ГЕОДЕЗІЯ І ГЕОДИНАМІКА

UDC 528.2/3

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REALIZATION OF THE INTERNATIONAL HEIGHT REFERENCE SYSTEM – STATE OF ART

Heights are relevant in geodesy, precise navigation, engineering, etc. Currently, there are over 100 vertical systems realized with geometric levelling and referenced to different tide gauges. Therefore, the accuracy of the vertical height systems is significantly lower than the accuracy of the global ITRF system. Currently International Height Reference System was defined and were undertaken first works on the establishment of a global height system. The **purpose** of this manuscript is describing efforts on definition and implementation of the global height system. **Methodology**. Searching in the library data base the relevant literature. Mainly works on the global vertical system realized by the Global Geodetic Observing System are realized by dedicated two working groups: JWG 0.1.1, JWG 0.1.2 and contributions of the IAG components or similar study groups or projects. Therefore the methodology based on searching the relevant literature in the library data base. **Results**. This work, in the introduction, provides information on the works concerning global height system conducted by the IAG in the last 30 years. The first real step toward the International Height Reference System (IHRS) was IAG Resolution No. 1, during the IUGG2015 General Assembly in Prague, July 2015. Then GGOS terms of reference that state the accuracy of the static geoid (geometry of any equipotential surface) should be 1 mm and spatial resolution 10 km. Time-dependent geoid should have accuracy of 1 mm and spatial resolution of 50 km, temporal resolution of 10 days. Accuracy of the ITRF coordinates should be 1 mm horizontal and 3 mm vertical. Velocities of position should be determined with accuracy 0.1 mm/a in a plane and 0.3 mm/a in vertical. Expected accuracy for W_P should be in positions: ~ 3×10^{-2} m^2s^{-2}-(about 3 mm) and accuracy of velocities ~ 3×10^{-3} m^2s^{-2} (about 0.3 mm/a). Next the manuscript presents a draft of the global vertical network and possible scenarios for the determination gravity potential at the points of this network. In summary, information are given about the planned works on the detail realization of the global vertical network in the near future. **Scientific novelty and practical significance.** The overview given herein on realization global vertical system is extremely helpful for researchers and scientific institutions and government organizations wishing to incorporate this problem.

Keywords. Height System, Global vertical reference system, gravity geopotential, International Height Reference System and Frame.

1. Introduction

The *International Terrestrial Reference Frame* ITRF is defined as a three-dimensional, geocentric reference system realized with an accuracy in the order of 10^{-9} for the three position components of stations forming the reference frame (Sanchez, 2008). Geodetic heights, i.e., the vertical component of positions, may be derived as geometrical heights referring to a reference ellipsoid. They are independent of the Earth gravity field and the datum is related to the fundamental geodetic parameters and standards e.g. GRS80 ellipsoid. The ITRF *Product Centre* of the IERS is actualizing this terrestrial reference frame in intervals of several years.

For many applications in science and practice, physical heights, instead geometric heights, based on differences of the potential of the Earth's gravity field are required. In particular for geodesy, precise navigation, geodynamics, engineering, coastal research, etc. There are about a hundred different physical height systems worldwide, related to different tide gauges, realized by spirit levelling as static systems, and reduced for the gravity effect by different models (Torge, 2001).

The tide gauges are related to a mean sea level at an arbitrarily selected epoch which differs from a mean global equipotential surface (the geoid) up to the order of a meter. The accuracy of the heights in these systems is limited locally by the error propagation of spirit levelling and globally by the datum realization with different tide gauges and different epochs by 10^{-6} to 10^{-7}. The repetition rate of physical height determination is in general only 10–50 years. As an example, the differences of the datums of the national height systems in Europe with respect to the Normaal Amsterdams Peil is from few centimeters up to 2.31 m in Belgium) (Sacher et al., 1999).

Therefore, the accuracy of present realizations of physical height reference systems in a global scale is about two orders of magnitude less than that of the ITRF. The repetition time rate differs by one order of magnitude. In the frame of global geodesy at centimeter-level, physical heights appear as inconsistent elements.

Currently, works on the global vertical system are realized by *the Global Geodetic Observing System*[1] (GGOS). GGOS of the *International Association of Geodesy* (IAG), taking care of providing a precise geodetic infrastructure for monitoring the System Earth, promotes the standardization of height systems worldwide. With the purpose to bring together existing initiatives and to address the activities to be faced, the GGOS Focus Area "*Unified Height System*" (formerly GGOS Theme 1) was established during the GGOS Planning Meeting 2010 (February 1–3, Miami/Florida, USA). Starting point were the results delivered by the IAG Inter-Commission Project 1.2 "*Vertical Reference Frames*[2]" (IAG ICP1.2 VRF), which was operative from 2003 to 2011.

After a work period of four years (2003–2007), a general concept for the definition and realization of a global vertical reference system (called also World Height System – WHS) was developed. The main aspects are documented in the Conventions for the Definition and Realization of a Conventional Vertical Reference System (CVRS)[3]. Based on the achievements of this first term, during the XXIV IUGG *General Assembly* (2 – 13 July, 2007) in Perugia, Italy, it was decided to extent the IAG ICP1.2 activities for a second period (2007 – 2011) with the major objective of initiating a pilot project for the WHS realization (WHS-PP). This project was to further expand and refine the reference frame infrastructure of the IAG, to provide users with information about existing vertical reference frames worldwide, and to relate the regional height systems to a global datum.

The activities of the GGOS in height system unification are realized by dedicated two working groups: JWG 0.1.1, JWG 0.1.2 and contributions of the IAG components or similar study groups or projects.

The main objective of the Working Group JWG 0.1.1 *Vertical Datum Standardization* for the period, 2011–2015, was to support the GGOS in the realization of a unified global height system by bringing together different groups working on the vertical datum problem to avoid unnecessary duplicity in activities and to joint efforts guaranteeing a homogeneous advance in the reference frame issues not only worldwide, but also at national and regional level.

Results of JWG 0.1.1 are different computations carried out which demonstrate that the 1998 W_0 value (62 636 856.0 ± 0.5 $m^2\ s^{-2}$) is not in agreement (and consequently it is not reproducible) with the newest geodetic models describing geometry and physics of the Earth (Sánchez, 2012). This leads us to conclude that the 1998 W_0 value is not suitable as a conventional reference value and a better estimate for W_0 has to be adopted by the IAG. The recommended new value is 62 636 853.4 $m^2\ s^{-2}$. It was officially adopted by the IAG in its Resolution No. 1, July 2015, as the conventional W_0 value for the definition and realization of the International Height Reference System (IHRS). A detailed description about the computation strategy of W_0, applied models, conventions and standards, as well as results is presented in the publication (Sánchez et al., 2016)

The JWG 0.1.1 also supported the activities of the GGOS Bureau of Products and Standards and compiled the chapter "*4.6 Height systems and their realizations*" of the "*Inventory of standards and conventions used for the generation of IAG products*" published in the IAG Geodesist's Handbook 2016 (Drewes et al. 2016).

Working Group JWG 0.1.2 *Strategy for the Realization of the International Height Reference System*[4], at present the main challenge is the realization of the IHRS; i.e., the establishment of the *International Height Reference Frame* (IHRF). It is expected 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 IHRS are known.

According to the GGOS objectives, the target accuracy of these global geopotential numbers is 1×10^{-2} $m^2\ s^{-2}$. In practice, the precise realization of the IHRS is limited by different aspects; for instance, there are no unified standards for the determination of the potential values W_P, the gravity field modelling and the estimation of the position vectors X follow different conventions, the geodetic infrastructure is not homogeneously distributed globally, etc. This may restrict the expected accuracy of $1\times10^{-2}\ m^2\ s^{-2}$ to some orders lower (from $10\times10^{-2}\ m^2\ s^{-2}$ to $100\times10^{-2}\ m^2\ s^{-2}$). Consequently, the next step is to outline the minimum set of fundamentals needed for a reliable and sustainable realization of the IHRS.

Expected results: the main result of this Working Groups should be a document similar to the IERS conventions; i.e., a sequence of chapters describing the different components to be consider for the precise and sustainable realization of the IHRS and its practical utilization.

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[1] http://176.28.21.212/en/focus-areas/unified-height-system/

[2] https://ihrs.dgfi.tum.de/index.php?id=3

[3] https://ihrs.dgfi.tum.de/fileadmin/user_upload/CVRS_ conventions_ final_ 20070629.pdf

[4] http://www.ggosdays.com/en/focus-areas/unified-height-system/working-group/012-ihrs-realization/

2. Realization of the International Height Reference System (IHRS)

2.1. Definition of IHRS

The first real step toward the *International Height Reference System* (IHRS) is IAG Resolution No. 1, during the IUGG2015 General Assembly in Prague, July 2015 (Drewes et al. 2016). IHRS is defined as a geopotential reference system co-rotating with the Earth in its motion in space. Coordinates of points attached to the solid surface of the Earth are given by:

✓ geopotential values $W(X,Y,Z)$ and their changes with time defined within the Earth's gravity field

✓ and by geocentric Cartesian coordinates X,Y,Z and their changes with time referring to the ITRS.

For practical purposes, potential values W and geocentric positions X,Y,Z can be transformed to geopotential numbers C_P and ellipsoidal heights h, respectively

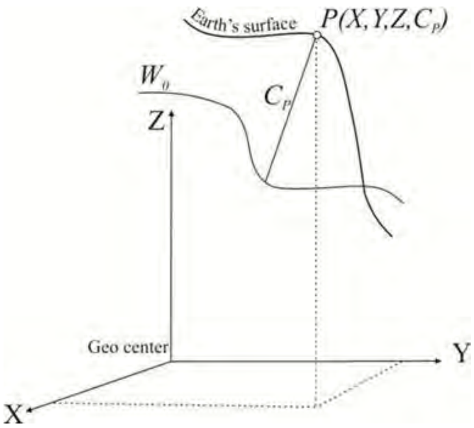

Fig. 1. Definition and recommended realization of the International Height Reference System

According to the IAG Resolution No. 1 five conventions define the IHRS:

✓ The vertical reference level is the geopotential at the geoid, or the geoid potential parameter W_0 as an equipotential surface of the Earth's gravity field. $U_0 = W_0$ is a defining parameter of the conventional geocentric level ellipsoid. The relationship between W_0 and the Earth body must be defined and reproducible.

✓ Parameters, observations and data shall be related to the mean tidal system/mean crust.

✓ The unit of length is the meter (SI). The unit of time is the second (SI).

✓ The vertical coordinates are the differences $-\Delta W_P$ between the potential W_P of the Earth's gravity field at the considered points P and the geoidal potential W_0. The potential difference $-\Delta W_P$ is also designated as geopotential number C_P :

$$C_P = W_0 - W_P$$

✓ The spatial reference of the position P for the potential $W_P = W(X,Y,Z)$ is expressed as coordinates X,Y,Z in the International Terrestrial Reference System ITRS.

2.2. Requirements on W_P

The GGOS terms of reference (Drewes et al. 2016) do not include physical heights or potential values but state that the accuracy of the static geoid (geometry of any equipotential surface) should be 1 mm and spatial resolution 10 km. Time-dependent geoid should have accuracy of 1 mm and spatial resolution of 50 km, temporal resolution of 10 days.

Accuracy of the ITRF coordinates should be 1 mm horizontal and 3 mm vertical. Velocities of position should be determined with accuracy 0.1 mm/a in a plane and 0.3 mm/a in vertical. Expected accuracy for W_P should be in positions: $\sim 3\times10^{-2}$ m^2s^{-2} (about 3 mm) and accuracy of velocities ~ 3×10^{-3} m^2s^{-2} (about 0.3 mm/a). The GGOS requirements are very ambitious. More realistic target values may be around: in positions: 10×10^{-2} m^2s^{-2} (about 1 cm) and in velocities: 10×10^{-3} m^2s^{-2} (about 1 mm/a).

2.3. Possibilities for the determination of W_P

The accuracy of the global geopotential numbers is expected to be $\pm3\times10^{-2}$ m^2s^{-2} (about 3 mm in physical heights). In practice, the achievement of this goal is limited by different aspects. For instance, there are no unified standards for the determination of the potential values W_P, the gravity field modelling and the estimation of the position vectors X,Y,Z follow different conventions. The geodetic infrastructure is not homogeneously distributed globally, etc. while the coordinates X,Y,Z are usually inferred from space geodetic techniques (like VLBI1, SLR2, GNSS3 and DORIS4) with an accuracy at the mm-level, the estimation of the potential values W_P may rely on:

✓ levelling with gravity reductions:

$$W_P = W_0 - C_P \tag{0-1}$$

✓ estimation of the anomalous potential T_P by solving the geodetic boundary value problem (GBVP); that is geoid or quasigeoid modelling:

$$W_P = U_P + T_P, \tag{0-2}$$

where U_P is the potential of an appropriately selected reference ellipsoid.

✓ Combination of ITRF positions with global gravity models (GGMs) in terms of spherical harmonics (C_{nm}, S_{nm}) of high degree:

$$W_P = f\left(X_P, C_{nm}, S_{nm}\right). \tag{0-3}$$

Each of these approaches presents advantages and drawbacks. For instance, the combination of levelling with gravity reductions provides a sub-millimeter relative accuracy (between neighboring levelling points referring to the same vertical datum), but an absolute accuracy (with respect to a global vertical datum) of about ±2 m equivalent to ±20 m^2s^{-2} (the same order of magnitude as the mean ocean dynamic topography). This is due to the fact that geopotential number C_{Pi} typically refers to a local vertical datum realized by the mean sea level registered at a tide gauge, whose potential value W_{0i} and its relationship to a global vertical datum W_0 are unknown.

In the case of the GBVP solution, the long-wavelength component of a GGM is usually combined with terrestrial gravity data following the remove-compute-restore approach (Tscherning ,1986); (Schwarz et al., 1990). Introducing the same GGM in the solution of the GBVP over different vertical datum zones allows the realization of a common reference level for those zones. In addition, if it is assumed that the reference level realized by the GGM represents the global vertical datum W_0, it is possible to estimate the discrepancies between this datum and the local ones W_{0i}. This approach provides an absolute accuracy from some cm to some dm, but the relative accuracy may be one or two orders lower. Main drawbacks of this approach are the use of different standards (like gravity anomaly types, tide systems and GGMs) and the restricted accessibility to terrestrial gravity data.

The availability of GGMs of high degree, like the EGM2008 model (Pavlis et al. 2012), (Pavlis et al., 2013) makes it possible to carry out a direct computation of W_P by introducing the ITRF coordinates X,Y,Z of any point into the spherical harmonic expansion equation representing a GGM. According to (Rummel et al., 2014), the expected accuracy after applying one of these models is ±40 cm^2 s^2 to ±60 cm^2 s^2 (equivalent to ±4 cm to ±6 cm) in well surveyed regions, and about ±200 to ±400 cm^2 s^2 (±20 to ±40 cm) with extreme cases of ±10 m^2 s^2 (±1 m) in sparsely surveyed regions. This approach is still unsuitable because the application of different standards, conventions and procedures in the estimation of the harmonic coefficients produces quite large discrepancies in the gravity field parameters derived from the GGMs. Furthermore, the restricted availability of terrestrial gravity decreases the reliability of the GGMs. In areas with few gravity data, the higher degrees of the GGMs do not contain the full signal of the Earth's gravity field and the so called 'omission error' increases strongly.

3. Realization of a global vertical reference frame

A reference frame realizes a reference system in two ways. Physically, by a solid monuments and 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.

Therefore Joint Working Group on the Strategy for the Realization of the International Height Reference System IHRS, at the first meeting in Thessaloniki, Sept. 2016, presented criteria for the selection of IHRF stations. First the structure of the network should be hierarchic. It means that first should be created a global network, worldwide distribution, including a core network to ensure sustainability and long term stability. Secondly regional and national densifications collocated with fundamental geodetic observatories ensure connection between X,Y,Z, W, g and time realization (reference clocks) to support the Global Geodetic Reference Frame (GGRF).

The network should contain constantly operating reference stations to detect deformations of the reference frame, reference tide gauges and national vertical networks in order to unification vertical datum and reference stations of the new Global Absolute Gravity Reference System (see IAG Resolution 2, Prague 2015).

It is needed availability of terrestrial gravity data around the IHRS reference stations for high resolution gravity field modelling (i.e., precise estimation of W). It means evenly distributed gravity points around the IHRF reference stations up to 210 km (~ 2°). The gravity data may exist or have to be observed. Mean accuracy of the gravity values should be better than ±100 μGal. It is desire to refer gravimetry to an absolute gravity station. Gravity point positions should be determined with GPS (some cm accuracy is sufficient). In mountain areas it is necessary ~50 % more gravity points.

3.1. First proposal for the IHRF reference network

A preliminary station selection based on VLBI, SLR and DORIS reference sites co-located with GNSS was performed in October 2016 (Sánchez et al., 2016). VLBI and SLR sites guarantee a long term maintenance of the geodetic facilities. DORIS and GNSS guarantee a homogeneous distribution worldwide. The GGOS Bureau for Networks and Observations supports this task by implementing 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.).

Based on the preliminary station selection of October 2016, national and regional experts were asked to evaluate whether these sites are suitable to be included in the IHRF and are gravity data around these sites available or if it possible to survey them. After the response 163 other IGS stations were added to the IHRF network, especially in those regions with poor coverage (Africa and Asia).

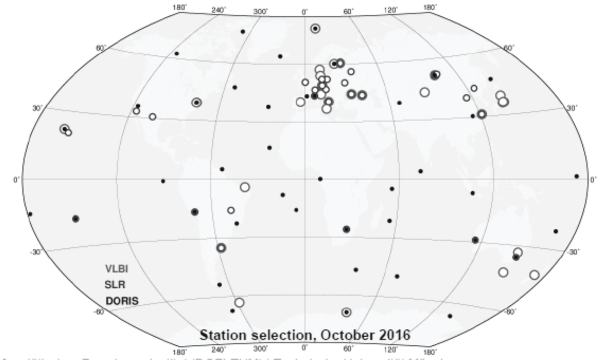

Fig. 2. Preliminary selection of IHRF reference stations (Sanchez et al., 2017)

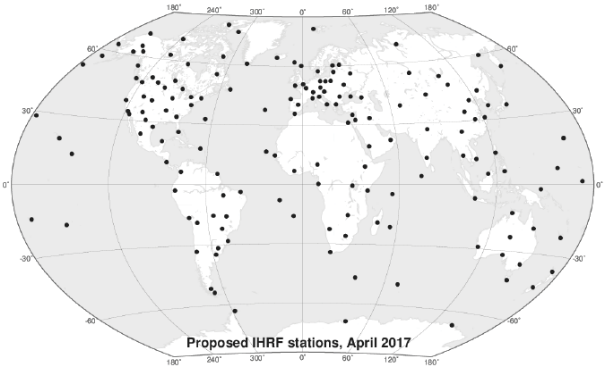

Fig. 3. First proposal for the IHRF reference network, Apr. 2017, (Sanchez et al., 2017)

In the designed network are included two Polish geodynamic stations: namely, Space Research Center Observatory in Borowiec and the Observatory of the Institute of Geodesy in Borowa Gora.

With this preliminary selection, next efforts focus on the computation of the potential values $W(P)$ and the estimation of their accuracy. Different methods are being evaluated.

As national and regional experts provided terrestrial gravity data around some IHRF sites, a direct computation of potential values (and their accuracy) is being performed. In this case, following experiments are being conducted:

✓ 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.,

✓ Comparison of different mathematical formulations (least-squares collocation, FFT, radial basis functions, etc.).

✓ Computation of potential values and their accuracy by national and regional experts responsible for the geoid modelling using their own data and methodologies.

✓ 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.

The comparison of the results obtained from these different approaches will provide a basis to outline further steps; especially, the identification of detailed standards and conventions for the IHRS realization and the implementation of a roadmap based on the available geodetic data.

Conclusions

The primary objective of the realization the IHRF, is to support the monitoring and analysis of the system Earth changes and to harmonize geodetic products. The more accurate the IHRF is, the more phenomena can be identified and modelled.

The IHRF was designed and at present, the main challenge is its realization. Therefore is necessary definition of the standards and conventions required for establishing an IHRF consistently with the IHRS resolution of the IAG. A main issue is precise modelling of the temporal changes in the geopotential numbers as vertical coordinate which also reflect time variations of X and W. Then formulation of the minimum requirements for the IHRF reference stations and development of strategies for collocation of IHRF reference stations with existing gravity and geometric reference stations at different densification levels.

Further identification of the geodetic products associated with the IHRF and description of the elements to be considered in the corresponding metadata for identifying the data files. Processing strategies for the determination of the potential values W_P and recommending an appropriate computation procedure based on the accuracy level offered by those strategies:

✓ approaches for the vertical datum unification to provide guidance for the integration of the existing local height systems into the global IHRS/IHRF,

✓ a proposal about the organizational and operational infrastructure required to maintain the IHRF and to ensure its sustainability.

The main result of this work probably should be a document similar to the IERS conventions, i.e., a sequence of chapters describing the different components to be considered for the precise and sustainable realization of the IHRS and its practical utilization.

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РЕАЛІЗАЦІЯ МІЖНАРОДНОЇ РЕФЕРЕНЦНОЇ СИСТЕМИ ВИСОТ – СУЧАСНИЙ СТАН

Висоти актуальні для геодезії, точної навігації, інженерії тощо. Нині існує понад 100 систем відліку висот, що реалізуються із геометричного нівелювання і відносяться до різних футштоків. Точність класичних систем висот значно нижча, ніж точність глобальної земної референцної системи ITRF. Сьогодні вже визначена Міжнародна референцна система висот та виконано перші роботи зі створення глобальної системи висот. **Метою** цієї статті є опис і аналіз заходів, спрямованих на визначення та реалізацію глобальної системи висот. **Методологія**. Пошук у бібліотечній базі даних відповідної літератури, що пов’язана з роботами, що стосуються глобальної системи висот. Основна діяльність в цьому напрямі ведеться у межах GGOS – Глобальної системи геодезичних спостережень за допомогою двох робочих груп: JWG 0.1.1, JWG 0.1.2 та відповідних структур IAG у формі або аналогічних дослідницьких груп, або проектів. **Результати**. Наведено інформацію про роботи, що стосуються глобальної системи висот, які виконувала IAG протягом останніх 30 років. Першим реальним кроком на шляху до Міжнародної референцної системи висот (IHRS) була Резолюція IAG № 1 Генеральної асамблеї IUGG2015 у Празі в липні 2015 р. Тоді технічним завданням GGOS було визначено точність статичного геоїда (геометрія будь-якої еквіпотенціальної поверхні), яка повинна становити 1 мм, а просторова роздільна здатність 10 км. Змінний у часі геоїд повинен мати точність 1 мм і просторову роздільну здатність 50 км протягом 10 днів. Точність координат ITRF має становити 1 мм в їхніх горизонтальних складових за точності швидкості зміни 0,1 мм/рік і до 3 мм вертикальної складової та точності швидкості 0,3 мм /рік. Очікувана точність для W_P повинна становити для координат: $\sim 3\times\frac{10^{-2}\,\text{м}^2}{\text{с}^2}$ (близько 3 мм) і для швидкості $\sim 3\times\frac{10^{-3}\,\text{м}^2}{\text{с}^2}$ (близько 0,3 мм /р). Подано проект глобальної вертикальної мережі й можливі сценарії визначення гравітаційного потенціалу в точках цієї мережі. Наведено відомості про заплановані роботи щодо детальнішої реалізації глобальної вертикальної мережі в найближчому майбутньому. **Наукова новизна і практичне значення**. Наведений огляд щодо реалізації глобальної системи висот надзвичайно корисний для дослідників, наукових установ і дослідницьких організацій, які бажають долучитися до вирішення цієї проблеми.

Ключові слова: система висот, глобальна референцна система висот, гравітаційний геопотенціал, Міжнародна система висот та їх реалізація.