GGOS Focus Area Unified Height System: Report, ongoing activities, outlook

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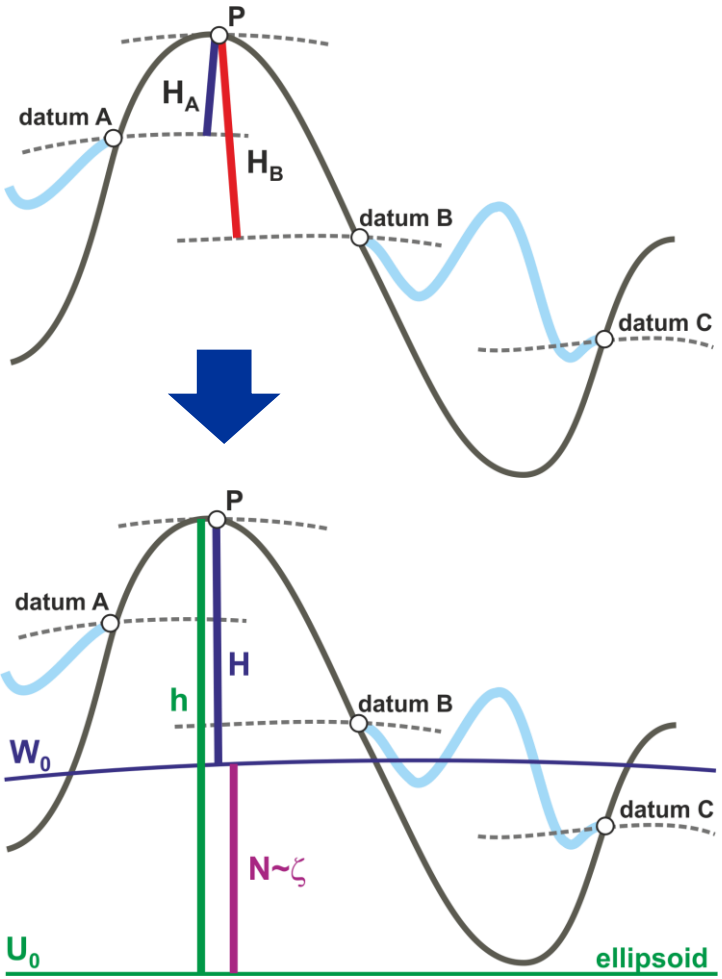
Introduction (1/2)

- The GGOS Focus Area Unified Height System (formerly Theme 1) was established during the GGOS Planning Meeting 2010 (February 1 - 3, Miami/Florida, USA).

- Objective: Unification of the existing height systems through the definition and realization of a global vertical reference system that
  - supports geometrical (ellipsoidal) and physical (normal, orthometric, geoid) heights world-wide with centimetre precision in a global frame;
  - enables the unification of all existing physical height systems (i.e., all geopotential differences shall be referred to one and the same reference equipotential surface with potential W_0); and
  - provides high-accuracy and long-term stability of the vertical coordinates.



Introduction (2/2)

- During the term 2011-2015, it was chaired by Michael Sideris (University of Calgary, Canada) and Johannes Ihde (Bundesamt für Kartographie und Geodäsie, Germany).
- The main result is the IAG resolution for the "Definition and realization of an International Height Reference System (IHRS)" released at the IUGG 2015 General Assembly in Prague, Czech Republic.
- The immediate objectives of the Focus Area Unified Height System are
  1) To define detailed standards, conventions, and guidelines to make the IAG Resolution applicable, and
  2) to establish the realization of the IHRS, i.e. the International Height Reference Frame (IHRF).

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

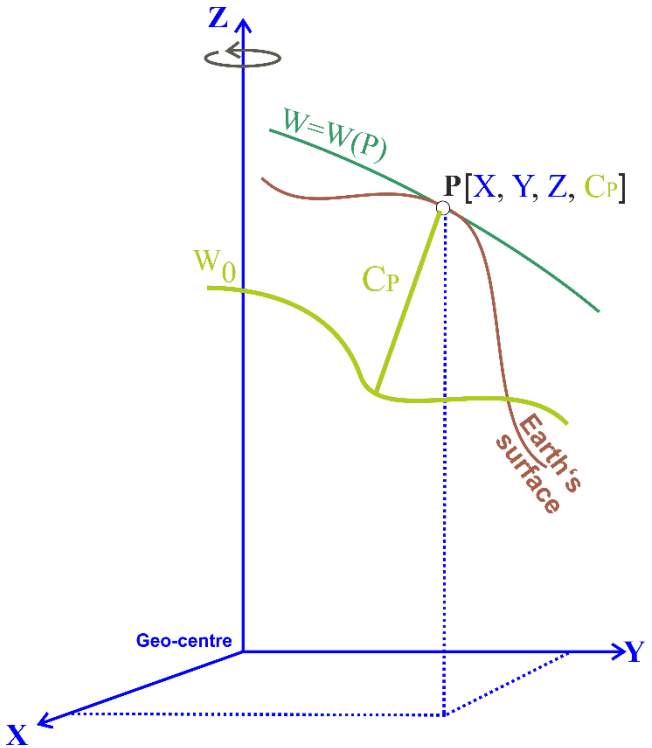
   $W_0 = \text{const.} = 62\,636\,853.4\ \text{m}^2\text{s}^{-2}$

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 estimation 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) Mean-tide system / Mean (zero) crust.

5) SI Units (meter and second).



Ongoing actions regarding the IHRS

1) Establishment of an International Height Reference Frame (IHRF)
   - Station selection for a global network (worldwide distribution) with regional and national densifications (local accessibility)
   - Determination of high-precise primary coordinates $\mathbf{X}_P$, $\dot{\mathbf{X}}_P$, W_P, $\dot{W}_P$ at the IHRF reference stations
2) Identification and preparation of 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.

Advances in the IHRS/IHRF implementation

1) Activities faced by the Joint Working Group on the Strategy for the Realization of the International Height Reference System (IHRS), (https://ihrs.dgfi.tum.de).

2) Coordinated work between:
   - GGOS Focus Area Unified Height System
   - GGOS JWG Establishment of the GGRF
   - International Gravity Field Service (IGFS)
   - IAG Commissions 1 (Reference Frames) and 2 (Gravity Field)
   - IAG Inter-commission Committee on Theory (ICCT)
   - Regional sub-commissions for reference frames and geoid modelling
   - GGOS Bureaus: Networks and Observations (BNO); Products and Standards (BPS).

3) Sep. 2016 (first meeting of the WG at GGHS2016, Thessaloniki): Brainstorming and definition of action items; criteria for the selection of IHRF stations.

4) Oct. 2016 (GGOS Days, Cambridge): Preliminary station selection for the IHRF.

5) Nov. 2016 – Mar. 2017: Interaction with regional/national experts about the preliminary station selection and proposal for further geodetic sites.

6) Apr. 2017: First proposal for the IHRF reference network.

7) Since May 2017: Numerical experiments for the computation of potential values $W(P)$ at the IHRF stations.

8) Since Aug. 2017 (IAG-IASPEI Assembly, Kobe): Discussion on standards and conventions for the IHRS/IHRF.

Criteria for the IHRF reference network configuration

1) Structure:
   - A global network → worldwide distribution with
   - A core network → to ensure sustainability and long term stability
   - Regional and national densifications → local accessibility

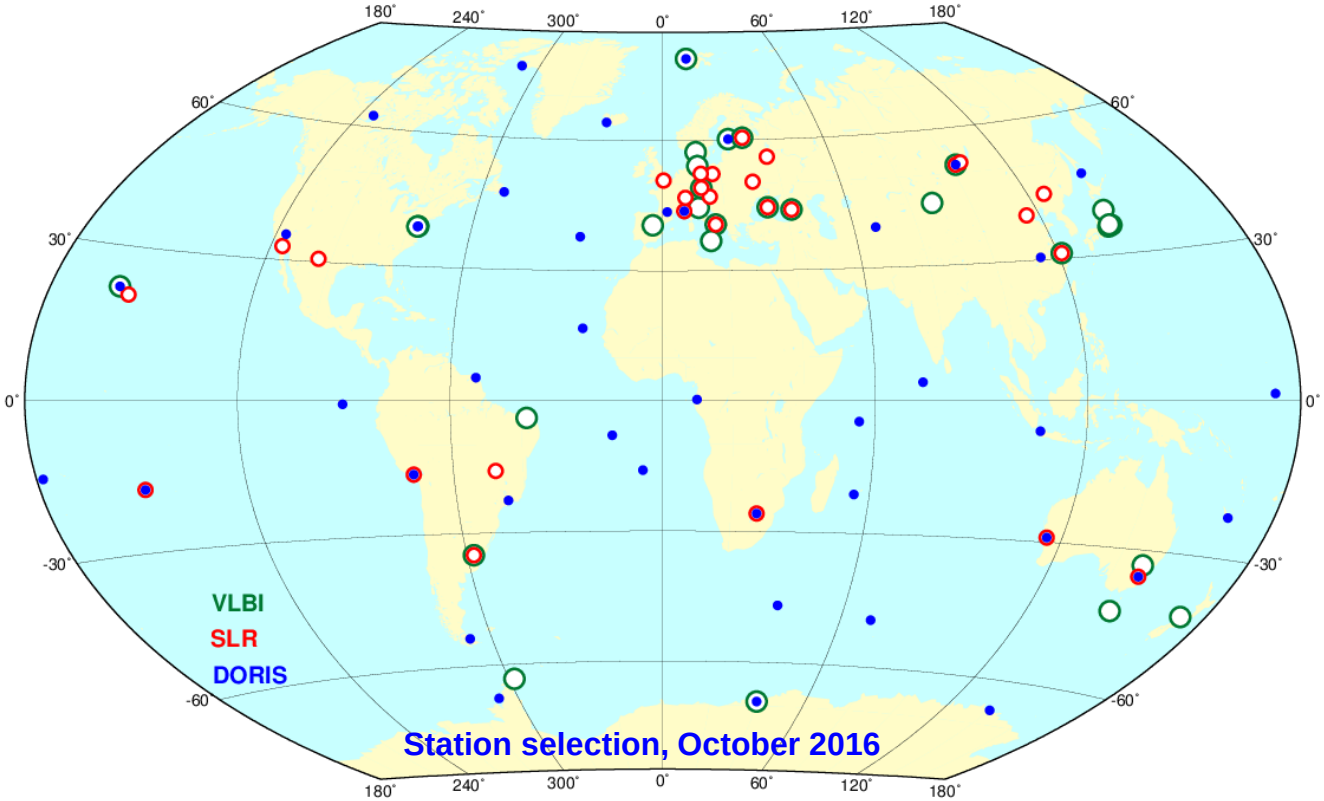
2) Collocated with:
   - fundamental geodetic observatories → connection between $\mathbf{X}$, W, g and time realization (reference clocks) → to support the GGRF;
   - continuously operating reference stations → to detect deformations of the reference frame;
   - reference tide gauges and national vertical networks → vertical datum unification;
   - reference stations of the new Global Absolute Gravity Reference System (see IAG Resolution 2, Prague 2015).

3) Main requirement: availability of terrestrial gravity data around the IHRS reference stations for high-resolution gravity field modelling (i.e., precise estimation of W).

Preliminary selection of IHRF reference stations (Oct. 2016)

Preliminary selection based on VLBI, SLR and DORIS reference sites co-located with GNSS:

- VLBI and SLR sites guarantee a long-term perdurability/maintenance of the geodetic facilities.
- DORIS and GNSS guarantee a homogeneous distribution worldwide.
- The GGOS Bureau for Networks and Observations supports this task with an inventory about further co-located observables at each site (e.g. absolute gravity, superconducting gravity-meter, reference clocks involved in the TT realization, etc.).

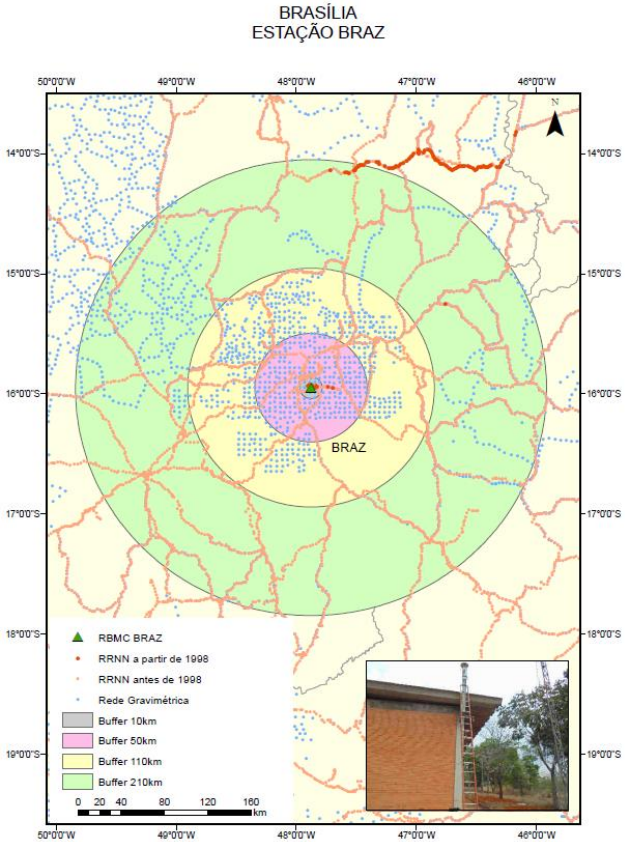


Refined station selection for the IHRF

Based on the preliminary station selection of Oct. 2016, national/regional experts were asked to

1) evaluate whether these sites are suitable to be included in the IHRF: Are gravity data around these sites available? If not, is it possible to survey gravity around them?

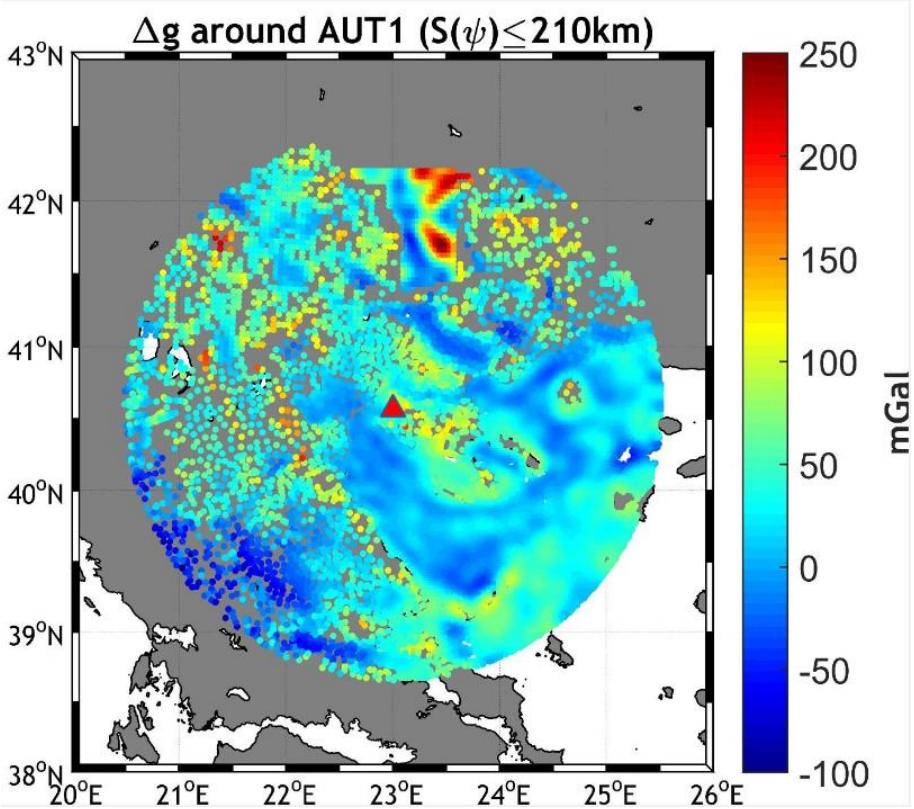
2) propose additional geodetic sites to improve the density and distribution of the IHRF stations in their regions/countries:
   - proposed sites shall be materialized by a continuous operating GNSS station;
   - stations belonging to the regional reference frames (like SIRGAS, EPN, APREF, etc.) are preferred;
   - gravity data around the proposed stations must be available;
   - GNSS stations co-located with the reference tide gauges and connected to the national levelling networks are required.



S. Costa and R. LUZ, IBGE, Brazil

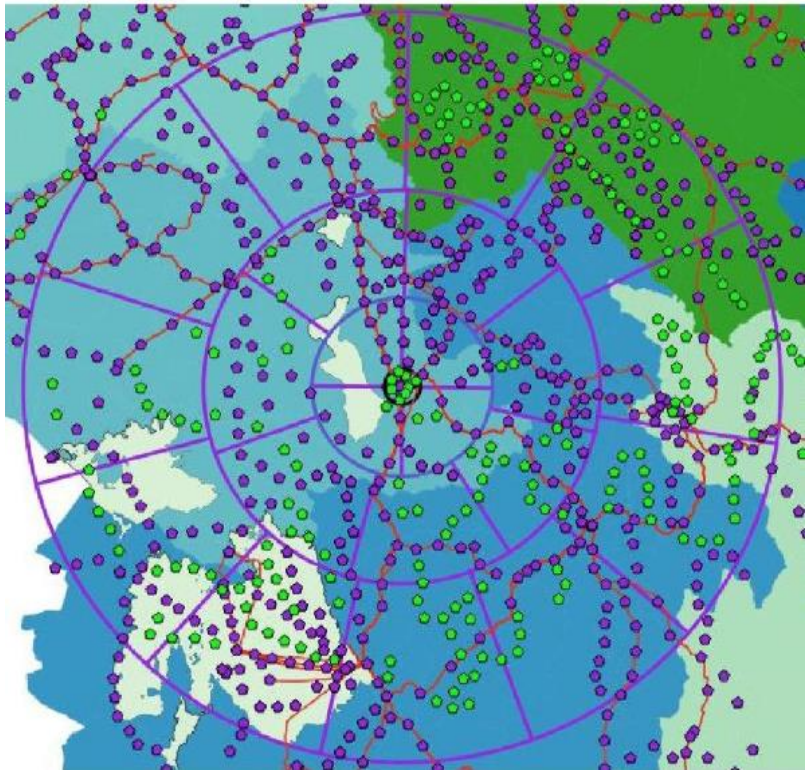
Refined station selection for the IHRF

EUREF station AUT1
Thessaloniki, Greece



G.S. Vergos and I.N. Tziavos, AUTH, Greece

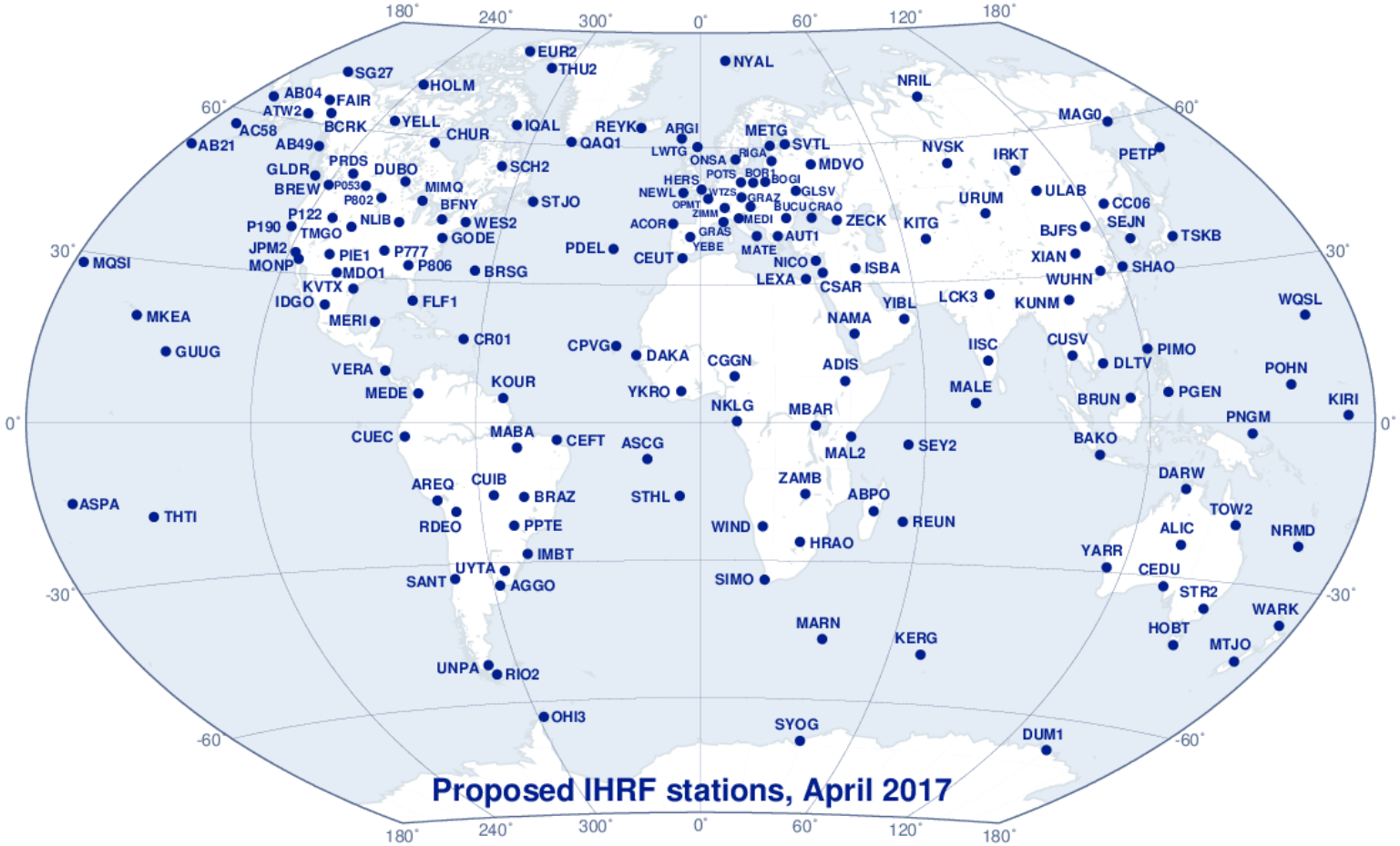
SIRGAS station RDEO
Challapata, Bolivia



A. Echalar, IGM, Bolivia

First proposal for the IHRF reference network (Apr. 2017)

163 proposed stations after the feedback from the regional/national experts. In those regions with poor coverage (specially in Africa and Asia), other IGS stations were added.



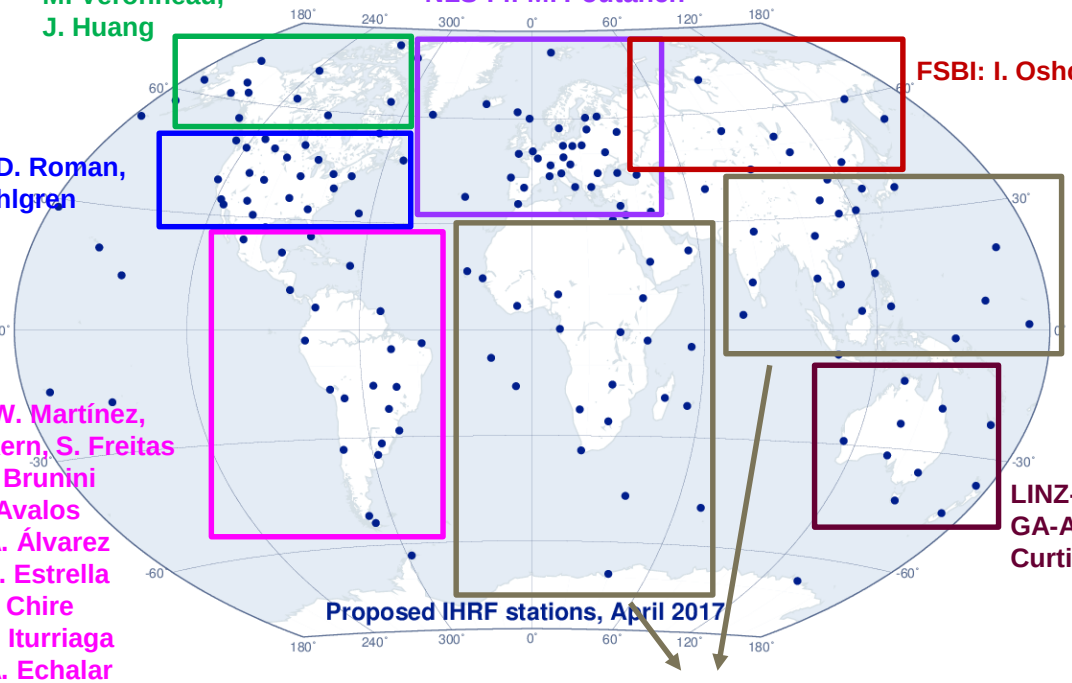
Interaction with regional/national experts for the IHRF station selection

IGIK-Pl: J. Krinsky
DTU-Dk: R. Forsberg
AUTH-Gr: G. Vergos
LGIA-LV: I. Liepins
LM-Se: J. Ågren, Nordic Geodetic Commission (NGK)
Swisstopo-Ch: U. Martí
IGN-Es: P. Vaquero
NLS-Fi: M. Poutanen

NRCan:
M. Véronneau,
J. Huang

FSBI: I. Oshchepkov

NGS/NOAA: D. Roman,
K. Choi, K. Ahlgren



SIRGAS: W. Martínez,
M.V. Mackern, S. Freitas
AGGO: C. Brunini
INEGI: D. Avalos
IGN-CR: A. Álvarez
IGM-Ec: C. Estrella
IGN-Pe: J. Chire
IGM-Cl: C. Iturriaga
IGM-Bo: A. Echalar
IGN-Ar: D. Piñon
SGM-Uy: N. Suárez
IBGE: S. Costa, R. Luz
EPUSP: D. Blitzkow, A.C.O.C. Matos

LINZ-Nz: M. Amos
GA-Au: R Ruddick
Curtin-Au: W. Featherstone

IGS stations
Since Aug. 2017:
H.A. Abd-Elmotaal (Egypt)
K. Matsuo (Japan)

Numerical experiments for the computation of the potential values $W(P)$ (1/2)

1) Based on this station selection, current efforts concentrate on the computation of the potential values $W(P)$ and the assessment of their accuracy.

2) Different approaches are being evaluated.

   – Simulations about the distribution and quantity of gravity points needed around the IHRF stations,
   – Simulations about the variation of potential values with time; i.e., $\dot{W}(P)$,
   – Comparison of different mathematical formulations (least-squares collocation, FFT, radial basis functions, etc.),
   – Computation of potential values (and their accuracy) based on global gravity models of high-degree (like XGM2016, EIGEN-6C, EGM2008, etc.),
   – Recovering potential values from existing local quasi-geoid models.

3) Objective: to identify detailed standards and conventions for the IHRS realization after the comparison of the results obtained from these different approaches.

Numerical experiments for the computation of the potential values $W(P)$ (2/2)

1) Computation of potential values using the latest GGMs of high-resolution:
   - EGM2008 (Pavlis et al., 2012), lmax = 2190
   - EIGEN-6C4 (Förste et al., 2014), lmax = 2190
   - XGM2016 (Pail et al., 2017), lmax = 719, extended to lmax = 2190 with EIGEN-6C4

2) Canada (M. Véronneau, J. Huang) provided terrestrial gravity data, we, at DGFI-TUM, are using different approaches for the computation of the potential values. They also provided potential values at the Canadian IHRF stations inferred from the current Canadian geoid.

3) H. Denker (IFE/LUH, Germany) computed potential values for the European IHRF stations using the same data and methodology he applies for the determination of the European quasi-geoid.

4) D. Blitzkow and A.C.O.C. Matos (EPUSP, Brazil) are computing potential values for the Brazilian IHRF stations using the same data and methodology they apply for the determination of the South American geoid.

5) G. Vergos (AUTH, Greece) performed different computations at the station AUT1 (Thessaloniki).

6) S. Freitas and J.L. Carrión-Sánchez (UFPR, Brazil) are testing different computation methods with different kinds of data at the reference tide gauge of Ecuador.

Main conclusions after the numerical experiments on $W(P)$ (1/2)

1) For highest accuracy, especially in mountain areas, it is not sufficient to use a combined GGM of high resolution (e.g. EGM2008, EIGEN-6C4, XGM2016), differences up to ±4 m^2s^{-2} (± 40cm).

2) High resolution local/regional gravity potential modelling is needed to realize IHRS, at least for the more accurate applications (at the 1 cm-level).

3) However, different processing strategies produce different potential values (up to ±1.2 m^2s^{-2} → ±12 cm). How can we ensure that the different computations are realising the same IHRS?

4) A "standard" procedure may not be suitable, as
   - different data availability and different data quality around the world exist (e.g. terrestrial gravity data, terrain models, GPS/levelling, etc.)
   - regions with different characteristics require particular approaches (e.g. modification of kernel functions, size of integration caps, geophysical reductions like GIA, etc.)

5) A "centralised" computation (like in the ITRF) is (still) complicated due to the restricted accessibility to terrestrial gravity data.

Main conclusions after the numerical experiments on $W(P)$ (2/2)

6) To fully exploit the existing data (to get the best possible accuracy), national/regional experts (managing the local gravity data) must be involved in the determination of the potential values at the IHRF stations located in their countries/regions.

7) To ensure consistency, we have to standardize as much as possible to get as similar and compatible results as possible with the different methods.

8) We have to formulate basic (or minimum) requirements, which a local/regional gravity potential or (quasi-)geoid computation has to fulfil to be considered as realization of the IHRS. Besides this, we can leave the choice of the method open to the gravity field modeller.

9) Nevertheless, we should work towards a standardization of the “IHRS method” as a long term goal.

Present activities and outlook (1/2)

1) Discussion on primary standards (started in Kobe, Aug 2017):
   - GGOS JWG: Strategy for the Realization of the IHRS (chair: L. Sánchez)
   - GGOS JWG: Establishment of the GGRF (chair: U. Martí)
   - IAG SC 2.2: Methodology for geoid and physical height systems (chair: J. Ågren)
   - ICCT JSG 0.15: Regional geoid/quasi-geoid modelling - Theoretical framework for the sub-centimetre accuracy (chair: J. Huang)
   - IAG JWG 2.2.2: The 1 cm geoid experiment (chair: Y.M. Wang)
   - IGFS: International Gravity Field Service (chair: R. Barzaghi, director Central Bureau: G. Vergos)
   - J. Mäkinen – tide system issues for the IHRS/IHRF
   - Recommendations of the GGOS-BPS Inventory (Angermann et la. 2016)

Present activities and outlook (2/2)

2) Experiment for “calibrating” computation methods:

- NGS/NOAA (Y.M. Wang) will provide terrestrial gravity data, airborne gravity, a digital terrain model, deflexions of the vertical and GPS/levelling data for an area of about 700 km^2 in Colorado, USA.
- With these data, the different processing groups should compute potential values for some virtual IHRF stations in that region.
- The results obtained individually should be compared to identify sources of discrepancy between the different computation methods.
- At present, the airborne gravity is being measured. It is expected to get access to the complete data set by spring 2018.
- Initial contributors: J. Ågren, J. Huang, L. Sánchez, V. Lieb, Y.M. Wang, I. Oshchepkov, V. Grigoriasis, S. Claessens, G. Vergos (more colleagues are welcome!).
- First results to be presented at the Symposium GGHS2018, Sep 17 - 21, 2018, Copenhagen, Denmark.

Initial standards/conventions

To compare the computation methods, all participants must use the same input data and basic characteristics. We outline at this first step:

- Molodensky approach to avoid orthometric hypotheses.
- Normal gravity field GRS80 and the IHRS W_0 for the zero degree correction.
- First degree terms assumed to be zero ($\mathrm{N1} = \zeta 1 = \mathrm{T1} = 0$). By this assumption, the geocenter is aligned with the origin of the selected ITRFXXXX.
- All computations in zero-tide system and then transformation of the final coordinates to the mean-tide system.
- Common satellite-only GGM: GOCO05s (Mayer-Gürr T., et al. 2015).
- Common high-resolution GGM: XGM2016 (Pail et al., 2017).

Immediate open questions:

1) ITRF coordinates in conventional tide-free system; IHRF coordinates in mean tide system. How make them consistent for the final user?
2) Should "common" GGM be replaced by "conventional" GGM? Who should decide on this? IGFS? IAG Commission 2? Colleagues working on the IHRF? IERS?
3) Should we use an updated (modern) reference ellipsoid instead of the GRS80?

Publications, presentations, business meetings

Papers

Sánchez L., Cunderlík R., Dayoub N., Mikula K., Minarechová Z., Šíma Z., Vatrt V., Vojtíšková M.: A conventional value for the geoid reference potential W_0. J. Geod., 10.1007/s00190-016-0913-x, 2016

Ihde J., Sánchez L., Barzaghi R., Drewes H., Foerste Ch., Gruber T., Liebsch G., Marti U., Pail R., Sideris M.: Definition and proposed realization of the International Height Reference System (IHRS). Surveys in Geophysics, 10.1007/s10712-017-9409-3, 2017

Sánchez L., Sideris M.G.: Vertical datum unification for the International Height Reference System (IHRS). Geophysical Journal International 209(2), 570-586, 10.1093/gji/ggx025, 2017

Sánchez L., Martí U., Ihde J.: Le chemin vers un système de référence altimétrique global et unifié. Association Française de Topographie, Revue XYZ 150: 61-67, 2017

Sánchez L. Chapter 4.6 Height systems and their realizations of the Inventory of standards and conventions used for the generation of IAG products, Angermann et al. 2016.

Scientific meetings

IAG-IASPEI 2017 Joint Assembly, Kobe, Japan, 2017-08-01
Unified Analysis Workshop 2017 (UAW2017), Paris, France, 2017-07-12
European Geosciences Union (EGU) General Assembly 2017, Vienna, Austria, 2017-04-27
Conseil national de l'information géographique, Paris, France, 2017-03-15
Symposium SIRGAS 2016, Quito, Ecuador, 2016-11-18
GGOS Days 2016, Cambridge (MA), USA, 2016-10-26

Business meetings

at the IAG-IASPEI 2017 Joint Scientific Assembly, Kobe, Japan, July 31, 2017
at the GGHS 2016 Symposium, Thessaloniki, Greece, September 21, 2016

Acknowledgments

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More information at
http://ihrs.dgfi.tum.de, www.ggos.org