Establishment of an International Height Reference System in the frame of GGOS

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Motivation

GGOS requires unified geodetic reference frames with

- an order of accuracy higher than the magnitude of the effects to be observed (e.g. global change);
- consistency and reliability worldwide (the same accuracy every where);
- long-term stability (the same accuracy at any time).

The ITRS and its realization (ITRF) provide

- geometric coordinates ($\mathbf{X}, \dot{\mathbf{X}}$) consistent globally;
- accuracy at mm ... cm level.

The existing height systems exhibit

- more than 100 realizations worldwide;
- discrepancies of dm ... m (different vertical datums, different physical heights, missing standardization);
- static heights $\rightarrow \dot{H} \equiv 0$;
- imprecise combination with geometric heights $|h - H - N| \rightarrow >> 0$;
- 1 ... 2 order of accuracy less than ($\mathbf{X}, \dot{\mathbf{X}}$).

Motivation

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.

This thematic is faced by the GGOS Focus Area 1 (Unified Height System)

- It was established in 2011 (former GGOS Theme 1)
- Objective: Establishment of a global unified vertical reference system, including compilation of standards and conventions as well as strategies for the integration of the existing height systems.

Present achievements:

- adoption of a conventional global reference level (W_0 value)
- IAG Resolution on the Definition and Realization of an International Height Reference System (IHRS).

International Height Reference System (IHRS)

Introduced by a Resolution of the International Association of Geodesy (IAG) during the General Assembly of the International Union of Geodesy and Geophysics (IUGG) in July 2015 (Prague)

resolves

- the following conventions for the definition of an International Height Reference System (see note 1):
  1. the vertical reference level is an equipotential surface of the Earth gravity field with the geopotential value W_0 (at the geoid);
  2. parameters, observations, and data shall be related to the mean tidal system/mean crust;
  3. the unit of length is the meter and the unit of time is the second (SI);
  4. the vertical coordinates are the differences $-\Delta W_P$ between the potential W_P of the Earth gravity field at the considered points P, and the geoidal potential value W_0; the potential difference $-\Delta W_P$ is also designated as geopotential number C_P: $-\Delta W_P = C_P = W_0 - W_P$;
  5. the spatial reference of the position P for the potential $W_P = W(\mathbf{X})$ is related as coordinates $\mathbf{X}$ of the International Terrestrial Reference System;

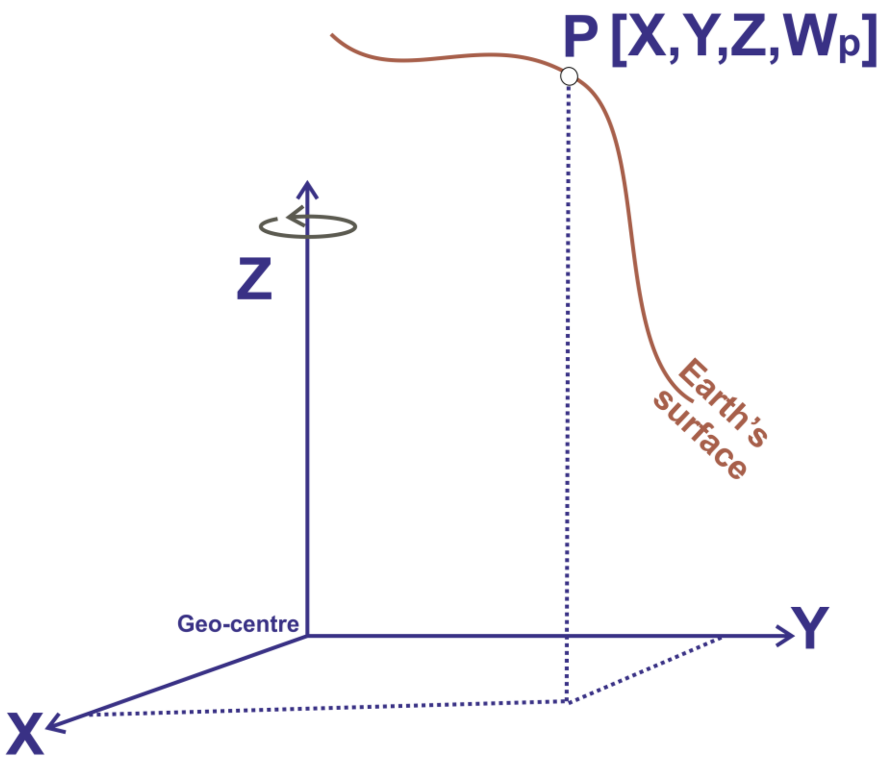
- W_0 = 62 636 853.4 m^2s^{-2} as realization of the potential value of the vertical reference level for the IHRS (see note 2).

International Height Reference System (IHRS)

1) IHRS: Geopotential reference system co-rotating with the Earth.

2) Coordinates of points attached to the solid surface of the Earth are given by

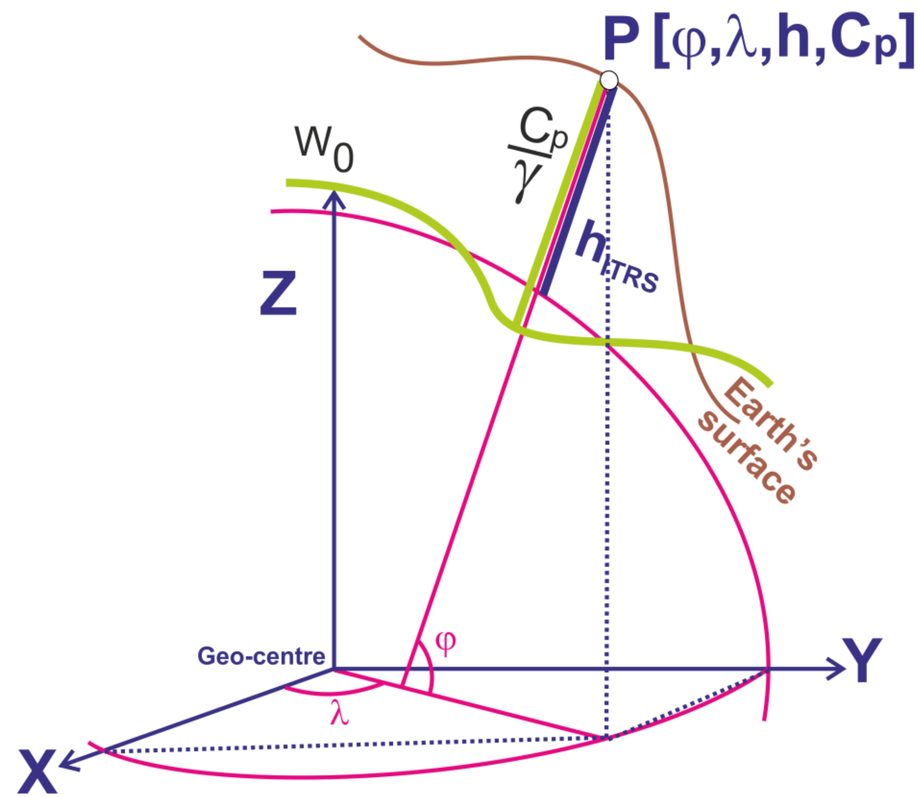
   - geopotential values $W(\mathbf{X})$ (and their changes with time $\dot{W}$), and
   - geocentric Cartesian coordinates $\mathbf{X}$ (and their changes with time $\dot{\mathbf{X}}$) in the ITRS.



International Height Reference System (IHRS)

For practical purposes, potential values $W(\mathbf{X})$ and geocentric positions $\mathbf{X}$ are to be transformed into vertical coordinates with respect to a reference level:

1) geometrical component
   - $h(t_0,X)$; $dh(X)/dt$
   - conventional level ellipsoid $U_0 = const.$
2) physical component
   - $C_p(t_0,X)$; $dC_p(X)/dt$
   - conventional fixed value $W_0 = const.$



Estimation of W_P

- Levelling + Gravimetry:

$$W_P = W_0 - C_P$$

- Solution of the geodetic boundary value problem (geoid computation):

$$W_P = U_P + T_P$$

- Global Gravity Modell + ITRF coordinates:

$$W_P = f(\mathbf{X}, GGM)$$

Drawbacks:

- Levelling + Gravimetry : local vertical datums, different gravity reductions, systematic error in levelling, etc.
- Solution of the geodetic boundary value problem: different standards, restricted accessibility to the gravity data, etc.
- GGM + ITRF: different standards, spatial resolution (mean and short wavelengths).

The main current deficit is the precise estimation of W_P

How to realise it?

ITRF coordinates + gravity field modelling

- Basic solution: satellite-only GGM
- Ideal case: satellite-only GGM + high resolution potential modelling
- At present, "most recommended" case: GGM including high degrees, i.e., the so-called *EGM2008FO*

Expected accuracy (Rummel et al. 2014, ESA project: HSU with GOCE):

- in well surveyed regions: 40 to 60 $cm^2s^{-2} \rightarrow$ 4 to 6 cm
- in sparsely surveyed regions: 200 cm^2s^2 to 400 $cm^2s^2 \rightarrow$ 20 to 40 cm (with extreme cases of 1 m!)

GGOS Requirements:

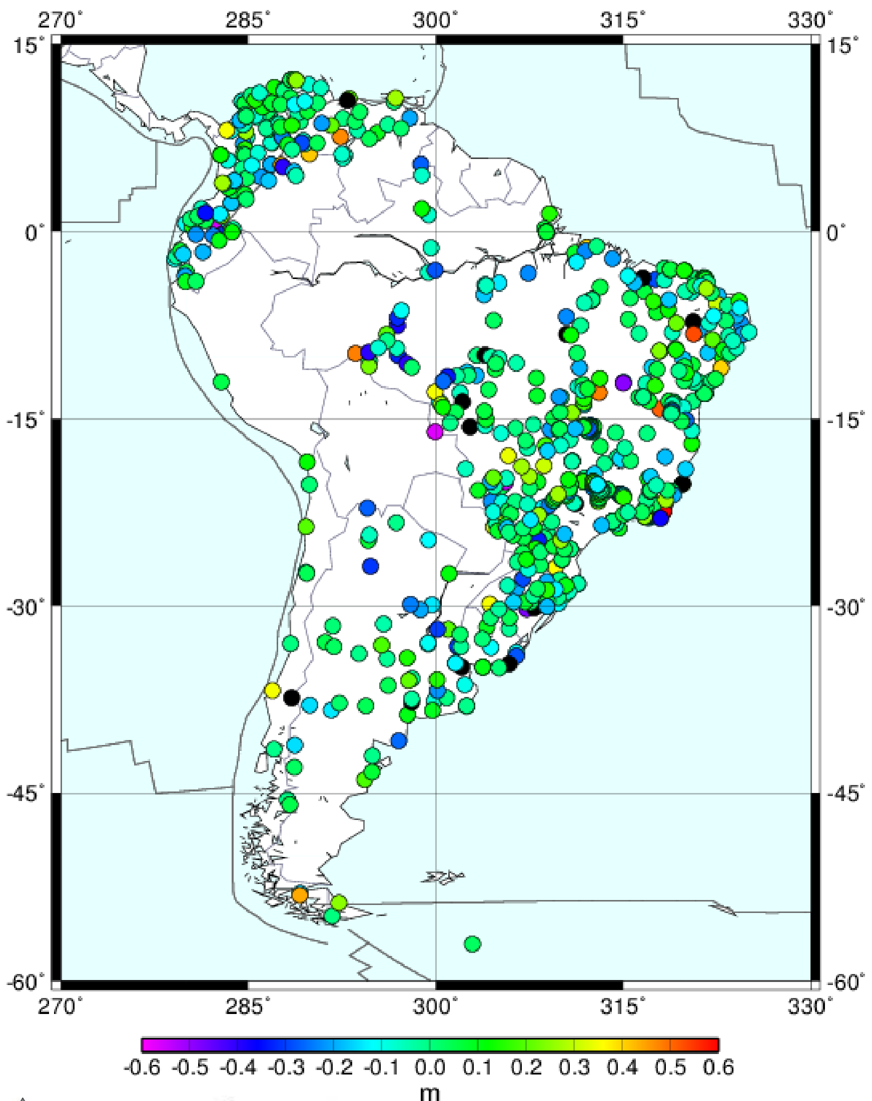
- do not include physical heights
- but geoid accuracy: static: 1 mm @ 10 km, stability 0.1 mm/yr
  time-dependent: 1 mm @ 50 km within 10 days
  stability 0.1 mm/yr
- ITRF coordinates: 1 mm horizontal, 3 mm vertical.
- Expected accuracy for $W_P \sim 3\times10^{-2}$ m^2s^{-2} (about 3 mm); more realistic 10×10^{-2} m^2s^{-2} (about 1 cm).

Computation of W_P

Example in South America:

- Computation of W_P using EGM2008 and EIGEN-6C4 (n,m = 2190)
- Computation of W_P using GO_CONS_GCF_2_DIR_R5 and GO_CONS_GCF_2_TIM_R5 (n,m = 280)
- Comparison of potential values W_p
- Potential differences divided by normal gravity to present results in meters
- Input coordinates $\mathbf{X}$ are always the same

Differences between the potential values W_P computed from EIGEN-6C4 and EGM2008 (n,m = 2190, results in [m])

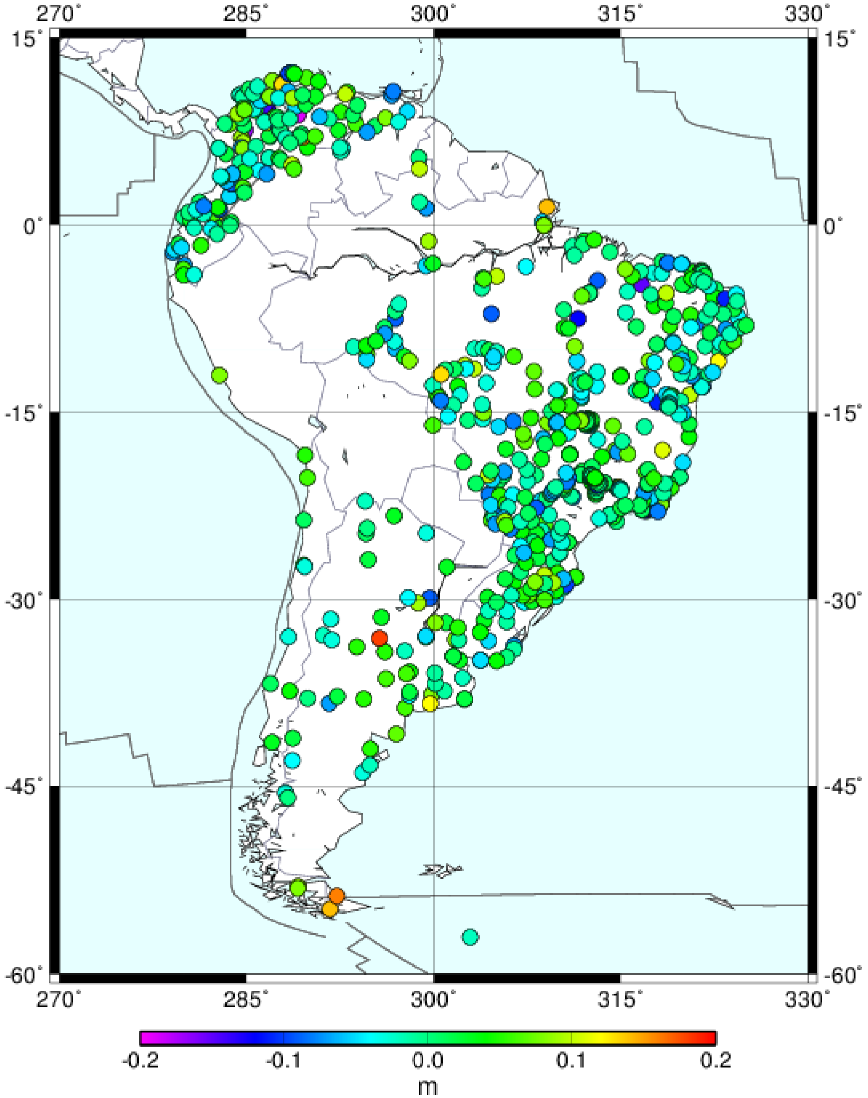


Min.:	-1.85 m
Max.:	1.94 m
Mean:	0.00 m
RMS:	0.14 m

Differences caused maybe by:

- recent satellite-based data included in the newest GGM
- approach for the estimation of high-degree orders

Differences between the potential values W_P computed from the satellite-only GGM GO_CONS_GCF_2_DIR_R5 and GO_CONS_GCF_2_TIM_R5 (n,m = 280, results in [m])

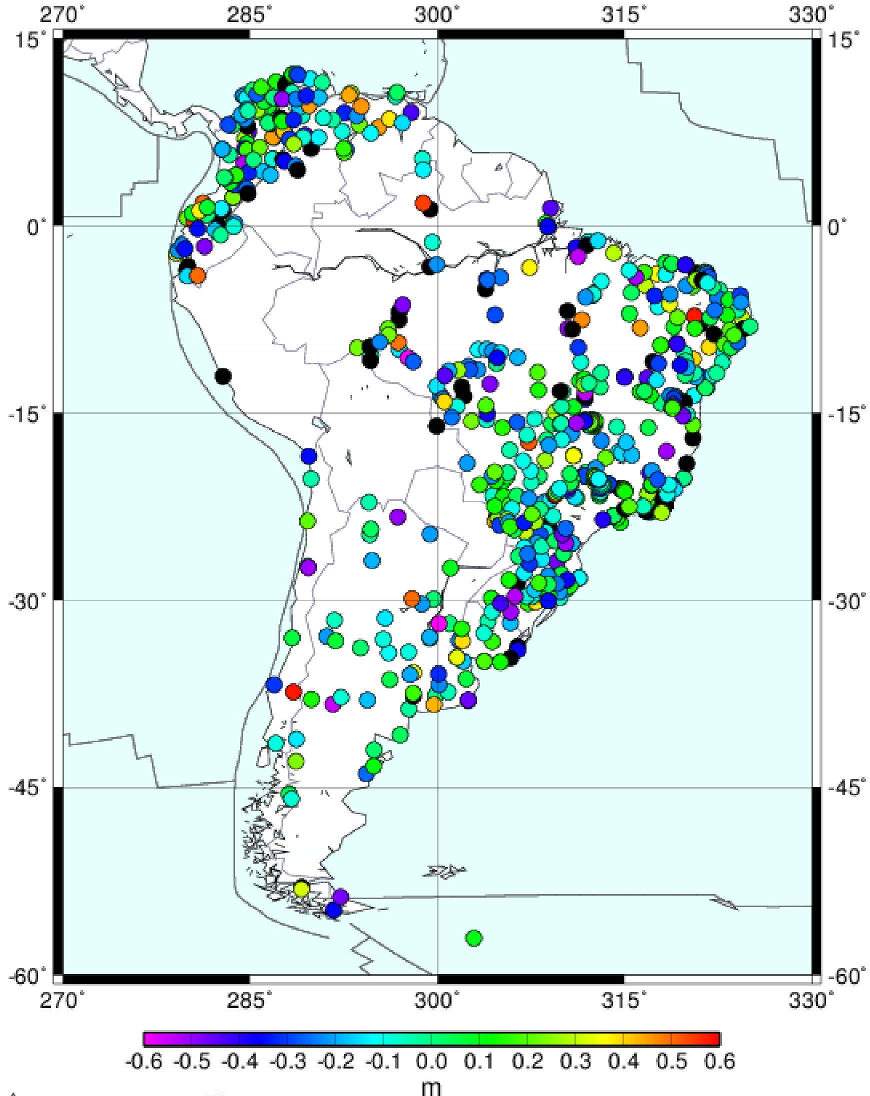


Min.:	-0.19 m
Max.:	0.18 m
Mean:	0.00 m
RMS:	0.04 m

Differences caused maybe by:

- the satellite-based data included in the GGM:
  - TIM: only GOCE
  - DIM: GOCE+GRACE+SLR
- approach for the estimation of the coefficients

Differences between the potential values W_P computed from EIGEN-6C4 (n,m = 2190) and GO_CONS_GCF_2_DIR_R5 (n,m = 280), results in [m]



Min.:	-2.47
Max.:	3.66
Mean:	-0.06
RMS:	0.30

Differences caused maybe by:
- the so-called omission error

Realization of the IHRS

- The state-of-the-art does not allow the establishment of an IHRS that satisfies the GGOS requirements.
- For that, it is necessary
  - an integrated global geodetic reference frame with millimeter accuracy;
  - long-term stability and worldwide homogeneity;
  - removal of inconsistencies between analysis strategies, models, and products related to the Earth's geometry and gravity field
  - outlining of standards that allow a consistent definition and realization.

Realization of the IHRS

Our proposal is:

- A reference frame (the International Height Reference Frame - IHRF) following the same hierarchy as the ITRF:
  - a global network with
  - regional and national densifications.
- This network shall be collocated with:
  - fundamental geodetic observatories (to make feasible the connection between position vectors $\mathbf{X}$, gravity potential W, international atomic time TAI, and absolute gravity $\mathbf{g}$);
  - continuously operating reference stations (to detect deformations of the reference frame);
  - geometrical reference stations of different densification levels (presumable with GNSS to allow access to the IHRF also in remote areas);
  - reference tide gauges and national vertical networks (for the vertical datum unification);
  - gravity reference stations.

Planned activities for the term 2015-2019

- Joint Working Group (JWG) on Strategy for the Realization of the International Height Reference System (IHRS) with the concurrence of
  - GGOS
  - IAG Commission 2 (Gravity field)
  - IAG Commission 1 (Reference Frames)
  - IAG Inter-commission Committee on Theory (ICCT)
  - International Gravity Field Service (IGFS)

- The JWG shall be established in the GGOS Focus Area 1 (Unified Height System) and report to the GGOS Bureau of Products and Standards (GGOS-BPS).

Planned activities for the term 2015-2019

Action items:

- To define the standards and conventions required to establish an IHRF consistent with the IHRS definition.
- To formulate minimum requirements for the IHRF reference stations.
- To identify the geodetic products associated to the IHRF and to describe the elements to be considered in the corresponding metadata.
- To review the processing strategies for the determination of the potential values W_P and to recommend an appropriate computation procedure based on the accuracy level offered by those strategies.
- To review different approaches for the vertical datum unification and to provide guidance for the integration of the existing local height systems into the global IHRS/IHRF.
- To develop a strategy for the collocation of IHRF reference stations with existing geometrical reference stations at different densification levels.
- To make a proposal about the organizational and operational infrastructure required to maintain the IHRF and to ensure its sustainability.