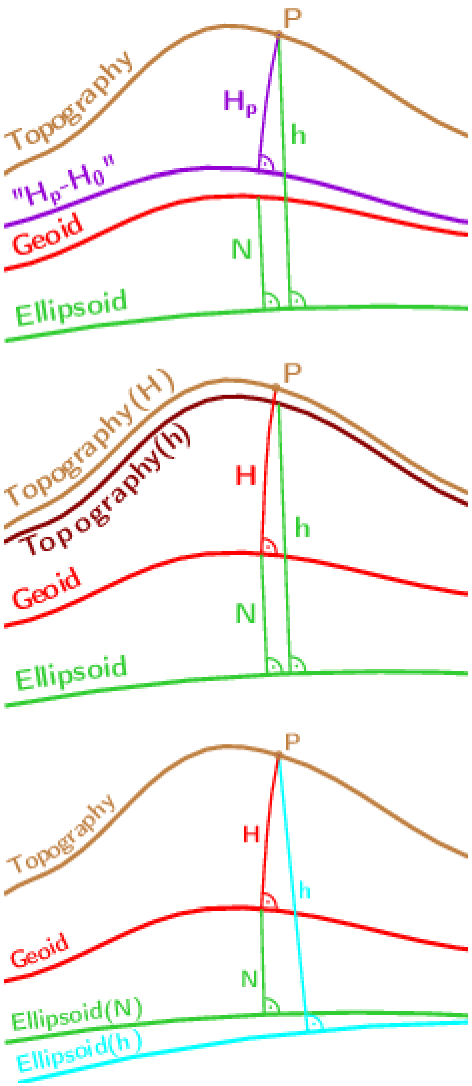
with consistency at the cm-level and worldwide.

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

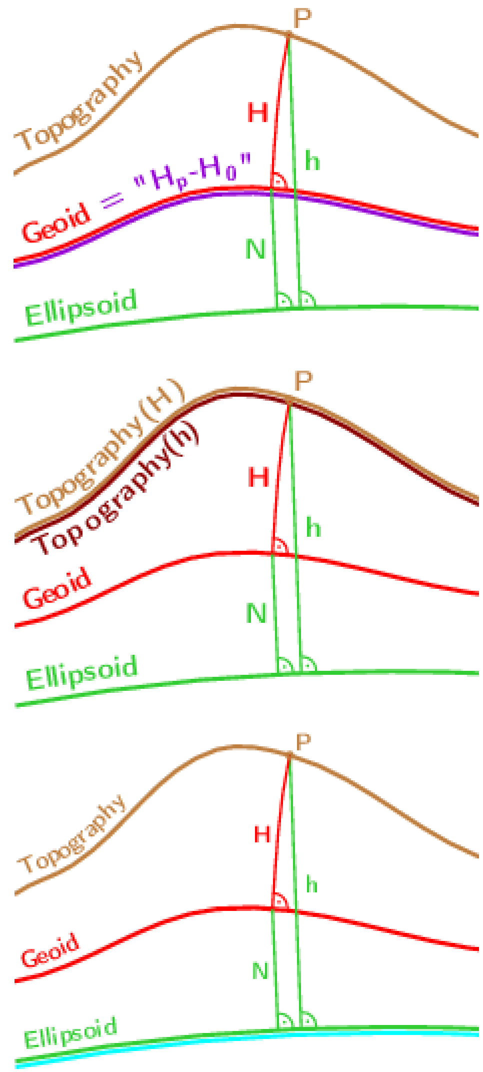
- Physical heights H usually refer to different local vertical reference levels (more than 100 worldwide).
- Different ellipsoid parameters (a, GM) are used in geometry and gravity.
- H and h are given in different reference epochs (usually dH/dt is unknown).
- Different solid Earth tide systems for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



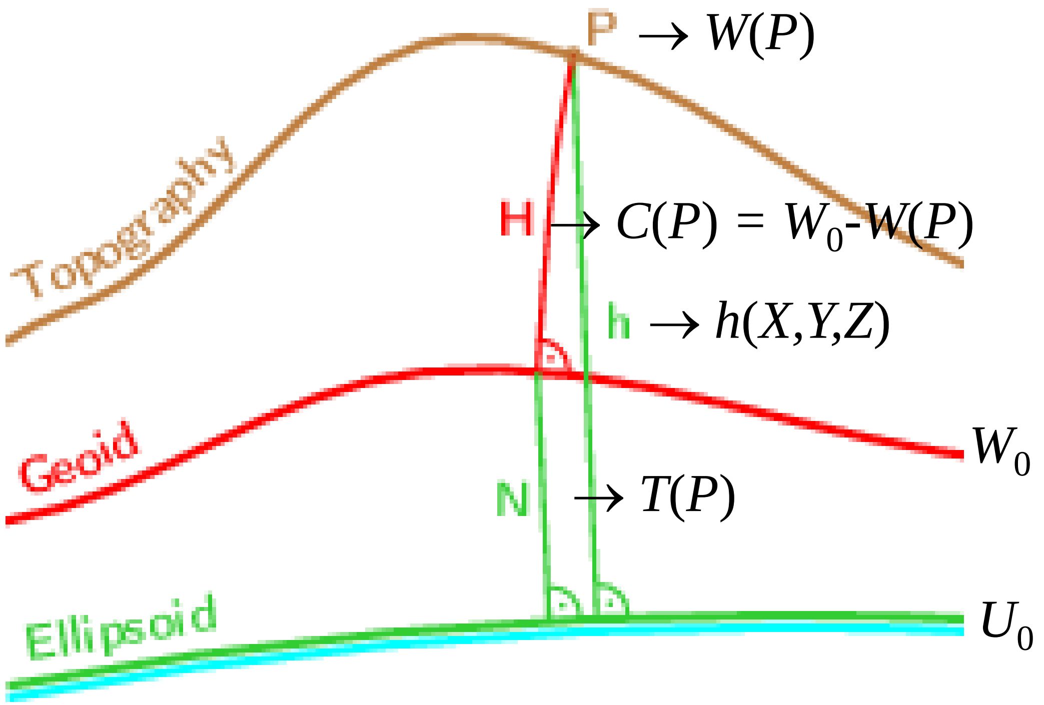
A global unified height system is needed to ensure consistency between h, H, N, worldwide and at the cm-level



- 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

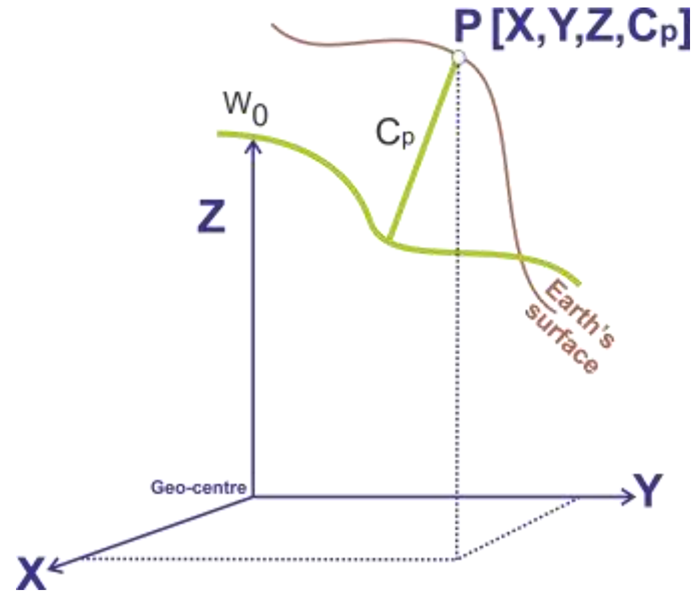
- $W_0 = U_0$
- Additional parameters: GM, ω, J_2

➡ Johannes' talk!

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 $\dot{C}(P)$).

4) The determination of $\mathbf{X}$, $\dot{\mathbf{X}}$ follows the standards (and conventions) adopted within the IERS for the ITRS/ITRF. Similar standards for the determination of W, $\dot{W}$ are (still) missing.

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 $X_P, \dot{X}_P, W_P, \dot{W}_P$.
- 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.

Requirements on W_P

The GGOS terms of reference do not include physical heights or potential values but state:

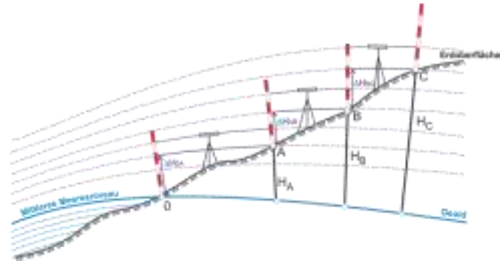
- Accuracy of the geoid (geometry of any equipotential surface)
  - Static geoid: 1 mm, spatial resolution: 10 km.
  - Time-dependent geoid: 1 mm, spatial resolution of 50 km, temporal resolution of 10 days

- Accuracy of the ITRF coordinates:
  - Positions: 1 mm horizontal, 3 mm vertical.
  - Velocities: 0.1 mm/a horizontal, 0.3 mm/a vertical.

- Inferred (expected) accuracy for W_P:
  - Positions: ~ 3×10^{-2} m^2s^{-2} (about 3 mm).
  - Velocities: ~ 3×10^{-3} m^2s^{-2} (about 0.3 mm/a).

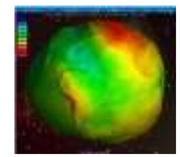
Possibilities for the determination of W_P

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)		

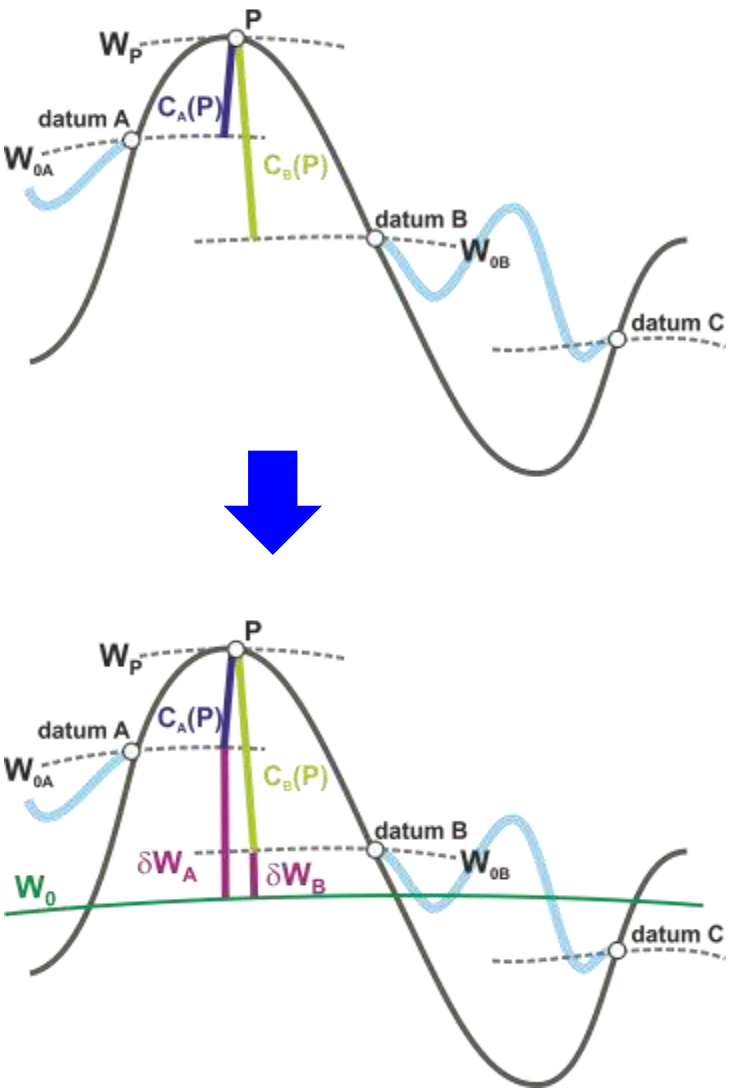
1) W_P from Levelling + Gravimetry

- 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}

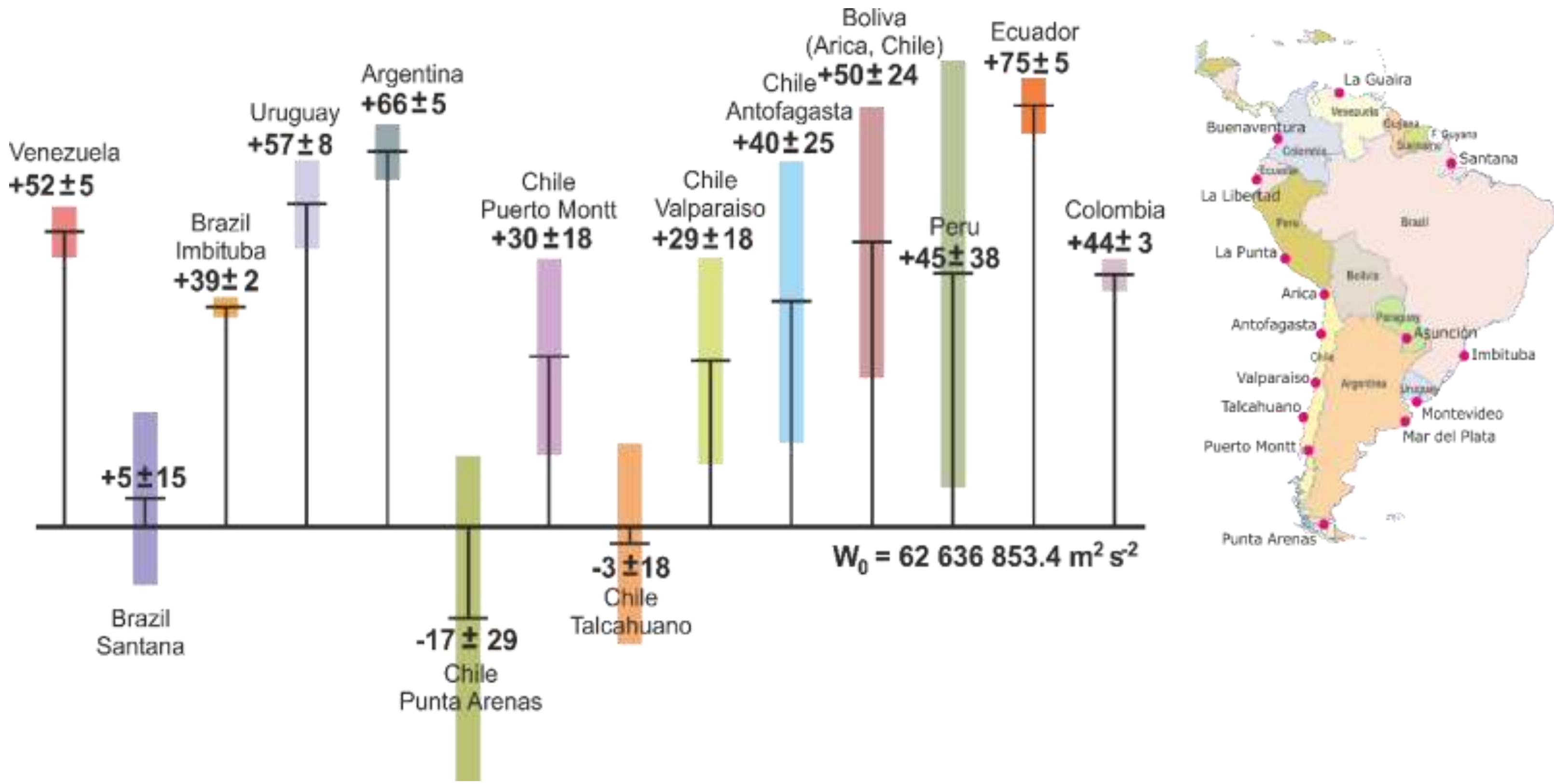
$$W_P = \left(W_{0,local} + \delta W\right) - C_P;$$

- 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

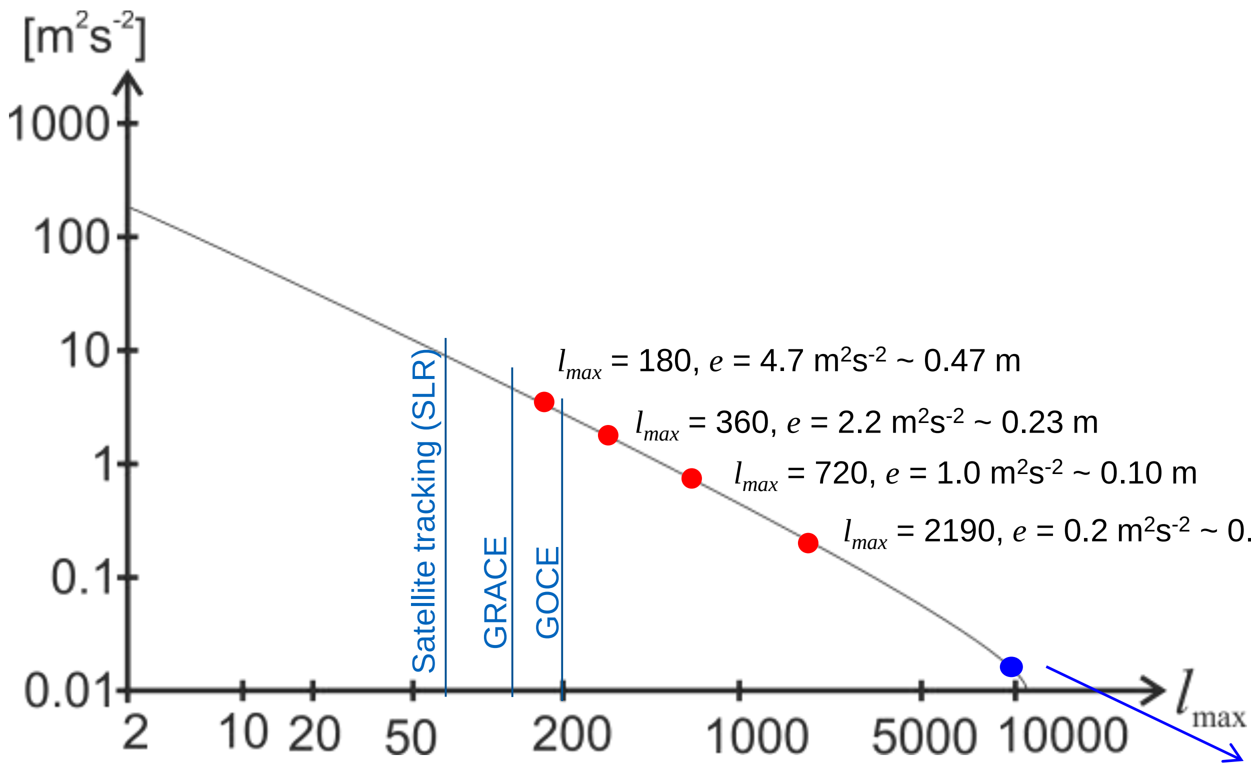
Example: δW (in cm) for the South American height systems w.r.t. the IHRS W_0 value.



➢ 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

Omission error (e) of the GGM in [m^{2}s^{-2}] according to Tscherning and Rapp (1974) (l_{max} does not contain the full signal of the Earth's gravity field).



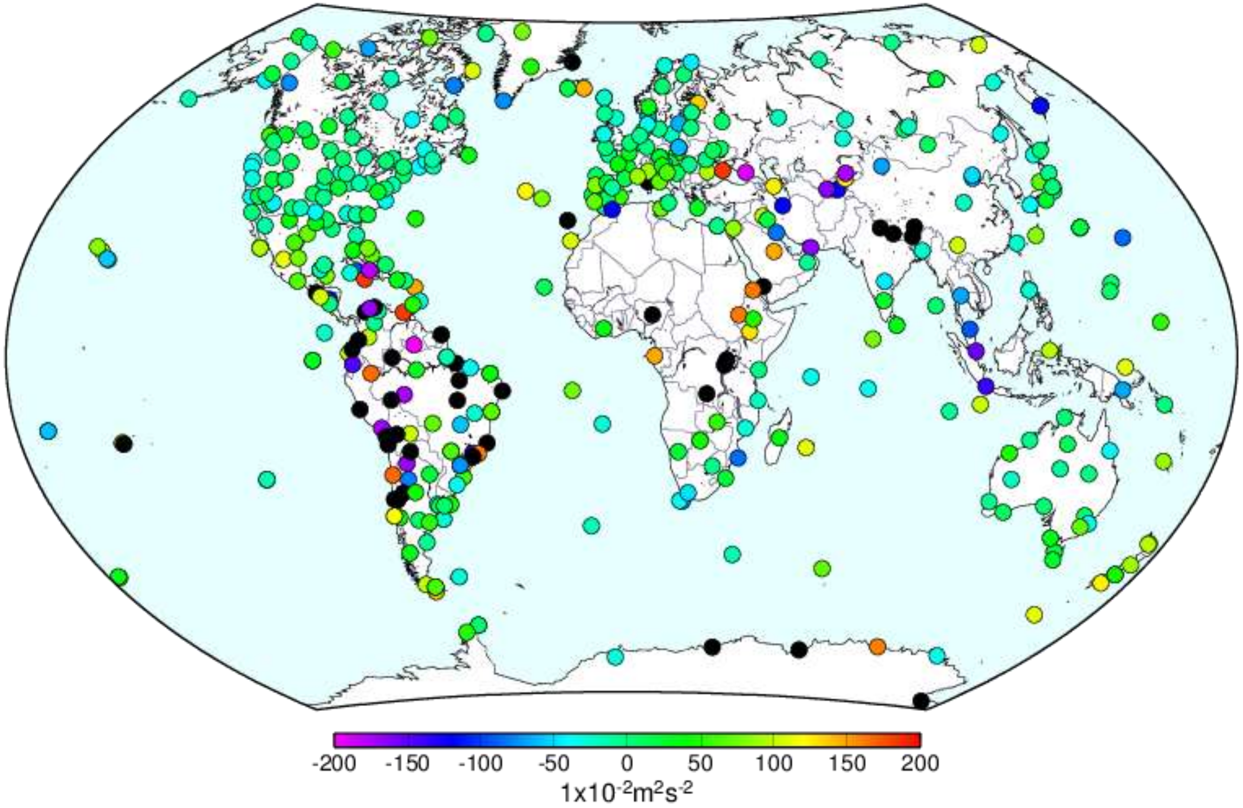
IHRS requirements
$\sigma_{(W(P))}$ = 0.01 m^{2}s^{-2}
l_{max} ~ 10800

The commission error has to be added to the omission error and the sum of both should be lower than $\sigma_{(W(P))}$ = 0.03 m^{2}s^{-2}

2) W_P from combined (high-resolution) GGMs

Example for the uncertainties of GGMs:

- 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 ±200 x 10^{-2} m^2s^{-2} (~ ± 2 m)
- Desired accuracy for W_P: ±0.03 m^2s^{-2}



➢ This strategy is not (yet) suitable for the IHRS realisation.

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

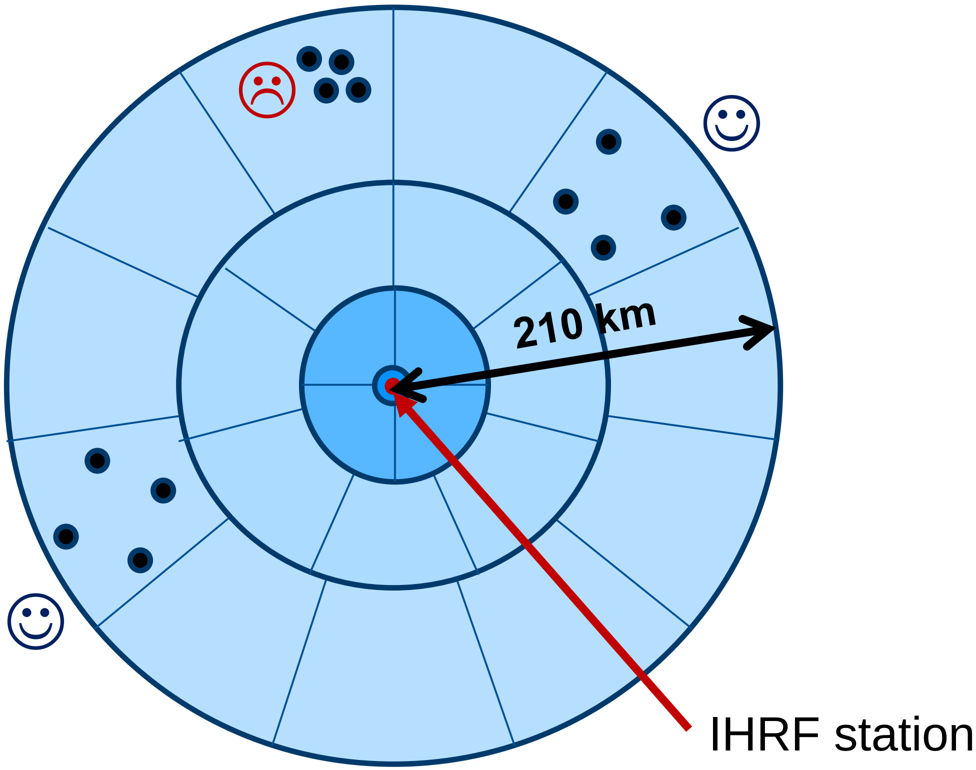
$$W_P = U_P + T_P$$

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

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°).
- 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**

How to get the terrestrial data?

☺ **Plan A**: To collect the gravity data (they may exist or have to be observed) around the IHRF core stations by means of

- the GGOS Bureau for Networks and Observations
- the Bureau Gravimétrique International (BGI)
- the responsible persons for each station directly (with the help of the IAG regional sub-commissions).

☺ **Plan B**: To ask national/regional agencies responsible for the geoid modelling to compute the residual component of the disturbing potential T_{res} directly. To ensure consistency, we have to define how they have to compute it.

😐 **Plan C**: To use existing grids with mean observed gravity anomalies (not from GGMs); e.g. from NGA and BGI.

☹ **Plan D**: To take an existing local geoid model.

☹ **Plan E**: To use a high-degree GGM.

This roadmap was discussed during the GGHS2016: International Symposium on Gravity, Geoid and Height Systems 2016, Thessaloniki, Greece, Sept. 2016; main conclusions are:

- A new generation of high-resolution (combined) GGMs is in development.
- Resolution of present versions is available at $n = 720$.
- Commission errors range from 0.1 m^2s^{-2} (North America, Europe, Australia) to 1.0 m^2s^{-2} (the rest of the world), plus omission error 1.0 m^2s^{-2}.
- Terrestrial gravity data is therefore still required, *at least* around the IHRF core stations.
- Colleagues involved in the computation of regional geoid models agreed to contribute to “a first approximation to the IHRF”.
- Contributors from: North America, Europa, Australia, Russia, South America.
- Still missing: Africa, Asia, Oceania.

For the future: would it be possible that the GGOS-BNO includes in the “Site requirements for GGOS core sites” gravity surveying around the stations as a requirement?

Reference network

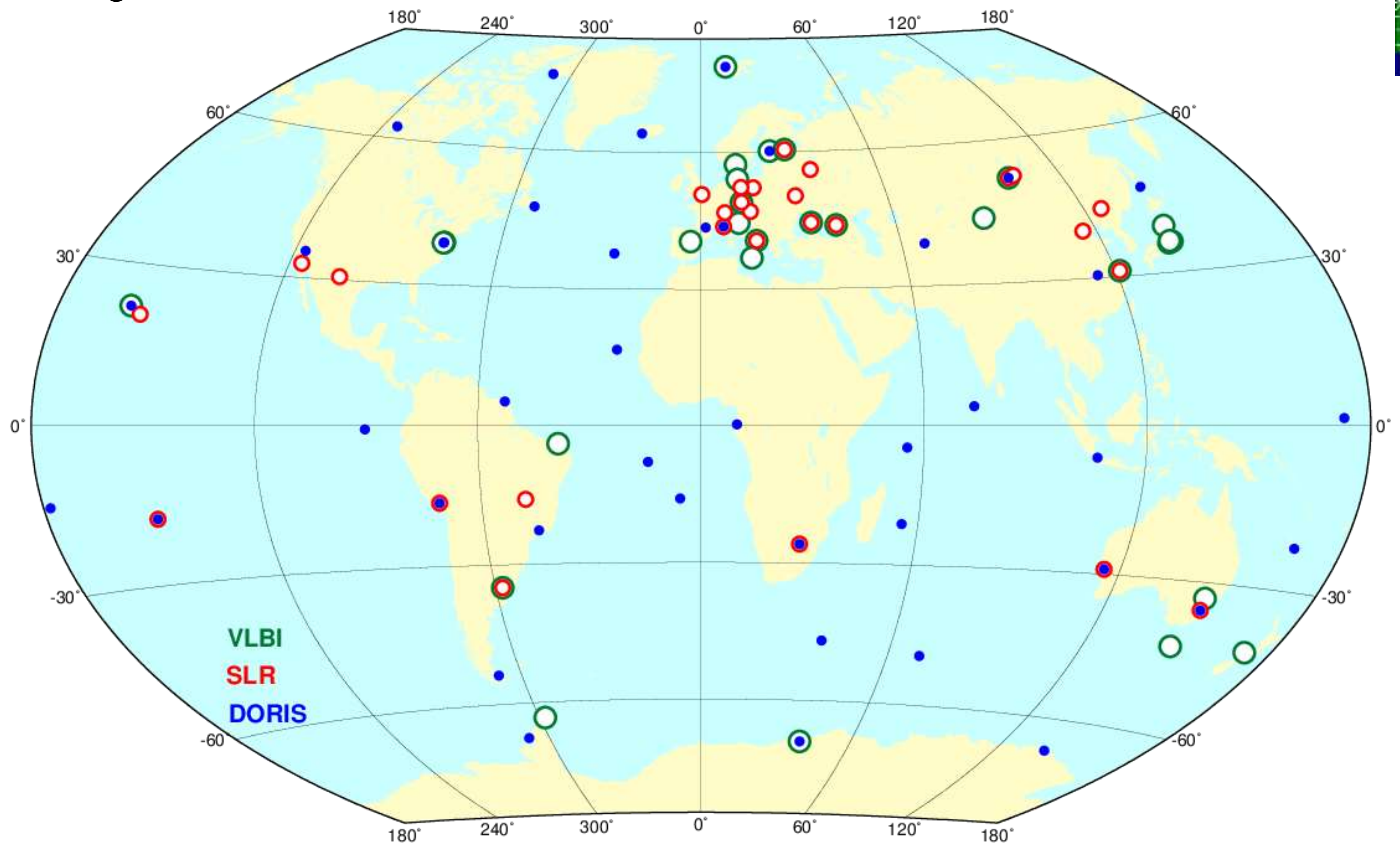
1) Hierarchy:
   - A global network → worldwide distribution, including
   - A core network → to ensure perdurability and long term stability
   - Regional and national densifications → local accessibility

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).

The IHRF is understood to be a component of the Global Geodetic Reference Frame (UN GGRF resolution 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.
3) Existing SLR stations collocated with GPS.
4) Existing DORIS stations collocated with GPS.

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 GNSS stations in cooperation with the regional IAG sub-commissions.

Still open:

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

Once the reference stations are selected, the next step is the computation of potential values (first results expected to be presented during IAG2017).

Expected IHRS products

1) A reference frame (IHRF): reference network with known high-precise coordinates $\mathbf{X}$, $\dot{\mathbf{X}}$, W, $\dot{W}$, C, $\dot{C}$.
2) Regular updates of the IHRF*yy* to take account for:
   - new stations;
   - coordinate changes with time $\dot{\mathbf{X}}$, $\dot{W}$;
   - improvements in the estimation of $\mathbf{X}$ and W (more observations, better standards, better models, better computation algorithms, etc.).
3) Transformation parameters δW for the integration of the existing height systems into the IHRS/ITRF.
4) For the "height transfer" a gravity field model is required in two ways:
   - A satellite-only GGM, if local agencies want to (are able to) compute the regional component T_{res};
   - A high-resolution (combined) GGM for applications of lower accuracy (> 10 cm).

GGOS-FA1 On-going activities

Coordinated work between:

- GGOS Focus Area 1
- 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

JWG on “strategies for the IHRS realization” (32 members, action items defined at GGH2016).

a. Proposal for the realisation of the IHRS: reference network for the IHRF.

b. Identification of required standards and conventions for the IHRS realisation.

c. Identification of geodetic products associated to the IHRF and description of the elements to be considered in the corresponding metadata (in agreement with the IGFS and the GGOS Bureau of Products and Standards).

d. Contribution/interaction of the IHRF with the GGRF (in agreement with the BPS-WG2: Establishment of the Global Geodetic Reference Frame (GGRF)).

Identification of required standards and conventions for the IHRS realisation.

Items being faced (names in red are coordinators)

1) Numerical standards (in agreement with the GGOS Bureau for Products and Standards)
2) Definition of the International Height Reference System (based on the paper Ihde et al. 2016) **Ihde**
3) Reference level: Conventional W_0 value **Sánchez**
4) International Height Reference Frame (**Pail, Marti, Wziontek, Barzaghi, Sánchez**), in agreement with the GGOS Bureau for Networks and Observations
5) Estimation of W_P
   - GGM characteristics for the global component of W_P **Gruber**
   - Regional component of W_P **Ågren, Huang**
   - Tide systems (conventions for conversion between them) **Mäkinnen**
   - Modelling of non-linear motions **???**
6) Vertical datum unification **Sánchez, Sideris**
7) IHRF products and servicing **???**
8) Inventory of related resolutions

Basics to complement/extend the IHRS resolution

1) Position paper about the definition and proposed realisation of the IHRS. Johannes Ihde, Laura Sánchez, Riccardo Barzaghi, Christoph Foerste, Thomas Gruber, Gunter Liebsch, Urs Marti, Roland Pail, Hermann Drewes, Michael Sideris. Paper submitted mid October to Surveys in Geophysics.

2) Paper with the *conventions* for the *conventional* W_0 value included the IAG 2015 Resolution 1. Laura Sánchez, Robert Cunderlík, Nadim Dayoub, Karol Mikula, Zussanna Minarechová, Zdislav Šíma, Villian. Vatrt, Marie Vojtíšková. Paper published in Journal of Geodesy (2016) 90:815–835, DOI 10.1007/s00190-016-0913-x.

3) Vertical datum unification for the International Height Reference System (IHRS): Strategies for the integration of the existing height systems into the IHRS. Laura Sánchez and Michael Sideris. Paper submitted mid October to Geophysics Journal International.

Inspiration

The first ITRF (ITRF89)

1) included station positions only (station velocities were neglected),
2) coordinates were given in zero (mean) tide system,
3) conversion to ellipsoidal coordinates used arbitrary values for a and f (the GRS80 was not considered),
4) had a precision from 11 to 60 mm.

It is important to have a “start point”, a “first approximation to the IHRF”. Once it is achieved, it can be improved by considering more and more details, that at the beginning may not be evident.

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IERS Standards

November 1989