Research Article

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Development and evolution of height systems in the context of SIRGAS: From the local vertical data to the International height reference frame

Abstract: In America, height systems were established during the twentieth century by connecting the leveling network to a tide gauge. In 1997, the Geodetic Reference System for the Americas (former Geocentric Reference System for South America) created Working Group III, called Vertical Datum, to assist in establishing a unified vertical reference system for the Americas. In this context, this article aims to trace the evolution of height systems in America, especially South America, and present the current situation in the region to contribute to the International Height Reference Frame. A brief chronological description of the systems of South American countries and the efforts developed by Working Group III over the past 25 years is presented. A bibliometric study assesses the scientific community's involvement in this field. The results revealed that some countries have been standing out in engagement in recent years. Finally, an evaluation is performed between recent global geopotential models and a regional gravity field model at the 17 stations that comprise the International Height Reference Frame in Latin America. The results indicate that the Andes region requires efforts in gravity densification and improvement of global models.

Keywords: geopotential models, International Height Reference Frame, international height reference system, vertical heights, SIRGAS

MSC 2020: 86A30

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1 Introduction

To determine and investigate Earth's geodynamic processes and change, it is essential to have stable geodetic reference systems that remain consistent across the globe over time (Ide et al. 2015). In this sense, the International Association of Geodesy (IAG) has been working on establishing an integrated geodetic reference from the densification and maintenance of the Global Geodetic Observing System (GGOS). Implementation is possible through physical points on Earth's surface, satellites in near-Earth orbit, celestial objects, and parameters that describe geometry and gravity over time (IAG 2016).

The IAG, through Resolution 69/266 (United Nations 2015), established the Global Geodetic Reference System (GGRS), materialized by the Global Geodetic Reference Frame (GGRF) (Drewes et al. 2016). Therefore, from a scientific and technical point of view, it is the responsibility of the IAG and GGOS to implement this geodetic reference frame in the most diverse segments of users around the Earth. On the other hand, the United Nations focuses on the geodetic infrastructure, the training capacity and education, standards, governance, and outreach necessary to achieve sustainable development goals.

The GGRS defines and conceptualizes a reference system using mathematical and physical models, constants, and numerical and physical conventions to support a reference. Once fully established, the GGRF comprises four reference frames and integrates three reference system components. The first component (position) is represented by its coordinates (X, Y, Z), which are managed by the International Celestial Reference Frame (ICRF) and the International Terrestrial Reference Frame (ITRF). The International Height Reference Frame (IHRF) defines the Earth's gravity potential (W) as the second component, which determines the physical height (H). Finally, the International Terrestrial Gravity Reference System (ITGRS) establishes the gravity vector (g) by the International Terrestrial Gravity Reference Frame (ITGRF).

The global geometric reference is reliable down to the centimeter level due to the definition, achievement, and maintenance of the International Celestial Reference System (ICRS) and the International Terrestrial Reference System (ITRS). Regarding the gravity component, it is essential to establish a global and current reference for the gravity component. This will help minimize the difference between the precise readings obtained with absolute gravimeters and the gravity values based on the International Gravity Standardization Net 1971 (IGSN71). Furthermore, the gravity reference is essential for a physical height system since it depends on gravity information for its materialization. Numerous local and regional height systems are currently in use. These systems are based on local observations of sea level and do not consider any changes over time. Due to the discrepancies between these systems, it is impossible to exchange data between them (Ihde and Sánchez 2005).

From this perspective, through "Working Group III: Vertical Datum" (WG-III), SIRGAS has been working on establishing a vertical reference system for the Americas. Since the IAG Resolution No. 1 publication in 2015 about the definition and implementation of the International Height Reference System (IHRS) (Drewes et al. 2016), WG-III has been working on establishing the IHRF in the SIRGAS region. In this sense, this article aims to present a history of height systems in the SIRGAS region and the activities of WG-III related to height systems. Additionally, this article presents numerical results related to implementing the IHRF on the continent using global Earth models.

In the last decade, countries from North America, Central America, and the Caribbean have started to become members of SIRGAS, while South American countries have been members of SIRGAS since its creation. For this reason, this article will focus on developing height systems in South America. On the other hand, it is essential to mention that substantial efforts have been made in all American continents in cooperation with IAG by subcommision 2.4b (Gravity and Geoid in South America) and 2.4c (Gravity and Geoid in North and Central America). In North America, the North America-Pacific Geopotential Datum of 2022 (NAPGD2022) should be recognized (Willberg et al. 2021).

2 Brief review of height systems in South America

A classical height system is a set of stations materialized by spirit leveling, expressed in height coordinates. Vertical Datum is the traditional name of the system's origin

(zero point), defined as the mean of a local sea level measured by a tide gauge in a certain period. Because of the nutation movements of the Earth, 18.6 years is the minimum period to establish a consistent mean sea level value. However, not all countries have tide gauge measurements related to this period. In addition, the dynamic ocean topography should be considered in the discussion about the variations in the tide gauges.

In South America, height systems are based on the mean sea level (MSL), and their heights are derived from leveling circuits and lines carried out at different times. Besides that, these measurements were frequently employed without gravity measurements or reductions and with different methodologies applied (Ihde and Sánchez 2005). To summarize, South America has 19 height data (Figure 1), 18 located in coastal areas, and one on the continent (Paraguay). Some countries, like Chile (with six), Argentina, and Brazil (with two), have multiple height references.

We checked the databases of all national agencies except for Paraguay, Guyana, and Suriname because we could not find any information. The type of height is also not homogeneous among South American countries. Brazil adopts normal heights (Figure 1, in green), Argentina, French Guyana, and Uruguay orthometric heights (Figure 1, in yellow), while Bolivia, Chile, Colombia, Ecuador, Peru, and Venezuela so-called normal-orthometric heights (Figure 1, in orange). The institutions responsible for these data consider the leveling heights as orthometric heights, but did not apply any gravimetric correction. So, in this article, these heights are considered normal-orthometric heights.

The following paragraphs briefly overview the history of vertical height systems used in South American countries. Starting with Argentina, approximately 100 years ago, the National Geographic Institute of Argentina (*Instituto Geográfico Nacional de Argentina* - IGN-AR), the agency responsible for the Argentine Geodesy, began implementing the first local height system on the continent. The first efforts took place in 1913, with the construction and measurements of the leveling network, which by the end of 1919 determined the provisional height of 1,045 stations from 1,620 km of the leveling line. However, the Mar del Plata tide gauge was considered the vertical reference only in 1923. Throughout the years, Argentina's vertical network has undergone two adjustments. The first one was in 1969 when the IGN sent to the US Army Topographic Command (USATC), currently the National Geospatial-Intelligence Agency (NGA), observations of the leveling lines and gravity observations made on the pillars. This adjustment was called "*Sistema de Referência Vertical Nacional do ano de* 1971 (SRVN71)." The second adjustment, "Sistema de Referencia Vertical Nacional 2016 (SRVN16),"

began in 2010 under the need to have heights based on geopotential numbers. At the end of the adjustment, in 2016, the IGN published for the community orthometric heights (IGN-AR 2017).

The agency responsible for the vertical component in Bolivia is the Military Geographic Institute of Bolivia (*Instituto Geográfico Militar de Bolivia* – IGM-BO). As a landlocked country, it relies on data from the tide gauge in Arica since it lacks direct access to the ocean, approximately 132 km (Arica–Chile to Charañā–Bolivia). The connection line Arica–Charafia–Visviri–Charañā was made in 1995 (Sánchez 2005a).

The Brazilian Institute of Geography and Statistics (*Instituto Brasileiro de Geografia e Estatística* – IBGE) established the leveling network in 1945 at the Torres tide gauge. The official datum was based on only 1 year of tide gauge measurements and remained in use until 1959. The Imbituba tide gauge was established as the new datum based on data collected between 1949 and 1957. During the implementation of the network across the country, it became clear that a second datum was necessary to establish the height reference for the state of Amapá. This was because it was not feasible to perform high-precision leveling across the lower course of the Amazon River. As a result, Santana was designated as the second datum in 1980. The Brazilian network underwent two more adjustments in the past years, one in 2011 and the second in 2018 (IBGE 2019).

In Chile, the first tide gauge to be used as an initial point for the vertical system was the Cartagena in the Valparaíso region in 1929 and is still considered the most important in the country. Based on these data, it was feasible to establish leveling lines across some areas of Chile and its territory. However, given the vastness and topographical diversity of the country, alternative data were required to define a system for the entire territory. Today Chile has six data: Arica, Antofagasta, Valparaíso, Talcahuano, Puerto Montt, and Punta Arenas. Because of earthquakes in the territory, remediations on the leveling lines have been needed (Maturana and Barriga 2002,

Figure 1: Types of heights and local vertical systems in South America.

Sánchez 2005a). The Military Geographic Institute of Chile (*Instituto Geográfico Militar de Chile* – IGM-CH) is responsible for maintaining the geodetic reference in the country.

During the 1940s, Colombia's Geographic Institute Agustín Codazzi (*Instituto Geográfico* Agustín Codazzi – IGAC) began to devote efforts to realizing a local vertical system. For this purpose, four tide gauges were implemented: two in the Caribbean Sea (Cartagena and Riohacha) and two in the Pacific Ocean (Buenaventura and Tucamo). Based on 17 years of observations (1951 to 1968), the Buenaventura tide gauge was selected as the height reference (IGAC 2023). Regarding leveling, seven stations were established as the foundation for the leveling lines (Sánchez and Martínez 2002). The national leveling system currently consists of more than 20,000 leveling points along 26,000 km, which were adjusted line by line in the 1985 adjustment. Nowadays, IGAC works on the adjustment based on geopotential numbers (IGAC 2023).

The Military Geographic Institute of Ecuador (*Instituto Geográfico Militar de* Ecuador – IGM-EC) received assistance from the Inter-American Geodetic Survey (IAGS) to implement the Vertical Datum. In 1948, the La Libertad tide gauge was installed. The primary height was calculated around 1960 using the average of measured values between 1950 and 1959, making it the official datum of the country (Paredes 1986). Leveling campaigns started in the 1970s. In 2010, the IGM-EC made a preliminary adjustment to the leveling network, adopting the average of observations between 1988 and 2009 as its origin (Carrión Sánchez 2017).

The establishment of a vertical network in Peru began in the 1940s, with the definition of tide gauges in the cities of Talara, Chimbote, Callao, San Juan de Marcona, and Matarani (Sulca 2014) Meanwhile, under the supervision of the National Geographic Institute of Peru (*Instituto Geográfico Nacional de Perú* – IGN-PE), the national geodetic leveling network had its official origin defined in the La Punta-Callao tide gauge (IGN-PE 2016).

The vertical network of Uruguay was established, at the first moment, based on Wharton's mean sea level. In 1948, the zero reference was changed to the Montevideo tide gauge based on the average sea level readings of more than 40 years. Concerning the leveling network, Uruguay underwent two adjustments. In the first one, in 1961, the first-order surveys were adjusted using normal gravity for orthometric correction (Pina et al. 2002). The second one was carried out in 2015. The leveling network, composed of 3,883 km of first-order, 2,947 km of second-order, and 4,700 km of third-order leveling lines, was adjusted using geopotential numbers (Croquis et al. 2022). In 2024, the connection between the IHRF station UYPT and the Vertical Datum

in Cabildo was carried out by spirit leveling. Besides that, the first-order leveling network was adjusted with respect to the absolute gravity station in UYPT (Caubarerre et al. 2024).

In Venezuela, the first tide gauge in La Guaia was established in 1948 by the Geographic Institute of Venezuela Simón Bolívar (*Instituto Geográfico de Venezuela Simón Bolívar* – IGVSB). The national leveling network started in the 1950s. In Venezuela, two networks are dedicated to heights: one in the north and one in the south. The northern network is considered high-accuracy and comprises several circuits near the Vertical Datum. However, the southern network has never been connected to a precision leveling network (Virla 2014).

Regarding the South American countries of French Guyana, Guyana, Paraguay, and Suriname, we did not find further information about their vertical systems. In French Guyana, the height datum used is in Cayenne, having only the coverage in the coastal zone, and the height adopted is orthometric. In Guyana, the height system is based on the Vertical Datum of Georgetown city (Guyana Lands and Surveys Commission 2023). Paraguay has a Vertical Datum located on the continent, under the Paraguay River, called Asunción. Finally, no information was found regarding its height system in Suriname. The summarized information on vertical systems in South America is presented in Table 1.

It is well known that local height data are incompatible since each reference, i.e., each tide gauge, is not located under the same level surface. In addition, the following aspects contribute to the previous statement:

- Spirit leveling operations were performed at different times with different techniques;
- The gravimetric reductions, when considered, are distinct, i.e., using different formulations;
- Occurrence of propagation errors as a result of leveling; and
- Time variations are not considered in heights and reference levels.

The aforementioned aspects cause uncertainties in the local data, making it impossible to exchange information between countries. According to Sánchez (2007), the discrepancies between values measured simultaneously from different systems can reach up to ±2 m globally. To demonstrate the height uncertainties between South American countries, we collected from the national agencies' height values from countries leveling connections. As an example, the discrepancies arrived up to 0.54 m between Brazil (Santana do Livramento station) and Uruguay (Rivera) (Figure 2). On the other hand, the difference between Monte Caseros

Table 1: Vertical systems in South America

Name	Network name	Responsible	Height datum	Height type
Argentina	Argentine leveling network	National geographic institute of Argentina	Mar del Plata	Orthometric[a]
Bolivia	National leveling network	Military geographic institute of Bolivia	Arica (Chile)	Normal-Orthometric[c]
Brazil	High accuracy height network	Brazilian institute of geography and statistics	Imbituba and Santana	Normal[b]
Chile	National leveling network	Military Geographic Institute of Chile	Valparaíso, Arica/ Antofagasta, Talcahuano, Puerto Montt, and Punta Arenas	Normal-Orthometric[c]
Colombia	Vertical network	Geographic Institute Agustín Codazzi	Buenaventura	Normal-Orthometric[c]
Ecuador	Vertical network	Military Geographic Institute of Ecuador	La Libertad	Normal-Orthometric[c]
Guyana	Not found	Guyana lands surveys commission	Georgetown	Not found
French Guiana	Not found	National institute of geographic and forest information	Cayenne	Orthometric[d]
Paraguay	Not found	Military geographical service	Asunción	Not found
Peru	National geodetic network leveling	National geographic institute of Peru	La Punta	Normal-orthometric[c]
Uruguay	Leveling network Uruguay	Military geographic service	Montevideo	Orthometric[e]
Venezuela	National leveling network	Geographic institute of Venezuela Simón Bolívar	La Guaira	Normal-Orthometric[c]

[a] https://www.ign.gob.ar/NuestrasActividades/Geodesia/Nivelacion/Introduccion.
[b] https://www.ibge.gov.br/geociencias/informacoes-sobre-posicionamento-geodesico/rede-geodesica/16283-rede-altimetrica.html?=&t=o-que-e.
[c] The institutions responsible for these data consider the leveling heights as orthometric heights, but they did not apply any gravimetric correction. So, in this article, these heights are considered normal-orthometric.
[4] https://geodesie.ign.fr/index.php?page=reseaux_nivellement_francais.
[5] Pina et al. (2002).

station in Argentina and Bella Unión station in Uruguay is 0.15 m. The discrepancy between Argentina (Paso de los Libres station) and Brazil (Uruguaiana station) is −0.40 m. It is worth mentioning that only Argentina and Brazil provided leveling network error, which in the Argentinean network is about 6 cm (IGN-AR 2017) and the Brazilian network varies from 1 to 15 cm (IBGE 2019).

3 Height systems in the SIRGAS context

In October 1993, during the International Conference for the Definition of a Geocentric Datum for South America, in Asuncion, Paraguay, an organization dedicated to the Geodesy called Geocentric Reference System for South America (in Spanish *Sistema de Referencia Geocentrico para la America del Sul* – SIRGAS) was established. The event was convened and sponsored by the IAG, the Pan American Institute of Geography and History (PAIGH), and the US Defense Mapping Agency (DMA), currently the National Geospatial-Intelligence Agency NGA (SIRGAS 1994).

The conference aimed to define and realize a geocentric datum in South America. In addition, the establishment and maintenance of the SIRGAS reference network was discussed. For this, it was defined as a goal to accomplish the proposed objectives, except for maintaining the reference network, since this is a long-term activity, to present it at the IAG Scientific Assembly in Rio de Janeiro in 1997. It was also necessary to coordinate and provide for the efforts in each country in South America, to assist in the connections of the existing national triangulation networks, and to concentrate efforts on the horizontal datum, postponing the Vertical Datum.

The organizational structure was divided into (SIRGAS 1994):

- a committee composed of one representative from each member country and each of the sponsoring institutions (IAG and PAIGH) and
- a Scientific Council of geodesist professionals to assist the committee in decision-making and analysis.

Two working groups were created to complete the objectives proposed in SIRGAS. The "Working Group I: Reference System" (WG-I) was responsible for establishing the reference system and deploying a network of GPS stations for continuous monitoring, including the existing GPS stations that belonged to the ITRF, besides adjusting them to the ITRF solution of that time. The second group, "Working Group II: Geocentric Datum" (WG-II) (nowadays SIRGAS at the National Level), aimed to integrate the stations of national GPS triangulation networks and adjust the networks. The objectives of the WG-I were achieved still in the Asunción conference when it was defined that the SIRGAS reference system should be the same as the IERS (International Earth Rotation Service) and the reference frame, achieved through the observation and high-precision analysis of the GPS network combined with ITRF. Concerning the WG-II, it was decided that the geodetic datum should be consistent with the Geodetic Reference System of 1980 (GRS-80) (Drewes 2022).

The creation of the working groups did not consider the physical component at that time. Only in 1997, during
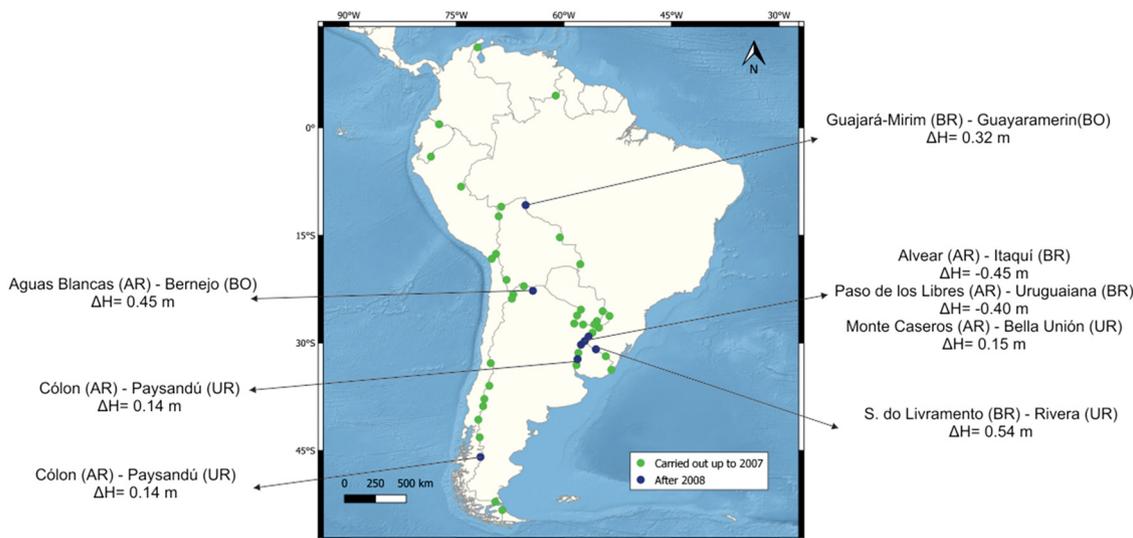
Figure 2: Height difference in leveling benchmark connections: in green leveling connections carried out up to 2007 and in blue, after 2008.

the General Assembly of the IAG in Rio de Janeiro, assuming the achievement of the main objectives of Working Groups I and II were the project's developments in the height component of the reference system discussed. Then, Working Group III "Vertical Datum" was created (SIRGAS 1998).

The WG-III creation was motivated by the need to establish a vertical reference in South America and unify the existing vertical systems. The first meeting occurred in Santiago, Chile, in 1998. On that occasion, the height types, the existing leveling networks, and the vertical reference datum were discussed. Technical document elaborated in 1998 about the "Vertical Reference System for South America" established that the height indicated for adoption among the countries would be the normal height published in SIRGAS Bulletin No 6 (SIRGAS 2002a). However, in the year 2000, a revision was made, and it was recommended that each country express its heights based on geopotential numbers and, subsequently, select the type of height, whether normal, orthometric, or other type. In addition, countries were suggested to adjust their leveling networks considering gravity corrections (Drewes 2022).

In May 2000, WG-I and WG-III joined their efforts to carry out a GPS campaign to determine heights accurately, re-observe the 1995 network, and assess station velocities, which are essential for temporal maintenance. The campaign covered 184 stations across the continent, including those of the SIRGAS1995 network, primary tide gauges in each country, boundary stations, and points for vertical control (Luz et al. 2002). This activity was the first step in unifying the vertical system in the SIRGAS region. Since the creation of WG-III, efforts have been made to assist countries in unifying and updating their height systems. The working group also has been working on clarifying information about height systems through capacity building. In 2002, as an example, the document "Urgent Need for a Modern Vertical Reference System" was published in bulletin number 7 (SIRGAS 2002b). The document presents the difficulties of having different height systems, different methodologies to calculate the geopotential number, and the possibility of adopting a single value of a potential gravity (W_0), as the reference surface.

Sánchez (2005b) presented to the SIRGAS community the Towards a Unified Vertical System for South America document. The presentation emphasized the main difficulties of the continent having several vertical data and pointed out the importance of having the physical component well defined to follow the accuracy achieved by the geometric component (h) arising from GNSS positioning.

Between 2005 and 2011, progress was made in creating a unified vertical system for the continent. In 2011, SIRGAS Resolution 2011 No. 1 about "Advances for the continental adjustment of national vertical networks in terms of geopotential numbers" was published to emphasize the leveling network adjustment regarding geopotential numbers (SIRGAS 2011). SIRGAS started to organize workshops,
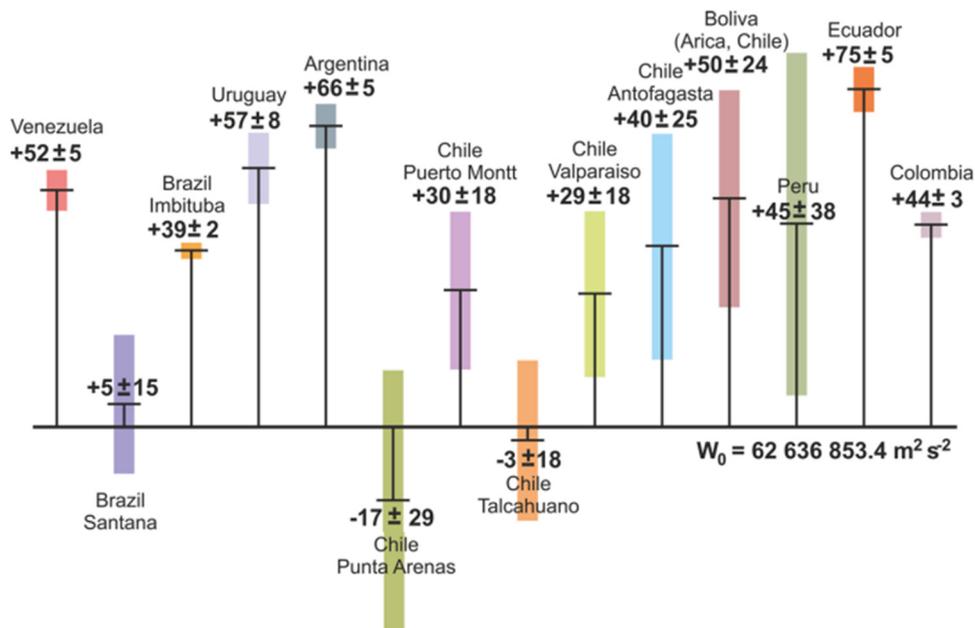
Figure 3: Discrepancies between local vertical data gravity potential and W_0. The color bars show the standard deviations. Units in cm (Sánchez and Sideris 2017).

in cooperation with geographic institutes and universities, to assist the countries in unifying and modernizing the vertical systems. Six meetings were held in Bolivia in 2014, Brazil in 2015, Ecuador in 2016, Costa Rica in 2017, Mexico in 2018, and Chile in 2022 (for more details, visit SIRGAS website: https://sirgas.ipgh.org/).

Since 2005, Sánchez (2005b) has computed a reference potential value. The conventional value for potential gravity was published in 2016 (Sánchez et al. 2016), which is $62636853.4 \text{ m}^2 \text{ s}^{-2}$. Sánchez and Sideris (2017) calculated the local gravity potential value at different tide gauges in South America and compared it with the W_0, previously established (Figure 3) (Sánchez and Sideris 2017). The authors used data from continuously operating GNSS stations connected with the national vertical data, in the study.

The efforts for vertical system unification intensified in 2015 when, at the General Assembly meeting of the International Union of Geodesy and Geophysics (IUGG), the IAG, through its Resolution No. 1, established the IHRS (IAG 2015). Since then, to assist countries in updating their vertical systems, SIRGAS has published SIRGAS Resolution 2016 No. 2, "Action for the implementation of the IHRF in the region" and SIRGAS Resolution 2017 No. 2, "Advances in the implementation of the IHRF in the region" (SIRGAS 2016). During the COVID-19 pandemic, SIRGAS has made webinars dedicated to the user community, which are available on the SIRGAS website (https://sirgas.ipgh.org/en/sirgas-events/webinars/). In 2021, Working Group III drew up two documents to assist SIRGAS member countries in implementing the IHRF (available at https://sirgas.ipgh.org/en/resources/guidelines/). The first, entitled
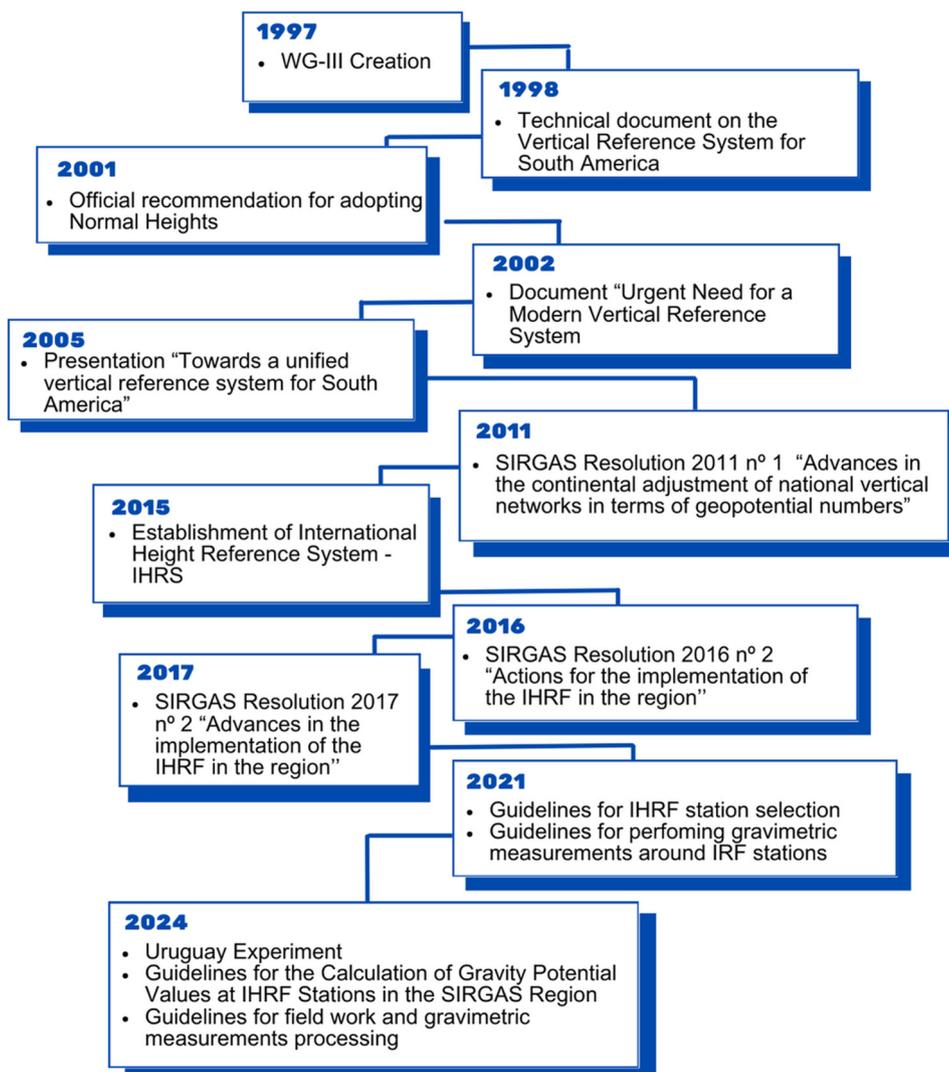

Figure 4: WG-III timeline activities.

"Guidelines for IHRF station selection" describes the requirements and recommendations for selecting an IHRF station. The instructions are aimed at institutions with a station planned to calculate their first IHRF implementation and those wishing to propose new stations. The second document, "Guidelines for performing gravimetric measurements around IHRF stations" describes the requirements and recommendations for performing terrestrial gravity measurements around IHRF stations. In 2024, WG-III made available two more documents: the first one is a guideline for calculating gravity potential values in IHRF stations, and the second one is a guideline for fieldwork and processing gravimetric measurements. Besides that, in 2024, an experiment called "Uruguay Experiment" about the computation of gravity potential values at IHRF was conducted. Three groups from Argentina, Brazil, and Uruguay independently computed the values at two IHRF stations in Uruguay. The objective was to ensure that the groups achieved the same results. The timeline (Figure 4) summarizes the main WG-III events.

In the sense of evaluating the impact of WG-III activities over the years, a bibliometric study was carried out to quantitatively analyze the publications made by the scientific community, taking keywords into account. The search was conducted in the Scopus database from 2005 (the year of the first publication in the base, using the keyword SIRGAS) to 2023. Figure 5(a) has two essential clusters related to the height systems: the first (shown in Figure 5(b)) regarding the Vertical Datum and the second (in Figure 5(c)) related to the IHRS. The colors indicate the year of publication. Since the IHRS and ITGRS resolution publication words (in yellow) as "geodetic reference system," "geodetic reference frame," and "IHRS" are present in recent articles and publications.

We used VOSviewer to visualize the network map of country co-authorship using the keyword SIRGAS (Figure 6). South America has seven countries, according to the results. Argentina has more connections (nine) than the other countries. Since 2020, the United States has been a member of SIRGAS, explaining the color yellow in the connections.

(a)

(b)

(c)
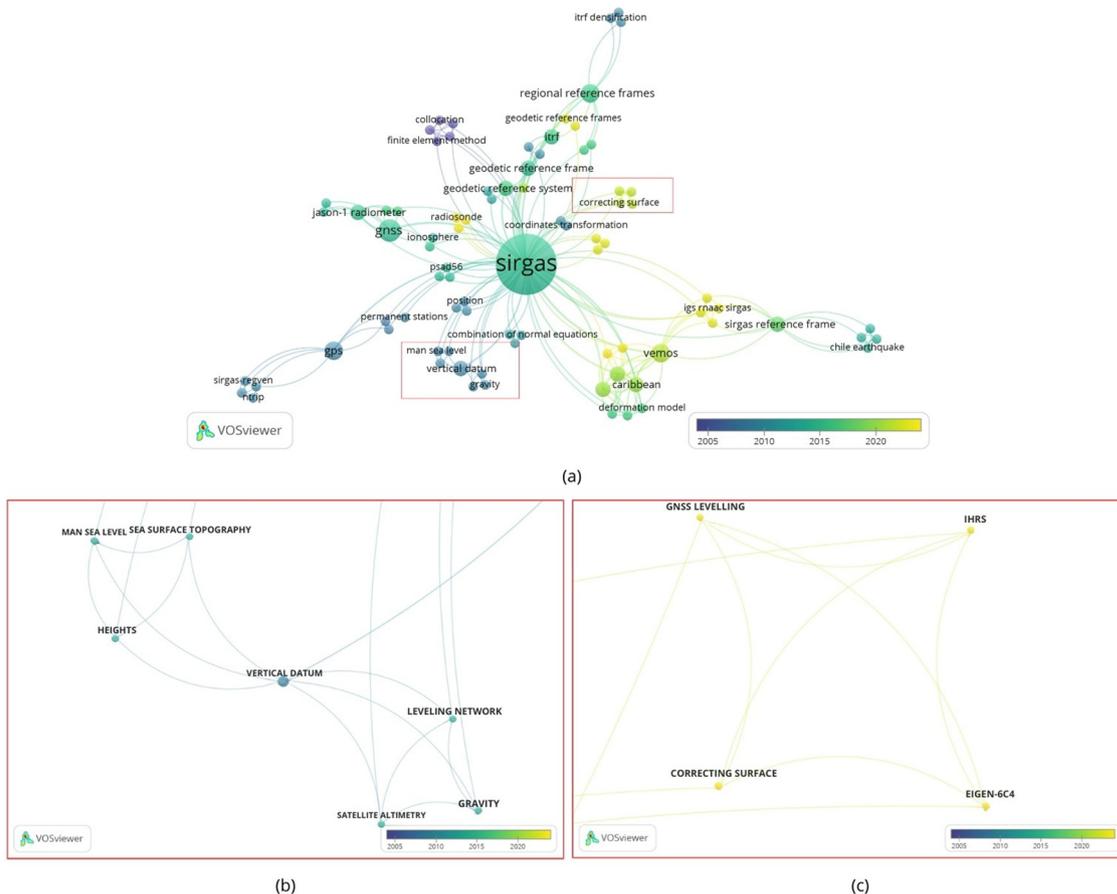
Figure 5: Map of occurrence of keywords focusing on height systems: (a) the relationships between keywords, the main one being SIRGAS, (b) first node concerning vertical systems and their relationships, and (c) second node about altimetric systems, whose color indicates more current publications.
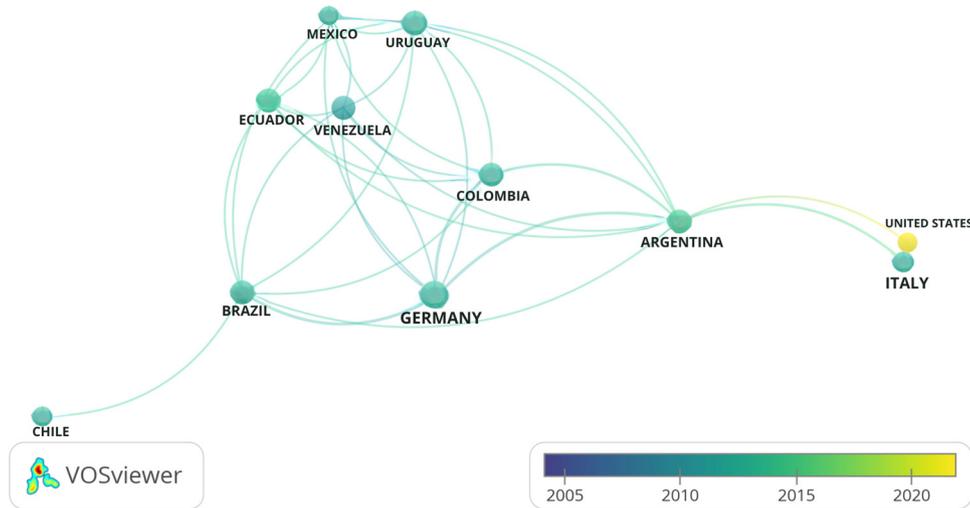
Figure 6: Relationship map between countries that publish with the theme SIRGAS.

We also conducted a search related to the number of keywords referring to the topics of WG-III. The following words were used: Geoid, Gravimetry, Tide Gauge, Vertical Datum, Global Geopotential Models, Geopotential Number, Height System, Absolute Gravity, Absolute Gravimeter, Absolute Gravimetry, Geopotential, IHRS, and IHRF. The results were divided into two periods: before 2015 (Figure 7(a)) and after 2015 (Figure 7(b)). The larger the keyword length, the more it was cited in scientific articles. Note that words such as IHRS and IHRF are presented in the search after 2015.

4 IHRS in the scopes of SIRGAS

Efforts to unify vertical systems have been discussed by SIRGAS countries and globally. The IAG Resolution 2015 No. 1 proposed that the IHRS is a system referring to an equipotential surface of the Earth's gravity field where the coordinates are expressed in terms of geopotential number (C_p) (Figure 8) obtained from the difference between the gravity potential at point P (W_p) and the conventional potential W_0 as in the following Eq. (1) according to Sánchez and Sideris (2017):

$$C_p = \Delta W_p = W_0 - W_p. \tag{1}$$

The vertical system in the SIRGAS region adopts the exact definition of IHRS and becomes a regional densification of IHRF in the following aspects (SIRGAS 2017):

- Be referenced to the value of W_0 conventional, as established by the IAG;
- National height system based on physical heights derived from leveling associated with gravity reduction or high-resolution gravity field analysis; and
- It must be associated with a specific reference epoch, i.e., it must consider changes in height and its reference level
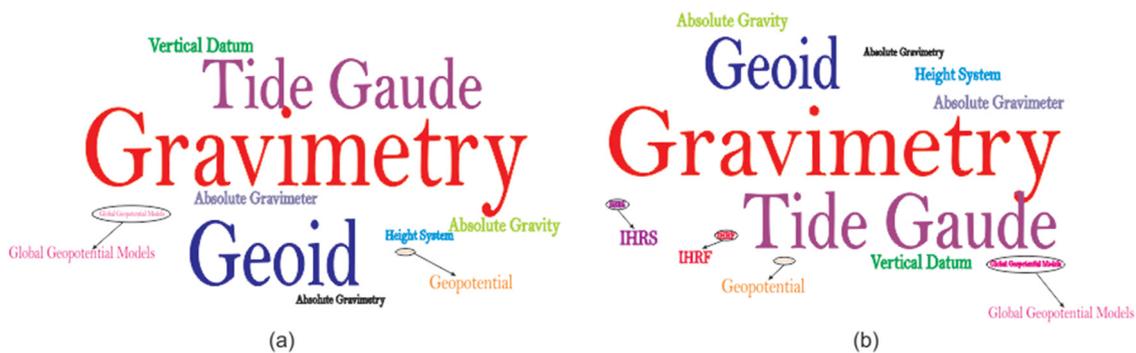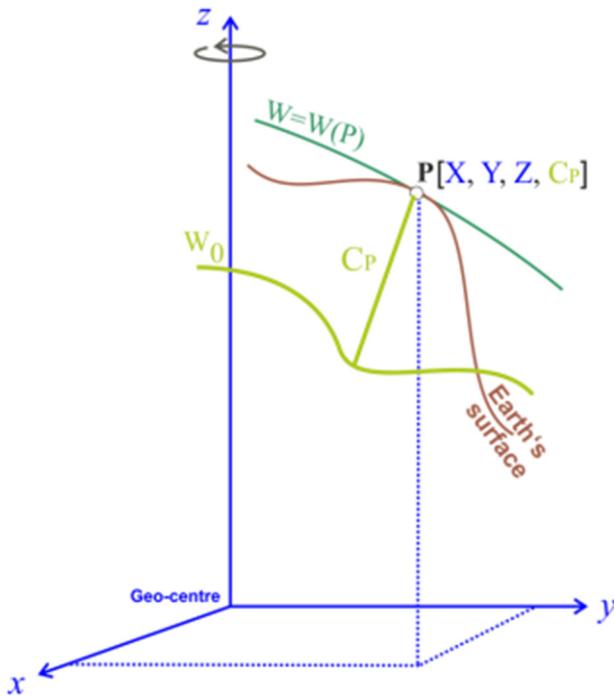

Figure 7: Words clouds related to WG-III: (a) demonstrates that prominent keywords such as Gravity, geoid, and tide gauge have been used in several studies for years and (b) presents more current words, demonstrating that after the publication of the IHRS, other quantities began to gain more prominence.

Figure 8: Components of the geopotential numbers (Sánchez and Sideris 2017).

concerning time. The respective reference surface (geoid or quasi-geoid) must be determined in a unified way over the entire continent. For the first realization, countries were requested to designate stations that could be included in the IHRF network following the recommendations and guidelines published by the "Unified Height System" focus area of the GGOS and Working Group 0.1.2: "Strategy for the realization of the IHRS" (Ihde et al. 2017, Sánchez 2019, Sánchez and Barzaghi 2020). In South America, 17 stations were proposed by the national agencies, and each station is materialized by a permanent GNSS station (Figure 9(a), in purple). Most of these stations are co-located with other geodetic techniques, such as VLBI (Figure 9(a), in yellow), DORIS (Figure 9(a), in blue), and SLR (Figure 9(a), in green). Furthermore, it is desired that the IHRF station should be linked to the local Vertical Datum. Gravity observation (preferably an absolute measure) and leveling connection with the local vertical network are recommended. Figure 9(b) presents the station with a leveling connection (in green) and gravity measure (in red). The international leveling connection (Figure 9(b), orange dots) is also recommended for the assessment in terms of the unified network in the region.

Therefore, regional unified height systems should be based on geopotential numbers because different physical heights (orthometric or normal heights) may introduce artificial errors in the connection of leveling networks at the borders between neighboring countries. In the context of SIRGAS, Uruguay (Faure and Suárez 2015), Argentina (IGN-AR 2017), and Brazil (IBGE 2019) concluded the
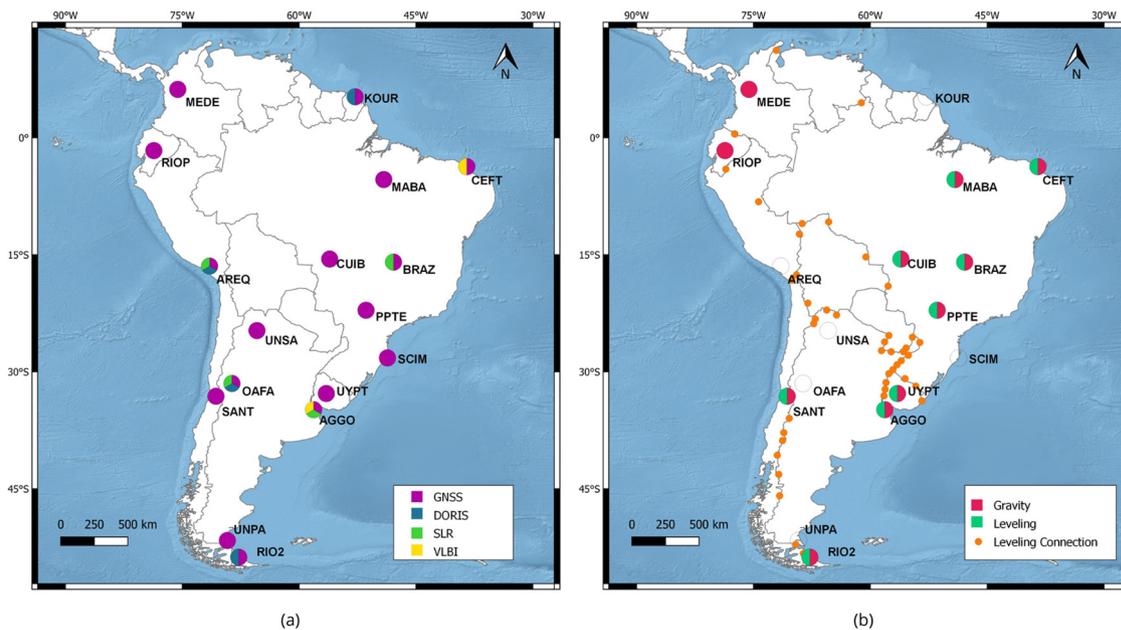
Figure 9: IHRF stations infrastructure: (a) stations with geodetic techniques and (b) stations with gravity and leveling measures and the international leveling connection (orange circles).

process of updating their systems to heights based on geopotential numbers. Ecuador, Colombia, and Venezuela are working towards concluding this task. Colombia presented a preliminary vertical system adjustment during Symposium SIRGAS 2022 (Sepúlveda et al. 2022).

In addition, gravity densification should be performed around IHRF stations within a radius of 210 km (~2°) (Sánchez et al. 2021). It is essential to fill the gaps around the reference station, where the distribution of gravity points should be as homogeneous as possible. On the other hand, for IHRF stations situated on the coast, marine or airborne gravity data may be an option (Ribeiro et al. 2023).

Sánchez et al. (2021) recommended a spatial resolution of 1′ to 3′ (around 2–4 km) around the IHRF station. Depending on the relief, especially in mountainous areas, gravity observations should have a better resolution than in flat areas. However, it is known that terrestrial gravity measures are costly and time-consuming activities. In remote areas, with the absence of roads and paths, such as forests and deserts, as well as on top of mountains, it is suggested that the airborne survey is intended for geodetic purposes (Sánchez et al. 2021, SIRGAS 2021).

4.1 Numerical tests

According to Sánchez et al. (2021), there are three ways to obtain the gravity potential at IHRF stations: (a) using the high-resolution Global Geopotential Models; (b) using regional models of the Earth's gravity field (geoid and quasi-geoid); and (c) transforming existing vertical systems to the IHRF. The last option is not precisely for calculating potential values but rather to allow unification and densification of the IHRF about existing height systems.

In the first case (a), GGMs can achieve an accuracy of 2 cm in areas with gravity densification and 20–40 cm in areas with terrestrial gravity scarcity in mountain areas (Guimaraes et al. 2022). The computation of W_p is possible by entering the ITRF coordinates in Eq. (2) (Barthelmes 2013), which represents the spherical harmonic coefficients representing in the spectral domain the global structure and irregularities of the gravity field of the Earth:

$$W_p(r, \lambda, \varphi) = \frac{GM}{R} \sum_{l=0}^{l_{\max}} \sum_{m=0}^{l} \left(\frac{R}{r}\right)^{l+1} P_{lm}(\sin\varphi) \times (\bar{C}_{lm}^w \cos(m\lambda) + \bar{S}_{lm}^w \sin(m\lambda)), \tag{2}$$

where (r, λ, φ) are the spherical geocentric coordinates of computation point (radius, longitude, latitude); R is the reference radius; GM is the product of gravitational constant and

mass of the Earth; l and m are the degree and order of spherical harmonic; P_{lm} is fully normalized Legendre function; and $\bar{C}_{lm}^w$, $\bar{S}_{lm}^w$ are Stokes' coefficients (fully normalized).

Based on the first case, a comparison in terms of normal heights has been carried out using the following strategy of computing geopotential values W_p at the IHRF stations applying the GGMs: EGM2008 (Pavlis 2012), EIGEN-6C4 (Foerste et al. 2014), GECO (Gilardoni et al. 2015), XGM2019 (Zingerle et al. 2020), and SGG-UGM-2 (Liang et al. 2020). The International Center for Global Gravity Field Models (ICGEM) service was used for the computation. The following parameters were selected: geodetic functional "gravity potential," reference system GRS-80, zero tide concept, and the zero-order term.

The geopotential numbers were calculated (Eq. (1)), and the respective normal height at each IHRF station was obtained from $H_P = \frac{C_P}{\bar{\gamma}}$, where $\bar{\gamma}$ is the mean gravity normal. To compare each model with the others, the average of four models was calculated, and the difference between the fifth model and the average was determined (Figure 10 and Table 2).

Among the four recent models, the EIGEN-6C4 stands out for its most significant standard deviation, registering a difference of 2.93 cm over SGG-UGM-2, which is the GGM with the slightest standard deviation. EIGEN-6C4 uses data from DTU12 for the oceans and EGM2008 for the continent, in addition to making use of a combination of satellites such as GOCE, GRACE, and LAGEOS, becoming the GGM that most incorporate data from gravimetric satellites compared to the other models. In turn, GECO, when using only data from EGM2008 and the GOCE satellite, presents a standard deviation of ±9.52 cm.

The XGM2019 model, in turn, is characterized by the broad combination of data used, in addition to employing their weighting. This model incorporates a 15′ resolution land and ocean gravity anomaly dataset provided by NGA, combined with gravimetric information from the EARTH2014 model and a 1-min resolution gravity anomaly dataset derived from radar altimetry over the oceans of the DTU13 model, together with the GOCO06S satellite. The standard deviation of this model varies by about ±2 cm about SGG-UGM-2.

Finally, SGG-UGM-2 has the slightest standard deviation among the most recent models. This model uses data from EGM2008, combined with data from several altimetry satellites, to achieve a resolution of 1′ in marine gravity anomaly data. It is observed that, although the four models present relatively small variations in terms of standard deviation, in some places, the construction of the model influenced more than in others, especially in areas with accentuated topography, such as the Andes, where the
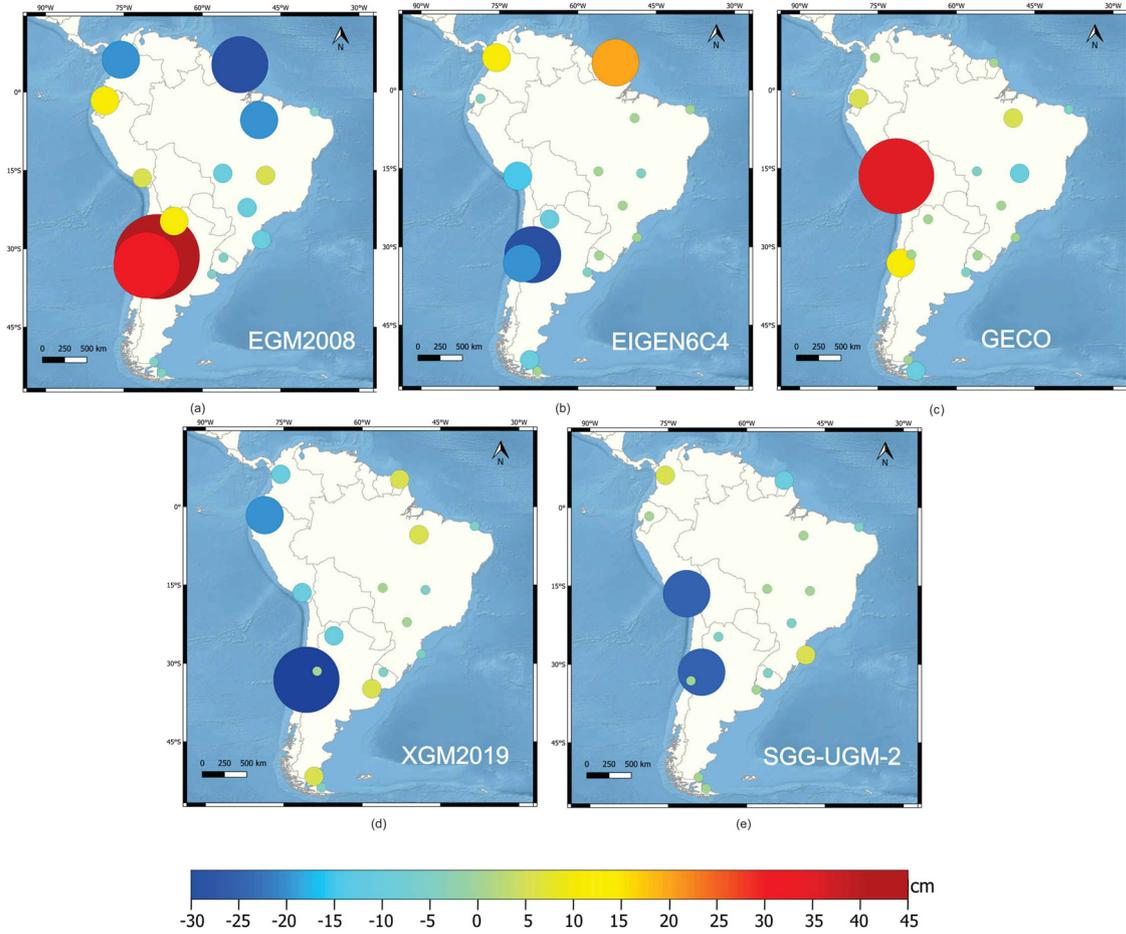
Figure 10: Comparison of the normal heights computed from the GGMs geopotential numbers: (a) EGM2008, (b) EIGEN-6C4, (c) GECO, (d) XGM2019, and (e) SGG-UGM-2.

Table 2: Statistics involving GGMs (in cm)

	EGM 2008	EIGEN 6C4	GECO	XGM 2019	SGG-UGM-2
Mean	1.98	−1.47	3.39	−2.56	−1.34
SD	±17.02	±11.12	±9.52	±10.14	±8.19
Max. neg	−26.69	−25.37	−6.92	−32.09	−21.37
Max. pos	43.78	23.61	35.33	9.48	8.95

resolution of the models 9 × 9 km is not suitable due to the scarcity of gravimetric data.

Due to the topography and the lack of gravity data, the most significant differences (Figure 10) in the comparison are the stations in the Andes region and their proximity.

The second case (b) is appropriate in the context of the potential values given by estimating the perturbation potential (T_P), from modeling the regional gravity field (geoidal and quasi-geoidal models) through the solution of the geodetic boundary value problem (GBVP) (Eq. (3)):

$$W_P = U_P + T_P, \tag{3}$$

where U_P is the normal potential of a reference ellipsoid computed for a position P.

If a quasi-geoidal model is available, the value of W_P is obtained from Eq. (4) (Sánchez et al. 2021):

$$W_P = W_0 - (h_P - \zeta_P) \cdot \bar{\gamma}_{QQ_0} \ [\text{m}^2 \ \text{s}^{-2}], \tag{4}$$

where $\bar{\gamma}_{QQ_0}$ is given by Eq. (5):

$$\bar{\gamma}_{QQ_0} = \gamma_0 \cdot \left[1 - \frac{1}{a} \cdot (1 + f + m - 2f \cdot \text{sen}^2\varphi_P) \cdot (h_P - \zeta_P) \right], \tag{5}$$

where φ_P is the latitude of the point, ζ_P is the height anomaly interpolated from a geoid or quasi-geoidal model, and f, m, and a are the parameters of the reference ellipsoid, GRS80 (Moritz 2000).

If a geoidal model is available, W_P is obtained from the following Eq. (6) (Sánchez et al. 2021):

$$W_P = W_0 - (h_P - N_P) \cdot \bar{g}_P \ [\text{m}^2 \ \text{s}^{-2}], \tag{6}$$

where $\bar{g}_P$ is the gravity along the plumb line between P_0 located at the geoidal surface and P on the physical surface, given by Eq. (7):

$$\bar{g}_P = g_P + 0.424 \times 10^{-6} \cdot (h_P - N_P) + TC_P, \qquad (7)$$

where N_P is the geoidal undulation, and g_P is the gravity value at the station; if it was not observed directly, it could be interpolated from the Earth gravity data set used for geoid determination. The factor 0.424×10^{-6} refers to an average density of the topographic masses considering $\rho = 2.670$ kg m^{-3} and TC_P is the terrain correction.

Considering this, efforts by the academic community to compute geoidal and quasi-geoidal models have been carried out. Guimarães et al. (2024) computed a geoidal and quasi-geoidal model for South America (SAM_GEOID2023 and SAM_QGEOID2023). In addition, there are available recent regional models of Argentina (GEOIDE-Ar 16) (Tocho et al. 2022) and Uruguay (UruGeoide202X) (Pina 2022).

We carried out an evaluation involving SAM_QGEOID2023 and GGMs at IHRF stations. We inferred the stations in terms of C_P by comparing the geopotential number calculated from the SAM_QGEOID2023 model with the potential gravity values of

Table 3: Statistics between GGMs and the SAM_QGEOID2023 model (in m^2 s^{-2})

	EGM 2008	EIGEN 6C4	GECO	XGM 2019	SGG-UGM-2
Mean	−0.90	−2.87	−3.25	−2.78	−2.88
SD	±9.97	±2.98	±3.65	±2.67	±3.08
Max. neg	−26.65	−11.99	−12.89	−10.92	−12.32
Max. pos	23.10	−0.12	−0.51	−1.05	−0.16

the GGMs (EGM2008, EIGEN6C4, GECO, SGG-UGM-2, and XGM2019). To calculate the C_P value, the W_P values of SAM_QGEOID2023 were obtained by Eq. (4), and subtracted from the value of W_0. As for GGMs, the "Gravity Potential" functional was obtained from ICGEM and W_0 was also subtracted, according to IHRS. Figure 11 and Table 3 present the results regarding the C_P value.

Table 3 shows that the four recent models' mean and standard deviation are very close. The XGM2019 presents results slightly better once it is the one used to fill the gaps in the SAM_QGEOID2023 model.
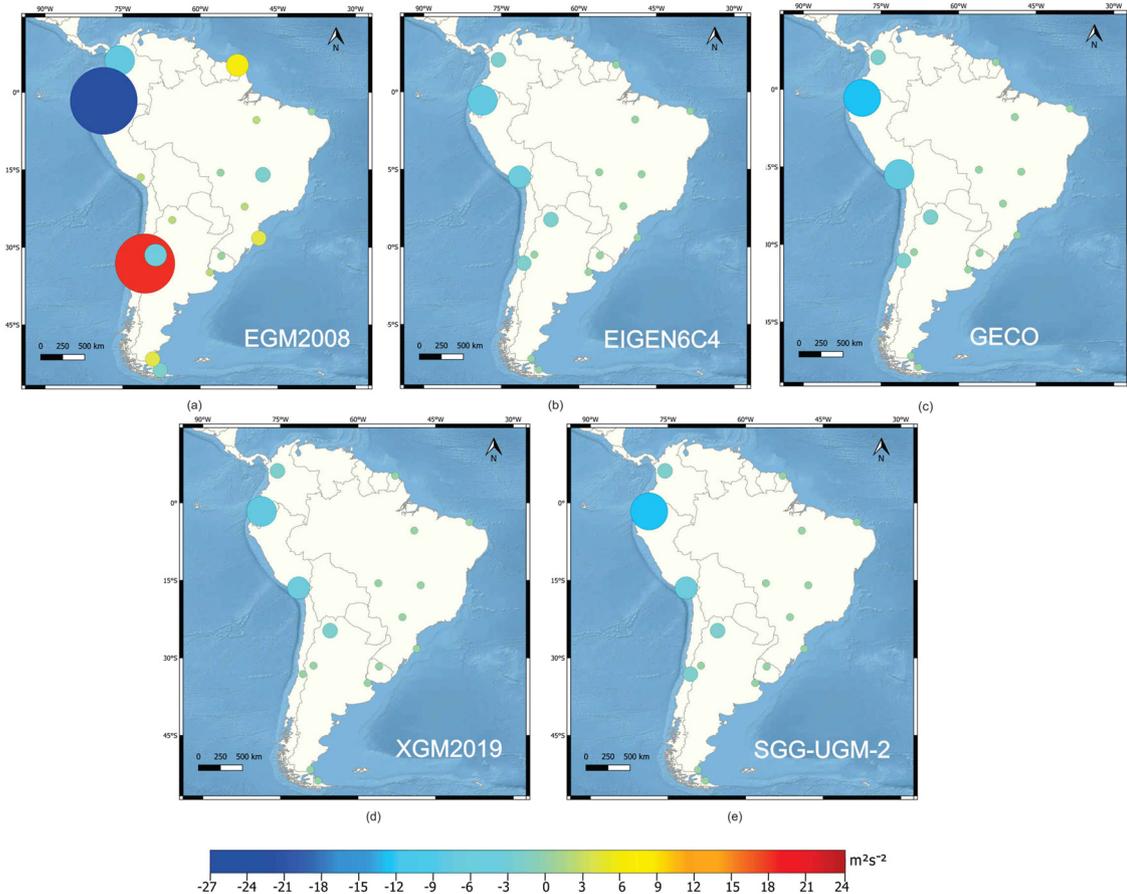
Figure 11: Difference between the geopotential numbers computed with SAM_GEOID2023 model and the GGMs at IHRF stations.

It can be seen in Figure 11 that the stations located in the Andes region present a more significant variation. We can consider this discrepancy because the models do not adjust satisfactorily in areas of accentuated relief since the resolutions of these models do not follow the accentuated variation in relief, unlike the flatter regions of Brazil, Uruguay, and the stations in Argentina, which present smaller discrepancies.

5 Final remarks and future perspectives

Establishing a consistent global system depends on efforts from the academic and governmental community through different spheres and institutions so that it is possible to update old systems and implement new technologies consistently over time.

In America, SIRGAS has been responsible for 30 years for assisting countries in implementing their geodetic systems. About 25 years ago, SIRGAS created Working Group III, which has contributed to the issue of vertical systems and helped countries with different tasks. Over the years, WG-III has contributed to developing training and guidelines to support SIRGAS member countries. Recently, the WG-III concentrated on computing potential gravity values related to the IHRF implementation. However, despite recurrent efforts on the part of this organization, some member countries are still resistant to opening the repositories. The countries whose information is easier to find are those where the implementation of the IHRF is more advanced, such as Argentina, Brazil, Colombia, and Uruguay. Also, the community must implement the ITGRF to achieve a consistent IHRF solution. Gravity densification is essential, especially around the IHRF stations and in the gaps.

Related to the results achieved in the article, GGM data is not yet an alternative to computing potential gravity values since the models are not developed to the degree and order to obtain the precision recommended. In the Andes region, gravity measures and the GGMs models should be improved in the following years, as well as topography models.

Finally, the first realization of the IHRF is a reality, and the community is working hard to complete this task. On the other hand, some aspects related to the local datum conversion to the IHRF should be implemented. Besides that, temporal variations of the height and gravity components are a challenge for the specialist and probably will be discussed in the following years.

Author contributions: All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Mariana Eiko Borba Inoue. The project supervision was performed by Gabriel do Nascimento Guimarães. The first draft of the manuscript was written by all authors. All authors read and approved the final manuscript.

Conflict of interest: The authors declare no conflict of interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

Informed consent: This study did not include human participants or personal data; therefore, informed consent was not required.

Data availability statement: The data used in this study is available from the corresponding author on reasonable request. The models SAM_GEOID2023 and SAM_QGEOID2023 are available on the International Service for Geoid (ISG) website for download. Further details regarding data sharing and access policies can be found in the Data Sharing Policy document available on the journal's website.

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