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Definition and Proposed Realization of the International Height Reference System (IHRS)

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Abstract Studying, understanding and modelling global change require geodetic reference frames with an order of accuracy higher than the magnitude of the effects to be actually studied and with high consistency and reliability worldwide. The International Association of Geodesy, taking care of providing a precise geodetic infrastructure for monitoring the Earth system, promotes the implementation of an integrated global geodetic reference frame that provides a reliable frame for consistent analysis and modelling of global phenomena and processes affecting the Earth's gravity field, the Earth's surface geometry and the Earth's rotation. The definition, realization, maintenance and wide utilization of the International Terrestrial Reference System guarantee a globally unified *geometric* reference frame with an accuracy at the millimetre level. An equivalent high-precision global

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physical reference frame that supports the reliable description of changes in the Earth's gravity field (such as sea level variations, mass displacements, processes associated with geophysical fluids) is missing. This paper addresses the theoretical foundations supporting the implementation of such a physical reference surface in terms of an International Height Reference System and provides guidance for the coming activities required for the practical and sustainable realization of this system. Based on conceptual approaches of physical geodesy, the requirements for a unified global height reference system are derived. In accordance with the practice, its realization as the International Height Reference Frame is designed. Further steps for the implementation are also proposed.

Keywords World height system · Global vertical reference system · Geodetic global reference frame · International Height Reference System and Frame

1 Motivation

To determine and investigate changes in the Earth system, geodesy can contribute with geodetic observations of high resolution in time and space as well as with reference frames of long-term stability (the same accuracy at any time) and homogeneous consistency worldwide (the same accuracy everywhere). For instance, mass transport processes and mass variations (due to geophysical signals) can be observed by gravimetric measurements directly. However, to describe very small changes associated with those processes, a high-accuracy reference frame is needed. As an example, the sea level rise of a few millimetres per year can only be detected if a stable spatial reference over a long time period with high accuracy is established globally. The contributions of geodesy to the study of the Earth system are focused on determining, monitoring, mapping and understanding changes in the Earth's shape, rotation and mass distribution; see, e.g., Plag and Pearlman (2009), Kutterer et al. (2012). In particular, the geodetic reference frames are the fundamental backbone for measuring and interpreting global change effects, for monitoring sea level variations and climate change, for natural disaster management and to provide reliable information for decision makers (IAG 2016).

The International Association of Geodesy (IAG), as the organization responsible for the advancement of the science of geodesy, enhances the definition and realization of geodetic reference systems that are in accordance with the increased precision of modern observational techniques and are capable of supporting the present needs of science and society regarding georeferenced data of high resolution. The definition, realization, maintenance and wide utilization of the International Terrestrial Reference System (ITRS, Petit and Luzum 2010) guarantee a globally unified *geometric* reference frame with accuracy at the millimetre level. The ITRS and its realization, the ITRF (International Terrestrial Reference Frame), are the basis to determine and monitor large- to small-scale displacements at high spatial and temporal resolutions. Some examples are surface deformations associated with natural hazards (such as seismic effects, landslides, subsidence), tectonic features (such as plate motion, surface deformation, slow slip interactions), vertical movements caused by mountain building and global isostatic adjustment (GIA) and small signals of surface deformations caused by oceanic, hydrologic or atmospheric loading. An equivalent high-accuracy global *physical* reference frame that supports the reliable description of changes related to the Earth's gravity field is currently still missing. Some examples of this kind of changes are sea level variations, redistribution of masses in oceans, continents and the Earth's interior, global ocean circulation and, in general, processes associated with geophysical fluids. Hence, at present a main objective of the IAG is the implementation of an integrated global geodetic reference frame that simultaneously supports the determination and monitoring of the Earth's geometry, rotation and gravity field changes with high accuracy worldwide. This objective is in accordance with the resolution adopted by the United Nations General Assembly on a *Global Geodetic Reference Frame for Sustainable Development* (A/RES/69/266) on February 26, 2015.

This paper is focused on the justification and design of a world height system as the basis for monitoring effects generated by gravity field variations and as a main component of a combined (integrated) geometric–physical reference system. It is addressed to users of geodetic reference frames in scientific and practical applications.

2 Introduction

The Earth's body may be described by its geometry and the potential of its gravity field. The determination of heights includes both of these aspects, the geometric part and the geopotential part. The former provides elevations above a reference ellipsoid (ellipsoidal or geometric heights h). The latter provides heights above a level surface of the Earth's gravity field (physical heights H). The realization of global geodetic reference systems is only possible using satellite techniques. The first global geometric network was realized in the 1960s with the PAGEOS satellite with an accuracy of 10^{-6} of the Earth's radius. Presently, space geodetic techniques allow an accuracy in geometric positioning of about 10^{-9} on global and continental scales. In contrast, physical heights can currently be determined globally only by 1 to 2 orders of magnitude less accurately than the geometric coordinates. This is because the existing height reference frames around the world refer to local (isolated) levels (usually the mean sea level determined at arbitrarily selected tide gauges), are static (do not consider vertical variations of the sea level or the reference points) and differ in the realization of the physical heights (different gravity corrections are applied to levelling measurements). Thus, at present, there are some hundred local and regional physical height systems in use, and they exhibit inconsistencies with respect to each other up to ±2 m (the same order of magnitude as the mean ocean dynamic topography). Although the determination of the ellipsoidal heights exhibits many advantages in comparison with the determination of levelling-based physical heights (such as high accuracy over long distances, quick and low-cost determination), the ellipsoidal heights cannot replace the physical ones because of their *geometrical* nature (i.e., they do not describe flow of water). In this way, the establishment of a global physical height reference system that provides one unified reference surface (i.e., a zero-height surface) for the consistent determination of physical heights worldwide is mandatory. This topic has been discussed by the geodetic scientific community for decades (see, e.g., Rummel and Teunissen 1988; Rapp and Balasubramania 1992). However, a reliable approach to a global height reference system is becoming only possible now thanks to the availability of modern geodetic techniques, especially the precise determination of geometrical coordinates by Global Navigation Satellite System (GNSS) positioning and satellite altimetry (in ocean areas), and accurate global gravity field models (GGMs) provided by the satellite missions GRACE (Gravity Recovery and Climate Experiment) and GOCE (Gravity and steady-state Ocean Circulation Explorer). Epoch-wise (monthly or weekly) global gravity models inferred from GRACE permit us to detect mass transports within the system Earth (such as ice melting processes in Arctic and Antarctica or ground water variations) and seasonal changes in the gravity field with magnitudes of about $\pm 10^{-8}$ m s^{-2} at a spatial resolution of 200–500 km, depending on signal strength, time scale and geographical location (Pail et al. 2015). GGMs inferred from GOCE observations improve the representation of the static (quasi-stationary) long wavelength component of the Earth's gravity field and permit us to model the geoid globally with an accuracy of about ±1 cm for a spatial resolution of 100 km. These static GGMs are useful to determine the dynamic ocean topography, to model lithospheric structures and dynamic solid Earth processes and, in particular, to realize a global unified reference surface for the accurate determination of physical heights worldwide.

Noting the advantages offered by these modern geodetic techniques and the necessity of providing a reliable physical reference system, the IAG established in 2014 an ad hoc group on an International Height Reference System with the objective to outline the minimal requirements for the definition and realization of a global unified vertical reference system (Ihde et al. 2015). This ad hoc group was supported by the Theme 1 (now Focus Area 1) of the Global Geodetic Observing System (GGOS), the IAG Commission 2 (Gravity Field) and the International Gravity Field Service (IGFS). The recommendations of this group were discussed during the 2015 General Assembly of the International Union of Geodesy and Geophysics (IUGG) in Prague, and they were presented and officially adopted by means of two IAG resolutions (Drewes et al. 2016): the first one devoted to the *definition and realization of an International Height Reference System*, and the second one devoted to *the establishment of a Global Absolute Gravity Reference System*. Both resolutions contribute to a global integrated geometrical and physical reference system.

The objective of this paper is to describe the primary principles for establishing a global physical height reference system based on existing developments and past project results, and to discuss relevant products from this information. Conventions and guidelines resulting from this work are directly related to the activities of several IAG sub-entities, namely GGOS Bureau for Products and Standards (Angermann et al. 2016), GGOS Focus Area 1 *Unified Height System* (Sideris 2013) and Focus Area 3 *Understanding and Forecasting Sea-Level Rise and Variability* (Schöne et al. 2013), the Inter-Commission Project 1.2 *Vertical Reference Frames* (Ihde 2007; Ihde et al. 2007), the working group *Vertical Datum Standardization* (Sánchez 2012), as well as the joint activities of IAG Commission 2 *Gravity Field* and the *Consultative Committee for Mass and Related Quantities* towards a *Strategy for Metrology in Absolute Gravimetry* (Marti et al. 2015). This work should provide a basis for harmonizing the geodetic products for geometry, gravity field and the time reference of the entire Earth.

3 General Concepts

3.1 Earth's Gravity Field, Geopotential Numbers and Physical Heights

Physical heights are inferred from potential differences ΔW of the Earth's gravity field. In geodesy, these gravity potential differences are usually known as geopotential numbers C_P. A geopotential number is the difference between the potential value W_P of a point P and the potential value W_0 of the vertical reference surface:

$$C_P = -\Delta W_P = W_0 - W_P. \tag{1}$$

As the geopotential numbers are given in $m^2\ s^{-2}$, to facilitate their use as measure for heights in practice, they are converted to vertical distances (given in m) by dividing C_P by a gravity value $\hat{g}$:

$$H_\mathrm{P} = \frac{C_P}{\hat{g}} = \frac{W_0 - W_P}{\hat{g}}, \quad \hat{g} = \frac{1}{H_\mathrm{P}} \int_0^{H_\mathrm{P}} g \mathrm{d}H_\mathrm{P} \tag{2}$$

H_P denotes a generic physical height. Introducing different types for $\hat{g}$ in Eq. (2) produces different values of H_P. As a consequence, we distinguish dynamic heights (H^d) with $\hat{g}$ as the gravity of the reference ellipsoid for an arbitrary standard latitude (usually 45°), normal heights ($H*$) with $\hat{g}$ as the average gravity of the reference ellipsoid between P and the quasi-geoid along the *ellipsoidal* plumb line, and orthometric heights H with $\hat{g}$ as the average gravity between P and the geoid along the Earth's gravity field plumb line (Fig. 1). More details about the conversion of geopotential numbers to metric heights can be found in the standard literature such as Hofmann-Wellenhof and Moritz (2005), Torge and Müller (2012).

The relationship with the geometric heights h is given by the geoid height N for the orthometric heights H and by the height anomaly ζ for the normal heights $H*$ (Fig. 1):

$$h = H + N = H^* + \zeta \tag{3}$$

There is no relationship between ellipsoidal and dynamic heights (H^d). The determination of normal heights is straightforward as the average gravity of the reference ellipsoid needed in Eq. (2) ($\hat{g} = \bar{\gamma}$) is analytically calculable. The determination of orthometric heights requires the formulation of hypotheses about the (unknown) Earth's internal mass distribution and the (unknown) vertical gravity gradient to estimate the mean real gravity (i.e., $\hat{g} = \bar{g}$). Therefore, different hypotheses produce different types of orthometric heights. To get an unequivocal relationship between orthometric heights and geoid [see Eq. (3)], both have to be computed using exactly the same hypotheses. Equations (2) and (3) demonstrate the necessity of consistency between the different types of heights before

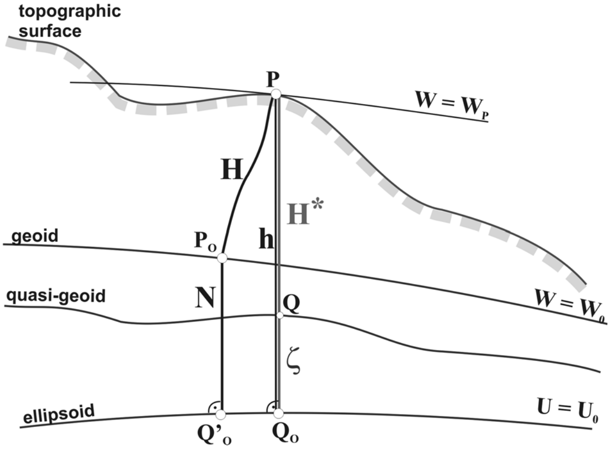

Fig. 1 Geometry between physical and geometric heights: orthometric height PP_0, normal height PQ, ellipsoidal height PQ_0, geoid undulation $P_0Q'_0$, height anomaly QQ_0

combination; different types of physical heights need associated equivalent types of reference surfaces.

The Earth's gravity field at a spatial position **X** can be represented by means of (1) the geopotential scalar field *W*(**X**) or (2) the Earth gravity vector field **g**(**X**). The gravity vector **g**(**X**) corresponds to the gradient of the scalar potential *W*(**X**):

$$\mathbf{g}(\mathbf{X}) = \operatorname{grad} W(\mathbf{X}) = -g \begin{pmatrix} \cos\Phi \cos\Lambda \\ \cos\Phi \sin\Lambda \\ \sin\Phi \end{pmatrix}, \tag{4}$$

with the natural coordinates astronomical latitude Φ and astronomical longitude Λ of a point *P*. The magnitude of the gravity vector **g**(**X**) is given by:

$$g_p = |\mathbf{g}(\mathbf{X})| = |\operatorname{grad} W_P| = \left(-\frac{\partial W}{\partial H}\right)_P \tag{5}$$

H denotes a physical height. In a very general notation, Eqs. (4) and (5) can be expressed as:

$$P(\mathbf{X}, W, g) = P(\mathbf{X}, W, -\partial W/\partial H) \text{ or} \tag{6a}$$

$$W(\mathbf{X}) = W_P \,\text{collocated with}\, \mathbf{g}(\mathbf{X}) = g_P = -\partial W_P/\partial H. \tag{6b}$$

The geopotential scalar field *W*(**X**) and the Earth gravity vector field **g**(**X**) are completely consistent with each other, and are functions of time in Euclidean space. Because of this, potential differences of the Earth's gravity field may be converted to physical heights *H* according to Eq. (2).

The Earth's gravity field vector can be directly observed by means of absolute gravity and astronomical latitude and longitude measurements. In practice, most of the available observations for terrestrial gravity field modelling are gravity values. Astronomical latitude and longitude observations are mainly used for validation and control purposes. Absolute potential values of the Earth's gravity field are not observable directly, but indirectly estimable by assuming that the gravitational potential *V* vanishes at infinity $V_\infty = 0$. Potential differences may be furnished by combining levelling measurements δn with gravity values *g*:

$$C_p = W_0 - W_P = \sum_0^P g\delta n. \tag{7}$$

The aforementioned equivalent field configurations of the Earth's gravity field require consistent treatment of gravity, potential and physical heights. For this reason, the interactions of the definition and realization of the IHRS with the definition and realization of an International Gravity Reference System (IGRS) as well as the International Terrestrial Reference System (ITRS) must be considered.

The accuracy of the widely used gravity reference network IGSN71 (International Gravity Standardization Net 1971, Morelli et al. 1974) is one to two orders lower than the current accuracy of absolute gravity measurements and generated products (e.g., Jiang et al. 2012), yet IGSN71 is still officially recognized as a valid tool despite this shortcoming. To support the implementation of a new gravity reference frame that is in accordance with the current high measurement accuracy, the IAG released a resolution *for the establishment of a global absolute gravity reference system* during the 2015 IUGG

General Assembly (Drewes et al. 2016). This resolution is a product of many efforts converging under the IAG Commission 2 (Gravity Field), the IGFS and the Consultative Committee for Mass and Related Quantities. The immediate activity for the following four years is to outline standards, conventions and procedures to define and realize the new gravity reference system.

3.2 Physical Height Reference Systems

In general, a reference system defines constants, conventions, models and parameters required for the mathematical representation of geometric and physical quantities. A reference frame realizes a reference system in two ways: physically, by a solid materialization of points; and mathematically, by the determination of coordinates referring to that reference system; i.e., the coordinates of the physical points are computed from the measurements, following the definition of the reference system. The datum fixes univocally the relation between a reference frame and a reference system. In the case of a vertical height reference system, the primary components are a reference surface (i.e., the zero-height level) and a vertical coordinate (i.e., a physical height or, more general, geopotential numbers). Its realization is given by a reference network, i.e., a set of points whose coordinates are of the same type as specified in the definition and referring to the vertical datum that establishes the level of the reference surface.

Physical Height Reference Systems (HRS) are related to the Earth's gravity field on or outside the solid Earth body. A global HRS is a geopotential reference system co-rotating with the Earth in its motion in space. In such a system, positions of points attached to the solid surface of the Earth are given by geopotential values and geocentric Cartesian coordinates $\mathbf{X}$ in a defined Terrestrial Reference System (TRS). A height or vertical reference frame (HRF) is a set of physical points with precisely determined geopotential values W_P or geopotential numbers C_P with respect to a geopotential reference value W_0. Such a HRF is said to be a realization of the HRS. The estimation of the coordinates $\mathbf{X}$, W_P or C_P includes their variation with time, i.e., $\mathrm{d}\mathbf{X}/\mathrm{d}t$, $\mathrm{d}W_P/\mathrm{d}t$, $\mathrm{d}C_P/\mathrm{d}t$.

3.3 Ideal Height Reference Systems

An ideal HRS is defined by values $W(\mathbf{X})$ of the scalar geopotential field of the Earth's gravity vector field $\mathbf{g}(\mathbf{X})$ in relation to a position given by coordinates $\mathbf{X}$ in the Euclidian space of an ideal TRS co-rotating with the Earth. For the TRS, the conventions of the International Terrestrial Reference System and Frame (ITRS, ITRF) defined in the conventions of the International Earth Rotation and Reference Systems Service (IERS) 2010 (Petit and Luzum 2010) are applied. Equivalent standards and conventions for the estimation of the potential values W are still missing (see Sect. 2).

For practical use, the geopotential values W_P at points $P(\mathbf{X})$ may be related to a physical reference level represented by an equipotential surface of the Earth's gravity field with a conventional value W_0. Thus, the vertical coordinates are the geopotential numbers C_P [see Eq. (1)] referring to the HRS zero-level W_0. This zero-level W_0 is called the vertical datum of the HRS. Geopotential numbers remain the preferred vertical coordinates for the HRS, since they are the primary source to determine any type of physical heights [see Eq. (2)].

Both the definition and the realization of a HRS require the implementation of standards and conventions that allow for a consistent definition (in accordance with geodetic theory) and a reliable realization (the best possible materialization of the reference system). The former case includes, for example, the type of coordinates, the conventions for the datum definition, the handling of time-dependent variations, the units. The latter case includes, among others, the station distribution of a primary reference network, the station characteristics, the models for data reductions, the computational procedures.

4 Standards, Conventions, Guidelines

4.1 Numerical Standards

Geodetic reference systems (GRSs) provide numerical values for the parameters of a geodetic Earth model, whose definition relies on the theory of the level ellipsoid. The defining parameters usually are the geocentric gravitational constant GM, the semi-major axis a, the dynamical form factor J_2 and the mean angular velocity of the Earth's rotation ω. The normal potential of the reference ellipsoid $U_0 = W_0$ may be used as a defining parameter instead of the semi-major axis a. Normally, the GRSs are updated from time to time when new and more accurate observations and models are available and an estimation of ellipsoid parameters closer to the actual Earth's shape and gravity field is suitable. In 1979, the IUGG, the IAG and International Astronomical Union (IAU) agreed upon the Geodetic Reference System 1980 (GRS80, Moritz 1980, 2000) as the replacement for the previous GRS67 (adopted at the 1967 IUGG General Assembly in Luzern). At the 1991 IUGG General Assembly in Vienna, new values for GM and a were recommended, while the other two defining parameters (J_2 and ω) were not changed. Although new best values for GM and a were introduced, the replacement of GRS80 by an updated GRS was not considered. As a matter of fact, while the value of the geocentric gravitational constant GM has not been changed since 1991, there is at present a wide variety of values for the semi-major axis a, which are mainly used in the computation of global gravity models. These a values and the 1991 GM value are not consistent with the conventional GRS80.

The IERS Conventions 2003 (McCarthy and Petit 2004) provide (see Table 1.1 therein) a list of numerical standards and associated parameters. In sections 4.1.4 and 4.2.5 of that conventions, the GRS80 is recommended for coordinate transformations. The GRS80 parameters provide the IAG recommendations for the conversion of ITRF Cartesian coordinates to ellipsoidal coordinates. This GRS80 is also used worldwide for many map projections, and millions of coordinates are related to it. Additionally, the GRS80 normal gravity formula has been widely used for the computation of gravity anomalies and normal heights.

Table 1 of this paper contains the defining parameters for different level ellipsoids. The values for the geocentric gravitational constant GM of the GRS80 and IERS Conventions 2010 differ by about 0.9 $m^3\ s^{-2}$; the semi-major axis a of both standards differs by 0.4 m, and the geopotential reference values (U_0 and W_0) differ by 4.85 $m^2\ s^{-2}$. Also noteworthy is that the IERS Conventions 2010 recommend different level ellipsoid parameters for different applications.

In the IERS Conventions 2010, Table 1.1 lists parameters that represent the current best estimates; these best estimates for level ellipsoid parameters have not been changed since 2003. It is not immediately evident how the 2010 estimates were determined. In addition, Table 1.2 of the same conventions contains the parameters of the GRS80 ellipsoid and it is designated as convention for the conversion of Cartesian coordinates to ellipsoidal ones. This is new compared to the preceding IERS Conventions 2003. These inconsistencies in

Table 1 Comparison of numerical values for some ellipsoid parameters

Ellipsoid	Semi-major axis a (m)	Dynamical form factor J_2	Geocentric gravitational constant GM in 10^8 ($\mathrm{m}^3\ \mathrm{s}^{-2}$)	Normal potential at ellipsoid U_0, geoidal potential W_0 ($\mathrm{m}^2\ \mathrm{s}^{-2}$)	Normal gravity at equator γ_e ($\mathrm{m\ s}^{-2}$)
GRS80	6,378,137	$1.082{,}63 \times 10^{-3}$*	3,986,005	$U_0 = 62{,}636{,}860.850$	9.780,326,7715
IERS 2010 Conventions	6,378,136.6** $\pm$ 0.1	$1.082{,}63{,}59 \times 10^{-3}$** $\pm 1 \times 10^{-10}$	$3{,}986{,}004.418 \pm 0.008$	$W_0 = 62{,}636{,}856.0 \pm 0.5$	

The mean angular velocity of the Earth's rotation ω remains the same in any case ($7{,}292{,}115 \times 10^{-11}$ rad s^{-1})

* Value given in tide-free system

** Value given in zero-tide system

the IAG and the IERS conventions should be removed in view of the development of integrated geodetic products and applications.

Since the most accepted definition of the geoid is understood to be the equipotential surface that coincides (in the sense of least-squares) with the worldwide mean ocean surface, the reference level W_0 for a global height system can be defined with the averaged potential value W_S at the mean sea surface sampled globally; i.e., $W_0 = W_S$. The value of W_0 depends on the Earth's gravity field, the definition of mean sea level, conventions about processing procedures and used models. As the mean sea level changes, it is expected that W_0 changes in the same way as W_S. Therefore, the definitions, conventions and conditions taken into account for the recommendation of a reference W_0 value shall be documented for further comparisons and monitoring of the mean sea level. However, given that W_0 may be introduced as a defining parameter of the mean Earth ellipsoid, the semi-major axis (a) of the level ellipsoid would be a derived parameter and it would change if W_0 changes. To provide a reference ellipsoid that remains unchanged with time, it would be necessary to decouple W_0 from the sea surface variations; i.e., a change of W_0 per year (in $\mathrm{m}^2\ \mathrm{s}^{-2}\ \mathrm{a}^{-1}$) would not be suitable. A main reason for the use of W_0 as defining parameter instead of the semi-major axis a is that W_0 is independent of the tide system. As a matter of fact, in the IERS Conventions 2010, W_0 is handled as a defining parameter, while the semi-major axis a is a derived parameter in the zero-tide system (see Table 1, Petit and Luzum 2010).

The IERS Conventions (2003 and 2010) include a W_0 value that was estimated in 1998 (Burša et al. 1998; Groten 1999, 2004). This value presents discrepancies of more than $-2\ \mathrm{m}^2\ \mathrm{s}^{-2}$ against recent computations (Sánchez et al. 2014). It must be decided whether a new value W_0 should be introduced as a more accurate estimate. As mentioned, for each new W_0 estimation, a new value for the semi-major axis (a) of the level ellipsoid would have to be derived. However, by a recalculation of the parameter W_0, the discrepancy existing between the values included in the IERS Conventions 2010 (see Table 1) and recent calculations will be eliminated and the estimation procedure can be documented to ensure the reproducibility of the newly adopted W_0 value.

For a global height reference system, any W_0 value within a range of a few $\mathrm{m}^2\ \mathrm{s}^{-2}$ (corresponding to a few decimetres in terms of heights) can be introduced as conventional without affecting the task of defining and realizing a global height reference system. However, like any reference system, 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 (i.e., global zero-height surfaces) as computations.

In any case, the complete set of ellipsoidal parameters should be computed for the best estimate of a new level ellipsoid as done for the GRS80. So far, this has not been the case.

Independently of the decision to replace the GRS80 by a new conventional set of level ellipsoid parameters, the current best-estimated value for W_0 should be defined (and fixed) as the potential value of the geoid. To ensure the reproducibility and interpretability of these changes, the procedure applied for the determination of W_0 must be well documented, including conventions and guidelines.

It is desirable that the recent best estimates for the parameters of the level ellipsoid are applied for all products of measurements and modelling of the Earth's gravity field and geometry, including the global height reference system. In this case, a new GRS could be computed. If the GRS80 remains as the conventional level ellipsoid, all necessary parameters must be then derived in accordance with the GRS80 values. For combination products such as GNSS levelling, the regulations for the reductions should be specified based on the different numerical parameters and underlying geometrical and gravity field relations.

The GRS80 represents the scientific status of the 1970s. In the concept of GRS80, the tidal systems and relativistic theories are not considered. From the view point of the authors, the GRS80 does not fulfil the present scientific needs. IAG is considering the necessity and usefulness of replacing GRS80 by a new GRS. If the computation of a new GRS is decided, an interdisciplinary working group should prepare and propose a full set of parameters to be presented and adopted at the 2019 IUGG General Assembly.

4.2 Permanent Tide

The geometry and gravity field of the Earth are influenced by the lunisolar (and to a far lesser extent planetary) tide effects; i.e., their determination depends on the tide system. A tide-free value is the quantity from which all tidal effects have been removed. This system assumes that the Sun and Moon do not exist. A mean-tide value is the quantity from which the periodical tidal effects have been excluded, but the permanent deformations (both direct and indirect) remain. This system reflects the constant effects caused by the Sun and Moon on the Earth (gravity/potential field and figure). The zero-tide value includes the indirect deformation only; i.e., periodical and permanent direct effects are removed. The indirect effect affects only the Earth's gravity/potential field, but not the Earth's figure. Therefore, zero-tide and mean-tide values for the Earth's surface (crust) are assumed to be identical. Since it is not possible to measure the Earth without the presence of the Sun and Moon, there are no experimental data to model the tide-free system and it is based on hypotheses about how the Earth were, if the Sun and Moon would not exist.

The IAG Resolution Number 16 adopted in 1983 at the General Assembly in Hamburg (Tscherning 1984) states that "the indirect effect due to the permanent yielding of the Earth should be not removed", and the fundamentals supporting this resolution have not changed. The zero-tide system is the most adequate tide system applicable to both gravity acceleration and gravity potential of the rotating and deforming Earth. The counterpart for the geometry is the mean/zero crust concept, where the mean sea surface corresponds to a crust deformed by mean/zero tides.

There is no justification for the application of a tide-free concept for both the geometry and the gravity field, since the tide-free crust and gravity do not correspond to the real Earth shape and are unobservable (Ekman 1989, 1996; Mäkinen and Ihde 2009). For the mean-tide geopotential the condition of the Laplace equation is not fulfilled, and even if the tide-free concept is kept for the terrestrial reference system parameters, the IAG Resolution No. 16 adopted in Hamburg in 1983 should be used for gravity and geopotential.

In practice, the geometrical coordinates **X** are given in a tide-free system based on the elastic response of the Earth to the semi-diurnal components of the tidal potential (Petit and Luzum 2010, Chapters 6 and 7). In the terrestrial gravity and spirit levelling processing, the tide-free system considers the Earth to be in a hydrostatic equilibrium (Munk and MacDonald 1960). These two different approximations cause discrepancies of up to 0.16 m in the tide-free vertical coordinates. The terrestrial gravity data are given in general in the zero-tide system (according to the IAG Resolution No. 16, 1983), but some values determined before 1983 refer to the tide-free system. The geopotential numbers are given in tide-free, zero-tide or mean-tide system. This depends on the application of the so-called astronomical reduction. This reduction produces coordinates in the tide-free system. If the indirect effect of the permanent tide is restored, they are given in zero-tide system. If the astronomical reduction is not taken into account, the geopotential numbers are assumed to

Table 2 Tide systems used in the determination of physical and geometrical coordinates

	Gravity $g \leftrightarrow \Delta g$	Geoid $W \leftrightarrow N$	Levelling height ΔH	Altimetry h	Mean sea level msl	Position $X \leftrightarrow h$
Mean tidal system Mean/zero crust (Stokes is not valid if masses outside the Earth surface)	Δg_m	N_m	ΔH_m	Relation to N_m for oceanographic studies h_{msl}		
Zero tidal system Zero/mean crust (recommended by IAG Res. No. 16, 1983)	$\Delta g_z \xrightarrow{\text{Stokes}} N_z$		ΔH_z C_p			
Non-tidal system Non-tidal crust (far away from the real Earth shape—there is no reason for the non-tidal concept)	$\Delta g_n \xrightarrow{\text{Stokes}} N_n$				X_n ITRF	

be in mean-tide system. The computation of the geoid is usually done in tide-free or zero-tide system. However, some models apply the elastic response approximation and others apply the hydrostatic equilibrium condition. Mean-tide system geoid models are also used especially for oceanographic applications.

To achieve consistency between the coordinates given in different tide systems and to support the combination of oceanographic and continental applications, parameters and products of a HRS should be related to the mean-tide system or mean crust (which is equivalent to a zero-tide crust). This means that a consistent transformation between the three tidal systems must be considered before combining gravity field and geometrical products. See Table 2 for the tide systems used currently in different geodetic observables.

5 Definition of an International Height Reference System (IHRS)

The IHRS is 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 (1) geopotential values $W(\mathbf{X})$ (and their changes with time $\mathrm{d}W(\mathbf{X})/\mathrm{d}t$) defined within the Earth's gravity field and, (2) geocentric Cartesian coordinates $\mathbf{X}$ (and their changes with time $\mathrm{d}\mathbf{X}/\mathrm{d}t$) referring to the ITRS. For practical purposes, potential values $W(\mathbf{X})$ and geocentric positions $\mathbf{X}$ can be transformed to geopotential numbers C_P and ellipsoidal heights h, respectively.

Five conventions define the IHRS:

(a) 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.

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

(c) The unit of length is the metre (SI). The unit of time is the second (SI).

(d) 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 [cf. Eq. (1)]:

$$C_P = -\Delta W_P = W_0 - W_P$$

(e) The spatial reference of the position P for the potential $W_P = W(\mathbf{X})$ is expressed as coordinates $\mathbf{X}$ in the International Terrestrial Reference System (ITRS).

These conventions (Ihde et al. 2015) were discussed and approved during the 2015 IAG General Assembly in Prague, and they are the main component of the *IAG Resolution for the definition and realization of an International Height Reference System*; see IAG Resolution No. 1 2015 in Drewes et al. (2016).

6 Conventions for the Realization of the IHRS

The IHRS establishes an unequivocal relationship between the Earth's gravity field (gravity, potential) and the geometry of the Earth. The IHRS is to be realized by combining a global station network, a GGM, and values for a set of parameters as an International Height Reference Frame (IHRF). The IHRF must be in accordance with the conventions underlying the definition of an IHRS, especially for conventions outlining how the elements can be derived. It is important to distinguish between the definition of the IHRS, physical heights derived in the IHRF (important for applications and users), and the unification of existing physical height systems aligned to a defined and realized IHRS.

Proposal for the elements of an IHRF:

(a) The reference geopotential value W_0 is achieved through best estimates. The procedure of the W_0 determination must be documented in conventions and guidelines to ensure the reproducibility and interpretability of changes.

In the resolution No. 1 2015, the IAG resolves $W_0 = 62{,}636{,}853.4\ \mathrm{m}^2\ \mathrm{s}^{-2}$ as realization of the potential value of the vertical reference level for the IHRS (see Sánchez et al. 2015, 2016).

(b) A central element of the IHRF is a GGM. The availability of GGMs of high resolution, such as EGM2008 (Pavlis et al. 2012, 2013) or EIGEN-6C4 (Förste et al. 2014), makes it possible to carry out a direct computation of $W(P)$ by introducing the ITRF coordinates $\mathbf{X}$ of any point into the spherical harmonic expansion equation representing a GGM. According to Rummel et al. (2014), the expected mean accuracy after applying one of these models is about ± 40 to $\pm 60\ \mathrm{cm}^2\ \mathrm{s}^{-2}$ (equivalent to ± 4 to ± 6 cm) in well-surveyed regions, and about ± 200 to $\pm 400\ \mathrm{cm}^2\ \mathrm{s}^{-2}$ (± 20 to ± 40 cm) with extreme cases of $\pm 10\ \mathrm{m}^2\ \mathrm{s}^{-2}$ (± 1 m) in sparsely surveyed regions. However, 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 of degrees higher than 300. 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. Therefore, for the realization of the IHRS and applications of high precision, it is proposed to choose one satellite-only

GGM for homogenous long wavelength approximation of the Earth's gravity potential as a matter of convention, and to refine this satellite-only GGM by combination of satellite altimetry and terrestrial (airborne, marine) gravity data.

(c) The potential difference $-\Delta W_P$ in relation to a conventional W_0 shall be known through an existing highest accuracy network of geodetic observation stations, where observations can be generated to derive the defining elements in the highest possible level of quality, consistent with other reference systems/frames.

(d) The reference network realizing the IHRF shall follow the same hierarchy of the ITRF reference network, i.e., a global network with regional/national densifications. This network shall be collocated with:

  - reference tide gauges (local vertical datum points);
  - main nodal points of the levelling networks;
  - border points connecting neighbouring vertical datum zones;
  - geometrical reference stations (ITRF and densifications);
  - fundamental geodetic observatories (connection between W_0, the International Atomic Time (TAI) and absolute gravity).

These stations must be at least:

- continuously monitored to detect deformations of the reference frame;
- referred to the ITRS/ITRF to precisely know their geometric coordinates;
- connected by levelling with the local vertical datum to precisely know their local geopotential numbers (to allow the vertical datum unification).

Additionally,

- It is the goal to estimate the Earth's gravity potential W_P at the IHRF stations with an accuracy of $1 \times 10^{-2}\ \mathrm{m}^2\ \mathrm{s}^{-2}$ by the combination of a GGM with gravity densification measurements $g(\mathbf{X})$.
- A standardization of the different data is required (tide system, reference epoch for station positions, reference gravity field for the solution of the geodetic boundary value problem—GBVP, etc.).

Product conventions and guidelines are necessary for all the aforementioned elements.

7 Guidelines for the Unification of Vertical Reference Systems Aligned to the IHRS

The primary objective of an IHRS and its realization (the IHRF) is to support the monitoring and analysis of the system Earth changes and to harmonize geodetic products. The more accurate the IHRS/IHRF is, the more phenomena can be identified and modelled. Thus, the IHRS/IHRF must provide potential values and their changes with time as accurately as possible. As many phenomena of the global change 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. Consequently, the global vertical datum unification with respect to the IHRS is a main component of the IHRS realization.

In the case of a global unified vertical datum, the primary step is to define a global reference surface (datum) assumed to be available all over the world.

At present, there are two basic concepts for the introduction of a global unified reference level:

- the first one is based on the adoption of an existing reference level, i.e., the vertical datum of any already established local height system or any existing value,
- the second one relies on the determination of an absolute (global) reference level in relationship to a defined global sea level status.

In the first case, the definition and realization of an absolute vertical datum is considered to be not important, since the primary vertical coordinates are level differences and the starting value to convert these differences to absolute values can arbitrarily be selected (e.g., Heck and Rummel 1990; Rummel and Heck 2000; Heck 2004; Gruber et al. 2012; Gerlach and Rummel 2013; Rummel et al. 2014). Here it is assumed that the reference level is already realized and the most important task is the connection of the existing height systems with that selected as absolute reference, especially height systems located in different continents. A relationship to the Earth body in the form of the global sea level is not given. Therefore, the authors prefer the second concept.

The realization of a global unified height system includes the connection of the existing local height systems to the global one (e.g., Balasubramania 1994; Rapp 1995; Ihde and Sánchez 2005; Sánchez 2007). In this paper, it is proposed to reach the first objective (definition of the global reference level) by adopting and realizing a certain W_0 value and the second one (connection of the local height datums to the global one) by applying any of the already existing strategies for vertical datum unification.

The general case for the HRS realization and unification consists of a combination of GNSS and levelling with geoid models. In general, the determination of potential values or potential differences of the Earth's gravity field is possible by integrating gravity over the height (combination of levelling and gravity values) or over the Earth surface (by solving the GBVP to estimate the anomalous potential). Most of the existing HRSs were realized

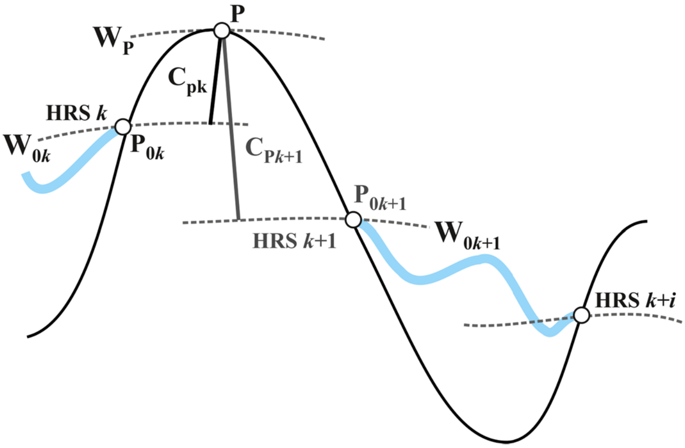

Fig. 2 Geometry of the existing physical reference systems: existing HRSs were in general realized by selecting as their vertical datum the mean sea level determined at a certain tide gauge P_0 and then connecting the vertical networks to that tide gauge. As the potential value at the reference tide gauges is unknown, it was assumed $W(P_0) = W_0$. The equipotential surfaces passing through the different reference tide gauges P_{0k} realize different (local) geoids, which are lying very close to sea surface (about ±2 m) and are practically parallel to each other, but no one coincides with a global geoid. The geopotential numbers of levelling points located at border regions and referring to two neighbouring HRSs are inconsistent

by levelling. Their zero-level is derived by long-term observations of the sea level at local tide gauges (Fig. 2). Normally, the W value of the zero-level of the classical levelling networks is not known and an arbitrarily selected value is introduced as reference. Independently of the selected W_0 value, these locally realized HRSs differ in the height by the stationary sea surface topography at the tide gauges and by inconsistencies in the definition of the vertical datum and coordinates (e.g., different reference epochs for the mean sea level computation, different gravity reductions for levelling). Globally, there are differences with the stationary sea surface topography of up to ±2 m.

There are two general possibilities for the realization and three for the unification of HRSs:

(a) For HRS realizations on continents, the usual method is the geometric levelling. For HRS unification, common adjustments of existing levelling networks over continents are suitable.
(b) The general case for realization and unification (especially for HRSs that cannot be connected by levelling directly) is the combination of GNSS positioning (i.e., ITRF coordinates) and levelling with a geoid model.
(c) An additional possibility for the unification of HRSs is the combination of tide gauge observations with sea surface topography information derived from satellite altimetry.

An integrated analysis of the different cases is useful, in particular with respect to the procedures employed.

7.1 Levelling and Common Adjustment of Existing Levelling Networks

This procedure is mainly used for the realization of HRS and the unification of existing HRFs located on the same continent. This case cannot be used for the realization of a global HRS. An example is the realization of the European Vertical Reference System (EVRS) (Ihde and Augath 2000, 2002) by the United European Levelling Network (UELN), which is the result of a common adjustment of 26 national European 1st order networks.

7.2 General Case for Realization and Unification: Combination of GNSS and GNSS/Levelling with a Geoid Model

The HRS realization at single points P at the Earth surface is given by:

$$W_P = U_0 + \frac{\partial U_0}{\partial h} h_{\mathrm{ITRF}} + T_P, \tag{8}$$

or in terms of normal heights and height anomalies by:

$$H^*_{\mathrm{P}} = h_{\mathrm{ITRF}} - \zeta_P \tag{9}$$

In Eq. [8], U_0 is the potential of the reference level ellipsoid and T_P is the disturbing potential:

$$T_P = W_P - U_P, \tag{10}$$

i.e., the difference between the actual (W) and the normal (U) potential at P. T is usually determined by solving the geodetic boundary value problem (GBVP) and integrating gravity over the whole Earth's surface σ (see, e.g., Heck and Rummel 1990; Rummel and Teunissen 1988). Height anomalies derived from the GBVP solution (ζ_{GBVP}):

$$\zeta_{\mathrm{GBVP}} = \frac{T_P}{\gamma} \tag{11}$$

are compared with the difference between ellipsoidal and normal heights at levelling bench marks ($\zeta_{H,h} = h - H^*$). The discrepancy ($\zeta_{\mathrm{GBVP}} - \zeta_{H,h}$) is added to the ζ_{GBVP} height anomalies in such a way that the quasi-geoid model is fitted to the local vertical datum to satisfy Eq. (9). In this case, normal height H^* and height anomaly ζ refer to the local HRS and do not allow the realization of a unified global HRS.

The transformation of geopotential numbers C_{Pk} referring to a local vertical datum to a global HRS is possible if the level W_{0k} of the regional HRF k is known (Fig. 3):

$$W_P = W_{0k} - C_{Pk} \tag{12}$$

With a GGM and ITRF positions, the potential of levelling points can be determined in a global system by means of:

$$W_P = U_P + T_{P\,\mathrm{GGM}} \quad \text{with} \quad U_P = U_0 + \frac{\partial U_0}{\partial h} h \tag{13}$$

$$\text{i.e.} \quad W_P = U_0 + \frac{\partial U_0}{\partial h} h_{\mathrm{ITRF}} + T_{P\,\mathrm{GGM}} \tag{14}$$

The potential W_{0k} of the zero-level in a regional HRF k and the difference to the global level ΔW_{0k} can approximately be derived by combining Eq. (14) with the geopotential numbers associated with the local HRS at given i points [cf. Eq. (12)]:

$$\begin{aligned} W_{0k,i} &= U_0 + \frac{\partial U_0}{\partial h_i} h_{i\,\mathrm{ITRF}} + T_{Pi\,\mathrm{GGM}} + C_{Pk,i} \\ &= U_0 - \gamma_0 \left(h_{i,\,\mathrm{ITRF}} - H^*_{k,i} - \zeta_{i\,,\mathrm{GGM}} \right) \end{aligned} \tag{15}$$

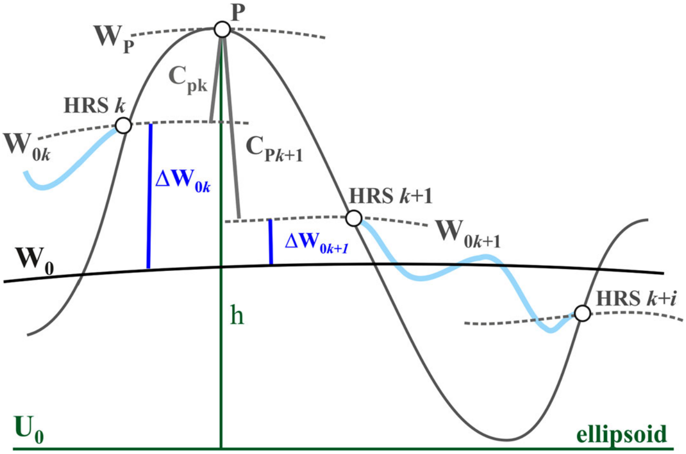

Fig. 3 Principle of the vertical datum unification: the main objective is to refer all existing geopotential numbers to one and the same global reference surface. Geopotential numbers referring to local HRSs can be transformed to the global IHRS by determining the potential difference between the local reference tide gauges (W_{0k}) and the global vertical datum W_0; i.e., $\Delta W_{0k} = W_{0k} - W_0$

The mean value of the potentials $W_{0k,i}$ can be assumed as the local reference level W_{0k}:

$$W_{0k} = \frac{1}{n}\sum_{i=1}^{n} W_{0\,k,i} \tag{16}$$

and its difference with respect to the global HRS level W_0 (cf. Fig. 3) is given by:

$$\Delta W_{0\,k} = W_0 - W_{0k} \tag{17}$$

ΔW_{0k} can also be estimated together with the anomalous potential T by solving the GBVP as proposed by Rummel and Teunissen (1988), and follow-up publications, such as Heck and Rummel (1990), Xu and Rummel (1991).

As already mentioned, some of the existing HRSs are realized by orthometric heights. However, for the vertical datum unification, we recommend the use of geopotential numbers or normal heights to minimize further discrepancies caused by dissimilarities in the hypotheses applied for the computation of orthometric heights. Additionally, to improve the accuracy of the results, the GGM used for the computation of the disturbing potential T has to be augmented with local or regional gravity data. To guarantee a homogenous unification, the GGM shall be conventional and h has to refer to the ITRF. Some examples of this procedure are given in Kotsakis et al. (2012), Grigoriadis et al. (2014), Rülke et al. (2014), Sideris et al. (2014) and Amjadiparvar et al. (2016).

7.3 Unification of HRSs by Combination of Tide Gauge Observations with Mean Ocean Dynamic Topography Information Derived from Satellite Altimetry

As the topographic surface on land areas, the sea surface may be represented by means of geometric or physical heights. The geometric heights, called mean sea surface heights h_{MSS}, are derived from satellite altimetry directly. The physical heights H_{MDT} are known as the mean ocean dynamic topography (MDT) and may be estimated either from an ocean circulation model or as the difference between the mean sea surface heights h_{MSS} and the geoid N (Fig. 4):

$$H_{\mathrm{MDT}} = h_{\mathrm{MSS}} - N = h_{\mathrm{S}} - r - N. \tag{18}$$

h_{S} denotes the height of the satellite with respect to a reference ellipsoid and r is the range measurement representing the distance between the satellite and the sea surface. In ocean areas, orthometric H and normal heights H^* (and with them, geoid and quasi-geoid) are practically identical; however, for consistency we continue using the quasi-geoid and height anomalies ζ. The topography of the sea surface represented by Eq. (18) refers to a geocentric reference ellipsoid (for h_{MSS}) and to a global (quasi-)geoid (for H_{MDT}) usually derived from a GGM. If the mean sea level is measured at a tide gauge, the physical heights of the sea surface H_{MSS} refer to the zero reference point of the tide gauge (TG zero in Fig. 4), which usually realizes the reference level of the local HRS; see $H_{\mathrm{MSS},k}$ and $H_{\mathrm{MSS},k+1}$ in Fig. 4.

The vertical datum unification based on the combination of tide gauge registrations with satellite altimetry data aims at connecting the mean sea surface registered at different tide gauges $H_{\mathrm{MSS},k}$ using a satellite altimetry-based MDT model. The level difference between two HRSs is given by:

$$\delta H_{k,k+1} = \Delta H_{0,k+1} - \Delta H_{o,k} = \left(H_{\mathrm{MDT},k+1} - H_{\mathrm{MSS},k+1}\right) - \left(H_{\mathrm{MDT},k} - H_{\mathrm{MSS},k}\right). \tag{19}$$

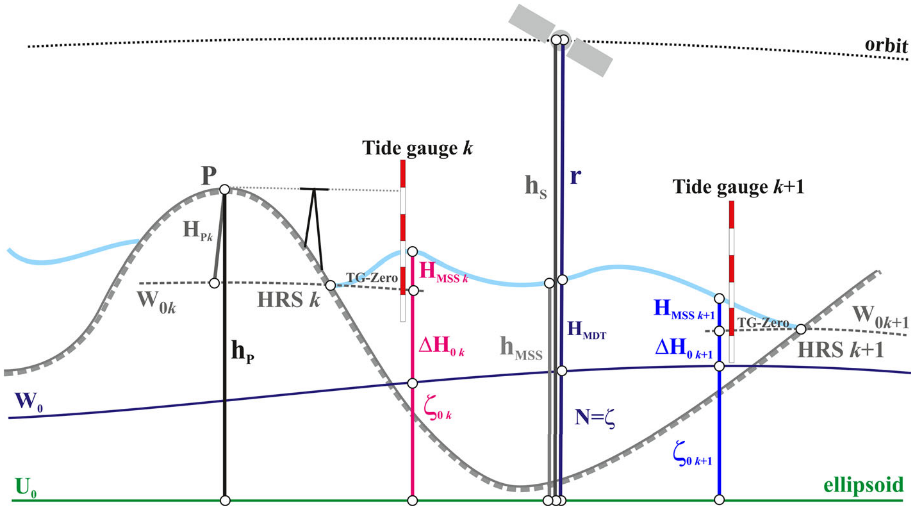

Fig. 4 Interrelationship between satellite altimetry-based mean ocean dynamic topography (H_{MDT}) and the mean sea surface registered at tide gauges ($H_{\mathrm{MSS}k}$) for the vertical datum unification at existing HRSs

In coastal areas, the MDT is influenced by local effects and satellite altimetry measurements cannot at present be used with high precision. Therefore, the use of offshore tide gauges is recommended.

8 Outlook

At present, the main challenge is the realization of the IHRS, i.e., the establishment of the International Height Reference Frame (IHRF). As mentioned in Sect. 4, it is expected that the IHRF will follow 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 0.01 m^2 s^{-2} to some orders of magnitude lower (from 0.1 to 1 m^2 s^{-2}). Consequently, the next step is to outline the minimum set of fundamentals needed for the realization of the IHRS. Among others, the following aspects have to be clarified:

- 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).
- Formulation of the minimum requirements for the IHRF reference stations.
- Development of strategies for collocation of IHRF reference stations with existing gravity and geometric reference stations at different densification levels.

- 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 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.

In accordance with the adopted resolution on a Global Geodetic Reference Frame for Sustainable Development, the GGRF is the fundamental requirement for a reliable determination of changes in the Earth system, for monitoring sea level rise and climate change, as well as to provide accurate information for decision makers. The GGRF network stations typically comprises (see IAG 2016):

- fundamental geodetic observatories employing all space geodetic techniques co-located with gravimetric instruments, enabling the connection between $\mathbf{X}$, W and g;
- other geodetic stations also including reference tide gauges, height datum points and gravity measurement points co-located where possible with space geodetic instruments.

In this sense, the IHRF will be an integral part of the GGRF.

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