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

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Thessaloniki, Greece, September 22, 2016
International Height Reference System (IHRS)  
IAG Resolution No. 1, Prague, July 2015

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

3) Parameters, observations and data in mean-tide system/mean crust (to support the combination of oceanic and continental realizations).
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For practical purposes, potential values $W(X)$ are to be transformed into potential differences with respect to a conventional $W_0$ value:

- $-\Delta W = C_p = W_0 - W_P$
- $C_p(t_0, X); dC_p(X)/dt$
- conventional fixed value $W_0 = \text{const.} = 62\,636\,853.4\,\text{m}^2\text{s}^{-2}$
- geopotential numbers are preferred, as they may be converted to any type of physical heights.

Remark:

- The determination of $X, \dot{X}$ 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: $\sim 3 \times 10^{-2} \text{ m}^2\text{s}^{-2}$ (about 3 mm).
  - Velocities: $\sim 3 \times 10^{-3} \text{ m}^2\text{s}^{-2}$ (about 0.3 mm/a).

The GGOS requirements are very ambitious. More realistic target values may be around

- Positions: $10 \times 10^{-2} \text{ m}^2\text{s}^{-2}$ (about 1 cm).
- Velocities: $10 \times 10^{-3} \text{ m}^2\text{s}^{-2}$ (about 1 mm/a).
Possibilities for the determination of $W_P$

- Levelling + Gravimetry:
  \[ W_P = W_0 - C_P; \quad C_P = \int_0^P g \, dn \]

- 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

- Combined (high-resolution) gravity field models:
  \[ W_P = f(X_P, GGM) \]
$W_P$ 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 $X$ 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 $\pm 200 \times 10^{-2}$ m$^2$s$^{-2}$ (~ $\pm 2$ m)
  - Desired accuracy for $W_P$: $\pm 10 \times 10^{-2}$ m$^2$s$^{-2}$
$W_p$ from high-resolution gravity field modelling

- **Accuracy:** some cm up to dm.
- **Advantages:**
  - High-precise satellite-only GGMs (SLR+GRACE+GOCE).
  - In some cases, terrestrial gravity data is only available at (for) national agencies (but not for global geoid modelling).
- **Main drawbacks:**
  - Lack of terrestrial gravity data (in sparsely surveyed regions).
  - Different standards applied in the local gravity field modelling.
  - Discrepancies between gravity field observables derived from the satellite-only GGMs.

**Example:**
- Differences between the $W_p$ values derived from EIGEN-6S4 (Förste et al. 2016) and GO_CONS DIR_R5 (Bruinsma et al. 2013)
- Differences
  - $-21 \times 10^{-2}$ to $7 \times 10^{-2}$ m$^2$s$^{-2}$
- Desired accuracy for $W_p$:
  - $\pm 10 \times 10^{-2}$ m$^2$s$^{-2}$
$W_P$ from Levelling + Gravimetry $\quad W_P = (W_{0\text{local}} + \delta W) - C_P$;

- **Relative** accuracy: mm, **absolute** accuracy: up to ±2 m.
- Advantage: basis for the height determination during the last 150 years.
- Drawback: local vertical datums, systematic errors in levelling, omission of time-dependent changes, etc.
- Requirement: **vertical datum unification within the IHRF**: determination of the potential differences between the global vertical datum $W_0$ and the local ones $W_{0i}$.
- Expected accuracy of the vertical datum parameters: cm in well-surveyed regions, dm in sparsely surveyed regions, extreme cases up to 1 m.

Example: **vertical datum parameters** (in cm) for the South American height systems w.r.t. the IHRS $W_0$ value.
Present challenges:

- Establishment of a vertical reference network as the main component of the *International Height Reference Frame* (IHRF).
- Determination of potential values $W_p$ at the reference network stations as accurate as possible.
1) To select a global reference network for the implementation of the IHRF (includes site specifications/characteristics)

- **Hierarchy:**
  - A global network $\rightarrow$ worldwide distribution
  - Regional and national densifications $\rightarrow$ local accessibility

- **Collocated with:**
  - fundamental geodetic observatories $\rightarrow$ connection between position vectors $X$, gravity potential $W$, reference clocks, and absolute gravity $g$;
  - continuously operating reference stations $\rightarrow$ to detect deformations of the reference frame;
  - geometrical reference stations of different densification levels $\rightarrow$ to allow access to the IHRF also in remote areas;
  - reference tide gauges and national vertical networks $\rightarrow$ vertical datum unification;

The IHRF is understood to be a component of the Global Geodetic Reference Frame (UN GGRF resolution 2015).
Strategy for the IHRS realization (2)

2) Compilation/generation of standards and conventions

- Identification of required standards and conventions for the IHRS realization:
  - Solid Earth/ocean/atmospheric tides,
  - Ocean/atmospheric/hydrological loading,
  - Plate tectonic motion, crustal deformation,
  - Precession, nutation,
  - LOD, polar motion,
  - Post-glacial rebound,
  - Is the precision of the reduction models sufficient?

- Handling of tide systems in vertical coordinates
  - Conventional conversion formulae between tide systems for consistent treatment.

- Modelling of non-linear motions
  - Conventional physical models
  - Can we assume dh/dt = dH/dt?

- Harmonization of analysis strategies, models, and products related to the Earth's geometry and gravity field (consistency between $X_p$ and $W_p$).
3) Estimation of potential values
   - Strategies for the determination of \( W \) and \( \dot{W} \) with high precision in accordance with the adopted standards and conventions
   - Specifications for procedures and computations
   - Molodensky approach to avoid disparities between orthometric hypothesis?
   - Fixed GBVP instead of scalar-free GBVP?
   - Which observational data are required?

4) Densification of the global network
   - by integration of the existing local height systems into the IHRF (vertical datum unification).

5) Maintenance and availability of the IHRF
   - Regular updates of the IHRF to take account for:
     - new stations;
     - coordinate changes with time \( \dot{X}, \dot{W} \);
     - improvements in the estimation of \( X \) and \( W \) (more observations, better standards, better models, better computation algorithms, etc.)
   - Geodetic products associated to the IHRF (description and metadata).
   - Organizational and operational infrastructure to ensure the IHRF sustainability.
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

1) Selection of core stations for the IHRF
   - in agreement with the GGOS Bureau for Networks and Observations, main requirement are gravity data around (~250 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.