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Research Article

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SIRGAS reference frame analysis at DGFI–TUM

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Abstract: The Deutsches Geodätisches Forschungsinstitut (DGFI) has been involved in the research activities of the Latin American Reference Frame SIRGAS since its establishment in 1993. DGFI coordinated the SIRGAS Global Positioning System campaigns of 1995 and 2000 and acted as an analysis centre of both campaigns contributing to the first two SIRGAS realisations known as SIRGAS95 and SIRGAS2000. In 1996, DGFI established the Regional Network Associate Analysis Centre for SIRGAS of the International GNSS (Global Navigation Satellite System) Service (IGS RNAAC SIRGAS) and took on responsibility for processing the SIRGAS continuously operating stations and generating weekly position solutions. Later followed the determination of cumulative (multi-year) solutions, consisting of station positions and constant velocities, providing accurate solutions for the SIRGAS reference frame. DGFI was integrated into the Technical University of Munich (TUM) in 2015, becoming DGFI–TUM, and based on the SIRGAS operational analyses, it continues investigating strategies to guarantee the reliability of the reference frame through time. This includes the estimation of the reference frame kinematics, evaluation, modelling, and reduction of seismic and post-seismic deformations on the reference frame, and modelling crustal kinematics in the SIRGAS region by continuous velocity models. This article summarises analysis strategies and science data products developed by DGFI–TUM as a SIRGAS analysis centre and as the IGS RNAAC SIRGAS. Special care is given to the determination of the most recent SIRGAS reference frame solution called SIRGAS2022, which is based on the second SIRGAS reprocessing campaign performed by DGFI–TUM to obtain homogeneously computed SIRGAS daily and weekly station position solutions referring to the IGS reference frame IGS14/IGb14 since January 2000.

Keywords: SIRGAS, SIRGAS second reprocessing campaign, SIRGAS2022, IGS RNAAC SIRGAS, SIRGAS GNSS historical data, SIRGAS reference frame, VEMOS

1 Introduction

In 1993, the Deutsches Geodätisches Forschungsinstitut (DGFI) initiated the establishment of a geocentric reference frame for South America that supports the determination of coordinates using the Global Positioning System (GPS); see Drewes (1995), Fortes et al. (1995). A new reference frame was needed as the existing South American geodetic datums were not geocentric, valid in certain regions only (every country used a different geodetic datum), and their realisations presented uncertainties of magnitudes larger than the accuracy provided by GPS (Caddess et al. 1993). Thus, they were not appropriate to provide the reference for GPS positioning and navigation. DGFI's initiative was supported by the International Association of Geodesy (IAG), the Pan-American Institute for Geography and History (PAIGH), and the US National Geospatial-Intelligence Agency (NGA), known as NIMA (National Imagery and Mapping Agency) at that time. The implementation of a geocentric reference frame in South America required the previous definition of constants, conventions, models, and parameters through a geocentric reference system. It was decided to fully adopt the International Terrestrial Reference System (ITRS; Petit and Luzum 2010). Accordingly, the realisation of the ITRS in South America was defined as a regional densification of the International Terrestrial Reference Frame (ITRF; Petit and Luzum 2010); see Hoyer et al. (1998). This new assemblage of reference (definition and realisation) was named SIRGAS (Sistema de Referencia Geocéntrico para América del Sur; Geocentric Reference System for South America); see, e.g., SIRGAS Project Committee (1997), Drewes et al. (1997). The meaning of this acronym changed in 2001 to Geocentric Reference System for the Americas following the recommendation of the 7th United Nations

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Cartographic Conference for the Americas (New York, January 22–27, 2001) to adopt SIRGAS as the conventional reference system in all American countries. In 2020, the meaning of the acronym SIRGAS changed once more to Geodetic Reference System for the Americas, because the objectives of SIRGAS were extended to the determination of a unified physical reference system for gravimetry, physical heights, and the geoid (see SIRGAS Statute adopted in November 2020; https://sirgas.ipgh.org/docs/SIRGAS_Statutes_%202020.pdf).

DGFI was established in 1952 as an independent research institute at the Bavarian Academy of Sciences and Humanities in Munich, Germany. In 2015, DGFI was integrated into the Technical University of Munich (TUM) and became DGFI–TUM. From now on, we refer to as DGFI–TUM, although the name of the Institute used to be DGFI until December 2014. DGFI–TUM has been involved in the SIRGAS research activities since the establishment of SIRGAS in 1993. DGFI–TUM played a central role in outlining the conventions adopted for the definition and realisation of SIRGAS (Fortes et al. 1995). Afterwards, DGFI–TUM coordinated the SIRGAS GPS campaigns of 1995 and 2000 and acted as an analysis centre of both campaigns contributing to the final solutions known as SIRGAS95 (Drewes et al. 1997, SIRGAS Project Committee 1997, Kaniuth et al. 1998) and SIRGAS2000 (Drewes et al. 2000, 2005, Kaniuth et al. 2002). In June 1996, DGFI–TUM established the Regional Network Associate Analysis Centre for SIRGAS of the International GNSS (Global Navigation Satellite System) Service (IGS RNAAC SIRGAS; Seemüller and Drewes 1998) and took on responsibility for processing the SIRGAS continuously operating stations to generate weekly position solutions and cumulative (multi-year) solutions for the determination of the SIRGAS reference frame. DGFI–TUM also supported the computation of national densifications of SIRGAS in Argentina (Moirano et al. 1998), Venezuela (Drewes et al. 1998), Colombia (Tremel et al. 2001), Chile (Baez et al. 2007), El Salvador (Figueroa et al. 2010), and Bolivia (Echalar and Sánchez 2010).

In the 2000s, most of the Latin American countries initiated the modernisation of their national reference frames by installing a rapidly increasing number of continuously operating GPS stations, and some of them were also capable of tracking GLONASS, and more recently Galileo and Beidou, i.e., common GNSS stations. To ensure an appropriate and long-term integration of these national reference frames into SIRGAS, two main measures were introduced (Sánchez and Brunini 2009; Brunini et al. 2012):

a) The SIRGAS reference stations were classified into a SIRGAS core network (SIRGAS-C) with homogenous continental coverage and SIRGAS national densification networks (SIRGAS-N); see Figure 1.
b) The installation of SIRGAS analysis centres under the responsibility of Latin American agencies, being a main goal to have at least one SIRGAS analysis centre per country.

In this context, since 2008, DGFI–TUM routinely processes the SIRGAS-C core network and combines this network with the weekly position solutions delivered by the Latin American analysis centres for the SIRGAS-N national densifications (Sánchez and Seitz 2011a). DGFI–TUM's weekly combinations are delivered to the IGS for the determination of the IGS global polyhedron and are the input data for the computation of cumulative solutions of the SIRGAS reference frame (see Figure 2). Based on these operational product series, DGFI–TUM investigates strategies to guarantee the reliability of the reference frame through time. This includes the estimation of the reference frame kinematics, evaluation, modelling and reduction of seismic and post-seismic deformations on the reference frame, and modelling surface kinematics in the SIRGAS region by continuous velocity models (VEMOS [Velocity Model for SIRGAS]); see, e.g., Drewes and Heidbach (2005, 2012), Sánchez and Drewes (2016a, 2020a); Sánchez et al. (2013, 2016).

This article describes analysis strategies and science data products developed by DGFI–TUM as a SIRGAS Processing and Combination Centre and as the IGS RNAAC SIRGAS. After a short description of the SIRGAS reference frame, Section 2 presents DGFI–TUM's processing and combination strategies applied for the weekly analysis of the reference frame in operational modus. Section 3 is devoted to the second SIRGAS reprocessing campaign (hereinafter referred to as SIRGAS-Repro2) performed by DGFI–TUM to obtain homogeneously computed SIRGAS daily and weekly solutions referring to the IGS reference frame IGS14/IGb14 (Rebischung 2016, 2020) since January 2000. Section 4 details the determination of the most recent SIRGAS reference frame solution, SIRGAS2022, which is based on the SIRGAS-Repro2 SINEX product series. Section 5 concludes the article by giving insights into current research and some outlook.

2 Operational computation of the SIRGAS reference frame

The SIRGAS reference frame (Figure 1) is currently consisting of 480 operational continuously operating GNSS stations (other 160 stations are decommissioned); 104 operational (and 34 decommissioned) stations belong to

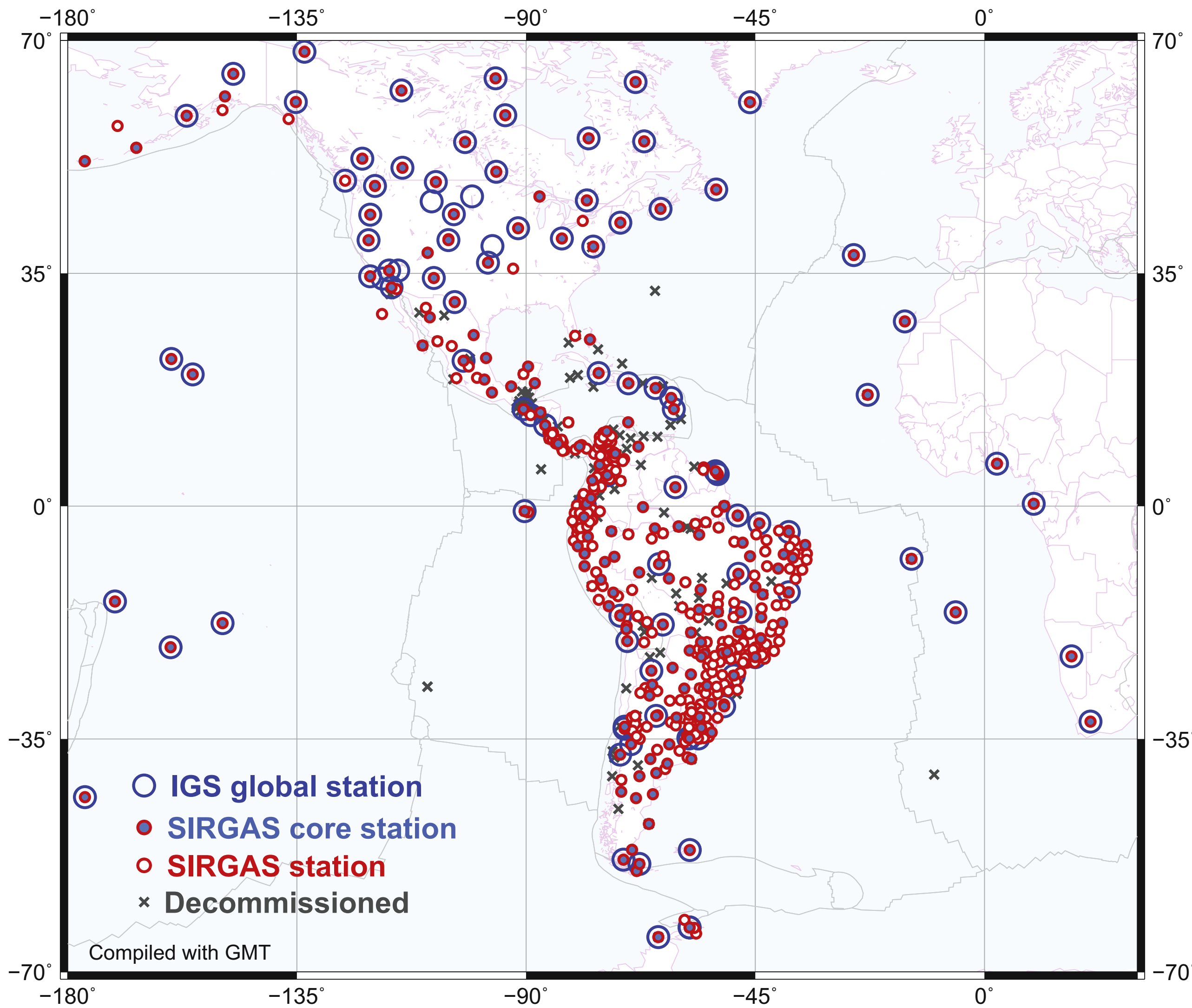

Figure 1: SIRGAS reference network (as of April 2022).

the IGS global network; and 376 operational (and 130 decommissioned) stations belong to the Latin American national reference frames. About 40 of the 105 operational IGS stations are located in North America and were added to the routine SIRGAS processing in 2021 to provide support (i.e., common stations) for a future combination of the North American national reference frames with SIRGAS. Eighty-six percent of the SIRGAS stations are tracking GLONASS, 31% Galileo, and 20% Beidou.

2.1 GNSS data analysis for SIRGAS at DGFI–TUM

Ten SIRGAS analysis centres (Table 1) process GPS and GLONASS observations to generate daily and weekly position solutions for a certain set of SIRGAS stations. Three analysis centres use GAMIT/GLOBK (Herring et al. 2015, 2018); the other centres employ the Bernese GNSS Software, version 5.2 (Dach et al. 2015). The distribution of the stations among the analysis centres ensures that each station is included in three individual solutions. The SIRGAS analysis centres follow unified standards for the computation of weekly loosely constrained solutions. These standards are based on the conventions outlined by the IERS (International Earth Rotation and Reference Systems Service; Petit and Luzum, 2010) and the GNSS-specific guidelines defined by the IGS (Johnston et al. 2017). An exception is that in the SIRGAS individual solutions, the satellite orbits and clocks as well as the Earth orientation parameters (EOPs) are fixed to the final weekly IGS values (SIRGAS does not compute these parameters),

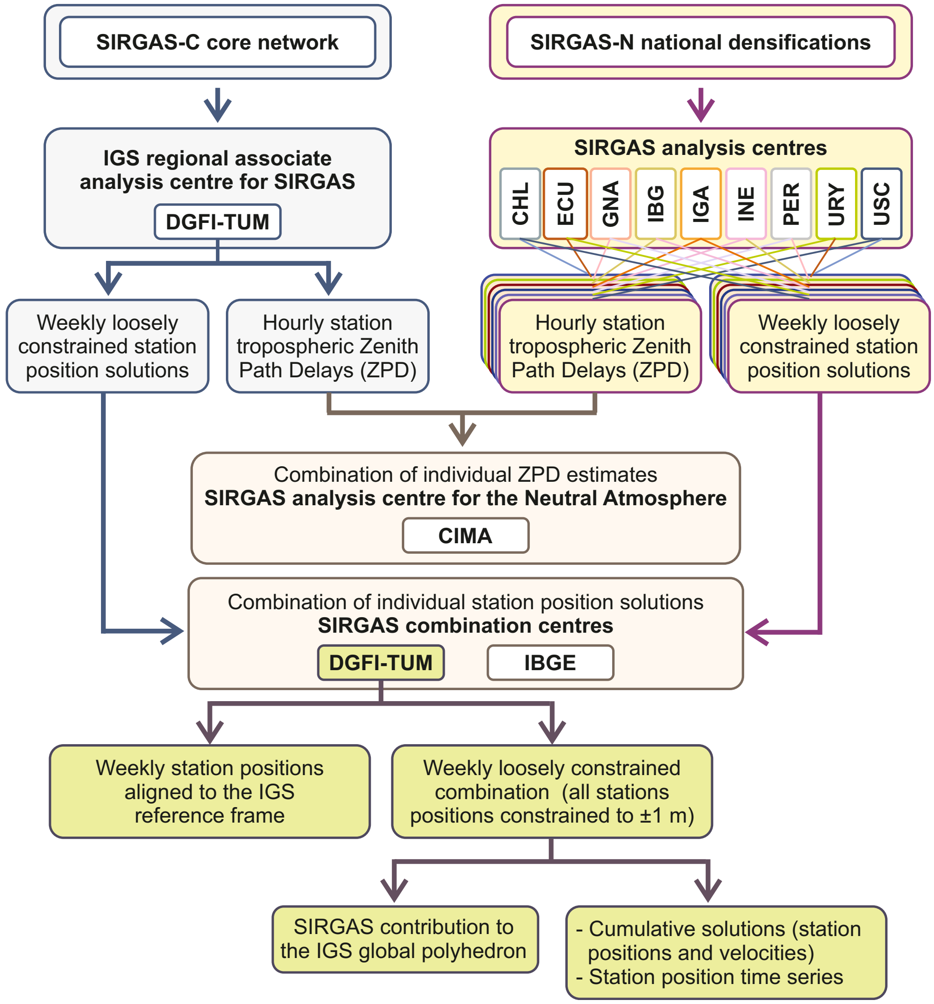

Figure 2: Data flow within the weekly analysis of the SIRGAS reference frame (see Table 1 for more details about the SIRGAS analysis centres).

and positions for all stations are constrained to ±1 m to generate loosely constrained solutions in the SINEX format. Table 2 summarises the procedure presently applied by DGFI–TUM in the weekly analysis of the SIRGAS-C network. As mentioned earlier, the other SIRGAS analysis centres apply similar procedures, although slight differences may occur, in particular in the phase ambiguity resolution (more details are presented in the guidelines compiled by Tarrío et al. 2021). The individual solutions are combined weekly to generate a unified position solution for the entire SIRGAS reference frame (see Section 2.2). In addition to the loosely constrained position solutions, the SIRGAS processing centres also deliver station tropospheric Zenith Path Delays (ZPD) with an hourly sampling rate. The SIRGAS analysis centre for the Neutral Atmosphere (CIMA) combines the individual ZPD estimates to generate consistent troposphere solutions over the entire SIRGAS region and to provide reliable time series of troposphere parameters, see Mackern et al. (2020).

2.2 Combination of the SIRGAS individual weekly solutions

Currently, there are two SIRGAS combination centres, one hosted by DGFI–TUM (Sánchez and Seitz 2011a, Sánchez et al. 2012) and the other one hosted by IBGE (Costa et al. 2012b), who also acts as a SIRGAS processing centre (see Table 1). The combination strategy of DGFI–TUM is based on three main characteristics (Sánchez and Seitz 2011a, Sánchez et al. 2012):

a) The input data for the combination are the constraint-free normal equations (including the complete

Table 1: SIRGAS analysis centres

ID	Agency/University	Software	Operative	
			From	To
DGF	DGFI–TUM: Deutsches Geodätisches Forschungsinstitut at the Technical University of Munich, Germany (Sánchez and Seitz 2011a, Sánchez et al. 2012)	BSW52[2]	1996-06-30	Present
CHL	IGM-CL: Instituto Geográfico Militar, Chile (Rozas et al. 2019)	BSW52	2013-01-01	Present
CIM	CIMA: Centro de Ingeniería in Mendoza, Argentina[1] (Mackern et al. 2012)	BSW52	2008-08-31	2012-12-31
ECU	IGM-EC: Instituto Geográfico Militar, Ecuador (Cisneros et al. 2013)	BSW52	2010-01-01	Present
GNA	IGN-AR: Instituto Geográfico Nacional, Argentina (Gómez et al. 2018)	GG[3]	2011-01-01	Present
IBG	IBGE: Instituto Brasileiro de Geografia e Estatistica, Brazil (Costa et al. 2012a)	BSW52	2008-08-31	Present
IGA	IGAC: Instituto Geográfico Agustín Codazzi, Colombia (IGAC 2021)	BSW52	2008-08-31	Present
INE	INEGI: Instituto Nacional de Estadística y Geografía, Mexico (Gasca 2018)	GG	2011-01-01	Present
LUZ	CPAGS-LUZ: Centro de Procesamiento y Análisis GNSS de la Universidad del Zulia, Venezuela (Cioce et al. 2017)	BSW52	2010-01-01	2019-02-09
PER	IGN-PE: Instituto Geográfico Nacional, Peru (Rodríguez Rocca 2021)	GG	2022-01-01	Present
UNA	CNPDG-UNA: Centro Nacional de Procesamiento de Datos GNSS, Universidad Nacional, Costa Rica (Moya Zamora et al. 2018)	BSW52	2014-01-01	2018-12-31
URY	IGM-UY: Instituto Geográfico Militar, Uruguay (Caubarrère 2018)	BSW52	2010-01-01	Present
USC	USCH: Centro de Procesamiento y Análisis Geodésico, Universidad de Santiago de Chile (Tarrío et al. 2020)	BSW52	2019-09-15	Present

[1]CIMA acts as the SIRGAS analysis centre for the Neutral Atmosphere since Nov. 2019 (Mackern et al. 2020).
[2]BSW52: Bernese GNSS Software, version 5.2 (Dach et al. 2015).
[3]GG: GAMIT/GLOBK: GNSS at MIT/Global Kalman filter (Herring et al. 2015, 2018).

statistical information) reconstructed from the SINEX files delivered by the SIRGAS analysis centres, i.e., the combination is performed at the normal-equation level.

b) Determination of relative weighting (or re-scaling) factors to compensate possible differences in the stochastic models of the individual solutions. The weighting factors are inferred from the variances obtained after solving the individual normal equations with respect to the IGS reference frame. Previously, the individual solutions are reviewed/corrected for possible format problems, metadata inconsistency with station log files, antenna correction model, etc., and outliers are identified by comparing the station positions obtained from each individual solution with each other and with the IGS weekly coordinates. Individual station solutions with large residuals (more than ±10 mm in the north or east (N/E) components, and more than ±20 mm in the height (h)) are removed from the normal equations before performing the weekly combination.
c) Alignment to the ITRF or IGS reference frame ensuring a minimum deformation of the SIRGAS network and the highest possible consistency with the IGS weekly positions. The SIRGAS weekly position solutions computed at DGFI-TUM used to be aligned to the ITRF version valid at the time of the computation. This was changed when absolute correction values for antenna phase centre offsets and variations (PCC) were adopted by the IGS in November 2006. The ITRF valid at that time was the ITRF2005 (Altamimi et al. 2007), which was based on relative PCC. Therefore, we decided to align the SIRGAS solutions to the IGS05 reference frame (Ferland 2006a, 2006b), which was consistent with absolute PCC values (Gendt 2006; Schmid et al. 2007). Since that time, the SIRGAS weekly position solutions computed at DGFI–TUM refer to the IGS reference frame and not directly to the ITRF. This does not pose any problem because according to Kouba (2015), the ITRF and the corresponding IGS reference frame (i.e., ITRF2008 (Altamimi et al. 2011) and IGS08/IGb08 (Ferland 2006a, 2006b), or ITRF2014 (Altamimi et al. 2016) and IGS14/IGb14 (Rebischung 2016, 2020)) are nominally identical. Another important feature of our solutions is the method to align the regional network to the global reference frame. Usually, no-net-rotation (NNR) and (or) no-net-translation (NNT) conditions are introduced with respect to the reference station positions propagated by means of constant velocities to the epoch of the respective solution. However, when the Maule Earthquake occurred

Table 2: GNSS data processing standards applied at DGFT-TUM for the analysis of the SIRGAS reference frame

Software:	
	– Bernese GNSS Software v.5.2, Dach et al. (2015)
Observables:	
	– GPS and GLONASS – Ionosphere-free linear combination – Sampling rate 30 s – Elevation cut-off angle 3° – Elevation-dependent weighting: $1/\cos^2 z$, with z being the zenith distance
Satellite data:	
	– Satellite orbits, satellite clock offsets, and EOPs are fixed to the combined IGS weekly solutions, https://igs.org/products/, Johnston et al. (2017)
Phase Centre Corrections (PCC) and antenna eccentricities:	
	– Satellite antenna to centre of mass spacecraft-specific *z*-offsets and block-specific *x*- and *y*-offsets from the model igs14.atx, Rebischung and Schmid (2016), https://files.igs.org/pub/station/general/ – PCC absolute calibration model for receiver and satellite antennas, model igs14.atx, Rebischung and Schmid (2016), https://files.igs.org/pub/station/general/ – Antenna radome calibrations applied, if given in igs14.atx. Otherwise, radome effects are neglected, and the standard antenna model (radome NONE) is used. – Marker to antenna eccentricities (d*N*, d*E*, d*U*) according to the site logs (ftp://ftp.sirgas.org/pub/gps/DGF/station/log/)
Phase ambiguities solution:	
	– Direct L1 and L2 ambiguity solution for baselines from 0 to 20 km – L3 and L5 ambiguity solution for baselines from 18 to 200 km – Wideline strategy for baselines from 180 to 9,000 km – Quasi ionosphere free strategy for baselines from 18 to 5,600 km – In the ambiguity solution, the ionosphere models of CODE (Centre for Orbit Determination in Europe) are provided as input to increase the number of ambiguities solved, http://ftp.aiub.unibe.ch/CODE/, Dach et al. (2020).
Troposphere modelling:	
	– The *a priori* zenith delay is modelled using the Vienna Mapping Function (VMF1; Boehm et al. 2006), and further atmospheric parameters are estimated in a 1-hour interval within the network adjustment using also the VMF1. – Horizontal gradient parameters are estimated to model azimuthal asymmetries (model described in Chen and Herring 1997) – The gridded VMF1 coefficients are provided by J. Boehm, TU Vienna, at https://vmf.geo.tuwien.ac.at/trop_products/GRID/
Tidal and non-tidal effects:	
	– Tidal corrections for solid Earth tide, permanent tide, and solid Earth pole tide are handled as described in the IERS Conventions 2010 (Petit and Luzum 2010). – Ocean tide loading is removed with the FES2014b model (Lyard et al. 2021). – Atmospheric tidal loading caused by the semidiurnal constituents S1 and S2 is removed with the model of van Dam and Ray (2010) (https://geophy.uni.lu/atmosphere/tide-loading-calculator/). – The reduction coefficients for the ocean tide loading are provided by M.S. Bos and H.-G. Scherneck at http://holt.oso.chalmers.se/loading/ – The reduction coefficients for the atmospheric tide loading are provided by T. van Dam at https://geophy.uni.lu/atmosphere/tide-loading-calculator/ATM1OnlineCalculator/ – Ocean tide geocentre coefficients are not applied since this correction is already contained in the final IGS products. – Non-tidal loading induced by atmospheric pressure, ocean bottom pressure, or surface hydrology is not removed.
Daily and weekly troposphere and station position solutions:	
	– Daily free normal equations are computed by applying the double difference strategy. The baselines are created by taking into account the maximum number of common observations for the associated stations.

(*Continued*)

Table 2: *Continued*

	– Daily free normal equations are aligned to the IGS reference frame to generate hourly ZPD estimates. Then, troposphere parameters are reduced from the normal equations. – Daily free normal equations are combined for computing a loosely constrained weekly solution for station positions (all station coordinates are loosely constrained to ±1 m). – Station single daily solutions with residuals larger than ±15 mm in the north or east (N/E) components and that more than ±30 mm in the height (*h*) are removed from the daily normal equations. RMS values of the residuals in the weekly combination should not be larger than ±10 mm in N/E and ±20 mm in *h*.
Results:	– DGFI–TUM's ZPD estimates and loosely constrained position solutions are made available to be combined with the corresponding solutions delivered by the other SIRGAS analysis centres. They are provided in the SINEX format and are identified with the file names DGFwwww[0...6].TRO and DGFwwww7.SNX, respectively. wwww represents the GPS week.

on February 27, 2010, most of the reference stations in the Southern part of South America were affected by strong co-seismic displacements and post-seismic deformations (e.g., Sánchez et al. 2013, Sánchez and Drewes 2016a). Therefore, it was not possible to continue using these (pre-seismic) coordinates as fiducial values; i.e., the SIRGAS weekly solutions suffered a loss of the frame of reference. To ensure a reliable datum realisation despite not having an updated (post-seismic) version of the ITRF or the IGS reference frame, different strategies were evaluated (Brunini et al. 2012), and it was decided to align the SIRGAS weekly solutions to the IGS reference frame using the coordinates determined within the IGS weekly combinations (files igsyyPwwww.snx, see https://igs.org/products/). For the weekly solutions, the SIRGAS network is constrained to the respective IGS weekly positions of the reference stations with a weight equivalent to the inverse of the square of their mean standard deviation. Figure 3 summarises DGFI–TUM's combination strategy to obtain weekly station

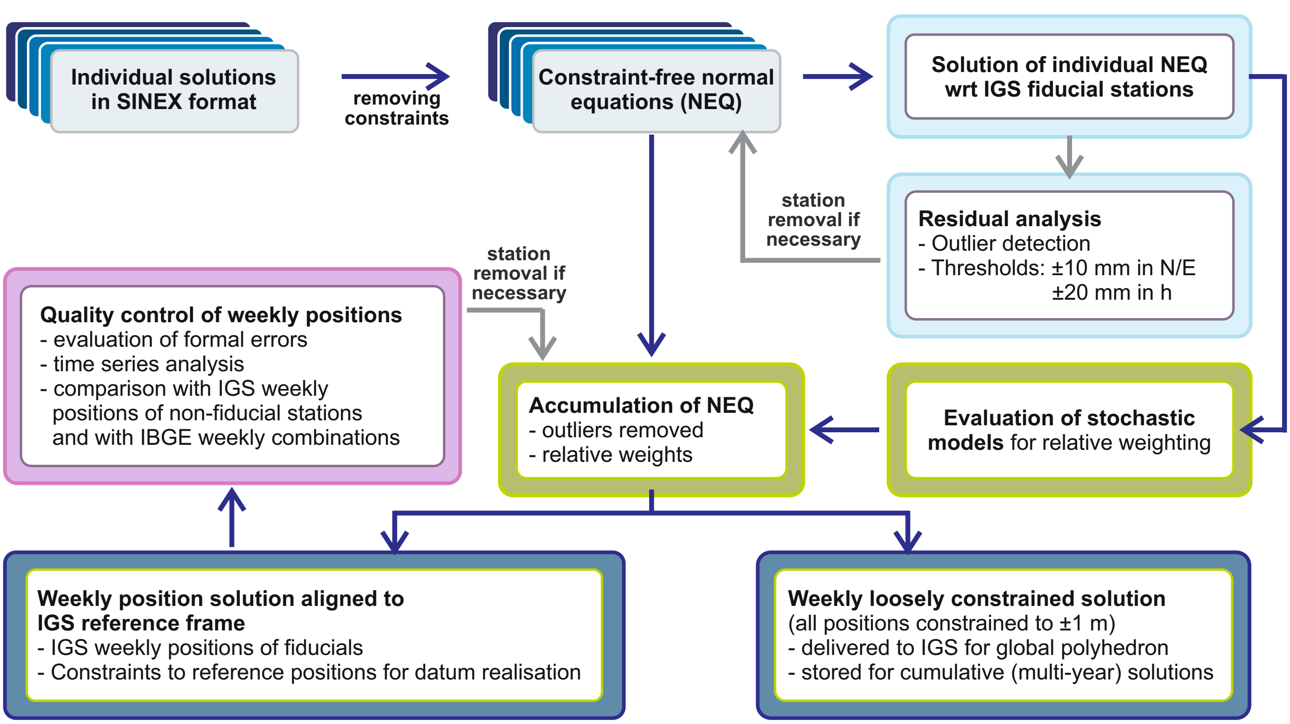

Figure 3: DGFI–TUM's strategy for the combination of the SIRGAS weekly individual solutions.

Table 3: Station distribution among the SIRGAS analysis centres (as of April 2022)

	Core network	Networks covering the three Americas (from Argentina in the South to Canada in the North)[1]		Networks covering the southern part of South America (Argentina, Chile, Uruguay, Paraguay, southern part of Brazil)		Networks covering the middle part of South America (Brazil, Ecuador, Peru)			Networks covering Mexico, Central America and the northern part of South America (Colombia, Venezuela, Surinam, Guyana, French Guyana)	
	DGF	**GNA**	**USC**	**CHL**	**URY**	**IBG**	**ECU**	**PER**	**IGA**	**INE**
DGF	**244**	115	105	32	26	65	32	38	43	32
GNA		**248**	121	46	58	76	23	19	25	13
USC			**223**	23	40	69	24	20	27	17
CHL				**93**	36	45	1	3	—	—
URY					**108**	55	—	1	—	—
IBG						**204**	43	28	26	1
ECU							**102**	30	43	8
PER								**81**	19	4
IGA									**106**	29
INE										**52**

[1]The networks processed by GNA (Argentina) and USC (Chile) were extended to North America to ensure that the North American stations added to SIRGAS in March 2021 are contained in three solutions. These stations are also processed by DGFI–TUM, but not all of them are included in the SIRGAS-C core network. Bold values indicate the total number of stations processed by each analysis centre.

positions for the SIRGAS reference frame. The SIRGAS weekly loosely constrained combinations computed by DGFI–TUM are called SIR*wwww*7.SNX, while the SIRGAS weekly station positions aligned to the IGS reference frame are named sir*yy*P*wwww*.crd/snx, where *wwww* represents the GPS week and *yy* represents the last two digits of the year.

2.3 Quality assessment of SIRGAS weekly solutions

The weekly analysis of the SIRGAS reference frame at DGFI–TUM includes a quality control at two levels: firstly, the individual solutions delivered by the SIRGAS processing centres are analysed to establish their quality and consistency and secondly, we ascertain accuracy and reliability of the station positions obtained after combining the individual solutions.

2.3.1 Evaluation of individual solutions

Table 3 summarises the station distribution among the presently active SIRGAS analysis centres. The redundancy of having each station in three solutions allows an effective identification of possible inconsistencies in the individual solutions. This identification is carried out by transforming the individual solutions to identical a priori values and generating time series for station positions. The individual normal equations are aligned to the IGS reference frame by constraining the positions of the IGS reference stations to the values determined within the IGS weekly solutions. Then, station position time series are generated for each station included in the individual solutions. In this way, three different time series for the same station are available. By comparing the time series among each other, it is easier to identify outliers and their possible causes: if outliers, discontinuities, or interruptions are identifiable in the three series, the problems may be individually associated with the station (tracking failures, unreported equipment changes, earthquakes, etc.). If outliers, jumps, or interruptions are not present in all the time series, the deficiencies may be associated with administrative issues in a particular analysis centre (neglecting of stations, incomplete download of RINEX files, disagreement with the log files, etc.). Figure 4 shows the mean repeatability RMS values of the weekly station positions after comparing the individual solutions with each other. These RMS values are understood as a measure of the consistency between the individual solutions. In the N/E component, the mean repeatability RMS values are around ±1.6 mm, while in the height, they vary between ±2.8 and ±4.2 mm.

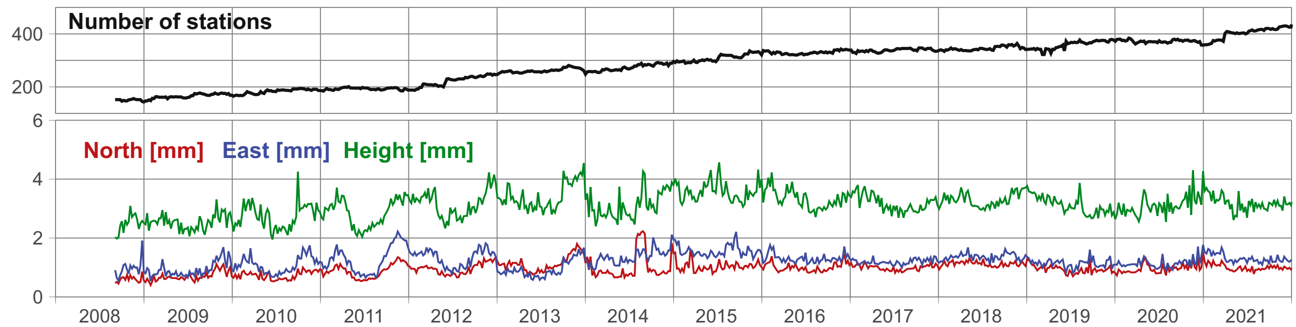

Figure 4: Mean RMS values of the station position repeatability between the SIRGAS individual solutions. The upper panel shows the number of processed stations.

The weekly individual solutions are also evaluated against the weekly combined solutions by means of a seven-parameter transformation. Figure 5 presents the RMS values of the weekly transformation parameters. These time series make evident the sensitivity of the individual solutions to changes in the configuration (geometry) of the individually processed networks. Always when a new SIRGAS analysis centre is installed or an operating one is decommissioned, there is a redistribution of the stations among the analysis centres (to ensure the rule of having each station in three solutions). The effects of this redistribution can be observed, for instance, in January 2014: UNA (Costa Rica) started to deliver solutions for a network covering Central America and the northern part of South America. Simultaneously, IGA (Colombia) and LUZ (Venezuela) stopped working for 1 year and ECU (Ecuador) took responsibility for the stations under IGA's and LUZ's care. To not overload ECU, some of the stations originally assigned to this analysis centre were transferred to URY (Uruguay). By doing so, ECU's and URY's networks became larger in terms of geographic coverage and the RMS values of transformation parameters with respect to the combined solution become smaller. Another example may be seen in January 2018. When LUZ and UNA were decommissioned, most of the stations under their care were given to IGA, who started to process a network very similar to that it was processed before UNA initiated activities in January 2014. In this way, the RMS values of IGA after 2018 are very similar to the RMS values before 2013. The change in USC's RMS time series observed in March 2021 is explainable due to the fact that USC's network was extended from the southern part of South America to North America, as USC (Chile) is one of the analysis centres processing the North American stations added to SIRGAS recently. The network processed by GNA (Argentina) was extended in a similar way like USC's network; however, no associated effect is detected in GNA's RMS time series. Indeed, the RMS values of INE (Mexico) and GNA (Argentina) are twice larger than the values of the other analysis centres (see Figure 5). The reason for this behaviour is not clear nor is it clear why from March 2020 onwards, the INE RMS values are larger and show a more erratic behaviour than before.

As mentioned in Section 2.2, the individual solutions are relatively weighted in the combination by means of re-scaling factors to compensate possible differences in the individual stochastic models. The re-scaling factors are inferred from the a posteriori variance obtained after solving the individual normal equations with respect to the IGS reference frame. These values represent the formal errors of the individual solutions. In this way, the worse the variance, the lower the weighting factor. Figure 6 compares the variance obtained for the individual solutions with the variance of the combined solution. In most cases, the variance values of the individual and combined solutions are quite consistent, except for GNA and INE. The behaviour of these values for these two analysis centres is very similar to that shown in Figure 5. The improvement of GNA's variance in mid-2019 seems to be a consequence of some software configuration changes carried out by this analysis centre (see Gómez et al. 2018).

2.3.2 Evaluation of weekly combined solutions

The quality assessment of the SIRGAS weekly combinations carried out by DGFI–TUM bases on the following criteria:

a) The mean standard deviation value obtained by aligning the SIRGAS network to the IGS reference frame indicates the formal error of the final combination (see blue lines in Figure 6). These values vary between ±1.5 and ±1.7 mm. They describe a slight periodic signature,

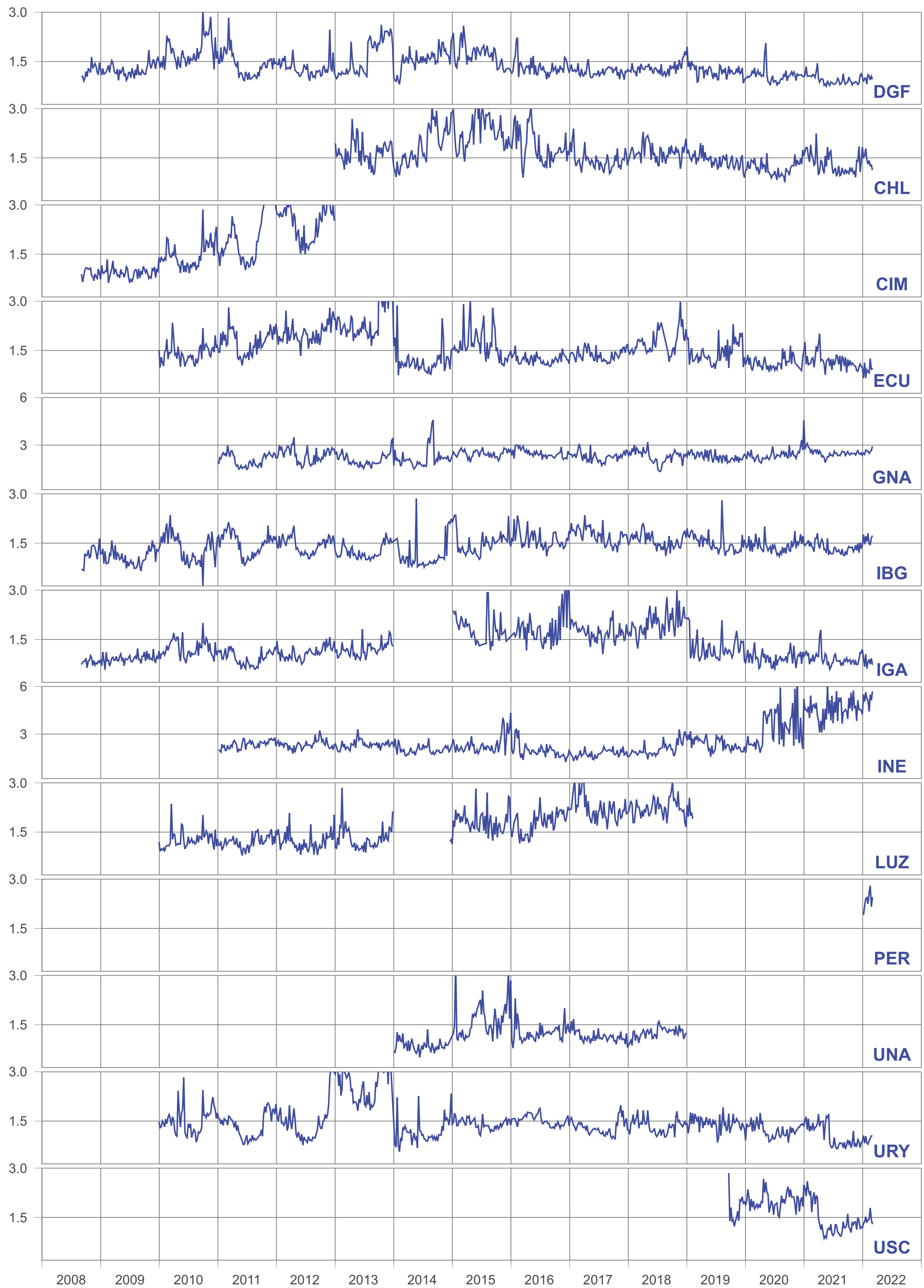

Figure 5: RMS values of a seven-parameter transformation between the individual solutions delivered by the SIRGAS analysis centres and the SIRGAS weekly combination (see Table 1 for more details about the SIRGAS analysis centres).

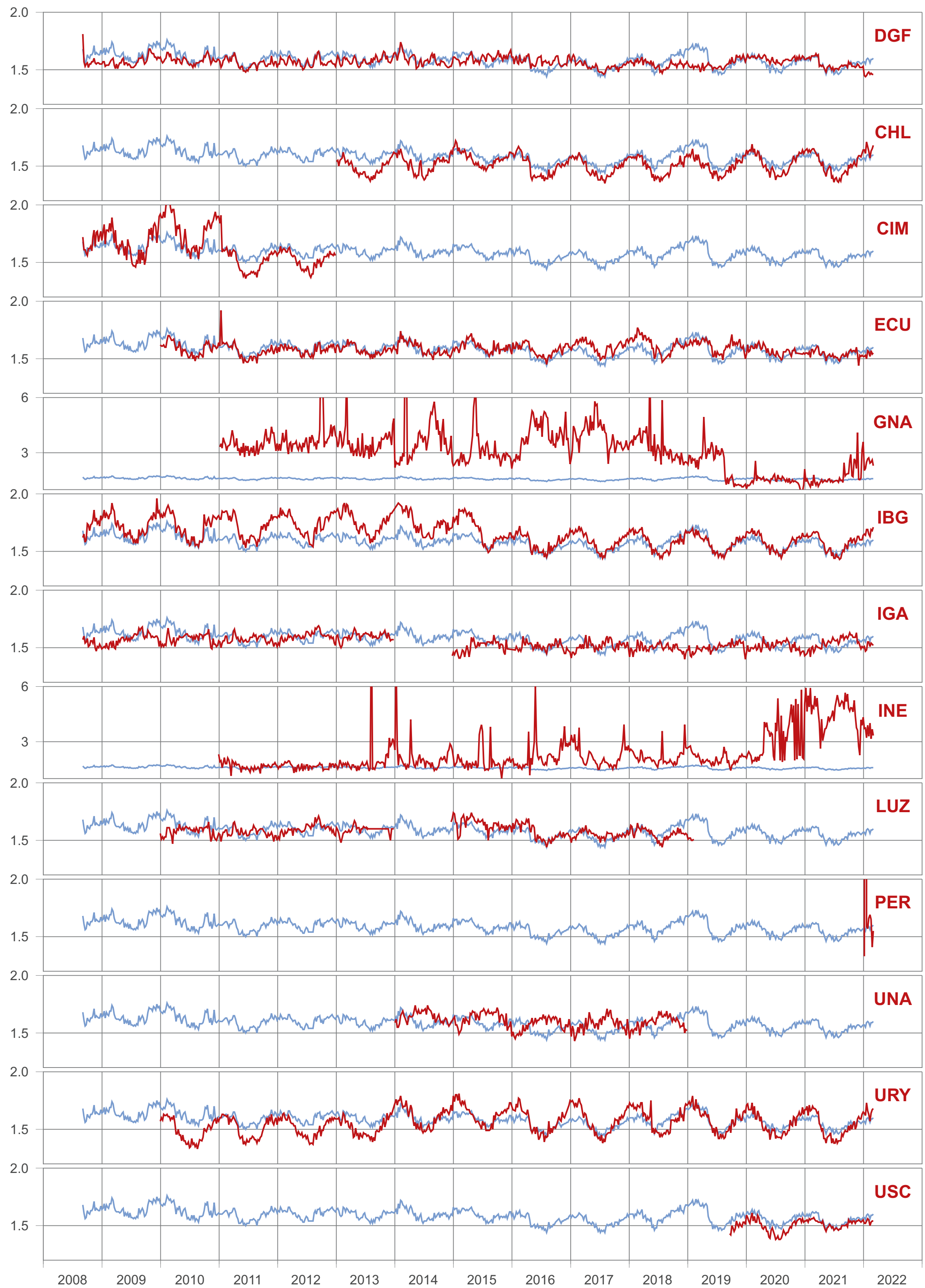

Figure 6: *A posteriori* variance values in mm after solving the individual station position solutions with respect to the IGS reference frame. These values represent the formal errors of the individual solutions. For comparison, the blue line in the plots represents the variance of the SIRGAS weekly combined solution.

which may be associated with seasonal signals present in the GNSS orbits, the EOPs, and the IGS reference coordinates.

b) Mean repeatability RMS values after combining the weekly individual solutions provide information about the internal consistency of the combined network (Figure 4). These values are around ±1.6 and ±3.5 mm in the N/E component and the height, respectively.
c) Comparison with the IGS weekly coordinates (igsyyPwwww.snx) indicates the consistency with the IGS global network (Figures 7 and 8). The station position residuals vary between ±2.8 mm in N/E and ±6.0 mm in h in 2000 and ±0.8 mm in N/E and ±2.6 mm in h in 2021 (see more details later).
d) Comparison with previous weekly solutions to determine the compatibility of the station positions from week to week (Figure 9). Station position residuals indicate a consistency around ±1.2 mm in N/E and ±3.0 mm in the height (see more details later).
e) Comparison with the IBGE weekly combination (ibgyyPwwww.snx, Costa et al. 2012b). In this case, differences are less than ±1 mm and are not further discussed here.

The SIRGAS weekly station positions refer to the IGS reference frame valid at the time when the GNSS data are routinely processed. When the IGS adopted absolute PCC values in November 2006 (together with the IGS05 reference frame), DGFI–TUM performed a first reprocessing campaign of the SIRGAS GNSS data between January 2000 and November 2006 (SIRGAS-Repro1; Sánchez and Seitz 2011a) to refer the weekly normal equations to the IGS05 (and absolute PCC). These reprocessed normal equations replaced the original ones, which referred to ITRF97 (Boucher et al. 1999) and ITRF2000 (Altamimi et al. 2002). In this way, the SIRGAS weekly operational solutions presently refer to:

- IGS05: from 2000-01-02 (GPS week 1042) to 2011-04-16 (GPS week 1631)
- IGS08: from 2011-04-17 (GPS week 1632) to 2012-10-06 (GPS week 1708)
- IGb08: from 2012-10-07 (GPS week 1709) to 2017-01-28 (GPS week 1933)
- IGS14: from 2017-01-29 (GPS week 1934) to 2020-05-16 (GPS week 2105)
- IGb14: from 2020-05-17 (GPS week 2106) to the present.

Updated releases of reference frames (i.e., ITRF, IGS reference frame, SIRGAS) are needed to take into account more observational data (larger time series), new stations, improved background models, refined analysis standards, etc. In general, it is valid to say the more recent a solution of a reference frame, the higher the accuracy of the reference frame. In this context, the consistency of the SIRGAS weekly combined solutions with the IGS reference frame is evaluated by means of transformation parameters (Figure 7) and the corresponding station position residuals (Figure 8). We perform this procedure in two ways: using only the fiducial stations considered for the alignment of the regional network to the IGS reference frame (red lines in Figure 7 and grey lines in Figure 8) and using all SIRGAS/IGS common stations (blue lines in Figure 7 and coloured lines in Figure 8). The chronological patterns shown in Figures 7 and 8 reveal the gradual improvement of the input data for the geodetic datum realisation (GNSS orbits, ITRS or IGS reference frame solutions, PCC models, etc.) as well as the configuration (station distribution) and analysis of the SIRGAS reference frame. A remarkable change occurs in October 2012. From this date onwards, the datum parameters (Figure 7) stabilise, and the strong seasonal signals and the extreme changes observed since 2000 are significantly reduced. At this time, three important modifications were implemented:

a) In agreement with the IGS working group "Reference Frame" (https://igs.org/wg/reference-frame/), about 40 SIRGAS stations are added to the IGS routine processing (Sánchez et al. 2012) and are also included in the second IGS reprocessing camping (IGS-Repro2, http://acc.igs.org/reprocess2.html), which is the basis for the GNSS contribution to the ITRF2014 (i.e., IGS14/IGb14).
b) Due to the unexplained erratic behaviour of the transformation parameters since the middle of 2009 (see Figure 7), it becomes necessary to increase the number of fiducial stations to investigate if the causes of such behaviour rely on a sparse distribution or poor quality of reference stations in the region. With this purpose, the SIRGAS network is extended beyond the SIRGAS region with the addition of IGS stations in Africa, Europe, North America, and Oceania (see Figure 1).
c) The IGb08 reference frame is introduced as the basis for the generation of the IGS products in replacement of IGS08 (Rebischung 2011, 2012). According to Rebischung (2012), the main reason for this replacement is the large number of IGS08 stations unusable for operational reference frame alignments because they either were decommissioned or were affected by strong earthquakes since 2009.5 (the same time when the strange behaviour observed in Figure 7 becomes evident). In particular, the IGS08 core network strongly deteriorated in South America, Africa, and Eastern Asia.

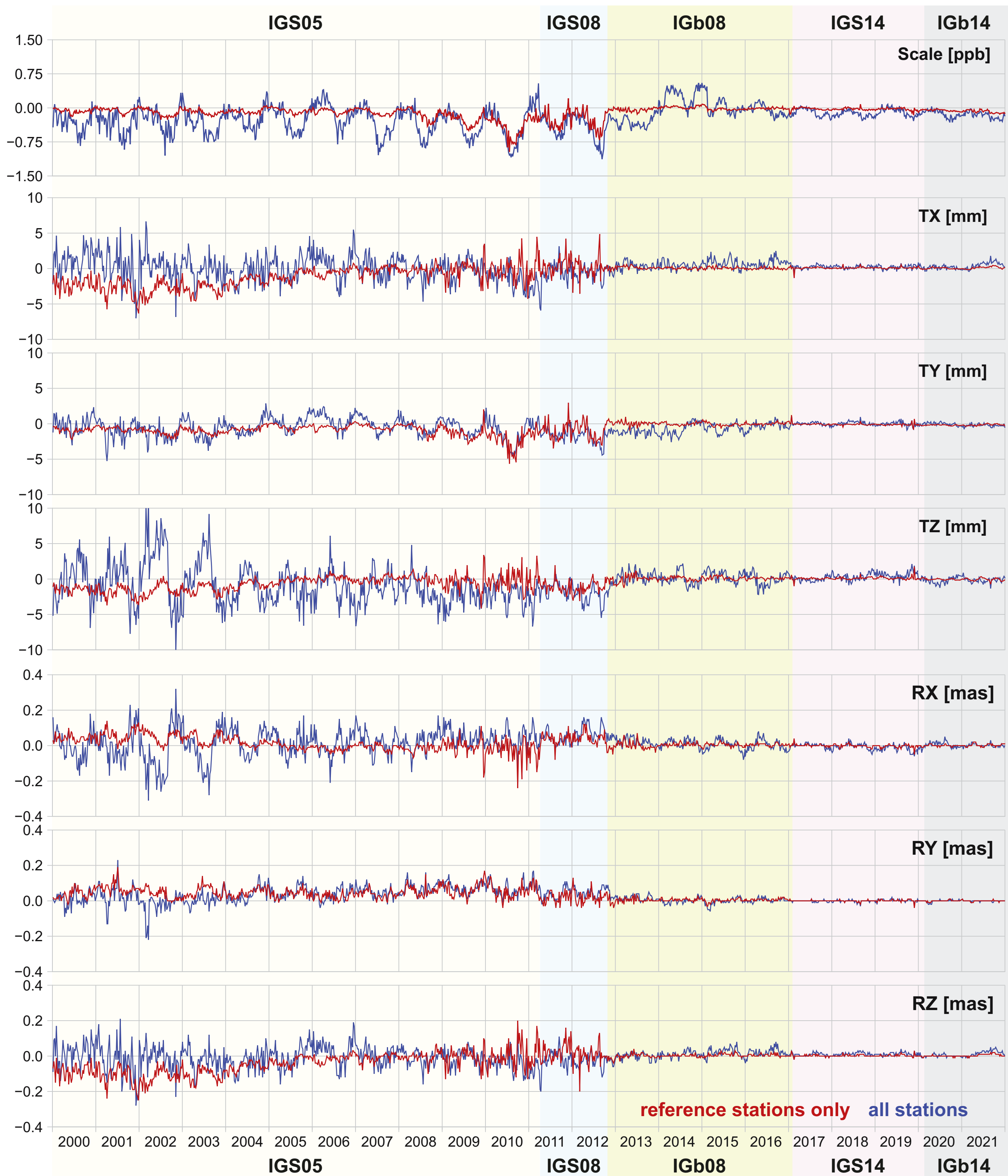

Figure 7: Differences in scale, translation, and rotation parameters between the SIRGAS and IGS weekly position solutions. Red lines represent parameters determined using fiducial stations only, while blue lines represent the values obtained when using all SIRGAS/IGS common stations. Background colours indicate the IGS reference frame in use.

The residuals shown in Figure 8 mirror a combined effect of reference frame changes, processing strategy refinements, software upgrades, addition or decommission of GNSS stations, station redistributions between the SIRGAS analysis centres, and different sets of fiducial stations. In general, one can see that the compatibility

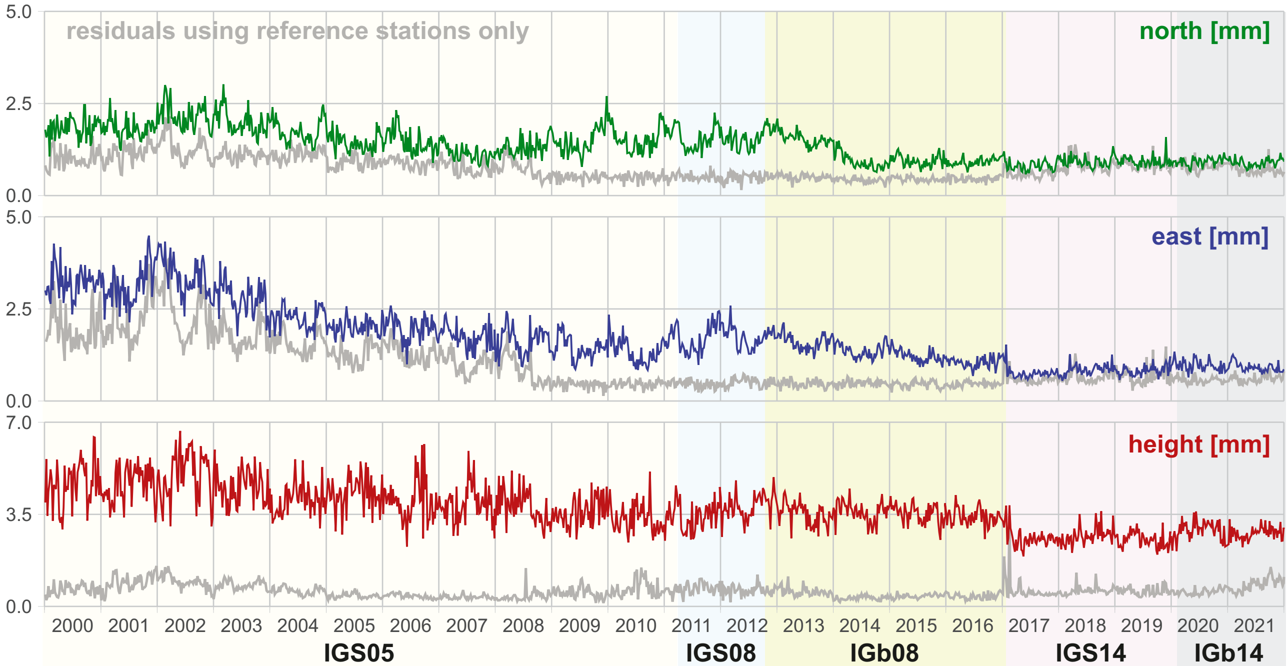

Figure 8: Mean RMS values of the station position residuals obtained after comparing the SIRGAS and IGS weekly position solutions. Grey lines represent the values obtained when comparing SIRGAS with the IGS fiducial stations only; coloured lines represent the values obtained when comparing all SIRGAS/IGS common stations. Background colours indicate the IGS reference frame in use.

of the SIRGAS weekly reference frame solutions with the IGS reference frame is about

– ±2.8 mm in N/E and ±6.0 mm in h for the IGS05 (January 2000 to April 2011);
– ±1.8 mm in N/E and ±3.5 mm in h for the IGS08/IGb08 (April 2011 to January 2017); and
– ±0.8 mm in N/E and ±2.6 mm in h for the IGS14/IGb14 (since January 2017).

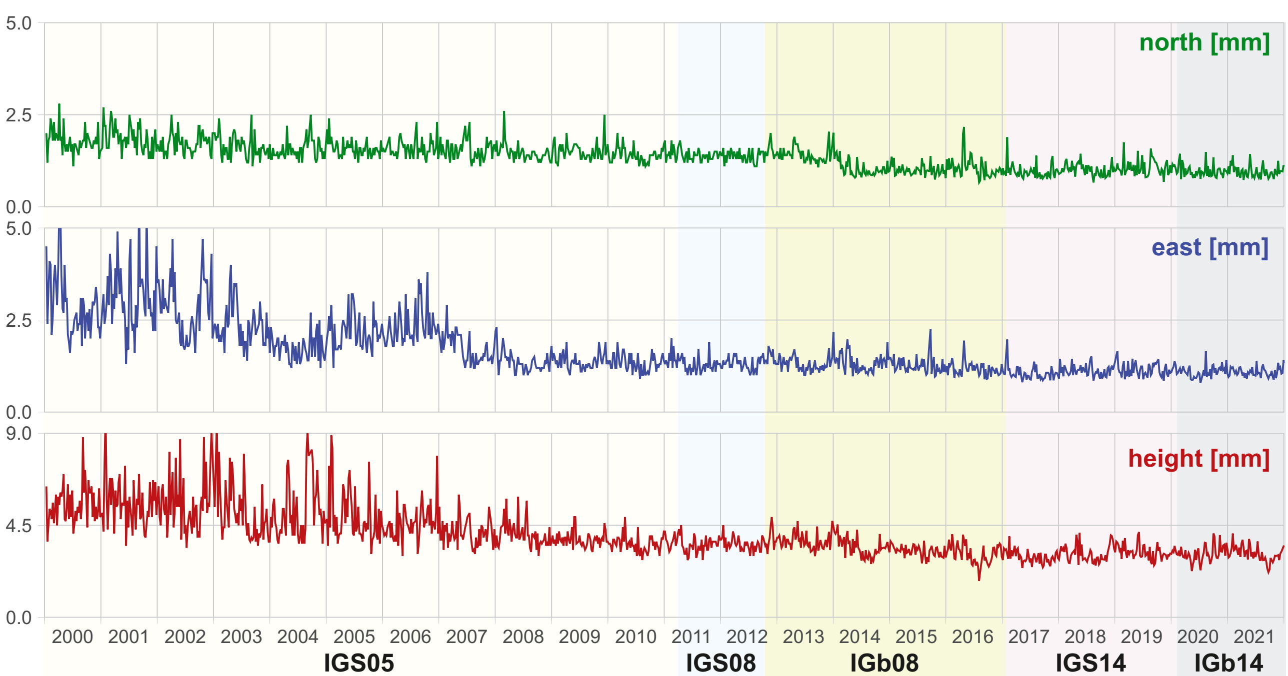

Figure 9: Mean RMS values of the station position residuals obtained after comparing the SIRGAS combined solutions between consecutive weeks. Background colours indicate the IGS reference frame in use.

An additional quality control of the weekly combinations is based on the comparison of station positions between consecutive weeks (Figure 9) to determine the consistency of the stations positions from week to week. The largest residuals are observed in the height (around ±6 mm) and in the East component (around ±2.5 mm) before 2008. Afterwards, the residuals are quite homogeneous: about ±1.2 mm in N/E and ±3.0 mm in the height.

If we define accuracy as the measure of a solution difference with respect to the IGS global network and precision as the solution repeatability over time, we can say that

– the comparison of the SIRGAS weekly combination with the IGS weekly coordinates (Figure 8) represents the accuracy of the SIRGAS weekly station positions, and
– the comparison of the SIRGAS weekly combination between consecutive weeks (Figure 9) represents the precision of the SIRGAS weekly station positions.

RMS values obtained for both criteria are very similar (about ±1.0 mm in N/E and ±3.0 in h since the introduction of the IGS14/IGb14); this indicates that the SIRGAS weekly station positions are homogeneously precise and accurate.

2.4 SIRGAS reference frame cumulative solutions

According to the data flow diagram presented in Figure 2, the next level in the SIRGAS reference frame analysis is the determination of a cumulative solution based on the normal equations obtained after the weekly combination of the individual solutions. These cumulative solutions (Table 4) are based on those models, standards, and analysis strategies widely applied at the time when they were computed and cover different time spans depending on the availability of the weekly solutions. Due to the frequent occurrence of strong earthquakes in the SIRGAS region as well as the use of different reference frames over time, the cumulative solutions are limited in time, and no one covers the complete time span backwards to 2000. For instance, the latest solution SIR17P01 considers the time span between April 2011 and January 2017. If we want to release a new cumulative solution based on the operational SIRGAS analysis products, we would have to limit the time span between January 2017 and the present. Instead of doing this, we have decided to reprocess all historical SIRGAS GNSS data from January 2000 to December 2021 using the same reference frame and analysis standards to obtain homogeneously computed normal equations (see Section 3). On the basis of this reprocessing, we then calculated a new SIRGAS reference frame cumulative solution (see Section 4).

3 SIRGAS-Repro2: homogeneous and consistent reanalysis of the SIRGAS GNSS historical data

To ensure reliability and long-term stability of geodetic reference frames, it is necessary to reanalyse the historical geodetic data from time to time using a unified set of newest standards and conventions over the complete

Table 4: SIRGAS reference frame cumulative solutions determined by DGFI–TUM

Solution	No. Stations	ITRF	PCC*	Data start	Data end	Reference
DGF00P01	31	ITRF97, 2000.4	Rel	1996-06-30	2000-02-27	Seemüller et al. (2002)
DGF01P01	48	ITRF2000, 2000.0	Rel	1996-06-30	2001-04-14	Seemüller et al. (2002)
DGF01P02	49	ITRF2000, 1998.4	Rel	1996-06-30	2001-10-20	Seemüller and Drewes (2004)
DGF02P01	53	ITRF2000, 2000.0	Rel	1996-06-30	2002-07-31	DGFI (2002)
DGF04P01	69	ITRF2000, 2003.0	Rel	1996-06-30	2004-07-31	Seemüller et al. (2004)
DGF05P01	95	ITRF2000, 2004.0	Rel	1996-06-30	2005-09-17	Seemüller (2005)
DGF06P01	94	ITRF2000, 2004.0	Rel	1996-06-30	2006-06-17	Seemüller (2009)
DGF07P01	106	IGS05, 2004.5	Abs	2002, 01/05-2005, 2006, 01/08-2007		Seemüller et al. (2007)
DGF08P01	126	IGS05, 2004.5	Abs	2002-01-02	2006-11-04	Seemüller et al. (2008)
SIR09P01	128	IGS05, 2005.0	Abs	2000-01-02	2009-01-03	Seemüller et al. (2009, 2011)
SIR10P01	183	ITRF2008, 2005.0	Abs	2000-01-02	2010-06-05	Seemüller et al. (2010)
SIR11P01	230	ITRF2008, 2005.0	Abs	2000-01-02	2011-04-16	Sánchez and Seitz (2011b)
SIR13P01	108	IGb08, 2012.0	Abs	2010-04-18	2013-06-15	Sánchez et al. (2016)
SIR14P01	242	IGb08, 2013.0	Abs	2010-04-18	2014-07-26	Sánchez (2015)
SIR15P01	303	IGb08, 2013.0	Abs	2010-04-18	2015-04-11	Sánchez and Drewes (2016b)
SIR17P01	345	IGS14, 2015.0	Abs	2011-04-17	2017-01-28	Sánchez and Drewes (2020b)

*Antenna phase centre corrections.

time span. As mentioned in Section 2.3, the first SIRGAS reprocessing campaign (SIRGAS-Repro1) was performed with the objective of determining normal equations referring to the IGS05, including absolute PCC. A reprocessing campaign referring to the IGS08/IGb08 frame was not undertaken. To eliminate spurious artefacts and systematics in the SIRGAS normal equation series, DGFI–TUM started the second SIRGAS reprocessing campaign SIRGAS-Repro2 in mid-2019. With the support of the SIRGAS Working Group I "Reference System" (https://sirgas.ipgh.org/en/organization/working-groups/working-group-i/), it was possible to complete a detailed inventory of the availability and quality of the existing RINEX files since 2000 and to update/correct the station log files according to the latest IGS standards for old GPS antennas and receivers. Based on the operational SIRGAS time series, the performance of each station was evaluated to decide if it should be included in the new reprocessing. Since the establishment of SIRGAS in 1993, about 640 continuously operating GNSS stations have been used for the realisation of SIRGAS, being more than 160 of them presently decommissioned. From the decommissioned stations, about 45 offer less than 2 years of observations or present very large data gaps. These stations were removed from the reference frame and are not included in SIRGAS-Repro2. Although the IGS RNAAC SIRGAS is in operation since June 1996, we decided to reprocess SIRGAS GNSS data since January 2000, as most of the oldest stations are IGS (and not regional) stations. Thus, their coordinates are included in the ITRF solutions. In SIRGAS-Repro2, we consider not only SIRGAS regional stations but also a set of IGS stations globally distributed (Figure 10) to have a larger number of stable fiducial stations.

As SIRGAS-Repro2 is based on a global GNSS network, we incorporated the simultaneous determination of GNSS satellite orbits, satellite clock offsets, EOPs, and station positions within the GNSS data processing. However, including all the SIRGAS regional stations reduces the reliability of the EOPs and GNSS orbits due to the dense station distribution in one particular region (see Figure 10). Consequently, we followed a two-step procedure: (a) orbit, satellite clock synchronisation, and EOP determination based on a global network, and (b) processing of the regional GNSS data fixing the previous determined orbits, satellite clocks, and EOPs. As this procedure is currently applied in the analysis of the regional reference frame (see Table 2), we concluded that, even though with a global station distribution, the SIRGAS-Repro2 computations can continue to be based on the IGS final products.

For the complete time span covered by SIRGAS-Repro2 (January 2000 to December 2021), 537 SIRGAS regional stations plus 128 IGS global stations (88 of them belonging to the IGS14/IGb14 reference frame) were reanalysed. Almost 2.6 million daily RINEX files were processed. The rejection rate for low-quality RINEX files is only 0.2%. Figure 11 shows the number of years processed

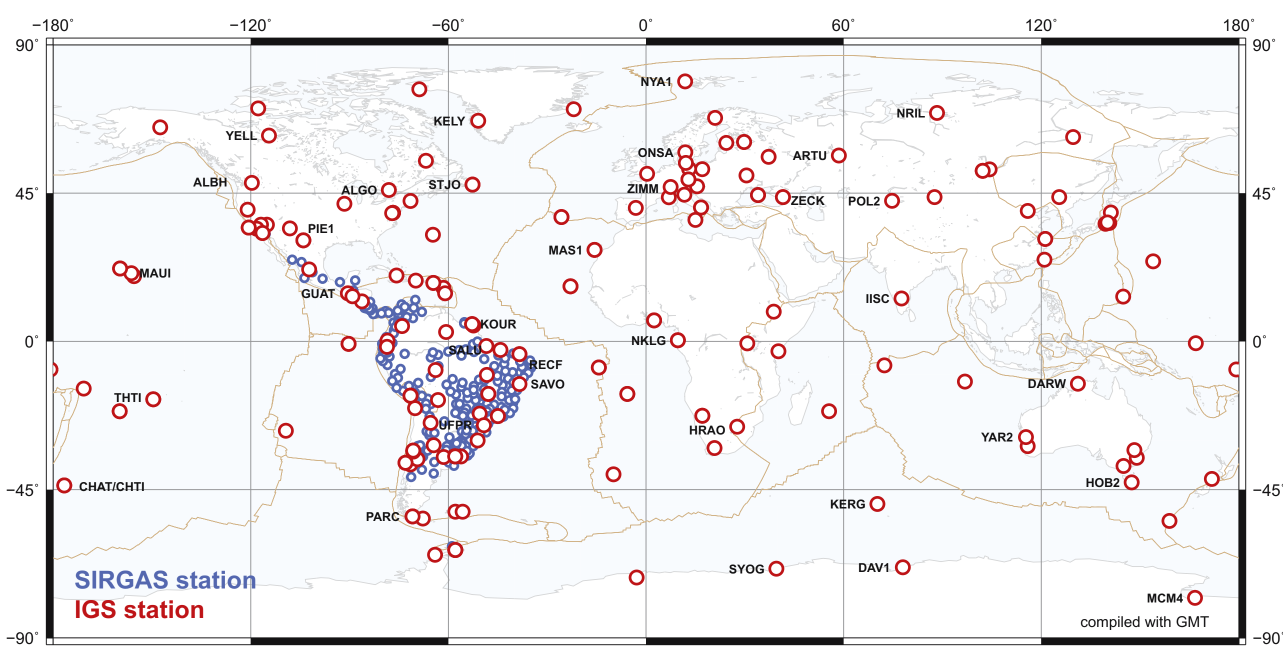

Figure 10: GNSS stations included in SIRGAS-Repro2. Stations with a label represent fiducial sites in the SIRGAS-Repro2 analysis.

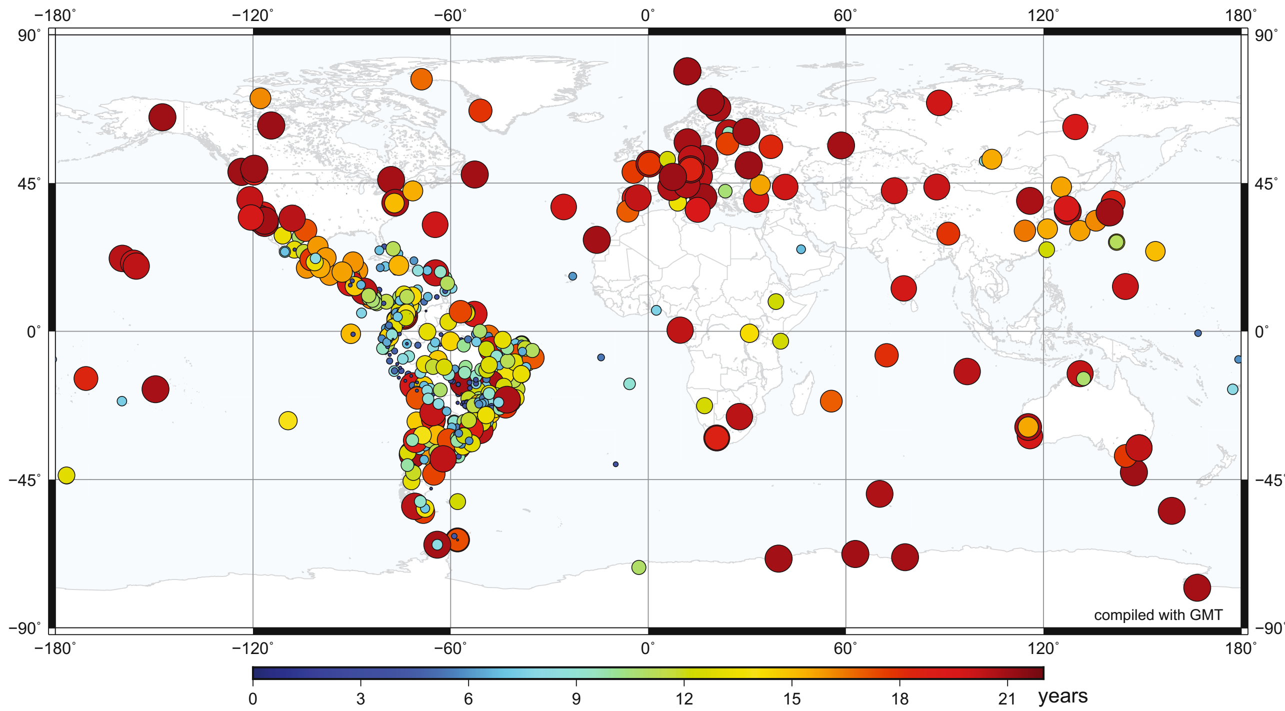

Figure 11: Time span of GNSS data included in SIRGAS-Repro2 per station.

per station. The GNSS observations were analysed following the standards summarised in Table 2, except that for the weeks before January 29, 2017 (when the IGS14 was adopted as the reference frame), the orbits, satellite clocks, and EOPs based on the IGS-Repro2 (in the following called IG2 products) were used (Griffiths 2019). From January 30, 2017, the operational and SIRGAS-Repro2 solutions are virtually the same, as both series are based on the IGS14/IGb14 and the IGS operational products.

The quality of the SIRGAS-Repro2 weekly solutions was evaluated in the same way as the operational weekly solutions are evaluated (see Section 2.3), i.e., consideration of the a posteriori mean standard deviation values and comparison with the IGS-Repro2 weekly solutions and with solutions of consecutive weeks. Figures 12 and 13 depict transformation parameters as well as RMS values of the differences between the SIRGAS-Repro2 weekly positions and the weekly coordinates of the IGS stations in IGS14/IGb14. The rotation and translation parameters are practically negligible; they are less than 0.01 mas and 1 mm, respectively, when using all SIRGAS/IGS common stations (blue lines in Figure 12), and they are around zero, when comparing only the fiducial stations (red lines in Figure 12). The scale parameter based on all SIRGAS/IGS common stations presents fluctuations between −0.2 ppb in 2000 and 0.0 ppb in 2017. The jump evident at the end of January 2017 is due to the fact that the IG2 products (generated within the second IGS reprocessing campaign and used for the SIRGAS-Repro2 analysis) are computed using a different PCC model than the operational IGS products based on the IGS14/IGb14. This change mainly affects the network scale and the height of the GNSS stations. Indeed, the scale values estimated using the fiducial stations only (red line in the uppermost panel in Figure 12) present a bias of about −0.02 ppb between 2000 and 2017 (when the IGS14/IGb14 was officially adopted by IGS). Then, these values are close to zero until the end of 2020. Afterwards, they describe a negative drift. Given that the current IGS reference frame solution (i.e., IGb14) contains GNSS data until February 2020, it is possible that this drift is produced by the extrapolation of the IGb14 station positions and velocities for operational reference frame alignments in the IGS products generation. This effect has to be further investigated as a similar behaviour is also observed in the translation parameters (Figure 12) and the station position residuals (Figure 13). Despite this, the improvement compared to SIRGAS operational solutions (Figures 7 and 8) is considerable.

According to Figure 13, the consistency of the SIRGAS-Repro2 station positions with the IGS14/IGb14 reference frame is about ±1.0 mm in N/E and ±3.0 in h before January

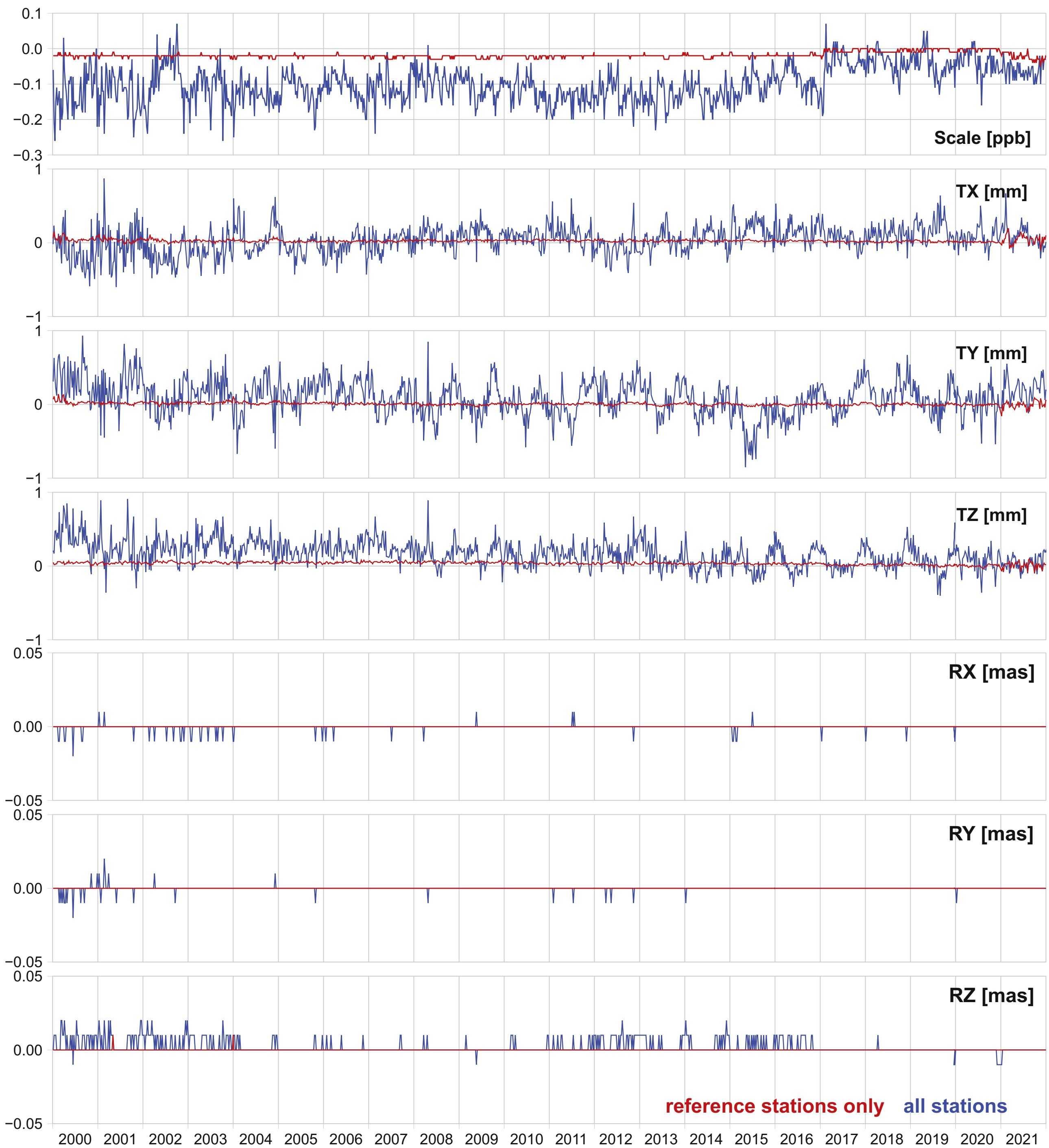

Figure 12: Differences in scale, translation, and rotation parameters between the SIRGAS-Repro2 station positions and the weekly coordinates of the IGS stations in IGS14/IGb14. Red lines represent parameters determined using fiducial stations only, while blue lines represent the values obtained when using all SIRGAS/IGS common stations.

2017. Afterwards, this consistency improves reaching values around ±0.8 mm in N/E and ±2.6 in h. Similarly, the comparison of the SIRGAS-Repro2 weekly station positions between consecutive weeks (Figure 14) indicates a precision about ±1.0 mm in N/E and ±3.0 in h.

4 SIRGAS2022: the newest SIRGAS reference frame solution

In this section, we describe the computation of a cumulative solution based on the SIRGAS-Repro2 normal equation

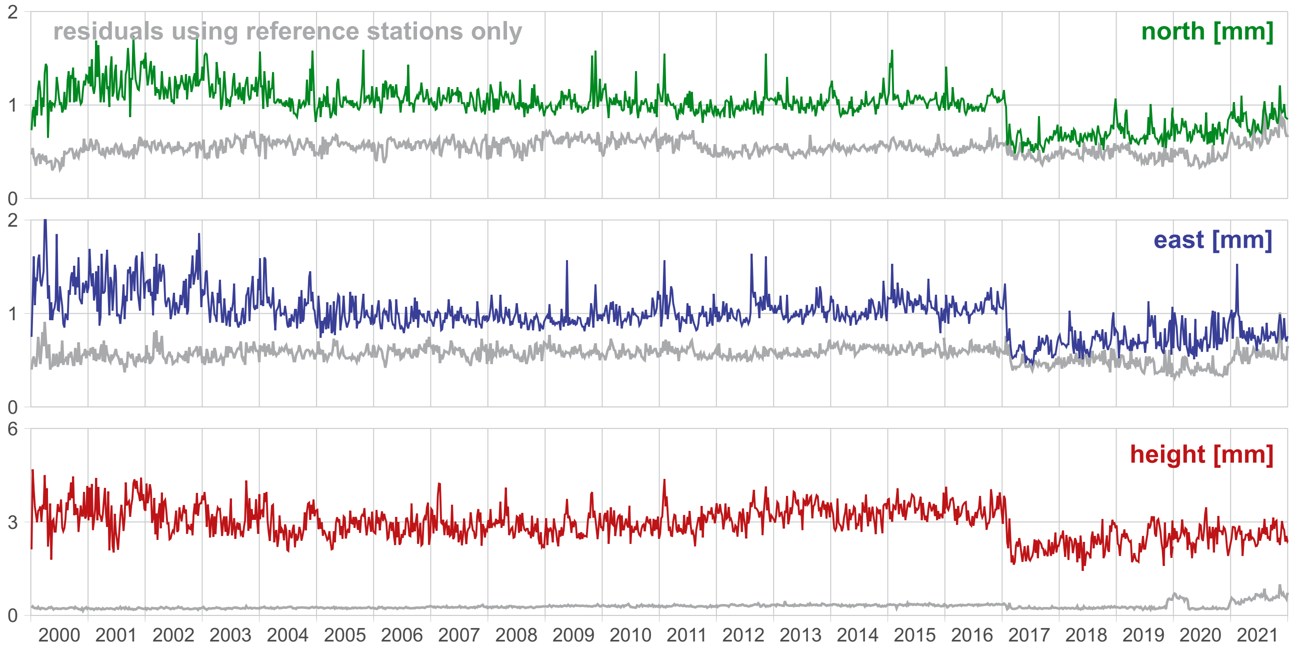

Figure 13: Mean RMS values of the station position residuals obtained after comparing the SIRGAS-Repro2 station positions and the weekly coordinates of the IGS stations in IGS14/IGb14. Grey lines represent the values obtained when comparing SIRGAS with the IGS fiducial stations only; coloured lines represent the values obtained when comparing all SIRGAS/IGS common stations.

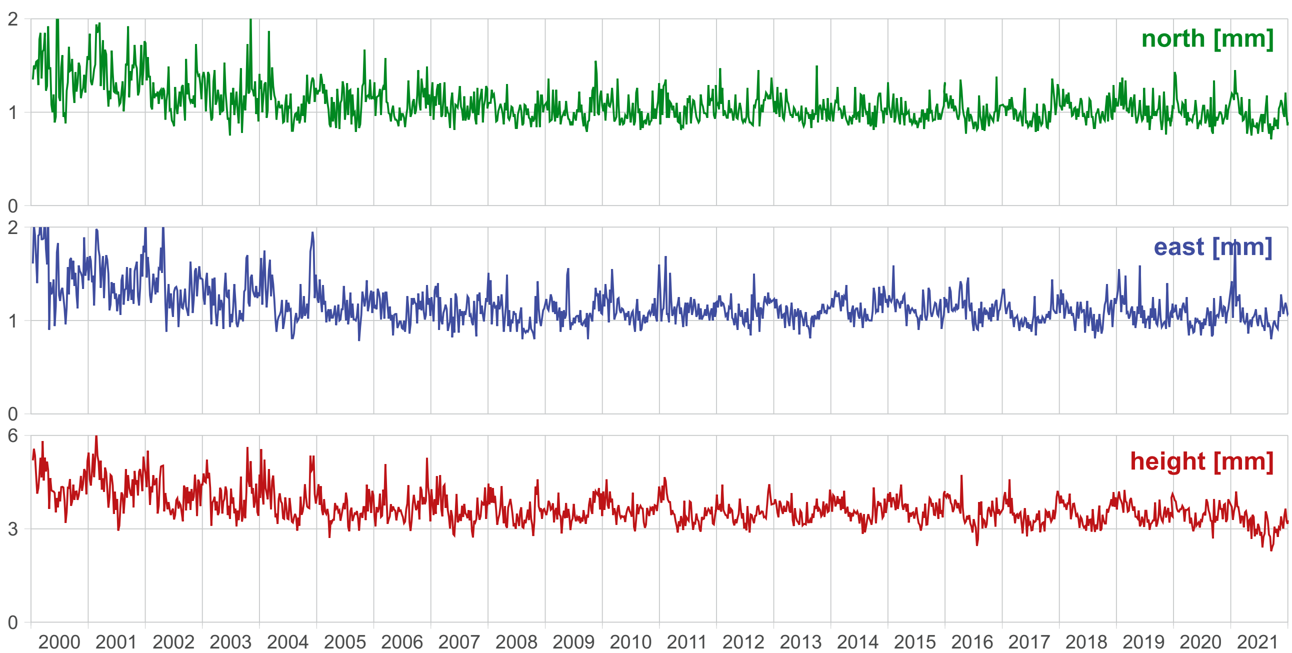

Figure 14: Mean RMS values of the station position residuals obtained after comparing the SIRGAS-Repro2 station positions between consecutive weeks.

series, hereinafter referred to as SIRGAS2022. SIRGAS2022 relies on all weekly IGS14/IGb14-based normal equations between January 2000 (GPS week 1043) and April 2022 (GPS week 2207), and it is planned to be updated every 6 months by adding those normal equations computed after the last date considered in the latest solution release.

Figure 15 summarises the procedure followed for the determination of SIRGAS2022. The first step is the outlier

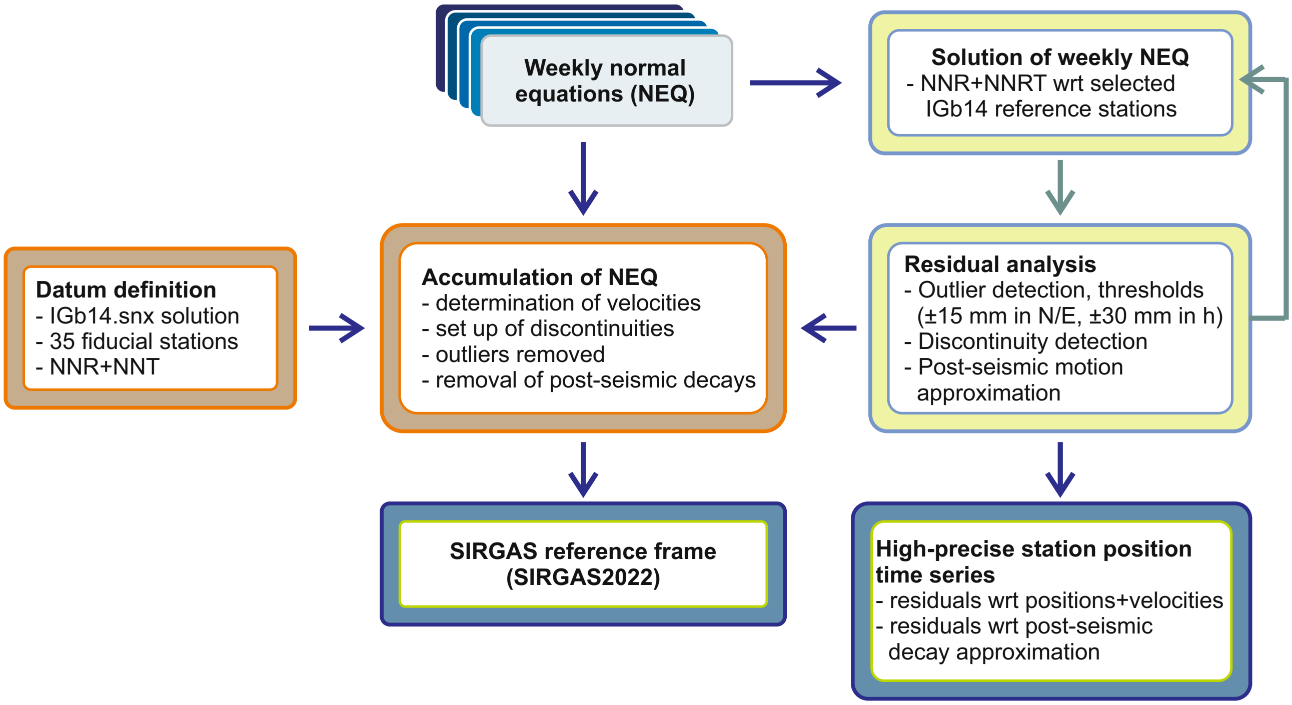

Figure 15: SIRGAS reference frame determination procedure.

and discontinuity detection by means of time series analysis. For this objective, the weekly normal equations are separately solved by applying NNR + NNT conditions with respect to selected IGS reference stations, and the weekly station positions are transformed to the IGb14.snx solution by means of a seven-parameter transformation. The station position residuals after the transformation are the input data for the time series analysis. Residuals larger than ±15 mm in N/E and ±30 mm in h are marked as outliers. Isolated outliers are reduced from the corresponding weekly normal equations, while successive outliers are assumed as a discontinuity. After each discontinuity, a new position is set up for the station. Residual time series are computed again considering the new station positions, and the procedure is repeated until no more discontinuities are found. The outlier and discontinuity detection is supported/verified by a visual screening of the time series.

Once all discontinuities are identified, their dates are correlated with the dates of equipment changes (retrieved from site logs) and dates of earthquakes to explain the causes of discontinuity. As we are working with weekly normal equations, this correlation helps us to identify the exact day on which the discontinuity occurred. Dates of unexplained discontinuities are compared with site log modifications and with the ITRF and IGS discontinuity tables. IGS stations with many discontinuities or strong co- and post-seismic signals located outside Latin America were excluded from the cumulative solution (38 stations in total). For the remaining IGS stations, in a few cases, we cannot detect some discontinuities considered in the ITRF or IGS solutions, and in other few cases, we detect discontinuities that are not included in the ITRF or IGS solutions. In any way, we strictly consider the discontinuities included in IGb14.snx for the 35 stations used as fiducial sites. These sites were selected according to the following criteria (see labelled stations in Figure 10):

- A more or less homogeneous global geographic distribution,
- Without co- or post-seismic effects (i.e., stations with post-seismic deformation model in the IGb14.snx solution are not considered as fiducials),
- No discontinuities in their time series after the end date covered by IGb14.snx (February 15, 2020), and
- Complete data coverage of the SIRGAS2022 time span (i.e., from January 2, 2000, to April 30, 2022).

Once outliers are removed and discontinuities detected, the weekly normal equations are combined and solved to compute the SIRGAS reference frame using the Bernese GNSS Software V.5.2 (Dach et al. 2015). The weekly normal equations are combined to a multi-year solution setting up station velocities, i.e., linear station position variations. The geodetic datum is realised by applying NNR and NNT conditions with respect to the IGb14 positions and velocities of the selected fiducial stations. If the discontinuities are caused by equipment replacements, a new station position is estimated after the discontinuity and constraints are applied to ensure that the station velocity before and after the discontinuity is the same. In a first run, stations with unexplained and co-seismic discontinuities are allowed to change the velocity. If the difference between the obtained velocities is less than the 0.6 mm/year (a-posteriori mean standard deviation of the velocities, see later), the velocities before and after the discontinuity are constrained to be equal and the solution is recomputed. In the case of a co-seismic displacement, the residual time series after the earthquake are approximated by means of logarithmic or exponential functions (following Savage and Prescott (1978) and Pollitz and Dixon (1998), respectively) to determine amplitude and time span of the post-seismic decay. Time series segments in which the decay amplitude of a station exceeds 2 cm are removed from the weekly normal equations, and the remaining segments with smooth decay are approximated linearly. Once the strong relaxation segments have been removed from the time series, a new cumulative solution is computed, new residual time series is generated, and the time-series analysis is repeated to identify remaining outliers, discontinuities, or post-seismic decays with amplitudes larger than 2 cm. This process is iteratively conducted until none of these anomalies remains.

In the determination of SIRAGS2022, 800 discontinuities were detected (Figure 16): 68.7% are caused by antenna changes, 20.9% correspond to co-seismic displacements, and 10.4% have unexplained causes. In addition, 75% of the co-seismic displacements are followed by strong post-seismic decays. In many cases (especially in Argentina, Chile, Ecuador, and Costa Rica), the post-seismic effects of different earthquakes overlap, making it difficult to approximate these effects by a single logarithmic or exponential function. This situation is further complicated by lack of data, malfunctioning, or dismantling of earthquake-damaged stations, as these factors decrease the reliability of the station position time series.

SIRGAS2022 (Figures 17 and 18) contains 587 stations with 1389 occupations. The SIRGAS2022 station positions refer to the IGb14 reference frame and are given at the epoch 2015.0. Their accuracy is estimated to be ±0.8 mm in N/E and ±1.4 mm in h 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 h. To evaluate the consistency of the SIRGAS2022 solution with IGb14.snx, the positions and velocities of those stations that were not used as fiducials were compared. Table 5 summarises the main statistical data. The largest differences occur at the South American IGS stations affected by earthquakes.

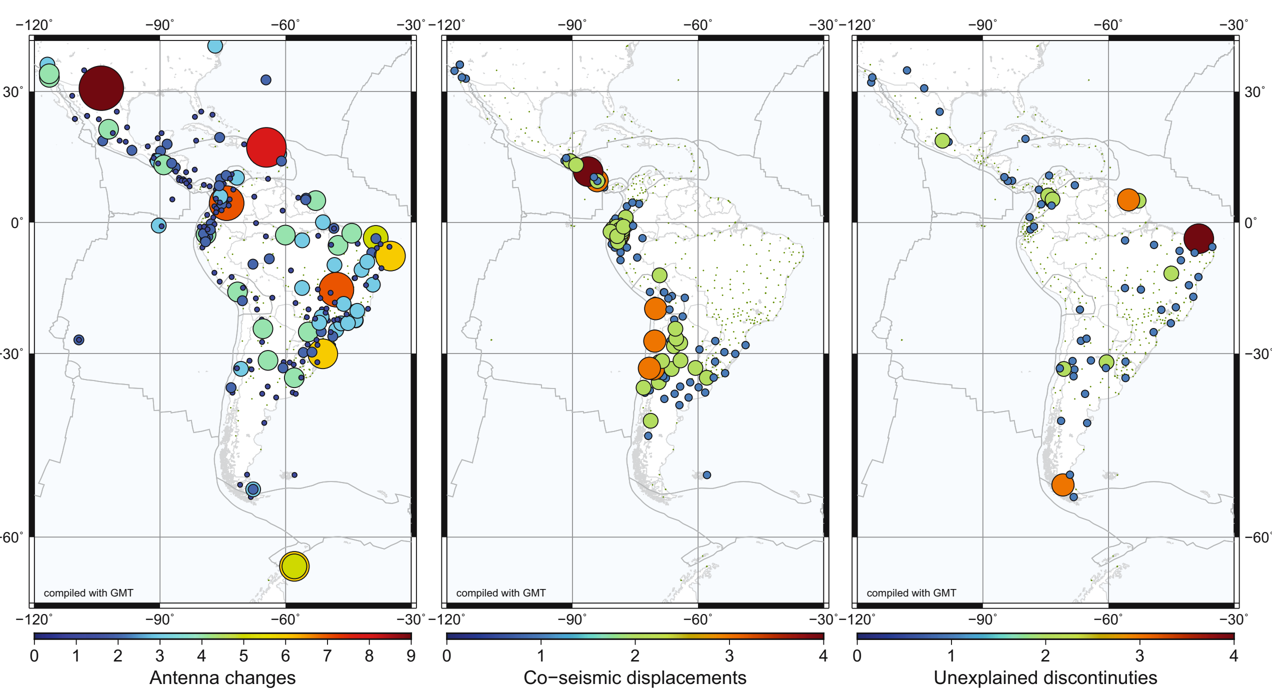

Figure 16: Time series discontinuities detected in SIRGAS2022: 68.7% are caused by antenna changes (left), 20.9% correspond to co-seismic displacements (centre), and 10.4% have unexplained causes (right).

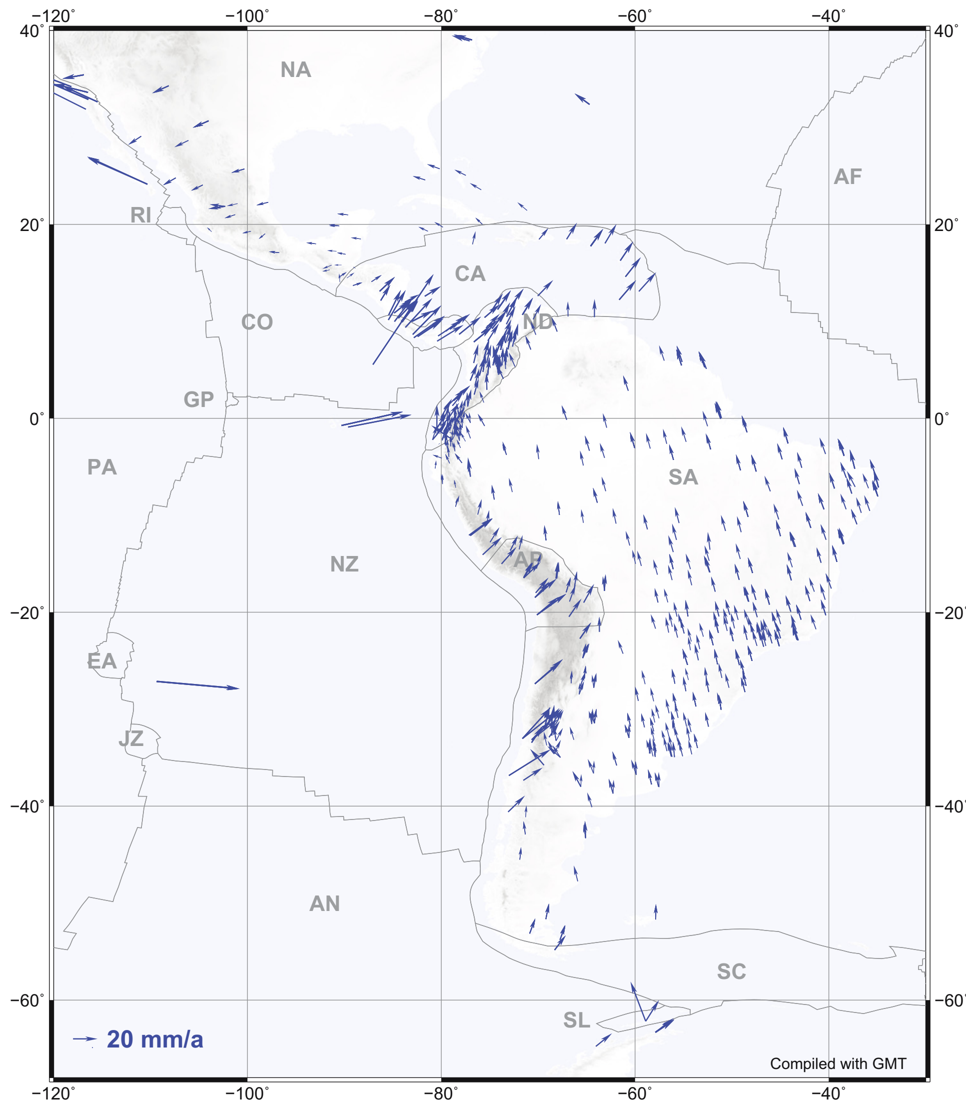

Figure 17: SIRGAS2022 horizontal velocities.

5 Summary and outlook

Since the establishment of SIRGAS in 1993, a huge progress has been made. The reference frame is currently realised by more than 400 continuously operating GNSS stations, and the Latin American countries have deployed a strong infrastructure for the measurement and analysis of the GNSS data, ensuring redundancy (10 processing centres and two combination centres) in the determination of weekly position solutions. The routine processing of SIRGAS is frequently affected by the occurrence of strong earthquakes, which disable the use of station coordinates obtained before the earthquakes. For this reason, cumulative reference frame solutions (ITRF, IGS, or SIRGAS) can become outdated at any time, meaning that they can no longer serve as a reference frame in a region affected by a major earthquake.

The SIRGAS weekly position solutions provide national geodetic and cartographic agencies (as well as other stakeholders) with up-to-date reference coordinates for their daily surveying activities. In general, these solutions are accurate enough to support navigation and positioning at any scale of precision. However, for scientific applications aimed at studying the effects of global change or understanding the phenomena inherent to the Earth system, it is necessary for the reference frame to have long-term stability, so that phenomena with signals of different amplitudes can be detected, modelled, and correlated over time. For this reason, DGFI–TUM has completed a reprocessing of all existing SIRGAS historical GNSS data

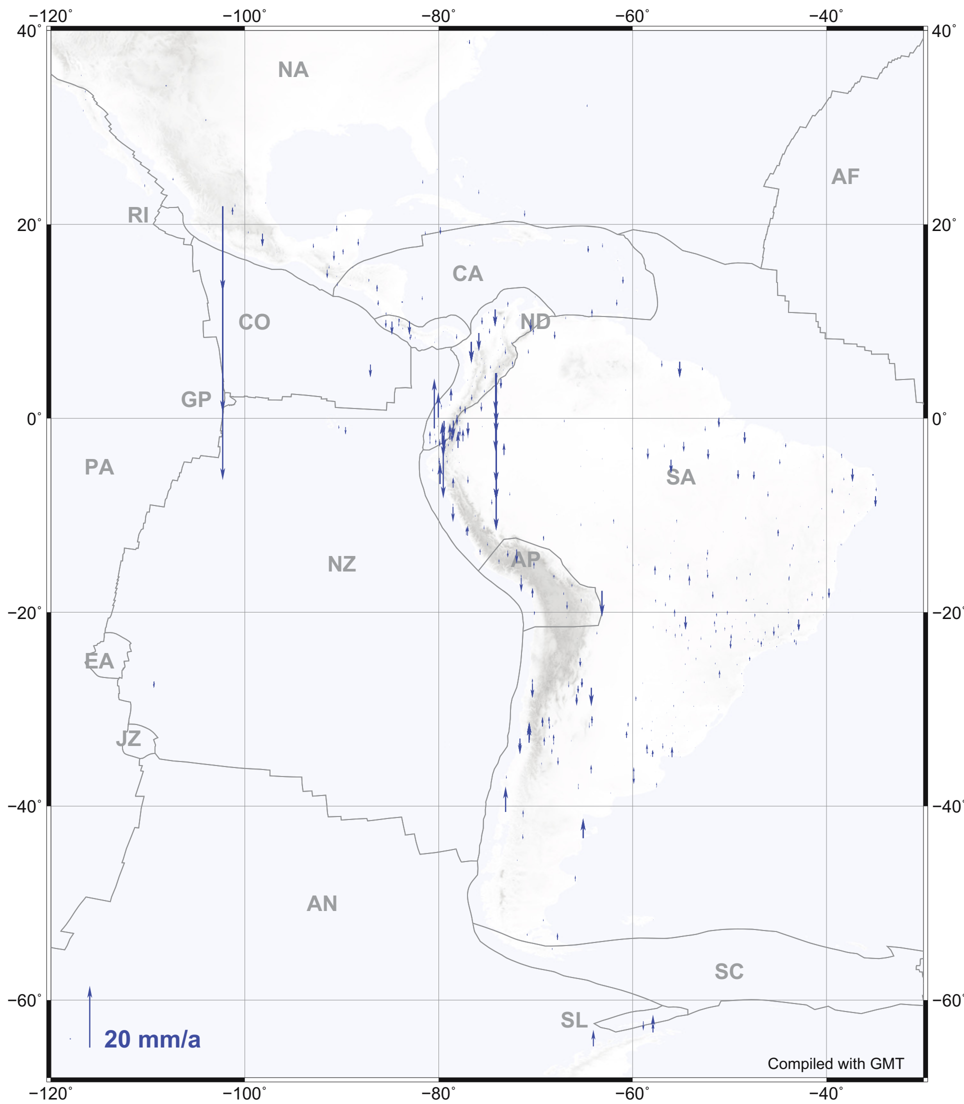

Figure 18: SIRGAS2022 vertical velocities.

Table 5: Differences between the IGb14 and SIRGAS2022 coordinates at IGS stations not used as fiducial stations, stations AREQ (Arequipa, Peru), and SANT (Santiago de Chile, Chile) are excluded from this comparison

	Dif. X (mm)	Dif. Y (mm)	Dif. Z (mm)	Dif. vX (mm/year)	Dif. vY (mm/year)	Dif. vZ (mm/year)
Mean	0.11	−0.08	0.27	0.00	−0.18	−0.17
STD	0.60	0.60	0.60	0.24	0.29	0.32
Min	−2.25	−1.82	−1.33	−0.96	−1.00	−1.26
Max	1.48	1.44	3.44	1.16	1.16	0.80

since 2000. By using a unified set of standards in the reanalysis of GNSS data over 22 years, we are minimising possible systematic signals in the time series, resulting in a set of high-quality and consistent normal equations at our disposal.

Having extended the GNSS network to a global scale (including all co-locations with SLR (Satellite Laser Ranging) and VLBI (Very Long Baseline Interferometry)), the SIRGAS-Repro2 normal equations are now the starting point for developing specialised research towards improved strategies. This includes the reliable realisation of the datum, the compilation of regional epoch reference frames, and the detection, modelling, and interpretation of Earth system-associated signals in GNSS data time series. The central idea is to realise the datum of the regional geocentric reference frame directly and epoch-wise (i.e., instantaneously for each solution), without the alignment to a global reference frame, but by combining normal equations of global GNSS (regionally densified),

Table 6: Surface kinematics models VEMOS

Model	Reference frame	Input station velocities	Start	End	Reference
VEMOS2003	ITRF2000	333	1995-05-01	2001-04-14	Drewes and Heidbach (2005)
VEMOS2009	ITRF2005	496	2000-01-02	2009-06-30	Drewes and Heidbach (2012)
VEMOS2015	IGb08	456	2010-03-14	2015-04-11	Sánchez and Drewes (2016c)
VEMOS2017	IGS14	515	2014-01-01	2017-01-28	Drewes and Sánchez (2020)

SLR, and VLBI networks using a minimum network configuration on a weekly basis. Thereby, the geocentric origin of the combined network should be realised from SLR, the scale should be realised from both SLR and VLBI, and the orientation should be kept consistent with that of the ITRF via an NNR constraint. Kehm et al. (2019, 2022) demonstrated that the main advantage of determining weekly position solutions of regional frames by combining GNSS, SLR, and VLBI normal equations is the direct geocentric realisation of the geodetic datum. The station position time series are related to the geocentre at any epoch, and they are not affected by the dislocation between the *origin of coordinates* and the centre of Earth masses as it is inherent to GNSS-only-based epoch reference frames with a datum aligned to a multiyear solution via NNT + NNR constraints. The approach turns out to be especially useful to detect, analyse, and interpret non-tidal loading signals in station-specific displacement time series with respect to geophysical processes in the Earth system. In this regard, our next objective is to study how this strategy can be implemented in the routine analysis of the SIRGAS reference frame at DGFI–TUM.

The constant velocities determined within the SIRGAS2022 cumulative solution are now the basis for the computation of a new model in the sequence of the VEMOS surface deformation models for Latin America. These models represent the mean horizontal surface motions within a certain period of time (Table 6). The latest one (VEMOS2017, Drewes and Sánchez 2020) covered the time until January 29, 2017 (when the IGS14 frame was adopted). Our next goal is to model the surface kinematics between 2017 and 2022. Besides horizontal deformations, this new model shall also cover vertical motions.

In the multiyear solutions before SIRGAS2022 (see Table 4), it was customary to approximate post-seismic motions with a sequence of constant velocities. In SIRGAS2022, periods with extensive seismic decay were removed from the analysis to determine reliable constant velocities valid for long periods. With these reliable constant velocities available, the weekly position estimates of stations affected by post-seismic decay are compared with the SIRGAS2022 linearly modelled positions, and the residuals are approximated by exponential or logarithmic functions. A forthcoming goal is to validate these models by correlation with geophysical models of earthquake response.

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Conflict of interest: Author states no conflict of interest.

Data availability statement: The SIRGAS science data products generated by DGFI–TUM are open access. Most of them are available at long-term data repositories like PANGAEA (Data Publisher for Earth & Environmental Science, https://www.pangaea.de/about/) or are provided via Internet and FTP media. DGFI–TUM hosted the SIRGAS portal https://www.sirgas.org/ between July 2007 and July 2021, when the SIRGAS Executive Committee moved the SIRGAS web site to https://sirgas.ipgh.org/. All official matters related to SIRGAS are available at the new site. The portal https://www.sirgas.org/ continues under the responsibility of DGFI–TUM, and it now presents analysis strategies, research results, and science data products generated by DGFI–TUM as a SIRGAS Processing and Combination Centre and as the IGS RNAAC SIRGAS. Thus, all the results described in this article are freely available at https://www.sirgas.org/.

References

Altamimi, Z., P. Sillard, and C. Boucher. 2002. "ITRF2000: A new release of the International Terrestrial Reference Frame for earth science applications." *Journal of Geophysical Research* 107(B10), 2214. doi: 10.1029/2001JB000561.

Altamimi, Z., X. Collilieux, J. Legrand, B. Garayt, and C. Boucher. 2007. "ITRF2005: A new release of the International Terrestrial Reference Frame based on time series of station positions and Earth Orientation Parameters." *Journal of Geophysical Research* 112, B09401. doi: 10.1029/2007JB004949.

Altamimi, Z., X. Collilieux, and L. Métivier. 2011. "ITRF2008: an improved solution of the international terrestrial reference frame." *Journal of Geodesy* 85, 457–73. doi: 10.1007/s00190-011-0444-4.

Altamimi, Z., P. Rebischung, L. Métivier, and X. Collilieux. 2016. "ITRF2014: A new release of the International Terrestrial Reference Frame modeling nonlinear station motions." *Journal of Geophysical Research and Solid Earth* 121, 6109–31. doi: 10.1002/2016JB013098.

Baez, J. C., S. C. R. De Freitas, H. Drewes, R. Dalazoana, and R.T. Luz. 2007. "Deformations control for the Chilean part of the SIRGAS 2000 frame." *International Association of Geodesy Symposia Series*, Vol. 130, p. 660–4. Berlin, Heidelberg: Springer. doi: 10.1007/978-3-540-49350-1_95.

Boehm, J., B. Werl, and Schuh H. 2006. "Troposphere mapping functions for GPS and very long baseline interferometry from European Centre for Medium-Range Weather Forecasts operational analysis data." *Journal of Geophysical Research* 111, B02406. doi: 10.1029/2005JB003629.

Boucher, C., Z. Altamimi and P. Sillard. 1999. *The International Terrestrial Reference Frame* (*ITRF97, IERS Technical Note 27*, p. 192. Paris: Central Bureau of IERS - Observatoire de Paris.

Brunini, C., L. Sánchez , H. Drewes, S. M. A. Costa, V. Mackern, W. Martinez, et al. 2012. "Improved analysis strategy and accessibility of the SIRGAS Reference Frame." *International Association of Geodesy Symposia Series*, Vol. 136, p. 3–10. Berlin, Heidelberg: Springer. doi: 10.1007/978-3-642-20338-1_1.

Caddess, H., H. Henneberg, E. Pallejá, and M. Pinch. 1993. "Inter-American geodetic integration." *International Association of Geodesy Symposia Series*, Vol. 111, p. 3–15. Berlin, Heidelberg: Springer. doi: 10.1007/978-3-642-88055-1_1.

Caubarrère, G. 2018. "Red Geodésica Nacional Activa de Uruguay (REGNA-ROU), Avances del proyecto IHRS, Centro Local de Procesamiento SIRGAS de Uruguay (SGM-Uy), Colaboración en el desarrollo de la Red Geodésica Nacional Activa de la República de Paraguay." *Symposium SIRGAS2018, Aguascalientes, Mexico, Oct 9–12, 2018*.

Chen, G. and T. A. Herring. 1997. "Effects of atmospheric azimuthal asymmetry on the analysis of space geodetic data." *Journal of Geophysical Research* 102(B9), 20489–502. doi: 10.1029/97JB01739.

Cioce, V., M. F. Rincón, E. Wildermann, G. Royero, R. Ceballos, C. Reinoza, et al. 2017. "Contribución de Venezuela al mantenimiento del marco de referencia continental: una mirada a las actividades de la Universidad del Zulia recientes del Centro de Procesamiento y Análisis GNSS SIRGAS." *Sympsoium SIRGAS2017, Mendoza, Argentina, Nov 22–Dec 1, 2017*.

Cisneros, D., R. Pazmiño , M. Amores, and Chavez A. 2013. "Actividades desarrolladas por el centro de procesamiento de datos GNSS del Ecuador – CEPGE." *Symposium SIRGAS2013, Panama City, Panama, Oct 24–26, 2013*.

Costa, S.M.A., A. L. Silva, and J. A. Vaz. 2012a. "Processing Evaluation of SIRGAS-CON Network by IBGE Analysis Center." *International Association of Geodesy Symposia*, Vol. 136, p. 868–9. Berlin, Heidelberg: Springer. doi: 10.1007/978-3-642-20338-1_108.

Costa, S. M. A., A. L. Silva, and J. A. Vaz. 2012b. "Report on the SIRGAS-CON Combined Solution, by IBGE Analysis Center." *International Association of Geodesy Symposia*, Vol. 136, p. 853–57. Berlin, Heidelberg: Springer. doi: 10.1007/978-3-642-20338-1_107.

Dach, R., S. Lutz, P. Walser, and Fridez P. Eds., 2015, *Bernese GNSS Software Version 5.2*. Astronomical Institute, University of Bern, https://boris.unibe.ch/id/eprint/72297.

Dach, R., S. Schaer, D. Arnold, M. S. Kalarus, L. Prange, P. Stebler, et al. 2020, *CODE final product series for the IGS*. Astronomical Institute, University of Bern. https://boris.unibe.ch/id/eprint/143807.

DGFI. 2002. Deutsches Geodätisches Forschungsinstitut (DGFI), Jahresbericht 2001/2002. DGFI, München. https://mediatum.ub.tum.de/doc/1295822/1295822.pdf.

Drewes, H. 1995. *Sistema de Referencia Geocentrico para America del Sur* (*SIRGAS*), *Proceedings IGS Workshop Densification of the IERS Terrestrial Reference Frame through regional GPS networks*, p. A65–73.

Drewes, H., L. P. Fortes, M. J. Hoyer, and R. Barriga. 1997. "Status report of the SIRGAS project." *IGS Annual Report 1996*, p. 433–6.

Drewes, H. and O. Heidbach. 2012. "The 2009 horizontal velocity field for South America and the Caribbean." *International Association of Geodesy Symposia Series*, Vol. 136, p. 657–64. Berlin, Heidelberg: Springer. doi: 10.1007/978-3-642-20338-1_81.

Drewes, H. and O. Heidbach. 2005. "Deformation of the South American crust estimated from finite element and collocation methods." *International Association of Geodesy Symposia Series*, Vol. 128, p. 544–49. Berlin, Heidelberg: Springer. doi: 10.1007/3-540-27432-4_6.

Drewes, H., K. Kaniuth, C. Voelksen, S. M. Alves Costa and L. P. Souto Fortes. 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, p. 32–7. Berlin, Heidelberg: Springer. doi: 10.1007/3-540-27432-4_6.

Drewes, H., H. Tremel, and J. N. Hernández. 1998. "Adjustment of the new Venezuelan national GPS network within the SIRGAS reference frame." *International Association of Geodesy Symposia Series*; Springer, Berlin, Heidelberg, 118, 193–8. doi: 10.1007/978-3-662-03714-0_31.

Drewes, H. and L. Sánchez. 2020. "Velocity model for SIRGAS 2017: VEMOS2017." *Technische Universitaet Muenchen, Deutsches Geodaetisches Forschungsinstitut* (*DGFI–TUM*), *IGS RNAAC SIRGAS*. doi: 10.1594/PANGAEA.912350.

Echalar, A. and L. Sánchez. 2010. Ajuste del Marco de Referencia Geodésico Nacional de Bolivia en SIRGAS: MARGEN-SIRGAS. SIRGAS-GTII Datum Geocéntrico. Instituto Geográfico Militar, La Paz, Bolivia. Deutsches Geodätisches Forschungsinstitut, Munich, Alemania, 18p, https://www.sirgas.org/fileadmin/docs/Reporte_MARGEN_SIRGAS.pdf.

Ferland, R. 2006a. [IGSMAIL-5447]: Proposed IGS05 Realization, https://lists.igs.org/pipermail/igsmail/2006/006818.html.

Ferland, R. 2006b. [IGSMAIL-5455]: IGS05 Fine Tuning, https://lists.igs.org/pipermail/igsmail/2006/006826.html.

Figueroa, C., W. Amaya, and L. Sánchez. 2010. Integración de la red geodésica básica nacional de El Salvador a SIRGAS. En: Revista Cartográfica, 85/86, 19–34. Instituto Panamericano de Geografía e Historia, Mexico.

Fortes, L. P., M. J. Hoyer, W. H. Subiza, and H. Drewes. 1995. "The SIRGAS project." *IGS Annual Report* 1994, 247–50.

Gasca, J. G. 2018. "Red Geodésica Nacional Activa en México 1993-2018." *Symposium SIRGAS2018, Aguascalientes, Mexico, Oct 9-12, 2018*.

Gendt, G. 2006. [IGSMAIL-5438]: IGS switch to absolute antenna model and ITRF2005, https://lists.igs.org/pipermail/igsmail/2006/006809.html.

Gómez, D., H. Guagni, D. Piñón, S. Cimbaro, and M. Bevis. 2018. "Nuevo clúster de procesamiento GNSS científico del Instituto Geográfico Nacional." *Symposium SIRGAS2018, Aguascalientes, Mexico, Oct 9–12, 2018*.

Griffiths, J. 2019. "Combined orbits and clocks from IGS second reprocessing." *Journal of Geodesy* 93, 177–95. doi: 10.1007/s00190-018-1149-8.

Herring, T. A., R. W. King, M. A. Floyd, and S. C. McClusky. 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, T. A., R. W. King , M. A. Floyd, and S. C. McClusky. 2018. GAMIT: GPS Analysis at MIT, Reference Manual, *Release* 10, 7. http://geoweb.mit.edu/gg/docs/GAMIT_Ref.pdf.

Hoyer, M., S. Arciniegas, K. Pereira, H. Fagard , R. Maturana , R. Torchetti, et al. 1998, "The definition and realization of the reference system in the SIRGAS project." *International Association of Geodesy Symposia Series*, Vol. 118, p. 167–73. Berlin, Heidelberg: Springer. doi: 10.1007/978-3-662-03714-0_27.

IGAC. 2021. La red geodésica nacional: Un servicio continuo y esencial para la planeación y el desarrollo territorial en Colombia, Subdirección de Geografía y Cartografía, Instituto Geográfico Agustín Codazzi – IGAC. Webinar SIRGAS: Actividades Geodésicas en las Americas, July 9, 2021.

Johnston, G., A. Riddell and G. Hausler. 2017. "The International GNSS Service. In Teunissen." Peter J.G., & Montenbruck, O., Eds.), *Springer Handbook of Global Navigation Satellite Systems*, 1st ed., p. 967–82. Cham, Switzerland: Springer International Publishing. doi: 10.1007/978-3-319-42928-1.

Kaniuth, K., H. Drewes, K. Stuber, H. Tremel, and J. Moirano. 1998. "Results of the SIRGAS95 GPS network processing at DGFI/I." *International Association of Geodesy Symposia Series*, Springer, Berlin, Heidelberg; 118, p. 180–6. doi: 10.1007/978-3-662-03714-0_29.

Kaniuth, K., H. Tremel , H. Drewes, K. Stuber, R. Maturana, and H. Parra. 2002. "Processing of the SIRGAS 2000 GPS campaign at DGFI." *International Association of Geodesy Symposia Series*, Vol. 124, p. 312–28. Berlin, Heidelberg: Springer. doi: 10.1007/978-3-662-04683-8_58.

Kehm, A., L. Sánchez, M. Bloßfeld, D. Angermann, H. Drewes, and F. Seitz. 2019. "Combination strategies for the realization of an Epoch Reference Frame for South America." *Geophysical Research Abstracts* 21, EGU2019-7951, 2019, EGU General Assembly 2019.

Kehm, A., L. Sánchez, M. Bloßfeld, M. Seitz, D. Angermann, H. Drewes, and F. Seitz. 2022. "Combination strategy for the geocentric realisation of regional epoch reference frames." *Journal of Geophysical Research: Solid Earth*, JGRB55890, doi: 10.1029/2021JB023880.

Kouba, J. 2015. A guide to using International GNSS Service products. https://files.igs.org/pub/resource/pubs/UsingIGSProductsVer21_cor.pdf.

Lyard, F. H., D. J. Allain, M. Cancet, L. Carrère, and N. Picot. 2021. "FES2014 global ocean tide atlas: design and performance." *Ocean Science* 17, 615–49. doi: 10.5194/os-17-615-2021.

Mackern, M. V., M. L. Mateo, A. V. Calori, A. M. Robin, and M. F. Camisay. 2012. Aportes a SIRGAS desde el centro de procesamiento CIMA: resultados obtenidos en el cálculo de la red SIRGAS-CON-D-SUR. Reunión SIRGAS2012, Concepción, Chile. Octubre 29–31, 2012.

Mackern, M. V., M. L. Mateo, M. F. Camisay and P. V. Morichetti. 2020. "Tropospheric Products from High-Level GNSS Processing in Latin America." *International Association of Geodesy Symposia Series*, 152. doi: 10.1007/1345_2020_121.

Moirano, J., C. Brunini, H. Drewes, and K. Kaniuth. 1998. "Realization of a geodetic reference system in Argentina in connection with SIRGAS." *International Association of Geodesy Symposia Series*, Vol. 118, p. 199–204. Berlin, Heidelberg: Springer. doi: 10.1007/978-3-662-03714-0_32.

Moya Zamora, J., S. Bastos Gutiérrez, and M. Mora Hernández. 2018. "Resultados del centro de procesamiento SIRGAS de Costta Rica: periodo 2018." *Symposium SIRGAS2018, Aguascalientes, Mexico, Oct 9–12, 2018*.

Petit, G. and B. Luzum Eds. 2010. "IERS Conventions 2010. IERS Technical Note 36. Verlag des Bundesamtes für Kartographie und Geodäsie." *Frankfurt a.M.*

Pollitz, F. F. and T. H. Dixon. 1998. "GPS measurements across the northern Caribbean plate boundary zone: Impact of postseismic relaxation following historic earthquakes." *Geophysical Research Letters* 25, 2233–6. doi: 10.1029/98GL00645.

Rebischung, P. 2011. [IGSMAIL-6354] Upcoming switch to IGS08/igs08.atx. https://lists.igs.org/pipermail/igsmail/2011/000188.html.

Rebischung, P. 2012. [IGSMAIL-6663] IGb08: an update on IGS08. https://lists.igs.org/pipermail/igsmail/2012/000497.html.

Rebischung, P. 2016. [IGSMAIL-7399] Upcoming switch to IGS14/igs14.atx. https://lists.igs.org/pipermail/igsmail/2016/001233.html, accessed on May 9, 2017.

Rebischung, P. 2020. [IGSMAIL-7921] Switch to IGb14 reference frame. https://lists.igs.org/pipermail/igsmail/2020/007917.html, accessed on April 4, 2020.

Rebischung, P. and R. Schmid. 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.

Rodríguez Rocca, K. D. 2021. *Implementación del Centro de Procesamiento Experimental SIRGAS PER* (*CPE-PER, Symposium SIRGAS2021, Lima, Peru. Nov 29–Dec 1, 2021*.

Rozas, S., I. Parada, C. Reyes, and C. Iturriaga. 2019. *Centro Oficial de Procesamiento SIRGAS IGM-CL: Instituto Geográfico Militar de Chile. Symposium SIRGAS2019, Río de Janeiro, Brazil. Nov 6–14, 2019*.

Sánchez, L. 2015. "SIRGAS Regional Network Associate Analysis Center, Technical Report 2014." Y. Jean and R. Dach, Eds. *International GNSS Service Technical Report 2014, 101–110, IGS Central Bureau*. https://kb.igs.org/hc/en-us/articles/206257267-Technical-Report-2014.

Sánchez, L., and C. Brunini. 2009. "Achievements and challenges of SIRGAS." *International Association of Geodesy Symposia Series*, Springer, Berlin, Heidelberg, 134, 161–6. doi: 10.1007/978-3-642-00860-3_25.

Sánchez, L., S. Cimbaro, V. Cioce , A. Echalar, G. González, W. Martínez, et al. 2012. "Improvement of the IGS station coverage in Latin America". *IGS Workshop 2012. Olsztyn, Polonia. July 24, 2012*, https://www.sirgas.org/fileadmin/docs/Boletines/IGS_stations_in_SIRGAS_A4.pdf.

Sánchez, L. and H. Drewes. 2016a. "Crustal deformation and surface kinematics after the 2010 earthquakes in Latin America." *Journal of Geodynamics*. doi: 10.1016/j.jog.2016.06.005.

Sánchez, L. and H. Drewes. 2016b. SIR15P01: Multiyear solution for the SIRGAS Reference Frame, Technische Universitaet Muenchen, Deutsches Geodaetisches Forschungsinstitut (DGFI–TUM), IGS RNAAC SIRGAS. doi: 10.1594/PANGAEA.862536.

Sánchez, L. and H. Drewes. 2016c. VEMOS2015: Velocity and deformation model for Latin America and the Caribbean, Technische Universitaet Muenchen, Deutsches Geodaetisches Forschungsinstitut (DGFI–TUM), IGS RNAAC SIRGAS. doi: 10.1594/PANGAEA.863131.

Sánchez, L. and H. Drewes. 2020a. "Geodetic monitoring of the variable surface deformation in Latin America." *International Association of Geodesy Symposia Series*. Vol. 152. Berlin, Heidelberg: Springer. doi: 10.1007/1345_2020_91.

Sánchez, L. and H. Drewes. 2020b. SIRGAS 2017 reference frame realization SIR17P01, Technische Universitaet Muenchen, Deutsches Geodaetisches Forschungsinstitut (DGFI–TUM), IGS RNAAC SIRGAS. doi: 10.1594/PANGAEA.912349.

Sánchez, L., H. Drewes, C. Brunini, M. V. Mackern, and W. Martínez-Díaz. 2016. "SIRGAS core network stability." *International Association of Geodesy Symposia Series*, Vol. 143, p. 183–90. Berlin, Heidelberg: Springer. doi: 10.1007/1345_2015_143.

Sánchez, L., W. Seemüller, H. Drewes, L. Mateo, G. González, A. Silva, et al. 2013. "Long-Term Stability of the SIRGAS Reference Frame and Episodic Station Movements Caused by the Seismic Activity in the SIRGAS Region." *International Association of Geodesy Symposia Series*. Vol. 138, p. 153–61. Berlin, Heidelberg: Springer. doi: 10.1007/978-3-642-32998-2_24.

Sánchez, L., W. Seemüller, and M. Seitz. 2012. "Combination of the Weekly Solutions Delivered by the SIRGAS Processing Centres for the SIRGAS-CON Reference Frame." *International Association of Geodesy Symposia Series*, Vol. 136, p. 845–51. Berlin, Heidelberg: Springer. doi: 10.1007/978-3-642-20338-1_106.

Sánchez, L. and M. Seitz. 2011a. "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*, Vol. 87, p. 48. doi: hdl:10013/epic.43995.d001.

Sánchez, L. and M. Seitz. 2011b. "SIRGAS reference frame realization SIR11P01." *Deutsches Geodätisches Forschungsinstitut, München* doi: 10.1594/PANGAEA.835100.

Savage, J. C. and W. H. Prescott. 1978. "Asthenosphere readjustment and the earthquake cycle." *Journal of Geophysical Research* 83, 3369–76. doi: 10.1029/JB083iB07p03369.

Schmid, R., P. Steigenberger, G. Gendt, M. Ge, and M. Rothacher. 2007. "Generation of a consistent absolute phase center correction model for GPS receiver and satellite antennas." *Journal of Geodesy* 81, 781–98. doi: 10.1007/s00190-007-0148-y.

Seemüller, W. and H. Drewes. 1998. "The IGS Regional Associate Analysis Center for South America at DGFI/I." *International Association of Geodesy Symposia Series*, Vol. 118, p. 211–5. Berlin, Heidelberg: Springer. doi: 10.1007/978-3-662-03714-0_34.

Seemüller, W. 2005. *Report on new activities of IGS Regional Associate Analysis for SIRGAS* (*IGS RNAAC SIR, Presented at the SIRGAS 2005 General Meeting. Caracas, Venezuela. November*. Available at http://www.sirgas.org/fileadmin/docs/Boletines/Bol09/21_Seemueller_IGS-RNAAC-SIR.pdf.

Seemüller, W. 2009. "The Position and Velocity Solution DGF06P01 for SIRGAS." *International Association of Geodesy Symposia Series*, Vol. 134, p. 167–72. Springer Verlag. doi: 10.1007/978-3-642-00860-3_26.

Seemüller, W. and H. Drewes. 2004. "Annual Report 2001 of IGS RNAAC SIR." In: *IGS 2001-2002 Technical Reports, JPL Publ. 04-017*, p. 285–90. https://kb.igs.org/hc/en-us/articles/202111876-Technical-Report-2001-2002.

Seemüller, W., K. Kaniuth, and H. Drewes. 2002. "Velocity estimates of IGS RNAAC SIRGAS stations." *International Association of Geodesy Symposia Series*, Vol. 124, p. 7–10. Springer Verlag. doi: 10.1007/978-3-662-04683-8_2.

Seemüller, W., K. Kaniuth, and H. Drewes. 2004. "Station positions and velocities of the IGS regional network for SIRGAS." *DGFI Report No. 76. Munich*. Available at http://www.sirgas.org/fileadmin/docs/DGFI_Report76.pdf.

Seemüller, W., M. Krügel, H. Drewes, and A. Abolghasem. 2007. "The new position and velocity solution DGF07P01 of the IGS Regional Network Associate Analysis Center for SIRGAS (IGS RNAAC SIR." In: *AGU Fall Meeting. San Francisco, USA, December 10–14*. Available at http://www.sirgas.org/fileadmin/docs/WS_DGF07P01.pdf.

Seemüller, W., M. Krügel, L. Sánchez, and H. Drewes. 2008. "The position and velocity solution DGF08P01 of the IGS Regional Network Associate Analysis Centre for SIRGAS (IGS RNAAC SIR)." *DGFI Report No. 79. DGFI, Munich*. http://www.sirgas.org/fileadmin/docs/Boletines/Bol13/DGFI_Report_on_IGS-RNAAC_SIR_Solution_DGF08P01.pdf.

Seemüller, W., L. Sánchez, and M. Seitz. 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, p. 675–80. Springer Verlag. doi: 10.1007/978-3-642-20338-1_110.

Seemüller, W., L. Sánchez, M. Seitz, and H. Drewes. 2010. "The position and velocity solution SIR10P01 of the IGS Regional Network Associate Analysis Centre for SIRGAS (IGS RNAAC SIR)." *DGFI Report No. 86, Munich*. http://www.sirgas.org/fileadmin/docs/SIR10P01_DGFI_Report_86.pdf.

Seemüller, W., M. Seitz , L. Sánchez, and H. Drewes. 2009. "The position and velocity solution SIR09P01 of the IGS Regional Network Associate Analysis Centre for SIRGAS (IGS RNAAC

SIR).” *DGFI Report No. 85, Munich*. http://www.sirgas.org/fileadmin/docs/DGFI_Report85.pdf.

SIRGAS Project Committee. 1997. *SIRGAS Final Report; Working Groups I and II IBGE*, Rio de Janeiro, 96.

Tarrío, J. A., S. Costa, A. da Silva, and J. Inzunza. 2021. “Processing guidelines for the SIRGAS analysis centres.” *SIRGAS Working Group I*. doi: 10.35588/dig.g3.2021.

Tarrío, J. A., C. Soto, A. González, B. Barraza, F. Isla, and M. Caverlotti. 2020. “Geodesy in Chile (SIRGAS USC CENTER): a place where the 4D component presents its maximum expression.” *GIM International May-June 2020*, 33, https://www.gim-international.com/magazine/may-june-2020.

Tremel, H., L. Sánchez and H. Drewes. 2001. “Procesamiento de la red GPS basica de Colombia: Marco Geocentrico Nacional - MAGNA.” *Revista Cartografica IPGH; No. 73*. p. 7–23.

van Dam, T. and R. Ray. 2010, S1 and S2 atmospheric tide loading effects for geodetic applications. Data set accessed 2022-04-15 at https://geophy.uni.lu/atmosphere/tide-loading-calculator/ATM1OnlineCalculator/.

Wessel, P., J. F. Luis, L. Uieda, R. Scharroo, F. Wobbe, W. H. F. Smith, et al. 2019. “The Generic Mapping Tools version 6.” *Geochemistry, Geophysics, Geosystems* 20, 5556–64. doi: 10.1029/2019GC008515.