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Geodetic Reference Systems: towards GGRS/GGRF

Sistemas Geodésicos de Referência: rumo ao GGRS/GGRF

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Abstract: One of the main challenges in Geodesy is the definition and realization of Global Geodetic Reference Systems with geometric and physical characteristics. This is necessary to fulfill the demands of different knowledge areas for information related to Earth Observation Systems (EOS) to be integrated into Geodetic Reference Networks (GRNs) with an accuracy of 10^{-9} or better. The development of satellite positioning systems has brought significant improvements in positional accuracy and made possible the replacement of classic GRNs by modern networks with global characteristics. Today, the issue of geometric coordinates is well resolved with the ITRS/ITRF (International Terrestrial Reference System/International Terrestrial Reference Frame). However, aspects associated with diverse physical processes, like mass redistribution reflections, are not addressed by purely geometric references. The approval of the GGRS/GGRF Resolution (Global Geodetic Reference System/Global Geodetic Reference Frame) emerges as a vision of integration between the terrestrial reference system, the celestial reference system, a global reference system with physical characteristics for heights and the new global absolute gravity network. Efforts have been made to define and realize this global height reference system. It is a complex task due to the classical characteristics of existing vertical reference systems, heterogeneity in terms of accuracy and spatial distribution of the data needed, especially data related to the Earth's gravity field. The need to establish standard procedures for integration with the global height reference system and the precision needed for the establishment of EOS are the big challenges for the future.
Keywords: Geodetic Reference System. Geodetic Reference Frame. Physical Heights. SIRGAS.

Resumo: O estabelecimento de Sistemas Geodésicos de Referência globais integrando características geométricas e físicas é um dos desafios atuais da Geodésia, principalmente devido às demandas de diversas áreas do conhecimento de que as informações relacionadas aos Sistemas de Observação da Terra (EOS – *Earth Observation Systems*), sejam integradas em Redes Geodésicas de Referência (RGRs) com uma acurácia de 10^{-9} ou melhor. O surgimento das técnicas de posicionamento espacial trouxe melhora significativa na qualidade posicional e possibilitou a substituição das RGRs clássicas por redes modernas com características globais. Hoje, a questão das coordenadas de caráter geométrico, está bem resolvida com o ITRS/ITRF (*International Terrestrial Reference System*/*International Terrestrial Reference Frame*). Todavia, aspectos associados a diversos processos físicos, tais como os reflexos das redistribuições de massa, não são atendidos por referenciais puramente geométricos. A aprovação da resolução para o GGRS/GGRF (*Global Geodetic Reference System*/*Global Geodetic Reference Frame*) surge com a visão da integração entre o referencial terrestre, o celeste, um referencial com características físicas para as altitudes e a nova rede global de gravidade absoluta. Esforços têm sido feitos para definição e realização deste referencial global para as altitudes. É uma tarefa complexa em vista das características clássicas dos referenciais verticais, heterogeneidade em termos de qualidade e distribuição espacial de dados necessários, principalmente os relacionados ao campo de gravidade da Terra. Apresentam-se como grandes desafios para o futuro a necessidade de estabelecimento de procedimentos padrão para a integração ao referencial altimétrico global e a precisão necessária para o estabelecimento dos EOS.
Palavras-chave: Sistema Geodésico de Referência. Rede Geodésica de Referência. Altitudes Físicas. SIRGAS.

1 INTRODUCTION

The definition, realization and maintenance of Geodetic Reference Systems (GRS) have been historically, and are currently, part of the principal attributions of Geodesy in scientific and technological contexts. In this sense, the practical applications of Geodesy which were directed, above all, to defining limits, providing data infrastructure for Cartography, Registry, Engineering, among countless others, have expanded tremendously. Geodesy currently provides the knowledge necessary for establishing Earth Observation Systems (EOS) that enable analysis of phenomena and effects related to the Earth's physical processes, providing the necessary infrastructure in terms of reference systems, databases and products for understanding the changes the planet is undergoing and which impact society as a whole (PLAG et al., 2009). With this in mind, in July 2003, during the XXIII International Union of Geodesy and Geophysics (IUGG) General Assembly, in Sapporo, Japan, the International Association of Geodesy (IAG) established the Global Geodetic Observing System (GGOS). The GGOS operates through IAG Commissions and Services to provide the geodetic infrastructure needed to monitor the Earth System and for global change research. Within current perspectives, it aims to provide a better understanding of the dynamics of the Earth System by quantifying planetary changes in space and time (GGOS, 2020). As GGOS developed over time four main working areas have been established (GGOS Focus Areas): 1. Unified Height System; 2. Geohazards Monitoring; 3. Sea Level Change, Variability and Forecasting; 4. Geodetic Space Weather research.

Integrating reference systems with geometric and physical characteristics is one of the biggest challenges that Geodesy has faced in recent years. This challenge arises from the need for observations related to the figure of the Earth (geometry and kinematics), Gravity field (mass distribution and redistribution) and Rotation of the Earth (link with "inertial space"), known as the "three pillars of Geodesy" and their activities, to be integrated to reference structures with an accuracy of 10^{-9} or better.

Specifically with regard to GRS, from the classical point of view their main aspects or characteristics are: local references; topocentric orientation; defined solely for geometric parameters; separation between the horizontal component (latitude and longitude) and the vertical component (height); not taking into consideration the temporal aspect to which coordinates are related; precision associated with coordinates is often unknown; the need to be realized from a starting point (referred to as Datum in Brazil) and materialization using conventional geodetic surveying techniques such as triangulation, trilateration, polygonation and spirit leveling. Over the course of time and as technological progress has occurred, new methodologies have emerged, as well as new equipment, increasingly powerful computers, new mathematical modeling, resulting in increasingly accurate observations and the need for more refined data treatment. For example, modern spatial positional techniques, such as VLBI (Very Long Baseline Interferometry), GPS (Global Positioning System) and SLR (Satellite Laser Ranging), have brought significant improvements to positional quality and the possibility of replacing classic reference systems with modern global geocentric reference systems involving three-dimensional (latitude, longitude and ellipsoidal height) characteristics, with information about coordinate quality and temporal variation. In both their definition and their realization, these new reference systems are based on geometric and physical parameters.

Today, the issue of three-dimensional geodetic coordinates has been well resolved by the ITRS/ITRF (International Terrestrial Reference System/International Terrestrial Reference Frame). These geodetic coordinates are usually expressed in the Cartesian form (X, Y, Z) or in the ellipsoidal form as latitude (φ), longitude (λ) and height (h). As orthometric, normal, dynamic heights, among other heights of a physical nature, or those of a mixed nature such as normal-orthometric height, are also geodetic coordinates, the expression ellipsoidal height is used for (h), as can be found in the international literature (see for example HOFMANN-WELLENHOF; MORITZ, 2005, p. 72, 81, ...).

Definition of an ITRS depends on fundamental geodetic constants involving the Figure of the Earth (dimensions), the gravity field (dynamic form factor and geocentric gravitational constant) and the Earth's rotation (angular velocity) which will be discussed in the next section. ITRF realization depends on the geometry and orientation in space of a global polyhedron of ITRF stations, at a given moment in time, whereby these are linked to the geocenter. This geocenter is realized based on the geopotential (or potential of the

Earth's gravity field), as it is linked to fixing harmonic coefficients of the gravity field (C_{10}, C_{11} *and* S_{11}) all equal to zero. These coefficients are associated with the coordinates of the mass center estimated for the reference epoch, which is the usual origin of global GRS (LAMBECK, 1988, p.13). A noteworthy aspect is that the temporal variations of latitude and longitude in the ITRS are aspects that are well mastered and established in global and regional velocity models, while variations in height are vanguard topics in Geodesy research. With regard to this aspect, global research involving Brazilian participation by Montecino et al. (2017), Ferreira et al. (2019) and Brassarote (2020) stands out.

The development of EOS principally with regard to the aspects of monitoring and consistent interpretation of key processes of planetary dynamics requires reference structures that integrate geometric space with physical space associated with the geopotential (or the potential of the Earth's gravity field). As such, by means of a Resolution approved on February 26th 2015, the United Nations General Assembly established a geodetic reference system for sustainable development, adopting the structured Geodesy approach, as per the premises of IAG/GGOS, and its Commissions and Services. This resulted in the recommendation for the GGRS/GGRF (Global Geodetic Reference System/Global Geodetic Reference Frame). This system/frame emerged with the vision of integration between a terrestrial GRS with geometric characteristics duly oriented in relation to a celestial reference system with fundamental characteristics and a global reference system for heights with physical characteristics. The latter is to be realized in geopotential space, i.e. the realization of this global reference system for heights will take place based on determination of the geopotential value, on points on the Earth's physical surface, through the modeling of the disturbing potential by solving the Geodetic Boundary Value Problem (GBVP). These premises were linked to a requirement for the inclusion of a new global absolute gravity network to replace the IGSN71 (International Gravity Standardization Net 1971), given that the latter no longer meets the current purposes of Geodesy. These ideas were consolidated by the IAG in July 2015 according to: Resolution No. 1 which established the IHRS (International Height Reference System) predicting its future realization as IHRF (International Height Reference Frame) based on geopotential numbers, and Resolution No. 2 which established the GAGN (Global Absolute Gravity Network). In April 2016, the IAG manifested its formal position regarding the GGRS/GGRF through a detailed description of its definition and realization (IAG, 2016). These aspects will be returned to later in this paper.

Huge efforts have been made to establish IHRS standardization procedures and to establish road-maps for its realization (IHRF), as well as for the GAGN. In South America these efforts are concentrated on activities related to SIRGAS Project Working Group III (WG-III). The complexity of the task arises mainly due to the classical characteristics of vertical reference system definition and realization, heterogeneity in terms of the quality and spatial distribution of the data needed, principally that of the data related to the Earth's gravity field. The need to establish standard procedures for integration with the global height reference system, as well as the precision needed to establish the EOS, are considerable challenges for the future.

As such, this article has sought to bring an overview of the evolution of GRS, both with regard to definition and realization, seeking to highlight the need to introduce physical aspects; address more current aspects related to the establishment of a unified reference system with physical characteristics for heights, and to present challenges to be overcome with the aim of establishing EOS.

2 FUNDAMENTAL CELESTIAL AND TERRESTRIAL REFERENCE SYSTEMS AND FRAMES

Defining a GRS, from a more conservative viewpoint, for three-dimensional geometric positioning on the physical surface of the Earth, involves the establishment of a set of parameters and conventions associated with an ellipsoidal reference surface duly positioned and oriented in relation to the Earth. An adequate reference system is thus realized for attributing coordinates to points on the physical surface of the Earth. Contemporarily, the reference surface is established by a set of geometric and physical parameters: geocentric gravitational constant (GM), semi-major axis (a), dynamic form factor (J_2) and angular rotation velocity (ω). The definition of the reference system also explains its origin, scale and reference epoch (TORGE; MÜLLER, 2012).

From a current viewpoint, realization or materialization of a GRS occurs through a set of points implanted on the physical surface of the Earth, the coordinates of which are determined based on the previously defined reference system. This set of points comprises the so-called geodetic reference networks, which can be global (e.g. ITRF2014), regional (e.g. SIRGAS – CON), national (e.g. SIRGAS2000) and even have other densifications, such as state and municipal networks. All these networks are usually established in a hierarchical manner as densifications of the most fundamental global network. This occurs thanks to the potentialities of using the GNSS (Global Navigation Satellite System) when establishing these networks.

However, other geodetic reference systems and networks coexist alongside the more up to date ones, such as for example networks established by classic geodetic surveying techniques. It is thus that geodetic networks are didactically divided into: vertical or altimetric networks, where the coordinate of interest is height, and which are derived from spirit leveling or geometric leveling (for which physical meaning must be sought); classical horizontal networks, where interest lies in determining the latitude and longitude coordinates, which were usually and incorrectly called "planimetric" coordinates (remembering that the reference surface for establishing these coordinates is ellipsoidal, i.e. a curved surface); and current three-dimensional networks. This division takes into account the fact of the coordinate having a physical or purely geometric characteristic and, moreover, that different observations and field surveying techniques are used for implementing each type of network. Geodesy also concerns the establishment of fundamental gravity networks and their densifications (TORGE; MÜLLER, 2012).

Reference systems are also needed for describing the position and movement of objects in the outer space, such as artificial satellites, quasars (quasi-stellar radio sources) and even other planets. The link between terrestrial and celestial reference systems is essential: given the bases and tools of modern Geodesy which are supported to a great extent by spatial observation methods.

2.1 Classical aspects of the definition and realization of a Geodetic Reference System

In the case of classical GRS, the definition of the reference ellipsoid was done using only geometric parameters, usually the semi-major axis (a) and flattening (f) as defined by Equation (1) (VANÍČEK; KRAKIWSKY, 1986):

$$f = \frac{a - b}{a} \tag{1}$$

where b is the semi-minor axis of the ellipsoid of revolution. The ellipsoidal reference surface can also be defined by semi-major axis (a) and semi-minor axis (b) or even by semi-major axis (a) and eccentricity (e). The search for an ellipsoid most aligned with the Earth has involved scientists since the beginning of the 19th century in the quest for increasingly refined parameters (SMITH, 1996).

Reference ellipsoid positioning and orientation were done in such a way as to align it with a given region, country or group of countries. In this case the ellipsoid is not geocentric, i.e. the center of the model does not coincide with the Earth's center of mass. Six topocentric parameters were needed in order to position and orient the reference ellipsoid: the geodetic coordinates (φ and λ) of an origin point (called Datum); an initial orientation, given by an initial azimuth; the distance along the normal from the reference ellipsoid to the geoid (geoid height N), and the components of the deviation of the vertical (meridian component ξ and first vertical component η) (COSTA, 1999).

Establishment of the geodetic coordinates at the origin point (Datum) and establishment of the initial azimuth was done by applying the so-called orientation equations which enable geodetic quantities and astronomical quantities to be related knowing the components of the deviation of the vertical. As such, the astronomical coordinates were determined at the origin point (latitude Φ and longitude Λ), as were those of the astronomical azimuth (A_a) from a direction originating at the Datum, and these astronomical quantities were converted into geodetic quantities through knowledge or judgment of the components of the deviation of the vertical, as per Eq. (2), Eq. (3) and Eq. (4) (GEMAEL, 1999):

$$\xi = \Phi - \varphi \quad (2)$$
$$\eta = (\Lambda - \lambda) cos\varphi \quad (3)$$
$$\eta = (A_a - A)\cot\varphi \quad (4)$$

where A is the geodetic azimuth of the direction considered. Eq. (5) is obtained by equalizing Eq. (3) and Eq. (4), which is known as Laplace’s Equation and it enables an astronomical azimuth to be converted into a geodetic azimuth:

$$A = A_a - (\Lambda - \lambda)\sin\varphi \quad (5)$$

Classical GRS realization was achieved by establishing horizontal geodetic networks based on geodetic surveying techniques such as triangulation, trilateration and polygonation. This network had a two-dimensional characteristic, whereby starting from the origin point directions and/or distances were measured in order to calculate the geodetic coordinates (φ and λ) of the remaining vertices of the network. The heights of the vertices were determined with a level of precision relatively inferior to that of the horizontal coordinates, using trigonometric leveling for instance. The purpose of these heights was to provide elements for reducing the bases (measured on the physical surface of the Earth) to the reference ellipsoid.

In Brazil, with effect from the beginning of the establishment of the Brazilian Geodetic System (BGS) in the 1940s, the country adopted two reference systems with classical characteristics: Córrego Alegre and SAD69. The BGS is characterized by the entire geodetic infrastructure necessary for cartographic location and representation on the Brazilian territory. Its establishment and maintenance are the responsibility of the Brazilian Institute of Geography and Statistics (IBGE), (IBGE, 2000).

The Córrego Alegre GRS was officially adopted by Brazil in the 1950s up until the 1970s. The reference surface used for its definition is the Hayford International Ellipsoid 1924, with a semi-major axis a = 6 378 388 m and flattening f = 1/297 (IBGE, 1996). The ellipsoid’s positioning and orientation occurred in a totally arbitrary manner, i.e. establishing nil values for geoid height and for the components of the deviation of the vertical at the Datum (Córrego Alegre vertex in the state of Minas Gerais). At the time it was the only form of realization possible in practice. In this case, with the imposition of the nil value for the components of the deviation of the vertical at the Datum, the geodetic coordinates of this vertex remained equal to its astronomical coordinates (IBGE, 1996):

Latitude $\varphi = \Phi$ = 19º 50’ 14.91” S and

Longitude $\lambda = \Lambda$ = 48º 57’ 41.98” W,

The orthometric height (H) of the Córrego Alegre vertex is 683.81 m and as its geoid height is nil it is considered that H=h. Due to its arbitrary orientation, there was good ellipsoid-geoid adaptation in the region of Minas Gerais and São Paulo, but further away from the origin discrepancies became quite evident.

SAD69 (South American Datum 1969) was officially adopted in Brazil from the end of the 1970s until February 2005, when it was replaced by SIRGAS. Its definition adopted as the geometric model of the Earth the 1967 International Reference Ellipsoid, defined by the parameters of a semi-major axis a = 6 378 160 m and flattening (1/298.247167427) rounded up to f = 1/298.25 (IBGE, 1998). The ellipsoid’s positioning and orientation occurred in a partially arbitrary manner, determining the values of the components of the deviation of the vertical (meridian component ξ = 0.31" and first vertical component η = -3.52") and established a nil value for geoid height at the Datum (Chuá vertex in the state of Minas Gerais). By means of astronomic determination at Chuá and knowing the values of the ξ and η components it was possible to calculate the geodetic coordinates of the vertex using the orientation equations presented above (Eq. (2), (3), (4) and (5)). The Chuá vertex coordinates can be seen in Table 1:

Table 1 – Chuá Vertex Coordinates.

Coordinate	Astronomical	Geodetic
Latitude	19º 45' 41.34" S ± 0.05"	19º 45' 41.6527" S
Longitude	48º 06' 07.80" W ± 0.08"	48º 06' 04.0639" W
Azimuth at the Uberaba vertex (counted from the South)	271º 30' 05.42" ± 0.21"	271º 30' 04.05"
Geoid height	N = 0 m	

Source: FISCHER (1973).

In this case, those responsible sought to position and orient the ellipsoid so as to obtain good alignment between the surface of the ellipsoid and the geoid in South America and, above all, so as to obtain better alignment between the ellipsoidal and orthometric heights at the ocean edges (IBGE, 2000).

In general, up to be beginning of the 1990s, the realization of the BGS was achieved through classic triangulation and polygonation procedures using the following basic observations: horizontal directions, vertical angles, distances and astronomic values – of coordinates and azimuths (OLIVEIRA, 1998) which implied relative accuracies of 1:50,000 to 1:100,000 or 20ppm to 10ppm (ppm - parts per million), in addition to points established with the TRANSIT system. Use of the TRANSIT system began in Brazil in the 1970s, when Doppler observations were conducted at stations of the fundamental geodetic network with the aim of estimating transformation parameters between the SAD 69 and the NSWC 9Z2 (which was the reference system associated with the precision ephemerides of the TRANSIT system) (CASTAÑEDA, 1986). Later, stations were also established in the Amazon region where it was not feasible to carry out classical geodetic surveys. Finally, in 1991 the IBGE adopted the GPS (Global Positioning System) in a systematic manner in its geodetic surveys with the aim of achieving densification of the horizontal network (COSTA, 1999).

With effect from the end of the 1980s and during the 1990s, increasingly frequent GPS use for positioning as well as distortions existing in the classic Fundamental Geodetic Networks, highlighted the inconsistencies existing between classical GRS and international reference systems based on geocentric ellipsoids. Moreover, geodetic positioning techniques, principally those based on satellites capable of directly providing the three coordinates (φ, λ, h), achieved right from the beginning relative precision of 1ppm or better, which made it necessary to adopt reference systems that enabled global georeferencing, so as to enable compatible information integration internationally, and which also took into consideration coordinate temporal variation in keeping with terrestrial dynamics.

2.2 Modern aspects of Geodetic Reference System definition and realization

A modern GRS is based on the adoption of an ellipsoid of revolution the origin of which coincides with the Earth's center of mass in a given epoch (geocenter) and the positioning and orientation of which are done in relation to the Earth as a whole, thus characterizing a geocentric system. The reference ellipsoid is taken to have an equipotential surface (level ellipsoid) as assumed in the so-called Normal Earth model, which determines that the reference ellipsoid has the same mass and angular velocity as the Earth and that its surface is equipotential. This model is the basis for establishing normal potential (sum of the gravitational potential of the Normal Earth and the centrifugal potential which is the same as that of the Real Earth) and normal gravity. This model is associated with the parameters that define conventional GRS, such as the example presented for the GRS80 (Geodetic Reference System, 1980) in Table 2. Evidently, different GRS have different parameters that need to be taken into consideration in conversions (Geocentric Gravitational Constant GM, equatorial radius a, dynamic form factor contained in coefficient J_2 of the geopotential and the angular velocity of the Earth ω). A three-dimensional Cartesian system is also associated, which has its origin in the geocenter, equatorial orientation and metric scale. Thus, the three-dimensional position of any point on the physical surface of the Earth can be represented by the coordinates (φ, λ, h) or (X, Y, Z).

The reference model recommended by the International Association of Geodesy (IAG) is the GRS80, which geometric and physical parameters can be seen in Table 2:

Table 2 – Parameters defining the GRS80.

Constant	Value	Description
GM	3.986005×10^{14} m^3s^{-2}	Geocentric gravitational constant
a	6378137 m	Earth's equatorial radius (semi-major axis)
J_2	1.08263×10^{-3}	Dynamic form factor
ω	7.292115×10^{-5} $rads^{-1}$	Angular velocity

Source: IERS (2010).

It is appropriate to highlight that the fundamental geodetic constants shown in Table 2 involve geometric and physical aspects. Whereas the semi-major axis *a* derives from indirect metric determinations that lead to relative precision better than 1ppb (part per billion), the geocentric gravitational constant *GM* (product of the Earth's mass including its atmosphere and the universal gravitational constant) derives from analysis of the orbital movement of satellites with orbits sufficiently stable to achieve precision of 1ppb under the gravitational action of the Earth. This is the case of the SLR missions coordinated by the International Laser Ranging Service (ILRS, 2000). The dynamic form factor $J_2 = - C_{20}$ is a dimensionless coefficient of the development of the geopotential in spherical harmonics, obtained from the orbital movement of satellites that are stable under the gravitational action of the Earth. This coefficient can currently be obtained with precision better than 1ppb. The angular velocity of the Earth is assessed using radio astronomy methods based on observation of quasars with temporal stabilities which, for practical purposes, can materialize an inertial reference system. These observations are done using the VLBI technique based on a global network of radio telescopes with resolution better than 10^{-4} arcsec (arcseconds) or 0.1mas (milliarcseconds). Time, involved in the determinations of the parameters mentioned, is based on atomic clocks with stability of 10^{-14} seconds or better in periods of one or more years.

Currently, the ITRS global GRS is understood as the basis for the hierarchization of the continental, national and regional geodetic reference system materialization for multipurpose applications. It is materialized through a network of fundamental stations distributed around the planet (polyhedron of stations) with three dimensional geodetic coordinates known in a reference epoch. This polyhedron is therefore the fundamental entity to be oriented in relation to a so-called inertial celestial reference system. These coordinates have associated standard deviation, have their respective velocities and can be compared with previous ITRF realizations. The coordinates of the stations are determined by GNSS tracking and also include a combination of solutions arising from different spatial techniques such as VLBI and SLR, for instance.

One of the attributions of the International Earth Rotation and Reference Systems Service (IERS) is to establish the connection between the ITRF station polyhedron and an inertial celestial reference system. Linking the polyhedron with the quasar-based International Celestial Reference System (ICRS), generates what are referred to as IERS Earth Orientation Parameters (EOP), which measure the true rotation of the Earth and its irregularities in relation to the ICRS. The EOPs are comprised of (IERS, 2020): **Universal time** corrected according to the movement of the pole (UT1), based on the Earth's rotation, the instability of which generates variations in the duration of the day which is described by the LOD (length of day) informed by the IERS; the **Coordinates of the Pole** – *x* and *y* are the coordinates of the Celestial Ephemeris Pole (CEP), where the *x* axis points in the direction of the ITRF zero meridian and the *y* axis points in the direction of the 90°W longitude meridian; **Celestial Pole Offsets** which are described by the International Astronomical Union (IAU) precession and nutation models. The differences observed with regard to the position of the conventional celestial model defined in the models are monitored and reported by the IERS.

These aspects are fundamental for defining the so-called modern reference systems and their implementation. In this sense, it can be stated that Geodesy, in essence, should be concerned with three types of reference system:

a) a celestial or inertial space-fixed reference system, which provides the coordinates of objects in space such as, for example, stars, quasars and artificial satellites;

b) an Earth-fixed geometric terrestrial reference system, which provides the coordinates of points on the physical surface of the Earth, and

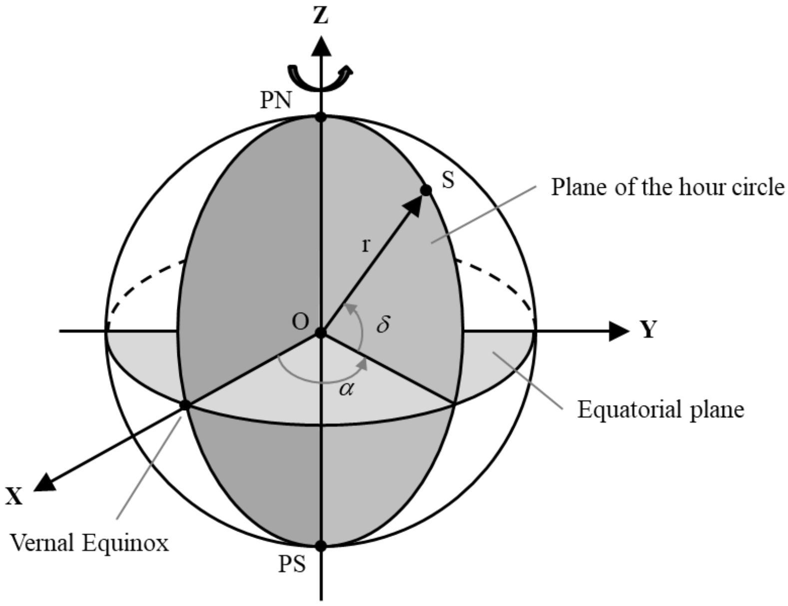
c) an altimetry system, linked to the Earth´s gravity field (or geopotential space).

It is important to highlight that a reference system with a single definition can have different realizations. The different realizations of the reference system are due, for example, to: equipment evolution, new data processing modeling, use of different adjustment methods, geodynamic effects on the network and use of a greater data period in processing; and this generates new coordinates for the stations.

2.2.1 CONVENTIONAL CELESTIAL REFERENCE SYSTEM, INTERNATIONAL CELESTIAL REFERENCE SYSTEM

The Conventional Celestial Reference System (CCRS) is also referred to as the equatorial or uranographic reference system (Figure 1). It is comprised of a non-rotating tri-dimensional Cartesian system, i.e. comprised of axes that do not rotate in relation to objects that can be considered to be space-fixed. The X axis is over the celestial Equator plane and is directed towards the vernal point in a given epoch; the Z axis is directed towards the North Celestial Pole; and the Y axis, on the equatorial plane, making it a righthanded system. The positions of points in space, such as stars and quasars, are described, in this reference system, by means of the right ascension coordinate (α) and the declination coordinate (δ). However, the position of artificial satellites in space is described in terms of time, in this reference system, using Cartesian coordinates (X, Y, Z).

Figure 1 – Conventional Celestial Reference System.



Source: Adapted from Torge; Muller (2012).

The orientation of International Celestial Reference System (ICRS) is established in the epoch J2000. Epoch J2000 refers to the Julian calendar date January 1st 2000, 12:00:00 Universal Time (12:00:00 UT).

Up until the end of 1997, celestial reference system realization occurred through a catalogue of equatorial coordinates (right ascension and declination) of a set of 1535 stars. The catalogue is called FK5 and coordinate uncertainty is in the order of 20 to 30 mas (milliarcseconds). The International Celestial Reference Frame (ICRF) officially replaced FK5 on 01/01/1998 and is comprised of a set of equatorial coordinates of extragalactic radio sources (quasars) determined using VLBI (SEEBER, 2003; TORGE; MULLER, 2012).

The ICRS has three realizations:

a) ICRF1 (1998) is formed by the coordinates of 608 quasars in epoch 2000.0 with uncertainty of 0.5 mas;

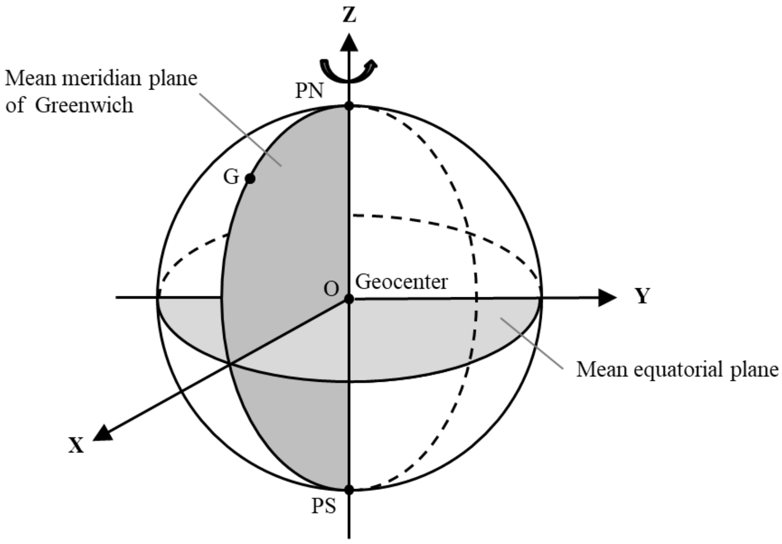
b) ICRF2 (2009) is formed by the coordinates of 3414 quasars in epoch 2000.0. This realization includes a 30-year time series of VLBI observations;

c) ICRF3 (2019) is formed by the coordinates of 4536 quasars in epoch 2000.0 with a significant number of quasars with uncertainty as to their position below 0.1 mas.

2.2.2 CONVENTIONAL TERRESTRIAL REFERENCE SYSTEM, INTERNATIONAL TERRESTRIAL REFERENCE SYSTEM

The Conventional Terrestrial Reference System (CTRS) (Figure 2) is an Earth-fixed system, i.e. it rotates and revolves with the Earth. It is a geocentric system in which the origin coincides with the Earth's center of mass in a given epoch. The tridimensional Cartesian system is oriented so that the XZ plane contains the mean Greenwich Meridian in a given epoch. The Z axis points to the Conventional International Origin (CIO), also called the Conventional Terrestrial Pole (CTP), which corresponds to the mean position of the pole between the years 1900 and 1905, while the Y axis makes the system righthanded (SEEBER, 2003; TORGE; MULLER, 2012).

Figure 2 – Conventional Terrestrial Reference System.



Source: Adapted from Torge; Muller (2012).

The International Terrestrial Reference System (ITRS) is defined by a set of International Association of Geodesy (IAG) and International Astronomical Union (IAU) conventions for establishing what is called the scientific vanguard of conventional terrestrial reference systems. Its origin is at the center of the Earth's mass including the ocean and the atmosphere. It uses the metric scale (SI – International System). Its orientation coincides with that given by the *Bureau Internationale de l'Heure* (BIH) in the epoch 1984.0 (± 3mas). It uses the GRS80 ellipsoid as the model of the Earth and its temporal evolution in orientation is guaranteed by the introduction of the NNR condition (No Net Rotation) – a network that does not have resulting rotation in relation to the horizontal Earth's plate tectonic movement.

ITRS materialization or realization is called the International Terrestrial Reference Frame (ITRF) and consists of a set of coordinates, velocities and their respective precisions for a given group of stations with different spatial techniques (e.g.: VLBI, SLR, LLR, GPS and DORIS). The IAG has scientific services dedicated to each one of the spatial observation techniques and each service has its own structure to process the data from each technique. Examples of IAG services include: IGS – International GNSS Service; ILRS – International Laser Ranging Service and IVS – International VLBI Service for Geodesy and Astrometry. The IERS performs the final combination of the different solutions and generates the ITRFyyyy, where yyyy refers to the year of the realization of the reference system. In addition, the IERS provides the Earth Orientation Parameters (EOP) to make the connection between the celestial and terrestrial reference systems.

The different ITRS realizations comprise: ITRF89; ITRF90; ITRF91; ITRF92; ITRF93; ITRF94; ITRF96; ITRF97; ITRF2000; ITRF2005; ITRF2008 and ITRF2014 (ALTAMIMI et al., 2016).

3 FUNDAMENTAL VERTICAL GEODETIC SYSTEMS AND FRAMES

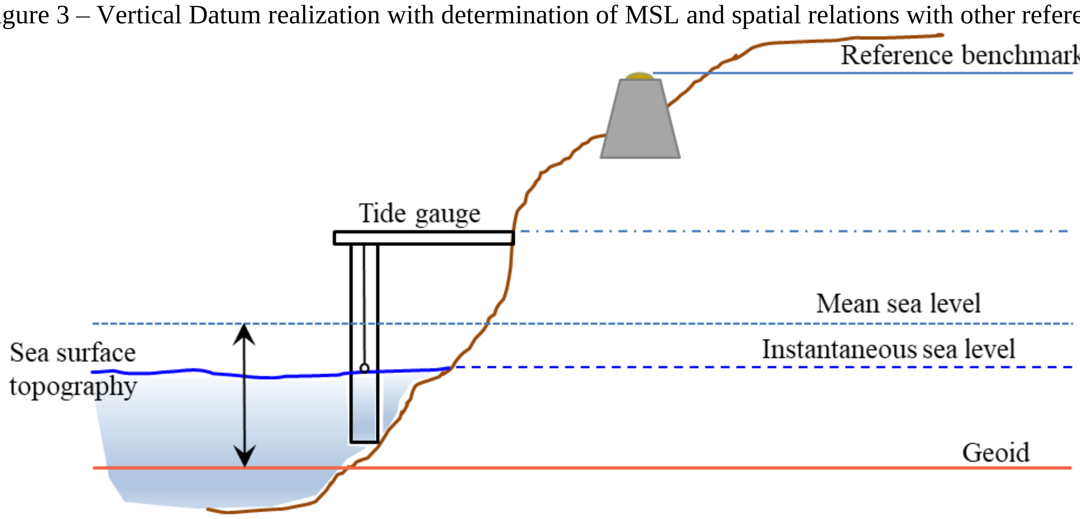
Heights with a practical sense are those determined by leveling operations and which are linked to the

Earth's gravity field. As such, the concept of height differences associated with vertical positioning must also have physical significance, whereby referenced height differences have two-way correspondence with gravity field potential differences. These are the height differences and heights that matter in the conception of construction works such as dams, ducts and canals, for example. These aspects were not met by heights known along the classic triangulation, trilateration and polygonation geodetic networks, so that those networks were usually called horizontal networks. The classic vertical networks using geometric leveling or spirit leveling, with leveling sections, lines and circuits based on a Vertical Datum thus far continue to be networks independent from the modern three-dimensional networks based on ITRF realizations and their densifications. Even with the advent of global positioning methods based on spatial technologies with easily obtained ellipsoidal heights, in general the latter do not meet the needs of a large range of applications. Even heights derived from classical vertical networks did not fully meet the two-way relationship with the geopotential related height differences mentioned above, given that the link with the gravity field was, in general, established partially based on a theoretical gravity field. This aspect will be discussed in more detail later, given that the classical vertical networks are also still predominant as national networks and still have restrictions with regard to their integration in a single global vertical geodetic reference system. The aspects raised in the previous sections also deserve more reflection: it is fundamental that the three-dimensional geometric reference system and the reference system for heights with physical meaning be integrated into a single GRS. As such, both of them need to converge on a single global realization. In this case, vertical reference systems need to abandon their local or regional characteristics and achieve global integration in geopotential space, as will be discussed in the following sections.

3.1 Classical aspects related to Vertical Datums and Vertical Geodetic Networks

In general, Vertical Datum (VD) realization is linked to Mean Sea Level (MSL), except in the case of those located in landlocked countries. MSL is obtained by means of long time series of tide gauge observation and is linked to a Benchmark (BM) located close to the tide gauge. In simplified terms, the variation in instantaneous (local) sea level in relation to zero on the tide gauge is monitored. The data obtained by monitoring are used to calculate the mean local sea level and the height of a BM close to the tide gauge is determined (Vaníček; KRAKIWSKY, 1986). In this classical definition for establishing a vertical datum it was assumed that MSL coincided with the geoid. This is amply rejected nowadays, so that current coastal tide gauge monitoring leads to the references expressed in Figure 3.

Figure 3 – Vertical Datum realization with determination of MSL and spatial relations with other references.



Source: The authors (2020).

Once the VD and its connection to one or more BMs close to the tide gauge have been established, the heights of the remaining stations that materialize the Vertical Geodetic Network (VGN) are then determined. For the most part, the fundamental VGNs are established by spirit (geometric) leveling. As such, the heights of the other points of the VGN are determined based on the height differences obtained by spirit leveling and referenced to the BM located close to the tide gauge. Gravimetric corrections (theoretical or based on observations) can be introduced into these networks in order to correct the effects of the geopotential on leveling and thus provide the heights with some physical meaning. These aspects will be discussed further on. According to Vaníček and Krakiwsky (1986), classical vertical networks, with corrections of a physical nature, propagate heights with precision estimates according to Eq. (6):

$$\sigma_H = 1.8 \times 10^{-3} \times S^{2/3} \text{ meters} \tag{6}$$

where *S* is the leveled distance in kilometers.

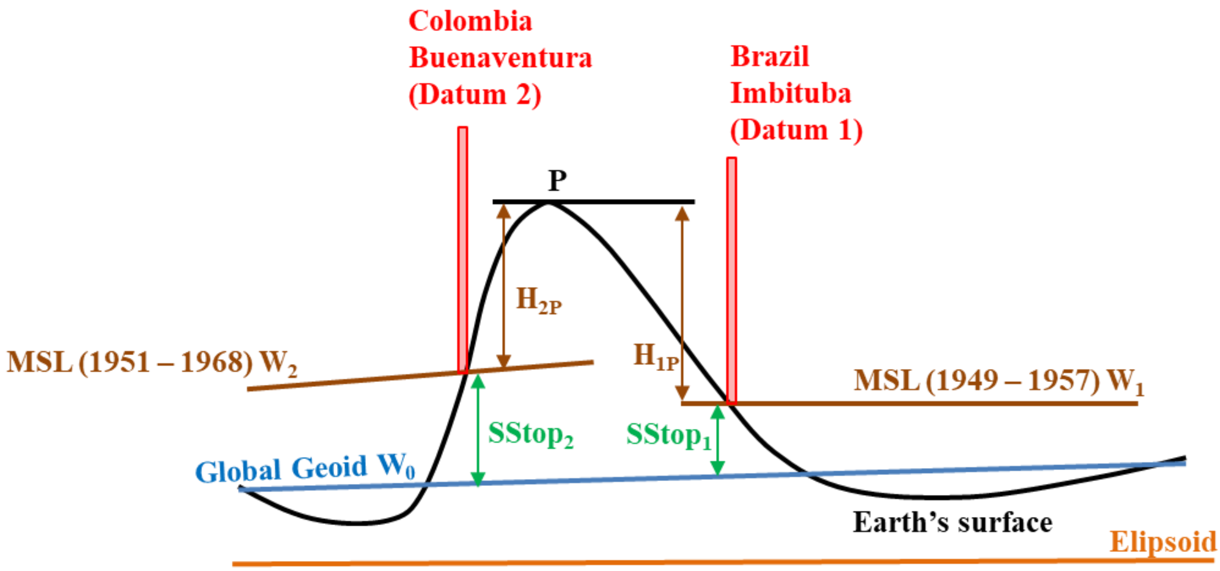
Later interlinking, based on spirit leveling, between different country's tide gauges and interlinking between vertical networks of neighboring countries, generally indicate differences in leveled heights for the same point which cannot be attributed just to leveling operation errors; as such the connection between different local vertical networks is generally inconsistent. These differences are related to the leveling process itself and also to the establishment of the reference level of each vertical network (MSL) and its temporal and spatial variations, as shown in Figure 4.

Here the main consideration is that the MSL is obtained at a tide gauge station after a given number of years of observation, this being valid for that place and for a given epoch, since MSL varies from one point to another and at the same point due to time (GEMAEL, 1999). Therefore, use of MSL as a reference surface for heights was widely accepted. However, from a modern point of view, it is acknowledged that MSL observed at any point of the oceans cannot be considered as coinciding with a global geoid (PAN; SJÖBERG, 1998). In other words, each VD realized using MSL is referenced to a particular equipotential surface (local "geoid"). As such, it is appropriate to highlight that this fact had already been recognized in the Gauss-Listing geoid definition (LISTING, 1873 apud HECK, 2004) which established that "the geoid is the equipotential surface of the Earth's gravity field, with geopotential W_0, that in the least squares sense best fits the undisturbed mean sea level". This condition is the basis of the oceanographic definition of a geoid, which is the currently most accepted geoid definition in view of the ease with which it can be realized based on satellite altimetry over the oceans, where each point where MSL is assessed can have its geopotential *W* determined in a global GRS. The oceanographic definition is based on the same Gauss-Listing hypothesis recognizing that the quasi-stationary equilibrium of the MSL is determined based on geostrophic equilibrium conditions which are affected by dynamic forcing factors and other physical variables, so that the global MSL surface is not equipotential (DE FREITAS et al., 2002). Each observation point has a specific geopotential *W* value. Taking σ to be the ocean surface, this definition can be expressed by Eq. (7) as:

$$\int_{\sigma} (W_0 - W)^2 d\sigma = mín \tag{7}$$

Globally, MSL has a discrepancy in relation to the global geoid called Sea Surface Topography (SST) (Figure 4). SST is caused by variations in atmospheric pressure, currents, among other factors (SEEBER, 2003) and may reach values of up to two meters (HECK; RUMMEL, 1990; FENOGLIO, 1996; SEEBER, 2003).

Figure 4 – Modern view in relation to the Vertical Datum.

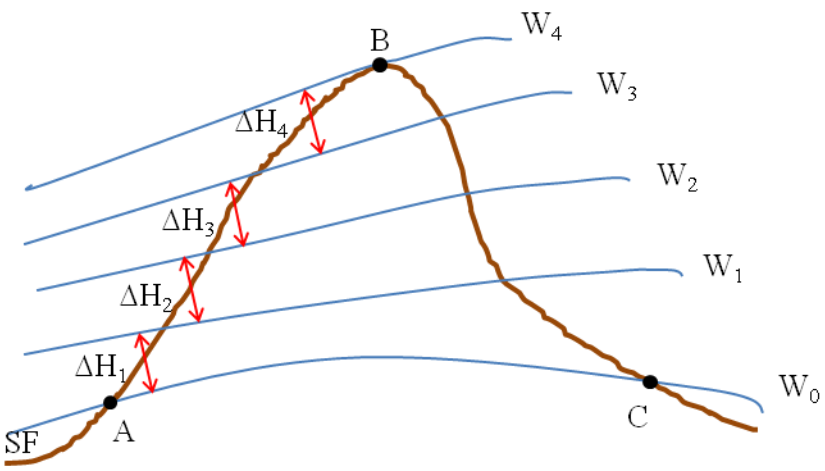


Source: Adapted from IBGE (2002).

In general, the classical aspects related to the establishment of the VD and to the materialization of the VGN do not permit data sharing between different countries. Factors that result in this include: VD determination based on the MSL at a given point and in a given epoch; the fact of some countries having more than one VD due to the impossibility of VGN densification throughout the entire country because of its geographic configuration; temporal variations not being taken into consideration both in the definition of the VD and also in the establishment of the network; different forms of establishing the vertical network which have or have not taken gravimetric corrections into account; among other aspects. The solution for these issues lies in the definition of a global reference surface and the definition of heights with physical meaning, as covered in the next item.

Definition of height with physical meaning is related to a difference in gravity potential (geopotential). In Figure 5 for example, the height of B is related to the $W_0 - W_4$ potential difference:

Figure 5 – Modern view in relation to spirit leveling.



Source: The authors (2020).

This difference in gravity potential is called the geopotential number (C). The geopotential number at point P (C_P) on the Earth's physical surface is thus defined as the difference between the geopotential at the geoid (W_0) and the geopotential at the point (W_P) as per Eq. (8) (HOFMANN-WELLENHOF; MORITZ, 2005):

$$C_P = W_0 - W_P \tag{8}$$

In practical terms, the geopotential number can be obtained by associating precise spirit leveling with gravimetry. In this way, the geopotential number is calculated based on height differences values (ΔH) and mean gravity values ($\bar{g}$) in each leveled section on the Earth's surface, as per Eq. (9):

$$C_P = \sum \bar{g}\, \Delta H \quad (9)$$

However, geopotential number values are not adopted to directly represent the vertical coordinate of a point, since they are difficult to interpret and visualize. It should be emphasized that the potential of gravity has unity [$m^2\ s^{-2}$], decreases as height increases and at MSL its value is not nil. A height with physical meaning (H_P) can be obtained, as shown in Eq. (10), by dividing the geopotential number by a particular gravity value (G):

$$H_P = \frac{C_P}{G} \quad (10)$$

It should be highlighted that the fact of the geopotential number calculation being associated with spirit leveling means that obtaining heights are associated with the definition of the local VD. In vertical networks established in this way, a systematic effect associated with the definition of the VD still remains.

For the purpose of illustration, it is appropriate to mention aspects of classical vertical networks in South America. The majority of the continent's countries established their VDs in the 1940s or 1950s. In Brazil, within the context of the Brazilian Geodetic System (BGS), some 95% of the Brazilian Vertical Network (BVN) is linked to the VD realized by means of time gauge observations made at the Port of Imbituba, on the coast of the state of Santa Catarina. The Brazilian Vertical Datum was established in 1958, based on time gauge observations made between 1949 and 1957. However, part of the BVN located in the state of Amapá is linked to the VD established at the Port of Santana. The connection between these two segments of the BVN is a task that is still currently underway (SANTACRUZ; DE FREITAS; LUZ, 2019).

Implementation of the BVN began in 1945 in Santa Catarina. As at that time Brazil still did not officially have a VD, the leveling network was connected to the Torres tide gauge in the state of Rio Grande do Sul in 1946. The Torres VD was of a temporary nature, as it had been defined from just one year of sea level observations (1919 - 1920), and was replaced by the Imbituba VD in 1958. The latter VD had been attributed with a longer time series of sea level observations (ALENCAR, 1990).

Up until mid 2018 the BVN was materialized exclusively by means of spirit leveling. The BM heights were referred to officially as orthometric heights. However, this term was not correct, since the leveled heights only received theoretical gravimetric corrections for the lack of parallelism of the equipotential surfaces of the normal (theoretical) gravity field, these heights were in truth "normal orthometric" heights. These corrections are calculated based on the normal (theoretical) gravity value, i.e. they do not use real gravimetric observations and are applied directly to measured height differences. With effect from 2018, the IBGE incorporated gravimetric corrections in the entire BVN and adjusted them based on geopotential numbers. In this way, even though the systematic effects of the VDs in the two segments of the network still remain, now the height differences effectively express true physical characteristics.

3.2 Modern aspects related to Vertical Datums and Vertical Geodetic Networks

The IAG Inter Commission Project ICP 1.2 - World Height System-Pilot Project (ICP1.2 – WHS-PP) was developed until 2011 from the perspective of Theme 1 of the Global Geodetic Observing System (GGOS), seeking to establish the bases of a global unified height system (IDHE; SIDERIS, 2010). The ICP1.2 – WHS achievements and proposed conventions, as well as the perspectives of the time, are described by Sánchez (2012). Global adoption of the GGOS by the international community as one of the pillars of the Earth Observation Systems (EOS) was recommended by the United Nations during its Regional Cartography

Conference in Bangkok, Asia, in November 2012, highlighting the need for the World Height System (WHS). The outcome of GGOS/IAG activities since 2003 and GGOS actions in the period 2011-2015 resulted in IAG Resolution No. 1 in July 2015: "Definition and realization of an International Height Reference System (IHRS)", which established diverse conditions and standards for a new World Height System totally linked to geopotential space. The single surface for height reference is fixed as the surface of the gravity field where the value of geopotential W_0 = 62 636 853.4 m^2s^{-2}. The primary vertical coordinate of each point P on the physical surface of the Earth is its geopotential number expressed as the negative value of its C_P potential difference, where $C_P = -\Delta W_P = W_0 - W_P$ in relation to the reference surface (IAG, 2015). In 2016, IAG set up the "Joint Working Group 0.1.2. on Strategy for Realization of the International Height Reference System (IHRS)" within GGOS Theme 1. Brazil has taken part in JWG 0.1.2 since it was set up, via SIRGAS Working Group III.

3.2.1 NATIONAL VERTICAL NETWORKS AND IHRS/IHRF

The main aspects to be considered in relation to the establishment of the IHRF refer to the need to integrate existing National Vertical Reference Networks (NVRNs) into the new concept brought by the IHRS. It is thus that the plurality of the characteristics of the NVRNs involving form of realization, precision, particular VDs, association or otherwise with gravimetry in order to determine geopotential numbers, temporal evolution and their maintenance, are relevant aspects to be taken into consideration alongside the need for new associated geodetic observations. De Freitas (2015) presents an overall view with regard to the basis and strategies for modernizing NVRNs in the context of SIRGAS in order to meet the principles of the IHRS, the IHRF and the future GGRF. The actions understood to be necessary are based on the following protocols:

a) Definition of strategies for the realization of existing networks through physical heights [H_P =f(C_P)];
b) NVRN linkage with SIRGAS continuous GNSS stations;
c) NVRN integration in geopotential space to form the SIRGAS Vertical Reference Network (SVRN);
d) Approaches to referencing the SVRN to the IHRS W_0 value;
e) SVRN association with a reference epoch and modeling of the temporal variations of the vertical coordinates, and
f) Planning of activities to establish a set of IHRF/GGRF stations in the region, as a basis for adequately referencing the NVRNs to the IHRS.

A synthesis of the scientific basis for applying these protocols is shown in Figure 6 and discussed below.

The relationship between the IHRF and the NVRN(i) can be established when the national network is realized based on geopotential numbers in the form $C_{Pi} = W_{0i} - W_P$, where W_{0i} is the geopotential at the VD_i and W_{Pi} is the geopotential value at point P obtained by association of gravimetry with leveling operations. This C_{Pi} geopotential number differs from the C_P of the global reference W_0 by a value expressed as the offset (δW) in the geopotential space, as per Eq. (11) (CARRIÓN, 2017):

$$\delta W = W_0 - W_{0i} = W_P - W_{Pi} \tag{11}$$

The offset in a corresponding metric unit is given by Eq. (12):

$$\Delta H = \frac{\delta W}{\gamma_0} \tag{12}$$

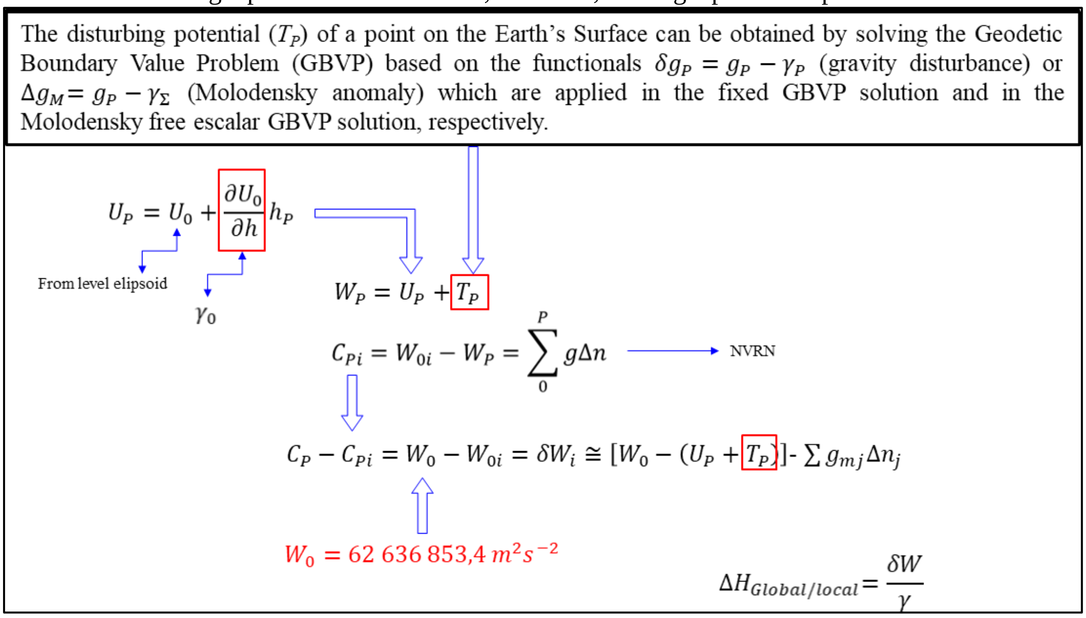
where γ_0 is the normal gravity in the surface of the reference ellipsoid which is easy to determine by mathematical formulae for each GRS involved.

In Eq. (13) it can be seen that in a point P the theoretical normal potential (U_P), which is also easy to determine, is related, at the same point, with the geopotential of the real Earth (W_P) as follows:

$$T_P = W_P - U_P \tag{13}$$

where T_P refers to the disturbing potential. The disturbing potential manifests disagreements of the real Earth in relation to the normal Earth to which the same mass and the same angular velocity of the real Earth is attributed and is geometrically related to the GRS reference ellipsoid. The disturbing potential is thus the central focus of determinations related to global reference systems, and is determined by solving the Geodetic Boundary Value Problem (GBVP) at each point for which W_P is intended to be obtained. These aspects involving the relationship between the NVRNs and the IHRS based on solving the GBVP, including the characteristics of each national VD, are summarized in Figure 6.

Figure 6 – Flowchart of the relationship between an NVRN and the IHRS within a modern conception based on geopotential numbers and, therefore, in the geopotential space.



Source: Adapted from Carrión (2017).

Dynamic aspects of Vertical Reference Networks need to be the object of intense research in the decade that is beginning now. The models of horizontal movements in the ITRF are well established and describe the tectonic effects of horizontal displacements. These movements, predicted in geophysical models such as NNRNUVEL-1A (No Net Rotation – Northern University Velocity Model 1A), relate well to recent horizontal geodetic models of velocity developed based on observations of continuous GNSS stations, such as the VEMOS 2017 model, for example, established based on the network of SIRGAS–CON stations (DREWES; SÁNCHEZ, 2020). However, many challenges remain for vertical networks, given that no ITRF realizations favor vertical displacement models. This is not by chance, since vertical modeling is extremely complex. It goes beyond modeling regular effects, or effects modeled globally on plate tectonics, and involves other global/regional/local modeling such as post-glacial rebound, seasonal or non-seasonal hydrologic loading, and even effects of seismic events. These aspects, which interfere with NVRN modeling and maintenance, are well discussed by MONTECINO et al. (2017), FERREIRA et al., (2019) and BRASSAROTE (2020) in studies conducted on the South American continent, as indicated in the Introduction.

4 GLOBAL GEODETIC REFERENCE SYSTEM (GGRS/GGRF)

Earth Observation Systems (EOS) require references that are stable over time, as well as global consistency in information referencing. This information, involving spatial and physical referencing on information related to variables that are fundamental for environmental monitoring, such as tectonic movements and mass redistribution due to diverse geophysical processes in the Earth system, has been attributed to Geodesy. In order to meet these demands, on February 26th 2015 the United Nations General Assembly adopted the Resolution on the Global Geodetic Reference Frame for Sustainable Development (A/RES/69/266) (UNITED NATIONS, 2015). The Global Geodetic Reference System (GGRS) involves the definition of a set of physical and mathematical models needed to describe geometric and physical positions and gravity in space and over time. Its materialization (GGRF) will take place through integration of different geodetic reference networks: ITRF, ICRF, the future IHRF and a new Global Absolute Gravity Network. It aims to establish a common reference for geometry and for the Earth's gravity field, through the combination of different GRS: It therefore involves the ITRS/ITRF, IHRS/IHR, the ICRS-ICRF and the Global Absolute Gravity Network (GAGN). GGRS realization will involve the following specifications (IAG, 2016):

a) For physical point P, potential $W_P = W(\boldsymbol{X})$ is assessed at the vector of position $\boldsymbol{X}((X, Y, Z)$ ITRF $\equiv (\varphi, \lambda, h)$ ITRF);

b) The time unit is the second and the unit of length is the meter, both as per the International System of Units (SI);

c) Physical height is C_P;

d) Gravity vector $\boldsymbol{g}$ is the geopotential gradient at point P;

e) Geometry and gravity are implicit functions of time;

f) Fundamental parameters and conventions are required for using models and procedures, such as a global geopotential model in spherical harmonics with spatial and point resolution compatible with the applications;

g) The ICRS provides the celestial basis for the GGRS, and

h) The relationship between the ITRS and the o ICRS is described by the EOPs.

The GGRF is based on the principle of a fundamental network of global reference terrestrial points and the national networks need to be integrated to this global network. Materialization of the global reference stations will involve other geodetic techniques apart from GNSS plus leveling, such as VLBI, SLR, DORIS, and other possible global techniques. The fundamental assumption of this integration, at all sites, is observation of absolute gravity with minimum resolution of 1 microGal and connection to the GAGN. As such, this network of GGRF stations will comprise (IAG, 2016):

a) Fundamental geodetic observatories employing all spatial geodetic techniques co-located with gravimetric instruments, enabling connection between $\boldsymbol{X}$, W and $\boldsymbol{g}$,

b) Other geodetic stations that also include reference tide gauges, height datum points and gravity measurement points co-located wherever possible with spatial geodetic instruments.

All GGRF stations will:

a) Operate continually, over the long term, to ensure GGRF stability;

b) Be equipped with state-of-the-art observation technology so as to produce measurements of geodetic quantities;

c) Be monitored continuously to detect surface deformations of the Earth's crust,

d) Be connected to the VDs to precisely relate their geopotential differences in order to achieve vertical datum unification.

5 CHALLENGES AND FUTURE PERSPECTIVES

Definition and realization of GRS that integrate the Earth's geometry and gravity field are essential for connecting observations related to the dynamics of the planet and global changes. As such they are the fundamental basis for establishing EOS. In this case, geodetic observations need to be integrated to reference structures with accuracy of 10^{-9} or better. An important question in this context is: how can this degree of accuracy be achieved and guaranteed?

Despite the GGRS having been defined and the principles for its realization (GGRF) having been established, how can the geographic distribution and the maintenance of these multi-technical stations be guaranteed over time so as to meet the requirements of the EOS?

Up until 2015 one of the great challenges faced by Geodesy was that of defining and realizing a global reference surface for heights by means of a geopotential value (W_0). Now that this value has been defined, the current task involves determining strategies that enable classical vertical networks to be connected to this reference surface, thus eliminating the discrepancies existing between the different vertical reference systems. This is not an easy task, given the lack of homogeneity in the distribution of gravimetry data, different strategies used to acquire and process data, among other factors. In this context, one of the questions to be answered is: what is the best strategy for this connection in view of existing databases?

Since 1997, SIRGAS has been working to establish a Vertical Reference System for Latin American and the Caribbean, and today it directs its activities towards meeting the international requirements for integration to the IHRS/IHRF. There are however big gaps in information on gravimetry and leveling among member countries. In many situations the data exist, but are in analog form, without metadata with information related to quality, connections and their background. Making an inventory of these data is extremely important for establishing strategies for integration with and connection to the IHRS. Gains are obtained by applying spatial positioning techniques, such as GNSS associated with terrestrial gravimetry, data from satellite altimetry missions and gravimetry missions as well as use of global geopotential models. Fundamental questions in this regard are therefore: how to keep databases consistent and up to date with adequate metadata? How to provide adequate training for people who work with this type of information? These are tasks that should be carried out continuously within the context of the SIRGAS project.

It is known that vertical deformations reach magnitudes greater than the tolerance allowed for maintaining a modern vertical reference system. In this respect, challenging aspects in relation to vertical reference systems refer to them being monitored over time, answering the following questions: how to ensure the consistency of the reference system/frame over time? How to model these variations that have a dominant cyclical (seasonal) component in some regions? Of relevance here is modeling of linear variations associated with subsidence and post-glacial rebound, the seasonal effects of hydrologic loading and co-seismic and post-seismic effects.

These questions reflect some of the challenges and future perspectives for Geodesy as we move towards GGRS/GGRF. They also reflect the challenges of Geodesy as a science capable of providing the basis necessary for monitoring the Earth System, a task with far-reaching practical impacts for a society seeking sustainable development.

6 FINAL CONSIDERATIONS

The advent of the space age has caused a revolution in terms of geodetic reference systems and frames. Reference systems with local characteristics have been gradually replaced by global reference systems. Another important aspect is the fact that it is no longer possible to separate purely geometric aspects from the physical aspects of the Earth and the creation of the EOS corroborates this affirmation. Monitoring the Earth System, and all its processes, with the aim of understanding their dynamics and providing the knowledge base needed for sustainable development of society is one of the great current challenges and Geodesy is the science capable for providing the entire base needed for such monitoring.

As the concept of the GGRS/GGRF requires integration between the terrestrial reference system, the celestial reference system, a reference system with physical characteristics for heights and the new global absolute gravity network, it can be stated that establishing and maintaining the vertical reference system is a task that requires the biggest efforts. Despite the reference system, i.e. the IHRS, having been defined and being well-conceived, there is still a long way to go before it will be materialized as the IHRF.

Adoption of a conventional value for the geopotential (W_0) has brought new perspectives for Geodesy. As vertical reference systems still have classical characteristics and data related to the Earth's gravity field lack homogeneous spatial distribution and quality, it will be necessary to establish a series of standard procedures aimed at integration with the global height reference system and achievement of the precision needed to establish the EOS. In this sense, progress has been made based on disturbing potential modeling by solving the GBVP.

Temporal modeling of heights is also a challenging task, given the need to take into consideration both regular and irregular effects in this height modeling. Plate tectonics, post-glacial rebound, hydrologic loading and seismic events, are examples of effects that interfere with temporal modeling of NVRNs.

Similarly to the IHRF, establishment of the GGRF will require great efforts on the part of the international scientific community in the sense of setting up fundamental geodetic observatories with good spatial distribution over the Earth, in stable places, with state-of-the-art technology, with the aim of achieving the precision required for establishing the EOS.

Authors' Contributions

Both authors took part in the concept, drafting, reviewing and editing stages of this article.

Conflicts of Interest

The authors declare that there is no conflict of interest.

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