Status of the SIRGAS Reference Frame: Recent Developments and New Challenges

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Abstract

In accordance with recent developments of the International Association of Geodesy (IAG) and the policies promoted by the Subcommittee on Geodesy of the United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM), a main goal of the Geodetic Reference System for the Americas (SIRGAS) is the procurement of an integrated regional reference frame. This frame should support the precise determination of geocentric coordinates and also provide a unified physical reference frame for gravimetry, physical heights, and a geoid. The geometric reference frame is determined by a network of about 500 continuously operating GNSS stations, which are routinely processed by ten analysis centers. The GNSS solutions from the analysis centers are used to generate weekly station positions aligned to the International Terrestrial Reference Frame (ITRF) and multi-year (cumulative) reference frame solutions. This processing is also the basis for the generation of precise tropospheric zenith path delays with an hourly sampling rate over the Americas. The reference frame for the determination of physical heights is a regional

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densification of the International Height Reference Frame (IHRF). Current efforts focus on the estimation and evaluation of potential values obtained from high resolution gravity field modelling, an activity tightly coupled with geoid determination. The gravity reference frame aims to be a regional densification of the International Terrestrial Gravity Reference Frame (ITGRF). Thus, SIRGAS activities are focused on evaluating the quality of existing absolute gravity stations and to identify regional gaps where additional absolute gravity stations are needed. Another main goal of SIRGAS is to promote the use of its geodetic reference frame at the national level and to support capacity building activities in the region. This paper summarizes key milestones in the establishment and maintenance of the SIRGAS reference frame and discusses current efforts and future challenges.

Keywords

GNSS reference networks · IHRF regional densification · ITGRF regional densification · ITRF regional densification · Regional reference frames · SIRGAS

1 Introduction

The Geodetic Reference System for the Americas (*Sistema de Referencia Geodésico para las Américas*, SIRGAS) was established in 1993 at an international conference in Asunción, Paraguay, organized by the International Association of Geodesy (IAG), the Pan-American Institute for Geography and History (PAIGH), the Deutsches Geodätisches Forschungsinstitut (DGFI), and the U.S. Defense Mapping Agency (DMA) (see e.g. Drewes 2022). During this meeting, participants defined the main goal of SIRGAS: the unification of the South American Datum using the Global Positioning System (GPS). Two Working Groups (WG) were formed to achieve this goal, "Reference Frame" (WGI) and "Geodetic Datum" (WGII, now called "SIRGAS at National level"). Their charge was to define, realize, and maintain a geocentric reference system and to support its integration to the national densifications.

The first frame realization, SIRGAS95, included stations only in South America (SIRGAS 1997). The second one, SIRGAS2000, included stations in countries in all the Americas (Drewes et al. 2005). Some years later, SIRGAS implemented a reference frame using only continuously operating GNSS (Global Navigation Satellite Systems) stations (see e.g. Brunini et al. 2012). In 1997 SIRGAS created the "Vertical Datum" WGIII for the determination of a vertical reference frame for South America that aimed to connect the existing levelling networks (Drewes 2022). This WGIII is currently dedicated to establish regional densifications of the International Height Reference Frame (IHRF) and the International Terrestrial Gravity Reference Frame (ITGRF) as to provide consistency for gravimetry, physical heights, and geoid.

Over the years, the SIRGAS WGI provided weekly products such as, coordinates, hourly zenith path delays (ZPD), and long-term products such as velocity models (VEMOS) and multi-year solutions.

Another important and strategic task carried out by SIRGAS is knowledge transfer and capacity building (see https://sirgas.ipgh.org/eventos-sirgas/cursos/). This paper summarizes activities carried out by the SIRGAS WGs, including efforts from the IGS Regional Network Associate Analysis Centre for SIRGAS (IGS RNAAC SIRGAS). Also, the SIRGAS executive committee recently joined the Regional Committee (UN-GGIM:Americas) of the Geodetic Reference Frame for the Americas WG. We discuss the activities and new responsibilities of SIRGAS within this WG.

2 Main SIRGAS Objectives and International Networking

SIRGAS mainly interacts with four international bodies: IAG, which provides guidance for the scientific and technical SIRGAS activities; the International GNSS Service (IGS), which provides support for the proper analysis of the SIRGAS reference frame; PAIGH, which provides a direct link to the national agencies responsible for the geodetic reference frames; and the chapter Americas of the United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM: Americas), which provides a policy framework for geodetic capacity building at the regional level. Based on this networking, the main objectives of SIRGAS are:

- To establish and maintain a continental geocentric reference frame that is a regional densification of the International Terrestrial Reference Frame (ITRF);
- To define and maintain a unified vertical reference system by means of physical and geometric heights consistent with IHRF;

- To develop and maintain updated a gravimetric geoid model of continental coverage; and
- To establish and maintain a continental absolute gravity reference network consistent with the ITGRF.

These goals are faced by the WGI and WGIII, whose chairs are also responsible for the IAG Sub-Commissions 1.3.b (Regional Reference Frames – South and Central America) and 2.4b (Gravity and Geoid in South America), respectively. The capacity building and knowledge transfer activities are coordinated by the WGII. The interaction with the IGS is done by the IGS Regional Associate Analysis Centre for SIRGAS (IGS RNAAC SIR). Efforts and results of these WGs are also reported to the PAIGH Cartography Commission. The interaction between SIRGAS and UN-GGIM: Americas is founded in the WG Geodetic Reference Frame for the Americas (GRFA-WG), which promotes and provides mechanisms for capacity development and knowledge transfer in the field of Geodesy among the Nations of the Americas. The main goal is to cooperate in the implementation of the UN Resolution about a “Global Geodetic Reference Frame for sustainable development” (A/RES/69/2663) adopted in 2015. To optimise resources and harmonise the SIRGAS and GRFA-WG activities, the president and vice-president of SIRGAS are the co-chairs of the GRFA-WG. Thus, SIRGAS is the meeting point for policy, science, technology, and capacity building in geodesy in the Americas.

3 Advances in the Physical Reference Frame

As mentioned, one of the main goals of SIRGAS is to establish a unified physical reference frame that ensures consistency between gravity observations, geoid model, and physical heights. Surface (terrestrial, airborne, shipborne) gravity values are the main input for the computation of levelling-based geopotential numbers (i.e., physical heights) and the high-frequency signals of the geoid. In turn, the disturbing potential determined for the geoid modelling is also needed for the calculation of geopotential numbers in the IHRF (see e.g., Sánchez et al. 2021). For this reason, SIRGAS seeks to ensure consistency between the gravity reference (Sect. 3.1), the geoid model (Sect. 3.2), and the IHRF coordinates (Sect. 3.3).

3.1 Reference Frame for Terrestrial Gravimetry

The gravimetric reference frame within SIRGAS is mostly based on local absolute gravity networks determined mainly by Micro-g LaCoste A10 gravity meter measurements (Blitzkow et al. 2018). Today, most of the countries have absolute gravity networks (Fig. 1), which are usually densified by relative gravimeter measurements. Current goals are to identify areas with few observations and to distribute and set new stations more homogeneously in order to support the establishment of the IHRF (Sánchez et al. 2021) and the precise determination of the geoid.

SIRGAS is also involved in establishing the International Terrestrial Gravity Reference System (ITGRS) and Frame (ITGRF; Wziontek et al. 2021) on a regional level. One of the key aspects of the ITGRF is the demand for reference stations that provide a precise gravity reference supporting frame accessibility at any time. In this regard, the Argentinean-German Geodetic Observatory (AGGO) located close to La Plata, Argentina (Fig. 1), plays a fundamental role as it provides continuous gravity measurements using a superconducting gravimeter (SG). These measurements were complemented with absolute gravity measurements performed with a FG5 gravity meter between 2019 and 2022. The combination of both allowed for the computation of a gravity reference function for the station (Antokoletz et al. 2020). According to Wziontek et al. (2021), these characteristics, and the available infrastructure, allow AGGO to be a core station of the ITGRF.

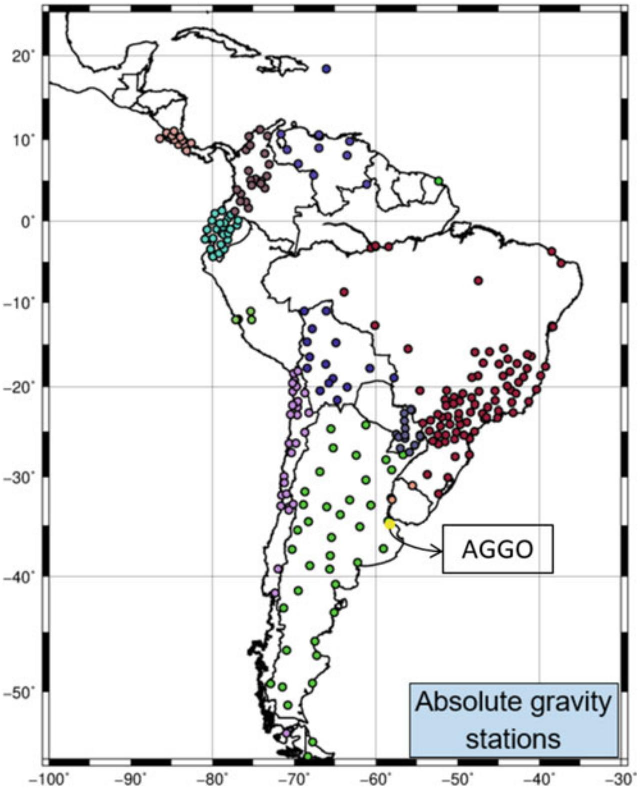

Fig. 1 Distribution of absolute gravity stations along Latin America (as of Sep, 2022). Different colours correspond to the network belonging to different countries. In yellow the station AGGO

In this context, one of SIRGAS' challenges is to evaluate the quality of the existing absolute gravity measurements in order to ensure its compatibility with the standards and recommendations given for the ITGRF (Wziontek et al. 2021). Regional comparisons at reference stations like AGGO will play a key role, since all gravity meters in the region must participate in these comparison campaigns. Other activities include (a) training and capacity building in gravimetry with the aim of homogenising field procedures and processing standards of absolute and relative gravity measurements; (b) constant support to the national agencies in charge of the gravimetric reference frames; and (c) compilation of detailed documentation and metadata of the existing absolute gravity data.

3.2 Recent Improvements in the Modelling of the Geoid

The most recent geoid and quasi-geoid models for South America, called GEOID2021 and QGEOID2021 (de Matos et al. 2021a, b) respectively, were calculated thanks to the collaboration of several South American organizations, especially national mapping agencies, private companies and universities. These models cover the area between 15°N and 60°S latitude and 100°W and 30°W longitude, with a 5′ grid resolution. The comparison between the estimated geoid heights and the GPS/levelling data at 4,464 points in Argentina (2,931), Chile (176), Colombia (464), Ecuador (703) and Venezuela (190) shows differences with RMS values ranging from 34 cm for Argentina to 92 cm for Ecuador. The comparison between height anomalies and GPS/levelling data at 1,108 points in Brazil shows differences with a RMS of about 41 cm. Looking at the RMS it is possible to verify the convergence of the geoid and quasi-geoid models in relation to the GPS/levelling points. While levelling points are linked to the local vertical data of the different countries, the geoid and quasi-geoid models are linked to the equipotential surface of the Earth's gravity field with geopotential value $W_0 = 62{,}636{,}853.4\ m^2\ s^{-2}$. This can explain the differences in the comparison. Besides that, the zero degree term added to the geoid model was equal to -17 cm, where it was considered that the normal potential U_0 was different from W_0. The grids for both models are available on the website of the International Service for the Geoid (ISG; Reguzzoni et al. 2021; de Matos et al. 2021a, b).

3.3 Standardisation of Physical Heights

In the last 25 years, SIRGAS has been actively working on the unification of vertical datums and the determination of a unified height system for the region. Since 2015, when the IAG defined the International Height Reference System (IHRS, see Drewes et al. 2016; Ihde et al. 2017), SIRGAS focused efforts to establish a regional densification of the IHRF and supported member states through workshops, schools, and webinars. In the region, 19 stations distributed over 10 countries were selected to compose the IHRF network. These stations are materialised by continuously operating GNSS stations and are integrated into the SIRGAS reference frame. Besides that, some of them are co-located with space geodesy and gravimetric techniques (Fig. 2).

It is recommended that regional unified height systems are based on geopotential numbers as different physical heights (orthometric or normal heights) are in use and they may introduce artificial errors in the connection of levelling networks at the borders between neighbouring countries. In this sense, SIRGAS provides training and capacity building to the national agencies responsible for the geodetic reference frames. To date, three member states have completed this task and three others are close to finish (Fig. 2). Furthermore, SIRGAS has emphasized the importance of international levelling connections (Fig. 2), gravity measurements and

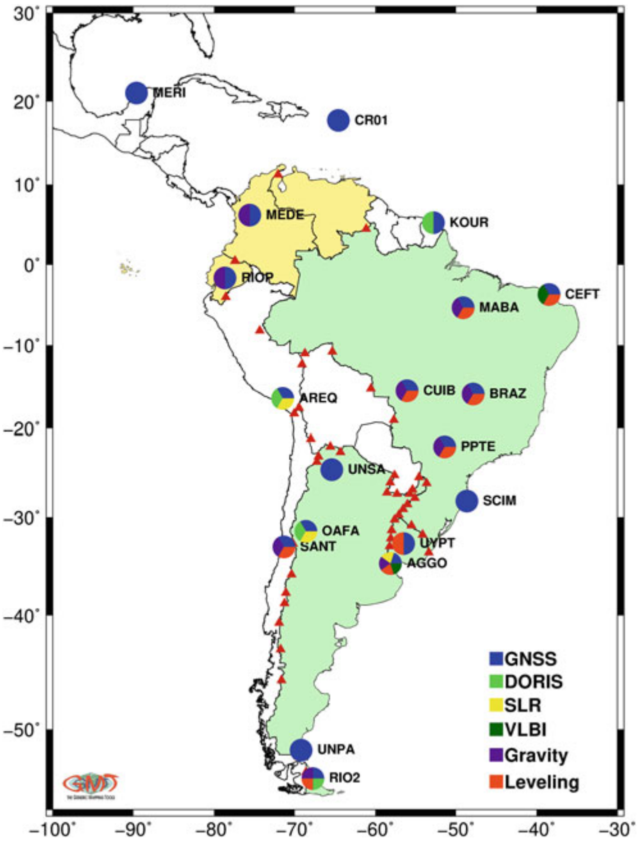

Fig. 2 Distribution of IHRF stations in Latin America (as of Sep, 2022), co-located with space techniques, gravity, and levelling. Triangles indicate the international levelling connections. Countries with vertical networks adjusted in terms of geopotential numbers are depicted in green and in yellow those in process

levelling connections at the IHRF stations. Two technical guides were developed: “Guidelines to select IHRF stations” and “Guidelines for gravimetric measurements around IHRF stations”, both available at https://sirgas.ipgh.org/. Additional ongoing activities are (a) station selection for national densifications of the IHRF, and (b) the determination of geopotential numbers at the Latin American IHRF stations (more details in Tocho et al. 2020; Guimarães et al. 2022a, b; Silva et al. 2022). The present challenges in this regard are the evaluation of discrepancies between different computation methods and the quality assessment in the determination of geopotential numbers.

4 Status of the Geometric Reference Frame

The current realization of SIRGAS is a network of 500 continuously operating GNSS stations (Fig. 3). From these stations, 109 belong to the IGS global network; the rest belong to the national reference frames. All SIRGAS stations track GPS, 89% of them track GLONASS, 39% Galileo, and 30% Beidou.

The SIRGAS reference stations are classified in core stations (core network, SIRGAS-C) and national densification stations (national networks, SIRGAS-N). All stations follow the same operational criteria and are analysed on a weekly basis in agreement with the standards of the International Earth Rotation and Reference Systems Service (IERS, Petit and Luzum 2010) and the IGS (Johnston et al. 2017). Currently, 10 SIRGAS analysis centres (SIRGAS-AC) process the GNSS data. Each station is included in at least three individual solutions. The SIRGAS-ACs generate weekly loosely constrained solutions (LCS) for station positions and Zenith Path Delays (ZPD) hourly estimates. The station positions’ LCS are combined by the SIRGAS combination centres to generate a unified solution of the reference frame (Sect. 4.1). The ZPD estimates are combined by the SIRGAS analysis centre for the neutral atmosphere (Sect. 4.2). The weekly combinations are the input for the determination of reference frame multi-year solutions (Sect. 4.3), which are the basis for the calculation of SIRGAS velocity models (Sect. 4.4). Table 1 summarizes present and former SIRGAS analysis centres. Figure 4 depicts the data flow within the SIRGAS reference frame analysis.

Fig. 3 SIRGAS reference network (as of Sep, 2022)

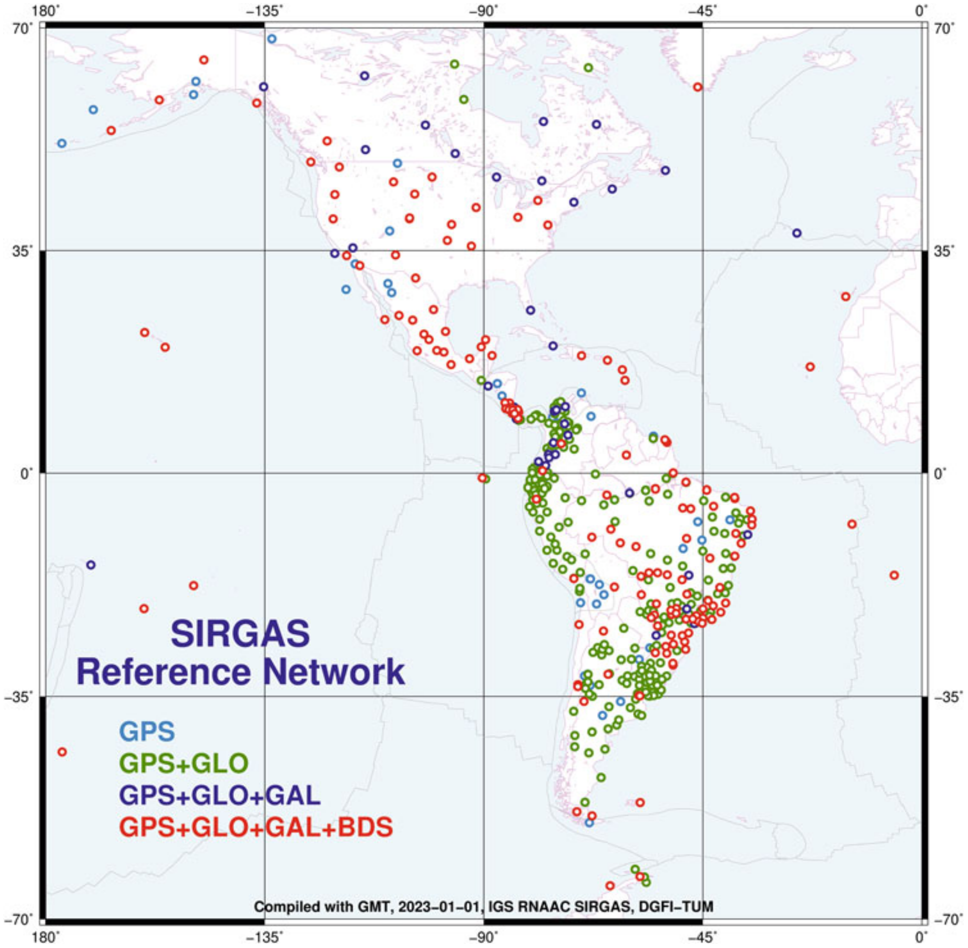

Table 1 Active and former SIRGAS analysis centres (as of Sep 2022). CIMA acts as the SIRGAS analysis centre for the neutral atmosphere since Nov. 2019. DGFI-TUM acts as the IGS regional network associate analysis centre for SIRGAS (IGS RNAAC SIR) since June 1996

Analysis centre	Country	Agency	Software	Coordinate solutions		Tropospheric estimates	
				Since	To	Since	To
DGF	Germany	Deutsches Geodätisches Forschungsinstitut, Technischen Universität München (DGFI-TUM)	BSW52[a]	1996-06-30	Present	2014-04-27	Present
ECU	Ecuador	Instituto Geográfico Militar (IGM-Ec)	BSW52	2010-01-01	Present	2014-12-21	Present
IBG	Brazil	Instituto Brasileiro de Geografia e Estatistica (IBGE)	BSW52	2008-08-31	Present	2014-04-27	Present
IGA	Colombia	Instituto Geográfico Agustín Codazzi (IGAC)	BSW52	2008-08-31	Present	2014-12-21	Present
CHL	Chile	Instituto Geográfico Militar (IGM-Cl)	BSW52	2013-01-01	Present	2014-04-27	Present
URY	Uruguay	Instituto Geográfico Militar (IGM-Uy)	BSW52	2010-01-01	Present	2014-04-27	Present
USC	Chile	Universidad de Santiago de Chile (USACH)	BSW52	2019-01-01	Present	2019-05-01	Present
GNA	Argentina	Instituto Geográfico Nacional (IGN-Ar)	GG[b]	2011-01-01	Present	2022-01-01	Present
INE	Mexico	Instituto Nacional de Estadística y Geografía (INEGI)	GG	2011-01-01	Present	–	
PER	Peru	Instituto Geográfico Nacional (IGN-Pe)	GG	2022-01-01	Present	–	
CIM	Argentina	Centro de Ingeniería Mendoza, Argentina (CIMA)	BSW52	2008-08-31	2021-12-31		
LUZ	Venezuela	Universidad de Zulia	BSW52	2010-01-01	2019-02-09	2014-12-14	2019-02-09
UNA	Costa Rica	Universidad Nacional de Costa Rica	BSW52	2014-01-01	2018-12-31	2014-01-01	2018-12-31

[a] BSW52: Bernese GNSS Software, version 5.2 (Dach et al. 2015)

[b] GG: GAMIT/GLOBK: GNSS at MIT/Global Kalman filter (Herring et al. 2015, 2018)

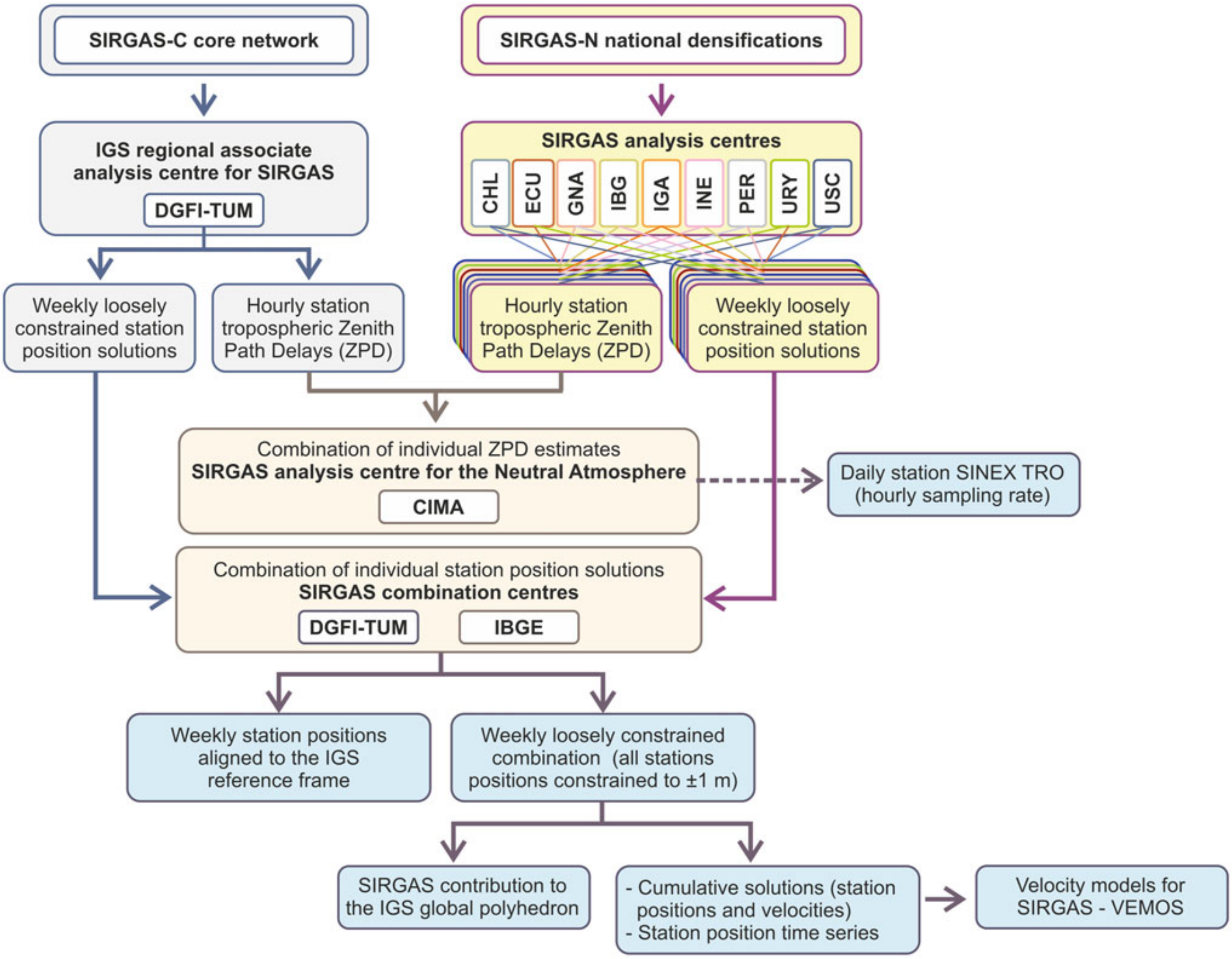

Fig. 4 Data flow in the analysis of the SIRGAS reference frame (adapted from Sánchez et al. 2022). Please see Table 1 for the SIRGAS-AC acronyms

4.1 Operational and Reprocessed SIRGAS Weekly Station Positions

In the weekly analysis of the SIRGAS reference frame, the IGS final satellite orbits, satellite clocks, and Earth orientation parameters (Johnston et al. 2017) are included as known parameters (see Tarrío et al. 2021). Thus, the SIRGAS weekly solutions are based on the models and standards valid at the time of computation and refer to the IGS reference frame in use during that specific time. Updated models, better processing standards or improved IGS reference frame solutions are directly reflected in the quality of the SIRGAS coordinates. As an example, Table 2 summarises the weekly station position repeatability and the consistency with the IGS weekly solutions of the SIRGAS positions referring to different IGS reference frames.

To ensure the long-term reliability of the SIRGAS reference frame, the complete GNSS data series are homogeneously reprocessed to refer all weekly normal equations to a unified set of standards and to the same reference frame. The first SIRGAS reprocessing, Repro1, comprised GNSS data from 2000-01-02 to 2008-08-30 and its main goals were to consider absolute corrections for the phase centre variations of the GNSS antennae and to refer positions and velocities to the IGS05 reference frame (see Sánchez and Seitz 2011).

The DGFI-TUM recently reprocessed all the GNSS data from de SIRGAS Reference Network and a set of globally distributed IGS stations, covering the time span between January 2000 and December 2021 (see Sánchez et al. 2022). This Repro2 refers to the IGS14/IGb14 reference frame (Rebischung and Schmid 2016; Griffiths 2019). In total, 537 SIRGAS and 128 IGS stations (with 88 in the IGS14/IGb14 reference frame) were reanalysed (Fig. 5). The normal equations obtained in Repro2 were the input for the computation of a new DGFI-TUM reference frame solution called

Table 2 Mean RMS values of the weekly SIRGAS station position repeatability and after comparing the SIRGAS station positions with the weekly coordinates of the IGS stations. The last row presents the values obtained from Repro2 (more details in Sánchez et al. 2022)

IGS reference frame	From	To	Weekly station position repeatability [mm]		Compatibility of weekly SIRGAS reference frame solutions with the IGS reference frame [mm]	
			N/E	Up	N/E	Up
IGS05	2000-01-02	2011-04-16	2.3	4.5	2.8	6.0
IGS08/IGb08	2011-04-17	2017-01-28	1.8	3.2	1.8	3.5
IGS14/IGb14	2020-05-17	2022-11-26	1.0	3.2	0.8	2.6
IGS14/IGb14	2000-01-02	2022-11-26	1.0	3.0	0.8	2.6

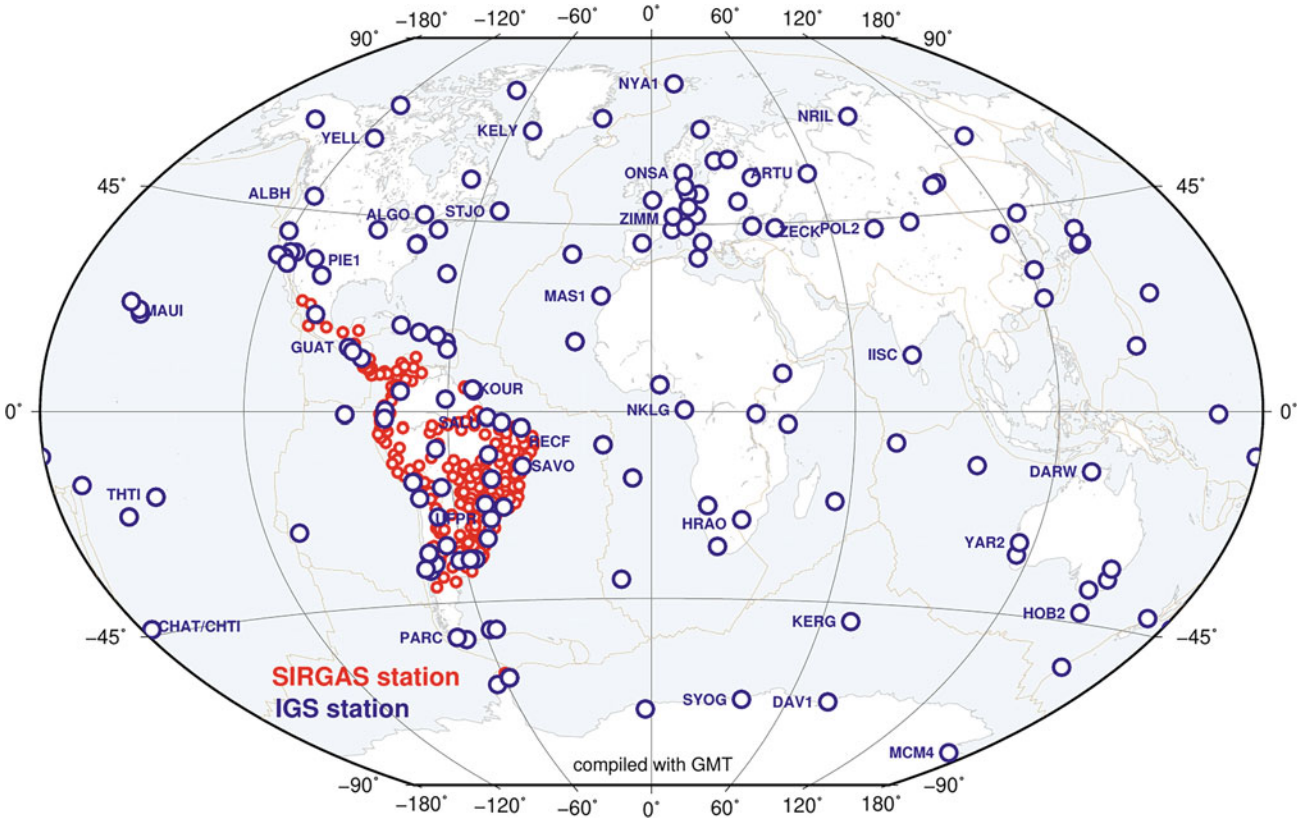

Fig. 5 GNSS network included in the latest SIRGAS data reprocessing. Labels identify the reference stations utilised for the geodetic datum realisation (adapted from Sánchez et al. 2022)

SIRGAS2022 (see Sect. 4.3). The Repro2 normal equations are available for combination with solutions from other SIRGAS-ACs to realize a SIRGAS-wide reference frame.

4.2 Combined Tropospheric Zenith Path Delays

The ZPDs estimated by the SIRGAS-ACs (see Table 1) are combined to generate the ZPD_{SIR} values in hourly sampling rates. This combination is performed on a weekly basis by CIMA, since Nov. 2019 (Mackern et al. 2020). The methodology is described in Mackern et al. (2022). Three or more individual solutions are needed to obtain statistical controls over the combined values of ZPD_{SIR}. Figure 6 shows significant progress towards this goal, mainly since 2019.

The ZPD_{SIR} precision was calculated using the mean annual Standard Deviation (SD) for each station. Table 3 summarises the results of the last precision analysis carried out for 2021.

The final ZPD_{SIR} have been validated (Mackern et al. 2020) with respect to final IGS' ZTD products (at 15 IGS stations) and with respect to computed ZTD at radiosonde stations (10 sites). This study shows that the ZPD_{SIR} agree with the corresponding values obtained by the IGS (mean RMSE 6.8 mm; mean bias −1.5 mm) as well as those from radiosondes (mean RMSE 7.5 mm; mean bias −2 mm).

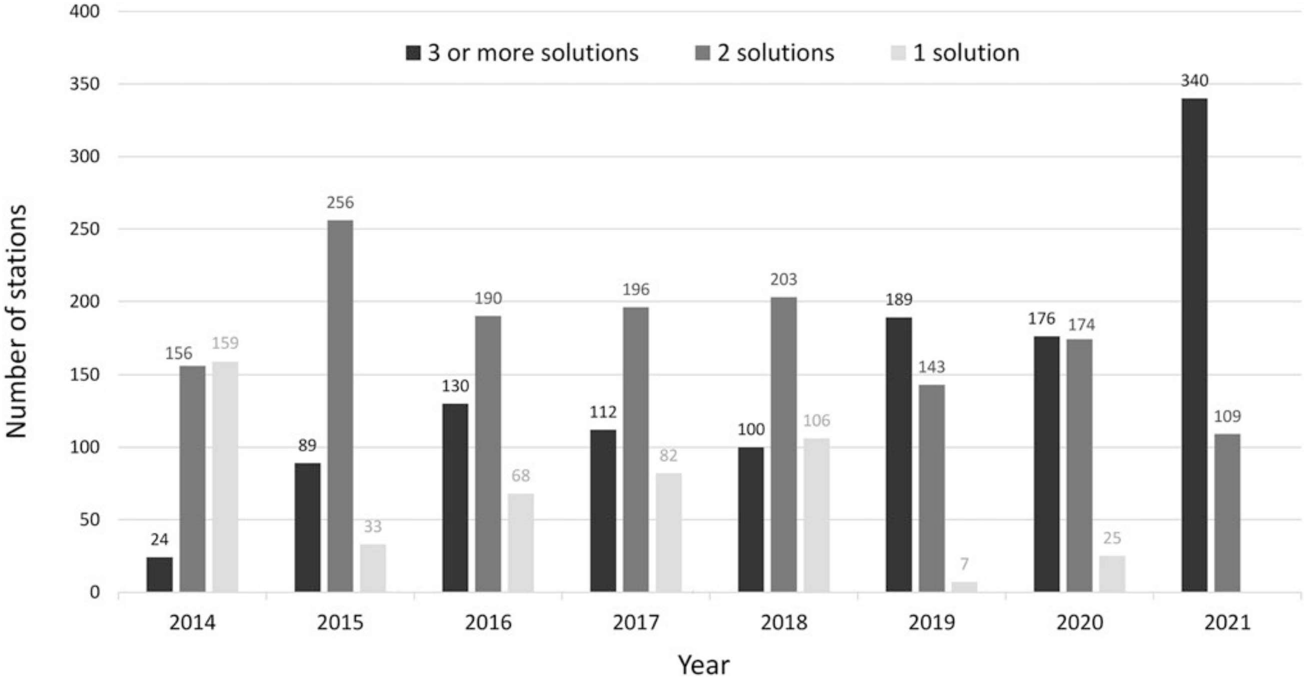

Fig. 6 Number of stations with 1, 2, 3 or more individual ZPD solutions before combination

Table 3 Precision ZPD analysis carried out for 2021 (Mackern et al. 2022)

	Mean RMS < 1 mm	1.1 mm < Mean RMS <3 mm	3.1 mm < Mean RMS <6 mm
Number of stations	309	113	150
Percent of stations	54	20	26

4.3 SIRGAS2022: The Latest DGFI-TUM Reference Frame Solution for SIRGAS

Due to the occurrence of seismic events in the SIRGAS region, the SIRGAS reference frame cumulative solutions require frequent updates (e.g., Seemüller et al. 2011; Sánchez and Seitz 2011; Sánchez and Drewes 2016, 2020). The latest DGFI-TUM reference frame cumulative solution, called SIRGAS2022, is based on the Repro2 normal equation series up to December 2021. The normal equations from January 2022 to April 2022 were obtained from the weekly combination of individual solutions from the SIRGAS-ACs and are all based on the weekly IGS14/IGb14 normal equations (Fig. 7). A description of the processing and analysis methodology can be found in Sánchez et al. (2022).

SIRGAS2022 (Fig. 8) contains 587 stations with 1,389 occupations. The station positions refer to the IGb14 and are given at the epoch 2,015.0. Their accuracy is estimated to be ±0.8 mm in N/E and ± 1.4 mm in U at the reference epoch. The accuracy of the velocities is assessed to ±0.6 mm/year in N/E and ± 1.0 mm/year in U.

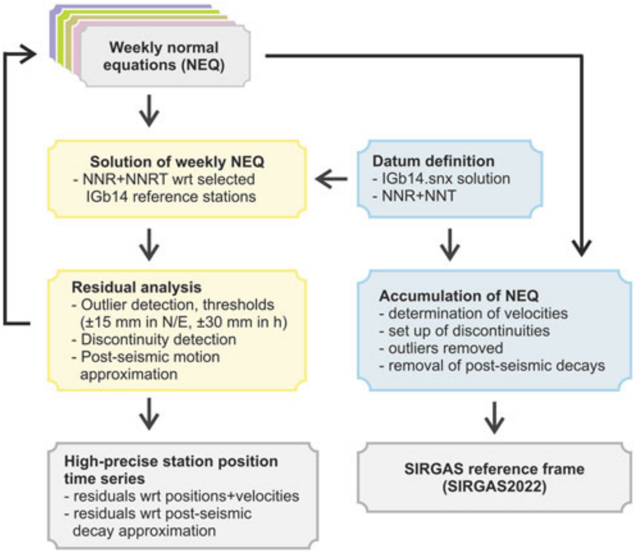

Fig. 7 Analysis steps in the determination of SIRGAS2022 (adapted from Sánchez et al. 2022)

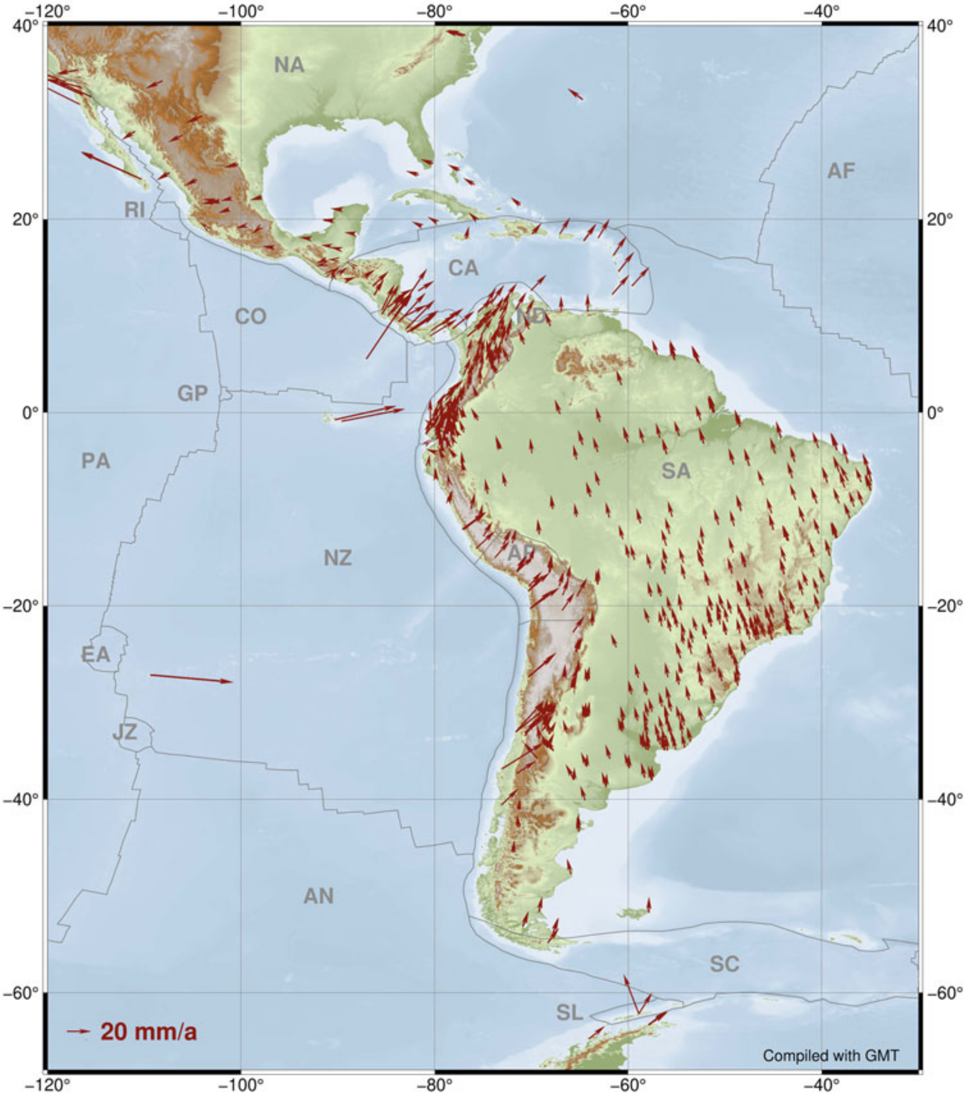

Fig. 8 SIRGAS2022 horizontal velocities

4.4 VEMOS: Overall Velocity Models for the Entire SIRGAS Region

The constant velocities determined in the computation of the SIRGAS reference frame cumulative solutions are the input for the prediction of velocity grids over the entire SIRGAS region (Fig. 9). They are needed to interpolate station motions in regions where no SIRGAS stations are in operation and serve as the basis for the analysis of regional surface deformations. The VEMOS models represent mean yearly horizontal surface displacements for a period of data used for the model (Table 4). A new updated version of VEMOS, including the latest processing results, is in preparation.

5 Final Remarks

SIRGAS is a well-established comprehensive regional geodetic reference frame and widely used in practical and scientific applications. The routine analysis of the SIRGAS reference frame is in accordance with the new models, standards, and procedures defined by the IERS and the IGS. The accuracy of the weekly SIRGAS station positions is 1.0 mm in N/E and about 3.0 mm in the vertical component. The accuracy of the latest DGFI-TUM reference frame solution SIRGAS2022 is estimated to be ±0.8 mm in N/E and ± 1.4 mm in U for the station positions at the reference epoch and ± 0.6 mm/year in N/E and ± 1.0 mm/year in

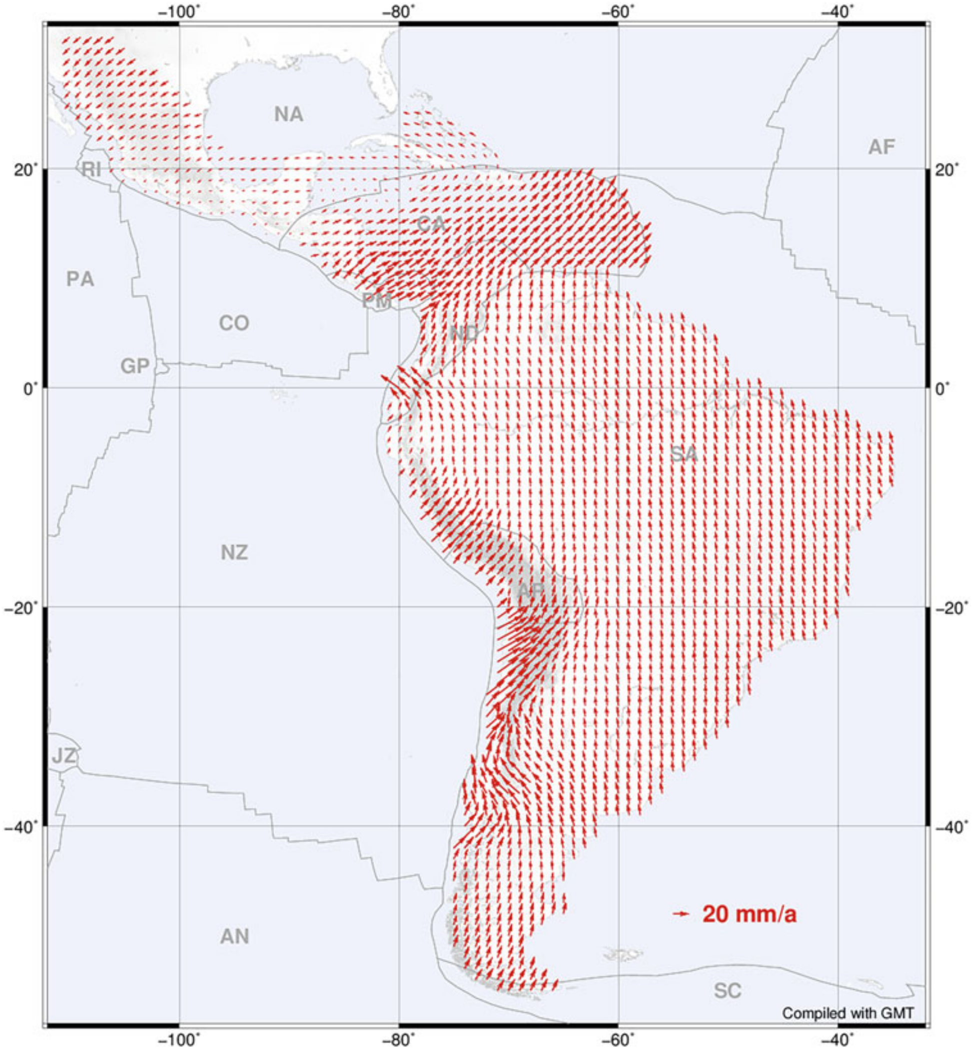

Fig. 9 VEMOS2017 (adapted from Drewes and Sánchez 2020)

Table 4 SIRGAS velocity models (more details in https://sirgas.ipgh.org/en/products/vemos/)

VEMOS	Reference frame	Observation period included		Reference
		From	To	
VEMOS2003	ITRF2000	May 1995	April 2001	Drewes and Heidbach (2005)
VEMOS2009	ITRF2005	January 2000	June 2009	Drewes and Heidbach (2012)
VEMOS2015	IGb08	March 2010	April 2015	Sánchez and Drewes (2016)
VEMOS2017	IGS14	January 2014	January 2017	Drewes and Sánchez (2020)

U for the velocities. Main challenges in the determination of the reference frame are the modelling of seismic and post-seismic effects and strong seasonal signals observed in the Amazon basin. A strategic priority of SIRGAS is the advancement in the establishment of a physical reference frame to support gravimetry, physical heights and geoid determination with an accuracy similar to that of the geometric reference frame. This is yet a difficult challenge to overcome. Current SIRGAS efforts are aimed at collecting the necessary data and linking the different national agencies through training and knowledge transfer. The joint work between SIRGAS and UN-GGIM: Americas highlights the importance of geodetic reference frames as a strategic tool for sustainable development. Yet, governmental support is needed to obtain human, technical, and financial resources to continue the development of SIRGAS. This governmental support can only be achieved by each of the members of SIRGAS, and we strive to provide the mechanisms to support raising the necessary awareness.

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Data Availability All SIRGAS products are freely available at https://sirgas.ipgh.org. and ftp.sirgas.org.

References

Antokoletz ED, Wziontek H, Tocho CN et al (2020) Gravity reference at the Argentinean–German Geodetic Observatory (AGGO) by co-location of superconducting and absolute gravity measurements. J Geod 94:81. https://doi.org/10.1007/s00190-020-01402-7

Blitzkow D, Oliveira Cancoro de Matos AC, Moraes Bjorkstrom I et al (2018) Absolute gravity network in South America-Comparisons. EGU General Assembly Conference Abstracts (p. 7815). https://ui.adsabs.harvard.edu/abs/2018EGUGA..20.7815B

Brunini C, Sánchez L, Drewes H, Costa SMA, Mackern V, Martinez W, Seemüller W, Da Silva AL (2012) Improved analysis strategy and accessibility of the SIRGAS Reference Frame, International Association of Geodesy Symposia Series, vol 136. Springer, Heidelberg, pp 3–10. https://doi.org/10.1007/978-3-642-20338-1_1

Dach R, Lutz S, Walser P, Fridez P (2015) Bernese GNSS Software Version 5.2. Astronomical Institute, University of Bern. https://boris.unibe.ch/72297/

de Matos ACOC, Blitzkow D, Guimarães GN, Silva VC (2021a) The South American gravimetric quasi-geoid: QGEOID2021. V. 1.0. GFZ Data Services. https://doi.org/10.5880/isg.2021.005

de Matos ACOC, Blitzkow D, Guimarães GN, Silva VC (2021b) The South American gravimetric GEOID: GEOID2021. V. 1.0. GFZ Data Services. https://doi.org/10.5880/isg.2021.006

Drewes H, Sánchez L (2020) Velocity model for SIRGAS 2017: VEMOS2017. Deutsches Geodätisches Forschungsinstitut der Technischen Universität München, PANGAEA. https://doi.org/10.1594/PANGAEA.912350

Drewes H (2022) Historical development of SIRGAS. J Geodetic Sci 12(1):120–130. https://doi.org/10.1515/jogs-2022-0137

Drewes H, Heidbach O (2005) Deformation of the South American crust estimated from finite element and collocation methods, International Association of Geodesy Symposia Series, vol 128. Springer, Heidelberg, pp 544–549. https://doi.org/10.1007/3-540-27432-4_6

Drewes H, Heidbach O (2012) The 2009 horizontal velocity field for South America and the Caribbean, International Association of Geodesy Symposia Series, vol 136. Springer, Heidelberg, pp 657–664. https://doi.org/10.1007/978-3-642-20338-1_81

Drewes H, Kaniuth K, Voelksen C, Alves Costa SM, Souto Fortes LP (2005) Results of the SIRGAS campaign 2000 and coordinates variations with respect to the 1995 South American geocentric reference frame, International Association of Geodesy Symposia Series, vol 128. Springer, Heidelberg, pp 32–37. https://doi.org/10.1007/3-540-27432-4_6

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

Griffiths J (2019) Combined orbits and clocks from IGS second reprocessing. J Geod 93:177–195. https://doi.org/10.1007/s00190-018-1149-8

Guimarães GN, Blitzkow D, Silva VC, Matos ACOC, Inoue MEB, Oliveira SL (2022a) New gravimetric infrastructure in Southeast Brazil: from absolute gravity network to a geoid model. J Surv Eng 148:3. https://doi.org/10.1061/(ASCE)SU.1943-5428.0000393

Guimarães GN, Blitzkow D, Matos ACOC, Silva VC, Inoue MEB (2022b) The establishment of the IHRF in Brazil: current situation and future perspectives. Rev Bras Cartogr 74(3):651–670. https://doi.org/10.14393/rbcv74n3-64949

Herring TA, King RW, Floyd MA, McClusky SC (2015) GLOBK: global Kalman filter VLBI and GPS analysis program, Reference Manual, Release 10.6, http://geoweb.mit.edu/gg/docs/GLOBK_Ref.pdf

Herring TA, King RW, Floyd MA, McClusky SC (2018) GAMIT: GPS Analysis at MIT, Reference Manual, Release 10.7. http://geoweb.mit.edu/gg/docs/GAMIT_Ref.pdf

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

Johnston G, Riddell A, Hausler G (2017) The international GNSS service. Springer handbook of global navigation satellite systems, pp 967–982. https://doi.org/10.1007/978-3-319-42928-1

Mackern MV, Mateo ML, Camisay MF, Morichetti PV (2020) Tropospheric products from high-level GNSS processing in Latin America. In: Freymueller JT, Sánchez L (eds) Beyond 100: the next century in geodesy, International Association of Geodesy Symposia, vol 152. Springer, Cham. https://doi.org/10.1007/1345_2020_121

Mackern MV, Mateo ML, Camisay MF, Rosell PA (2022) Quality control of SIRGAS ZTD products. J Geodetic Sci 12(1):42–54. https://doi.org/10.1515/jogs-2022-0136

Petit G, Luzum B (2010) IERS conventions (IERS technical note; no. 36). IERS conv. Cent. 179

Rebischung P, Schmid R (2016) IGS14/igs14.atx: a new framework for the IGS products. Fall Meeting of the American Geophysical Union, San Francisco, USA, December 2016. https://mediatum.ub.tum.de/doc/1341338/file.pdf

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

Sánchez L, Drewes H (2016) Crustal deformation and surface kinematics after the 2010 earthquakes in Latin America. J Geodyn. https://doi.org/10.1016/j.jog.2016.06.005

Sánchez L, Drewes H (2020) Geodetic monitoring of the variable surface deformation in Latin America, International Association of Geodesy Symposia Series, vol 152. Springer, Heidelberg. https://doi.org/10.1007/1345_2020_91

Sánchez L, Seitz M (2011) Station positions and velocities of the SIR11P01 multi-year solution, epoch 2005.0. Deutsches Geodätisches Forschungsinstitut der Technischen Universität München, PANGAEA. https://doi.org/10.1594/PANGAEA.835098 [In supplement to: Sánchez L; Seitz M (2011): Recent activities of the IGS Regional Network Associate Analysis Centre for SIRGAS (IGS RNAAC SIR) - Report for the SIRGAS 2011 General Meeting August 8–10, 2011. Heredia, Costa Rica. DGFI Report, 87, 48 pp. hdl:10013/epic.43995.d001]

Sánchez L, Ågren J, Huang J, Wang YM, Mäkinen J, Pail R, Barzaghi R, Vergos GS, Ahlgren K, Liu Q (2021) Strategy for the realisation of the International Height Reference System (IHRS). J Geod 95:33. https://doi.org/10.1007/s00190-021-01481-0

Sánchez L, Drewes H, Kehm A, Seitz M (2022) SIRGAS reference frame analysis at DGFI-TUM. J Geodetic Sci 12(1):92–119. https://doi.org/10.1515/jogs-2022-0138

Seemüller W, Sánchez L, Seitz M (2011) The new multi-year position and velocity solution SIR09P01 of the IGS Regional Network Associate Analysis Centre (IGS RNAAC SIR), International Association of Geodesy Symposia Series, vol 136. Springer, pp 675–680. https://doi.org/10.1007/978-3-642-20338-1_110

Silva VC, Blitzkow D, Almeida FGV, Matos ACOC, Guimarães GN (2022) Computation and analysis of geopotential number in São Paulo, Brazil. Earth Sci Res J 26(2):107–118. https://doi.org/10.15446/esrj.v26n2.100645

SIRGAS Project Committee (1997) SIRGAS final report; working groups I and II IBGE, Rio de Janeiro, 96 p

Tarrío JA, Costa S, da Silva A, Inzunza J (2021) Processing guidelines for the SIRGAS analysis centres, SIRGAS Working Group I. https://doi.org/10.35588/dig.g3.2021

Tocho CN, Antokoletz ED, Piñón DA (2020) Towards the realization of the International Height Reference Frame (IHRF) in Argentina. In: Freymueller JT, Sánchez L (eds) Beyond 100: the next century in geodesy, International Association of Geodesy Symposia, vol 152. Springer. https://doi.org/10.1007/1345_2020_93

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