Achievements of the GGOS Focus Area Unified Height System

Laura Sanchez and Riccardo Barzaghi

Abstract

The Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG) promotes the standardisation of height systems worldwide. The GGOS Focus Area Unified Height System (GGOS-FA-UHS) was established to lead and coordinate the efforts needed towards the establishment of a global standard for the precise determination of physical heights. During the 2011–2015 term, various discussions focused on the best possible definition of a global unified vertical reference system, resulting in the IAG Resolution for the *Definition and Realisation of an International Height Reference System* (IHRS), which was adopted at the 2015 General Assembly of the International Union of Geodesy and Geophysics (IUGG) in Prague, Czech Republic. During the period 2015–2019, activities were undertaken to investigate the best strategy for the implementation of the IHRS; i.e., the establishment of the *International Height Reference Frame* (IHRF). A preliminary selection of stations for the IHRF reference network was made and different calculation methods for the determination of potential values as IHRF coordinates were evaluated. For the period 2019–2023, the objectives of the GGOS-FA-UHS focused on (*i*) compiling detailed standards, conventions and guidelines to support a consistent determination of the IHRF at global, regional and national levels; (*ii*) coordinating with regional/national experts in gravity field modelling the computation of a first IHRF solution; and (*iii*) designing an operational infrastructure that will ensure the long-term sustainability and reliability of the IHRS/IHRF. This infrastructure was approved by the IAG Executive Committee in December 2023 and will operate under the responsibility of the International Gravity Field Service (IGFS). With these objectives achieved, the GGOS-FA-UHS completed its goals and was closed during the IUGG 2023 General Assembly in Berlin, Germany. This paper presents a comprehensive report on the activities and achievements of the GGOS-FA-UHS.

Keywords

Global unified height system · IHRF Coordination Centre · International Height Reference System (IHRS) and Frame (IHRF) · Reference level W_0 · World height system

L. Sanchez (✉)
Deutsches Geodätisches Forschungsinstitut, Technische Universität München (DGFI-TUM), Munich, Germany
e-mail: lm.sanchez@tum.de

R. Barzaghi
Department of Civil and Environmental Engineering, Politecnico di Milano, Milan, Italy
e-mail: riccardo.barzaghi@polimi.it

International Association of Geodesy Symposia,
https://doi.org/10.1007/1345_2024_249,

1 Introduction

Most existing physical height systems do not meet the accuracy requirements of modern geodesy. They refer to local sea surface levels, are stationary (do not consider time variations), realise different types of physical heights (orthometric, normal, normal-orthometric heights, etc.), and their combination in a global frame leads to uncertainties on the metre scale. The International Association of Geodesy (IAG), as the organisation responsible for the advancement of the science of Geodesy, promotes the definition and implementation of geodetic reference systems that respond to the increased precision of modern observation techniques and can support the current needs of science and society for high-resolution georeferenced data (IAG 2017). In recent decades, enormous progress has been made in the *International Celestial Reference System* (ICRS, Ma and Feissel 1997) and the *International Terrestrial Reference System* (ITRS, Petit and Luzum 2010) as well as in their realisations the *International Celestial Reference Frame* (ICRF) and the *International Terrestrial Reference Frame* (ITRF), respectively. The definition, implementation, and maintenance of the ICRS/ICRF and ITRS/ITRF guarantee a globally unified geometric reference frame with cm-level reliability. An equivalent high accuracy global physical reference system needs to be implemented. There is no doubt that the existing height systems follow the best conditions offered by the state of the art at the time they were established. However, they have been realised individually, generally using non-standardised procedures. As a result, there are currently about hundred local and regional physical height systems in use, with discrepancies between them of up to ± 2 m. The geodetic data that depend on them (e.g., physical heights, gravity anomalies, geoid models, digital terrain models, etc.) are usable only in limited geographical areas; their global combination or with satellite-based data (in particular Global Navigation Satellite System (GNSS) positioning) show discrepancies of much greater magnitude than the accuracy required today.

The GGOS Focus Area Unified Height System (GGOS-FA-UHS, formerly GGOS Theme 1) was established during the 2010 GGOS Planning Meeting with the aim of bringing together existing initiatives for the establishment of a global unified vertical reference system and to address the activities to be undertaken. The starting point was the results of the IAG Inter-Commission Project 1.2 Vertical Reference Frames (IAG-ICP1.2-VRF; Ihde 2007), summarised in the document *Conventions for the Definition and Realisation of a Conventional Vertical Reference System—CVRS* (Ihde et al. 2007). Based on this document, the initial objectives of the GGOS-FA-UHS were defined as (Sideris and Ihde 2012; Sánchez 2016):

- Refine standards and conventions for the definition and realisation of a global unified vertical reference system, including unification/harmonisation of standards and conventions that are used by the geometric and gravity Scientific Services of the IAG.
- Make a recommendation about the reference value W_0 to be adopted as the conventional reference level for the global vertical reference system.
- Coordinate the generation of a set of consistent geodetic products for the realisation of the global vertical reference system, including a global vertical reference frame with regional and national densifications and a catalogue and guidelines for height system unification.
- Design of strategies for the appropriate maintenance and use in practice of the global vertical reference system considering determination of time-dependent changes and the alignment/update of the definition and its realisation with future improvements in geodetic observations, data analysis, and modelling.
- Servicing the vertical datum needs of other geosciences such as, e.g., hydrography and oceanography.

In line with these objectives, the following is a summary of the progress made towards the establishment of a unified global vertical reference system.

2 Inventory of Standards Presently Used in the Vertical Coordinate Determination

GGOS, through its Bureau of Products and Standards (GGOS-BPS), started in 2012 to compile an inventory of standards, constants, resolutions, and conventions adopted and used by IAG and its components for the generation of IAG products. The aims are to contrast adopted and applied standards and conventions, to identify gaps, inconsistencies, and deficiencies, and to propose new standards where appropriate. The first version of the GGOS-BPS inventory was published in 2016 (Angermann et al. 2016) and an updated version, including recent innovations in geodetic data analysis and modelling, was published in 2020 (Angermann et al. 2020). The GGOS-FA-UHS supported this activity by compiling and updating *Chapter 4.6 Height Systems and their Realisations*. This document describes in detail the discrepancies of the local physical height systems and their combination with geometric (ellipsoidal) heights and geoid undulations or height anomalies. In the 2016 version of the inventory, particular care was taken to provide a detailed list of corrections or reductions applied to the various vertical coordinates to remove or preserve geophysical effects that affect vertical positioning. In the 2020 update, a description of the standards outlined for the implementation of a global unified height system has been included (see next section).

3 Conventions for the Definition of a Global Vertical Reference System

In 2014, an ad-hoc group was established with the objective to outline the minimal requirements for the definition and realisation of a global unified physical vertical reference system (Ihde et al. 2015). The first recommendation of the ad-hoc group was to introduce a univocal name for the new system. During the last four decades, various names have been used to identify a global vertical reference system; e.g., world height system, global vertical datum, world vertical datum, global vertical network, global height datum unification, global unification of height systems, global unified height reference system, etc. To avoid this multiplicity of names, the ad-hoc group recommended the name *International Height Reference System* (IHRS) with the realisation *International Height Reference Frame* (IHRF). This name is consistent with other reference systems and frames used in Geodesy: ICRS/ICRF, ITRS/ITRF and ITGRS/ITGRF. The latter refers to the *International Terrestrial Gravity Reference System and Frame* (Wziontek et al. 2021).

The ad-hoc group focused on discussing the basic requirements for the establishment of a physical reference system, including a reference for gravity field dependent heights and a reference for gravimetry. The recommendations of this group were discussed during the 2015 General Assembly of the International Union of Geodesy and Geophysics (IUGG) and were presented and officially adopted by two IAG resolutions (Drewes et al. 2016): The first resolution is dedicated to the definition and implementation of an *International Height Reference System*. The second resolution focuses on the establishment of a *Global Absolute Gravity Reference System*.

The foundations for the definition and realisation of the IHRS are extensively discussed in Ihde et al. (2017). This publication is the scientific basis for the IAG Resolution No. 1, 2015 and provides the framework for the realisation of the IHRS. The fundamental conventions for the definition of the IHRS are:

- The vertical reference level is an equipotential surface of the Earth gravity field with the geopotential value $W_0 = 62{,}636{,}853.4\ \mathrm{m}^2\ \mathrm{s}^{-2}$. W_0 is understood to be the potential of the geoid or the geoidal potential value.
- Parameters, observations, and data shall be related to the mean tidal system/mean crust.
- The unit of length is the metre, and the unit of time is the second of the International System of Units (SI).
- The vertical coordinates are the differences $-\Delta W(P)$ between the potential $W(P)$ of the Earth's gravity field at the considered point P, and the geoidal potential value W_0; the potential difference $-\Delta W(P)$ is also designated as geopotential number $C(P) = -\Delta W(P) = W_0 - W(P)$.
- The spatial reference of the position P for the potential $W(P) = W(\mathbf{X}_P)$ is given by the coordinate vector $\mathbf{X}_P = \mathbf{X}(P)$ in the ITRS/ITRF.

The estimation of the coordinates $\mathbf{X}(P)$, $W(P)$ (or $C(P)$) includes their variation with time; i.e., $d\mathbf{X}(P)/dt$, $dW(P)/dt$ (or $dC(P)/dt$). For practical purposes, positions $\mathbf{X}(P)$ may be transformed to ellipsoidal coordinates to get the geometric (or ellipsoidal) heights $h(P)$, and $C(P)$ may be transformed to a physical height (orthometric H, dynamic H^d or normal height H^*).

4 Conventional Reference Value W_0

W_0 is defined as the potential value of a particular level surface of the Earth's gravity field called the geoid. Since the most accepted definition of the geoid is understood to be the equipotential surface that coincides with the worldwide mean ocean surface, a usual empirical approximation to W_0 is the averaged potential value W_S at the mean sea surface. In this way, W_0 depends not only on the Earth's gravity field modelling, but also on the mean sea surface modelling. Consequently, like any reference parameter, W_0 should be based on adopted conventions that guarantee its uniqueness, reliability, and reproducibility; otherwise, there would be as many W_0 reference values as computations. During the 2011 IUGG General Assembly, the GGOS-FA-UHS, the IAG Commissions 1 (Reference Frames) and 2 (Gravity Field) and the IGFS established a joint working group devoted to the Vertical Datum Standardisation (Sánchez 2012; Sánchez et al. 2014). The main objective was to recommend a convention for the geopotential value W_0 to be introduced as the reference level for the realisation of the IHRS. At that time, the most used W_0 value was the one included as a conventional constant in the conventions of the International Earth Rotation and Reference Systems' Service (IERS; Petit and Luzum 2010). This so-called IERS W_0 value corresponded to a best estimate available in 1998 (Burša et al. 1998; Groten 1999, 2004). It presents discrepancies of about $-2.6\ \mathrm{m}^2\ \mathrm{s}^{-2}$ (corresponding to a level difference of around +27 cm) with respect to newest computations based on the latest Earth's surface and gravity field models (e.g. Čunderlík and Mikula 2009; Čunderlík et al. 2014; Dayoub et al. 2012; Sánchez 2008). This working group convened the different groups working on the determination of a global W_0 to coordinate a unified computation (cf. Sánchez et al. 2014). Following aspects were analysed:

- Sensitivity of the W_0 estimation to the Earth's gravity field model (especially omission and commission errors and time-dependent Earth's gravity field changes).
- Sensitivity of the W_0 estimation to the mean sea surface model (e.g., geographical coverage, time-dependent

sea surface variations, accuracy of the mean sea surface heights).
- Weighted computation of the W_0 value based on the input data quality.

Different methodologies, different global gravity models, different mean sea surface models, different reference epochs, and different weights for the input data were evaluated. Based on the results, detailed conventions to ensure the reproducibility of a reference W_0 value were outlined. As the usual approximation of W_0 is the averaged potential value W_S at the mean sea surface; it is expected that W_0 changes in the same way as W_S changes. However, W_0 as a reference parameter should be defined as time-independent, and it should be necessary to decouple it from the Earth's gravity field and sea surface variations. Thus, it was recommended to adopt the potential value valid at a certain epoch and to keep it fixed for a long-term period (e.g., 30 years). If desired, it is possible to monitor the changes of the potential value W_S at the sea surface and to compare it with the adopted W_0 value. When large differences appear (e.g., $> \pm 2$ m^2 s^{-2}, equivalent to a mean sea level change of ± 20 cm) the adopted W_0 may be replaced by an updated value. In conclusion, the working group members recommended the potential value obtained for the epoch 2010.0 (62,636,853.4 m^2 s^{-2}) as the present best estimate for the W_0 value. IAG accepted this recommendation and adopted this value as the conventional reference level for the realisation of the IHRS, see IAG Resolution 1, 2015. A detailed description of the W_0 computation strategy, conventions, and results is given by Sánchez et al. (2016).

During the GGOS/IERS Unified Analysis Workshop held in Paris, France, July 10–12, 2017, the GGOS-BPS pointed out the necessity of consistency between the IERS Conventions and the IAG Resolution No. 1, 2015 and recommended the use of the IAG conventional W_0 value whenever a reference potential is needed in geodetic work. IERS followed this recommendation and in Nov 17, 2017, the old W_0 value from 1998 was replaced with the new one in the IERS Conventions (see IERS Convention 2010, version 1.1.0, available at http://iers-conventions.obspm.fr/conventions_versions.php#official_target).

5 Reference Network for the Establishment of the International Height Reference Frame (IHRF)

It is proposed that the IHRF follows the same structure as the ITRF: a global network with regional and national densifications, whose geopotential numbers referring to the global IHRF are known. To advance in this goal, the GGOS-FA-UHS installed the joint working group *Strategy for the Realisation of the IHRS* for the term 2015–2019 (Sánchez 2019). This working group was supported by the IGFS, the IAG Commissions 1 and 2 (*Reference Frames* and *Gravity field*), the *Inter-commission Committee on Theory* (ICCT), the *regional sub-commissions for reference frames and geoid modelling*, and both *GGOS Bureaus* (*Networks and Observations* and *Products and Standards*). In particular, there was a strong cooperation with the IAG joint working group 2.2.2: *The 1-cm geoid experiment* (Wang and Forsberg 2019); the IAG Sub-Commission 2.2: *Methodology for geoid and physical height systems* (Ågren and Ellmann 2019), the ICCT joint study group 0.15: *Regional geoid/quasi-geoid modelling - Theoretical framework for the sub-centimetre accuracy* (Huang and Wang 2019) and the IAG joint working group 2.1.1: *Establishment of a global absolute gravity reference system* (Wziontek and Bonvalot 2019).

A brainstorming and definition of action items took place at a working group meeting carried out during the *International Symposium on Gravity, Geoid and Height Systems 2016* (GGHS2016) in Thessaloniki (Greece) in Sep 2016. This meeting was attended by 70 colleagues and allowed us to identify the activities to be faced immediately. A main output are the criteria for the selection of IHRF reference stations:

- GNSS continuously operating reference stations to detect reference frame deformations.
- Co-location with fundamental geodetic observatories to ensure a consistent connection between geometric coordinates, potential and gravity values, and reference clocks.
- Co-location with reference stations of the ITGRF.
- Preference of stations belonging to the ITRF and the regional reference frames (like SIRGAS, EPN, APREF, etc.).
- Co-location with reference tide gauges and connection to the national levelling networks to facilitate the vertical datum unification.
- Availability of terrestrial gravity data around the IHRF reference stations as main requirement for high-resolution gravity field modelling (i.e., precise estimation of potential values).

Based on these criteria, a preliminary station selection for the IHRF was initiated in 2016. This selection was based on a global network with worldwide distribution, including a core network (to ensure sustainability and long-term stability of the reference frame) and regional/national densifications (to provide local accessibility to the global frame). The core network includes fundamental geodetic observatories, ITRF sites with more than two space geodetic techniques, ITGRF reference stations and selected IGS reference stations to ensure a global coverage as homogeneous as possible. During 2017–2018, regional and national experts were asked to evaluate whether the preliminary selected sites are suitable to be included in the IHRF (availability of gravity data or possibilities to survey them); and to propose additional geodetic sites to improve the density and distribution of the IHRF stations in their regions/countries. After the feedback from the regional/national experts, the first approximation to the IHRF reference network was completed in 2019. This network comprises about 170 stations and currently, it is regularly refined in agreement with changes/updates of other geodetic reference frames (ITRF and ITGRF and their densifications).

6 Determination of Potential Values as IHRS Coordinates

After the preliminary station selection for the IHRF reference network, efforts concentrated on the computation of station potential values and the assessment of their accuracy. Different approaches were evaluated:

– As some national/regional experts provided us with terrestrial gravity data around some IHRF sites, a direct computation of potential values was performed using a combination of terrestrial gravity data and different global gravity models (GGM) as well as different mathematical formulations (least-squares collocation, Fast Fourier Transformation, radial basis functions, etc.).
– Computation of potential values by national/regional experts responsible for the geoid modelling using their own data and methodologies.
– Computation of potential values based on GGM of high-resolution (such as XGM2016 (Pail et al. 2018), EIGEN-6C4 (Förste et al. 2014), EGM2008 (Pavlis et al. 2012), etc.).
– Recovering potential values from existing local models of geoid undulations or height anomalies.

The comparison of the results showed discrepancies up to the dm-level. The main conclusions of this experiment were:

– The use of only GGMs is (at present) not suitable for the estimation of precise potential values. GGMs may be used if there is *no other way* to determine potential values (e.g., Sánchez et al. 2021; Wang et al. 2021)
– A *standard* procedure for the computation of potential values may be not appropriate as different data availability and different data quality exist around the world and regions with different characteristics require particular approaches (e.g., modification of kernel functions, size of integration caps, geophysical reductions like the global isostatic adjustment, etc.).
– A *centralised* computation (like in the ITRF) is complicated due to the restricted accessibility to terrestrial gravity data.

To overcome these inconveniences, during the *IAG-IASPEI Joint Scientific Assembly* (Kobe, Japan, Aug 2017) was agreed to initiate a new experiment towards:

– The computation of IHRF coordinates using exactly the same input data and the own methodologies (software) of colleagues involved in the gravity field modelling, and
– The comparison of the results, to identify a set of standards that allow to get as similar and compatible results as possible.

In the same IAG-IASPEI 2017 Assembly, J. Ågren (Chair of IAG SC 2.2; Ågren and Ellmann (2019)) and J. Huang (Chair of ICCT JSG 0.15, Huang and Wang (2019)) proposed to establish an interaction with the JWG 2.2.2 (chaired by Y.M. Wang, Wang and Forsberg (2019)). Aim of JWG 2.2.2 was the computation and comparison of geoid undulations using the same input data and the own methodologies/software of colleagues involved in the geoid computation. The comparison of the results should highlight the differences caused by disparities in the computation methodologies. In this frame, it was decided to extend the *geoid experiment* to the computation of station potential values as IHRF coordinates. With this proposal, the US NGS/NOAA agreed to provide terrestrial and airborne gravity data and a digital terrain model for an area of about 730 km $\times$ 560 km with height variations up to 3,000 m in Colorado (USA). With the NGS/NOAA data, different groups working on the determination of IHRF coordinates computed potential values for some virtual geodetic stations located in that region. Afterwards, the results of the individual groups were compared with the *Geoid Slope Validation Survey 2017* (GSVS17, Van Westrum et al. 2021), which provides potential differences inferred from first order levelling measurements and gravity corrections along a validation line. The Colorado data were distributed in Feb 2018, together with a document summarising a minimum set of basic requirements (standards) for the computations in order to get as similar and compatible results as possible (Sánchez et al. 2018).

Fourteen solutions contributed to this experiment (Wang et al. 2021; Sánchez et al. 2021). When evaluating them to the independent GSVS17 GNSS/levelling data, it was proved that all methods and processing approaches provide results that agree to each other at the 2-cm level in terms of standard deviation from the mean value. The overall discrepancies range from -9 cm to $+8$ cm. These discrepancies mainly reflect the disagreement between the data preprocessing and computation methods as the input data are assumed free of error and a proper error propagation analysis is not performed yet. However, it is evident that the discrepancies between the different solutions are highly correlated with the topography, suggesting further investigations on the handling of terrain gravity effects (model and strategy). Wang et al. (2021) and Sánchez et al. (2021) summarise a detailed comparison of the 14 solutions that contributed to the Colorado experiment. Van Westrum et al. (2021) provide a detailed description of the measurement and data analysis of the reference GNSS/levelling validation data along the GSVS17 profile. The input gravity and topographic data, the GNSS/levelling validation data, and the 14 geoid and quasi-geoid models produced within the Colorado experiment are available from the International Service for the Geoid (ISG, Reguzzoni et al. 2021) and can be used as a basis to evaluate any geoid computation method or software anywhere. Based on the results of the Colorado experiment, Sánchez et al. (2021) present a detailed roadmap for the realisation of the IHRS, including:

- Strategy for the determination and evaluation of IHRF coordinates depending on the data availability (especially surface gravity data and topography models),
- Strategy to improve the input data required for the determination of IHRF coordinates,
- Strategy for the IHRF implementation at the regional and national level,
- Strategy to ensure the usability and long-term sustainability of the IHRF.

Following this, during the 2019 IUGG General Assembly in Montreal, Canada, the IAG released a new resolution promoting the implementation of the IHRS at regional and national levels; see IAG Resolution No. 3, 2019 in Poutanen and Rózsa (2020). Additionally, the GGOS-FA-UHS coordinated the publication of a Journal of Geodesy special issue on *Reference Systems in Physical Geodesy* including most of the solutions contributing to the Colorado experiment. This special issue also contains papers facing important issues related to the establishment of the IHRF and ITGRF as well as to the improvement of accurate geoid modelling and the long-term stability of absolute gravity observations. (Sánchez et al. 2023).

7 Vertical Datum Unification for the International Height Reference System (IHRS)

A main component of the IHRS realisation is the integration of the existing height systems into the global one; i.e., existing physical heights (or geopotential numbers) should be referred to one and the same reference level realised by the conventional W_0. This procedure is known as vertical datum unification and its main result are the potential differences (called vertical datum parameters) between the local and the global reference levels. The motivation for the vertical datum unification rises from the fact that the local physical height systems have been the reference for height determination during the last 150 years and they provide a higher accuracy in contiguous areas than the combination of ellipsoidal heights with geoid undulations or height anomalies. If the local height systems are appropriately integrated into the IHRS, the existing vertical data can be modernised and be useful for geodetic applications of global context.

Sánchez and Sideris (2017) rigorously derive the observation equations for the vertical datum unification in terms of potential quantities based on the geodetic boundary value problem (GBVP) approach. Those observation equations are then empirically evaluated for the vertical datum unification of the North American and South American height systems. In the first case, simulations performed in North America provide numerical estimates about the impact of omission errors and direct and indirect effects on the vertical datum parameters. In the second case, a combination of local geopotential numbers, ITRF coordinates, satellite altimetry observations, tide gauge registrations, and high-resolution gravity field models is performed to estimate the level differences between the South American height systems and the global level W_0. Results show that indirect effects vanish when a satellite-only gravity field model with a degree $n \geq 180$ is used for the solution of the GBVP. However, the component derived from satellite-only global gravity models has to be refined with terrestrial gravity data to minimise the omission error and its effect on the vertical datum parameter estimation. The empirical evaluations demonstrate that the vertical datum unification should be based on geodetic stations of highest quality and standardised geodetic data; for example, geometric coordinates should refer to the same ITRF and be given in the same tide system and reference epoch as the geopotential numbers and gravity field model. After a standardisation of the input data used in the unification of the South American height systems and a rigorous error propagation analysis, it is evident that the vertical datum parameters can be estimated with accuracy better than ± 5 cm in well-surveyed regions and some decimetres ($\pm$ 40 cm) in sparsely surveyed regions. Sánchez and Sideris (2017) also provide detailed guidelines for the appropriate data treatment when the integration of a local vertical datum into the IHRS is desired.

8 A First Solution for the IHRF

Based on the outcomes of the Colorado experiment, we classified the computation of potential values in three main scenarios:

(a) Regions without (or with very few) surface gravity data,
   - The only option to determine potential values is the use of GGM of high resolution (GGM-HR).

  - Expected mean accuracy values around the ±4.0 m^2 s^{-2} (±40.0 cm in terms of height) level or even worse in regions with strong topography gradients.
  - It could be improved for instance to the ±1.0 m^2 s^{-2} (±10.0 cm) level if new and better surface gravity data are included in the GGMs.
  - To avoid multiple potential values provided by different GGM-HRs at the same point, it is necessary to select one GGM-HR as reference model.

(b) Regions with some surface gravity data, but with poor data coverage or unknown data quality,
  - The reliability of the existing (quasi-)geoid models is poor.
  - Additional gravity surveys around the IHRF stations would help to increase the accuracy of the geopotential numbers computed at those specific stations.

(c) Regions with good surface gravity data coverage and quality.
  - Potential values may be inferred from precise geoid/quasi-geoid regional models.

Using this classification, we started in the beginning of 2021 the computation of a first solution for the IHRF. As an initial action, a short description of the "step by step" to infer IHRF potential values from local/regional geoid/quasi-geoid models was prepared. It is based on the IHRS paper published by Sánchez et al. (2021) and was distributed to the members of the working group *Implementation of the International Height Reference Frame* (Sánchez 2023), so that they can compute potential values at the IHRF stations located in their countries using their present/latest geoid/quasi-geoid models. This activity is supported by about 40 colleagues from Canada, Mexico, USA, Germany, Italy, Switzerland, Austria, Sweden, Finland, Australia, Japan, China, South America, Russia, and Africa. Complementary, the ISG and the IGFS are evaluating the quality and documentation of the different regional models available at the Geoid Repository of ISG in order to identify which models can be used to infer potential values. This action is useful for the IHRF computation in areas underrepresented in the working group. Simultaneously, we are computing potential values for all the IHRF stations using GGM extended with topography-based synthetic gravity signals, reaching resolutions up to degree 80,000 … 90,000. As mentioned, this would be the only option available in those regions where no geoid/quasi-geoid models are available. At the end, we have different potential values for the same points. The agreement of the different GGM and the models stored by ISG with the own computations performed by the colleagues of the working group will allow us to decide which GGM + topography models perform better. The results of these computations were presented at the IUGG2023 General Assembly in Berlin, Germany and are being compiled in a paper to be published in the near future.

9 Operational Infrastructure for the Long-Term Sustainability of the IHRF

An IHRS/IHRF objective is to support the monitoring and analysis of Earth's system changes. The more accurate the IHRS/IHRF is, the more phenomena can be identified and modelled. Thus, the IHRS/IHRF must provide vertical coordinates and their changes with time as accurately as possible. As many global change phenomena occur at different scales, the global frame should be extended to regional and local levels to guarantee consistency in the observation, detection, and modelling of their effects. From this perspective, we are proposing the establishment of an operational infrastructure within the IGFS that takes care of

(a) Maintenance of the IHRF reference network in accordance with the GGOS Bureau of Networks and Observations (Pearlman et al. 2019) and the coordinators of the reference networks for the ITRF, ITGRF and their regional densifications. This activity should be faced by the *IHRF Reference Network Coordination*.
(b) Maintenance of a catalogue with the conventions and standards needed for the IHRF. This should consider a harmonisation with the conventions and standards kept by the GGOS-BPS, the IERS Conventions (for the determination of the ITRF), and the standards applied in the ITGRF and the global gravity field modelling. This task should be carried out by the *IHRF Conventions' Coordination*.
(c) The national/regional agencies/entities contributing to the realisation of the IHRF in their regions may be considered as *IHRF Associate Analysis Centres*. The input data would then be provided by existing IAG gravity field services and local data centres; e.g., GGM are provided by International Centre for Global Earth Models (ICGEM, Ince et al. 2019) and surface gravity data are provided by the Bureau Gravimétrique International (BGI) and refined/complemented with gravity data available at local data centres. In a similar way, one can proceed with digital elevation models.
(d) The combination and quality assessment of the regional/national solutions as well as the release of the final (official) IHRF solution will be faced by the *IHRF Combination Coordination*.

(e) Finally, the IHRF Reference Network Coordination, Conventions' Coordination, Associate Analysis Centres and Combination Coordination will report to the *IHRF Coordination Centre*, which, in turn, would report directly to the IGFS Central Bureau

The IGFS presented this proposal to the IAG Executive Committee at its meeting on 10 December 2023 and it was unanimously approved. Thus, a new component of the IGFS dedicated to the IHRF has been created and will ensure the long-term availability and reliability of the IHRF. More details about this operational infrastructure are presented by Sánchez et al. (2024).

10 Closing Remarks

The implementation of a global reference system for physical heights such as the IHRS is a major challenge and requires the support of a broad scientific community. Therefore, the establishment of the IHRS/IHRF is only possible within a global and structured organisation such as the IAG. The IHRS/IHRF provides a unified frame for height determination around the world, ensuring that different national and regional height systems can be related and compared in a consistent manner. However, strong international cooperation on a voluntary basis is essential to ensure its long-term stability and availability. The GGOS-FA-UHS has motivated this cooperation for 12 years. From now on, this cooperation will be facilitated by the IGFS, which is establishing an appropriate organisational infrastructure to provide a framework for countries to work together towards common goals related to the maintenance and continuous development of the IHRS/IHRF.

Acknowledgements The progress described in this report has been made possible thanks to the support of more than 70 colleagues over 12 years. Their contribution is deeply appreciated.

References

Ågren J, Ellmann A (2019) Report of the sub-commission 2.2: methodology for geoid and physical height systems, reports 2015-2019 of the International Association of Geodesy (IAG), Travaux de l'AIG, vol 41, pp 155–160

Angermann D, Gruber T, Gerstl M, Heinkelmann R, Hugentobler U, Sánchez L, Steigenberger P (2016) GGOS Bureau of Products and Standards: inventory of standards and conventions used for the generation of IAG products. In: Drewes H, Kuglitsch F, Adám J, Rózsa S (eds) The geodesist's handbook 2016, J Geod 90:1095–1156. https://doi.org/10.1007/s00190-016-0948-z

Angermann D, Gruber T, Gerstl M, Heinkelmann R, Hugentobler U, Sánchez L, Steigenberger P (2020) Bureau of Products and Standards: inventory of standards and conventions used for the generation of IAG products. In: The geodesists' handbook 2020, J Geod 94(11):221–292. https://doi.org/10.1007/s00190-020-01434-z

Burša M, Kouba J, Raděj K, True S, Vatrt V, Vojtíšková M (1998) Mean Earth's equipotential surface from TOPEX/Poseidon altimetry. Studia geoph et geod 42:456–466. https://doi.org/10.1023/A:1023356803773

Čunderlík R, Mikula K (2009) Numerical solution of the fixed altimetry–gravimetry BVP using the direct BEM formulation. International Association of Geodesy Symposia Series, vol 133, pp 229–236. https://doi.org/10.1007/978-3-540-85426-5_27

Čunderlík R, Minarechová Z, Mikula K (2014) Realization of WHS based on the static gravity field observed by GOCE. International Association of Geodesy Symposia Series, vol 141, pp 211–220. https://doi.org/10.1007/978-3-319-10837-7_27

Dayoub N, Edwards SJ, Moore P (2012) The Gauss–Listing potential value Wo and its rate from altimetric mean sea level and GRACE. J Geod 86(9):681–694. https://doi.org/10.1007/s00190-012-1547-6

Drewes H, Kuglitsch F, Ádám J, Rózsa S (2016) Geodesist's handbook 2016. J Geod 90:907. https://doi.org/10.1007/s00190-016-0948-z

Förste C, Bruinsma SL, Abrikosov O, Lemoine JM, Marty JC, Flechtner F, Balmino G, Barthelmes F, Biancale R (2014) EIGEN-6C4 the latest combined global gravity field model including GOCE data up to degree and order 2190 of GFZ Potsdam and GRGS Toulouse. GFZ Data Services. https://doi.org/10.5880/icgem.2015.1

Groten E (1999) Report of the International Association of Geodesy Special Commission SC3: fundamental constants. XXII IAG General Assembly, Birmingham

Groten E (2004) Fundamental parameters and current (2004) best estimates of the parameters of common relevance to astronomy, geodesy and geodynamics. The geodesist's handbook 2004. J Geod 77:724–731. https://doi.org/10.1007/s00190-003-0373-y

Huang J, Wang YM (2019). Report of Joint Study Group 0.15: regional geoid/quasigeoid modelling—theoretical framework for the sub-centimetre, reports 2015-2019 of the International Association of Geodesy (IAG), Travaux de l'AIG, vol 41, pp 495–499

IAG (2017) Description of the global geodetic reference frame. Position paper adopted by the IAG Executive Committee in April 2016. J Geod 91:113–116. https://doi.org/10.1007/s00190-016-0994-6

Ihde J (2007) Inter-Commission project 1.2: Vertical Reference Frames. Final report for the period 2003-2007. In: Drewes H, Hornik H (eds) IAG Commission 1—Reference Frames, Report 2003–2007. DGFI, Munich Bulletin No. 20, pp 57–59

Ihde J, Amos M, Heck B, Kersley B, Schöne T, Sánchez L Drewes H (2007) Conventions for the definitions and realization of a conventional vertical reference system (CVRS), unpublished

Ihde J, Barzaghi R, Marti U, Sánchez L, Sideris M, Drewes H, Förste C, Gruber T, Liebsch G, Pail R (2015) Report of the Ad-hoc Group on an International Height Reference System (IHRS). In: Drewes H, Hornik H (eds) Reports 2011-2015 of the International Association of Geodesy (IAG), Travaux de l'AIG, vol 39, pp 549–557

Ihde J, Sánchez L, Barzaghi R, Drewes H, Förste C, Gruber T, Liebsch G, Marti U, Pail R, Sideris M (2017) Definition and proposed realization of the International Height Reference System (IHRS). Surv Geophys 38(3):549–570. https://doi.org/10.1007/s10712-017-9409-3

Ince ES, Barthelmes F, Reißland S, Elger K, Förste C, Flechtner F, Schuh H (2019) ICGEM—15 years of successful collection and distribution of global gravitational models, associated services, and future plans. Earth Syst Sci Data 11(2):647–674. https://doi.org/10.5194/essd-11-647-2019

Ma C, Feissel M (1997) Definition and realization of the International Celestial Reference System by VLBI astrometry of extragalactic objects. IERS technical note 23, Paris, Central Bureau of IERS - Observatoire de Paris, 282 p

Pail R, Fecher T, Barnes D, Factor JF, Holmes SA, Gruber T, Zingerle P (2018) Short note: the experimental geopotential model XGM2016. J Geod 92:443. https://doi.org/10.1007/s00190-017-1070-6

Pavlis N-K, Holmes SA, Kenyon SC, Factor JK (2012) The development of the Earth Gravitational Model 2008 (EGM2008). J Geophys Res 117:B04406. https://doi.org/10.1029/2011JB008916

Pearlman M, Behrend D, Craddock A, Noll C, Pavlis E, Saunier J, Matthews A, Barzaghi R, Thaller D, Maennel B, Bergstrand S, Müller J (2019) GGOS: Current Activities and Plans of the Bureau of Networks and Observations, Abstract No. EGU2019-6181, presented at the European Geosciences Union General Assembly, Vienna, Austria, April 07-12, 2019

Petit G, Luzum B (2010). IERS Conventions (2010). IERS technical note 36, Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, 179 pp., ISBN 3-89888-989-6

Poutanen M, Rózsa S (2020) The geodesist's handbook 2020. J Geod 94:109. https://doi.org/10.1007/s00190-020-01434-z

Reguzzoni M, Carrion D, De Gaetani CI, Albertella A, Rossi L, Sona G, Batsukh K, Toro Herrera JF, Elger K, Barzaghi R, Sansó F (2021) Open access to regional geoid models: the International Service for the Geoid. Earth Syst Sci Data 13:1653–1666. https://doi.org/10.5194/essd-13-1653-2021

Sánchez L (2008) Approach for the establishment of a global vertical reference level. International Association of Geodesy Symposia Series, 132, pp 119–125. https://doi.org/10.1007/978-3-540-74584-6_18

Sánchez L (2012) Towards a vertical datum standardisation under the umbrella of Global Geodetic Observing System. J Geod Sci 2(4):325–342. https://doi.org/10.2478/v10156-012-0002-x

Sánchez L (2016) GGOS Focus Area 1: Unified Height System—Terms of reference. In: Drewes H, Kuglitsch F, Ádám J, Rózsa S (eds) Geodesist's handbook 2016, J Geod 90: 1091. https://doi.org/10.1007/s00190-016-0948-z

Sánchez L (2019) Report of the GGOS focus area "unified height system" and the Joint Working Group 0.1.2: strategy for the realization of the International Height Reference System (IHRS), reports 2015-2019 of the International Association of Geodesy (IAG), Travaux de l'AIG, vol 41, pp 583–592

Sánchez L (2023) Report of the GGOS focus area "unified height system", reports 2019-2023 of the International Association of Geodesy (IAG), Travaux de l'AIG, vol 43, pp 710–717

Sánchez L, Sideris MG (2017) Vertical datum unification for the International Height Reference System (IHRS). Geophys J Int 209(2):570–586. https://doi.org/10.1093/gji/ggx025

Sánchez L, Dayoub N, Čunderlík R, Minarechová Z, Mikula K, Vatrt V, Vojtíšková M, Šíma Z (2014) W_0 estimates in the frame of the GGOS working group on vertical datum standardisation. International Association of Geodesy Symposia Series, 141: 203–210. https://doi.org/10.1007/978-3-319-10837-7_26

Sánchez L, Čunderlík R, Dayoub N, Mikula K, Minarechová Z, Šíma Z, Vatrt V, Vojtíšková M (2016) A conventional value for the geoid reference potential W_0. J Geod 90(9):815–835. https://doi.org/10.1007/s00190-016-0913-x

Sánchez L, Ågren J, Huang J, Wang YM, Forsberg R (2018) Basic agreements for the computation of station potential values as IHRS coordinates, geoid undulations and height anomalies within the Colorado 1 cm geoid experiment, unpublished

Sánchez L, Ågren J, Huang J, Wang YM, Mäkinen J, Pail R, Barzaghi R, Vergos GS, Ahlgren K, Liu Q (2021) Strategy for the realisation of the International Height Reference System (IHRS). J Geod 95:3. https://doi.org/10.1007/s00190-021-01481-0

Sánchez L, Wziontek H, Wang YM, Vergos G, Timmen L (2023) Towards an integrated global geodetic reference frame: preface to the special issue on reference systems in physical geodesy. J Geod 97(6). https://doi.org/10.1007/s00190-023-01758-6

Sánchez L, Barzaghi R, Vergos G (2024) Operational infrastructure to ensure the long-term sustainability of the International Height Reference System and Frame—IHRS/IHRF. International Association of Geodesy Symposia Series, IUGG2023, vol 157. https://doi.org/10.1007/1345_2024_250

Sideris MG, Ihde J (2012) GGOS theme 1: unified height system—terms of reference. In: Drewes H (ed) Geodesist's handbook 2012, J Geod 86: 923–924. https://doi.org/10.1007/s00190-012-0584-1

Van Westrum D, Ahlgren K, Hirt C, Guillaume S (2021) A Geoid Slope Validation Survey (2017) in the rugged terrain of Colorado, USA. J Geod 95:9. https://doi.org/10.1007/s00190-020-01463-8

Wang YM, Forsberg R (2019) Report of the Joint Working Group 2.2.2: the 1 cm geoid experiment, reports 2015-2019 of the International Association of Geodesy (IAG), Travaux de l'AIG, vol 41, pp 178–179

Wang YM, Sánchez L, Ågren J, Huang J, Forsberg R, Abd-Elmotaal HA, Barzaghi R, Bašić T, Carrion D, Claessens S, Erol B, Erol S, Filmer M, Grigoriadis VN, Isik MS, Jiang T, Koç Ö, Li X, Ahlgren K, Krcmaric J, Liu Q, Matsuo K, Natsiopoulos DA, Novák P, Pail R, Pitoňák M, Schmidt M, Varga M, Vergos GS, Véronneau M, Willberg M, Zingerle P (2021) Colorado geoid computation experiment—overview and summary. J Geod 95:12. https://doi.org/10.1007/s00190-021-01567-9

Wziontek H, Bonvalot S (2019) Report of the Joint Working Group 2.1.1: establishment of a global absolute gravity reference system, reports 2015-2019 of the International Association of Geodesy (IAG), Travaux de l'AIG, vol 41, pp 147–152

Wziontek H, Bonvalot S, Falk R, Gabalda G, Mäkinen J, Pálinkáš V, Rülke A, Vitushkin L (2021) Status of the international gravity reference system and frame. J Geod 95:7. https://doi.org/10.1007/s00190-020-01438-9